DATE FILED: June 28, 2023 5:06 AM

SUPREME COURT OF COLORADO 2 East 14th Ave. Denver, CO 80203	
Original Proceeding Pursuant to Colo. Rev. Stat. § 1-40-107(2) Appeal from the Ballot Title Board	
In the Matter of Title, Ballot Title, and Submission Clause for Proposed Initiative 2023-2024 #46 (Concerning Oil and Gas Permits That Incorporate the Use of Fracking) **Petitioner:** Steven Ward **v.** **Respondents:** Paul Culnan and Patricia Nelson **and** **Title Board:** Theresa Conley, Kurt Morrison, and Jerry Barry	**▲ COURT USE ONLY ▲**
Attorney for Petitioner: Suzanne M. Taheri, #23411 WEST GROUP LAW & POLICY 6501 E. Belleview Ave, Suite 375 Englewood, CO 80111 Phone Number: (303) 263-0844 Email: st@westglp.com	Case Number:

PETITION FOR REVIEW OF FINAL ACTION OF BALLOT TITLE SETTING BOARD CONCERNING PROPOSED INITIATIVE 2023-2024 #46 ("CONCERNING OIL AND GAS PERMITS THAT INCORPORATE THE USE OF FRACKING")

On behalf of Steven Ward, a registered elector of the State of Colorado, the undersigned counsel hereby respectfully petitions this Court to review the actions of the Ballot Title Setting Board with respect to Proposed Initiative 2023-2024 #46 – Concerning Oil and Gas Permits That Incorporate the Use of Fracking, pursuant to Section 1-40-107, C.R.S.

STATEMENT OF THE CASE

A. Procedural History of Proposed Initiative 2023-2024 #46

Paul Culnan and Patricia Nelson (hereafter "Proponents") proposed Initiative 2023-2024 #46 (the "Proposed Initiative"). Proponents submitted their Proposed initiative to the Title Board for setting of a title and submission clause pursuant to § 1-40-106, C.R.S.

The Title Board held a hearing on May 17, 2023, where it was determined that the Proposed Initiative contained a single subject as required by Colo. Const. art. V, §1(5.5) and § 1-40-106.5, C.R.S., and set a title. On May 24, 2023, Petitioner filed a Motion for Rehearing stating that the Proposed Initiative does not constitute a single subject and that the Title Board set misleading titles and included a catch phrase on the ballot title.

The Title Board held a rehearing on June 21, 2023, at which time the Board denied Petitioner's Motion for Rehearing in its entirety.

B. Jurisdiction

Petitioner is timely requesting a review of the actions of the Title Board by the Supreme Court pursuant to § 1-40-107(2), C.R.S.

As required by § 1-40-107(2), C.R.S., attached to this Petition for Review are certified copies of the final copy of the Proposed Initiative as submitted to the Title Board, the determination by the Title Board at its initial hearing on the Proposed Initiative, the initial Fiscal Summary for the Proposed Initiative prepared by the Director of Research of the Legislative Council of the General Assembly, the Motions for Rehearing; and the determination by the Title Board to deny the Motions for Rehearing.

GROUNDS FOR REVIEW

Petitioner respectfully submits that the Title Board erred in its determination with respect to the single subject and clear title requirements in Colo. Const. art. V, §1(5.5), and §§1-40-106 and 1-40-106.5, C.R.S. As outlined in the Motion for Rehearing, the Proposed Initiative contains multiple subjects and fails to describe the purpose and effects of the Proposed Initiative fairly or accurately.

PRAYER FOR RELIEF

Petitioner respectfully requests that, after consideration of the parties' briefs, this Court reverse the determination of the Title Board and direct the Title Board to reject title setting for the Proposed Initiative because it contains more than one subject or otherwise direct the Title Board to correct the title to address the deficiencies outlined in the Petitioner's briefs.

Dated: June 26, 2023

Respectfully submitted,

s/Suzanne Taheri
Suzanne Taheri #23411
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CERTIFICATE OF SERVICE

I hereby certify that on this 28th day of June, 2023, a true and correct copy of the **PETITION FOR REVIEW OF FINAL ACTION OF BALLOT TITLE SETTING BOARD CONCERNING PROPOSED INITIATIVE 2023-2024 #46 ("CONCERNING OIL AND GAS PERMITS THAT INCORPORATE THE USE OF FRACKING")** was served via the Colorado Court's E-Filing System to the following:

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Suzanne Taheri

Duly signed original on file at West Group

DATE FILED: June 28, 2023 5:06 AM

STATE OF COLORADO

DEPARTMENT OF STATE

CERTIFICATE

I, **JENA GRISWOLD,** Secretary of State of the State of Colorado, do hereby certify that:

the attached are true and exact copies of the filed text, fiscal summary, motion for rehearing, and the rulings thereon of the Title Board for Proposed Initiative "2023-2024 #46 'Concerning Oil and Gas Permits That Incorporate the Use of Fracking'"..

......................................**IN TESTIMONY WHEREOF** I have unto set my hand ....
and affixed the Great Seal of the State of Colorado,
at the City of Denver this **23**rd day of June, 2023.

SECRETARY OF STATE

<u>Ballot Title Setting Board</u>

Proposed Initiative 2023-2024 #46[1]

The title as designated and fixed by the Board is as follows:

A change to the Colorado Revised Statutes concerning discontinuing the issuance of new oil and gas operation permits that utilize fracking by December 31, 2030, and, in connection therewith, requiring the phase-out of new oil and gas operation permits that utilize fracking; allowing permitted oil and gas operations that utilize fracking to continue; and requiring the state to explore transition strategies for impacted oil and gas workers who may transition to other employment.

The ballot title and submission clause as designated and fixed by the Board is as follows:

Shall there be a change to the Colorado Revised Statutes concerning discontinuing the issuance of new oil and gas operation permits that utilize fracking by December 31, 2030, and, in connection therewith, requiring the phase-out of new oil and gas operation permits that utilize fracking; allowing permitted oil and gas operations that utilize fracking to continue; and requiring the state to explore transition strategies for impacted oil and gas workers who may transition to other employment?

Hearing May 17, 2023:
Single subject approved; staff draft amended; titles set.
The Board made a technical correction to the text of the initiative.
Board members: Theresa Conley, Kurt Morrison, Jerry Barry
Hearing adjourned 4:28 P.M.

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[1] Unofficially captioned **"Concerning Oil and Gas Permits That Incorporate the Use of Fracking"** by legislative staff for tracking purposes. This caption is not part of the titles set by the Board.

Ballot Title Setting Board

Proposed Initiative 2023-2024 #46[1]

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Hearing May 17, 2023:
Single subject approved; staff draft amended; titles set.
The Board made a technical correction to the text of the initiative.
Board members: Theresa Conley, Kurt Morrison, Jerry Barry
Hearing adjourned 4:28 P.M.

Hearing June 21, 2023:
Foster and Ward motions for rehearing were denied in their entirety.
Proponents motion for rehearing denied in its entirety.
Board members: Theresa Conley, Kurt Morrison, Jerry Barry
Hearing adjourned 12:15 P.M.

[1] Unofficially captioned **"Concerning Oil and Gas Permits That Incorporate the Use of Fracking"** by legislative staff for tracking purposes. This caption is not part of the titles set by the Board.

Be it Enacted by the People of the State of Colorado:

SECTION 1. Declaration of purpose. (1) The People of the State of Colorado find and declare that:

(a) Protecting Colorado's land, air, and water depends upon an expeditious transition from polluting fossil fuel energy sources to clean energy sources;

(b) The use of fracking during oil and gas operations in our state contributes significantly to water shortages and degradation, ozone pollution, and greenhouse gas emissions, which lead to increased drought, wildfires, and dangerous air quality, which results in significant harm to public health and safety, agriculture, winter sports, and other sectors of our economy;

(c) Ending the expansion of oil and gas operations using fracking in an orderly and planned manner through a gradual phase out of new permits by 2030, and prioritizing permit reductions in disproportionately impacted communities, will reduce greenhouse gas emissions and other pollution, protect lands and water, and enhance economic growth in the state as part of an ongoing transition to clean renewable energy; and

(d) Workforce development and other assistance for impacted workers and communities will help to ensure the most successful energy transition.

SECTION 2. In Colorado Revised Statutes, 34-60-103, **add** (4.1) and (4.7) as follows:

34-60-103. Definitions. As used in this article 60, unless the context otherwise requires:

(4.1) "DISPROPORTIONATELY IMPACTED COMMUNITY" HAS THE SAME MEANING AS PROVIDED IN SECTION 24-4-109(2)(b)(II).

(4.7) "FRACKING," OTHERWISE KNOWN AS "HYDRAULIC FRACTURING," MEANS AN OIL AND GAS EXTRACTION PROCESS IN WHICH FRACTURES IN ROCKS BELOW THE EARTH'S SURFACE ARE OPENED AND WIDENED BY INJECTING PROPPANTS, WATER, AND CHEMICALS AT HIGH PRESSURE.

SECTION 3. In Colorado Revised Statutes, 34-60-106, **amend** (2.5)(b); and **add** (20.5) as follows:

34-60-106. Additional powers of commission – rules – definitions – repeal.

(2.5)(b) The nonproduction of oil and gas resulting from a conditional approval or denial authorized by this subsection (2.5), AND THE PHASING OUT AND DISCONTINUATION OF NEW OIL AND GAS OPERATION PERMITS REQUIRED BY SUBSECTION (20.5) OF THIS SECTION, ~~does~~ DO not constitute waste.

(20.5) BY JANUARY 1, 2026, TO REDUCE WATER CONSUMPTION, LOWER GREENHOUSE GASES AND OTHER POLLUTANTS, AND PROTECT LAND, AIR, AND WATER, THE COMMISSION SHALL PROMULGATE RULES TO DISCONTINUE THE ISSUANCE OF NEW OIL AND GAS PERMITS THAT INCORPORATE THE USE OF FRACKING BY DECEMBER 31, 2030. AT A MINIMUM, THE RULES MUST ADDRESS:

(a) A TIMETABLE FOR THE ORDERLY SUBMISSION AND CONSIDERATION OF APPLICATIONS FOR NEW OIL AND GAS PERMITS INCORPORATING THE USE OF FRACKING BY OPERATORS BETWEEN JANUARY 1, 2026, AND DECEMBER 31, 2030, WITH CRITERIA FOR AN ITERATIVE AND CONSISTENT

REDUCTION IN PERMITS APPROVED EACH YEAR DURING THAT TIME PERIOD, WHILE PRIORITIZING REDUCTIONS IN DISPROPORTIONATELY IMPACTED COMMUNITIES;

(b) THE REPEAL OF EXISTING COMMISSION RULES RELATED TO THE ISSUANCE OF NEW PERMITS, AS DEFINED IN SECTION 34-60-103(7.5), THAT INCORPORATE THE USE OF FRACKING;

(c) THE AMENDMENT OF CURRENT COMMISSION RULES TO PROHIBIT THE MODIFICATION AND REQUIRE THE EXPIRATION OF ALL PREVIOUSLY ISSUED PERMITS THAT INCORPORATE THE USE OF FRACKING BY DECEMBER 31, 2033, IF DRILLING OPERATIONS HAVE NOT COMMENCED BY THAT DATE;

(d) THE CONTINUATION OF COMMISSION RULES ENSURING THE PROTECTION OF PUBLIC HEALTH, SAFETY, WELFARE, THE ENVIRONMENT, AND WILDLIFE FOR ALL EXISTING OIL AND GAS OPERATIONS; AND

(e) TRANSITIONING THE COMMISSION'S DUTIES TO PRIMARILY THE MONITORING, PLUGGING, AND REMEDIATING OF FACILITIES PERMITTED PRIOR TO DECEMBER 31, 2030, AND THE PERMITTING OF ANY NEW OIL AND GAS FACILITIES AND OIL AND GAS LOCATIONS THAT ARE NOT PROHIBITED BY SECTION 34-60-106(20.5).

SECTION 4. In Colorado Revised Statutes, 29-20-104, **amend** (1)(h)(II) as follows:

29-20-104. Powers of local governments – definition. (1) Except as expressly provided in section 29-20-104.5, the power and authority granted by this section does not limit any power or authority presently exercised or previously granted. Each local government within its respective jurisdiction has the authority to plan for and regulate the use of land by:

(h) Regulating the surface impacts of oil and gas operations in a reasonable manner to address matters specified in this subsection (1)(h) and to protect and minimize adverse impacts to public health, safety, and welfare and the environment. Nothing in this subsection (1)(h) is intended to alter, expand, or diminish the authority of local governments to regulate air quality under section 25-7-128. For purposes of this subsection (1)(h), "minimize adverse impacts" means, to the extent necessary and reasonable, to protect public health, safety, and welfare and the environment by avoiding adverse impacts from oil and gas operations and minimizing and mitigating the extent and severity of those impacts that cannot be avoided. The following matters are covered by this subsection (1)(h):

(II) The location and siting of oil and gas facilities and oil and gas locations, as those terms are defined in section 34-60-103 (6.2) and (6.4), EXCEPT FOR THOSE OIL AND GAS FACILITIES AND OIL AND GAS LOCATIONS PROHIBITED BY SECTION 34-60-106(20.5).

SECTION 5. In Colorado Revised Statutes, **add** 8-83-604 as follows:

8-83-604. Oil and gas worker transition – office of future of work. ON OR BEFORE JUNE 1, 2025, THE OFFICE SHALL CREATE A PROGRAM TO EXPLORE TRANSITION STRATEGIES FOR OIL AND GAS WORKERS. THE PURPOSE OF THE PROGRAM IS TO IDENTIFY STRATEGIES AND FUNDING TO ASSIST SECTORS OF OIL AND GAS EMPLOYEES WHO WILL TRANSITION TO OTHER EMPLOYMENT AS A RESULT OF THE STATE'S REDUCED RELIANCE ON FOSSIL FUEL EXTRACTION. THE OFFICE SHALL CONSULT WITH OTHER RELEVANT OFFICES AND AGENCIES WITHIN THE STATE AND RELEVANT OFFICES OR AGENCIES OUTSIDE OF THE STATE REGARDING SUCCESSFUL WORKFORCE TRANSITION MODELS AND PROGRAMS IMPLEMENTED BY THOSE OFFICES OR AGENCIES. THE PROGRAM MUST EXPLORE FEDERAL, STATE, AND LOCAL SOURCES OF FUNDING AND FINANCIAL INCENTIVES TO ASSIST

TRANSITIONING WORKERS AND COMMUNITIES ECONOMICALLY RELIANT ON OIL AND GAS PRODUCTION.

SECTION 6. **Effective Date**:

This act takes effect on the date of the proclamation of the Governor announcing the approval, by the registered electors of the state, of the proposed initiative.

IN RE: TITLE, BALLOT TITLE, AND SUBMISSION CLAUSE FOR INITIATIVE 2023-2024 #46 ("CONCERNING OIL AND GAS PERMITS THAT INCORPORATE THE USE OF FRACKING")

Initiative Proponents;
Paul Culnan and Patricia Nelson

Objector:
Timothy E. Foster

MOTION FOR REHEARING

By undersigned counsel, Timothy E. Foster, a registered voter of Mesa County, objects to the titles set for Initiative #46, pursuant to C.R.S. § 1-40-107(1)(a)(I).

On May 3, 2023, the Title Board set the following ballot title and submission clause for Initiative #46:

> *Shall there be a change to the Colorado Revised Statutes concerning discontinuing the issuance of new oil and gas operation permits that utilize fracking by December 31, 2030, and, in connection therewith, requiring the phase-out of new oil and gas operation permits that utilize fracking; allowing permitted oil and gas operations that utilize fracking to continue; and requiring the state to explore transition strategies for impacted oil and gas workers who may transition to other employment?*

I. The Board approved a misleading and inaccurate title.

A. The titles uses a term ("fracking") that is jargon and will mislead voters, and this confusion will be substantial as the titles use this term three (3) times.

Proposed section 34-60-103(45.7) of this initiative defines "fracking" as follows;

> "FRACKING," OTHERWISE KNOWN AS "HYDRAULIC FRACTURING," MEANS AN OIL AND GAS EXTRACTION PROCESS IN WHICH FRACTURES IN ROCKS BELOW THE EARTH'S SURFACE ARE OPENED AND WIDENED BY INJECTING PROPPANTS, WATER, AND CHEMICALS AT HIGH PRESSURE."

1. *"Fracking" is not a commonly understood term, as it is jargon for "hyrdraulic fracturing" and connotes multiple, conflicting popular meanings.*

According to one of the state's leading scholars on contemporary issues in the American West, Professor Patricia Limerick of the University of Colorado who directed the Center of the American West at CU,[1] "Even the most fundamental terms can lead conversationalists into muddles; in some instances, **participants in the unconventional oil and gas debate use the exact same words in very different ways** (for a case study, head straight to hydraulic fracturing)." *See* https://www.colorado.edu/center/west/projects-publications/energy-mining/hydraulic-fracturing-glossary#Hydraulic%20Fracturing (last viewed May 22, 2023) (emphasis added). In that regard, "In public debates about unconventional oil and gas extraction, **the terms 'hydraulic fracturing' and 'fracking' are used in multiple, and sometimes conflicting, ways.** The confusion this causes has the potential to derail conversations and stall communication." *Id.* (emphasis added).

The specifics of miscommunication around this term are telling. "**Some people use 'hydraulic fracturing' and 'fracking' to mean the particular and specific technique** used to fracture oil-and-gas-bearing formations far below the surface. **Others use the terms to mean the whole process of constructing and operating a well, plus maintaining and operating surface facilities** like compressors, storage ponds, and pipelines." *Id.* (emphasis added). Thus, "fracking" is as easily and regularly interpreted to mean a technology used to recover certain oil and gas reserves as it is to mean the entire recovery operation, including all of the involved facilities and processes. This latter meaning is inconsistent with proposed section 34-60-103(45.7) in #46.

Prof. Limerick's caution relates directly to the exercise of setting a ballot title on this topic. "**This disconnection in meaning can cause participants in the same conversation to talk past each other. Clear use of terms is key to making conversations on** hydraulic fracturing (or '**fracking**') productive and **meaningful**." *Id.* (emphasis added). Certainly, that clarity is the goal of this Board and the title setting process generally.

Thus, the use of "fracking" in the titles is likely to leave voters with inconsistent and inaccurate understandings of the measure on which they are asked to vote.

2. *"Fracking" has multiple defined meanings on which voters are likely to rely, and if left unaddressed in the titles, this inconsistency will mislead voters.*

As noted above, #46 defines "fracking" as "an oil and gas extraction process in which fractures in rocks below the earth's surface are opened and widened by injecting proppants, water, and chemicals at high pressure." But this definition does not reflect the common definition(s) used for "fracking."

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[1] Prof. Limerick's professional qualifications can be found at https://www.colorado.edu/center/west/about/patty-limerick (last viewed May 23, 2023). Her co-authors for the material cited here were Prof. Adrianne Kroepsch and Will Rempel of the University of Colorado.

For example, at the initial title setting hearing, proponents pointed the Title Board to an industry trade association website that asks, "What is fracking?" But when that publicly accessible source answers the question, it does so with a definition that varies in a material way from proposed section 34-60-103(45.7). It adds the element, not found in #46, of conditioning "fracking" on the use of "a technique known as horizontal drilling."

> Fracking, or hydraulic fracturing, first invented in 1947, is the process of extracting oil or natural gas from rock formations through drilling – today, **using a technique known as horizontal drilling** – and then using high pressured water to move the natural gas or oil to the surface where it is collected.

https://www.cred.org/explore/what-is-fracking (last viewed May 22, 2023) (emphasis added). But Initiative #46's definition of "fracking" is not limited to horizontal drilling and thus is significantly broader than the source of common understanding identified by Proponents. In addition to this difference from #46, this definition omits the elements of a process using "proppants" and "chemicals" which are contained in #46's definition.

Additionally, the dictionary definition of "fracking" to which Prof. Limerick pointed in her writing, cited above, is the Merriam-Webster dictionary definition, and it states that "fracking" means "the **injection of fluid** into shale beds at high pressure in order to free up petroleum resources (such as oil or natural gas)." https://www.merriam-webster.com/dictionary/fracking (last viewed May 22, 2023) (emphasis added). Unlike proposed section 34-60-103(45.7), this definition refers to the injection of "fluid" rather than "water" and omits any reference to "proppants" or "chemicals."

As if these meanings did not create enough concern, HB22-1348 was adopted last year and amended the same title, article, and part of the Colorado Revised Statutes as #46 seeks to amend. Section 1, subsection (2)(b) of that bill's legislative declaration equates "hydraulic fracturing" with "fracking" in a manner similar to proposed section 34-60-103(45.7) of #46. *See* https://leg.colorado.gov/sites/default/files/2022a_1348_signed.pdf (last viewed May 22, 2023).

That law's definition of "hydraulic fracturing treatment" is different than #46's definition of fracking/hydraulic fracturing. Under C.R.S. § 34-60-132(p), a hydraulic fracturing treatment "means all stages of the treatment of a well by the application of hydraulic fracturing fluid under pressure, which treatment is expressly designed to initiate or propagate fractures in an underground geologic formation to enhance the production of oil and gas." As compared to #46, this current statutory definition does not refer to "proppants" or "chemicals," substitutes "fluid" for "water," requires only "pressure" rather than "high pressure," and includes "all stages" of the process instead of just the "extraction process" addressed by #46.

Therefore, however common a word "fracking" may be in common parlance, it isn't a term that has a commonly accepted or understood meaning. That gap in understanding will lead to a similar gap in voter appreciation on what Initiative #46 is seeking to accomplish and should not be embraced in these titles.

> *3. "Fracking" is accomplished in ways that do not meet this measure's definition of the term, but voters can only presume the titles' unqualified reference to "fracking" is all-inclusive.*

Initiative #46 conditions "fracking" on the use of the injection of "water, proppants, and chemicals at high pressure." But there are waterless fracking technologies as well, and because "fracking" is not defined in the ballot title, voters would be lead to believe that the waterless technologies are also included.

For instance, one form of fracking uses carbon dioxide instead of water in the fracturing process. https://pubs.acs.org/doi/pdf/10.1021/acsomega.1c01059 (last viewed May 22, 2023). Other technologies include using liquid petroleum gas or emulsion-based fluids as "waterless" forms of this process. *See* Joint Research Center of European Commission, "State of the art report on waterless stimulation techniques for shale formations," 4-6, 8-9 (2016). https://publications.jrc.ec.europa.eu/repository/handle/JRC103643 (last viewed May 23, 2023).

By its terms, Initiative #46 would not affect these alternative technologies. But voters would not be aware of that fact, based on the use of a too-inclusive term, "fracking," in the titles.

> *4. To provide clarity to voters, the initiative's definition should be used instead of the term that causes confusion.*

Titles must not include vague language that leads to voter confusion. "[T]he clear title requirement seeks to accomplish two overarching goals: prevent voter confusion and ensure that the title adequately expresses the initiative's intended purpose." *In re Title, Ballot Title & Submission Clause for 2015-2016 #156*, 2016 CO 56, ¶11, 413 P.3d 151, 153. Titles should use a definition that "adopts a legal standard that is new and likely to be controversial, even though limited in application to the implementation of the proposed" measure. *In re Proposed Initiative on Parental Notification of Abortions for Minors*, 794 P.2d 238, 242 (Colo. 1990).

To meet those standards, the titles here should be revised as follows, even if the other changes addressed elsewhere in this motion are not also made:

> *Shall there be a change to the Colorado Revised Statutes concerning discontinuing by December 31, 2030 the issuance of new oil and gas operation permits that utilize ~~fracking~~ an oil and gas extraction process in which fractures in rocks below the earth's surface are opened and widened by injecting, at high pressure, water, chemicals, and materials intended to prevent fractures from closing[2] ~~by December 31, 2030~~, and, in connection therewith, requiring the phase-out of such new oil and gas operation permits ~~that utilize fracking~~; allowing permitted oil and gas operations ~~that utilize fracking~~ to continue; and requiring the state to explore transition strategies for impacted oil and gas workers who may transition to other employment?*

[2] Initiative #46's definition lists injections of "proppants, water, and chemicals." As "proppants" is defined by the statute to be amended by #46 as "materials inserted or injected into an underground geologic formation during a hydraulic fracturing treatment that are intended to prevent fractures from closing," C.R.S. § 34-60-132(s), that definition is used in this title language to provide clarity to voters.

Besides its clarity that will benefit voters, this revised language also meets the Supreme Court's test for ballot titles dealing with the issue of oil and gas development raised by #46. In *In the Matter of the Title, Ballot Title and Submission Clause for Initiative 2013-2014 #90*, 2014 CO 63, 328 P.3d 155, the Court found that a ballot title that referred to "oil and gas development" did not need to also include the phrase, "including hydraulic fracturing." Even though "including hydraulic fracturing" was part of the proposed initiative in *#90*, it was not needed in the titles as "the reference in the title to 'oil and gas development' is sufficient to describe the scope of the initiative." *Id.* at ¶36. Here, #46 refers to an "oil and gas extraction process," and the title could do use that wording to meet the clear title requirement in law.

B. The title is misleading as it states only "permitted" oil and gas operations will be allowed to continue their operations.

The title states that #46 "allow[s] permitted oil and gas operations to continue." Here, "permitted" is a vague term, given the double meaning of that word as "allowed" or "authorized" or as having received a "permit" from the Colorado Oil and Gas Commission.

C. The title is misleading in stating that the measure "allow[s] permitted oil and gas operations to continue" as there is no such provision in #46.

Initiative #46 does not expressly provide for the continued operation of any permitted location or facilities. At most, it provides for "[t]he continuation of commission rules ensuring the protection of public health, safety, welfare, the environment, and wildlife for all existing oil and gas operations." *See* proposed § 34-60-106(20.5)(d).

In other words, #46 provides for continued rules for issues *relating to* oil and gas operations. It does not affirmatively provide for continuation of oil and gas operations in their own right. If such continuation may occur due to already existing laws, that is a characterization of current law that is beyond the Title Board's power to include here. This phrase should thus be deleted from the titles.

D. The title is misleading where it in referring to the "phasing out" of permits.

The title states that this measure "requir[es] the phase-out of new oil and gas operation permits." This reference will confuse voters.

The common meaning of "phase-out" is "to stop using something gradually in stages over a period of time."[3] As a result, voters will be left with the impression that #46 imposes limited *durations* on any new permits granted. But that's not what the measure does. It changes the Commission's power to grant permits rather than changing the effective period during which new permits can be used.

[3] https://www.oxfordlearnersdictionaries.com/us/definition/american_english/phase-out#:~:text=phase%20somethingout&text=to%20stop%20using%20something%20gradually,phased%20out%20by%20next%20year.

In terms of the substantive law changed by this measure, #46 only uses "phasing out" of a new permit regarding its provision that its new limits "do not constitute waste." *See* proposed § 34-60-106(2.5)(b). To the extent that Proponents intend that "phasing out" is shorthand for the required "reduction in permits approved each year" between 2026 and 2030, the title should be specific about that construction, as addressed above.

E. The title is misleading because it does not reflect #46's prohibition on permit modification or its required expiration of certain of the new permits.

Initiative #46 requires Commission rules "to **prohibit** the modification and require the expiration of all previously issued permits by December 31, 2033, if drilling operations have not commenced by that date." *See* proposed § 34-60-106(20.5)(c); *see also* proposed § 29-20-104(1)(h)(II) (permitting of new facilities and locations "is prohibited pursuant to section 34-60-106(20.5)").

A provision that alters the modification of operating permits is a key element of an initiative. Changes to what will or will not be permitted under the initiative – such as potential modification of permits – must be accurately described in the titles. *See In re Title, Ballot Title and Submission Clause, and Summary for Initiative 1999-2000 #215*, 3 P.3d 11 (Colo. 2000) (striking title language that incorrectly portrayed a measure's limit on modifying certain extractive permits).

Similarly, the title is silent about the required expiration of permits granted where oil and gas production has not commenced. The measure does not just limit the number of new permits to be issued but also reimposes time clock for activation of certain of those new permits. This is an important feature of Initiative #46 that should be related in the titles.

F. The title is misleading in that it does not relate that the measure specifically "prohibit[s]" permitting of any new "oil and gas facilities" and "oil and gas locations."

This title is couched as a discontinuation of permitting of oil and gas operations. But the measure itself refers to the legal changes as a prohibition. *See* proposed § 34-60-106(20.5)(c) (permit modification is prohibited) and § 29-20-104(1)(h)(II) (permitting of new oil and gas facilities and locations is prohibited).

In addition, the title does not identify to what this prohibition applies. Yet, the measure is specific that it applies to "oil and gas facilities" and "oil and gas locations" which have specific definitions that are different than "oil and gas operations." *Compare* C.R.S. § 34-60-103(6.2), (6.4), and (6.5).

The titles should be specific as to the measure's undisputed "prohibition" on permitting of oil and gas "facilities" and "locations."

RESPECTFULLY SUBMITTED this 24th day of May, 2023.

RECHT KORNFELD, P.C.

s/ Mark Grueskin
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CERTIFICATE OF SERVICE

I, Mark Grueskin, hereby affirm that a true and accurate copy of the **MOTION FOR REHEARING ON INITIATIVE 2023-2024 #46** was sent this day, May 24, 2023, via email to Paul Culnan and Patricia Nelson, via their counsel of record, Martha Tierney, at:

mtierney@tls.legal

s/ Mark Grueskin

EXHIBIT
Morant
Foster A

DISTRICT COURT, CITY AND COUNTY OF DENVER, COLORADO 1437 Bannock Street Denver, CO 80202	
STEVEN WARD, et al., Plaintiffs, v. STATE OF COLORADO, by and through JARED S. POLIS, in his official capacity as Governor of Colorado, et al., Defendants.	▲ COURT USE ONLY ▲
PHILIP J. WEISER, Attorney General RUSSELL D. JOHNSON, Sr. Assistant Attorney General* SHELBY A. KRANTZ, Assistant Attorney General* REED MORGAN, Assistant Attorney General* DANNY RHEINER, Assistant Attorney General* JEREMY JOHNSTON, Assistant Attorney General* SKYE WALKER, Assistant Attorney General Fellow* YOU NA HAN, Assistant Attorney General Fellow* Ralph L. Carr Colorado Judicial Center 1300 Broadway, 8th Floor Denver, CO 80203 Telephone: 720-508-6351 (Johnson); x6437 (Krantz); x6335 (Morgan); x6570 (Rheiner); x6345 (Johnston); x6767 (Walker); x 6392 (Han) FAX: 720-508-6038 E-Mail: russell.johnson@coag.gov; shelby.krantz@coag.gov; reed.morgan@coag.gov; danny.rheiner@coag.gov; jeremy.johnston@coag.gov; skye.walker@coag.gov; youna.han@coag.gov Registration Numbers: 48482 (Johnson); 53866 (Krantz); 40972 (Morgan); 48821 (Rheiner); 54424 (Johnston); 58330 (Walker); 57881 (Han) *Counsel of Record	Case No. 2023CV31432

JOINT MOTION TO EXCLUDE EXPERT TESTIMONY OF SETH MASKET

Defendant State of Colorado, by and through Jared S. Polis, in his official capacity as Governor of Colorado, and Jena Griswold, in her official capacity as Secretary of State[1] (collectively, "the State"), respectfully submit this Motion to Exclude Expert Testimony of Dr. Seth Masket ("Motion").

C.R.C.P. 121 § 1-15(8) Certification. Counsel for the State have conferred with counsel for Plaintiffs via email regarding this Motion. Although Plaintiffs provided a second expert disclosure during conferral, the State disagrees that such disclosure cured the deficiencies in the initial expert disclosure. Plaintiffs also asserted that Dr. Masket would not testify regarding ultimate conclusions of law; as argued below, the State disagrees. For these reasons, the parties were unable to reach a resolution. Plaintiffs oppose the Motion.

INTRODUCTION

On May 15, 2023, Plaintiffs filed a complaint under section 1-11-203.5, C.R.S., challenging whether SB23-303 ("SB303") and Proposition HH, the Referred Measure within SB303, contain a single subject and a clear title. The parties submitted simultaneous opening briefs on May 30, 2023, and will submit simultaneous response briefs by June 5, 2023. The statute requires the district court to "adjudicate [the matter] within ten days of the date of filing of the answer"—here, June 9, 2023.

[1] As detailed in her opening brief, the Secretary of State takes no position on the merits of Plaintiffs' claims. *See* Sec'y of State's Op. Br. (May 31, 2023). But for the reasons stated in Parts II and III of the Argument below—and in particular because allowing expert testimony of the sort proposed here would negatively impact the title setting process for the Title Board, which the Secretary of State is responsible for convening, *see* § 1-40-106(1), C.R.S.—the Secretary joins this Motion.

On May 30, Plaintiffs served a disclosure of expert testimony for Dr. Seth Masket under C.R.C.P. 26(a)(2)(B)(II). *See* Ex. A. Dr. Masket is the Director of the Center on American Politics and a Professor of Political Science at the University of Denver. Plaintiffs assert that Dr. Masket will testify "regarding voter behavior and the adequacy of the proposed ballot language." Ex. A at 2. The disclosure also identified Toby Damisch, a second expert to testify "regarding the adequacy of the proposed ballot language," but Plaintiffs have withdrawn Mr. Damisch. *Id.*

On May 31, the State conferred with Plaintiffs regarding the May 30 expert disclosure. The State noted that the disclosure was insufficient and did not comply with C.R.C.P. 26(a)(2)(B)(II). The State requested that Plaintiffs supplement the disclosure by close of business on June 1 with the missing components—a "complete description of all opinions to be expressed and the basis and reasons therefor" and "copies of any exhibits to be used as a summary of or support for the opinions." *See* Ex. B. The State also submitted an informal discovery request for "[a]ll documents, opinions, memoranda, correspondence, including email, prepared or received by Dr. Seth Masket or Toby Damisch, including from any attorney for Plaintiffs, considered or relied upon by Dr. Seth Masket or Toby Damisch, relating to their opinions or testimony in this case." *See id.*[2]

On June 1, Plaintiffs filed and served a second disclosure of expert testimony under C.R.C.P. 26(a)(2)(B)(II). *See* Ex. C. The disclosure states that Plaintiffs will call Dr. Masket to "review past ballot titles related to taxation questions which are in the possession of the state[,]" and to "testify on voter behavior[,] [which] will support the claims made in the Complaint

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[2] These materials are discoverable pursuant to *Gall v. Jamison*, 44 P.3d 233, 239 (Colo. 2002).

regarding the inadequacy of the ballot titles." Ex. C. The disclosure says nothing else about Dr. Masket's opinions or the bases for them.

On June 2, Plaintiffs sent the State a report titled "Colorado Political Climate Survey" (Dec. 10, 2021). Ex. D. It is unclear what relationship this document has to Dr. Masket's opinions, if any.

The State asks the Court to exclude the expert testimony of Dr. Masket for three reasons. First, Plaintiffs' disclosures are legally deficient under C.R.C.P. 26(a)(2)(B)(II), and such deficiencies will cause prejudice to the Governor if Dr. Masket is permitted to testify because the Governor is not able to adequately prepare for hearing or trial. Second, although it is impossible for the State to assess in light of Plaintiffs' deficient disclosures, it appears that Dr. Masket will testify about the legal adequacy of the proposed ballot title, which is an ultimate issue of law for this Court, not Dr. Masket, to decide, and Dr. Masket's testimony is seemingly speculative. Finally, experts are not permitted to opine on the adequacy of a ballot title as a question of law and allowing them to do so here would complicate the initiative title-setting process.

LEGAL STANDARD

"Trial courts have broad discretion to determine the admissibility of expert testimony[.]" *Estate of Ford v. Eicher*, 220 P.3d 939, 942 (Colo. App. 2008). "The admission of … expert testimony is governed by CRE 702." *Id.* Under that rule, an expert may testify as to their opinions "[i]f scientific, technical, or other specialized knowledge will assist the trier of fact to understand the evidence or to determine a fact in issue[.]" C.R.E. 702.

Anyone who will be called as an expert witness must be disclosed under C.R.C.P. 26(a)(2)(B). Plaintiffs have disclosed Dr. Masket as a nonretained expert, so their disclosure

must include, among other things, "a complete description of all opinions to be expressed and the basis and reasons therefor." C.R.C.P. 26(a)(2)(B)(II)(a). A failure to provide an adequate disclosure requires exclusion of the expert testimony, unless the failure is harmless. *See* C.R.C.P. 37(c)(1).

ARGUMENT

I. Dr. Masket's testimony should be excluded because Plaintiffs' disclosures are legally deficient and prejudicial to the Governor.

Failure to timely disclose information required under C.R.C.P. 26(a) may prejudice the opposing party by robbing them of the ability to adequately prepare for trial or hearing and to fully cross-examine the expert witness. *Clements v. Davies*, 217 P.3d 912, 916 (Colo. App. 2009). The party that fails to timely disclose its expert bears the burden "to establish that its failure to disclose was substantially justified or harmless, or that excluding the evidence would be disproportionate to the harm caused by the nondisclosure." *Gravina Siding & Windows Co. v. Gravina*, 516 P.3d 37, 49 (Colo. App. 2022).

Plaintiffs' cursory expert disclosures do not even come close to complying with the requirements of C.R.C.P. 26(a)(2)(B)(II). In their expert disclosure, Plaintiffs disclosed broad and vague categories of topics. *See generally* Exs. A and C. The Governor only knows that Dr. Masket will "review past ballot titles related to taxation questions," "testify regarding voter behavior," and provide commentary on and support for Plaintiffs' claims regarding the "adequacy of the proposed ballot language." *Id.* Plaintiffs have failed to provide the Governor with a "complete description of all opinions to be expressed and the basis and reasons therefore." C.R.C.P. 26(a)(2)(B)(II)(a). Plaintiffs also did not disclose "copies of any exhibits to be used as a

summary of or support for the opinions," to the extent there are any. *See* C.R.C.P. 26(a)(2)(B)(II)(c). Plaintiffs' expert disclosure is simply not a meaningful disclosure. Essential details are missing. For example:

- What ballot titles Dr. Masket reviewed;
- What opinions he has about "voter behavior";
- What he relied on to form his opinions about voter behavior;
- What opinions he has about the "inadequacy of the ballot titles";
- What he relied on to form his opinions about the "inadequacy of the ballot titles"; or
- Which ballot titles he has opinions about.

Plaintiffs' inadequate disclosures are especially grave in light of the expedited and compressed nature of proceedings under section 1-11-203.5, C.R.S. While courts can excuse untimely disclosures if the other party has a fair opportunity to respond to the disclosure, *see Berry v. Keltner*, 208 P.3d 247, 250 (Colo. 2009), the Governor here has no such opportunity. The Governor is working diligently to meet the expedited deadlines imposed by section 1-11-203.5 and does not have the necessary information to adequately prepare for Dr. Masket's expert witness appearance. As such, Dr. Masket's testimony must be excluded as unduly prejudicial.

II. Dr. Masket's testimony should be excluded because his opinions appear to consist entirely of legal conclusions and speculation.

Plaintiffs propose that Dr. Masket will "review past ballot titles" and "support the claims made in the Complaint regarding the inadequacy of the ballot titles." *See* Ex. C at 2. But the adequacy of the ballot titles is the exact question the Court must ultimately answer. At the heart of this litigation is whether the titles of SB303 and/or the Referred Measure violate the single

subject and clear expression requirements enumerated in the Colorado Constitution. No expert can tell the Court how to rule on those questions.

While C.R.E. 704 permits expert witnesses to give opinions on ultimate issues of fact, this rule does not permit expert witnesses to offer testimony on ultimate issues of law. *People v. Collins*, 730 P.2d 293, 306 (Colo. 1986); *Johnson v. Dept. of Safety*, 503 P.3d 918, 925 (Colo. App. 2021) ("[E]xpert witnesses may not testify as to ultimate conclusions of law."). Put simply, an expert cannot tell the finder of fact what results to reach. *People v. Gaffney*, 769 P.2d 1081, 1087 (Colo. 1989) (quoting Fed. R. Evid. 704 Advisory Committee's Note).

Dr. Masket's testimony regarding the proposed ballot language will not "assist the trier of fact to understand the evidence or to determine a fact in issue." C.R.E. 702. Rather, it will offer commentary on the precise legal question central to this case and squarely before this Court—whether the bill and ballot title meet constitutional standards. This is not a permitted use of expert testimony and should therefore be excluded.

Dr. Masket's proposed testimony on "voter behavior" also fails to comply with C.R.E. 702. While Plaintiffs' inadequate disclosures again make it unclear what testimony Dr. Masket will offer on "voter behavior," it seems as though any such testimony would necessarily be speculative. For expert testimony to be admissible under C.R.E. 702, it must be both reliable and relevant, *Farmland Mut. Ins. Companies v. Chief Indus., Inc.*, 170 P.3d 832, 835 (Colo. App. 2007), and must be "grounded in the methods and procedures of science, not on a subjective belief or unsupported speculation." *People ex rel. M.M., Jr.*, 215 P.3d 1237, 1250 (Colo. App. 2009).

How voters will react to the bill or the ballot title is necessarily speculative, and fundamentally irrelevant because the clarity of a ballot title is an inherent question of law for the Court to decide based on the title's wording. *See, e.g.*, *In re Title, Ballot Title, & Submission Clause for 2013-2014 #90*, 2014 CO 63, ¶ 9 ("[W]e must examine [a proposed initiative's] wording to determine whether the initiatives and their titles comport with the single subject and clear title requirements."). Plaintiffs have failed to disclose any additional information that would suggest Dr. Masket's opinions are nonspeculative, relevant, and otherwise admissible.

III. Dr. Masket's testimony should be excluded because the Supreme Court frequently rules on ballot title disputes without experts opining on the legal questions in those disputes.

The Supreme Court hears dozens of ballot title disputes every year. In the 2021-2022 election cycle, for example, the Court heard 53 appeals from the Title Board. *See 2021/2022 Ballot Initiatives*, Colo. Judicial Branch (June 2, 2003), https://tinyurl.com/3smhdvj3. Every proponent and opponent of an initiative who appeared before the Title Board has a direct and immediate right of review of the Board's decisions to the Colorado Supreme Court. *See* § 1-40-107(2). That review, like the review Plaintiffs seek here, "is limited" to two questions of law: "whether [the measure] comports with the single-subject requirement and whether the title as a whole is fair, clear, and accurate." *In re Title, Ballot Title, & Submission Clause for 2015-2016 #63*, 2016 CO 34, ¶ 7.

The title's accuracy and the adequacy or "inadequacy of the ballot titles" is therefore a legal determination the Court must make. As argued above, that is not a factual question for an expert. For example, in a prior measure before the Title Board, individuals objecting to the term "open mining" used in a title presented polling data showing that voters were confused by the

term. *See In re Title, Ballot Title & Submission Clause for 1999-2000 #215*, 3 P.3d 11, 14-15 (Colo. 2000). But the Supreme Court did not credit that polling data, or any other factual testimony, and instead made the legal determination that the term did "not render the titles misleading to the voters." *See id.* at 15; *see also In re Title, Ballot Title, & Submission Clause for 2009-2010 #45*, 234 P.3d 642, 650 (Colo. 2010) ("The standard cannot be that a phrase becomes a catch phrase if the petitioner proves that it polls with the public better than other phrases."). The Court makes its own determinations as to whether voters would be confused by a ballot title without resort to expert testimony. *See, e.g.*, *In re Title, Ballot Title, & Submission Clause for 2015-2016 #156*, 2016 CO 56, ¶ 13 ("We conclude that the title set for Initiative #156 does not satisfy the clear title requirement because it is … inherently confusing."); *In re Title, Ballot Title, & Submission Clause for 1999-2000 #29*, 972 P2d 257, 266 (Colo. 1999) ("[N]o voter confusion or surprise would ensue because the summary is phrased in a non-legalistic and accurate fashion."). Courts resolve the legal question of whether a measure is misleading based on the text of the measure itself, not how the measure compares to an undefined, untested model of "voter behavior." *See, e.g.*, *In re 2013-2014 #90*, 2014 CO 63, ¶ 9.

Finally, if the Court accepts Dr. Masket's expert testimony, it could open the door to similar testimony being presented to the Title Board and the Supreme Court. Dueling expert witnesses may soon become the expected norm. The initiative process already asks proponents to devote significant time and resources to see an initiative through the process and onto the ballot. Adding an expectation of obtaining expert testimony to opine—either affirmatively or to rebut a well-financed opponent of the initiative—about the inadequacy of the title would be detrimental

to Coloradans' "fundamental right" of initiative. *See Loonan v. Woodley*, 882 P.2d 1380, 1383 (Colo. 1994).

CONCLUSION

For the reasons stated above, the State respectfully requests that the Court strike Dr. Masket's expert disclosure and exclude Dr. Masket from providing written or oral testimony in this litigation.

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CERTIFICATE OF SERVICE

This is to certify that I have duly served the within **JOINT MOTION TO EXCLUDE EXPERT TESTIMONY OF SETH MASKET** upon all parties herein by Colorado Courts E-Filing, this 5th day of June 2023, addressed as follows:

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EXHIBIT
Movant Foster B

SUPREME COURT STATE OF COLORADO 2 East 14th Avenue Denver, CO 80203	DATE FILED: May 13, 2014 4:14 PM
Original Proceeding Pursuant to Colo. Rev. Stat. § 1-40-107(2) Appeal from the Ballot Title Setting Board .	
In the Matter of the Title, Ballot Title, and Submission Clause for Proposed Initiatives 2013-2014 #85, #86, #87, and #88 ("OIL AND GAS OPERATIONS") **Petitioners**: Mizraim Cordero and Scott Prestidge, v. **Respondents:** Caitlin Leahy and Gregory Diamond and **Title Board:** Suzanne Staiert, Daniel Domenico, and Jason Gelender.	▲ **COURT USE ONLY** ▲
JOHN W. SUTHERS, Attorney General SUEANNA P. JOHNSON, Assistant Attorney General, Atty. Reg. No. 34840* Ralph L. Carr Colorado Judicial Center 1300 Broadway, 6th Floor Denver, CO 80203 Telephone: 720-508-6155 FAX: 720-508-6042 E-Mail: Sueanna.Johnson@state.co.us *Counsel of Record	Case Nos. 2014SA116, 2014SA119, 2014SA122 and 2014SA125

OPENING BRIEF OF THE TITLE BOARD

CERTIFICATE OF COMPLIANCE

I hereby certify that this brief complies with all requirements of C.A.R. 28 and C.A.R. 32, including all formatting requirements set forth in these rules. Specifically, the undersigned certifies that:

The brief complies with C.A.R. 28(g).

It contains 4,656 words.

The brief complies with C.A.R. 28(k).

It contains under a separate heading (1) a concise statement of the applicable standard of appellate review with citation to authority; and (2) a citation to the precise location in the record (R. , p.), not to an entire document, where the issue was raised and ruled on.

/s/ Sueanna Johnson

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CONSTITUTIONAL PROVISIONS

Suzanne Staiert, Daniel Domenico, and Jason Gelender, as members of the Ballot Title Setting Board (the "Title Board"), by and through undersigned counsel, hereby submit their Opening Brief.

STATEMENT OF THE ISSUES

I. The issues presented for review by the Petitioners.

1. Whether Proposed Initiatives 2013-2014 #85 through #87 contain multiple subjects because they propose setback distances for new oil and gas wells in addition to providing that the setbacks are not takings under the Colorado constitution.

2. Whether the titles set by the Title Board for Proposed Initiatives 2013-2014 #85 through #88 are misleading because they fail to inform voters that the setbacks are limited to oil and gas resources belonging to the State of Colorado.

3. Whether the titles set by the Title Board for Proposed Initiatives #85 through #87 are misleading because they fail to inform voters that the measures might bar federal takings claims.

4. Whether the titles set by the Title Board for Proposed Initiatives 2013-2014 #85 through #88 should have used the word "prohibition" instead of "statewide setback."

5. Whether the titles set by the Title Board for Proposed Initiatives 2013-2014 #86 through #88 conflict with the titles set for other measures.

II. The issue presented for review by the Proponents.

6. Whether the titles set by the Title Board for Proposed Initiatives #85 and #87 are misleading and fail to advise the public of the central purpose of the measures because the words "including those using hydraulic fracturing" were omitted.

STATEMENT OF THE CASE

Caitlin Leahy and Gregory Diamond are proponents for Proposed Initiatives 2013-2014 #85 through #88. Mizraim Cordero and Scott Prestidge through counsel objected to the titles set by the Title Board on grounds #85 through #88 contained multiple subjects and the titles were misleading and omitted material information. At the rehearing, the Title Board found #85 through #88 contained a single subject, but modified the titles in response to two issues raised by the Petitioners. The Proponents objected to the removal of the words "hydraulic fracturing" from the titles. The Petitioners filed this appeal raising single subject and unclear and misleading title arguments. The Proponents filed cross-petitions for #85 and #87 arguing the titles were misleading because of the omitted words.

STATEMENT OF THE FACTS

On March 21, 2014, Proponents Caitlin Leahy and Gregory Diamond ("Proponents") filed Proposed Initiatives 2013-2014 #85 through #88 ("#85," "#86," "#87," "#88" or collectively "Initiatives") with the Colorado Secretary of State. The Title Board held a hearing on April 3, 2014, and after finding a single subject, set titles for the Initiatives.

#85 seeks to amend the Colorado constitution by creating article XXX, which requires that new oil and gas wells must be located at least 1,500 feet from any occupied structure. The measure defines "occupied structure," and "oil and gas operations," authorizes a homeowner to waive the setback, and states that the setback is not a taking under the Colo. Const., art. II, §§ 14 and 15 for which just compensation is required. An "occupied structure" is defined as any structure or building that requires a certificate of occupancy or is intended for human occupancy, including homes, schools, and hospitals.

#86 and #87 are substantially similar to #85, except that the new oil and gas wells must be located at least 2,000 feet or one-half mile (2,540 feet), respectively, from any occupied structure. Additionally, the measures use the term "oil and gas development" rather than "oil and gas operations," yet the plain language of the definition appears to be the same.

The title set by the Title Board at the April 3rd meeting for #85 stated as follows:

> An amendment to the Colorado constitution concerning a statewide setback requirement for new oil and gas wells, and, in connection therewith, requiring any new oil and gas well, including those using hydraulic fracturing, to be located at least 1,500 feet from the nearest occupied structure; authorizing a homeowner to waive the setback for the homeowner's home; and establishing that the statewide

setback is not a taking of private property requiring compensation under the Colorado constitution.

The titles set for #86 and #87 were similar in all respects to #85, except the setback requirements of 2,000 feet or one-half mile, respectively, were substituted.

#88 is similar to #86, as it has the same setback distance, but the measure has three differences. First, #88 uses and defines the term "oil and gas operations" similar to #85. Second, the measure allows for any property surface owner to waive the setback requirement, as opposed to just homeowners. And third, the measure excludes language that the setback is not a taking under the Colorado constitution.

At the April 3rd meeting, the Title Board set the title for #88 as follows:

> An amendment to the Colorado constitution concerning a statewide setback requirement for new oil and gas wells, and, in connection therewith, requiring any new oil and gas well, including those using hydraulic fracturing, to be located at least 2,000 feet from the nearest occupied structure; and authorizing property owner to waive the setback for any structure located on the owner's property.

Also at that hearing, counsel for the Proponents represented to the Title Board that they would select only one of the four initiatives to circulate for placement on the November ballot.

On April 10, 2014, Mizraim Cordero and Scott Prestidge ("Petitioners") filed motions for rehearing ("motions") on grounds #85 through #88 contained multiple subjects. Of relevance to this appeal, the Petitioners argued that the Initiatives contained multiple subjects because they deprived property owners of their rights guaranteed under the Colo. Const., art. II, §§ 14 and 15. The motions also argued that the titles set by the Title Board were unclear and misleading.

At the April 16, 2014 rehearing, the Title Board again found that the Initiatives contained a single subject. The Title Board, however, modified the titles in response to two concerns raised by Petitioners: specifically (1) the use of the term "hydraulic fracturing" was a catch-phrase and politically charged term that should be removed; and (2) the titles did not inform voters that the Initiatives were an override to current statewide setback rules. The Proponents objected to the removal of the term "hydraulic fracturing" from the titles, as they contended this was a central purpose of their measures. Following the rehearing, the title for #85 stated:

> An amendment to the Colorado constitution concerning a statewide setback requirement for new oil and gas wells, and, in connection therewith, *changing existing setback requirements to require* any new oil and gas well be located at least 1,500 feet from the nearest occupied structure; authorizing a homeowner to waive the setback for the homeowner's home; and establishing that the statewide setback is not a taking of private property requiring compensation under the Colorado constitution.

The italics refer to the modified language. The titles for #86 and #87 were substantially similar, except for modification of the setback distances. The title for #88 included the italicized language found in #85, and likewise removed the term "hydraulic fracturing," but was similar in all other respects to its original title.

The Petitioners then filed this appeal on April 23, 2014 raising both single subject and unclear title arguments. The Proponents filed two cross-petitions regarding #85 and #87, in which they argue that removal of the words "hydraulic fracturing" render the titles misleading.

SUMMARY OF THE ARGUMENT

The titles for #85 through #87 contain a single subject – specifically they require statewide setbacks for new oil and gas wells from occupied structures. The provision that the setbacks are not considered takings under the Colo. Const., art. II, §§ 14 and 15 is related to the measures, and does nothing more than set forth the scope of the setbacks.

The titles for #85 through #88 are clear and not misleading. First, the Title Board properly relied on the Proponents' testimony that the use of the possessive in Colorado was not intended to limit application of the setback requirements to just oil and gas resources belonging to Colorado, but rather the measures intended to apply to private and federal mineral interests as well.

Second, the Title Board properly excluded any reference from #85 through #87 that the measures might bar federal takings claims, as the Title Board may not interpret or opine on the legal effects of the measure.

Third, the Title Board has broad discretion in its drafting authority, and it did not abuse that discretion when it decided to use the term "statewide setback" instead of "prohibition" to refer to the required distance of an oil and gas well to an occupied structure. The term "setback" is understandable to voters, and is language found in the measures.

Fourth, the titles for #85 through #88 do conflict with one another, as the material differences between the measures are identified. The Proponents have represented they will only circulate one of the four Initiatives for placement on the ballot. Even assuming, however, that the four Initiatives appear on the ballot, voters would be able to identify and understand the differences between the measures, and if more than one of the measures passed, the one with the greatest number of votes would take effect.

Finally, the removal of the words "hydraulic fracturing" from the titles for #85 through #88 was not improper. Although the term may not necessarily constitute a catch phrase, it may be politically charged language that has the potential to appeal to voters based on emotion rather than the merits of the measure. Even assuming the term is not a catch phrase, because the measure applies to all oil and gas wells regardless of whether hydraulic fracturing is used, removal of the term does not render the titles misleading or inaccurate.

ARGUMENT

I. Initiatives #85 through #87 contain a single subject.

The Petitioners argue that #85 through #87 contain multiple subjects because the setback distances are distinct from the provision that states the setbacks are not a taking under the Colorado constitution. This argument should fail.

A. The standard of review to determine single subject.

The Title Board may not set title for a ballot initiative that contains more than onc subjcct. Colo. Const., art. V, § 1(5.5); *see also* § 1-40-106.5(1)(a), C.R.S. The single subject requirement prohibits the inclusion of "incongruous subjects in the same measure, especially the practice of putting together in one measure subjects having no necessary or proper connection." § 1-40-106.5(1)(e)(I), C.R.S.; *see also Kelly v. Tancredo (In re Proposed Ballot Initiative on Parental Rights)*, 913 P.2d 1127, 1130-31 (Colo. 1996); *In re Title*, 900 P.2d 104, 113 (Colo. 1995) (stating that "... so long as an initiative encompasses *related* matters it does not violate the single subject requirement of [the] state constitution.") (Scott, J., concurring) (emphasis in original).

A measure contains a single subject if the matters encompassed are "necessarily and properly connected" to each other rather than "disconnected or incongruous." *Kemper v. Hamilton (In re Title, Ballot Title & Submission Clause 2011-2012 #3)*, 274 P.3d 562, 565 (Colo. 2012) ("*In re #3*"). Stated differently, if a measure tends to carry out one general purpose, then minor provisions necessary to effectuate that purpose will not violate the single subject rule. *In re Title v. John Fielder*, 12 P.3d 246, 253 (Colo. 2000); *see also Ausfahl v. Caldera (In re Title for 2005-2006 #74)*, 136 P.3d 237, 239 (Colo. 2006) (the single subject is not violated unless the text of the measure carries out "two distinct and separate purposes" which are not "dependent upon or connected with each other.") Likewise, the measure contains a single subject even if it has different effects or it makes policy decisions that are not inevitably interconnected. *Fielder*, 12 P.3d at 254. In order to satisfy the single subject requirement, the Title Board is "vested with considerable discretion in setting the title," and therefore the Supreme Court liberally construes the single-subject requirement. *Title v. Apple*, 920 P.2d 798, 802 (Colo. 1996).

B. The new setback requirements in #85 through #87 are connected to the provision that the requirements are not a taking under the Colorado constitution.

The single subject as represented by the Proponents at the April 3rd hearing was characterized as a setback requirement for all new oil and gas wells from occupied structures. The Proponents stated that the remainder of the measures, including Section 3 that contains the no takings provision, is either purpose, definition, or implementation. The Petitioners, on the other hand, argue that the no takings provision is distinct from the statewide setbacks, as voters could support distance requirements for oil and gas wells, yet expect that if the setbacks were deemed a taking of private property, they would still be subject to just compensation under the Colorado constitution. The Petitioners' argument should be rejected.

The no takings provision is directly related to the measure. It removes the setback requirements under the measure from the term "taking" as the term is used in Colo. Const. art. II, §§ 14 and 15. It does not relate to or affect any other constitutional provision or state statute. It does nothing more than define the scope of the measure.

This Court rejected a similar challenge in *Smith v. Bogan (In re Title, Ballot Title and Submission Clause and Summary for 1997-98 #112),* 962 P.2d 255 (Colo. 1998). In that case, the measure included a provision "making unconstitutional any state law or regulation that does not treat livestock operations uniformly based upon the similarity in the potential impact on the environment of the livestock operation." *Id.* at 256. Objectors claimed that this provision violated the single subject requirement by invalidating existing laws. The Court rejected this argument. *Id.* Similarly, this Court should reject the Petitioners' argument, and uphold the Title Board's finding of a single subject for #85 through #87.

II. The titles for the Initiatives are fair, clear, and accurate.

The Petitioners raise four arguments to support that the titles for the Initiatives are unclear and misleading. Specifically, they argue: (1) the titles for the Initiatives do not notify voters that the setback requirements are limited to oil and gas resources belonging to the state; (2) the titles for #85 through #87 do not inform voters of the potential barring of federal takings claims; (3) the titles for the Initiatives use the term "statewide setback" instead of the more common word "prohibition;" and (4) the title for #86 through #88 conflict with #85. The Proponents cross-petition with respect to #85 and #87, arguing the titles are misleading because the Title Board removed the words "including those using hydraulic fracturing." The arguments should be rejected and the titles approved.

A. The standard of review with respect to setting a title.

The Title Board's duty in creating a title and submission clause is to summarize the central features of a measure. *In re Petition on Sch. Fin.*, 875 P.2d 207, 210 (Colo. 1994). Not every feature of a measure must appear in the title. *Fielder,* 12 P.3d at 256. The title should be a brief statement that fairly and accurately represents the true intent and meaning of the proposed text of the initiative. § 1-40-102(10), C.R.S.; *see also* § 1-40-106(1)(b), C.R.S. (ballot titles shall be brief, but the Title Board should consider the public confusion that might result with misleading titles).

The Court's limited review "prohibits [it] from addressing the merits of a proposed initiative, and from suggesting how an initiative might be applied." *In re Title, Ballot Title and Submission Clause for Proposed Initiative 2001-02 No. 43,* 46 P.3d 438, 443 (Colo. 2002). The actions of the Title Board are presumptively valid. *In re 1999-2000 #104*, 987 P.2d 249, 254 (Colo. 1999); *see also Tancredo*, 913 P.2d at 1131 (stating that the Supreme Court grants "great deference to the board's broad discretion in the exercise of its drafting authority.")

The title set by the Title Board is reviewed as a whole to determine if it is fair, accurate, and complete. *In re #3,* 274 P.3d at 565. A title will be upheld if the Title Board's language "clearly and concisely reflects the central features of the initiative." *Paredes v. Corry (In re*

Title, Ballot Title, & Submission Clause 2007-2008 # 61, 184 P.3d 747, 752 (Colo. 2008). The Supreme Court will only reverse the Title Board's title if it contains "a material or significant omission, misstatement, or misrepresentation." *In re Title v. Buckley*, 972 P.2d 257, 266 (Colo. 1999); *see also Brown v. Peckman (In re Title)*, 3 P.3d 1210, 1213 (Colo. 2000) (the Supreme Court will reverse the actions of the Title Board in setting the title when the chosen language is "clearly misleading.")

B. The Initiatives are not limited to oil and gas resources belonging to Colorado.

The Petitioners argue that the titles for the Initiatives do not reflect that the setback requirements pertain only to new oil and gas wells in which the resources belong to the State of Colorado. The Petitioners base this argument on the definition of "oil and gas operations" or "oil and gas development" used in the measures in which the possessive form is used to refer to Colorado's oil and gas resources. This arguments should be rejected.

At the rehearing, the Proponents stated that the definition of "oil and gas development" or "oil and gas operations" referred to oil and gas resources located within the Colorado, and was not intended to limit application of the setback requirements to oil and gas resources belonging to private or federal mineral interests. When setting the title, it is appropriate for the Title Board to consider the testimony of the proponents concerning the intent and meaning of the proposal. *See Title v. Swingle*, 877 P.2d 321, 327 (Colo.1994); *see also Hayes v. Ottke (In re Title, Ballot Title, & Submission Clause for Proposed Initiatives 2011-2012 Nos. 67, 68, 69)*, 293 P.2d 551, 555 (Colo. 2013) (the Board must give deference to the intent of the proposal as expressed by the proponents balanced with setting titles that avoid public confusion).

The Title Board did not improperly set the titles for the Initiatives, as the Proponents' testimony is consistent with the broad purpose enunciated in Section 1 of the measures. The purpose of the measures state that the effects of oil and gas development or operations impact local communities, and that for the public health, safety, and welfare, statewide setbacks for new oil and gas wells are required so that such operations are conducted away from occupied structures. Nothing in the plain language limits application of the setback requirements to new oil and gas wells in which the resources must belong to the state.

C. The Title Board properly excluded any reference to federal takings claims.

The Petitioners contend that the titles for #85 through #87 do not inform voters that federal takings claims may be barred. This argument should be rejected.

This Court has consistently held that neither the Court nor the Title Board may interpret a measure or "construe it future legal effects." *In re Title, Ballot Title and Submission Clause for 2007-2008, #57*, 185 P.3d 142, 145 (Colo. 2008). Whether federal takings claims are barred or limited by the measures is subject to interpretation and goes to the legal impact of the measure if passed. *See In re Title, Ballot Title and Submission Clause and Summary for 1999-2000 #255,* 4 P.3d 485, 498 (Colo. 2000) (titles are not "misleading because they do not refer to the Initiative's possible interplay with existing state and federal laws.");

see also In re Branch Banking Initiative, 612 P.2d 96, 99 (Colo. 1980) (upholding Title Board's exclusion from the title that the proposed initiative might conflict with federal banking law).

The Proponents indicated at the initial title setting that inclusion of the words "Colorado constitution" in #85 through #87 was meant to clarify to voters that the new setback requirements may not be considered a taking under Colorado law, but that property owners may nonetheless have applicable federal claims under the U.S. Constitution. Accordingly, it was proper for the Title Board to exclude any reference to any potential effects of federal takings claims.

D. The term "statewide setback" is informative and understandable.

The Petitioners argue that the term "statewide setback" used in the titles for the Initiatives has an "alliterative quality" that is not informative, and the more common word "prohibition" should be used instead. This argument should fail.

The Title Board is granted broad discretion in its drafting authority, and this Court will not reverse unless the words employed are "clearly misleading." *See Tancredo*, 913 P.2d at 1131. Likewise, the Title Board is not required to draft the best possible title. *See Outcelt v. Schuck*, 961 P.2d 1077, 1082 (Colo. 1998). Here, the titles inform voters that the statewide setback refers to the distance a new oil and gas well must be located from an occupied structure. Voters are familiar with the term setback with respect to zoning ordinances. And the term "statewide setback" comes directly from the Initiatives. As such, the Title Board's use of the term "statewide setback" is not clearly misleading, and should be upheld.

E. The titles for #86 through #88 do not conflict with other titles previously set by the Title Board for similar measures.

The Petitioners argue that the titles for #86 through #88 violate § 1-40-106(3)(b), C.R.S., as they conflict with the title set for #85. The Petitioners argument should be rejected.

The Proponents have represented to the Title Board that they will only select one of the four initiatives for circulation of signatures. The Title Board has accepted these representations in the past based on the built-in incentives in the system that proponents would not want to incur the additional cost of obtaining signatures for multiple similar measures, as well as risk possible public confusion by having similar measures appear on the ballot. Therefore, this Court should decline to rule on this issue unless more than one initiative is found to be circulated. *See In re Second Initiated Constitutional Amendment*, 613 P.2d 867, 870 (Colo. 1980) (because proponents advised they would not circulate two similar initiatives, the Supreme Court declined to address whether the titles selected conflict, but retained jurisdiction to address conflicting title issues if both were circulated for signatures).

Assuming this Court does rule on this issue, the titles do not conflict. Section 1-40-106(3)(b), C.R.S., states that, "ballot titles . . . shall not conflict with those selected for a petition previously filed for the same election . . ." The Court has construed this language to mean that, "[w]hat is prohibited are conflicting ballot titles which fail to distinguish between overlapping or conflicting proposals." *In re Title,* 873 P.2d 718, 722 (Colo. 1994).

The titles for #85 through #88 set forth the material differences between the four measures. Specifically, the four titles indicate the different setback distances, the waiver for homeowner or property owners, and whether the setbacks are not considered a taking under the Colorado constitution. Even if all four measures were placed on the ballot, there is nothing that prohibits two conflicting amendments to be proposed and even adopted within the same election. *See Petition on Sch. Fin.*, 875 P.2d at 213. Voters will not be confused if all four Initiatives were to appear on the ballot, because the titles lay out the distinctions. And if two or more of the measures were approved by the voters, the one with the most votes would take effect. *See In re Interrogatories Prepounded by Senate Concerning House Bill 1078*, 308, 315 (Colo. 1975) (in the event of conflicting provisions, the measure that receives the greatest number of votes prevails and the other measure does not become law). As such, the titles for #86 through #88 do not conflict with #85.

F. The titles for the Initiatives properly excluded the words "hydraulic fracturing."

The Proponents argue that eliminating the words "hydraulic fracturing" from the titles does not inform the public of a central purpose of the measures and makes them misleading. The Petitioners, on the other hand, requested the removal of the term at the rehearing on grounds it constituted a catch phrase or was a politically charged term.

The use of catch phrases or slogans should be carefully avoided by the Title Board. *Garcia v. Chavez*, 4 P.3d 1094, 1100 (Colo. 2000). Catch phrases "consist of words which form the basis of a slogan for use by those who expect to carry out a campaign for or against an initiated constitutional amendment." *In re Title*, 873 P.2d 733, 741 (Colo. 1994). The Court considers the existence of a catch phrase or slogan in the context of contemporary political debate. *Garcia*, 4 P.3d at 1100. The Court's task "is to recognize terms that provoke political emotion and impede voter understanding, as opposed to those which are merely descriptive of the proposal." *Id.*

In *Garcia*, 4 P.3d at 1100, the Court held that the phrase "as rapidly and effectively as possible" was a catch phrase, because it impermissibly masked the substantive debate about whether English-only immersion was the "most rapid and effective" method to teach non-English speakers. The Court held that the use of those words tips the debate on the issue as submitted to the electorate. *Id.* Even though the measure contained the language found in the title, the Court determined that "the Title Board is not free to include this wording in the titles, if as here, it constitutes a catch phrase." *Id.*

At the rehearing for #85 through #88, the Petitioners pointed to the current Colorado debate surrounding the impacts of hydraulic fracturing on the environment in support of their request for removal. The Petitioners likewise argued that the Proponents put that term "hydraulic fracturing" in their Initiatives precisely because of its emotional appeal. The Proponents countered that they did not want to hide that the Initiatives concern oil and gas operations and development that use hydraulic fracturing methods, as this was a central component of their measures.

The Title Board found that the term may not constitute a catch phrase, but it may be considered politically charged language that should be excluded. The Title Board also reasoned that the setback requirements apply to all new oil and gas wells using hydraulic fracturing, so inclusion of the term was not material and exclusion still made the title accurate. Likewise, the Title Board reasoned that inclusion of the phrase may be misleading, as a voter might want to vote in favor of the measure because it agrees to a setback distance for oil and gas wells using hydraulic fracturing, but not necessarily for all oil and gas operations or development.

The fact that the Proponents acknowledged that including the word "fracking" would be objectionable underscores that hydraulic fracturing – while the technical term – nonetheless has the potential to invoke a pejorative association that may appeal to voters on the basis of emotion rather than further understanding of the measure. *See In re Title*, 875 P.2d 871, 875-76 (Colo. 1994) (the Court reversed the Title Board holding that the terms "open government" and "consumer protection" were catch phrases because it was clear that the terms could likely be used for slogans). Likewise, even though the words "hydraulic fracturing" is contained in the measure, the Title Board acted properly in excluding them. *See Garcia*, 4 P.3d at 1100. Finally, even assuming that the words "hydraulic fracturing" do not constitute a catch phrase or are not politically charged, the Title Board's action should nonetheless be upheld, because they have broad discretion in their drafting authority, and removal of the words does not make the title "clearly misleading." *See Tancredo*, 913 P.2d at 1131.

CONCLUSION

Based on the foregoing authorities and reasons, this Court should affirm the actions of the Title Board and approve the titles for #85 through #88.

Respectfully submitted this 13th day of May, 2014.

JOHN W. SUTHERS
Attorney General

/s/ Sueanna P. Johnson

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CERTIFICATE OF SERVICE

This is to certify that, on this 13th day of May, 2014, I duly served this **OPENING BRIEF OF THE TITLE BOARD** on all parties via ICCES or regular mail, first class postage prepaid, addressed as follows:

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EXHIBIT
Movant
Foster C

Western Colorado
LATINO CHAMBER of Commerce

June 20, 2023

Dear Members of the Colorado Title Board -

We write to you today in opposition to the proposed modification to Initiatives #46 and #47, the ballot measure(s) which would utilize the term "fracking" as the catch-all term for oil and gas operations being banned by the measure. Terms like "oil and gas", "oil and gas production", "oil and gas facilities" and "oil and gas workers" are common parlance among Hispanics and Spanish-language speakers among both supporters and critics of oil and gas development within the community and when communicating with the community. This is proof positive that the term "fracking" is, very simply, not widely utilized among Hispanics, Latinos, and Spanish speaking Coloradans. To ensure full and fair consideration of any ballot measure, we urge the title board to use the common language "oil and gas production" rather than more technical and less-well-known terminology like fracking or hydraulic fracturing.

The Spanish-speaking community of Colorado, like any other group, consists of diverse and intelligent individuals who can comprehend complex concepts when provided with accurate and appropriate information.

While the term "fracking" is understood by industry and political insiders, it is still a phrase that is relatively unknown to many Coloradans without context, especially among non-English speakers. It is an English-language-derived, shortened, and colloquial term for hydraulic fracturing that provides no context or explanation for the process, which is essential for any voter in deciding if it should continue in Colorado. If the board finds it necessary to define a specific process, we believe it is best to provide more details and context when explaining the process of fracturing rocks below the earth's surface and injecting high-pressure water, chemicals, and materials intended to prevent those fractures from closing to allow for oil and gas extraction.

A 2016 study by the Clean Air Task Force (CATF), League of United Latin American Citizens (LULAC), and the National Hispanic Medical Association (NHMA), titled "The Impact of Air Pollution from the Oil and Gas Industry," mentions the term "fracking" a total of zero times, "hydraulic fracturing" just once, and "oil and gas" 120 times[1].

Even amongst organizations not supportive of the oil and gas industry, the term "fracking" is not commonplace. A 2022 polling memo from the progressive organization Data for Progress which gauged public opinion among Hispanic and Spanish speaking

[1] https://cdn.catf.us/wp-content/uploads/2016/09/21094458/CATF_Pub_LatinoCommunitiesAtRisk.pdf

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voters on the industry fails to mention either "fracking" or "hydraulic fracturing" even once.[2]

Recent news stories, such as a 2023 Axios story that highlighted Hispanic workers in the oil and gas industry, also did not mention either "fracking" or "hydraulic fracturing" a single time.[3]

The State of Colorado has a responsibility to ensure transparency, fairness, and inclusivity in its governance and legislative processes. We ask that the title board ensure this by providing a more widely understood term or an expansive definition of the hydraulic fracturing process for those requesting a Spanish ballot.

Sincerely,

Sonia Gutierrez, Vice President
Western Colorado Latino Chamber of Commerce

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[2] https://www.filesforprogress.org/memos/dfp_Climate_Power_Latino_Voters.pdf
[3] https://www.axios.com/2023/04/25/oil-and-gas-climate-change-gabe-vasquez-sylvia-garcia

COLORADO TITLE SETTING BOARD

IN THE MATTER OF THE TITLE AND BALLOT TITLE AND SUBMISSION CLAUSE FOR INITIATIVE 2023-2024 #46

MOTION FOR REHEARING

On behalf of Steven Ward, registered elector in the State of Colorado, the undersigned counsel hereby submits this Motion for Rehearing of the Title Board's ("Board") May 17, 2023, decision related to Initiative 2023-2024 #46 ("Measure").

On May 17, 2023, the Board conducted a hearing on Proposed Initiative 2023-2024 #46. The Board found a single subject and proceeded to set title as follows:

> "A change to the Colorado Revised Statutes concerning discontinuing the issuance of new oil and gas operation permits that utilize fracking by December 31, 2030, and, in connection therewith, requiring the phase-out of new oil and gas operating permits that utilize fracking; allowing permitted oil and gas operation that utilize fracking to continue; and requiring the state to explore transition strategies for impacted oil and gas workers who may transition other employment."

As demonstrated below, the Measure is in direct violation of the Colorado Constitution and unequivocally conflicts with established legal precedent related to single subject and clear title. The Board lacks jurisdiction to set title as the Measure contains multiple subjects. Petitioner additionally asserts the title is not clear, contains a catch phrase and omits important features of the Measure.

I. Single Subject: The Title Board Lacks Jurisdiction Over #46 Because the Measure Does Not Contain a Single Subject.

The purpose of the Measure is to require the Colorado Oil and Gas Conservation Commission (the "Commission") to discontinue issuance of oil and gas permits by December 31, 2030. However, the Measure strays far from this subject and contains multiple provisions that are disconnected from the purpose.

As set forth in the Colorado Constitution and affirmed by the Colorado Supreme Court, the single subject requirement guards against a measure confusing voters in two separate ways. First, combining subjects with no necessary or proper connection for the purpose of garnering support for the initiative from various factions that may have different or even conflicting interests could lead to the enactment of Measures that would fail on their own merits. *In re Title, Ballot Title and Submission Clause for Proposed Initiative 2001-02 No. 43*, 46 P.3d 438, 442 (Colo. 2002). Second, the single subject requirement prevents "voter surprise and fraud occasioned by the inadvertent passage of a surreptitious provision 'coiled up in the folds' of a complex initiative."

Id. see also In re Title, Ballot Title and Submission Clause for Proposed Initiative for 2011-12 No. 3, 274 P.3d 562, 566 (Colo. 2012).

A. The Measure Vaguely Invalidates Certain Rules and Preserves Other Rules Rendering Impact of Measure Incomprehensible and Creating Separate and Distinct Subjects.

The Measure requires the continuation of a subset of Commission Agency Rules that ensure the "protection of public health, safety, welfare, the environment, and wildlife for all existing oil and gas operations." ("continued rules")[1] The Commission's current rules define their scope and application:

> The Commission's Rules are promulgated to regulate Oil and Gas Operations in a manner to *protect and minimize adverse impacts to public health, safety, welfare, the environment, and wildlife resources*, and to protect against adverse environmental impacts on any air, water, soil, or biological resource resulting from Oil and Gas Operations. (2 CCR § 404-1, Rule 201 a.) (emphasis added)

Logically, this means that *all* the rules must be codified. However, the Measure doesn't allow for this result. While the Measure requires the continued rules, it also requires the repeal of existing Commission rules related to new permits ("repealed rules").

To add to the confusion, the Measure does not identify with any specificity which rules should be continued, or which rules should be repealed. The Measure also does not provide for a solution when the purpose of a continued rule is intertwined with the purpose of the same rule that must be repealed. In this regard, people voting on this Measure will not even know which rules they are voting on repealing. The Measure's impact on eliminating certain rules and preserving other rules is incomprehensible.

Furthermore, SB19-181 specifically changed the statutory mission of the Commission to regulate Oil and Gas Operations in a manner "to protect public safety, health, welfare, the environment and wildlife resources". Suggesting now that banning oil and gas is *necessary* "**in order to protect public health, safety, welfare, the environment , and wildlife"** directly conflicts with the existing statute that requires regulations that protect these same categories. The measure surreptitiously changes the mission of the Commission and forces it to operate in conflict with the statute.

References to public health and safety are found throughout the regulations. It is difficult to comprehend how the Commission could continue rules ensuring protection of public health and

[1] **SECTION 3.** 34-60-106 (20.5)(d) THE CONTINUATION OF COMMISSION RULES ENSURING THE PROTECTION OF PUBLIC HEALTH, SAFETY, WELFARE, THE ENVIRONMENT, AND WILDLIFE FOR ALL EXISTING OIL AND GAS OPERATIONS.

safety without eviscerating much of the commission's rules. The mandate to protect public health and safety is integral to other commission duties.[2]

If the Board cannot comprehend the actual effect of the initiative, the initiative cannot be forwarded to the voters and must, instead, be returned to the proponent." *In re Proposed Initiative for 1999-2000 No. 25*, 974 P.2d 458, 469, (Colo. 1999).

B. Rule Mandates Combined with a Materially Changing Authority/Jurisdiction of the Commission are Separate and Distinct Subjects.

The Measure operates to remove the discretion the Commission would otherwise have over rulemaking provided under Colorado Administrative Procedures Act. C.R.S. § 24-4-103 and § 34-60-108.

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[2] 2 CCR § 404-1, 301. GENERAL REQUIREMENTS FOR APPROVAL, CHANGES TO OPERATIONS, AND FILING FEES FOR OIL AND GAS OPERATIONS a. Approval. All operations governed by any regulation in this Series require written approval of the Commission, or Director where applicable. The Commission or Director, where applicable, will approve operations only if they protect and minimize adverse impacts to public health, safety, welfare, the environment, and wildlife resources, and protect against adverse environmental impacts on any air, water, soil, or biological resource resulting from Oil and Gas Operations. Operators will obtain the Commission's or Director's, where applicable, approval through the procedures provided in this and such other applicable Commission Rules. The Commission, or Director, where applicable, may require any conditions of approval that are determined to be necessary and reasonable to protect and minimize adverse impacts to public health, safety, welfare, the environment, and wildlife resources, or to protect against adverse environmental impacts on any air, water, soil, or biological resource resulting from Oil and Gas Operations.
2 CCR § 404-1, 303. PROCEDURAL REQUIREMENTS FOR OIL AND GAS DEVELOPMENT PLANS
a. **Components of an Oil and Gas Development Plan Application.** Prior to commencing Oil and Gas Operations at an Oil and Gas Location that meets the criteria of Rule 304.a, an Operator will have an approved Oil and Gas Development Plan. An Operator will submit to the Commission the following:
….
(4) Any other relevant information that the Director determines is **necessary and reasonable** to determine whether the proposed operation meets the Commission's Rules **and protects and minimizes adverse impacts to public health, safety, welfare, the environment, and wildlife resources.** The Director will provide the Operator with the reason for the request in writing.

2 CCR § 404-1, 201. EFFECTIVE SCOPE OF RULES AND REGULATIONS
a. The Commission's Rules are promulgated to regulate Oil and Gas Operations in a manner to protect and minimize adverse impacts to public health, safety, welfare, the environment, and wildlife resources, and to protect against adverse environmental impacts on any air, water, soil, or biological resource resulting from Oil and Gas Operations. Except as set forth in Rule 201.d, the Commission's Rules are effective throughout the State of Colorado, and are in force in all pools and fields, unless the Commission amends, modifies, alters, or enlarges them through orders or Rules that apply to specific individual Pools or Fields…
d. These rules will not apply to:
(1) Indian trust Lands and minerals; or
(2) The Southern Ute Indian Tribe within the exterior boundaries of the Southern Ute Indian Reservation. The Commission's Rules will apply to non-Indians conducting Oil and Gas Operations on lands within the exterior boundaries of the Southern Ute Indian Reservation where both the surface and oil and gas estates are owned in fee by persons or entities other than the Southern Ute Indian Tribe, regardless of whether such lands are communitized or pooled.
2 CCR § 404-1, 901. GENERAL STANDARDS
a. Addressing Impacts and Potential Impacts to Public Health, Safety, Welfare, the Environment, and Wildlife Resources. Whenever the Director has reasonable cause to determine that an Operator, in the conduct of any Oil and Gas Operations, is impacting or threatening to impact public health, safety, welfare, the environment, or wildlife resources, the Director may require the Operator to take action to avoid, minimize, or mitigate the potential impacts to public health, safety, welfare, the environment, or wildlife resources, including but not limited to…

While the Measure directs the actions of the Board, it does not factor for the Commission's inability to codify these rules without oversight. The board's actions in adopting the rules are not a *fait accompli* to banning permits. Under the Colorado Constitution, the General Assembly and Governor ultimately maintain authority over rulemaking through the annual rule review bill and power to veto. This interference in the rulemaking process by an administrative agency has no proper or necessary connection to the discontinuance of permits. Nor is there any connection between the mandate on continued rules and the discontinuance of permits.

Furthermore, SB19-181 specifically changed the statutory mission of the Commission to regulate Oil and Gas Operations in a manner "to protect public safety, health, welfare, the environment and wildlife resources". Suggesting now that banning oil and gas is *necessary* "**in order to protect land, air, and water"** directly conflicts with the existing statute that requires regulations that protect land, air and water. The board cannot change its mission and operate in conflict with the statute.

An initiative violates the single subject rule when it proposes a shift in governmental powers that bear no necessary or proper connection to the central purpose of the initiative. *In re Title, Ballot Title, Submission Clause for 2009-2010 No. 91,* 235 P.3d 1071, 1077 (Colo. 2010) (citing *In re No. 29*, 972 P.2d at 262–65; *In re # 64*, 960 P.2d at 1197–1200.)

This codification of existing rules, combined with the establishment of a new independent oil and gas board, was a basis for the board's rejection of jurisdiction in 2019-2020 Initiatives #307-#310, *Establish the Independent Oil and Gas Board.* The same principle applies here where the Measure operates to codify existing rules and change the jurisdiction of an administrative agency.

C. Discontinuance of Permits that Incorporate Fracking is Vague and Applies to Matters Unrelated to the Initial Permitting Process

The Commission rules and permit application processes for new oil and gas production do not incorporate a method to determine if oil and gas production incorporates "fracking". An operator cannot simply check a box. The COGCC's 300 series rules (2 CCR § 404-1) cover the permitting process. Rule 303 provides for the extensive documentation operators must provide to get a permit to drill. It includes a cumulative impacts data evaluation repository (air resources, public health, water resources, terrestrial and aquatic wildlife resources and ecosystems, etc). The commission would be required to develop a parallel permitting system that somehow phases out permitting over several years. https://cogcc.state.co.us/documents/reg/Rules/LATEST/300%20Series%20-%20Permitting%20Process.pdf

C.R.S. § 34-60-103(7.5) defines "Permits" broadly to include "any permit, sundry notice, notice of intention, or other approval, including any conditions of approval, which is granted, issued, or approved by the commission." Repealing all rules related to new "permits" would leave the commission without the tools to do much of its work. For example, operators submit sundry notices for a wide range of purposes. These purposes are disconnected from the proponent's stated intent and create distinct and separate subjects.

D. The Repeal of Permits Creates Another Separate and Distinct Subject.

The discontinuance of permits is a subject separate from the revocation of existing permits. One is a change to future applications and the other is the revocation of an existing right. It is further unclear whether this revocation of existing permits would apply to the common practice of refracking.

The single subject requirement for ballot initiatives is meant to prevent proponents from engaging in this type of "log rolling" tactics of combining multiple subjects into a single initiative in the hope of attracting support from various factions that may have different or even conflicting interests. *Johnson v. Curry (In re Title, Ballot Title, & Submission Clause for 2015-2016 #132)*, 374 P.3d 460, 465 (Colo. 2016). Voters who want to discontinue permits but not affect existing property rights will have to choose between these competing interests. There is no reason to presume that voters who may support the former would support the later.

A voter who supports the Measure's provision related to discontinuance of permits may not even be aware that the Measure will result in the revocation of existing permits. This subject is buried in the Measure. Combining different subjects creates the risk of surprising voters with a surreptitious' change, because voters will focus on the discontinuance of permits and overlook the revocation.

E. Changing COGCC's Duties to Monitoring, Plugging and Remediating is Another Separate and Distinct Subject.

The Measure transitions the jurisdiction of the GOGCC to "primarily monitoring, plugging, and remediating of facilities permitted prior to December 31, 2030." Currently, under C.R.S. § 34-60-106 the Commission has broad powers over oil and gas production in Colorado. These include several powers that are unrelated to monitoring, plugging, and remediating facilities, including:

- Issuance of certificates of clearance in connection with the transportation and delivery of oil and gas;
- Limit the production of oil or gas, or both, from any pool or field for the prevention of waste;
- Power to make determinations, execute waivers and agreements, grant consent to delegations, and take other actions required or authorized for state agencies by those law and regulation of the United States which affect the price and allocation of natural gas and crude oil;
- Prescribe special rules and regulations governing the exercise of function delegated to or specified for it under the federal "Natural Gas Policy Act of 1978";
- As to class II injection wells classified in 40 CFR 144.6, may perform all acts for the purpose of protecting underground sources of drinking water in accordance with state programs authorized by 42 U.S.C. sec. 300f et seq., and regulations under those sections, as amended. Regulating venting and flaring;
- Communitizing and unitizing leases to maximize resource recovery;
- Review MIT (mechanical integrity tests) and Bradenhead tests to ensure well integrity;

- Regulate transportation of exploration and production waste.

These functions are not necessarily related to the permitting process. Yet, the Measure, without explicitly repealing the responsibilities, requires that the Commission no longer work on these issues as a "primary" function. In this regard, the Measure is now allocating time management of a state agency.

As stated above, an initiative violates the single subject rule when it proposes a shift in governmental powers that bear no necessary or proper connection to the central purpose of the initiative. *In re Title, Ballot Title, Submission Clause for 2009-2010 No. 91, supra.*

F. Creating New Duties in "Office of Future Work" Is a Separate and Distinct Subject.

The Measure creates an "office of future work" to transition workers and communities from oil and gas.[3] This has no connection to the discontinuance of permits. At best, it addresses a potential consequence of the Measure. This provision is only inserted in the Measure to garner support from a faction that would not support the discontinuance of oil and gas permits but do support government sponsored employee services. Measures which can pass only by combining subjects that appeal to different factions violate the single-subject requirement. *See In re 2011-2012 No. 3*, 274 P.3d at 566.

The intent to logroll is nowhere clearer than in the Proponent's own statements. Kate Christensen, an organizer with Safe and Healthy Colorado (the special interest group behind the measure) countered arguments by the Colorado Oil and Gas Association that the measure would cause significant job losses. Dismissing the argument, Christensen said nothing about the provision related to work force services. Instead, she claimed it wasn't an issue worthy of consideration because the oil and gas industry in Colorado contributes less than 1% of the state's total employment. https://www.publicnewsservice.org/2023-05-22/climate-change-air-quality/coalition-turns-to-co-voters-to-phase-out-fracking-permits/a84555-1. The proponents cannot credibly claim this is a necessary connected feature of the measure while also claiming the voters need not consider job loss as an important issue. The provision is clearly inserted in the measure to garner support for a subject that could not pass on its own merit.

Additionally, the creation is wholly removed from oil and gas regulatory statutes. Instead, it is created by adding a new § 8-83-604 to C.R.S., Title 8, Labor and Industry. By proposing

[3] **SECTION 5.** 8-83-604 THE PURPOSE OF THE PROGRAM IS TO IDENTIFY STRATEGIES AND FUNDING TO ASSIST SECTORS OF OIL AND GAS EMPLOYEES WHO WILL TRANSITION TO OTHER EMPLOYMENT AS A RESULT OF THE STATE'S REDUCED RELIANCE ON FOSSIL FUEL EXTRACTION. THE OFFICE SHALL CONSULT WITH OTHER RELEVANT OFFICES AND AGENCIES WITHIN THE STATE AND RELEVANT OFFICES OR AGENCIES OUTSIDE OF THE STATE REGARDING SUCCESSFUL WORKFORCE TRANSITION MODELS AND PROGRAMS IMPLEMENTED BY THOSE OFFICES OR AGENCIES. THE PROGRAM SHALL EXPLORE FEDERAL, STATE, AND LOCAL SOURCES OF FUNDING AND FINANCIAL INCENTIVES TO ASSIST TRANSITIONING WORKERS AND COMMUNITIES ECONOMICALLY RELIANT ON OIL AND GAS PRODUCTION.

initiative #45, which does not contain this provision, Proponents demonstrate they can change the permit process without creating a new “office of future work”. These provisions are legally independent of each other.

G. The Addition of the New Definition of “Fracking” Creates a Separate and Distinct Subject.

The Commission currently has a number of promulgated rules and regulations to related to fracking.[4] The definition used by the proponents change that definition, not just in the permitting process, but throughout the rules. This is a clear violation of single subject.

In a recent Supreme Court single subject case this precise type of change to a definition caused the Board to lose jurisdiction to set title. *See In re Title, Ballot Title and Submission Clause for 2021-2022 #16 (In re # 16)*, 489 P.3d 1217 (2021) In that case, the purpose of the measure was to extend the state’s animal cruelty laws to livestock. In doing so the Court found the proponents added a second subject: a redefinition of “sexual act with an animal” that applied to all animals. The Court held that this was impermissible, holding: “Initiative 16 fails to satisfy the single-subject requirement because expanding the definition of ‘sexual act with an animal’ isn’t necessarily and properly connected to the measure’s central focus of incorporating livestock into the animal cruelty statutes.” *Id.* ¶ 41.

The same conclusion holds true here. By redefining fracking throughout the rules, the proponents change regulations in matters unrelated to the initial permitting. This change is not necessarily connected to the purpose and is a violation of single subject.

Adding to the confusion, the proponent’s definition conflicts with other industry definitions. For example, the USGS definition of hydraulic fracturing, is the process of injecting water, sand, and/or chemicals into a well to break up underground bedrock to free up oil or gas reserves. https://www.usgs.gov/mission-areas/water-resources/science/hydraulic-fracturing#overview

H. The Measure Will Operate to Remove the Regulatory Power of the State.

By discontinuing fracking in Colorado, the measure operates to prohibit oil and gas activity on federal land as well as private property. While states have authority to regulate oil and gas operations on federal land, they may not prohibit the practice absent express preemption.

[4] Base fluid, hydraulic fracturing additive, hydraulic fracturing fluid, hydraulic fracturing treatment, and proppant. Dep't of Nat. Res. Reg. 100 Series, 2 Colo. Code Regs. 404-1 (2015) Fracking process, Rule 205a of the Department of Natural Resources' Regulations, 2 Colo. Code Regs. 404-1 (2015), which is titled, "Hydraulic Fracturing Chemical Disclosure," requires operators to disclose substantial information about wells that they have fracked, including the chemicals used. Dep't of Nat. Res. Regs. 305.c(1)(C)(iii), 308B, 316C.a, 2 Colo. Code Regs. 404-1 (2015) provides for additional reporting and notice of an intent to conduct fracking activities. Other rules and regulations govern the disposal of exploration and production waste, including waste associated with the fracking process.

In *California Coastal Comm'n v. Granite Rock Co.*, 480 U.S. 572 (1987), the U.S. Supreme Court ruled federal land use statutes and regulations don't preempt state assertions of authority on federal lands but only when the state regulates, not when the state prohibits.

II. The Ballot Title and Submission is Incomplete, Misleading and Contains a Catch Phrase.

A. Catch Phrase: The use of the term "fracking" is a catch phrase.

The current title includes reference to "fracking". It is improper to include this term in the question for several reasons. First, the practice of fracking applies to the vast majority of oil and gas production in Colorado. *See City of Longmont Colo. v. Colo. Oil & Gas Ass'n,* 369 P.3d 573, 576 (2016). Folding the term into the question only serves to confuse voters that may be led to believe this is a subset of production, when in fact operates as a full ban. The Supreme Court has said as much finding that it is "undisputed that fracking is now the standard for virtually all oil and gas wells in Colorado." *Id.,* at 581.

Additionally, "Catch phrases" and words that could form the basis of a slogan should be carefully avoided in writing a ballot title and submission clause. *Splets v. Klausing,* 649 P.2d 303 (Colo.1982). "Catch phrases" are words that work to a proposal's favor without contributing to voter understanding. By drawing attention to themselves and triggering a favorable response, catch phrases generate support for a proposal that hinges not on the content of the proposal itself, but merely on the wording of the catch phrase. *Garcia v. Chavez (In re Title, Ballot Title & Submission Clause),* 4 P.3d 1094, 1100 (Colo. 2000).

The Court determines the existence of a catch phrase or slogan in the context of contemporary political debate. *See In re Ballot Title 1999-2000 # # 227 & 228, 3 P.3d 1, 6; In re Workers Comp Initiative,* 850 P.2d 144, 147 (Colo. 1993). In setting the titles, the Board must "correctly and fairly express the *true* intent and meaning" of the proposed initiative and must "consider the public confusion that might be caused by misleading titles." § 1-40-106(3)(b), C.R.S. (2023); *In re Ballot Title 1999-2000 # # 245(f) & 245(g),* 1 P.3d 739, 743 (Colo. 2000).

The Court found the words operate as both a catch phrase and a slogan. They mask the policy question regarding whether the most rapid and effective way to teach English to non-English speaking children is through an English immersion program, a question of great public debate. The Court further found that the "as rapidly and effectively as possible" language in the titles tipped the substantive debate on an issue to be submitted to the electorate. Even though the initiative contained this language, the Title Board was not permitted to include the wording where it is constituted a catch phrase. *Citing See In re Proposed Initiative on "Obscenity,"* 877 P.2d 848, 850-51 (Colo. 1994).

By custom and practice, the board has used the scientific term of "hydraulic fracturing". The use of the term "fracking" by the proponents is clearly intending to evoke a reaction in the voters and will no doubt serves as a basis for their campaign.

B. Misleading: The Title is Misleading and Fails to Inform Voters of Measures' Central Features.

In fixing a title and a summary, the Board's duty is "'to capture, in short form, the proposal in plain, understandable, accurate language enabling informed voter choice . . . .'" In re Proposed Initiative for 1999-2000 No. 29, 972 P.2d 257, 266 (Colo. 1999) (quoting *In re Ballot Title "1997-1998 # 62"*, 961 P.2d 1077, 1083 (Colo. 1998)). Here, because the original text of the proposed initiative is difficult to comprehend, the titles and summary are not clear.

The title does not even inform voters of substantial and material changes in state law resulting from this Measure. The title fails to inform voters that this Measure will redefine fracking, transform the jurisdiction and duties of the Commission and serve to preempt federal law. The title does not inform voters that the Measure will eliminate certain Commission Rules and preserve other Commission Rules. And the title does not even mention the fact that the Measure would transform the Colorado Oil and Gas Conservation Commission into a minimized role of "primarily monitoring, plugging, and remediating of facilities permitted prior to December 31, 2030."

Further, the title is misleading in that it states it "allows for existing oil and gas operations" when, in fact, it does not allow for permit amendments and repeals existing permits if the well is not operational by 2033.

For the foregoing reasons, the Petitioner respectfully requests the Board grant the motion for rehearing and deny the title as set.

Respectfully submitted this 24th day of May 2023.

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COLORADO TITLE SETTING BOARD

IN THE MATTER OF THE TITLE AND BALLOT TITLE AND SUBMISSION CLAUSE FOR PROPOSED INITIATIVE 2023-2024 #46

MOTION FOR REHEARING ON PROPOSED INITIATIVE 2023-2024 #46

On behalf of Patricia Nelson and Paul Culnan, registered electors of the State of Colorado and designated representatives for Proposed Initiative 2023-2024 #46, the undersigned counsel hereby submits to the Title Board this Motion for Rehearing on Proposed Initiative 2023-2024 #46 ("Initiative #46") and as grounds therefore state as follows:

I. THE TITLE SET BY TITLE BOARD AT MAY 17, 2023 HEARING

On May 17, 2023, the Title Board set the following ballot title and submission clause for Initiative #46:

> Shall there be a change to the Colorado Revised Statutes concerning discontinuing the issuance of new oil and gas operation permits that utilize fracking by December 31, 2030, and, in connection therewith, requiring the phase-out of new oil and gas operation permits that utilize fracking; allowing permitted oil and gas operations that utilize fracking to continue; and requiring the state to explore transition strategies for impacted oil and gas workers who may transition to other employment?

II. GROUNDS FOR REHEARING

A. The Ballot Title and Submission Clause Is Misleading Because It Does Not Correctly and Fairly Express Its True Intent and Meaning.

The title of the Initiative is misleading and does not correctly and fairly express the initiative's true intent and meaning because it omits language informing voters that the intent of the measure is to protect land, air, and water. Section 1-40-106(3)(b), C.R.S. provides:

> In setting a title, the title board shall consider the public confusion that might be caused by misleading titles and shall, whenever practicable, avoid titles for which the general understanding of the effect of a "yes" or "no" vote will be unclear. The title for the proposed law or constitutional amendment, which shall correctly and fairly express the true intent and meaning thereof, together with the ballot title and submission clause. . ..

Titles and submission clauses should "enable the electorate, whether familiar or unfamiliar with the subject matter of a particular proposal, to determine intelligently whether to support or oppose such a proposal." *In re Title, Ballot Title & Submission Clause for Proposed Initiative on Parental Notification of Abortions for Minors*, 794 P.2d 238, 242 (Colo. 1990)). The purpose of reviewing an initiative title for clarity parallels that of the single-subject requirement: voter protection through reasonably ascertainable expression of the initiative's purpose. *See id.*

The primary purpose of Initiative #46 as expressed in the Declaration of Purpose and in the body of the measure itself in the proposed language at C.R.S. 34-60-106(20.5) is to protect Colorado's land, air, and water. The measure achieves this purpose by phasing out new oil and gas operation permits that utilize fracking between January 1, 2026, and December 31, 2030, at which time no new permits that utilize fracking may be issued.

Notably, Objector Ward made the argument that 25% of respondents to a poll did not believe there was a problem with fracking as it pertains to protecting land, air, and water.[1] Indeed, this is precisely why the title needs to inform voters of the true meaning and intent of the measure. Study and after study demonstrate that fracking is detrimental to land, air, and water.[2] A title should contribute to voter understanding and purpose of the initiative. *In re Title, Ballot Title & Submission Clause*, etc., 646 P.2d 916, 922 (Colo. 1982) ("the language adopted by the Board reflects the content of the initiative").

Here, based on an objector's own arguments, the title for Initiative #46 is one for which the general understanding of the effect of a "yes" or "no" vote will be unclear without inclusion of the "to protect land, air, and water" language. *See* generally C.R.S. §1-40-106(3)(b); *see also In re Proposed Initiative on "Obscenity,"* 877 P.2d 848, 850-51 (Colo. 1994). As a result, the title for Initiative #46 does not enable voters to make an informed choice because it does not correctly and fairly express its true intent and meaning.

B. <u>Language That Is Not a Catch Phrase But That Describes the Intent of the Measure Is Appropriately Included in the Title</u>.

Each member of the Title Board appropriately rejected the argument that "to protect land, air and water" was a catch phrase at the May 17, 2023, hearing.[3] Instead, they seem to have decided not to include the language in the title for Initiative #47 due to proposed hypothetical arguments raised in the Foster Motion for Rehearing on proposed initiatives 2023-2024 #44 and #45 that suggested that the Title Board would be bound to include language of the intent of a measure in titles in the future.[4] The Title Board, however, already has a history of including language regarding intent in setting titles when it contributes to voter understanding and the purpose of the measure. *See, for e.g.*, Initiative 2021-2022 #58, for which the Title Board set the following title (emphasis supplied):

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[1] *See* Title Board hearing audio recording from May 17, 2023 at https://csos.granicus.com/player/clip/385?view_id=1&redirect=true&h=3e91faadd4a13e770940c80a86cc7a94, Taheri 2:55:49-2:56:10. Note that portions of the audio cited herein refer to the rehearing for Proposed Initiatives 2023-2024 #44 and #45, which are very similar to Proposed Initiatives 2023-2024 #46 and #47, and the Designated Representatives-Petitioners sought the same "to protect land, air, and water" language in the titles for #44 and #45.
[2] *See for e.g.,* Proponents' Exhibits 1, 2a, 2b, and 3 introduced during the rehearing for Proposed Initiatives 2023-2024 #44 and #45.
[3] *Id.,* Conley 2:30:25-37; Barry 2:31:30-49; Morrison 2:32:59-33:18; Conley 2:37:30-41; Conley 2:38:37-57.
[4] *Id.,* Conley 2:30:42-51; Morrison 2:32:27-51.

> Shall there be a change to the Colorado Revised Statutes concerning legal regulated access to natural medicine for persons 21 years of age or older, and, in connection therewith, defining natural medicine as certain plants or fungi that affect a person's mental health and are controlled substances under state law; establishing a natural medicine regulated access program for supervised care, and requiring the department of regulatory agencies to implement the program and comprehensively regulate natural medicine *to protect public health and safety*; creating an advisory board to advise the department as to the implementation of the program; granting a local government limited authority to regulate the time, place, and manner of providing natural medicine services; allowing limited personal possession, use, and uncompensated sharing of natural medicine; providing specified protections under state law, including criminal and civil immunity, for authorized providers and users of natural medicine; and, in limited circumstances, allowing the retroactive removal and reduction of criminal penalties related to the possession, use, and sale of natural medicine?

See also Initiative 2021-2022 #108, for which the Title Board set the following title (emphasis supplied):

> Shall there be a change to the Colorado Revised Statutes concerning statewide funding for additional affordable housing, and, in connection therewith, dedicating state revenues collected from an existing tax of one-tenth of one percent on federal taxable income of every individual, estate, trust, and corporation, as defined in law, for affordable housing and exempting the dedicated revenues from the constitutional limitation on state fiscal year spending; allocating 60% of the dedicated revenues to affordable housing financing programs *that will reduce rents, purchase land for affordable housing development, and build assets for renters*; allocating 40% of the dedicated revenues to programs that *support affordable home ownership, serve persons experiencing homelessness, and support local planning capacity*; requiring local governments that seek additional affordable housing funding to expedite development approvals for affordable housing projects and commit to increasing the number of affordable housing units by 3% annually; and specifying that the dedicated revenues shall not supplant existing appropriations for affordable housing programs?

The titles for Initiatives for 2021-2022 #58 and #108 demonstrate that the Title Board's inclusion of "to protect land, air, and water" in the title for Initiative #46 would not set new precedent that binds the Title Board to always include language of intent in its titles. Rather, the titles for Initiatives 2021-22 #58 and #108 confirm that it is appropriate to include language of meaning and intent when such language adds to voter understanding. *See In re Title, Ballot Title & Submission Clause, & Summary for 1997-98 # 112 (Livestock Operations),* 962 P.2d 255, 256 (Colo. 1998) (Supreme Court approves use of "to protect the environment and human health" in summary). Similarly, the words "to protect land, air, and water" are descriptive terms that will present the meaning and intent of Initiative #46 to voters in a straightforward manner. *See In re Ballot Title for 2009-2010 No. 45.,* 234 P.3d 642 (Colo. 2010).

III. DATE OF REHEARING

Per discussion at the initial Title Board hearing on Initiative #46, the Designated Representatives respectfully request that the rehearing at which all Motions for Rehearing filed on Initiative #46 take place on June 21, 2023, rather than on June 7, 2023 because one of the Designated Representatives and their counsel have a conflict on the next regular Title Board meeting on June 7, 2023.

IV. CONCLUSION

Based on the foregoing, Patricia Nelson and Paul Culnan request a rehearing of the Title Board for Initiative 2023-2024 #46 on June 21, 2023, because the title fails to fairly express the initiative's true meaning and intent.

Respectfully submitted this 24th day of May 2023.

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CERTIFICATE OF SERVICE

The undersigned hereby certifies that on the 24th day of May, 2023, a true and correct copy of **MOTION FOR REHEARING ON PROPOSED INITIATIVE 2023-2024 #46** was filed and served via email or U.S. mail, postage prepaid, to the following:

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Article

Health Symptoms and Proximity to Active Multi-Well Unconventional Oil and Gas Development Sites in the City and County of Broomfield, Colorado

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Abstract: City and County of Broomfield (CCOB) residents reported over 500 health concerns between January 2020 and December 2021. Our objective was to determine if CCOB residents living within 1 mile of multi-well unconventional oil and gas development (UOGD) sites reported more frequent health symptoms than residents living > 2 miles away. We invited 3993 randomly selected households to participate in a health survey. We applied linear regression to test associations between distance to UOGD and summed Likert scores for health symptom categories. After covariate adjustment, respondents living within 1 mile of one of CCOB's UOGD sites tended to report higher frequencies of upper respiratory, lower respiratory, gastrointestinal and acute symptoms than respondents living more than 2 miles from the sites, with the largest differences for upper respiratory and acute symptoms. For upper respiratory and acute symptoms, scores differed by 0.81 (95% CI: 0.06, 2.58) and 0.75 (95% CI: 0.004, 1.99), respectively. Scores for adults most concerned about air pollution, noise and odors trended higher within 1 mile for all symptom categories, while scores among adults least concerned trended lower. Scores trended higher for lower respiratory, gastrointestinal and acute symptoms in children living within 2 miles of UOGD, after covariate adjustment. We did not observe any difference in the frequency of symptoms reported in unadjusted results. Additional study is necessary to understand relationships between proximity to UOGD and health symptoms.

Keywords: epidemiology; unconventional oil and gas development; health symptoms; air pollution; hydraulic fracturing; acute exposure symptoms

check for updates

Citation: Weisner, M.L.; Allshouse, W.B.; Erjavac, B.W.; Valdez, A.P.; Vahling, J.L.; McKenzie, L.M. Health Symptoms and Proximity to Active Multi-Well Unconventional Oil and Gas Development Sites in the City and County of Broomfield, Colorado. *Int. J. Environ. Res. Public Health* **2023**, *20*, 2634. https://doi.org/10.3390/ijerph20032634

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1. Introduction

1.1. Unconventional Oil and Gas Development

The United States (US) is now the world's top producer of both oil and natural gas [1], largely because of advances in extraction technology over the past 20 years [2,3]. These technological advances allow operators to co-locate many wells on one site (multi-well sites) and reduce the number of well pads in an area, as well as pipeline routes, and production facilities [4]. However, there is a growing concern regarding the increase in intensity, frequency and duration of air pollutant and noise emissions related to multi-well unconventional oil and gas development (hereinafter referred to as UOGD) sites [5,6].

Colorado is among the top five oil-producing states, with the majority of UOGD sites operating within the Denver–Julesburg basin (DJB) in northeast Colorado, including the urban corridor along the Northern Front Range [7]. Concurrent to UOGD growth, the Northern Front Range has experienced intensive population growth over the past 20 years [8]. Co-current intensive population and UOGD growth in the DJB led to a 14% increase in the size of the DJB population living within 1 mile of an UOGD site between 2000 and 2012 [9]. The rate of population growth continues to increase across Colorado's Front Range, but especially within the City and County of Broomfield (CCOB). The CCOB is expected to experience a population increase of 24% by 2030 (from 2020 population counts) [10], double the projected population increase of 12% for the entire state [8]. Approximately 10.4% of CCOB's 74,112 residents currently live within 1 mile of 6 multi-well UOGD sites; another 15.1% live between 1 and 2 miles from the sites [11].

1.2. Oil and Gas History in the City and County of Broomfield

The CCOB is one of two consolidated municipal and county governments in the state of Colorado [12], created out of parts of four neighboring counties in 2001. These adjacent counties are as politically and economically diverse as Boulder County, which has historically had a progressive environmental and conservation ethos [13], and Weld County, whose economy relies heavily on resource and mineral extraction [14]. This diversity provides a unique nexus and test case for the risks, challenges and opportunities relating to UOGD in proximity to urban environments.

In 2018, a Denver-based UOGD operator received permits [15] from the Colorado Oil and Gas Conservation Commission (COGCC) to drill 84 unconventional oil and gas wells across six UOGD sites in the rapidly urbanizing area of north/central Broomfield. Prior to COGCC approval and amidst much public outcry from high-income neighborhoods opposing the construction of the UOGD sites, city officials negotiated the final locations of the pads along with an agreement that enumerated a series of measures (referred to as best management practices, or BMPs) intended to reduce impacts to health, safety and the environment [16].

The final, negotiated well pad locations were constructed on CCOB-owned public lands and are surrounded by single-family residential areas, some of which are 1000 ft. from the nearest pad (see UOGD locations in Figure 1). After the approval of the locations for the six UOGD sites, strong opposition from nearby residents remained, and concerns were raised about cumulative exposures to toxic air emissions from living near multiple sites, as well as exposure to additional traffic, dust, noise and lighting. One year after the six multi-well pad project was approved, Colorado Senate Bill 181 (SB-181), which paved the way for the COGCC to adopt new oil and gas locations setback distances at a minimum of 2000 ft. from occupied residential structures, was passed by the state legislature. This landmark bill was supported, in part, by a risk assessment that demonstrated a potential for health impacts to occur up to 2000 ft. from UOGD as a result of possible exposure to air toxics [17,18].

1.3. Air and Noise Pollution

Multiple studies have demonstrated potential impacts to human health from air pollutants emitted from Colorado's UOGD well sites [5,6,18,19]. The CCOB has a robust air quality monitoring network with 14 sensors surrounding the six multi-well UOGD sites [20]. Previous studies indicate that the use of BMPs, such as closed loop flowback systems, can reduce the frequency of increased ambient air volatile organic compounds (VOCs) concentrations [21].

While BMPs, such as the closed loop flowback systems used in Broomfield, lower air pollutant emissions from UOGD well sites, reducing VOCs during pre-production activities is dependent upon available technological mitigations. Broomfield's monitoring system has demonstrated that, regardless of strict BMPs, there are still numerous increases in the frequency, magnitude and duration of VOC emissions during pre-production operations, especially during well bore drilling (likely attributed to drill cuttings containing hydrocarbons) and coiled tubing/mill out [22].

Noise from UOGD occurs in nearly all phases of well development and into production [6,23]. Noise can disturb nearby residents and disproportionately impact vulnerable populations, including the elderly and chronically ill [24]. Recent studies indicate that

BMPs, such as sound walls, are not effective in mitigating noise exposures for nearby residents [6,25].

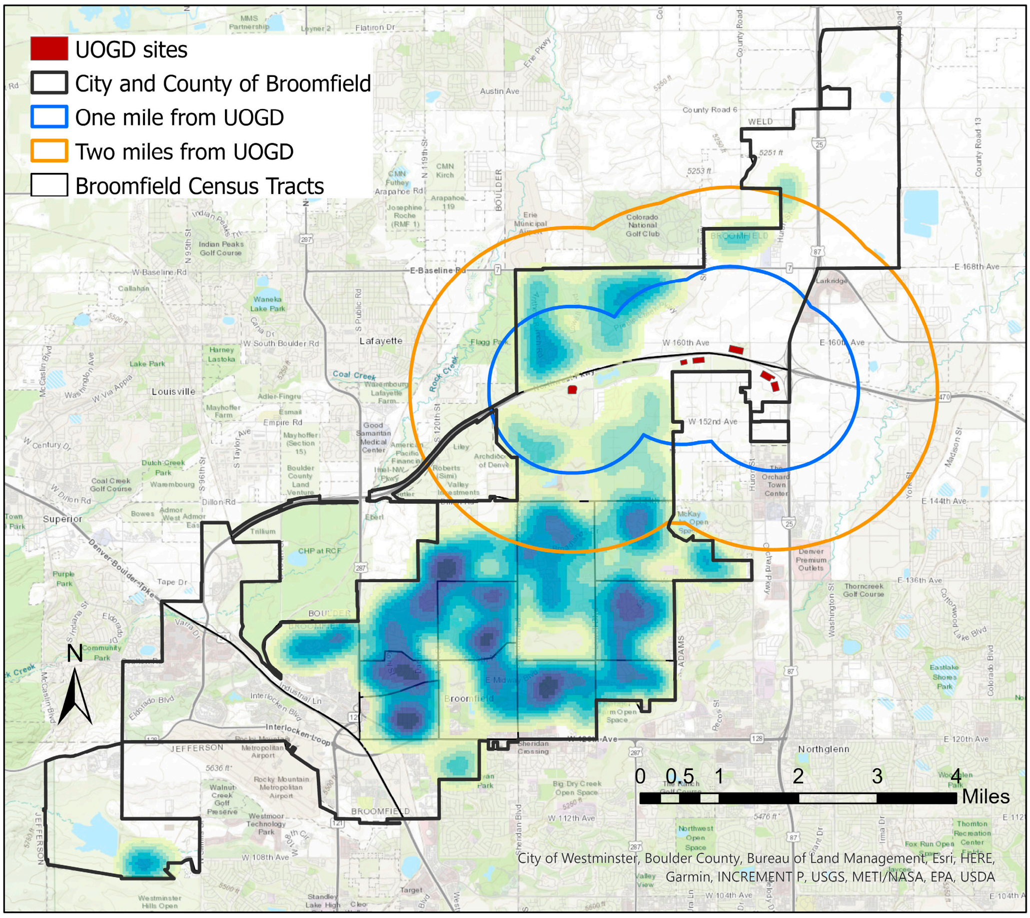

Figure 1. Kernel Density map indicating location densities of 3993 households randomly selected to participate in the health survey. Darker colors indicate a greater number of surveys were sent to that location.

1.4. Human Health Impacts and Proximity to UOGD

Several months after the commencement of construction and drilling at several of the UOGD sites, residents began to complain to city officials of health symptoms they believed were caused by air toxics and noise related to UOGD [26]. The CCOB's Department of Public Health and Environment formalized a way for residents to submit health complaints online and within a 2-year period (2020–2021), during which time several well pads were being constructed, residents reported over 500 health concerns. The majority of concerns were related to air pollution, noise and odor associated with six multi-well UOGD sites [26]. Health concern reports increased during pre-production and included reports of headaches, eye and throat irritation, and nosebleeds. Over all phases of UOGD, residents most commonly reported difficulty sleeping and anxiety or stress and often stated noise disturbances from nearby oil and gas operations as the cause [27]. The Human Health Risk Assessment [17,18], which gave support for the passage of Colorado Senate Bill 181 (SB-181), was the basis for CCOB's health collection efforts, as the risk assessment recommended efforts focusing on population-specific, local data collection.

The body of epidemiological literature indicates that UOGD affects the health of nearby residents. A current review found that, in 25 of 29 studies, there was at least one statistically significant association between UOGD exposure and adverse health outcomes (hospitalizations, adverse birth outcomes, cancer and asthma exacerbations) [28]. More recently published studies report associations between intensity of oil and gas activity and indicators and exacerbations of cardiovascular disease [29–31], and further evidence of associations with adverse birth outcomes [32–34]. Additionally, residents living within 1 km of an UOGD site self-report more skin conditions and upper respiratory symptoms than those living farther away [35].

Several studies document sociopsychological impacts in residents living near UOGD sites due to anxieties related to the potential release of toxins and carcinogens [36]. Commonly reported symptoms from those living near UOGD included psychosocial stress associated with community change [23], worry [37,38] and adverse mental [39] and physical health effects [40]. As UOGD outpaces the scientific community's ability to understand potential health effects, studies of self-reported outcomes are a vital way to understand health impacts in order to influence public policy [40]. After the onset of pre-production UOGD activities and the notably large number of symptoms reported to CCOB's Department of Public Health and Environment, it became clear that a more robust study was needed to better assess self-reported health symptoms and distance to UOGD. Our objective is to determine whether CCOB residents living near the CCOB's multi-well oil and gas sites, which are considered to have some of the most rigorous BMPs in the State of Colorado, report more health symptoms than CCOB residents not living near the sites. At the time this study was conducted, no other studies have aimed to associate symptoms at various proximities to UOGD in a jurisdiction that requires such extensive BMPs.

2. Materials and Methods

We conducted a cross-sectional study of 3993 randomly selected CCOB households to collect data on self-reported health symptoms between October and December 2021.

2.1. Study Area and Population

The CCOB is located in Colorado's Front Range with a total land area of 33 square miles and a population of approximately 74,000 [11]. In 2021, CCOB was rated as the fifth healthiest county in the United States, according to research conducted by University of Missouri Extension Center for Applied Research and Engagement Systems (CARES) [41]. Seventy-six percent of the population identifies as white alone [11]; 59% have obtained a Bachelor's degree or higher; and the median household income is $107,638, nearly one-third higher than the state of Colorado's median household income [42]. Prior to the start of this research, 84 UOGD wells were permitted for development in Northern CCOB (Figure 1) located across six sites. During the time health surveys were being collected, 30 wells were in the production phase, with another 21 wells in the pre-production phase (drilling, hydraulic fracturing and/or the coiled tubing/mill out), and 33 wells had no activity.

2.2. Survey Instrument

We designed our survey and questions based on symptoms collected in prior oil and gas survey research [35,43] as well as symptoms collected by the State of Colorado's Department of Public Health and Environment's Oil and Gas Health Information and Response line, and the CCOB's Health Concern line. An important objective of this research is to understand symptoms and proximity to UOGD sites, and building off symptoms defined in the previous literature helps to characterize how the population in CCOB may report similar or different symptoms related to living near or away from UOGD. Surveys contained Likert scale questions, commonly used in epidemiological survey research [35,43], and provided a way to quantify responses. We asked about the frequency of 20 separate symptoms experienced in the past 14 days. Choices included never, once, 2–5 times, 5–13 times or everyday (0–4 Likert scale). The survey also contained questions on occurrence of each symptom (yes, no) within the past two and five years: before major UOGD projects began, preexisting chronic health conditions, demographics, household size, smoking (tobacco and marijuana) status and exercise habits, as well as the degree of concern for nine environmental issues (e.g., noise, odor, air, etc.) by using a 0–4 Likert scale—not at all concerned, slightly, somewhat, moderately or extremely concerned (see Supplemental Material, "Survey"). Survey data were collected using ESRI's ArcGIS Survey123 platform.

2.3. Household Selection and Recruitment

Households were randomly selected using ArcGIS Desktop version 10.8.1. Random selection helped reduce participant bias and ensure households were targeted at locations throughout CCOB. There are approximately 21,000 residential parcels in CCOB [11], and 19% received a postcard in the mail with a survey link. Approximately one-fourth of the total number of parcels are located in CCOB's two northernmost census tracts; these tracts contain all UOGD activity in CCOB. Since the survey mentioned that this research was related to UOGD activity, we expected a greater response rate from those living in the census tracts near UOGD than from those living in the tracts farther away. To ensure an adequate sample size was collected, we weighted the distribution of randomly selected households for population density while also oversampling in the southernmost census tracts (which are located further from UOGD) (Figure 1). To accomplish this, a fishnet grid was created for the two northernmost census tracts and again for the 13 southernmost census tracts. The centroid of each grid was attached to the nearest residential parcel for household selection. Initially, about 1800 households were selected throughout CCOB to receive surveys in the mail. However, due to a low response rate within the first month of data collection, this process was repeated again and approximately 2200 additional households were selected to receive postcards with a link to the survey. Households were also sent two to three reminder postcards to encourage participation. Overall, we sent postcards with a link to the survey via QR code to 524 households within 1 mile of UOGD, 693 households within 1–2 miles of UOGD and 2776 households located >2 miles from UOGD activity.

Postcards were translated into English and Spanish and stated the intent of the research, the length of time expected to complete the health survey (20–30 min) and instructions for accessing the survey via QR code or webpage (see Supplemental Material, "Postcard"). Survey questions were available in English and Spanish.

We asked that only one adult complete the survey per household. To reduce selection bias, instructions asked that the adult selected was the one whose birthday was closest to the date they received the survey in the mail and that the adult lives in the household full time. We encouraged additional survey questions for children to be completed per household by an adult for a child under the age of 18 living in their household, if applicable, and asked that the same selection method be applied for the child. The Institutional Review Board for the University of Colorado (COMIRB) reviewed and approved this research (COMIRB# 21-3719).

2.4. Residence Proximity to Nearest Multi-Well Oil and Gas Site

We used ArcGIS to calculate the distance between each respondent's residence and each UOGD site in CCOB. We then classified residences according to their distance from the nearest UOGD site into distance bands of less than 1 mile, 1–2 miles or >2 miles. We based the 1- and 2-mile cut points on residential locations for CCOB residents filing health complaints attributed to UOGD between 2019 and 2021 [26]. Complainants lived predominantly in CCOB's two northernmost census tracts where homes are within 2 miles of the multi-well oil and gas sites, with most complainants living within 1 mile of a multi-well oil and gas site.

2.5. Outcomes

We grouped health symptoms from the household survey based on physiological organ system [35] and mental health. We assigned: coughs, nasal congestion, runny nose, throat irritation and bloody noses to upper respiratory; shortness of breath and lung irritation to lower respiratory; dizziness, difficulty concentrating, headaches, numbness and tingling, ringing ears and hearing loss, and muscle aches and weakness to neurological; nausea and vomiting to gastrointestinal; and anxiety and stress, difficulty sleeping, difficulty concentrating, and lack of energy and fatigue to mental health.

We also performed a principal component analysis on all symptoms. The first three components capture 58% of the variability, with Eigenvalues > 1. The first component captured 33% of the variability, with Eigenvectors > 0.1 for all symptoms. The second component captured 7.2% of the variance, with Eigenvectors > 0.1 for primarily mental health symptoms (anxiety/stress, difficulty concentrating, lack of energy/fatigue, difficulty sleeping). The third component captured another 6.6% of the variance, with Eigenvectors > 0.1 for several acute symptoms (nausea, vomiting, nosebleeds, lung irritation, shortness of breath, cough and throat irritation). Based on these PCA results, we assigned all symptoms to an outcome group named total symptoms and symptoms with Eigenvectors > 0.1 in the third component to an outcome group named acute response. We had already created a mental health outcome group with the symptoms loading to the second component.

2.6. Statistical Analysis

The mean Likert score for each self-reported outcome and the total number of symptoms reported as occurring at least once (Likert score > 0) in the past 14 days for each respondent were calculated according to the distance of the respondent's residence (<1, 1–2 or >2 miles) from the nearest multi-well UOGD site. Because many symptoms surveyed may also be associated with COVID and of higher COVID infection rates in Colorado's Hispanic/Latino, Native Hawaiian/Pacific Islander, American Indian/Alaska Native and African American communities in 2021 [44], we assigned responses from the race/ethnicity choices into two groups: (1) White, Asian, Asian/White or Asian/White/Native Hawaiian/other Pacific Islander and (2) Hispanic/Latino, Hispanic/Latino/White, American Indian/Alaska Native, Native Hawaiian/other Pacific Islander or Black/White, or other. No survey respondents identified as only Black. We classified reported occupation as management or professional; service, sales, or office; natural resources, construction, maintenance, production, transportation, or material moving; and not working [45].

Because the distribution of the summed Likert scores for adults was log normal, all summed scores were log transformed to approximate a normal distribution. Summed Likert scores for children approximated a normal distribution. We applied the method of least squares linear regression to test the association between residence distance from the closest UOGD site (distance band) and the mean overall number of symptoms and mean summed Likert scores for all symptoms as well as the mean summed Likert scores for each of six groups of health symptoms (upper respiratory, lower respiratory, gastrointestinal, neurological, acute response and mental health, see supplemental material, Table S1) for unadjusted and adjusted models. We ran separate models for adult respondents and children (<18 years) because children did not provide their own responses and there were fewer covariates available for children. Based on a priori knowledge of their association with both exposure and outcomes, we adjusted both the adult and child models for age (ordinal), gender identification (male and female or other), smoked or smoker ever present in household (yes/no), number of chronic health conditions reported (continuous) and number of children under 18 years of age living in household (continuous). The adult model was also adjusted for days per week of exercise (continuous), alcoholic drinks consumed each week (ordinal), hours per day spent at residence (ordinal), level of education (ordinal), race/ethnicity (dichotomous), occupation (categorical) and years at current residence (<, ≥2 years). An evaluation of correlation between co-variates indicated little correlation between covariates. We evaluated for effect modification by performing stratified analysis for gender, smoker ever present in household, years at current residence, age (<, ≥55 years), number of chronic conditions (0, >0) and hours per day spent at residence (<, ≥13 h). Additionally, we evaluated for mediation as well as effect modification by the three most frequently reported environmental concerns (air pollution, noise and odors) in CCOB's oil and gas complaint database [26] by using multiple linear regression with (1) the mediator (sum of Likert scores for air pollution, noise and odor concerns) as the dependent variable and setback distance as the main predictor; (2) the sum of Likert scores for a group of health symptoms as the dependent variable and the mediator as the main predictor; and (3) the sum of Likert scores for a group of health symptoms as the dependent variable and setback distance as the main predictor [46]. We considered mediation to be present if all three regressions returned statistically significant results for the main predictor [47]. To evaluate for effect modification, we stratified by the median summed Likert score (<, ≥4) for air pollution, noise and odor concerns, as well as stratifying by the median summed Likert score (<, ≥8) for the remaining seven environmental concerns in the survey (light, dust, wildlife, traffic, water, oil spill, waste). Given the exploratory nature of this study, no adjustments were made for multiple comparisons, and significance was established at the two-sided 0.05 level. We conducted all statistical analysis using SAS 9.3 (SAS Institute, Cary, NC, USA).

3. Results

Four hundred twenty-seven adults responded to our survey, and 59 adults provided responses for a child living in their household. Response rates for the three distance bands ranged from 10–11.6%, and the overall response rate was 10.7% (Table 1).

3.1. Demographics

Demographic results are presented in Table 1. According to the U.S. Census [11], CCOB does not have extensive racial diversity, with 76% of respondents identifying as white alone, which is reflected in our survey respondents. In general, a higher proportion of respondents living within 1 mile and 1–2 miles (than from those living more than 2 miles away) from one of CCOB's UOGD sites identified as male, never smoked or lived with someone that smoked, consumed more alcoholic beverages, were aged 55 years or older, spent less time at home each day and lived less than 2 years in their current home. Level of concern with oil and gas stressors (air pollution, noise and odors) did not differ by distance band.

3.2. Self-Reported Health Symptoms

We observed no differences in unadjusted analysis of self-reported health symptoms by setback distance (Table 2). A full list of symptoms can be viewed in Supplemental Material (Table S1).

After covariate adjustment, the total number of symptoms reported at least once in the past 14 days and summed Likert scores for all symptoms trended higher as distance to UOGD decreased (Table 3). Respondents living within 1 mile of one of CCOB's UOGD sites tended to report higher frequencies of upper respiratory, lower respiratory, gastrointestinal and acute symptoms than respondents living 1–2 miles and more than 2 miles from the sites, with the largest differences for upper respiratory and acute symptoms. Mean summed Likert scores differed by 0.81 (95% CI: 0.06, 2.58) and 0.75 (95% CI: 0.004, 1.99) for upper respiratory and acute symptoms, respectively. We observed null results for mental health and neurological symptoms in our adjusted model.

Level of concern for the top three environmental complaints (noise, odor and air) in CCOB's oil and gas complaint database did not mediate the relationships between reported symptoms and distance band (see Supplemental Material, Tables S2 and S3); however, air pollution, noise and odor concerns did modify the relationship (Table 3). Among respondents reporting greater concern for air pollution, odor and noise (sum Likert scores within the top 50th percentile, ≥4), those living within 1 mile of CCOB's UOGD sites reported 2.88 more health symptoms in the past 14 days (95% CI: 1.14, 4.63) than those living > 2 miles from the sites. Among these respondents, we also observed a 7.26 mean difference in the sum of Likert scores for the sum of all symptoms (95% CI: 3.16, 11.35) and statistically higher means for all symptom categories between those living <1 mile and >2 miles from the UOGD sites (Table 4). Among respondents reporting less concern for air, odor and noise (Sum Likert scores less than the 50th percentile, <4), those living within 1 mile of CCOB's UOGD sites reported fewer health symptoms in the past 14 days and lower frequencies of all symptom categories than those living >2 miles. Stratified analysis by the median summed Likert score (<, ≥8) for the six remaining environmental concerns indicate effect modification to a lesser extent (see Supplemental Material Table S4).

Table 1. Demographics of adult survey respondents and household distance from well site.

Parameter	Within 1 Mile	1–2 Miles	>2 Miles	Total
Number of survey respondents (response rate [%])	61 (11.6)	69 (10.0)	297 (10.7)	427 (10.7)
	Age in Years (%)			
18–44	18	5.9	23.9	21.8
45–54	8.2	29	20.2	19.9
55–64	14.8	29	20.5	21.1
65–74	41	14.5	26.9	26.9
≥75	18	11.6	8.5	10.3
White alone (%) [1]	89.9	90.2	90.9	90.6
Female (%)	44.3	44.9	59.3	54.8
Never smoked or lived with someone who smoked (%)	88.5	89.9	82.5	84.5
Average Days of Exercise per Week	3.9	4.7	3.5	3.8
	Average number of alcoholic drinks per week (%)			
None	31.1	44.9	40.7	40.1
1–2	27.9	17.4	23.6	23.2
3–5	19.7	20.3	9.5	19.7
6–10	13.1	14.5	11.1	11.9
>10	8.2	2.9	5.1	5.2
	Average Hours Spent in Home Per Day (%)			
Less than 8	6.6	5.8	1.4	2.8
8–12	19.7	14.5	12.1	13.6
13–15	16.4	24.6	20.9	20.8
16–20	47.5	21.7	31	31.9
≥21	9.8	33.3	34.7	30.9
<2 years in household	19.7	5.8	7.7	9.1
	Occupation (%)			
Management, professional and related occupations	29.5	42.0	52.5	47.5
Service, sales, office, natural resources, construction, maintenance, production, transportation and material moving occupations [2]	11.5	8.7	9.1	9.4
Not working (retired, homemaker, student, unemployed)	59.0	49.3	38.4	43.1
Mean Likert Score for Concerns about air, noise and water	4.9	4.8	4.6	4.7

[1] Percentage of respondents that identified as white. Approximately 10% of respondents identified as either Asian alone (2.6%), Hispanic/Latino alone (2.1%), American Indian/Alaska Native, Native Hawaiian/other Pacific Islander, Asian/White, Hispanic/Latino/White, Black/White or other. No survey respondents identified as Black or African American alone. [2] No respondents reported that they worked in the oil and gas industry.

Table 2. Unadjusted model for difference in means for survey respondents living more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021.

Outcome	Unadjusted Model Main Analysis (N = 427)	
	Difference between >2 Mile and 1–2 Mile Means (LCL, UCL)	**Difference between >2 Mile and <1 Mile Means (LCL, UCL)**
Total Number of Symptoms (N)	−0.31 (−1.57, 0.96)	−0.44 (−1.77, 0.89)
Total summed Likert Score	−0.92 (−3.14, 1.67)	−1.01 (−3.34, 1.71)
[1] Upper Respiratory (summed Likert Score)	−0.40 (−1.06, 0.41)	0.15 (−0.62, 1.09)
[2] Lower Respiratory (summed Likert Score)	0.03 (−0.16, 0.25)	0.04 (−0.16, 0.28)
[3] Mental Health (summed Likert Score)	−0.06 (−0.82, 0.88)	−0.88 (1.55, 0.04)
[4] Neurological (summed Likert Score)	−0.34 (−1.10, 0.57)	−0.39, (−1.18, 0.56)
[5] Gastrointestinal (summed Likert Score)	−0.003 (−0.13, 0.14)	0.020 (−0.12, 0.18)
[6] Acute (summed Likert Score)	−0.13 (−0.70, 0.53)	0.17 (−0.46, 0.90)

[1] Upper Respiratory = cough + nasal congestion + runny nose + throat irritation + nosebleeds. [2] Lower Respiratory = short breath + lung irritation. [3] Mental Health = anxiety stress + diff sleeping + difficulty concentrating + lack energy fatigue. [4] Neurological = dizziness + difficulty concentrating + headaches + numbness tingling + ringing ears hearing loss + muscle aches weakness pain. [5] Gastrointestinal = nausea + vomiting. [6] Acute = nausea + vomiting + Nosebleeds + lung irritation + short breath +cough + throat irritation. LCL = lower 95% confidence level, UCL = upper 95% confidence level.

While we did not observe modification by gender identification, we did observe greater mean differences in summed Likert scores for upper respiratory (1.54, 95%CI: 0.16, 2.97) and acute symptoms (1.30, 95%CI: 0.13, 2.47) in respondents identifying as male. Likewise, while we did not observe modification by number of chronic conditions, we did observe lower mean differences in summed Likert scores for upper respiratory (0.75, 95%CI:−0.83, 2.33) and greater differences for acute symptoms (1.20 95%CI: −0.16, 2.58) in respondents reporting more than one chronic condition (see Supplemental Material, Table S5). In sensitivity analyses for respondents that identified as white, never smoked or lived with someone that smoked, lived in their current home for 2 or more years, were at home more than 12 h per day and were aged 55 years or older, we observed results similar to results for all respondents (see Supplemental Material, Table S6).

3.3. Results for Children

Fifty-nine respondents reported health symptoms for one child in their household. Because of the small population of children, we compared children living < 2 miles to children living > 2 miles from Broomfield's UOGD sites. Parents living < 2 miles from a Broomfield UOGD site reported more symptoms and higher frequencies of all symptoms, except neurological symptoms, in their children than those living more than 2 miles from the sites, after covariate adjustment (Table 4). The mean total number of symptoms differed by 2.29 (95% CI: 0.05, 4.53), and mean summed Likert scores differed by 0.83 (95% CI: 0.12, 1.54), 0.81 (95% CI: 0.3, 1.31) and 2.38 (95% CI: 0.36, 4.41) for lower respiratory, GI and acute symptoms, respectively, between children residing <2 and >2 miles from Broomfield's UOGD sites. We observed null results for mental health and neurological symptoms in our adjusted model for children.

Table 3. Difference in means for survey respondents living more than 2 miles, 1–2 miles, and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021 [1].

Outcome	Main Analysis (N = 427)		Sum Likert Score for Odors, Noise and Air in Top 50th Percentile (≥4, N = 239)		Sum Likert Score for Odors, Noise and Air in below the 50th Percentile (<4, N = 188)	
	Difference between >2 Mile and 1–2 Mile Means (LCL, UCL)	**Difference between >2 Mile and <1 Mile Means (LCL, UCL)**	**Difference between >2 Mile and 1–2 Mile Means (LCL, UCL)**	**Difference between >2 Mile and <1 Mile Means (LCL, UCL)**	**Difference between >2 Mile and 1–2 mile Means (LCL, UCL)**	**Difference between >2 Mile and <1 Mile Means (LCL, UCL)**
Total Number of Symptoms (N)	0.31 (−0.94, 1.55)	0.70 (−0.62, 2.02)	−0.05 (−1.59, 1.49)	***2.88 (1.14, 4.63)***	0.25 (−1.60, 2.05)	−1.51 (−3.26, 0.23)
Total summed Likert Score	0.56 (−1.64, 4.53)	1.57 (−1.04, 6.20)	−0.37 (−2.92, 5.32)	***8.53 (2.39, 20.17)***	0.61 (−1.99, 6.44)	−3.09 (−4.23, 0.33)
[2] Upper Respiratory (summed Likert Score)	−0.15 (−0.63, 0.97)	0.81 (0.06, 2.58)	−0.34 (−0.93, 1.64)	***3.16 (0.82, 8.60)***	−0.18 (−0.66, 1.34)	−0.58 (−0.87, 0.54)
[3] Lower Respiratory (summed Likert Score)	0.09 (−0.11 0.47)	0.18 (−0.06, 0.63)	0.15 (−0.14, 0.87)	***0.51 (0.03, 1.62)***	−0.11 (−0.27, 0.26)	−0.13 (−0.28 0.22)
[4] Mental Health (summed Likert Score)	0.88 (−0.31, 3.43)	0.24 (−0.75, 2.53)	0.18 (−0.96, 3.45)	***2.62 (0.21, 8.45)***	1.21 (−0.40, 6.10)	−1.33 (−2.44, 0.42)
[5] Neurological (summed Likert Score)	0.13 (−0.50, 1.42)	0.05 (−0.59, 1.38)	−0.03 (−0.74, 1.86)	***1.42 (0.001, 4.68)***	0.07 (−0.72, 2.27)	−1.01 (−−1.29, 0.25))
[6] Gastrointestinal (summed Likert Score)	0.03 (−0.09, 0.23)	0.09 (−0.05, 0.32)	0.01 (−0.17, 0.26)	***0.30 (0.01, 0.84)***	−0.03 (−0.14, 0.19)	−0.005 (−0.12, 0.21)
[7] Acute (summed Likert Score)	0.09 (−0.44, 1.03)	***0.75 (0.004, 1.99)***	−0.027 (−0.79, 1.64)	***2.76 (0.89, 6.24)***	−0.07 (−0.55, 0.94)	−0.47 (−0.81, 0.30)

[1] Adjusted for age, sex, race, smoking, alcohol consumption, time spent in home, number of children <18 years in home, exercise, number of chronic health conditions, time of residence at current home, education level and occupation. [2] Upper Respiratory = cough + nasal congestion + runny nose + throat irritation + nosebleeds. [3] Lower Respiratory = short breath + lung irritation. [4] Mental Health = anxiety stress + diff sleeping + difficulty concentrating + lack energy fatigue. [5] Neurological = dizziness + difficulty concentrating + headaches + numbness tingling + ringing ears hearing loss + muscle aches weakness pain. [6] Gastrointestinal = nausea + vomiting. [7] Acute = nausea + vomiting + nosebleeds + lung irritation + short breath +cough + throat irritation. LCL = lower 95% confidence level, UCL = upper 95% confidence level. **Bold Italics** indicate statistically significant results at a *p*-value < 0.05.

Table 4. Difference in means for 59 children living more than 2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021 [1].

Outcome	Difference between >2 Mile and <1 Mile Means (LCL, UCL)
Total Number of Symptoms (N)	***2.29 (0.05, 4.53)***
Total summed Likert Score	3.99 (−1.65, 9.64)
[2] Upper Respiratory (summed Likert Score)	1.63 (−0.63, 3.89)
[3] Lower Respiratory (summed Likert Score)	***0.83 (0.12, 1.54)***
[4] Mental Health (summed Likert Score)	0.06 (−1.81, 1.93)
[5] Neurological (summed Likert Score)	−0.36 (−1.87, 1.14)
[6] Gastrointestinal (summed Likert Score)	***0.81 (0.3, 1.31)***
[7] Acute (summed Likert Score)	***2.38 (0.36, 4.41)***

[1] Adjusted for age, sex, smoking, number of children <18 years in home, number of chronic conditions. [2] Upper Respiratory = cough + nasal congestion + runny nose + throat irritation + nosebleeds. [3] Lower Respiratory = short breath + lung irritation. [4] Mental Health = anxiety stress + diff sleeping + difficulty concentrating + lack energy fatigue. [5] Neurological = dizziness + difficulty concentrating + headaches + numbness tingling + ringing ears hearing loss + muscle aches weakness pain. [6] Gastrointestinal = nausea + vomiting. [7] Acute = nausea + vomiting + nosebleeds + lung irritation + short breath + cough + throat irritation. LCL = lower 95% confidence level, UCL = upper 95% confidence level. **Bold Italics** indicate statistically significant results at a p-value < 0.05.

4. Discussion

This large cross-sectional health survey of randomly selected households, to the best of our knowledge, is the first study to date on the association between self-reported health symptoms and active UOGD sites utilizing well-defined BMPs. In adjusted models, survey respondents living within 1 mile of a multi-well UOGD site in CCOB reported greater frequencies of upper respiratory and acute response symptoms in the past 14 days than respondents living more than 2 miles from the sites. Respondents living within 2 miles of a UOGD site also reported that their children experienced greater frequencies of lower respiratory, GI and acute response symptoms in the past 14 days as well as a greater number of total symptoms, in adjusted models. We observed null results for mental health and neurological symptoms in our adjusted models. Among respondents most concerned with odors, noise and air pollution, those living within 1 mile reported greater frequencies for all types of symptoms; while among respondents least concerned with odors, noise and air pollution, those living within 1 mile reported less frequencies for all symptom types than those living more than 2 miles from the sites.

Our results are similar to previously published studies that found associations between proximity to unconventional natural gas development in Pennsylvania's Marcellus Shale and upper respiratory symptoms [35,40,48]. However, our study is the first to report greater frequencies of self-reported nosebleeds, nausea, vomiting and shortness of breath symptoms near UOGD sites. One potential explanation is that the previous studies evaluated exposure proximity to unconventional natural gas well sites and included single well sites, while we evaluated proximity to large multi-well unconventional oil and natural gas sites in our study. Larger multi-well sites that include oil extraction may increase cumulative impacts from exposure to air pollutants, such as volatile organic compounds (VOCs), which are commonly emitted from UOGD sources and can cause a variety of acute health reactions including, but not limited to nose and throat irritation, dizziness and nausea [49].

The CCOB's air quality monitoring system has documented numerous VOC release events from multi-well UOGD sites that were attributed to drilling and hydraulic fracturing activities during the survey period. From November–December 2021, plumes of BTEX emissions (benzene, toluene, ethylbenzene, xylenes) were frequently observed at a monitoring station within a CCOB neighborhood and were consistent with transport from UOGD sites in pre-production phases, located 1.5 miles away. On December 4, 2021, several large plumes were captured throughout the day near a UOGD site, showing elevated VOCs, including benzene levels that reached a 1-hour average estimated at 224 parts per billion (ppb) [22], exceeding the Agency for Toxic Substances and Disease Registry's (ATSDR) federal, short-term Minimum Risk Level of 9 ppb [50]. One hour benzene averages are calculated by analyzing a one minute benzene canister sample and then applying conversion factors to each minute of the total VOC (TVOC) indicator reading for a one- hour duration [51]. This event was one of the highest total TVOC readings ever recorded in CCOB. Laboratory results of air samples confirm the plume was significantly influenced by oil and gas activity, and wind direction suggests the plume was sourced from nearby UOGD operations during the start of coiled tubing/mill out. Overall, air quality events captured by CCOB's monitoring network lasted, on average, for 3.5 h and TVOC's concentrations reached 23,000 ppb. Further research, which could estimate levels of pollutants for those living at various distances, could help identify potential exposure scenarios that might be linked to health outcomes.

Results from this research have important implications for future policy efforts that aim to reduce resident exposure to emissions from UOGD sites. This research calls into question the adequacy of Colorado's current 2000 ft. setback [52] as CCOB's air quality monitoring program has evidence of oil and gas plumes traveling over one mile and into neighborhoods. Residents in Broomfield are uniquely situated near six UOGD sites with dozens of wells, which may result in cumulative emissions exposure. Even with the most stringent BMPs in place, emissions during pre-production activities contained elevated levels of BTEX and other air toxics that may have contributed to some of the symptoms reported in our health survey. This research builds off the current body of epidemiological oil and gas literature by highlighting that cumulative emissions exposure may result from living in proximity to multiple UOGD sites. Research such as this can help inform state policymakers about BMPs and setback distances that aim to protect public health.

Interestingly, we found that a respondent's level of concern with the top three complaints (air pollution, noise and odors) in CCOB's oil and gas complaint database significantly modified the relationship between frequency of symptoms and setback distance. This could be due to perception bias, where those most concerned about environmental stressors are more likely to notice and/or report symptoms and those with less concerns are less likely to report symptoms or a psychosomatic effect where the anxiety and concern with pollution is causing some of these symptoms. It could also be due to recall or awareness bias in which individuals with health symptoms are more likely to remember perceived environmental exposures or notice environmental exposures. However, our mediation analysis indicates that level of environmental concerns did not differ by setback distance (see Supplemental Material, Table S2), which indicates these biases may not explain the differences in symptoms by setback distance. It also may be possible that affiliation bias (a respondent's affiliation concerning UOGD) affected our results through either over- or under-reporting symptoms. Our cross-sectional design limits our ability to further evaluate the temporality of the bias.

Our study benefited from random selection of households with response rates evenly distributed by setback distances from CCOB's UOGD sites and more than enough adult respondents to detect differences in frequencies of symptoms by setback distance. We were also able to adjust for many covariates that could be associated with the symptoms. We used well-established methods to evaluate the proximity of households to UOGD by using ArcGIS software 10.8.1 and geocoding the household locations for those that completed a survey.

Inherent biases in self-reporting (as previously discussed) may have affected our results. Additionally, selection bias within a household could have occurred if respondents purposely selected an individual within the household with greater (or fewer) symptoms, rather than choosing one adult (and one child, if applicable) whose birth date is closest to the date they received the survey in the mail. Participation bias may have occurred if those in favor of and/or not in favor of UOGD in CCOB or those experiencing symptoms were more or less likely to respond to the survey.

With only 59 children and fewer covariates for children, our results for children lack precision and may be biased towards the null. While we did adjust our analysis for many potential confounders, it is possible that an unexplained confounder or residual confounding is present with an unknown effect on our results. Proximity to major roadways, the COVID pandemic and source of drinking water may have affected our results. However, respondents living within 1 mile and greater than 2 miles were equally likely to be living near a major roadway (Figure 1); thus, proximity to a major roadway was not likely a major confounder. Because our survey was conducted when COVID incidence in CCOB was relatively low and COVID incidence was not associated with proximity to UOGD in CCOB, the COVID pandemic was not likely a major confounder. We also note that our stratified analysis by age and race, both known to be associated with COVID incidence, indicate that neither age or race confounded the results (see Supplemental Material, Table S6). Because CCOB lies within the Denver metro region and most residential properties are connected to municipal water sourced from outside of Broomfield [53], source of drinking was not likely a major confounder.

We did not include other populations living near the six UOGD sites in CCOB, and our results may not represent resident symptoms outside of CCOB. Some residents in adjacent Adams County were among the closest individuals living to pre-production development. While including counties with residents living in close proximity to CCOB's UOGD would have improved precision, it is not possible to know how it would affect our results. Including all residents within proximity to UOGD regardless of jurisdictional boundaries would improve the representativeness and generalizability of future studies.

5. Conclusions

Our results indicate that people living within 1 mile of multi-well unconventional oil and natural gas sites more frequently report upper respiratory and acute (e.g., nosebleeds, nausea, shortness of breath) symptoms than people living more than 2 miles from the sites. Because our cross-sectional design does not provide temporal information, it is not possible to determine if proximity to UOGD caused any of the reported symptoms. A possible explanation for the increase in symptoms reported near oil and gas sites could include cumulative and additive impacts from exposure to emissions from multiple UOGD sites. However, other explanations are possible. Additional study using more precise estimates of exposure and objective measures of health outcomes, as well as qualitative designs with focus groups would be useful to better understand the relationship between proximity to UOGD and the health symptoms reported in this study.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijerph20032634/s1, Figure S1: Survey; Figure S2: Postcard; Table S1: Frequency of health symptoms (unadjusted) for adults within the past 14 days and distance from unconventional oil and gas development; Table S2: Mediation analysis for adult survey respondents living more than 2 miles, 1–2 miles, and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Association between distance band and summed Likert score for oil and gas environmental concerns (air pollution, noise and odors); Table S3: Mediation analysis for adult survey respondents living more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Association between Likert scores for reported health symptoms and summed Likert score for oil and gas environmental concerns (air pollution, noise and odors); Table S4: Difference in means for adult survey respondents living more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Sensitivity Analysis for respondents at home more than 12 h a day and stratified analysis Likert score for environmental concerns other than oil and gas in the upper and lower 50th percentile; Table S5: Difference in means for adult survey respondents living more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Stratified by gender and chronic conditions; Table S6: Difference in means for adult survey respondents living more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Sensitivity Analysis for respondents identifying as white, never smoked or lived with a smoker, 55 years and older and lived in their home for 2 or more years.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board for the University of Colorado (COMIRB# 21-3719, 4 August 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are openly available at https://www.broomfieldvoice.com/oil-and-gas-health-survey (accessed on 1 July 2022).

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Conflicts of Interest: The authors declare no conflict of interest.

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Final Report: Human Health Risk Assessment for Oil & Gas Operations in Colorado

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Abbreviations and Acronyms

Abbreviation	Definition
AEGL	Acute Exposure Guidance Level
AERMAP	AERMOD terrain pre-processor
AB_Vrain	Anheuser-Busch/Ft. St. Vrain
AERMET	AERMOD meteorology pre-processor
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
APEX	Air Pollutants Exposure Model
ATSDR	Agency for Toxic Substances and Disease Registry (U.S. Department of Health and Human Services)
BMCL	benchmark concentration-low. 95% lower confidence limit on the estimated concentration at the BR level
BMR	benchmark risk; magnitude of effect identified as "adverse" in dose-response modeling; 1.0 standard deviation change versus controls in this analysis
BTEX	benzene, toluene, ethylbenzene, xylene
CDPHE	Colorado Department of Public Health and Environment
CHAD	Consolidated Human Activity Database
Chi/Q	air concentration per unit emission, or exposure concentration per unit air concentration (depending on the context)
cm	centimeter
COGCC	Colorado Oil and Gas Conservation Commission
COOP	Cooperative Observer Network
CSU	Colorado State University
D-J	Denver-Julesburg
deg	degrees
EPA	U.S. Environmental Protection Agency
ESL	Effects Screening Level (from TCEQ)
°F	degrees Fahrenheit
fracking	hydraulic fracturing
ft	feet
g/s	gram per second
GC	Garfield County
HHRA	human health risk assessment
HI	hazard index
HQ	hazard quotient
IRIS	Integrated Risk Information System (from EPA)
IUR	inhalation unit risk
LOD	limit of detection
LOAEL	lowest observed adverse effect level; lowest dose or exposure associated with statistically significant effect
log10	logarithm base 10
m	meters
m/s	meters per second
max	maximum
mg/kg/day	milligrams per kilogram per day
micro	microenvironment

Abbreviation	Definition
min	minimum
MRL	Minimum Risk Level (from ATSDR)
NA	not applicable
NFR	Northern Front Range
NLCD	National Land Cover Database
NWS	National Weather Service
O&G	oil and gas
OEHHA	California Office of Environmental Health Hazard Assessment
PD	pharmacodynamics adjustment
PK	pharmacokinetic adjustment
POD	point of departure; experimental or human endpoint used to derive health criteria
ppm	parts per million
ppb	parts per billion
PPRTV	Provisional Peer-reviewed Toxicity Value (from EPA)
Q	emission rate, or air concentration (depending on the context)
QA	quality assurance
QC	quality control
PEN	penetration factor
RBC	red blood cells
REL	Reference Exposure Level (from OEHHA)
ReV	Reference Value (from TCEQ)
RfC	Reference Concentration (from EPA)
RGDR	regional gas dose ratio; used to adjust for differences in absorption of inhaled toxicants between animals and humans
SD	standard deviation
St_Vrain	Ft. St. Vrain
TCEQ	Texas Commission on Environmental Quality
TRM	Tracer Ratio Method
U-P	Uinta-Piceance
U.S.	United States
UF	uncertainty factor
ugm-3, ug/m^3, $\mu g/m^3$	microgram per cubic meter
UTM	Universal Transverse Mercator
VOC	volatile organic compound
V_p	vapor pressure

Executive Summary

In 2017, the Colorado Department of Public Health and Environment conducted a screening assessment and systematic review of potential risks associated with chemicals released to the air from oil and gas operations. The assessment found that the concentrations of chemicals detected in air near oil and gas operations were consistent with low risks of harmful health effects. Systematic review of 27 studies of populations residing near oil and gas operations found limited and inconsistent evidence for harmful health effects.

One of the recommendations of the 2017 assessment was for “continued evaluation of health risk using more comprehensive exposure data such as data from the Colorado State University studies that directly measured emissions of substances from oil and gas operations….” This report summarizes the results of a quantitative human health risk assessment, based on those emission measurements, which ICF (we) conducted in conjunction with the Colorado Department of Public Health and Environment.

Scientists from Colorado State University conducted on-site air monitoring of 47 volatile organic compounds at oil and gas extraction facilities in Garfield County and the Northern Front Range in Colorado, which are areas of historically intense oil and gas extraction activity. Utilizing emission rates estimated from the air monitoring during specific activities (drilling, hydraulic fracturing, flowback, and production), we employed state-of-the-science air dispersion models to estimate short- and long-term chemical air concentrations around hypothetical oil and gas facilities of various sizes, located in Garfield County and the Northern Front Range. We then used advanced exposure modeling and protective health-based guidelines to estimate chemical exposures and potential health risks for hypothetical people of all ages living within 2,000 feet of the hypothetical facilities. This includes areas 500 feet from the facilities, which is the current Exception Zone Setback distance for well and production facilities relative to a building unit (as established by the Colorado Oil and Gas Conservation Commission). We focused particularly on conservative (health-protective) hypothetical scenarios where people spend all of their time at a location close to an oil and gas facility for the lifetime of the facility. These hypothetical locations are those that tend to experience higher modeled air concentrations, relative to other locations, due to the interaction between emissions and meteorological conditions. The modeled people at these hypothetical locations are often outdoors or in highly ventilated areas, especially during times of short-term peak modeled concentrations. We assessed 1-hour (acute) exposures as well as multi-day (subchronic) exposures and exposures greater than one year (chronic).

Exposure modeling for most chemicals indicated that acute exposures were below guideline levels for all hypothetical people and facilities. At the 500-foot distance, for a small number of chemicals (including benzene, toluene, and ethyltoluenes), the highest estimated acute exposures exceeded guideline levels at the most-exposed (downwind) locations, in isolated cases by a factor of 10 or more during oil and gas development activities, particularly during flowback activities at smaller well pads. Those highest predicted acute exposures decreased rapidly with distance from the hypothetical facilities, but remained above guideline levels out to 2,000 feet under a relatively small number of oil and gas development scenarios. Our identification of these estimated exceedances of acute health guidelines is highly conservative, in that these highest-estimated exposures occur when the highest chemical emissions are highly concentrated by “worst-case” meteorological conditions onto a hypothetical person who is outdoors or in a highly ventilated area, which might happen only rarely. For example, at the 500-foot distance from the facility, central-tendency acute benzene exposures during flowback activities tended to be a factor of 1.6–2.7 smaller than the absolute maximum exposures, and while some of the highest acute benzene exposures were more than a factor of 10 above guideline levels at the NFR site, they were below 10 for most people on most days of the simulations. The average differences in acute exposure between sites were less than a factor of 2, and exposures were much smaller during production activities relative to development activities.

Most modeled subchronic exposures (lasting less than one year) were also far below guideline levels during development activities (not evaluated for production activities, which last decades). This was true for all chemicals at the 500-foot distance from the facility, although emissions of trimethylbenzenes during fracking activities helped lead to subchronic exposures slightly above guideline levels for combined exposures to multiple chemicals with neurotoxicity critical effects. These exposures were generally higher near smaller well pads, and the exposures generally decreased with increasing distance from the facility. As with the highest acute exposures, our identification of these estimated exceedances of subchronic health guidelines is conservative—these are scenarios when emissions tended to be much higher than average and concentrated frequently (by meteorological conditions conducive to worse air quality) onto a hypothetical person who is always relatively close to the hypothetical facility and is often outdoors or in a highly ventilated area. During more typical conditions, central-tendency multi-chemical exposures related to neurotoxicity critical effects at locations 500 feet from the facility (for example) tended to be a factor of 1.7–2.5 smaller than the absolute maximum exposures, and while some of the highest neurotoxicity-related exposures were slightly above guideline levels at the Garfield County sites, they were below guideline levels for the majority of people during most of the simulations. The average differences in subchronic exposure between sites were less than a factor of 2 or 3.

We also estimated chronic exposures for production operations, which can continue for up to 30 years after well development, as well as for some large flowback operations that can last 14–15 months. At the 500-foot distance from the facility, chronic exposures during the 14–15-month flowback activities were far below guideline levels for individual chemicals and only slightly above guideline levels for combined exposures to multiple chemicals with neurotoxicity or hematological critical effects (which include n-nonane, benzene, m+p-xylene, and trimethylbenzenes). Extending the exposure period to also include the preceding drilling and fracking activities led to similar results. The chronic exposures during production operations were generally the lowest, relative to guideline levels, from among all simulated exposures in the assessment. At the 500-foot distance from the facility, all chronic non-cancer exposures during production activities were below guideline levels, and the average incremental lifetime cancer risk from chronic benzene exposure was 5-in-one million or less (dropping below 1-in-one million before the 2,000-foot distance). When estimates of chronic exposure include exposure to development activities occurring sequentially with exposure to production activities, exposures were only slightly higher than those estimated during the production activities alone.

Additional measurements could help to refine the risk estimates in these assessments and/or allow for assessments that are more site-specific. Such measurements could include additional air monitoring similar to what this study is based on, or continuous measurements near oil and gas sites and inside and outside buildings near those sites, including personal-exposure measurements. Whereas the assessment in this study is primarily focused on identifying the potential for risks above levels of concern, assessments based on additional or different data may be more focused on time sequences of exposure that are more site- and population-specific.

1. Project Background

Colorado's rapidly growing population, in parallel with increased oil and gas extraction activities in Colorado's Northern Front Range (NFR) and Garfield County, has led to populations living and working in close proximity to oil and gas (O&G) operations. As a result, **growing public health concern has developed in recent years about the health risks to people living near existing and potential future O&G operations**. To date, assessing the public health risk has been challenging due to the lack of high quality measurements of the types and emission rates of volatile organic compounds (VOCs) that are emitted from O&G well development and production activities.

Colorado State University (CSU) recently completed two studies, listed below, quantifying emission rates of 47 VOCs[1] during different phases of O&G development and during O&G production.

- Colorado's Garfield County (Uinta-Piceance [U-P] Basin): (CSU, 2016a)
- Colorado's NFR (Denver-Julesburg [D-J] Basin): (CSU, 2016b)

In 2015, the Colorado Governor's Oil and Gas Task Force developed a set of recommendations that would foster responsible development of O&G in Colorado. One of the recommendations from the Task Force was to **address public health concerns in part by conducting human health risk assessments (HHRAs) using the CSU VOC emission-rate studies**.

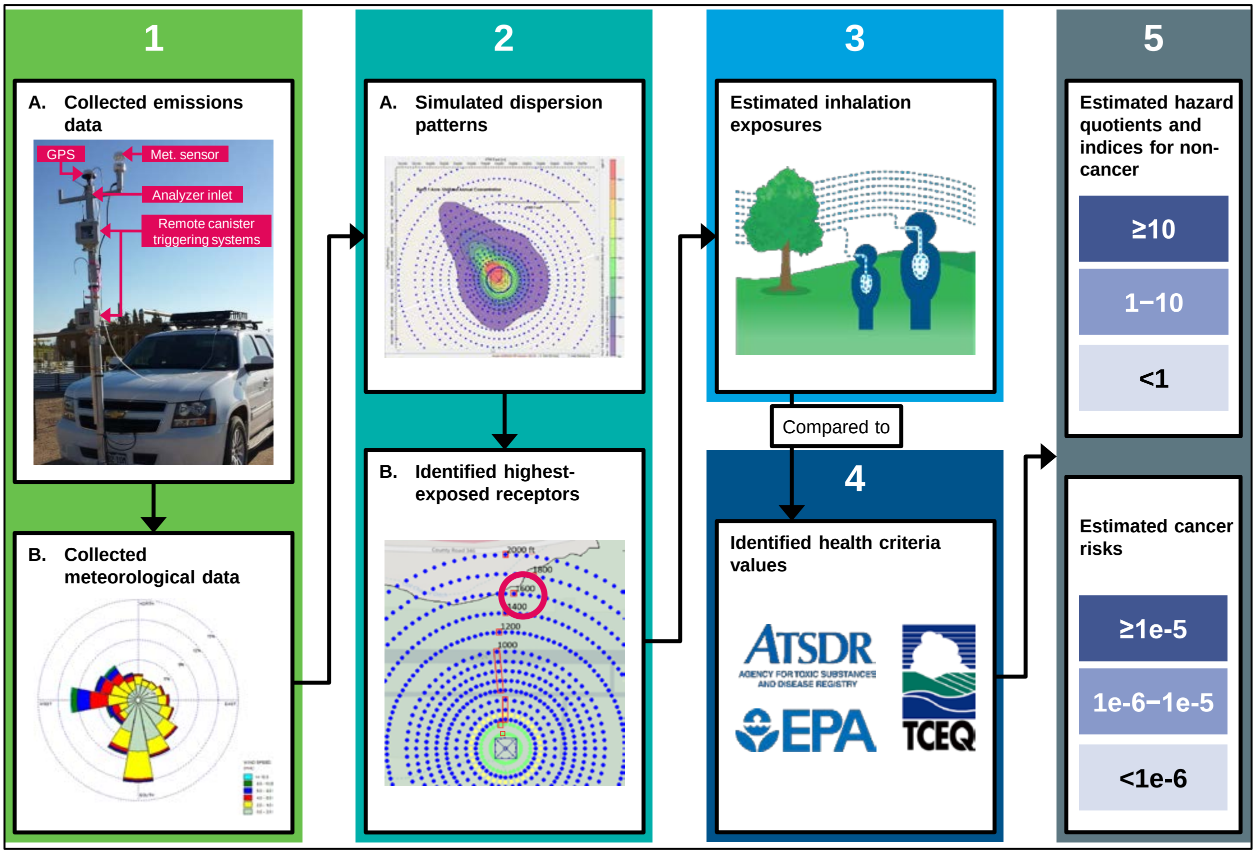
The Colorado Department of Public Health and Environment (CDPHE) developed a request for proposal to solicit a contractor to conduct the two HHRAs listed below.

1. HHRA for O&G operations in **Colorado's NFR**
2. HHRA for O&G operations in **Colorado's Garfield County**

ICF was the contractor selected to **conduct these HHRAs in a probabilistic fashion to quantify the potential cancer and non-cancer (acute, subchronic, and chronic) health risk to people from inhalation of the VOCs emitted during the different phases of O&G development and production**. ICF ("we") are conducting this study within the framework set by CDPHE, and all work undertaken is in consultation with CDPHE staff on the overall approach, major assumptions, and parameterizations.

In this report, we describe the approach and results of these HHRAs. Briefly here, we show in Figure 1-1, and enumerate below, the steps of the risk assessment methodology that we followed for the HHRAs.

[1] CSU collected samples in some cases of 49 VOCs. However, one was the tracer (acetylene, also known as ethyne) and we do not include it in these HHRAs. Another was i-butene, which CSU did not collect during most experiments and is chemically very similar to 1-butene, which they collected regularly; we do not include i-butene in these HHRAs. We therefore refer to 47 VOCs in these HHRAs.



Notes: The methods for each step of the figure are more fully described as noted: 1A = Section 2.3; 1B = Section 2.5; 2A = Section 2; 2B = Sections 2.7.3 and 2.8; 3 = Section 3; 4 = Section 4; 5 = Section 5. Figure depicting collection of emissions data is from Figure 2.3 of (CSU, 2016a).

Figure 1-1. Illustration of the Steps in the Risk Assessment

1. **Collect emissions** of VOCs of interest using air sampling during O&G activities in Garfield County and the NFR (as we describe in Section 2.3, utilizing work conducted by CSU), and **download meteorology data** for several sites in those areas (as we describe in Section 2.5).

2. **Simulate spatial dispersion** of the VOCs, based on collected emissions data and meteorology data (as we describe in Section 2).
    a. For each scenario, we determined where VOC air concentrations are likely to be highest (as we describe in Sections 2.7.3 and 2.8), and we used these receptor locations for further analysis.

3. **Estimate inhalation exposure** to each VOC and groups of VOCs with similar critical effects for individual adults and children, at each receptor location identified above and across different durations of exposure (acute, subchronic, and chronic) (as we describe in Section 3; supported by Appendix A).

4. **Identify protective health criteria values** for each VOC and duration of exposure (as described in Section 4; supported by Appendix B, Appendix C, and Appendix D).

5. **Identify activities and scenarios where inhalation exposures exceed health criteria** for hypothetical individuals living and working near the modeled, hypothetical well pads, during each of the O&G activities (as shown in Section 5; supported by Appendix E). Also, examine distributions of air concentrations, exposures, and hazards for the assessed VOCs.
    a. We report in Section 4 the specific methods used to calculate each risk metric.

In Section 6, we present a summary of the data gaps, uncertainties, and variabilities within the data and methods used in the HHRAs, as well as the sensitivity of the risk results to certain aspects of the assessments (we discuss these in more detail in each preceding section). Finally, in Section 7, we look ahead to possible future work, at the discretion of CDPHE, which may further refine these estimates of potential health risks to individuals living and spending time near O&G facilities.

2. Modeling of Air Concentrations

2.1. Overview of Approach

Air-dispersion model formulations and methods used to simulate the dispersion processes (e.g., steady-state Gaussian, Gaussian-puff, Eulerian grid models) have inherent spatial limitations for estimating concentrations. These limitations are essential to consider in model selection, along with how emissions are incorporated into the model, the distance over which the model formulation is appropriate, the regulatory status, and model-evaluation history. **U.S. EPA's AERMOD model is the best candidate model for this assessment** because

1. its model formulation represents the state of the science, with similarity-theory-based boundary layer calculations;

2. the steady-state Gaussian assumption is valid over the distances under consideration in this study, which are 150–2,000 feet (ft) (45.7–609.6 meters [m]);

3. the model will estimate concentrations to the nearest meter; and

4. it has a long history of application and as well as model evaluation, although model-validation studies for low-level or ground-level emission source releases are limited to Project Prairie Grass (Haugen, 1959).

Near-source air concentrations are largely determined from the emission source strength and ambient meteorological conditions. In both of their emission-rate studies (CSU, 2016a, 2016b), CSU identified that individual **VOC emission rates from each O&G activity may vary by several orders of magnitude** within each O&G activity type. Dispersion models applied in a regulatory context are designed for emission sources with known emission rates or well-defined patterns of temporal variation. For sources that emit with substantial irregularity, the acute (short-term) health risk can be exaggerated when applying an air dispersion model to the improbable coincidence of the highest emission-release rate with worst-case meteorological conditions. To provide information on the probability for these events, the results are best expressed as a probability distribution that can be solved by randomizing the emission source strength and meteorological conditions by applying the Monte Carlo method to determine expected maxima of acute air concentrations, rather than using just the absolute highest (and improbable) worst-case concentration.

A Monte Carlo air-concentration analysis builds a set of results of possible outcomes (a distribution of values) by varying the input variables—in this case, the widely varying VOC emission rates and meteorology, and also the variable durations of the activities. Each AERMOD simulation, or "iteration", creates a set of results. Thousands of simulations are made, each using a different set of input values selected at random from the range of possible meteorology and emission inputs as well as activity durations. The result is a distribution of possible air-concentration outcomes. In general, we retain from each iteration the mean and maximum air concentration at each modeling receptor (location of model outputs), creating a distribution of mean and maximum values from across the iterations. These values are then passed to the exposure assessment for use in exposure modeling. A sufficient number of simulations is reached when the statistical characteristics (mean, standard deviation) of the distribution minimally changes when more realizations are added. We conduct this Monte Carlo analysis for well-development activities, but not for well-production activities where we are less concerned with hour-by-hour and day-by-day variabilities and more concerned with longer-term averages across the many years of O&G production.

Application of the Monte Carlo approach is widely used in addressing problems associated with emissions from irregularly emitting sources, as it provides more realistic estimates of health risk (Li et al., 2008; Lonati and Zanoni, 2013). In addition, Monte Carlo is used to establish protective zones for intermittent irregular sources (Balter and Faminskaya, 2016). For irregularly varying power-plant emissions, the Electric Power Research Institute sponsored the development of a Monte Carlo tool, EMVAP (Paine et al., 2014), useful in assessing compliance with National Ambient Air Quality Standards (Guerra, 2014). The approach is endorsed by the State of Washington's Department of Ecology (Washington State DOE, 2011) for use in compliance with the 1-hour NO_2 standard for diesel generators.

We provide further discussion and details on the Monte Carlo approach in Section 2.7.

2.2. Oil and Gas Activities

The **D-J Basin** extends over an area of more than 70,000 square miles covering northeastern Colorado and extending into southwest Nebraska and southeast Wyoming. The Wattenberg field has been the center of unconventional O&G extraction (COGCC, 2007) and is mostly in Weld County but also extends into portions of Adams and Boulder Counties. More than half of COGCC permits in 2015 and 2016 were for Weld County, with about 87 percent of Colorado's active wells located in Weld County and five surrounding counties. This broad area is referred to in these HHRAs as the **NFR**.

The other location of concentrated O&G activity is **Garfield County**, located in western Colorado on top of the **U-P Basin** where natural gas is trapped within shale/tight sand sedimentary formations. Most of the hydrocarbons extracted in this basin are in the form of natural gas from sandstone lenses in the Williams Fork Formation. Extracting the gas economically from this basin mostly requires the use of unconventional gas-extraction techniques.

O&G development in both of these locations is anticipated to continue using methods such as horizontal drilling and hydraulic fracturing along with continued refinements to these technologies.

The typical vertical depth of a well is 5,000–9,000 ft; after reaching a location near the shale/sandstone formation, a directional drill may be used for horizontal drilling for 5,000 ft or more. Multiple horizontal wells accessing the same or other close-by formations can be drilled from one pad. The **drilling** phase usually takes 4–10 days per well. Most wells in Garfield County are vertically drilled, while wells in the NFR more often include horizontal drilling. After drilling is complete, **hydraulic fracturing ("fracking")** is used to inject water, sand, and chemicals into the well at high pressures. The fluid opens the previously made fractures and connects them to create better pathways for more efficient flow of O&G to the surface. Fracking is applied to each well in sections and, at completion, each section is closed using a cement plug. The fracking phase of each well can span a period of 2–5 days. After the entire well is fracked, the plugs are drilled out to enable the flow of fracking fluid, water, oil, and natural gas to the surface. This phase of well completion is known as **flowback**. The flowback water is typically stored on-site and later transported for underground (well injection) storage or recycling and re-use in future fracking activities. Traditionally, a flowback period can last for 6–12 days for each well, until the fluid flow hits a marketed or metered line (signaling the start of the O&G production phase). In the NFR, flowback periods for vertical-only wells are much shorter, typically just a single day, while the tight sand formations in Garfield County require a flowback period of 13–30 days.

This study estimates VOC air concentrations during each phase of well development and during production in both the NFR and Garfield County. We discuss these O&G activities in the following two subsections.

2.2.1. Well Development

A new well-pad site undergoes three primary development activities sequentially[2] to create new, O&G-producing wells. These activities are

- drilling,
- fracking, and
- flowback.

The duration over which these activities occurs is highly variable, depending upon the geologic setting, the operator, and so on. Horizontal drilling and flowback are generally longer processes. To determine the best estimate for the duration of each activity in Garfield County, CSU held discussions with site operators/supervisors who were part of CSU's Garfield County emission-measurement program (CSU, 2016a). The operators interviewed included: Encana,

[2] Sequentially: each well is drilled one at a time, then each well is fracked one at a time, and then each well undergoes flowback operations one at a time. In some cases, multiple wells may be undergoing flowback at the same time (flowback is started one well at a time, but flowback may start at another well before flowback is completed on the previous well), which may be a topic of sensitivity analysis in later stages of these HHRAs. During O&G production, multiple wells can produce at the same time.

Ursa Operating Company LLC, WPX (now Terra Energy Partners), and Williams. The companies worked together to provide average duration values for O&G activities in Garfield County. For the NFR, CDPHE estimated durations for each activity based on discussions with COGCC and environmental managers representing a number of O&G operators.

The average durations for each development activity, shown in Table 2-1, are considered generally representative based on the best available information. On average, horizontal wells make up about 70 percent of the O&G development in the NFR, while in Garfield County horizontal wells make up only about 15 percent of the O&G development. **This distribution of duration values is maintained in our Monte Carlo air-dispersion analysis**, as discussed in Section 2.7, where these durations are randomly selected and combined with randomly selected emission rates (based on CSU measurements across a total of 20 experiments, as discussed in Section 2.3) and randomly selected local meteorological conditions.

Table 2-1. Activity Durations (per Well) for Oil and Gas Development Simulations

Location	Type of Drilling	Horizontal Drilling Distance (miles)	Prevalence of Drilling Type and Distance	Average Duration per Well (days)		
				Drilling	Fracking	Flowback
Northern Front Range	Vertical	Not applicable	30%	3	2.5	1
	Horizontal	1	52%	4	2	6
		1.5	11%	5	3	7.5
		2	6%	6	4	9
		2.5	1%	7	5	11.5
Garfield County	Vertical	Not applicable	85%	4	1	13
	Horizontal	1	13%	6	2	15
		2	2%	7	4	30

Sources: Colorado State University and the Colorado Oil and Gas Conservation Commission (see text).

2.2.2. Well Production

Production from the O&G wells occurs over many years, as compared to days or weeks per well for O&G development. CSU completed a total of 11 production experiments (locations) in the NFR (CSU, 2016b), reflecting a variety of well ages, number of wells, and O&G production rates. The number of producing wells per pad in each experiment ranged from one to 18. Three of the experiments were at well pads that had recently gone into production: experiment number 7 took place two days after the well pad went into production, while experiment numbers 15 and 5 took place two and seven months, respectively, after the well pads went into production.

2.3. Emission Source Strength

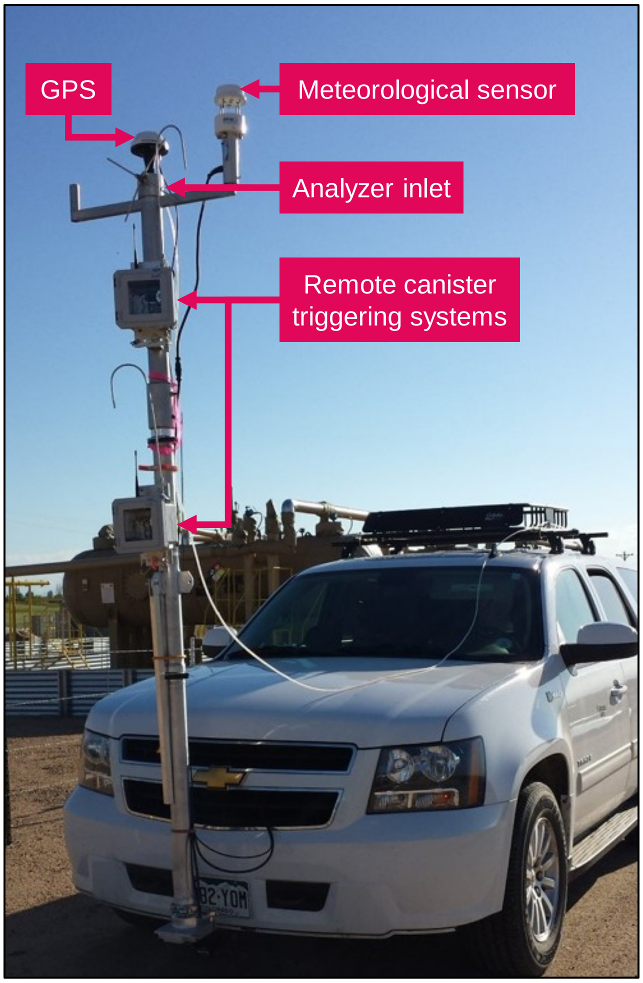
A variety of VOCs can be released to the atmosphere from O&G development and production activities. The primary focus of the CSU studies (CSU, 2016a, 2016b) was to characterize the source strength of these VOC emissions from these activities.

CSU researchers worked with several industry partners to identify sites suitable for conducting the studies. Table 2-2 contains a summary of the number of experiments and measurements that CSU conducted and that are viable for these HHRAs. Experiments contain one or more sampling events (separated by some amount of time but on the same day), and events contain one or more unique canister sample measurements (often at different heights). Non-viable measurements included experiments where multiple O&G activities were occurring at the same time (e.g., flowback and fracking occurring for two wells at the same pad), liquid load-out operations, and remote fracking. CSU conducted field experiments in both Garfield County and in the NFR during flowback and fracking operations. They conducted field experiments during drilling operations only in Garfield County, and they conducted experiments during production operations only in the NFR.

Table 2-2. Summary of Colorado State University Field Experiments and Measurements Used in these Assessments

		Counts of Field Data with Available Emission Rates			
		Drilling	Fracking	Flowback	Production
Northern Front Range	**Experiments** (unique well pads and locations)	0	3	3	11
	Events (unique sampling events)	0 (used Garfield County data for risk assessments)	16	14	55
	Measurements (total canister samples)	0	40	36	150
Garfield County	**Experiments** (unique well pads and locations)	5	4	5	0
	Events (unique sampling events)	13	12	24	0 (used Northern Front Range data for risk assessments)
	Measurements (total canister samples)	35	29	80	0

The measurement approach was based on using the Tracer Ratio Method (TRM), described by Lamb et al. (1995), which enables quantification of emission rates. In this approach, CSU used acetylene as the tracer gas, which is co-located with the major emission source on the well pad and is emitted at a controlled, constant rate. At the same time, **CSU sampled air roughly downwind of the source to obtain 3-minute-average air concentrations of VOCs.** They did so by positioning a vehicle, equipped with a real-time analyzer for acetylene, downwind of the well pad to detect the tracer gas and locate the emission plume (vehicle pictured in Figure 2-1). When a plume was clearly identified, one to three evacuated Silonite®-coated stainless steel canister(s) were remotely triggered and filled to collect air samples for three minutes. They typically made canister samples at 2–3 heights (typically between 6 and 16 ft, 1.8 and 4.9 m). CSU also sampled air upwind of the source to obtain 3-minute-average background concentrations of VOCs. We assume that the VOCs measured by the background samples do not to originate from the well pad—an assumption based on the wind direction at the time of sample collection.



Source: Figure 2.3 of (CSU, 2016a).

Figure 2-1. Mobile Plume Tracker with its External Components for Plume Identification and Sampling

In a laboratory, CSU later analyzed the sampled canisters for a suite of 47 VOC species, listed in Table 2-3,[1] using Gas Chromatography with Flame Ionization Detection,[3] resulting in estimates of chemical air concentrations at each canister location and time. They corrected the downwind air concentrations by removing background concentrations (VOCs that are not emitted at the well pad) as measured by the upwind canisters, resulting in air concentrations limited to emissions associated with the sources of interest on the well pad. Most of the 47 VOCs had more than 80 percent of their values above the level of detection; the exceptions were isoprene, 1-pentene, 1-butene, and trans-2-butene. Further discussion on levels of detection can be found in Section 2.10.1.2.

[3] At the beginning of the CSU studies, they used a Hewlett Packard (HP) GC-FID system, coupled with an Entech pre-concentration unit, for cryogenic trapping and the subsequent analysis of VOCs. This system was only able to quantify 28 VOCs. They replaced this system with a Shimadzu GC-FID system, coupled with an in-house pre-concentration unit, by Experiment 3, at which time the full suite of 47 VOC species could be analyzed. For these HHRAs, we retained the data from these first two experiments, and we provide in Section 2.7.2 the details on how these data were incorporated into the Monte Carlo simulations.

Table 2-3. The 47 Chemicals Measured During the Field Experiments and Used in these Assessments

benzene	2-ethyltoluene	1-pentene
isobutane	3-ethyltoluene	cis-2-pentene
n-butane	4-ethyltoluene	trans-2-pentene
1-butene	n-heptane	propane
cis-2-butene	n-hexane	propene
trans-2-butene	isoprene	n-propylbenzene
cyclohexane	isopropylbenzene	styrene
cyclopentane	methylcyclohexane	toluene
n-decane	2-methylheptane	1,2,3-trimethylbenzene
1,3-diethylbenzene	3-methylheptane	1,2,4-trimethylbenzene
1,4-diethylbenzene	2-methylhexane	1,3,5-trimethylbenzene
2,3-dimethoxypropane	3-methylhexane	2,2,4-trimethylpentane
2,4-dimethylpentane	n-nonane	2,3,4-trimethylpentane
ethane	n-octane	m+p-xylene
ethene	isopentane	o-xylene
ethylbenzene	n-pentane	

Notes: Colorado State University collected samples in some cases of 49 chemicals. However, one was the tracer (acetylene, also known as ethyne) and we do not include it in this assessment. Another was i-butene, which they did not collect during most experiments and is chemically very similar to 1-butene, which they collected regularly; we do not include i-butene in this assessment. We therefore refer to 47 chemicals in these risk assessments.

The **rate of emission (mass per time) of a VOC resulting from O&G activities** is the tracer emission rate multiplied by the ratio of the background-corrected VOC air concentration to the background-corrected tracer air concentration. Through this tracer technique, the complex dispersion and turbulent mixing that occurs between the emission point and the measurement point is directly accounted for by the dilution of the tracer. To assure that the best estimate of the emission rate is used in these HHRAs, we are using the highest measured emission rate from each sampling location and experiment, with additional processing as described in Section 2.3.1.

During O&G development activities, operators typically drill each well sequentially (if there are multiple wells), then frack sequentially, then start flowback sequentially, before the multiple wells enter the production phase. We ensured that the CSU-derived emission rates used in these HHRAs reflected these typical operating procedures. Doing so allows us to estimate air concentrations from emissions during the drilling, fracking, or flowback phases of a single well, and then in later stages of the HHRA to aggregate over time people's potential exposures to O&G emissions when multiple wells undergo these activities back-to-back. At four out of the five experiments for flowback activities in Garfield County, more than one well was undergoing flowback simultaneously. In these cases, we divided the estimated emission rates by the number of wells undergoing flowback, assuming that emissions from flowback were proportional to the number of wells undergoing flowback. That is, we ensured for the HHRA that all VOC emissions during development activities reflected a single well. In several cases, we excluded measurements taken during times when multiple activities were occurring simultaneously at the well pad (e.g., flowback and fracking at the same time) and measurements taken during activities other than those listed above (e.g., liquid load-out; remote fracking).

Most of the production sites where CSU conducted experiments had multiple wells producing O&G, but we did not normalize their emissions because we found no clear and systematic correlation between VOC emissions and the number of producing wells, the number of on-site storage tanks, or the O&G production rates. This adds a high degree of uncertainty to the scalability of O&G production emissions with the operating characteristics of the well pad.

Table 2-4 contains a summary of the 3-minute emission rates by activity for several of the VOCs: isoprene and BTEX compounds (benzene, toluene, ethylbenzene, and xylenes). We chose to illustrate these five (out of 47) VOCs because of the past importance of BTEX compounds in O&G operations (particularly benzene; see McMullin et al., 2018) and because isoprene was believed to have relatively low health-criteria values. Flowback has the highest emission rates of these VOCs, except for toluene where drilling was highest. For a given chemical within a given activity, the maximum and minimum emission rates differ by at least 1.49 orders of magnitude (a factor of 30), up to over 4.67 orders of magnitude (a factor of 46,700) for benzene during drilling.

Table 2-4. Statistics on 3-minute-average Emission Rates for Selected Chemicals

Activity	Site	Statistic	3-minute-average Emission Rate (grams per second)				
			Benzene	Toluene	Ethylbenzene	Xylenes[a]	Isoprene
Drilling	Garfield County (used for all sites in these assessments)	Maximum	7.67E-01	1.17E+01	1.63E-02	2.59E-01	1.07E-02
		Mean	1.34E-01	2.70E+00	3.29E-03	4.87E-02	1.41E-03
		Minimum	1.63E-05	7.27E-03	3.98E-04	3.90E-04	1.71E-05
		Range[b]	4.67E+00	3.21E+00	1.61E+00	2.82E+00	2.80E+00
Fracking	Garfield County	Maximum	5.34E-01	2.20E+00	2.21E-01	6.65E+00	2.54E-02
		Mean	1.57E-01	8.07E-01	6.01E-02	1.67E+00	3.14E-03
		Minimum	4.36E-03	1.91E-02	3.57E-03	1.93E-03	4.67E-05
		Range[b]	2.09E+00	2.06E+00	1.79E+00	3.54E+00	2.74E+00
	Northern Front Range	Maximum	3.84E-02	2.36E-01	1.88E-02	7.43E-02	3.07E-03
		Mean	1.04E-02	4.01E-02	3.62E-03	1.98E-02	7.45E-04
		Minimum	6.06E-04	1.34E-03	3.11E-04	1.57E-03	2.20E-05
		Range[b]	1.80E+00	2.25E+00	1.78E+00	1.68E+00	2.14E+00
Flowback	Garfield County	Maximum	2.29E-01	4.36E+00	1.55E+00	6.69E+00	8.32E-02
		Mean	6.37E-02	4.27E-01	8.05E-02	6.22E-01	9.72E-03
		Minimum	5.58E-03	1.92E-02	4.97E-04	2.04E-02	2.69E-05
		Range[b]	1.61E+00	2.36E+00	3.49E+00	2.52E+00	3.49E+00
	Northern Front Range	Maximum	1.34E+00	3.52E+00	2.73E-01	2.88E+00	6.42E-04
		Mean	2.75E-01	7.25E-01	5.69E-02	5.51E-01	1.82E-04
		Minimum	4.15E-02	1.15E-01	6.37E-03	6.24E-02	8.05E-06
		Range[b]	1.51E+00	1.49E+00	1.63E+00	1.66E+00	1.90E+00
Production	Northern Front Range (used for all sites in these assessments)	Maximum	2.14E-01	2.03E+00	9.43E-02	3.02E-01	4.03E-03
		Mean	1.37E-02	1.06E-01	3.73E-03	1.89E-02	4.24E-04
		Minimum	2.64E-05	4.85E-05	4.27E-05	1.70E-04	1.73E-05
		Range[b]	3.91E+00	4.62E+00	3.34E+00	3.25E+00	2.37E+00

Notes: The drilling, fracking, and flowback emissions reflect one well, while the collection of production emissions reflect a variety of numbers of wells, from one to 18.

[a] All isomers of xylene are combined. All of the VOC data as reported by CSU are available in the CSU reports (CSU, 2016a, 2016b) and can be downloaded from CSU archive.at https://dspace.library.colostate.edu/.

[b] The range shown is in orders of magnitude, calculated as the difference in the logarithms (base 10) of the maximum and minimum values shown; that is, log(maximum) - log(minimum). For example, a range of 4.67E+00 is a range of 4.67 orders of magnitude (approximately a factor of 46,700).

2.3.1. Derivation of One-hour-average Emission Rates

The emission rates that CSU derived were based on 3-minute-average air concentrations and so they are best characterized as 3-minute-averaged emission rates for each measurement.

Acute health effects are assessed using 1-hour exposures, not 3 minutes. Further, AERMOD cannot model emissions and dispersion at time steps smaller than one hour, and so it typically expects 1-hour-average emission rates and outputs 1-hour-average (or longer) air concentrations. **We did not assume that the 3-minute-average emission rates were sustained for a full hour; such an assumption might be extreme in some cases, leading to large overestimations or underestimations in air concentrations at the highest or lowest emission rates**, respectively. The higher 3-minute-average emissions that CSU observed may have been short-lived times of peak emissions (e.g., several flowback collection tanks opened at the same time), and the lower emissions may have been short-lived times of low emissions (e.g., the process of laying down pipes during drilling). Without additional measurements, especially continuous measurements over longer periods of time, we cannot be certain about the frequencies and durations of particularly high and particularly low emission rates.

However, environmental concentrations and emission rates of chemicals have historically been shown to be well-represented by log-normal distributions (that is, the log of concentrations and emissions are normally distributed). It is a common assumption in stochastic modeling, and it is non-negative and has a theoretical basis whenever the process is the result of several multiplicative random factors. Therefore, **we assume that the emission rates are log-normally distributed** (both the 3-minute- and 1-hour-average rates). Theoretically, the assumption is that the 1-hour-average emission rates are obtained by the mean of 20 3-minute-average samples taken consecutively within an hour, and that those averages are log-normally distributed, with a mean similar to that of the 3-minute distribution but with a lower variance (**a tighter distribution with lower maximum rates and higher minimum rates**).

Given the relatively small number of emission experiments and samples, the non-continuous nature of the experiments, and the wide variance in emission rates overall (both between sampling events and within the same hour when available), we made use of all the highest measured emission rates for each VOC from each sampling location and experiment (as discussed in Section 2.3 above). We assumed that there was no difference in the distribution of emission rates from one day or sampling event to another. We also assumed that the 3-minute-average emission rates are uncorrelated.

We detail below the steps for deriving the new distributions of 1-hour-average emission rates. Note that all specifications of "log" in this section represent the natural logarithm.

1. For a log-normal distribution with mean *m* and variance *v*, the underlying normal has:

2.

$$mean = m\_log = log\left(\frac{m}{sqrt\left(1+\frac{v}{m^2}\right)}\right) \quad \text{Eq. 2-1}$$

$$standard\ deviation = s\_log = sqrt\left(log\left(1+\frac{v}{m^2}\right)\right) \quad \text{Eq. 2-2}$$

The mean of 20 3-min samples will make up a 1-hour sample.

[The variance of the mean of 20 uncorrelated 3-minute samples] is 1/20 of [the variance of one mean 1-hour sample]. However, we reduce this by one degree of freedom due to the uncertainty in the mean of the distribution, which is calculated here rather than given or assumed (i.e., 1/19 rather than 1/20).

3. Let *x* represent a vector of 3-minute samples, with mean *mx*, standard deviation *sx*, and variance *vx*.

   Let *y* represent the corresponding vector of 1-hour samples, assuming no correlation between 3-minute intervals used to arrive at them. Then it is expected to have:

$$mean = my = mx \quad \text{Eq. 2-3}$$

$$variance = vy = \frac{vx}{19} \quad \text{Eq. 2-4}$$

4. Let *mx_log* and *sx_log* respectively be the mean and standard deviation of the underlying normal distribution for the 3-minute samples. Then:

5.

$$mean = mx\_log = log\left(\frac{mx}{sqrt\left(1+\frac{vx}{(mx)^2}\right)}\right) \quad \text{Eq. 2-5}$$

$$standard\ deviation = sx\_log = sqrt\left(log\left(1+\frac{vx}{(mx)^2}\right)\right) \quad \text{Eq. 2-6}$$

   Let *my_log* and *sy_log* respectively be the mean and standard deviation of the underlying normal distribution for the 1-hour samples. Then:

$$mean = my\_log = log\left(\frac{mx}{sqrt\left(1+\frac{\frac{vx}{19}}{(mx)^2}\right)}\right) \quad \text{Eq. 2-7}$$

$$standard\ deviation = sy\_log = sqrt\left(log\left(1+\frac{\frac{vx}{19}}{(mx)^2}\right)\right) \quad \text{Eq. 2-8}$$

6. From the mean *mx* and standard deviation *sx* of vector *x* (a set of 3-minute sample data for a chemical), we can estimate the mean and standard deviation of the underlying normal distribution (using Eq. 2-5 and 2-6).

   Using Eq. 2-7 and 2-8, we can calculate mean *my* and standard deviation *sy* of the underlying normal distribution for the corresponding mean 1-hour data *y*.

   Using the above values, we can estimate the vector of mean 1-hour data *y*:

   Each *x* value has a *z*-score, which is the number of standard deviations above or below the mean on the underlying normal, given by:

$$z[i] = \frac{log(x[i]) - mx\_log}{sx\_log} \quad \text{Eq. 2-9}$$

The *z*-scores for the corresponding *y* values (samples from the distribution of 1-hour data) are:

$$y[i] = e^{my\_log + (z[i] \times sy\_log)} \quad \text{Eq. 2-10}$$

Due to the relatively small sample size for the 3-minute-average data, the means will sometimes be noticeably different between the 3-minute-average and derived 1-hour-average distributions. Maximum acute exposures in these HHRAs will typically coincide with the maximum emissions, and so **we expect that maximum acute exposures and risks will tend to be several factors smaller using the 1-hour-average rates compared with 3-minute-average rates**, which we believe is reasonable given the variable nature of O&G emissions and the assumed log-normal distribution.

We replaced each CSU-measured 3-minute-average emission rate with a 1-hour-average rate from the same part of the distribution. For example, for the drilling activity, if the 3-minute-average rate for benzene in the first experiment corresponded to the 25th percentile of the overall distribution of 3-minute-average benzene emission rates from drilling, then we replaced it with the 25th-percentile value from the corresponding distribution of 1-hour-average rates. This means that we do not extrapolate out beyond the maximum and minimum percentiles present in the 3-minute data.

Whereas Table 2-4 contains summary statistics on 3-minute-average emission rates, Table 2-5 contains the same summaries but for the corresponding 1-hour-average emission rates. The means of the 1-hour-average rates and means of the 3-minute-average rates typically agree within about 10 percent for these chemicals (and generally across all chemicals and O&G activities, not shown). With the 1-hour-average rates, it still remains true that flowback has the highest emission rates for benzene, ethylbenzene, and isoprene, and drilling has the highest emission rates for toluene, though emissions of xylene are now highest during fracking in Garfield County. As expected, the maximum values in Table 2-5 are all lower than those in Table 2-4, typically by a factor of 2–3 for development activities and by a factor of about 4 for production, while the minimum values are several factors to several orders of magnitude higher (the same is generally true across all chemicals, not shown). As a result, the ranges of the 1-hour-average rates decrease sometimes by more than a factor of 2 relative to those of the 3-minute-averge rates, so that the maximum and minimum 1-hour-average rates differ by at least a factor of 2.6 for the chemicals shown in the tables, up to 2 orders of magnitude for toluene during O&G production.

Table 2-5. Statistics on Derived 1-hour-average Emission Rates for Selected Chemicals

Activity	Site	Statistic	1-hour-average Emission Rate (grams per second)				
			Benzene	Toluene	Ethylbenzene	Xylenes	Isoprene
Drilling	Garfield County (used for all sites in these assessments)	Maximum	2.72E-01	4.84E+00	5.93E-03	9.51E-02	3.64E-03
		Mean	1.14E-01	2.30E+00	3.21E-03	4.36E-02	1.11E-03
		Minimum	8.57E-03	4.89E-01	1.96E-03	1.20E-02	3.48E-04
		Range[a]	1.50E+00	9.96E-01	4.81E-01	9.00E-01	1.02E+00
Fracking	Garfield County	Maximum	2.35E-01	1.11E+00	9.32E-02	2.73E+00	8.34E-03
		Mean	1.48E-01	7.59E-01	5.74E-02	1.49E+00	2.67E-03
		Minimum	6.35E-02	3.19E-01	2.97E-02	2.58E-01	8.36E-04
		Range[a]	5.68E-01	5.40E-01	4.97E-01	1.02E+00	9.99E-01
	Northern Front Range	Maximum	1.64E-02	7.86E-02	6.59E-03	3.18E-02	1.23E-03
		Mean	9.60E-03	3.74E-02	3.44E-03	1.86E-02	6.87E-04
		Minimum	5.08E-03	1.59E-02	1.95E-03	1.02E-02	2.96E-04
		Range[a]	5.09E-01	6.93E-01	5.30E-01	4.93E-01	6.19E-01
Flowback	Garfield County	Maximum	9.34E-02	1.15E+00	4.42E-01	1.77E+00	2.44E-02
		Mean	6.20E-02	4.21E-01	6.58E-02	6.04E-01	7.57E-03
		Minimum	3.55E-02	1.75E-01	1.10E-02	2.16E-01	1.53E-03
		Range[a]	4.20E-01	8.18E-01	1.60E+00	9.14E-01	1.20E+00
	Northern Front Range	Maximum	5.14E-01	1.35E+00	1.02E-01	1.07E+00	2.89E-04
		Mean	2.65E-01	6.99E-01	5.54E-02	5.30E-01	1.68E-04
		Minimum	1.74E-01	4.66E-01	3.30E-02	3.18E-01	8.13E-05
		Range[a]	4.70E-01	4.63E-01	4.92E-01	5.26E-01	5.51E-01
Production	Northern Front Range (used for all sites in these assessments)	Maximum	5.26E-02	5.20E-01	2.23E-02	7.06E-02	1.07E-03
		Mean	1.17E-02	6.96E-02	3.04E-03	1.65E-02	3.94E-04
		Minimum	1.49E-03	5.17E-03	6.98E-04	3.93E-03	1.71E-04
		Range[a]	1.55E+00	2.00E+00	1.50E+00	1.25E+00	7.96E-01

Notes: The drilling, fracking, and flowback emissions reflect one well, while the collection of production emissions reflect a variety of numbers of wells, from one to 18.

[a] The range shown is in orders of magnitude, calculated as the difference in the logarithms (base 10) of the maximum and minimum values shown; that is, log(maximum) - log(minimum). For example, a range of 1.50E+00 is a range of 1.50 orders of magnitude (approximately a factor of 32).

2.4. Emission Source Characterization

The HHRA focuses on identifying potential effects of O&G emissions on neighboring residential populations. Typical O&G sites are in rural or suburban-fringe locations, and as such it is not appropriate to use AERMOD's urban setting, which is for locations with high population densities leading to urban-boundary-layer effects on local-scale air movement.

Well pads are frequently developed with multiple wells, which increases the size of the well-pad footprint. We used **three well-pad configurations for development activities** in these HHRAs:

- single well,
- low number of multiple wells, and
- high number of multiple wells.

Table 2-6 shows the number of wells and size of well pad (working area) associated with each of these three configurations, determined by CDPHE using professional judgment and recent permits submitted to COGCC. The emissions from these work areas include a number of sources. **Emissions during drilling** operations are expected to reflect a mixture of well emissions and combustion from engines. **Emissions during fracking** include combustion sources associated with power generation and any materials volatilized from chemicals used in fracking liquids. **Emissions during flowback** are primarily from the flowback liquids emerging from the wells, while emissions associated with combustion are much lower since combustion activities are limited during flowback operations.

Table 2-6. Well-pad Configurations Used in the Modeling of Development Activities

<table>
<tr><th rowspan="3">Location</th><th colspan="6">Well-pad Configurations</th></tr>
<tr><th colspan="2">Single Well</th><th colspan="2">Low Multi-well</th><th colspan="2">High Multi-well</th></tr>
<tr><th>Number of Wells</th><th>Working Area (acres)</th><th>Number of Wells</th><th>Working Area (acres)</th><th>Number of Wells</th><th>Working Area (acres)</th></tr>
<tr><td>Northern Front Range</td><td rowspan="2">1</td><td rowspan="2">1</td><td>8</td><td rowspan="2">3</td><td rowspan="2">32</td><td rowspan="2">5</td></tr>
<tr><td>Garfield County</td><td>16</td></tr>
</table>

For the production phase of O&G operations, we utilized one size of well pad for these HHRAs: 1 acre. This was the approximate average well-pad size for the sites that CSU sampled during production operations, which varied from 0.2 to 2.3 acres. The numbers of wells in production and the year when production started varied across the production sites where CSU sampled. The numbers of wells varied from one to 18, and the year when production started varied between 2008 and 2016. As discussed in Section 2.3, there is a high degree of uncertainty in the relationship between parameters such as well number, production rate, etc. and emission rates; thus, we have low confidence in the accuracy of scaling production emissions based on these parameters. Therefore, we modeled the CSU-derived emissions as-is (after conversion to 1-hour-average rates, as discussed in Section 2.3.1) with no normalization and from a single size of well pad without scaling to different numbers of wells. This means that the variability in air concentrations we estimate from production operations reflect the variability of emissions and well/well-pad characteristics observed by CSU during their experiments, except with the truncations inherent in our derivation of 1-hour-average rates. **Emissions during production** at the O&G sites represent a variety of operations with differing O&G production rates, numbers of wells, numbers of condensate tanks, and emissions control equipment (e.g., bulk separator, 1-, 2-, and 3-stage separators).

Because all of these emissions are dispersed over time at various locations and heights across the well pad, we characterized an emission source as a **square volume source** covering the pad. This characterization implies that the emissions come equally from all parts of the pad. Per recommendations in the AERMOD User's Guide (EPA, 2016b), we set the initial lateral dispersion equal to the length of the side of the source divided by 4.3. Emissions from the well are warmer than ambient temperatures, with an estimated exit gas temperature of 275 °F (135 °C). We parameterize the initial buoyancy of emissions on the well pad by assuming an **initial release height of 10 ft** (3.05 m) above ground level, leading to an initial vertical dispersion equal to 10/2.15=4.65 ft (1.42 m) per AERMOD User's Guide recommendation (EPA, 2016b).

2.5. Meteorology

Representative meteorological data are needed for the two study areas to make possible the best characterization of the atmospheric dispersion conditions in which the O&G activities operate and enable accurate estimations of air concentrations. CDPHE's Modeling and Emissions Inventory Unit has archived historical meteorological data sets from across Colorado. These surface meteorological data sets include National Weather Service (NWS) sites (primarily collected for aviation purposes), sites run by CDPHE (primarily used for CDPHE's air-quality-monitoring program), and sites run by private industry (typically for use in air-dispersion models).

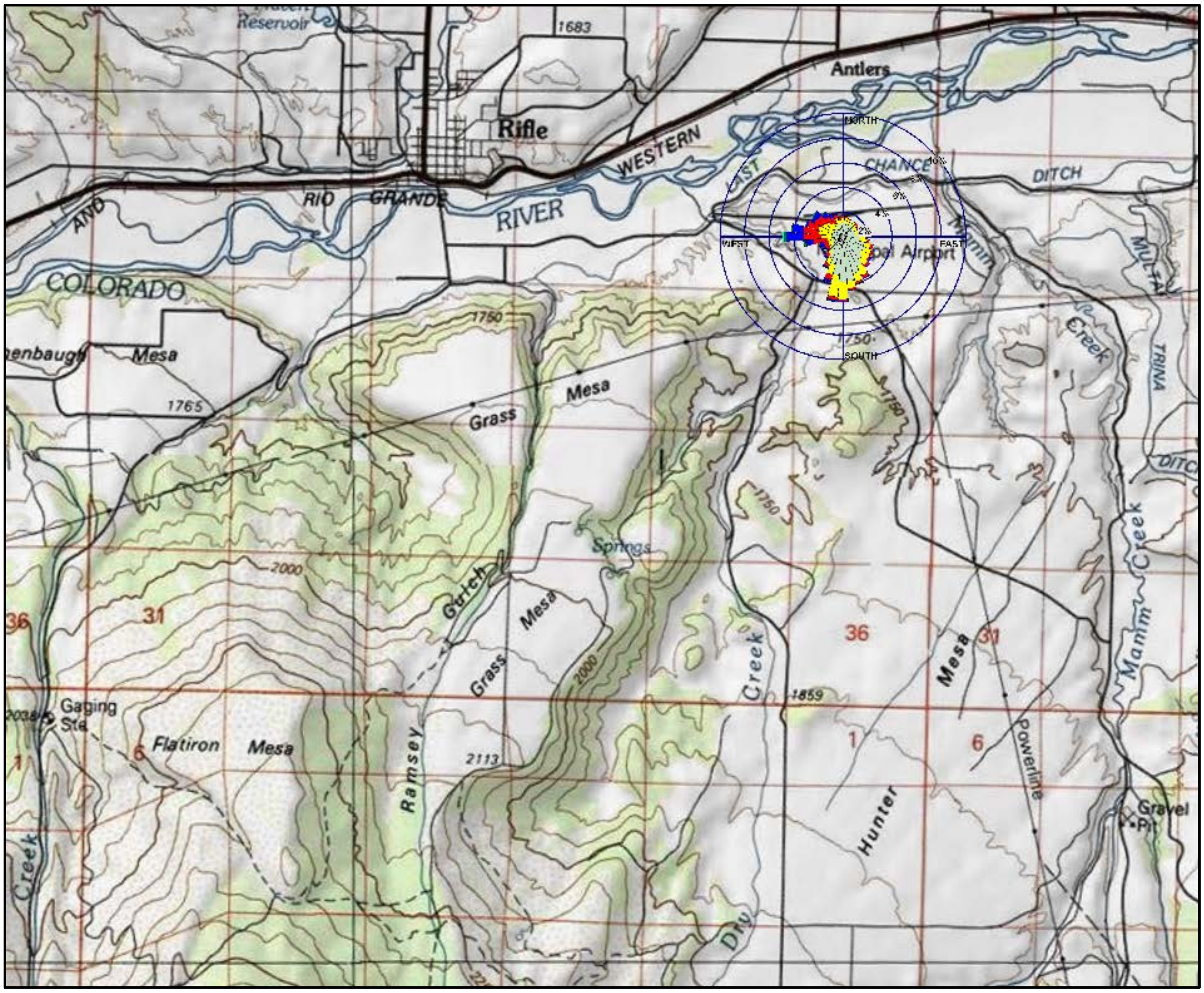
The dispersion of air contaminants at the two study locations are influenced by a variety of factors including local terrain, continental-scale weather systems, local-scale weather systems, and mountain/valley wind systems. **CDPHE carefully reviewed the archive data sets and considered these dispersion factors to select the most representative surface meteorology for these HHRAs**, as discussed in the following subsections. Upper-air meteorological data for Garfield County modeling were from the Grand Junction site (Weather Bureau Army Navy identifier 23066), while for NFR they were from the Denver/Stapleton International Airport (identifier 23062).

2.5.1. Garfield County

The area in Garfield County with O&G development is dominated by **plateaus and the Colorado River Valley**. In this complex terrain environment, local winds are generally caused by differential heating of the valley walls versus the valley floor. This causes **mountain/valley wind flows** in the absence of larger weather systems. In a mountain/valley wind system, air will move down-valley or -slope from near sunset to a few hours after sunrise. Once the sun has risen and heated the upper portions of the valley or slope, the air flow will reverse and go uphill. During the transition from one flow to the other, there can be a period of light and variable winds, typically lasting one or two hours.

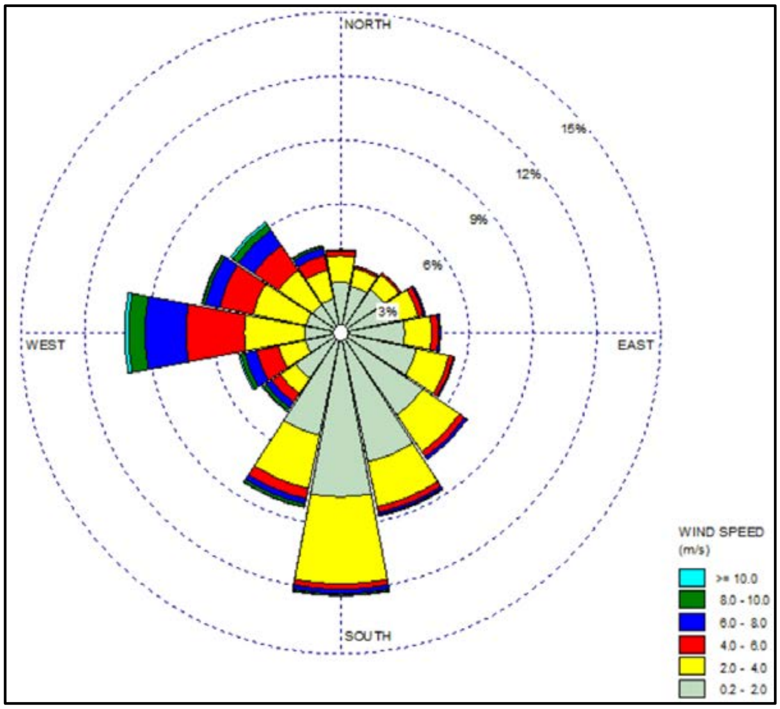
The mountain/valley wind-flow circulation dominates most hours of the year with the exception of when large weather systems are moving through or on top of the plateaus/ridges at night. At these ridge-top locations during the night, a local-scale wind system develops, caused by a temperature inversion near the mountain top. This causes the higher mountains to the east of Garfield County to act as a dam, which causes a pressure gradient resulting in air flow from the south on the plateaus/ridge tops in Garfield County. Because the O&G development in Garfield County is occurring in both the valleys and on top of the plateaus/ridges, two meteorological data sets are needed to characterize the meteorology and dispersion.

A review of the available data for the **valley locations** showed that the best available data set is the **Rifle Garfield County Airport** (Weather Bureau Army Navy identifier 03016) in the Colorado River Valley, operated by the NWS. The Rifle meteorological data set is strongly influenced by the Colorado River Valley, which is orientated east-west at Rifle, and two nearby valley creeks—Mamm Creek and Dry Creek. Both Dry and Mamm Creek Valleys are orientated south-north. The NWS meteorological tower at Rifle is located on the south side of the Colorado River Valley at this location, as shown in Figure 2-2 where the wind rose is placed at the tower location toward the top-right of the figure. The wind rose can be more easily seen in Figure 2-3, showing primarily southerly wind flows (winds from the south) and westerly flows, due to daytime upslope flow in the Colorado River Valley and due to nighttime drainage flow from Dry Creek and occasionally Mamm Creek. These wind-flow patterns are broadly representative of the valley locations in Garfield County where O&G development have recently taken place and are anticipated to continue.



Notes: Plot made using WRPLOT View, by Lakes Environmental Software. Winds are shown as “blowing from”.

Figure 2-2. Terrain Features near Rifle, Colorado (Garfield County Valley Site), with Annual Wind Rose (2005–2009) Placed at the Location of the National Weather Service Meteorological Tower

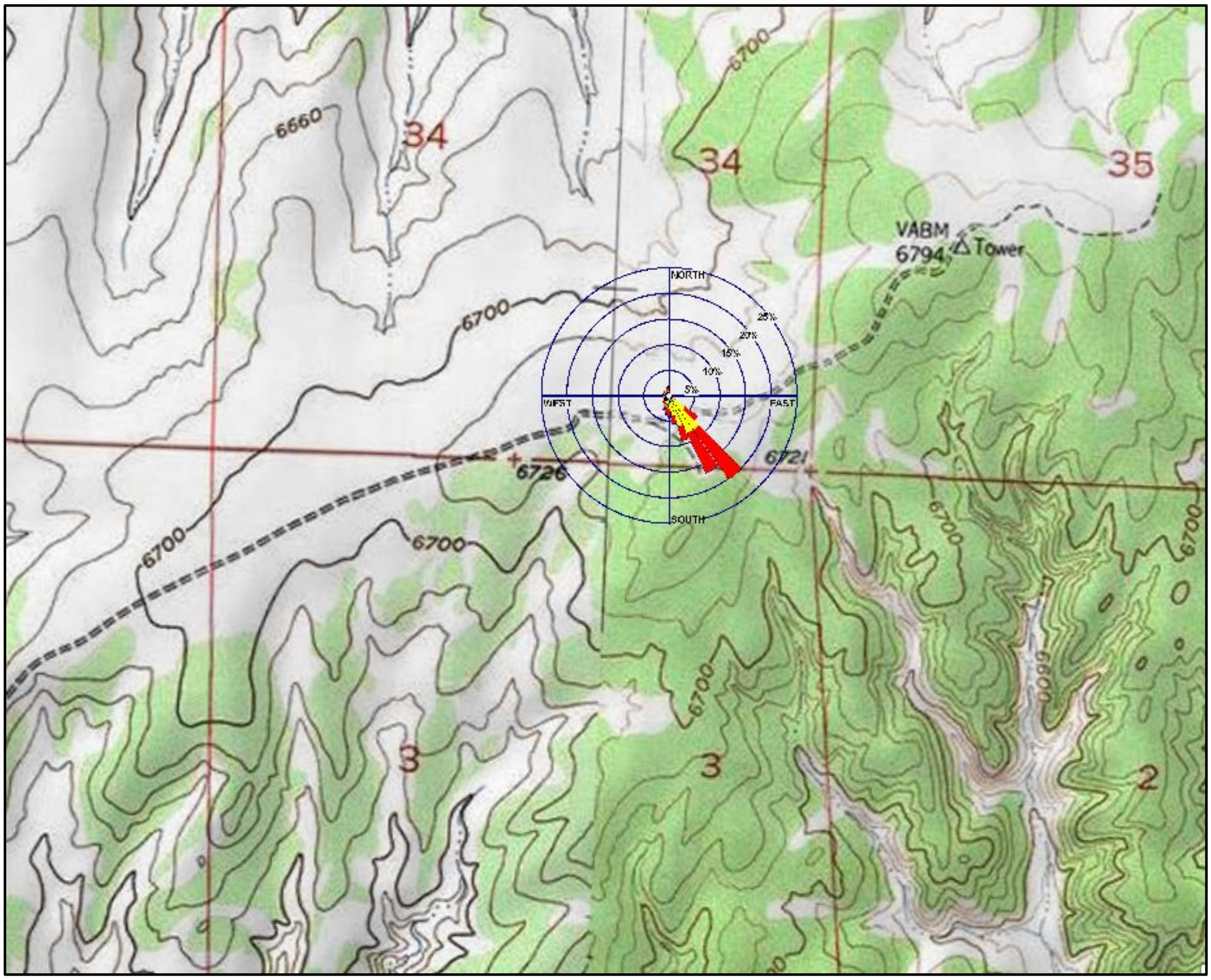


Notes: Plot made using WRPLOT View, by Lakes Environmental Software. Winds are shown as “blowing from”.

m/s = meters per second.

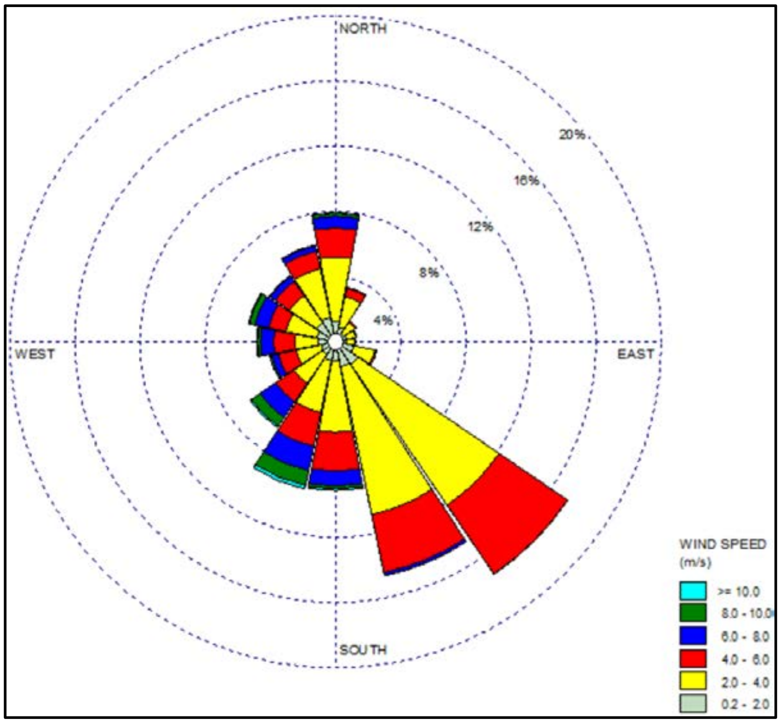
Figure 2-3. Rifle, Colorado (Garfield County Valley Site) Annual Wind Rose (2005–2009)

There were no NWS, CDPHE, or private meteorological data for **ridge-top and plateau locations** in Garfield County. However, a private-industry data set was available, called **BarD**, located about 15 miles (about 24 km) to the north of Garfield County in adjacent Rio Blanco County. This station location is in a small saddle between slightly higher terrain to the northeast and southwest, as shown in Figure 2-4 where the nighttime wind rose is placed at the tower location toward the center of the figure. The winds at night are channeled by the higher terrain, causing the near-surface southerly wind to be southeasterly (from the southeast) at BarD. We show in Figure 2-5 the full (all hours of the day) annual wind rose, showing both the prominent effect of the nighttime southeasterly flow and also the influence of the daytime flow when the air moves along a more north or south direction. The differences should be small in the wind-flow pattern or dispersion characteristics at BarD versus those found on top of the plateaus/ridges in Garfield County.



Notes: Plot made using WRPLOT View, by Lakes Environmental Software. Winds are shown as “blowing from”.

Figure 2-4. Terrain Features near the BarD Meteorological Station (Garfield County Ridge-top Site), with Annual Nighttime-only Wind Rose (2002 and 2004) Placed at the Location of the Station



Notes: Plot made using WRPLOT View, by Lakes Environmental Software. Winds are shown as "blowing from".

m/s = meters per second.

Figure 2-5. BarD (Garfield County Ridge-top Site) Annual Wind Rose (2002 and 2004)

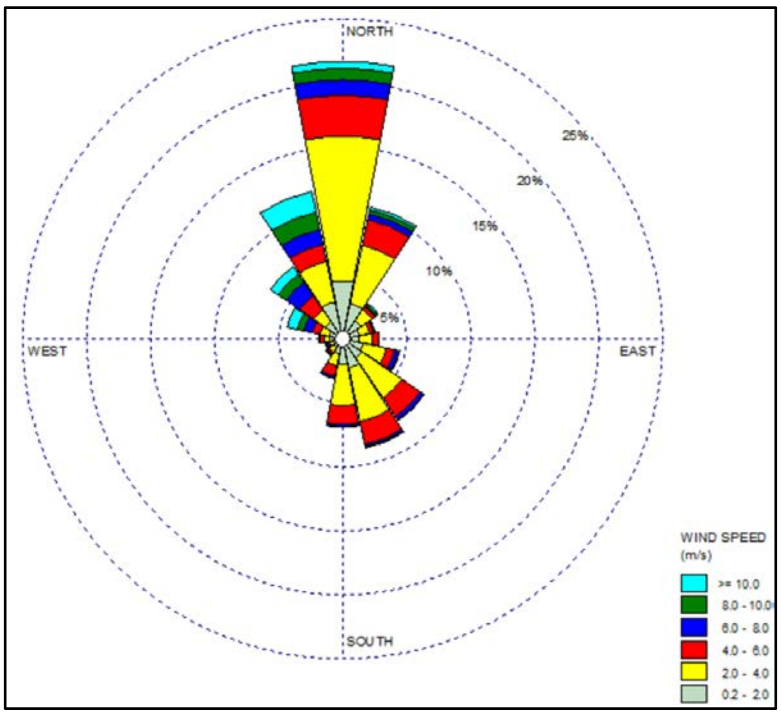
2.5.2. Northern Front Range

Much like in Garfield County, dispersion conditions in the NFR area are strongly influenced by the terrain. The terrain in the O&G development area of the NFR generally consists of **low rolling hills and the South Platte River Valley and its associated tributary valleys**. The **Cheyenne Ridge to the north** and the **Rocky Mountains to the west** of the NFR area also play a role in the wind-flow pattern in the study area. Winds flow out of Wyoming, resulting in a northerly wind component (from the north) as the air flows down the Cheyenne Ridge into the South Platte River Valley. Along the Front Range of the Rocky Mountains, these winds are northerly but further to the east, away from the Front Range, they become northwesterly. The winds are strongest and more prevalent near the Cheyenne Ridge, becoming weaker farther south and dissipating by the time they reach the South Platte River Valley. When the local-scale system does not set up and there is not a strong weather system in the area, the local winds are dominated by the **mountain/valley wind systems** in the valleys of the South Platte River, its tributaries, and on the slopes of the low rolling hills. As the NFR covers a considerable area, two meteorological stations were identified from the available archived meteorological data sets: the Anheuser-Busch and Ft. St. Vrain meteorological data sets, both of which are from private industry.

The **Anheuser-Busch site** is in the northwest portion of the NFR area. It experiences the northerly wind coming off the **Cheyenne Ridge** as well as the drainage downslope flowing down the Cheyenne Ridge at night, as seen in the annual wind rose in Figure 2-6. The southerly winds in the annual wind rose reflect the daytime upslope flow of the mountain/valley wind flow.

Ft. St. Vrain, located 27 miles (43 km) to the south of the Anheuser-Busch site, is in the heart of the O&G development fields in the NFR. This site is located near the confluence of the St. Vrain Creek and the South Platte River. As seen in the annual wind rose in Figure 2-7, while the Ft. St. Vrain site does experience the northerly wind off the Cheyenne Ridge, it is dominated by the mountain/valley wind system in the valleys of **South Platte River and Ft. St. Vrain Creek**, which are oriented in a southwest-northeast direction.

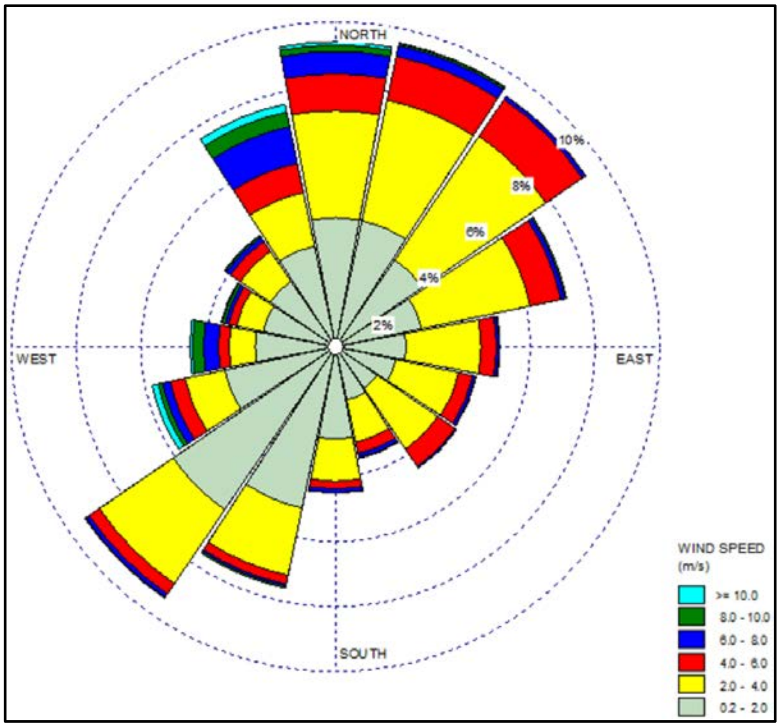
We do not present terrain figures near these two meteorological sites because the terrain in the immediate vicinity is relatively flat (the winds are dominated by more regional-scale terrain features). Because the NFR covers a fairly large geographical region, neither meteorological station fully characterizes the NFR region, but the combined set of the two stations provides an overall broad meteorological characterization for the O&G development fields in the NFR. We blended these two data sets as part of the Monte Carlo simulation of O&G development, as described in Section 2.7.2 (and, for O&G production, as part of the exposure simulations, as discussed in Section 2.9.2).



Notes: Plot made using WRPLOT View, by Lakes Environmental Software. Winds are shown as “blowing from”.

m/s = meters per second.

Figure 2-6. Anheuser-Busch (a Northern Front Range Site) Annual Wind Rose (1988)



Notes: Plot made using WRPLOT View, by Lakes Environmental Software. Winds are shown as “blowing from”.

m/s = meters per second.

Figure 2-7. Ft. St. Vrain (a Northern Front Range Site) Annual Wind Rose (2009)

2.5.3. Processing of Meteorological Data

In Table 2-7, we show a summary of the meteorological data sets as used in these HHRAs, along with additional information needed for processing the data for use in AERMOD.

Table 2-7. Characteristics of the Meteorological Data Sets

Broad Oil and Gas Area	Surface Station					Upper-air Station	Year(s) of Data	Number of Hours with Missing Data (percent)
	Name	Latitude (degrees)	Longitude (degrees)	Base Elevation (feet)	Frequency of Wind Data			
Northern Front Range	Anheuser-Busch	40.623	-105.008	5,025	Hourly	Denver	1988	474 (5%)
	Ft. St. Vrain	40.244	-104.873	4,793	15 minutes	Denver	2009	31 (<1%)
Garfield County	BarD	39.914	-108.374	6,743	15 minutes	Grand Junction	2002, 2004	118 (<1%)
	Rifle	39.524	-107.727	5,502	1 minute	Grand Junction	2005–2009[a]	1,155 (3%)

[a] January and February 2010 used in first two months of 2005 at Rifle.

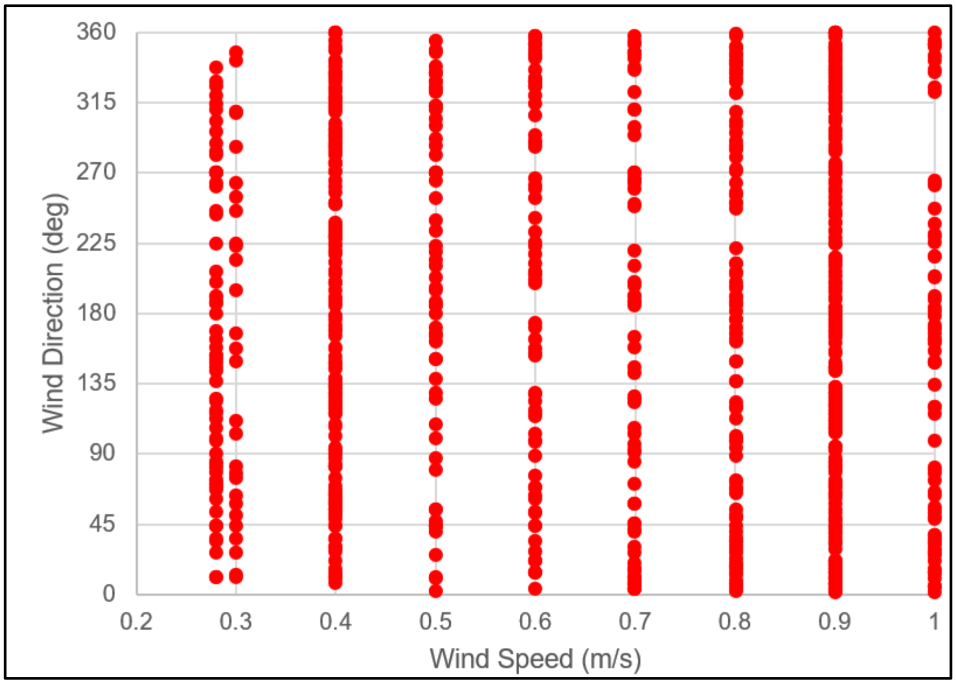
Of the four stations, only **Rifle** is a NWS station, and all others are privately collected data. Data were not available for the first two months of 2005 at Rifle, so we substituted those times with data from the first two months of 2010. The Rifle data include archived **1-minute wind records**, with the most recent time period available being March 3, 2005 through 2009. These 1-minute meteorological data were prepared for input to AERMOD using the AERMINUTE (version 15272) pre-processor, which processes the 1-minute wind data to generate hourly-average winds for input to AERMET (version 16216), which is then processed with the other surface and upper-air data for use in AERMOD.

The **other three sites** were all processed using AERMET with 15-minute average data for BarD and Ft. St. Vrain and hourly data for Anheuser-Busch. The Anheuser-Busch data set used cloud-cover observations from Stapleton Airfield as no on-site cloud cover or turbulence measurements were measured at Anheuser-Busch.

All data sets used a minimum threshold wind speed of 0.2 m/s. Since the Rifle, Ft. St. Vrain, and Anheuser-Busch data sets did not include turbulence measurements (e.g., standard deviation in wind direction), they were adjusted per EPA recommendation using EPA's **ADJ_U*** option in AERMET. This option addresses issues with AERMOD's tendency to overestimate air concentrations due to underestimating the surface friction velocity (u*) during light-wind, stable conditions. The BarD dataset included turbulence measurements, so this low-wind adjustment was not necessary.We considered the three types of low-wind-speed processing options in AERMOD but did not utilize them. The most relevant option for these HHRAs was LOWWIND3, which increases the minimum sigma-v from 0.2 m/s (default) to 0.3 m/s and removes the upwind dispersion but then modifies the downwind dispersions to account for plume meander. However, (1) this option has shown a tendency to underestimate with increasing distance from the source, particularly in conjunction with the ADJ_U* option, (2) the well pads are modeled as volume sources, which by default incorporate plume meander at low wind speeds, and (3) including the ADJ_U* option addresses most of the bias issue for overestimating concentrations at low wind speeds.

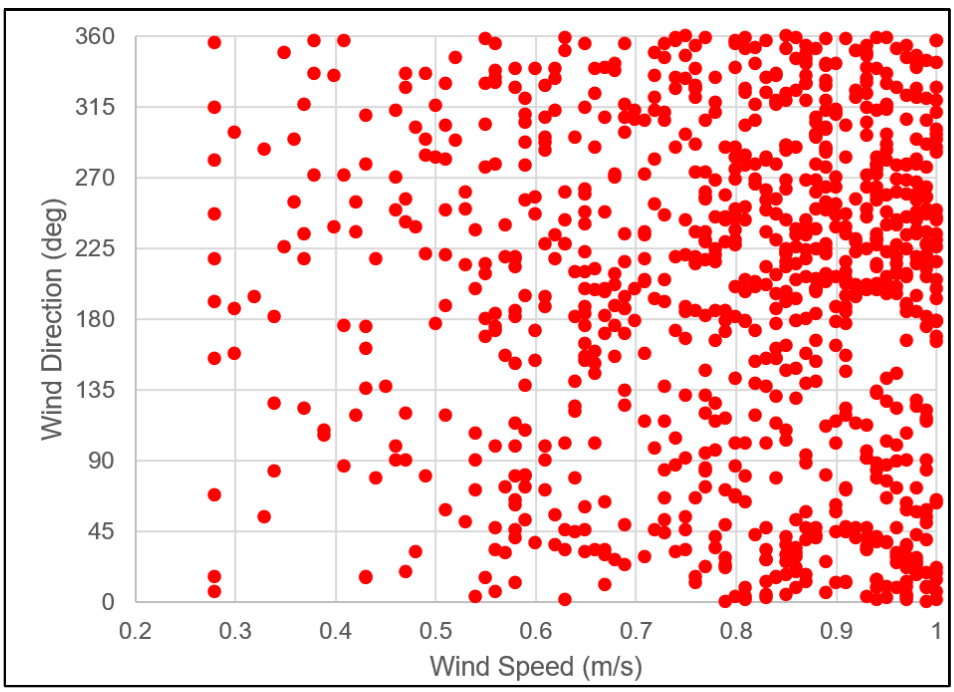
We carefully reviewed the data sets for the distribution and frequency of low wind speeds, since the concentrations estimated by AERMOD are inversely proportional to the wind speed and, as a result, the lowest wind speeds lead to the highest estimated concentrations for the near-ground-level releases in these HHRAs. In the bullets below, we discuss the frequencies of low-wind observations at the selected meteorological stations.

- For the Anheuser-Busch station (see Figure 2-8), the lowest wind speeds appear evenly distributed across all directions, and approximately 10 percent of all hours had wind speeds less than 1.0 m/s (with no missing wind data).
- The Ft. St. Vrain location (Figure 2-9) has a similar distribution with just under 10 percent of all hours reporting wind speeds less than 1.0 m/s and no missing wind data.
- The Rifle location (Figure 2-10) also had about 9 percent of all hours each year with wind speeds less than 1.0 m/s, but it had considerably more of these hours closer to 1.0 m/s than 0 m/s, compared to the stations already discussed. In addition, Rifle had 999 hours of calm wind speeds recorded over the five-year period, which were removed from the AERMOD outputs as these hours are flagged and reported as zero concentrations in the model.
- BarD had the lowest frequency of low wind speeds (Figure 2-11), with just 3 percent of the hours having winds less than 1.0 m/s, which is consistent with a more exposed ridge-top/plateau location. Two BarD hours had calm winds and these are also removed from the AERMOD outputs.



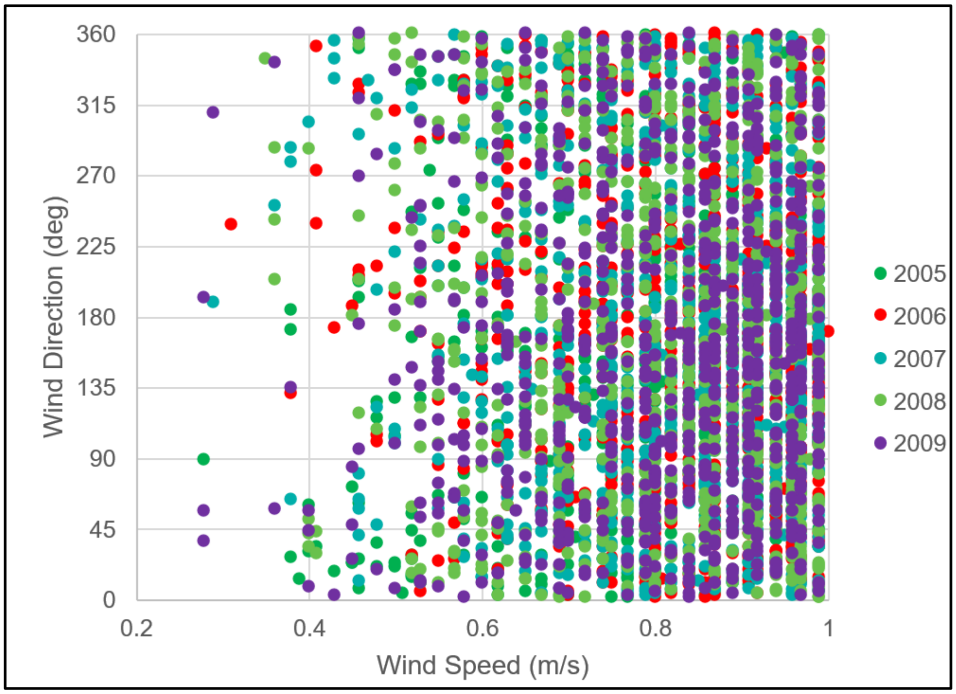
Notes: deg = degrees; m/s = meters per second.

Figure 2-8. Distribution of Low Wind Speed versus Direction at Anheuser-Busch (a Northern Front Range Site)



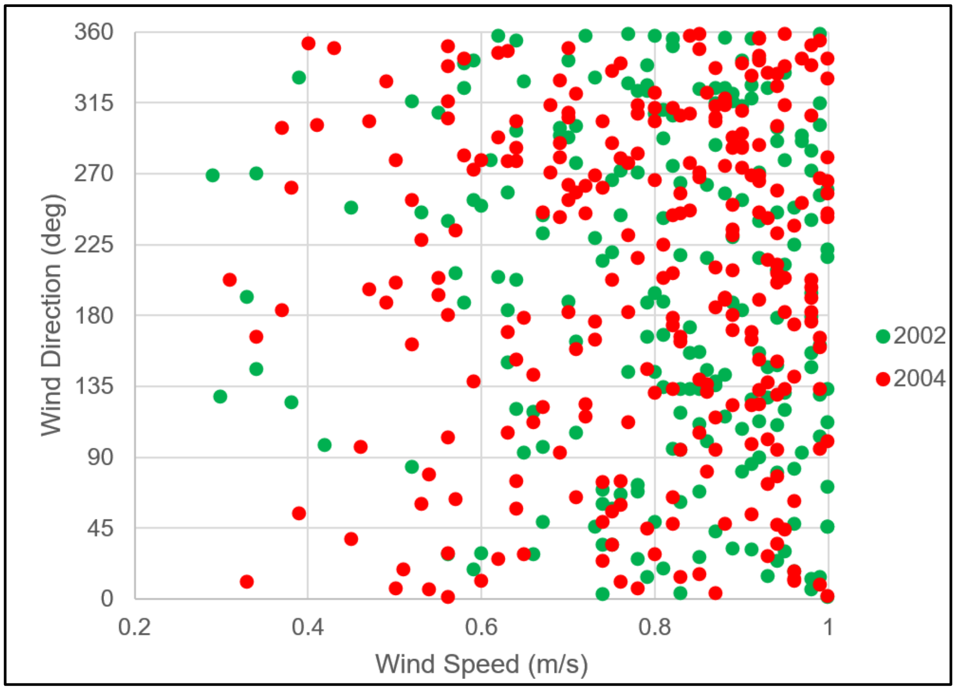
Notes: deg = degrees; m/s = meters per second.

Figure 2-9. Distribution of Low Wind Speed versus Direction at Ft. St. Vrain (a Northern Front Range Site)



Notes: deg = degrees; m/s = meters per second.

Figure 2-10. Distribution of Low Wind Speed versus Direction at Rifle (Garfield County Valley Site)



Notes: deg = degrees; m/s = meters per second.

Figure 2-11. Distribution of Low Wind Speed versus Direction at BarD (Garfield County Ridge-top Site)

2.5.3.1. Surface Characteristics

CDPHE has developed a program, called AERGIS, which uses the same requirements as the EPA's AERSURFACE land-cover preprocessor, the output of which is information on the **surface micrometeorological characteristics** of albedo, surface roughness length, and Bowen Ratio. This program facilitates the development of site-specific data by allowing CDPHE to enter moisture conditions by month and to use a more-recent National Land Cover Database (NLCD)[4] than what is currently accepted by AERSURFACE. We show in Table 2-8 the NLCD versions used per meteorological site. CDPHE uses 12 30-degree sectors for land-cover analysis, consistent with the smallest sector size recommended in the AERMOD implementation guide (EPA, 2015), to determine the monthly Bowen Ratio, albedo, and surface-roughness values for each sector.

To characterize the surface moisture condition, relative to a climate normal, for use in determining the Bowen Ratio, CDPHE used the Climatography of the United States No. 20 Monthly Station Climate Summaries, 1971–2000 Colorado Issue, Date: February 2004. In Table 2-8, we show the data source for monthly precipitation for each site. The surface moisture condition is defined as wet, average, or dry relative to climatology precipitation probabilities in the climate summary. If the actual precipitation amount for the month is less than the 0.3 climatography probability level, it is considered dry, while values between the 0.3 and 0.7 levels are considered normal, and values above the 0.7 level are considered wet.

Table 2-8. Land-cover Data and Precipitation Stations used in Determining Surface Characteristics

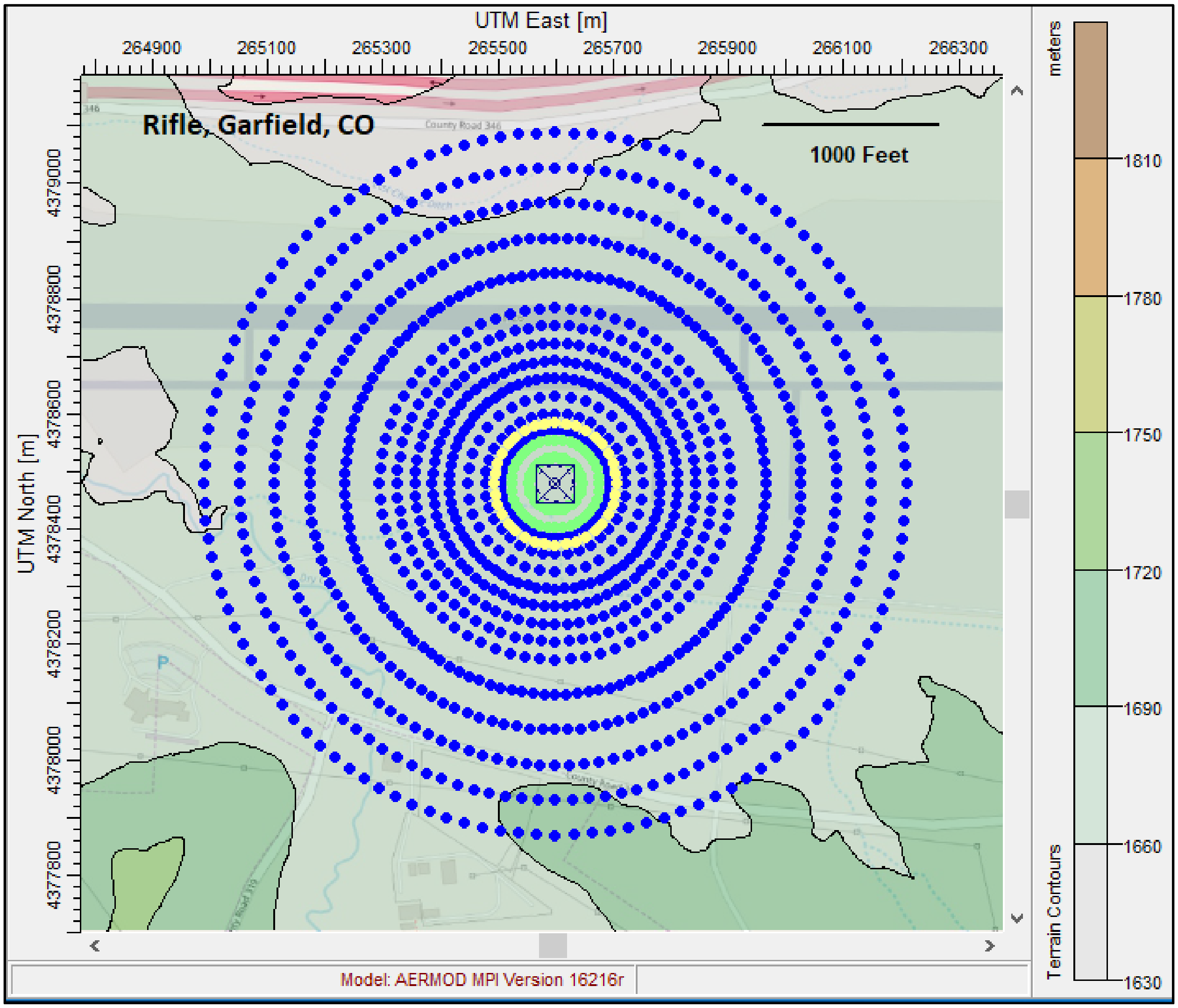
Broad Oil and Gas Area	Surface Station Name	National Land-cover Database	Surface Moisture	
			Cooperative Observer Precipitation Station	Data Source
Northern Front Range	Anheuser-Busch	1992	Fort Collins	National Oceanic and Atmospheric Administration: https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-data sets/cooperative-observer-network-coop
	Ft. St. Vrain	2001	Greeley	
Garfield County	BarD	2001	Altenbern	Western Regional Climate Center: https://wrcc.dri.edu/
	Rifle	2001	Rifle	

2.5.3.2. Terrain Characteristics

Terrain data are from the U.S. Geological Survey's Digital Topographical Database using the National Elevation Dataset[5] files at a resolution of 1/3 arc second (approximate horizontal resolution of 10 m). We prepared the acquired data sets for use in AERMOD using the terrain pre-processor program AERMAP (version 11103).

The terrain at all four meteorological sites was **general flat with less than 30-m elevation change within 2,000 ft (610 m) of the station**. The largest change in topography is found at Rifle, as seen with the elevation contours in Figure 2-12. The figure also contains locations of modeling receptors at Rifle, which we discuss in Section 2.6.

[4] National Land Cover Database: www.mrlc.gov
[5] National Elevation Dataset: https://lta.cr.usgs.gov/NED



Notes: Green receptors are used for the oil and gas production phase only. Yellow receptors are at a 350-foot distance representing the current state setback for "outside activity areas". Blue receptors are used for all risk-assessment modeling.

UTM = Universal Transverse Mercator; m = meters.

Figure 2-12. Terrain Contours and Receptor Locations at Rifle (Garfield County Valley Site)

2.6. Receptors

Receptors are locations where the model estimates air concentrations. For these HHRAs, we chose a set of polar-coordinate receptors which are characterized as a set of **concentric circles** or rings. We chose concentric rings to facilitate summaries of HHRA output (estimates of air concentrations, exposure, and potential risk) at each distance from the well pad. The distances between rings are measured from the center of the well pad. As discussed in the bullets below, we used slightly different sets of receptors for well development versus well production (see also Table 2-9), each **extending out to 2,000 ft** (610 m) from the center of the well pad.

- Well development has 14 rings, beginning at 300 ft (91 m), then 350 ft, then at 100-ft spacing from 400 to 1,000 ft, and then at 200-ft spacing from 1,000 to 2,000 ft (610 m).
- Well production has 16 rings—the same 14 rings as well development, plus two inner rings (150 and 250 ft [46 and 76 m]).

These distances include the default setback distances listed under COGCC Rule 600 Series Safety Regulations. The 500-ft distance is of particular interest because it is COGCC's current Exception Zone Setback for well and production facilities relative to a building unit. The 350-ft ring represents the minimum "outside activity area" distance (outdoor venues or recreational areas owned or operated by local government). We included the additional, closer receptors for well production because some homes are closer than 500 ft from existing production areas. The number of receptors per ring increases with increasing distance from the well pad, as shown in Table 2-9, in order to maintain a spacing of approximately 100 ft or less between individual receptors along a ring. The receptor spacing is also illustrated in Figure 2-12. We placed all receptors at the "breathing" height of 1.8 m, meaning that we estimated air concentrations at 1.8 m off the ground.

Table 2-9. Receptor Layout and Spacing

Ring Number	Radial Distance from Center (feet)		Number of Receptors	Distance Between Receptors Along the Ring (feet)
	Development	Production		
1	None	150	36	26.2
2	None	250	36	43.6
3	300	Same as Development	36	52.4
4	350		36	61.1
5	400		36	69.8
6	500		36	87.3
7	600		72	52.4
8	700		72	61.1
9	800		72	69.8
10	900		72	78.5
11	1,000		72	87.3
12	1,200		120	62.8
13	1,400		120	73.3
14	1,600		120	83.8
15	1,800		120	94.2
16	2,000		120	104.7

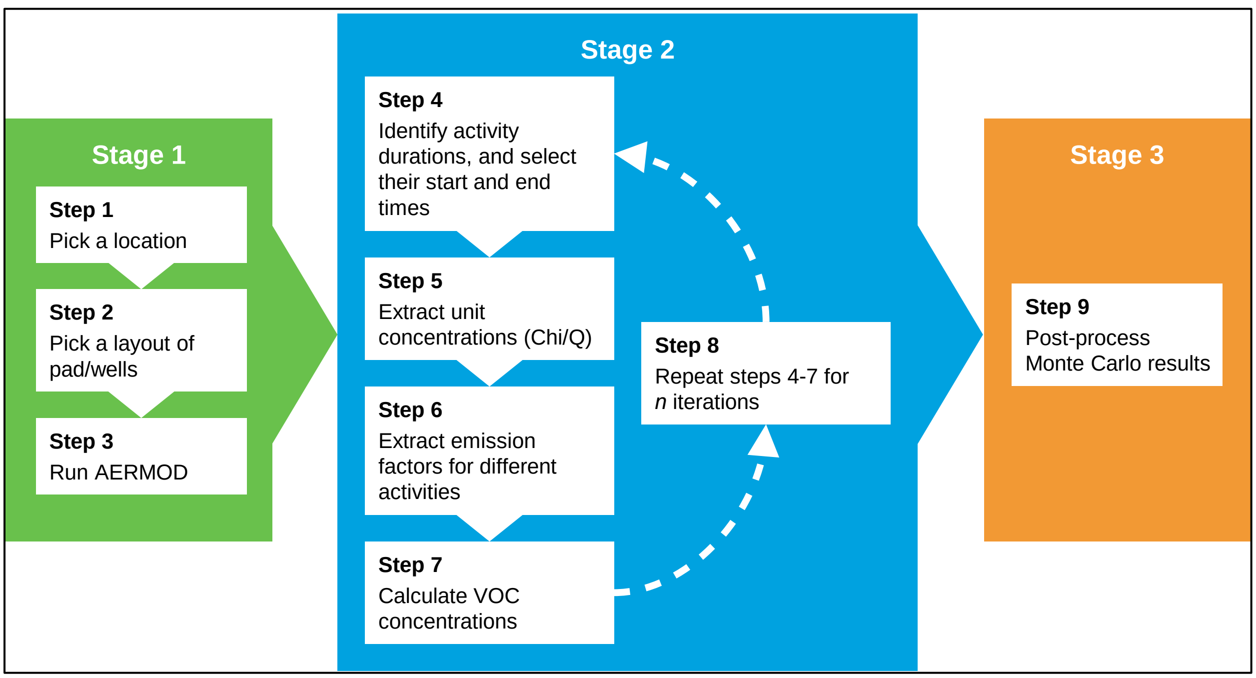
2.7. Monte Carlo Simulations with AERMOD (for Oil and Gas Development Activities)

As discussed below, we utilized Monte Carlo probabilistic-sampling techniques to create a wide variety of air-quality scenarios during O&G development activities, where individual development activities typically last days per well. This level of probabilistic sampling was not needed for O&G production activities, as discussed later in Section 2.8.

2.7.1. Monte Carlo Workflow

To better understand concentrations of VOCs generated from an O&G site during development activities, any “single-point” estimation is replaced by a statistical distribution using Monte Carlo sampling. This provides additional information about the uncertainty and variability around its central-tendency values. The Monte Carlo method is a statistical technique by which a quantity is calculated repeatedly across some number of iterations, using randomly sampled inputs, within the range of their variability. If the number of iterations is large enough, results will closely approximate the full range of possible outcomes and provide information on the likelihood of each outcome (EPA, 1994). **The Monte Carlo method creates a full range of possible outcomes for each of the 47 VOCs, as it includes the major variables in the inputs (meteorology, emissions, and activity duration) to determine VOC concentrations**. Because of the computational demands for running AERMOD repeatedly with varying emissions and meteorology, it is more efficient to run AERMOD using unit emissions (1 gram per second [g/s]) for all hours of meteorology, save those results, and then post-process the results with activity durations and actual emissions to obtain a full set of possible outcomes. We conducted these Monte Carlo calculations using the statistical software R (R Core Team, 2012).

We present in Figure 2-13 a workflow diagram for the Monte Carlo processing, which has three stages consisting of nine steps in total.



Notes: VOC = volatile organic compound; Chi/Q = concentration per unit emission.

Figure 2-13. Workflow of Monte Carlo Method (for Oil and Gas Development Activities)

- **Stage 1 is “pre-Monte Carlo stage”**, which selects the modeling scenario and runs the AERMOD model. Steps 1 and 2 decide the physical location (from among the four meteorological locations) and size of the well pad (1, 3, or 5 acres). Based on the selected location, Step 3 executes AERMOD using location-specific meteorology, unit emissions, and all receptor locations. This results in outputs of unit-emission concentrations (concentrations reflecting unit emissions) for all hours of the period of the meteorology data.[6]

- **Stage 2 is the Monte Carlo simulation**. For each O&G activity and location, we first identify its duration based on prevalence (see Table 2-1) and a random beginning date (Step 4)—that is, a specific time period for the activity. Next (Step 5), we extract unit-emission concentrations at all receptors for the time period from the AERMOD output, which is followed by (Step 6) randomly picking a set of activity- and location-dependent emission rates (which we discuss in Section 2.3). In Step 7, we calculate VOC concentrations by multiplying unit-emission concentrations by the selected emission rates. Steps 4 through 7 are considered one Monte Carlo "iteration". In order to fully develop the VOC distributions, Step 8 repeats the previous four steps for *n* iterations, with the output from each iteration saved to create the statistical distribution.

- **Stage 3 is the "post-Monte Carlo stage"** where we calculate various air-concentration metrics potentially useful for subsequent exposure and risk modeling (e.g., maximum, median, and various percentile values).

2.7.2. Monte Carlo Simulation

In constructing the Monte Carlo-based modeling approach for development activities, we make a key distinction between different types of input variables: decision variables or probabilistic variables. Each decision variable has a predetermined set of possible values and each value is equally likely to be selected.

In these HHRAs, the decision variables are

- the **sites of O&G operations** and

- the **sizes of well pads**.

Although two meteorological sites are included in the NFR, they are treated as one in the Monte Carlo simulation, as the meteorology is sampled randomly but in equal quantities between the two sites. Each unique combination of decision variables is referred to as a **scenario**, on which a Monte Carlo simulation is conducted. We constructed a total of nine Monte Carlo scenarios for development activities: three for O&G operation sites (one for NFR, two for Garfield County) by three well-pad sizes (1, 3, and 5 acres; Table 2-6).

We select the probabilistic variable's value based on pre-defined probabilities, which includes the **duration** of the three development activities, the **beginning date and hour** of the activity, and the **emission rate**. We use probabilities to select the duration of the activities (see "prevalence" column in Table 2-1), and we use uniform probability distributions to select the emission rate and the beginning date and hour.

For a given scenario, we conduct a Monte Carlo simulation by calculating VOC concentrations using various combinations of probabilistic variables. Each independent calculation of VOC

[6] AERMOD flags outputs when the wind speed is calm or missing, or when other key meteorological parameters are missing, and reports the concentrations as zero. We exclude these periods from the unit-emission concentrations.

concentrations from a set of inputs is known as a Monte Carlo **iteration**. For each iteration, we randomly sample a value for each input variable and then calculate the associated VOC concentrations. We conduct thousands of iterations until we reach convergence in the distribution of values from all iterations (see Section 2.7.4 on convergence testing).

In conducting a Monte Carlo simulation, we first sample the duration of the activity. We do this by generating a random number from a uniform distribution between 0 and 1, and then we compare against the empirical prevalence distribution listed in Table 2-1. For example, if the generated value is 0.6 and the site location is NFR, we would select a set of activities associated with horizontal 1.5-mile development. This is because 0.6 is greater than 0.52, the upper bound of the horizontal 1-mile activity set, but less than the upper bound of the horizontal 1.5-mile activity set (which is 0.52+0.3=0.82). Thus, in this example, the durations of the drilling, fracking, and flowback activities would be 5, 3, and 7.5 days per well, respectively. However, if the site location is Garfield County, we would select a set of activities associated with vertical development, since 0.6 is greater than the upper bound of horizontal 2-mile activity set (which is 0.13+0.02=0.15), and the activity durations would be 4, 1, and 13 days per well for drilling, fracking, and flowback, respectively.

Once we decide the activity durations, we generate two random numbers from a uniform distribution to represent the starting date and hour the activity. We use uniform random numbers with different ranges in selecting starting date since each site has different time windows of meteorology in the modeling: Rifle has a five-year window, BarD has two years, and Anheuser-Busch and Ft. St. Vrain each have one year. We assume that an activity can start at any hour of day and day of year.

For the NFR, note again that we use the Anheuser-Busch and Ft. St. Vrain meteorological data to produce only one (blended) set of VOC-concentration distributions, which means the algorithm needs to select a meteorological site first before choosing activity durations.

All of the procedures described above happen in Step 4 of Figure 2-13. In Step 5, we extract unit-emission concentrations from AERMOD outputs for a given simulated starting time and duration. In Step 6, we randomly select site-specific emission rates for each activity. For a given iteration of Step 6, the selected emission rate for each VOC comes from the same emission-sampling event in the CSU experiment data—that is, all emissions used in an iteration were observed simultaneously in the CSU experiments. We hold the emission rates constant over the duration of the iteration (the activity time period). As discussed in Section 2.3, due to data availability, the emission rates for drilling activities in NFR simulations come from the data collected in Garfield County. In addition, any sampled missing value for the drilling activity from the first two CSU experiments are re-sampled from the other nine samples[3]. We list in Table 2-2 (the "Events" rows) the number of emission rates associated with each site and activity. The last step within an iteration (Step 7) is to multiply the sampled unit-emission concentrations by the randomly selected emission values for each VOC to produce a set of VOC concentrations as a time series of values within the activity time period. In Step 8, we repeat Steps 4–7 thousands of times until we reach convergence in the distribution of values from all iterations (see Section 2.7.4 on convergence testing).

2.7.3. Post Processing

In Stage 3 (which is the final step, Step 9), we post-process the results of Monte Carlo simulations for development activities by **summarizing the statistical distributions of results from the thousands of iterations**. We describe below the detailed post-processing calculations. The first three bullets below allow us to identify the receptor along each distance ring that experiences the highest air concentrations on average, for each VOC, O&G location, and activity independently. The final bullet below is where we collect statistics describing the distributions of air concentrations at those selected receptors.

1. Calculate maximum concentrations per iteration: At a given receptor for a given VOC, O&G location, and activity, we have dozens to hundreds of estimated 1-hour-average air concentrations for each Monte Carlo iteration, depending on the activity duration used. In this calculation, we find the maximum 1-hour value from each iteration—that is, the single highest estimated 1-hour-average air concentration. This creates a set of iteration-maximum concentrations at each receptor for each VOC, O&G location, and activity. These iteration-maximum concentrations can be relatively low or relatively high, depending on the receptor location, the emission rate used for a VOC, and the meteorological conditions over the activity duration.

2. Calculate mean-maximum concentrations at each receptor: For each set of maximum values saved in Bullet 1 above, calculate the mean of all the maximum values—the mean-maximum 1-hour-average air concentration at each receptor for each VOC, O&G location, and activity.

3. Identify the "expected-maximum" receptor at each distance: From among all the receptors along a given distance ring (a given distance from the center of the well pad), identify the receptor with the largest mean-maximum 1-hour-average air concentration as calculated in Bullet 2 above. We do this at each distance ring for each VOC, O&G location, and activity. The highest mean-maximum value represents the **"expected-maximum" concentration** at that distance from the well pad. These expected-maximum concentrations can be viewed as the most likely worst-case concentrations and are a reflection of the meteorological conditions modeled at the O&G site.

4. Summarize concentrations at expected maximum receptors: For each expected-maximum receptor identified in Bullet 3 above, extract an array of values from each of the Monte Carlo iterations, including each iteration's mean and maximum 1-hour-average air concentration as well as the 50th, 95th, 99th, and 99.9th percentiles of 1-hour-average air concentrations. We then use these values in the exposure assessment, as discussed in Section 3.

2.7.4. Convergence Testing of Monte Carlo Simulations

Monte Carlo is a useful approach to quantify model uncertainties (Frey and Patil, 2002), and its framework is conceptually straightforward. However, in order to assure that results fully characterize the distributions and minimize uncertainties, it is necessary to test and verify that the model results are converging with additional modeling iterations. **After a certain number of iterations, the distributions are sufficiently characterized and additional iterations add**

little value. Since Monte Carlo-based simulations do not have well-established convergence criteria, we adopted a qualitative method of convergence testing.

We derive the 47 VOCs' concentrations based on the same set of unit-emission concentrations estimated by AERMOD, so the burden of proving convergence is tied to the variability in the VOC emission rates. This means that all Monte Carlo simulation results will converge if it is shown that the concentrations converge for VOCs with relatively high variability in their emission rates. We selected the VOCs listed below because of their high variabilities in 3-minute-average emission rates.

- benzene for drilling (3-minute-average emission rates vary by 4+ orders of magnitude)
- t-2 butene for fracking (3-minute-average emission rates vary by 5+ orders of magnitude) and
- n-butane for flowback (3-minute-average emission rates vary by 5+ orders of magnitude)[7]

Note that we conducted this convergence testing prior to the derivation of 1-hour-average emission rates. However, the VOCs listed above still have among the highest variabilities in emission rates when using the 1-hour-average rates (though the variabilities are lower overall: 1.5 orders of magnitude variation for benzene from drilling, 3.8 orders of magnitude for t-2 butene from fracking, and 2.1 orders of magnitude for n-butane from flowback). The lower variabilities when using 1-hour-average emission rates should lead to a more rapid convergence of the modeling results than when using 3-minute-average rates. Therefore, this convergence testing is still applicable and robust when utilizing 1-hour-average emission rates.

We also expect that VOC concentrations in the outer rings contain more variability than in the inner rings due to added uncertainty during dispersion. Thus, we focused the convergence testing on the outer-most ring. We describe below each step in the convergence testing.

1. Run the Monte Carlo simulation 10,000 times on the outer-most ring of receptors (2,000 ft from the center of the well pad) for each selected VOC and each O&G development activity and O&G location.

2. For each of the 10,000 iterations, identify the maximum 1-hour-average air concentration at each receptor (for each selected VOC and each O&G activity and location).

3. From the collection of maximum 1-hour-average concentrations at each receptor (for each selected VOC and each O&G activity and location), calculate the mean and standard deviation ($\overline{\mathrm{VOC}_{max,n,k}}$ and $S_{VOC,n,k}$, Eq. 2-11 and 2-12) (Ballio and Guadagnini, 2004).

$$\overline{\mathrm{VOC}_{max,n,k}} = \frac{1}{n}\sum_{i=1}^{n} \mathrm{VOC}_{i,k} \quad \text{Eq. 2-11}$$

$$\mathrm{S}_{VOC,n,k} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\mathrm{VOC}_{i,k} - \overline{\mathrm{VOC}_{max,n,k}}\right)^2} \quad \text{Eq. 2-12}$$

where

[7] Toluene is also included as a VOC of interest to see if convergence occurs more rapidly for this VOC, as it tends to have less variability in each activity and generally higher emission rates.

k represents the k^{th} modeled VOC
i represents the i^{th} Monte Carlo iteration
n represents total number of Monte Carlo iterations.

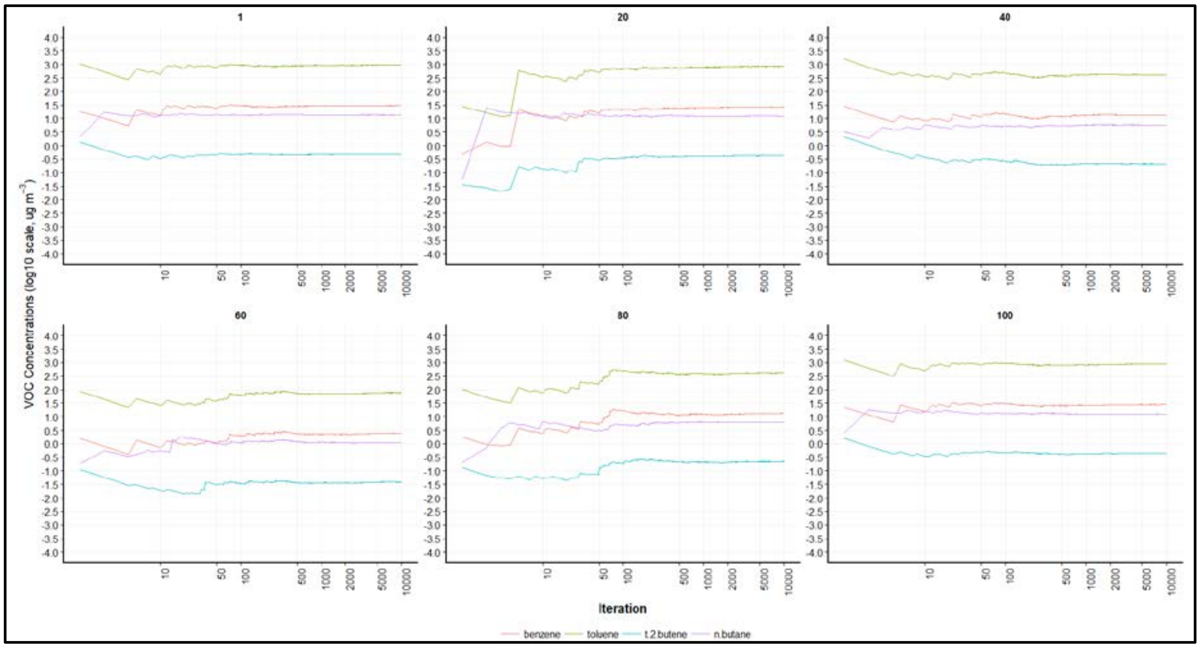
4. Select several receptors to visualize the trends in $\overline{\text{VOC}_{max,n,k}}$, and $S_{VOC,n,k}$ as the number of iterations increases towards 10,000. If the variation in concentration becomes small (converges) with increasing number of iterations, then we consider the results to be stable and converging.

Table 2-10 contains the results of this convergence testing: the approximate number of iterations needed to reach convergence based on the steps outlined above. We estimated that we need **2,000 Monte Carlo iterations** for distributions of air concentrations to reach convergence.

Figure 2-14 through Figure 2-17 help illustrate how we determined these numbers of iterations. Figure 2-14 and Figure 2-15 respectively contain the trends in mean-maximum concentrations and standard deviations of concentrations (log transformed) sampled from receptors on the 2,000-ft ring at Rifle during drilling. The selected receptors are separated by 60-degree intervals to illustrate that convergence has been reached in all directions. The figures show that the mean reached convergence after about 200 iterations while the standard deviation reached convergence by about 500 iterations, although the speed of convergence varied among receptors due to the effects of meteorology. Figure 2-16 and Figure 2-17 respectively contain the trends in mean-maximum concentrations and standard deviations of concentrations (log transformed) for the three O&G development activities at the three O&G sites for the slowest-converging receptor (the so-called receptor number 80). Both plots show that the speed to reach convergence is location- and activity-dependent. For example, it appears that more iterations are needed to reach convergence at Rifle than at the other two locations, which is likely due to the longer meteorological data periods available for Rifle (five years) than at the two other locations (one or two years). Across activities, drilling takes less than 1,000 iterations to converge, flowback needs up to 1,500 iterations, and fracking needs up to 2,000 iterations. In general, the mean converges faster than the standard deviation. We used 2,000 iterations in our post-processing so that the distribution sizes are the same size regardless of O&G location or activity.

Table 2-10. Iterations Required to Reach Convergence, by Well-development Site and Activity

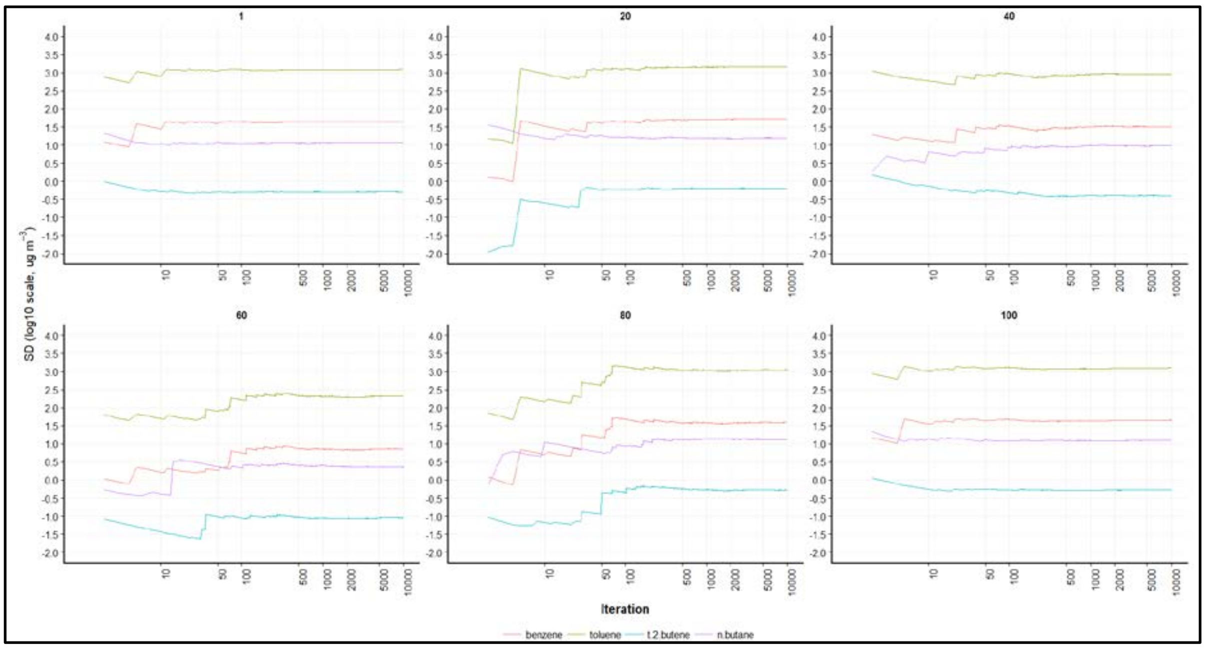
Broad Oil and Gas Area	Site	Drilling	Fracking	Flowback	Overall
Garfield County	Rifle	1,000	2,000	1,000	**2,000**
	BarD	1,000	2,000	1,000	**2,000**
Northern Front Range	Anheuser-Busch / Ft. St. Vrain	1,000	2,000	1,500	**2,000**



Notes: The numbers at the top of each plot indicate the receptor number. Receptor number 1 is approximately due north of the well pad, while the other receptors are equally spaced clockwise around the receptor ring.

VOC = volatile organic compound; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10.

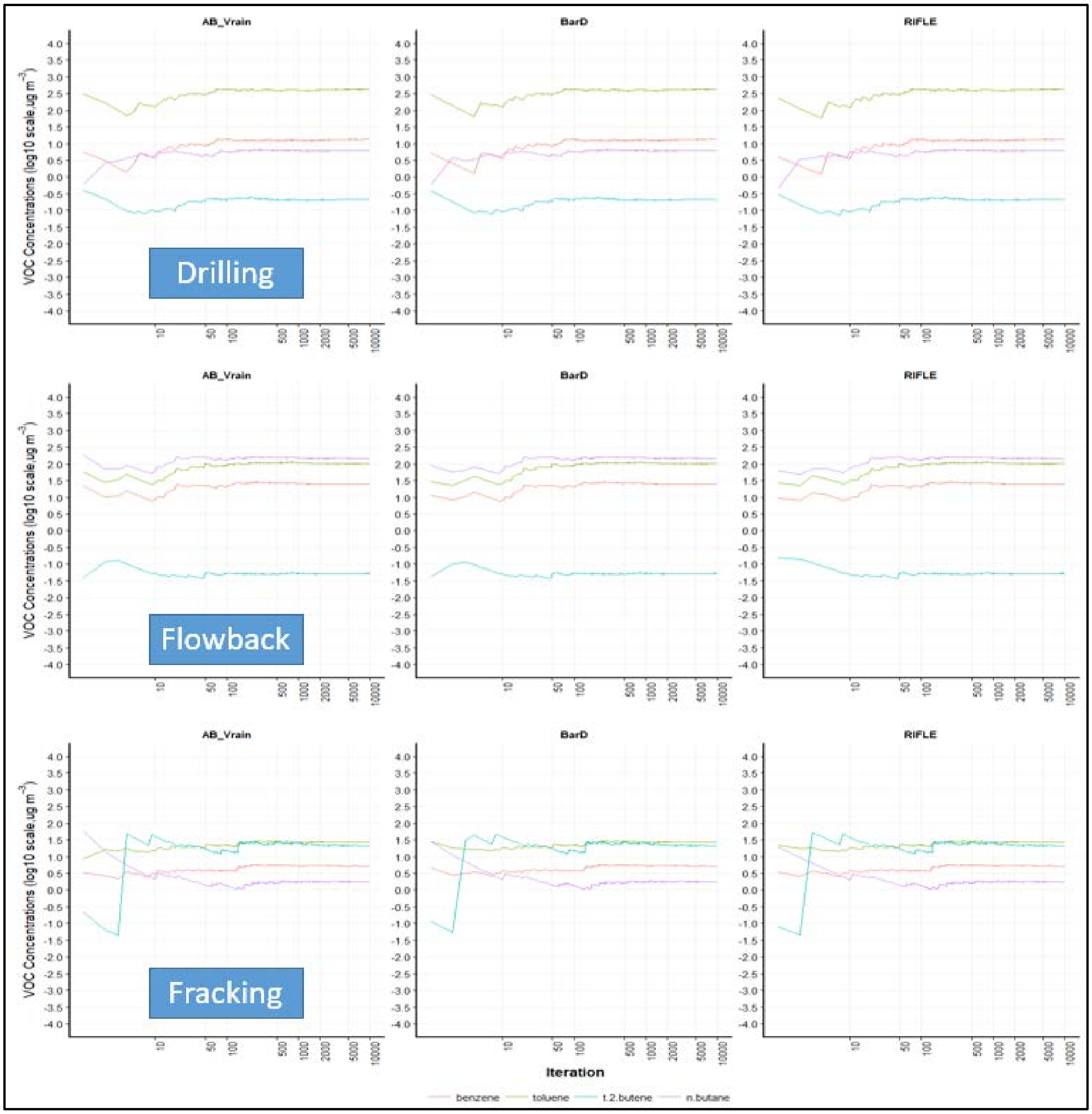
Figure 2-14. Cumulative Plot of Mean-maximum Hourly Concentration at Selected Receptors: Drilling Activity, 2,000-foot Ring, Rifle Location, 1-acre Well Pad



Notes: The numbers at the top of each plot indicate the receptor number. Receptor number 1 is approximately due north of the well pad, while the other receptors are equally spaced clockwise around the receptor ring.

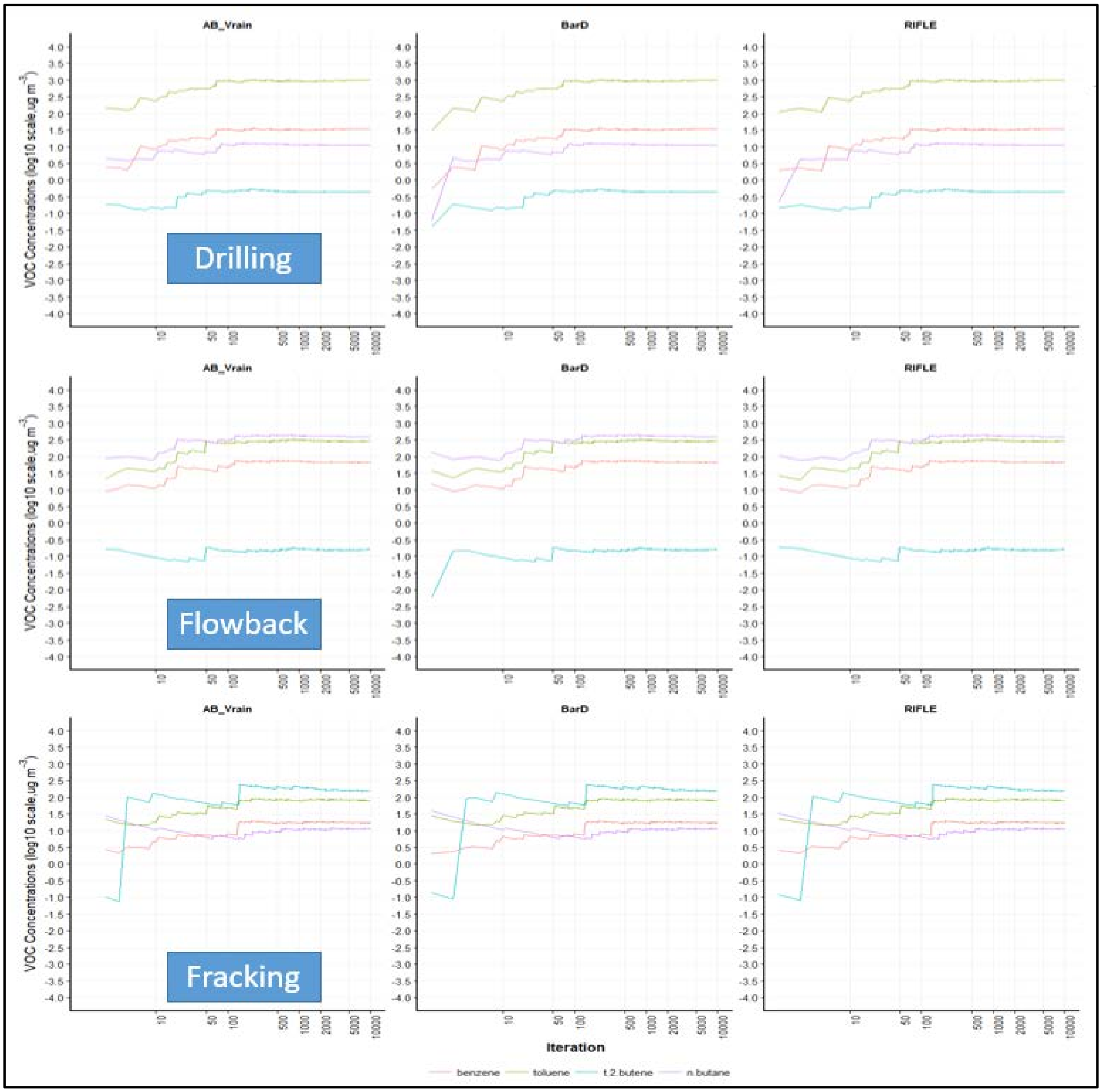
SD = standard deviation; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10.

Figure 2-15. Cumulative Plot of Standard Deviation of Maximum Hourly Concentration at Selected Receptors: Drilling Activity, 2,000-foot Ring, Rifle Location, 1-acre Well Pad



Notes: AB_ST = the Northern Front Range Anheuser-Busch/Ft. St. Vrain sites; BarD and Rifle = the Garfield County ridge-top and valley sites; VOC = volatile organic compound; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10.

Figure 2-16. Cumulative Plot of the Mean-maximum Hourly Concentrations: All Activities, Selected Receptor (Number 80) on the 2,000-foot Ring, 1-acre Well Pad



Notes: AB_ST = the Northern Front Range Anheuser-Busch/Ft. St. Vrain sites; BarD and Rifle = the Garfield County ridge-top and valley sites; VOC = volatile organic compound; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10.

Figure 2-17. Cumulative Plot of Standard Deviation of Maximum Hourly Concentrations: All Activities, Selected Receptor (Number 80) on the 2,000-foot Ring, 1-acre Well Pad

2.8. Processing Steps for Oil and Gas Production

The discussion in Section 2.7 pertains to O&G development activities, since the embedded uncertainties in the estimated VOC concentrations related to development activities are best characterized through Monte Carlo simulations (we provide further discussion on uncertainty in

Section 2.10.2). Production from the O&G wells occurs over many years (chronic exposures) rather than the variable short time periods for the development stage. This **simplification for the production stage** allows us to use AERMOD directly to generate all possible hourly values of unit-emission concentrations (i.e., all possible meteorological-driven dispersion conditions), with no need for Monte Carlo probabilistic sampling of activity durations and start times.

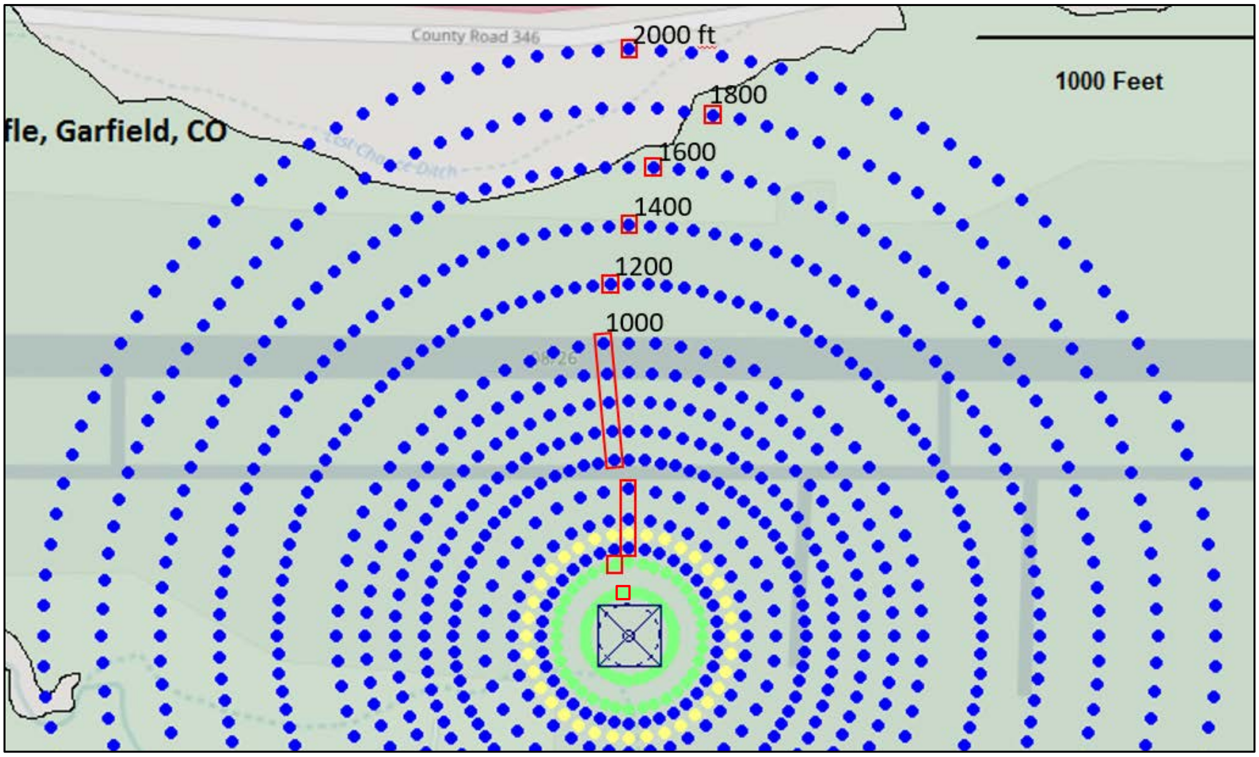
We used AERMOD to generate a full year of 1-hour-average air concentrations at every receptor using unit emissions (1 g/s), for each full year of meteorological data: five years for Rifle, 2 years for BarD, and 1 year each for Anheuser-Busch and Ft. St. Vrain. For each O&G location, we distill the data into a single year of values at a single receptor per ring (a single year of values per distance from the center of the well pad), as we describe in the bullets below.

1. For each year of AERMOD outputs at an O&G location, calculate the site-wide annual-average unit-emission concentration. Use all hourly values from all receptors to do this calculation. This results in a single overall average unit-emission concentration per O&G location per year.

2. For each O&G location, identify the year with the highest average value as calculated in Bullet 1 above. That is, the year that overall had the worst unit-emission air concentrations, which is a reflection of the meteorological conditions in that year. The Anheuser-Busch and Ft. St. Vrain meteorological data sets were only one year each, so this year-selection step only applies to the Rifle and BarD data sets.

3. For the year selected in Bullet 2 above, identify the receptor with highest annual-average average for each ring. That is, the receptor that overall had the worst unit-emission air concentrations at that distance. As an example, see Figure 2-18 where we illustrate the receptors selected for production assessment at the Rifle location in Garfield County.

4. For each receptor identified in Bullet 3 above, and for the year identified in Bullet 2 above, **extract the full year of hourly unit-emission air concentrations** for that location. Later in the exposure assessment (as discussed in Section 3), we combine these values with the derived 1-hour-average emission rates during O&G production operations, resulting in hourly estimates of air concentrations during O&G production.



Notes: Dots are all receptors initially modeled in the dispersion assessment. The green rings of receptors are only used for production activities, while the yellow ring is a special 350-foot distance included in all modeling. Red rectangles indicate the selected receptors for this scenario.
ft = feet.

Figure 2-18. Example of Selected Receptor Locations Based on High Annual-average Air Concentrations, for Production Activities at the Garfield County Valley Site (Rifle)

2.9. AERMOD Modeling Results

In this section, we present a sample of the AERMOD modeling results created primarily for quality assurance. These samples are generally representative of a larger set of plots and figures which we reviewed but do not present here. The box-and-whisker plot is a standardized way of displaying the distribution of data using five metrics: minimum (lower whisker), one standard deviation below mean (lower bound of the box), median (bar in the box), one standard deviation above mean (upper bound of the box), and maximum (upper whisker).

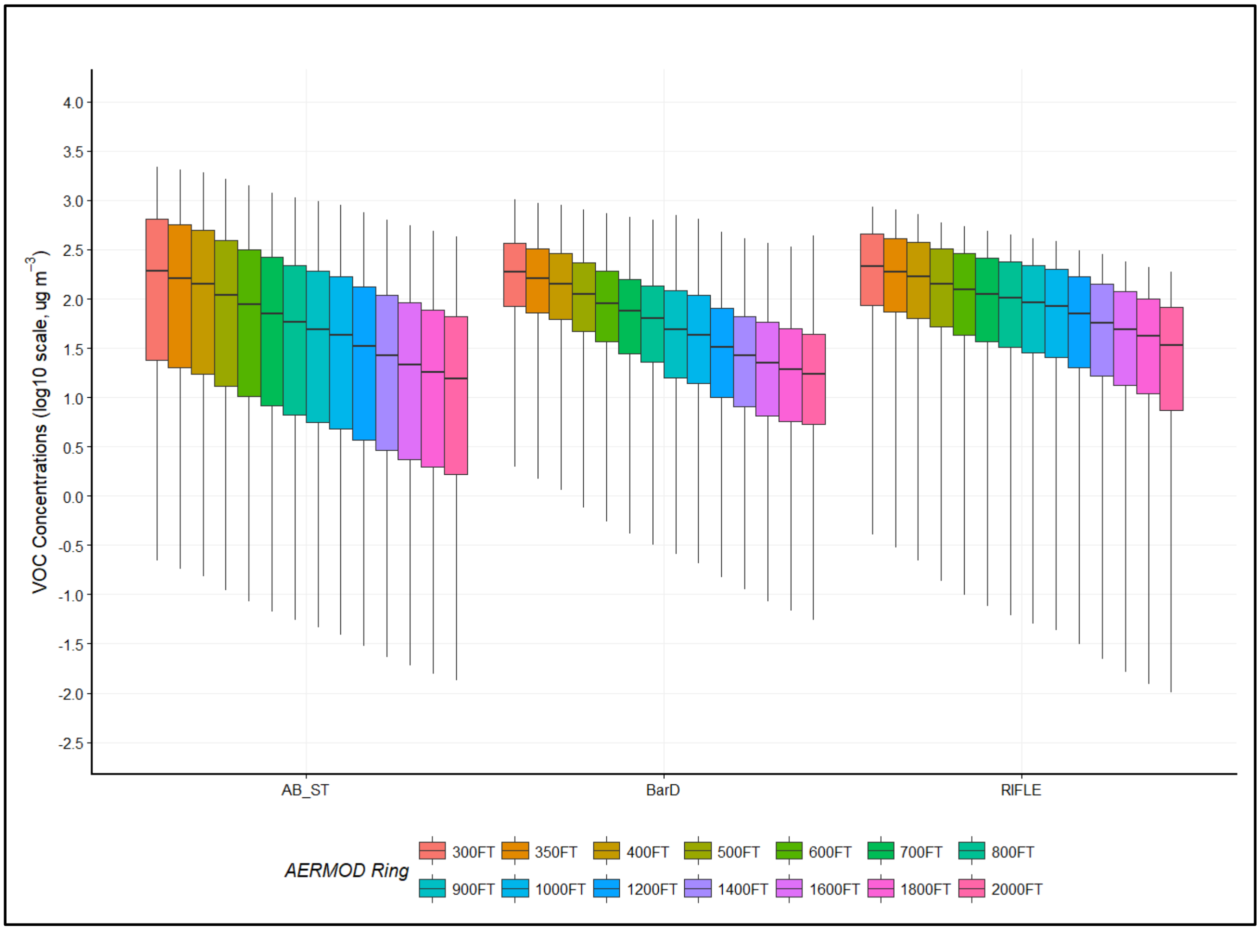
2.9.1. Well Development

In the subsections below, we present a variety of analyses into the variations of modeled VOC concentrations—by distance from the center of the well pad, by O&G activity, by receptor, and by size of well pad.

2.9.1.1. Variation in Chemical Concentration by Distance

Figure 2-19 contains box-and-whisker plots of the collection (across the three development activity types) of maximum 1-hour-average benzene concentrations from each iteration, at distances 300–2,000 ft, for each of the three O&G sites. That is, each box-and-whisker item contains 6,000 data points, which are the maximum 1-hour-average concentrations from each of the 2,000 iterations of drilling modeling, the 2,000 iterations of fracking modeling, and the 2,000 iterations of the flowback modeling. These sets of maximum values come from the data collected in Step 4 in Section 2.7.3, at each VOC's "expected-maximum" receptor at each distance. These maximum values per iteration will be used in the acute exposure assessments (see Section 3.3.1), for each development type separately (see Section 2.9.1.2 for maximum concentrations separated by development activity).

As expected, **concentrations decline with distance from the well pad and there is a substantial range of values at each distance**. The large ranges of values are a reflection both of the range of benzene emission values and the range of meteorological conditions experienced at the selected receptors across all the iterations. The NFR data set (AB_ST) shows the largest ranges of benzene values, due to a larger range of benzene emission values used in the NFR modeling as compared to the Garfield County modeling, and also potentially due to the merged nature of the data set (we randomly merged concentrations utilizing Anheuser-Busch meteorology data with those utilizing Ft. St. Vrain meteorology). While maximum concentrations in some iterations are quite low (e.g., less than 1 microgram per cubic meter at the 300-ft distance at AB_ST and Rifle), they are well below one standard deviation from the mean of the concentrations (well outside the box). In contrast, the highest maximum concentrations in the data sets tend to be much closer to the medians (much closer to the box).

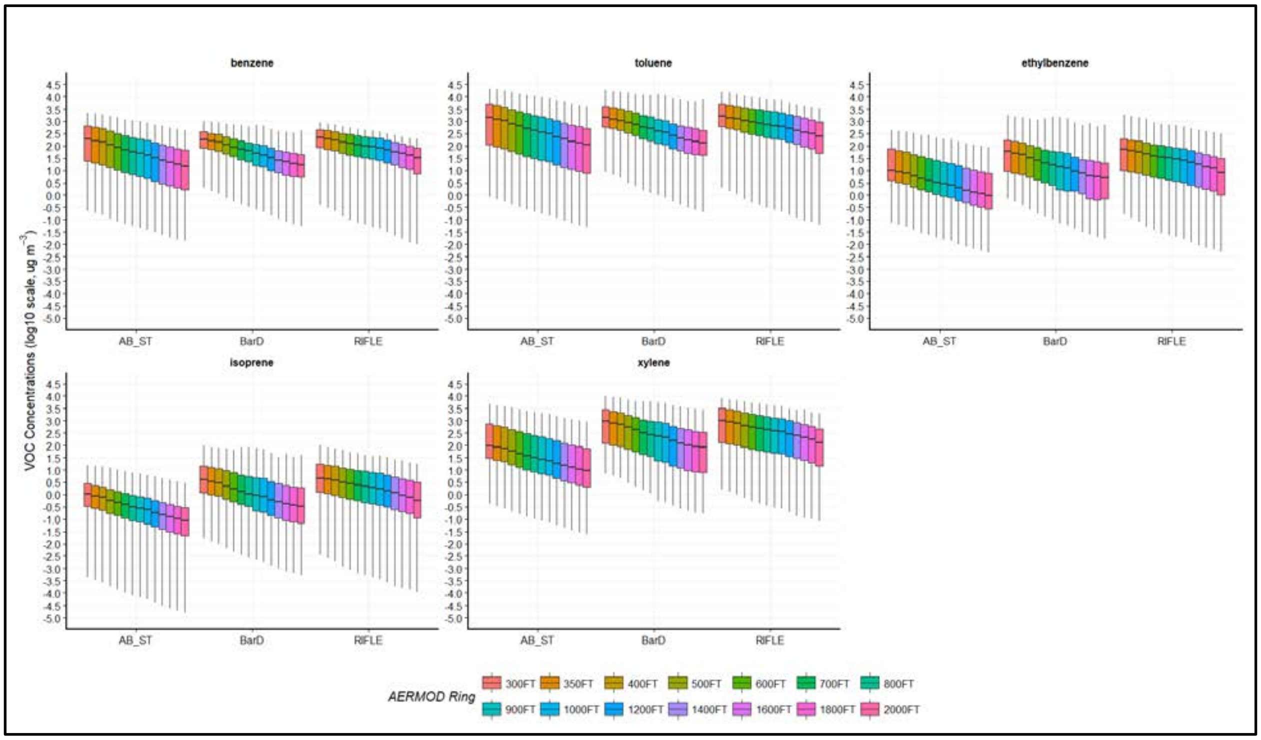


Notes: Values have been transformed via logarithm base 10. Each box-whisker plot indicates maximum and minimum (top and bottom whiskers), mean ± 1 standard deviation (top and bottom of box), and median (bar inside box).

AB_ST = the Northern Front Range Anheuser-Busch/Ft. St. Vrain sites; BarD and Rifle = the Garfield County ridge-top and valley sites; VOC = volatile organic compound; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10; ft = feet.

Figure 2-19. Distribution of Maximum 1-hour-average Benzene Concentrations by Distance and Well-development Location (1-acre Well Pad Only), Across All Development Activity Types

Figure 2-20 presents the same benzene plots as in Figure 2-19 but also includes isoprene and the other BTEX compounds. These plots all show the same expected trend: general decreases in concentrations by several factors from 300 ft to 2,000 ft away from the well pad. The extent of the boxes and the whiskers depends on the ranges of emission rates and meteorological conditions sampled across the iterations, by chemical and site.



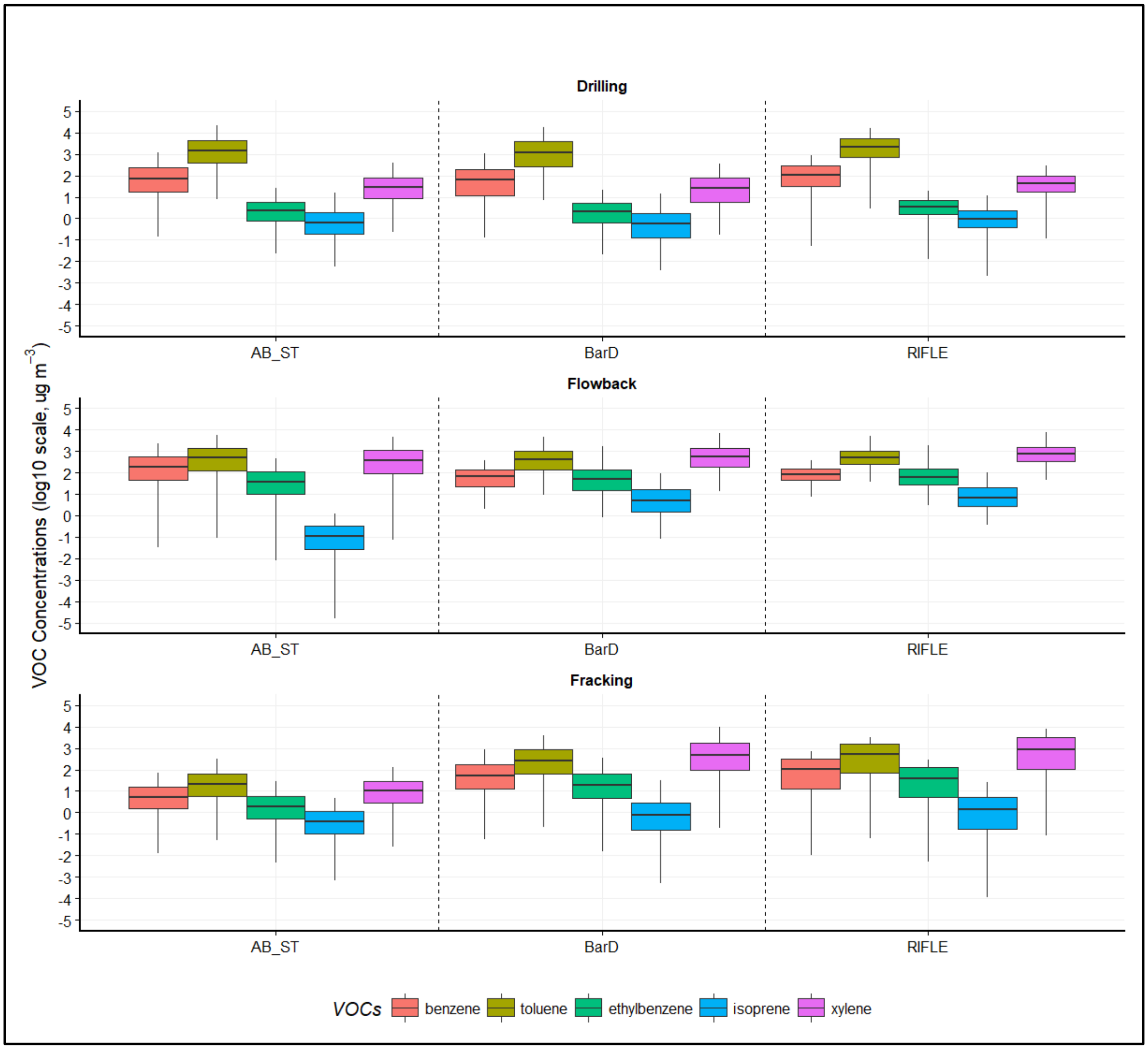
Notes: Values have been transformed via logarithm base 10. Each box-whisker plot indicates maximum and minimum (top and bottom whiskers), mean ± 1 standard deviation (top and bottom of box), and median (bar inside box).

AB_ST = the Northern Front Range Anheuser-Busch/Ft. St. Vrain sites; BarD and Rifle = the Garfield County ridge-top and valley sites; VOC = volatile organic compound; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10; ft = feet.

Figure 2-20. Distribution of Maximum 1-hour-average Concentrations for Selected Chemicals by Distance and Development Location (1-acre Well Pad Only), Across All Development Activity Types

2.9.1.2. Variation in Chemical Concentration by Activity

Utilizing the same sets of data as in Figure 2-20 for BTEX and isoprene, Figure 2-21 contains plots of concentrations disaggregated by development activity, for each location and across all distances from the well pad. That is, the plots show the full range of iteration-maximum 1-hour-average concentrations for each development activity. These maximum values per iteration will be used in the acute exposure assessments (see Section 3.3.1). Among these selected VOCs, concentrations of toluene and xylenes are higher across most of the activities and locations, while concentrations of isoprene are lowest. There is some tendency for the BTEX and isoprene boxes and whiskers for fracking activities to be longer (wider range of values) for the Garfield County modeling, and for flowback activities to be longer for the NFR modeling; this is **consistent with the variations in the emissions data**. Fracking shows substantially higher median-maximum concentrations (by an order of magnitude or more) for the BTEX pollutants in the Garfield County modeling relative to the NFR modeling. This is due to the much higher fracking emission rates measured for BTEX pollutants in Garfield County relative to the NFR.



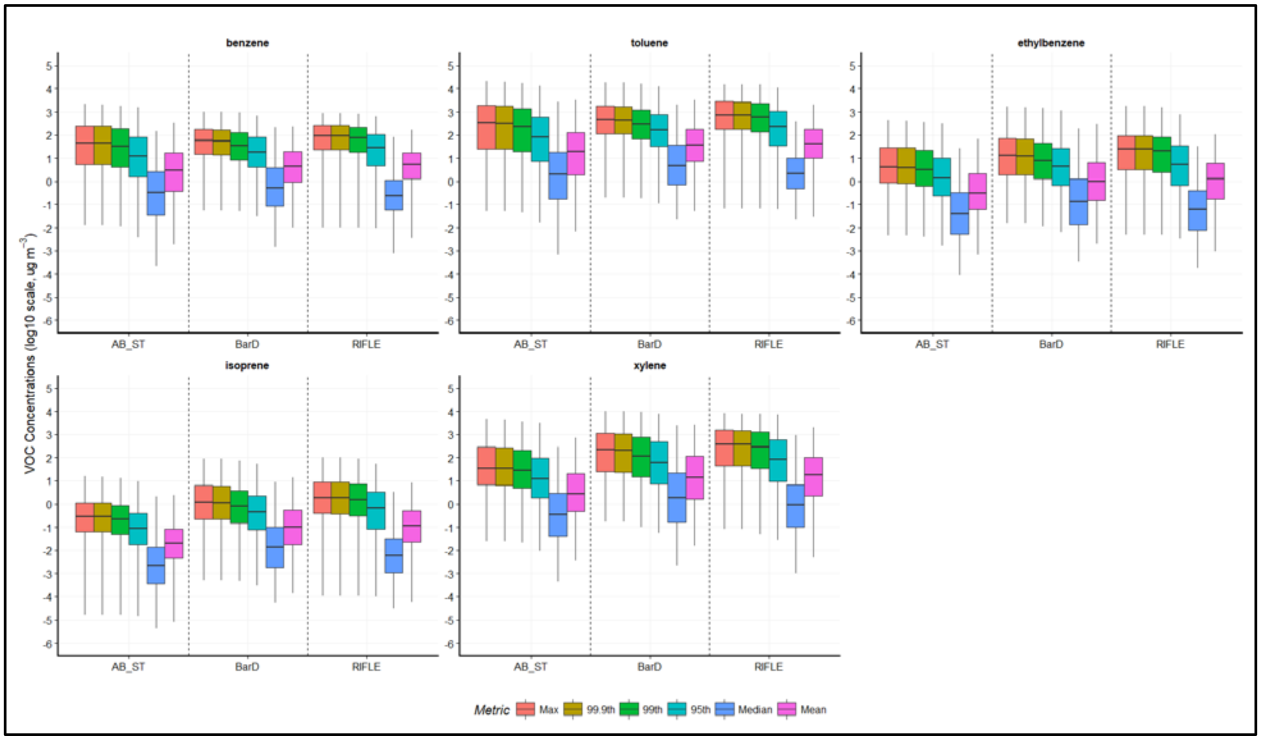
Notes: Values have been transformed via logarithm base 10. Each box-whisker plot indicates maximum and minimum (top and bottom whiskers), mean ± 1 standard deviation (top and bottom of box), and median (bar inside box).

AB_ST = the Northern Front Range Anheuser-Busch/Ft. St. Vrain sites; BarD and Rifle = the Garfield County ridge-top and valley sites; VOC = volatile organic compound; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10.

Figure 2-21. Distribution of Maximum 1-hour-average Concentrations for Selected Chemicals by Development Activity and Well-development Location (1-acre Well Pad Only), Across All Distances

2.9.1.3. Other Statistical Measures of Chemical Concentration

Figures in the previous two subsections are based on the iteration-maximum 1-hour-average VOC concentrations, which are the highest modeled concentrations from each Monte Carlo iteration, which represent **upper bounds of short-term air concentrations** dependent upon the emission rates and meteorological conditions. In this subsection, we explore concentrations for a broader range of statistical measures or metrics. Figure 2-22 contains distributions of VOC concentrations using the same maximum values as the previous figures, but it also includes five other metrics: mean, median, and the 99.9th, 99th, and 95th percentiles from each Monte Carlo iteration. These metrics are across all distances, at the selected “expected-maximum” receptor at each distance. In comparison to the maximum 1-hour-average concentrations, the 99.9th- and 99th-percentile values are slightly smaller, while the typical 95th-percentile values are less than an order of magnitude lower, and the typical means and medians are about one and two orders of magnitude lower, respectively. These last two metrics, the median and mean, represent a **lower bound on the typical short-term concentrations**. We utilize iteration-mean concentrations in the subchronic and chronic exposure assessments (see Section 3.3.1).



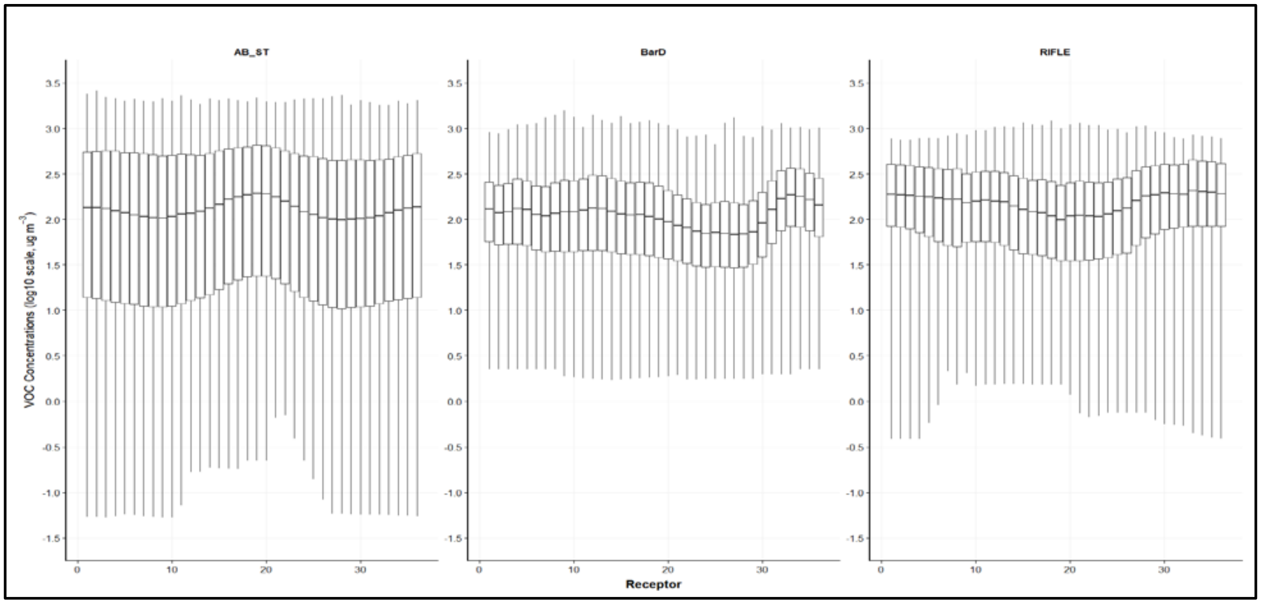
Notes: Values have been transformed via logarithm base 10. Each box-whisker plot indicates maximum and minimum (top and bottom whiskers), mean ± 1 standard deviation (top and bottom of box), and median (bar inside box).

AB_ST = the Northern Front Range Anheuser-Busch/Ft. St. Vrain sites; BarD and Rifle = the Garfield County ridge-top and valley sites; VOC = volatile organic compound; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10.

Figure 2-22. Distribution of 1-hour-average Concentrations for Selected Chemicals by Metric and Well-development Location (1-acre Well Pad Only), Across All Development Activity Types and All Distances

2.9.1.4. Variation in Chemical Concentration by Receptor

Since there are dozens of receptors located in all directions covering 300–2,000 ft around each O&G location, we examine how VOC concentrations vary with changes in wind direction. Figure 2-23 contains distributions of maximum 1-hour-average concentrations of benzene across all 36 receptors on Ring 3 (300 ft from the center of the well pad) for each location. The “wave” shape of the VOC concentrations across directions is **primarily a function of the prevailing meteorology** (primarily wind speed and atmospheric stability) associated with different wind directions, leading to peak median concentrations for southern receptors (near receptor 20) at the merged Anheuser-Busch/Ft. St. Vrain location and for receptors near the north-northwest at the Garfield County locations.



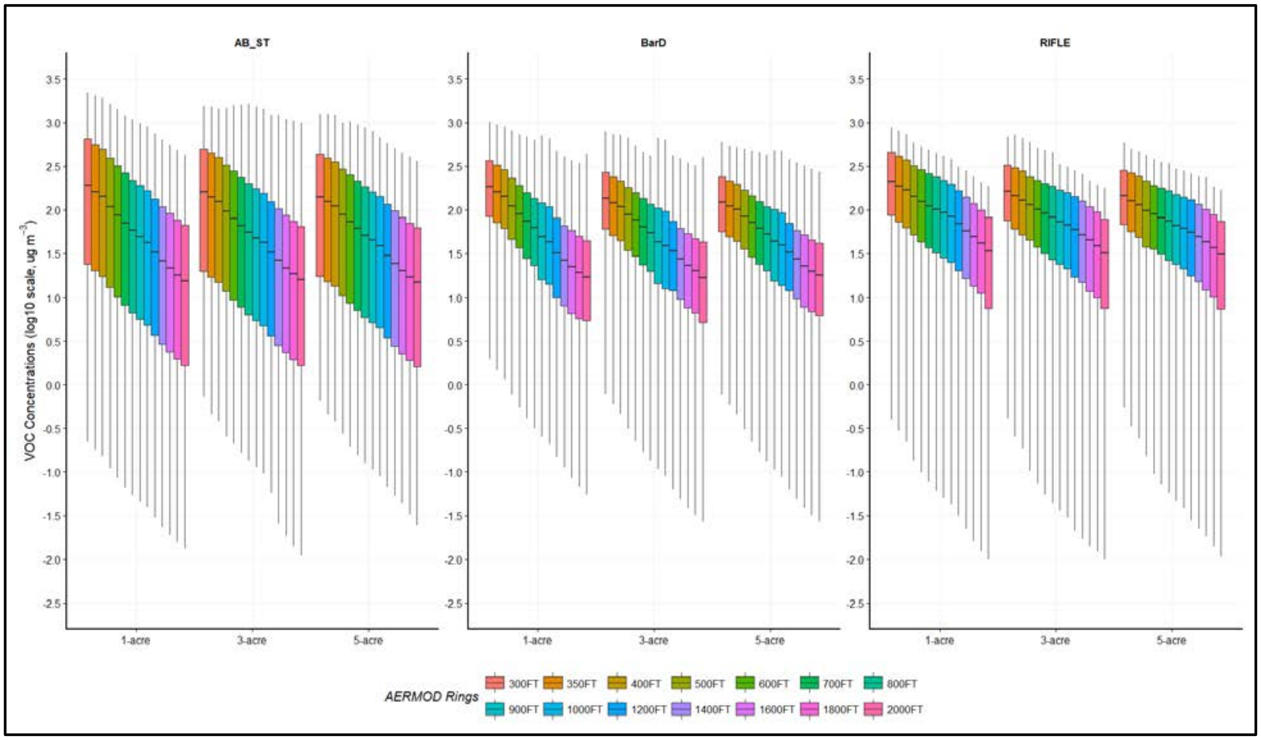
Notes: Values have been transformed via logarithm base 10. Each box-whisker plot indicates maximum and minimum (top and bottom whiskers), mean ± 1 standard deviation (top and bottom of box), and median (bar inside box).

AB_ST = the Northern Front Range Anheuser-Busch/Ft. St. Vrain sites; BarD and Rifle = the Garfield County ridge-top and valley sites; VOC = volatile organic compound; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10.

Figure 2-23. Distribution of the Maximum 1-hour-average Benzene Concentrations at 10-degree Intervals at 300-foot Distance, by Well-development Location (1-acre Well Pad Only), Across All Development Activity Types

2.9.1.5. Variation in Chemical Concentration by Size of Well Pad

Figure 2-24 is similar to Figure 2-19 except that it also shows the distributions of benzene concentrations at the other two modeled well-pad sizes: 3 and 5 acres. These distributions show how the typical (median) **modeled concentrations from emissions from larger well pads tend to be about the same or less than those from emissions from smaller well pads (if only a single well is developed on each pad)**. Decreases in median and maximum concentration with increases in well-pad size are more apparent at receptors closer to the well pad (within the first 500 ft or so). As you go out farther in distance from the well pad, the impact on concentrations from changes in well-pad size typically becomes smaller. When emission rates are held constant, increasing the size of the emission source (the size of the well pad) leads to more initial diffusion of the emissions, creating lower air concentrations at the well pad and, in turn, at most of the nearby receptors. That initial diffusion has less impact at farther receptors, where atmospheric dispersion has further diffused the emissions.



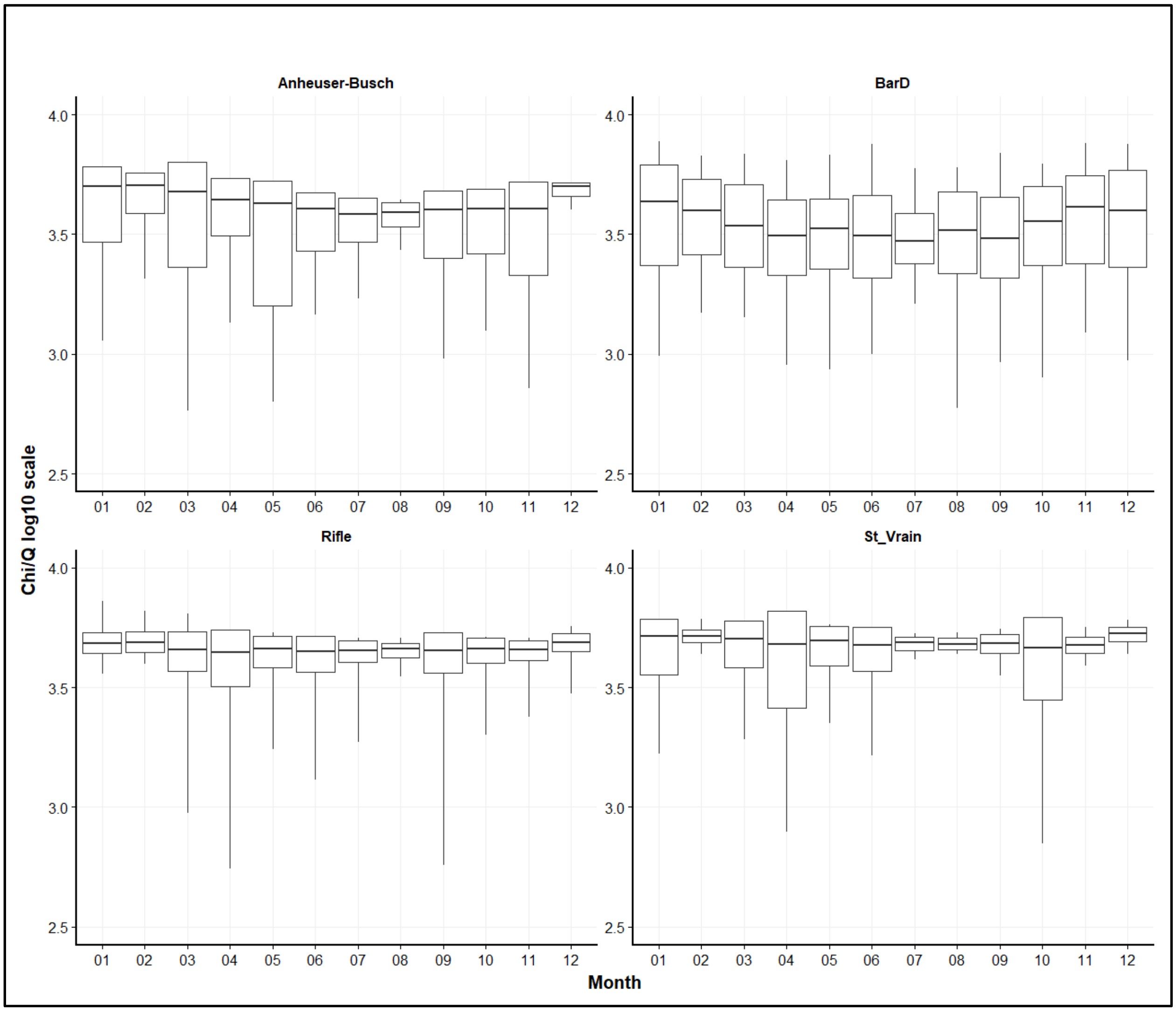
Notes: Values have been transformed via logarithm base 10. Each box-whisker plot indicates maximum and minimum (top and bottom whiskers), mean ± 1 standard deviation (top and bottom of box), and median (bar inside box).

AB_ST = the Northern Front Range Anheuser-Busch/Ft. St. Vrain sites; BarD and Rifle = the Garfield County ridge-top and valley sites; VOC = volatile organic compound; ug m^{-3} = micrograms per cubic meter; log10 = logarithm base 10; ft = feet.

Figure 2-24. Maximum Benzene Concentrations by Distance and Well-pad Size, Across All Development Activity Types

2.9.2. Well Production

For O&G production, the air-dispersion assessment only produced unit-emission air concentrations, since the variation in the emission source strength is handled within the subsequent exposure assessment where longer-term averages are of greater interest. Figure 2-25 shows the monthly trend for daily-maximum 1-hour-average unit-emission air concentrations, which suggests **some seasonal variation** in unit-emission concentrations for BarD and Anheuser-Busch, possibly due to lower wind speeds during the winter months. All locations except BarD tend show the **largest variability during transitional months** (spring and fall) for unit-emission air concentrations. Table 2-11 presents the annual-average unit-emission concentrations for the four meteorological locations. For each site, we pass to the exposure assessment the full time series of 1-hour-average unit-emission concentrations for the "worst-case" year—the year with the highest annual average. The Anheuser-Busch and Ft. St. Vrain meteorological data sets were only one year each, so we passed both of those years of data to the exposure assessment, and the exposure modeling will evaluate both sets in combination as a merged exposure scenario (as discussed in a Section 3.3.1).



Notes: Values have been transformed via logarithm base 10. Each box-whisker plot indicates maximum and minimum (top and bottom whiskers), mean ± 1 standard deviation (top and bottom of box), and median (bar inside box).

St_Vrain = the Northern Front Range Ft. St. Vrain site; Anheuser-Busch = the Northern Front Range Anheuser-Busch site; BarD and Rifle = the Garfield County ridge-top and valley sites; Chi/Q = concentration per unit emission; log10 = logarithm base 10.

Figure 2-25. Distribution of Daily-maximum 1-hour-average Unit-emission Concentration by Month and Meteorological Location

Table 2-11. Maximum Annual-average Unit-emission Concentration by Meteorological Location

Broad Oil and Gas Area	Name of Meteorological Station	Year	Annual-average Unit-emission Air Concentration (µg/m^3)
Garfield County	Rifle	2005	4,415
		2006	4,607
		2007	4,612
		2008	**4,703**
		2009	4,539
	BarD	2002	3,535
		2004	**3,675**
Northern Front Range	Ft. St. Vrain	**2009**	**4,802**
	Anheuser-Busch	**1988**	**3,868**

Notes: Bolded years are the ones whose data were passed to the exposure assessment.
µg/m^3 = micrograms per cubic meter.

2.9.3. Comparison to Monitored Values

The modeled air concentrations from these HHRAs cannot be properly compared to the observed, monitored concentrations in the CSU field experiments. We did not design the HHRA modeling to reproduce the conditions during the experiments. Though the emissions used in these HHRAs are based on those CSU experiments, there are several key differences between the experiments and the HHRA modeling that prevent meaningful monitor-to-model comparison. We list these differences below.

1. The observed concentrations in the CSU experiments correspond to 3-minute averages.

2. The modeled concentrations in the HHRA correspond to 1-hour averages, based on a conversion of 3-minute-average emissions to 1-hour-average emissions.

3. The concentrations are highly variable: while any 3-minute measured value may be representative of the 1-hour average at that time, it may also be representative of a peak or minimum concentration relative to the 1-hour average.

4. The meteorological conditions during the CSU experiments were from specific times in the 2013–2016 time frame, and they were specific to the locations of the monitored O&G sites.

5. The meteorological conditions used in the HHRA correspond to thousands of hours from various years up until 2010, and they are specific to the Rifle, BarD, Anheuser-Busch, and Ft. St. Vrain station sites.

6. Air concentrations are highly sensitive to meteorological conditions, which can fluctuate on a minute-by-minute basis, and which can be quite different just miles apart.

7. The measurement distances relative to the tracer-gas release in the CSU experiments were variable between tens to hundreds of meters, with a median distance near 100 m or so (340 ft or so).

8. The modeled distances relative to the centers of the well pads in the HHRA were fixed at several distances from 300 to 2,000 ft (also including 150 and 250 ft for production activities).

9. Air concentrations, whether measured or modeled, can be quite sensitive on the scale of tens of meters when the source of emissions is nearby.

10. The monitored values were observed generally within the emission plume, near the centerline when possible, where concentrations are largest.

11. The modeled values in the HHRA that were saved and passed to the exposure and risk assessments were not necessarily within the plume or near the plume centerline. We predetermined the receptor (location) at each distance where we saved summary air-concentration statistics from each AERMOD Monte Carlo iteration. Those statistics were means, maxima, medians, and various higher percentiles of the hourly concentrations during each iteration. During a given iteration, the maximum 1-hour-average modeled air concentration may have been from a location near the plume centerline (from when the winds were blowing directly toward that receptor), but it may also have been far outside the centerline (from when winds were blowing in a different direction).

In their reports (CSU, 2016a, 2016b), CSU conducted AERMOD modeling utilizing the acetylene tracer-gas emission rates that they derived from the monitored values and also utilizing on-site meteorology (observed during the times of their monitoring) where possible. They observed that more than 90 percent of the modeled values were within one order of magnitude of their corresponding observed values. They note, as we note above, that air concentrations are very sensitive to location relative to the centerline of the plume, the temporal representation of the emissions, and meteorological fluctuations.

2.9.4. Results Passed to the Exposure Assessment

As shown in Table 2-12, for each O&G development activity, we pass to the exposure assessment various air-concentration metrics (means, medians, and percentiles of the 1-hour-average concentrations) from each Monte Carlo iteration, for all VOCs and locations, at the selected maximum receptor on each distance ring. For the production stage, we pass to the exposure assessment a full year of 1-hour-average unit-emission concentrations, for the year with the maximum annual-average concentration, for all sites and at the selected maximum receptor on each distance ring.

Table 2-12. Results Passed to the Exposure Assessment

Variable	Development Stage	Production Stage
Locations	3 (Anheuser-Busch and Ft. St. Vrain are merged; BarD; Rifle)	4 locations (Anheuser-Busch and Ft. St. Vrain are treated separately and merged later in the exposure assessment; BarD; Rifle)
Well-pad sizes	3 sizes (1, 3, and 5 acres)	1 size (1 acre)
Data type	Metrics of 1-hour-average concentrations, for each chemical and each Monte Carlo iteration	1-hour-average unit-emission concentrations
Durations	Data from each Monte Carlo iteration represent a randomly selected activity duration	One year of 1-hour-average concentrations
Metrics	6: maximum, 99.5th, 99th, & 95th percentiles, median, and mean	1-hour-average values
Number of receptors per distance ring	14 rings with one receptor per ring, selected based on highest mean-maximum hourly concentration across all iterations. Selection made independently for each chemical, activity, and location.	16 rings (the same 14 as development, plus 2 closer in) with one receptor per ring based on the highest annual-average concentration. Selection made independently for each site.

2.10. Characterization of Data Gaps, Uncertainties, Variabilities, and Sensitivities

In this section, we qualitatively discuss known gaps, uncertainties, and variabilities in the air-dispersion input data (Section 2.10.1), which include

- data gaps in meteorology data,
- model uncertainty with respect to wind-speed measurements flagged as calm,
- uncertainty in the modeling approach with respect to the selected meteorological data sets' representativeness of Garfield County and the NFR,
- uncertainty in the modeling approach with respect to representativeness of local terrain relative to the larger regions,
- uncertainties related to the instruments used to sample and analyze the air concentrations and the methods used to derive emission rates from those samples, and
- the high variability in the emissions data and those data's representativeness of other sites and times that were not sampled.

We also discuss specific checks we conducted primarily on the model inputs but also on a summary of the model outputs to ensure that we were correctly using the data and the model (Section 2.10.2). We also qualitatively discuss uncertainties in our dispersion-modeling approach (Section 2.10.3), with a focus on a known bias in AERMOD as well as on our selections of source configuration. Additionally, we conducted some brief analyses to evaluate the sensitivity of the estimated air concentration results to some inputs/assumptions in the APEX modeling, as we discuss in detail in Section 2.10.4.

2.10.1. Gaps, Uncertainties, and Variabilities in Data

2.10.1.1. Meteorology Data

Meteorological data used for dispersion modeling often have some hours where key parameters are missing. During these times, AERMOD will not calculate any dispersion and will not output any air concentrations (or the concentrations will be 0). We first ensured that the frequency of hours with **missing key data or calm winds** ("bad hours") was small—5 percent or less of the selected meteorology data were "bad hours." We did not use any of these hours in the Monte Carlo iterations as AERMOD is unable to determine concentrations.

The BarD and Ft. St. Vrain meteorological data sets had relatively few hours with no wind speed data or missing key data. The Anheuser-Busch data set had a series of entire days of "bad hours" in parts of July and August, which may mean that summertime dispersion characteristics at this site are not as well represented in the air-concentration data passed to the exposure assessment as compared to other seasons, more so for the longer-duration flowback activities than the shorter drilling and fracking activities (though most days in June, late July, and late August are free of "bad hours"). The frequency of "bad hours" diminished at Rifle from 2005 to 2010, but we discarded some of the Monte Carlo iterations that took place in 2005 because about half the days in 2005 contained at least one "bad hour." Many of the "bad hours" at Rifle in 2005 were due to calm winds reported by the station during hours when one-minute wind data were not available; without those high-frequency wind reports, we must rely on the hour-averaged wind data reported by the station, where hourly wind speeds below about 1.5 m/s are flagged as calm. The number of hours when one-minute data were not available at Rifle generally diminished over time, leading to reduced instances of calm winds in later years. The other meteorological data sets (BarD, Ft. St. Vrain, and Anheuser-Busch) were private-industry data sets that did not use the same calm cutoff and had relatively few reports of calm winds.

Terrain, vegetative and hydrological features, and man-made features can all affect dispersion processes and, therefore, mixing of air contaminants across relatively short distances. No set of meteorological data from one site will completely match conditions at another site, but we worked with CDPHE to identify several sites with meteorological data that, taken together, reflect some of the **variability in weather conditions across Garfield County and across the NFR**. Terrain (and hydrological features) varied between these selected sites, and so the terrain elevations used for these sites in the HHRA dispersion modeling reflected some of the terrain variability across Garfield County and the NFR. (However, elevation changes were generally less than 30 m across the 2,000-ft domain radii used in these HHRAs).

2.10.1.2. Emission Rate Data

The CSU data on O&G emissions technically only reflect the O&G sites they visited and the specific activities going on during the sample collection periods. We must **assume that the collected data are generally representative of O&G sites and operations in Garfield County and the NFR**, and, as discussed in Section 2.3, that assumption is supported by CSU's consultation with industry and state partners to select representative sites as well as CSU's efforts to collect data at a variety of times. Still, CSU did not and could not capture all possible sites, operators, and on-site hour-by-hour or minute-by-minute activities that can affect emission rates, and so uncertainty remains about the full distribution of O&G emissions data in these areas of Colorado. CSU also did not sample emissions from drilling activities at the NFR or production activities in Garfield County, and so **we must assume that drilling emissions from Garfield County are representative of drilling emissions in the NFR, and that production emissions from the NFR are representative of production emissions in Garfield County**. While this is a reasonable assumption for this analysis and based on the best data available, we acknowledge that different practices for drilling may result in different VOC emissions (e.g., use of bentonite clay versus petroleum-based drilling lubricant), and different formations and O&G composition may yield varying emissions of VOCs between production sites (e.g., wet gas versus dry gas). This adds uncertainty to our analysis, but can be addressed by future measurements of emission rates of VOCs from drilling from the NFR and production from Garfield County.

As discussed in Section 2.3, the **non-continuous nature of CSU's air sampling** leads to uncertainties about how O&G emission rates vary hour-by-hour or within the hour. However, CSU collected samples across several sites and seasons, and at some sites they collected several samples in a day or within an hour. From these non-continuous samples, it is clear that **O&G emissions are highly variable**. This variability existed across different VOCs and across the different sites where CSU conducted the experiments, and it also existed across different samples taken at the same site. We did not explicitly treat any of these emission rates as outliers or unacceptable data, though our derivation of 1-hour-average emission rates (see Section 2.3.1) resulted in a smaller variance in the rates used in the modeling. As we will discuss in subsequent reports for these HHRAs, acute exposure calculations use the higher (peak) air concentrations and are not particularly affected by the high variability in emission rates, while chronic exposure calculations tend to reflect the mean of the emission rates and in that sense are also not particularly affected by the emission variability. Uncertainties in the representativeness of these emissions data could be reduced in the future with continuous air monitoring for key VOC's at a variety of O&G sites.

CSU conducted several controlled-release experiments prior to the Garfield County and NFR measurements, where acetylene and methane were collocated and released at known emission rates to calculate **TRM uncertainties**. Wells (2015) provides a detailed description of these experiments. The TRM uncertainty in the controlled-release experiments was characterized to have an accuracy (mean bias) of +22.6 percent and a precision (relative standard deviation) of ±16.7 percent. CSU used replicate canisters, collected during the studies, to evaluate the precision of TRM for individual VOC emission rates. Precision (pooled relative standard deviation) varied between approximately 1 and 55 percent for individual VOCs, with most values less than 20 percent. The uncertainties of the TRM were much lower than the variabilities in emission rates observed.

CSU analyzed VOCs following procedures similar to EPA's TO-12 method. They cryogenically pre-concentrated the canister sample analytes before being directed to GC-FID systems. They calibrated the system using dilutions of a 1 parts per million Linde Gas certified high pressure standard. They analyzed six clean canisters, filled with ultra-high purity nitrogen, to calculate the **limit of detection** (LOD) of the system. The results of calibration tests and LODs for the all GC-FID systems used as part of the Garfield County and NFR projects were reported by CSU (CSU, 2016a, 2016b). In some instances, concentrations were below the calculated LODs, in which case the measured value was replaced with half the LOD value (LOD/2) for the corresponding VOC. In most cases, this resulted in zero emission rates when the background concentration of VOC was subtracted from the LOD/2 value. About 80 percent of the VOCs collected had values above the LOD. The exceptions to this were for four VOCs: isoprene, 1-

pentene, 1-butene, and trans-2-butene. In Garfield County, isoprene, 1-pentene, 1-butene, and trans-2-butene had 75, 82, 60, and 80 percent of the values below LOD, respectively. For the NFR, isoprene, 1-pentene, 1-butene, and trans-2-butene were below LOD 92, 90, 93, and 53 percent of the time, respectively. Our estimates of hazards and risks (see Section 5) indicated that exposures to these four chemicals, based on the emissions derived from these canister measurements, were always far below health-based criteria, indicating little potential for adverse health effects from these exposures.

2.10.2.Quality Control of Model Inputs, Quality Assurance of Outputs

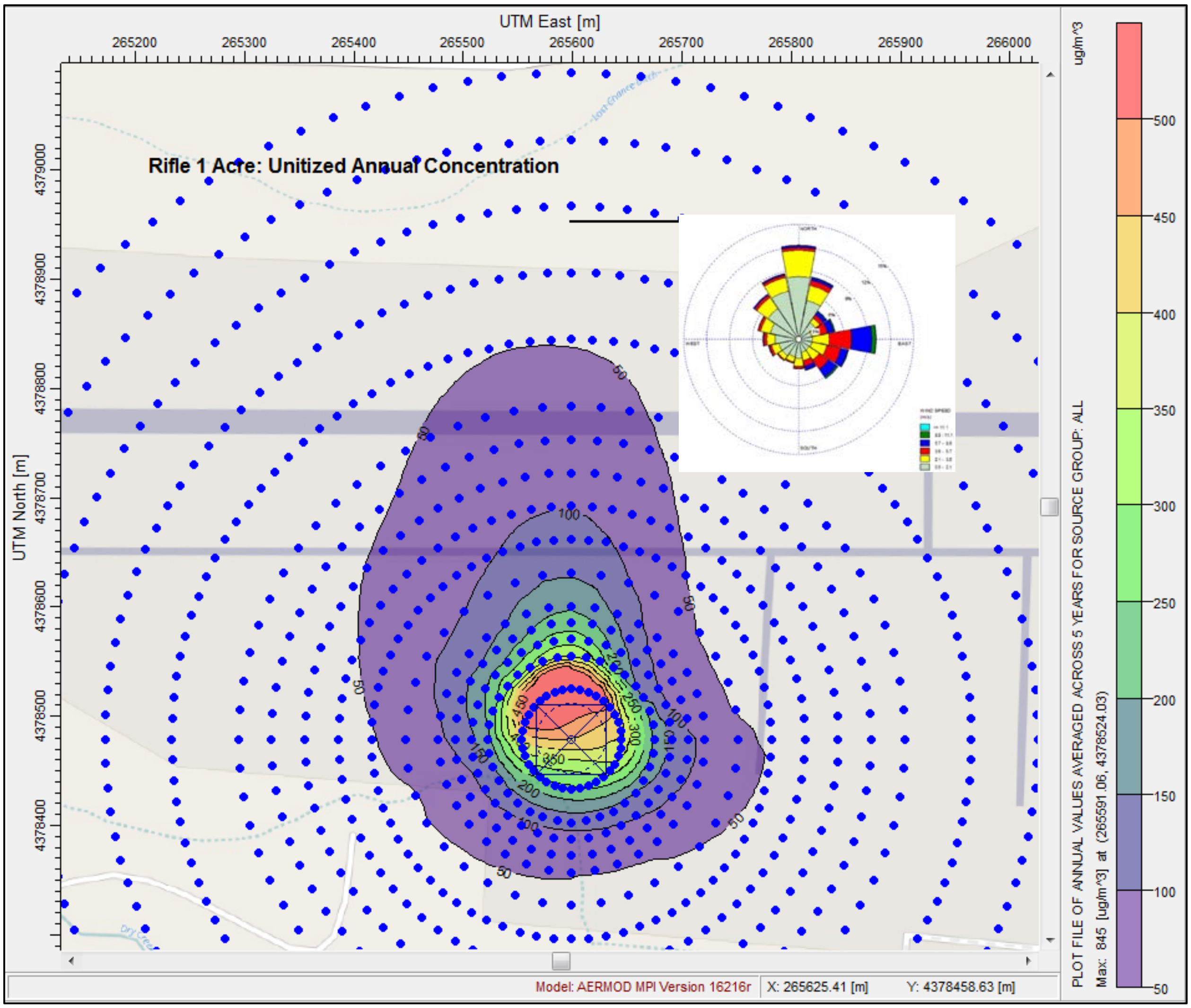
To assure the integrity of the modeling results, we conducted a number of quality checks to confirm that the data used as input to AERMOD were of highest quality and properly prepared for the model. We briefly discuss those checks here and indicate if changes were needed as a result.

As discussed in Section 2.5.3, three of the meteorological sites had 9–10 percent of the hours with **wind speeds less than 1.0 m/s**—these are the periods which will likely yield the highest air concentrations. The fourth site (BarD) showed a much lower frequency of these lower wind speeds, which is consistent with what might be expected for the more exposed ridgetop site for BarD. This check required no changes to the methodology.

We checked **ranges in the meteorological variables against historical ranges**. We found that the Anheuser-Busch temperature data were biased high, with the lowest temperature for the year at just -12 °C (10 °F). This prompted a more thorough review of the raw data set used in the AERMET processing, where we discovered that the raw measurements were in degrees Fahrenheit (not Celsius as expected) and the wind speeds were in miles per hour (not m/s as expected), and these data were being improperly converted as a result. CDPHE reprocessed the data in AERMET with the correct units, producing a new AERMOD-ready meteorological data set for the modeling.

While the emission rates are highly variable, we conducted a simple quality check by examining the **variability between the largest and smallest measurement across all VOCs** to identify if any extreme outliers may be present. This assumes the inherent variability in the emissions data is limited to within same range across all VOCs. We used the original 3-minute-average rates calculated by CSU. The review showed that the range in emissions typically spanned about three orders of magnitude. Drilling, fracking, and flowback had maximum spans of 4.8, 5.3, and 5.2 orders of magnitude, respectively. Production the highest maximum span at 6.5 orders of magnitude, which was expected given that the production samples ranged from recently completed wells to wells more than seven years old. This check required no changes to the methodology.

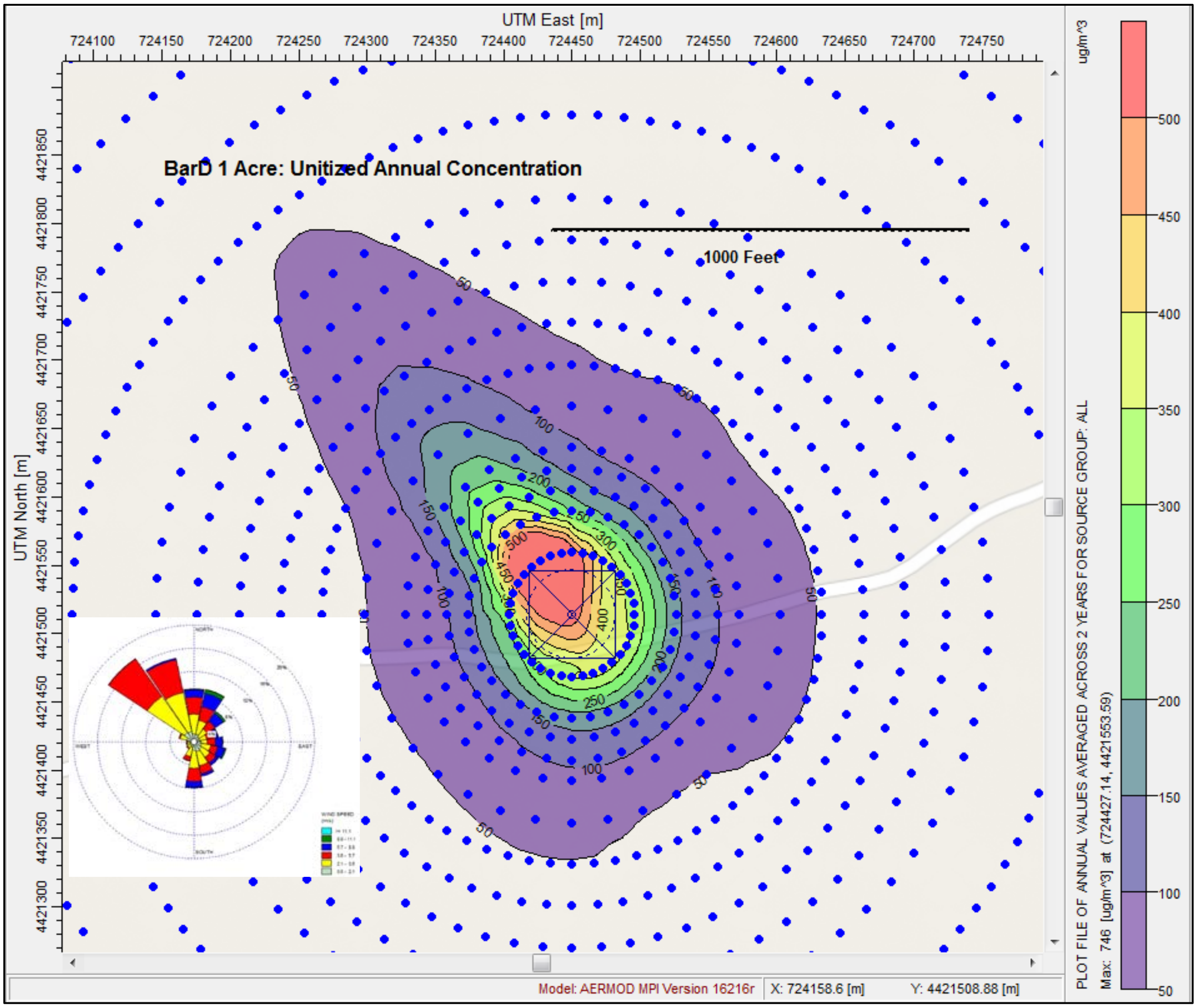
To bring additional confidence that we accurately completed the dispersion modeling, we compared the **spatial patterns of modeled annual-average concentrations** at unit emission rates with the corresponding annual wind rose plots. We show these spatial patterns of concentrations along with insets of the wind roses in Figure 2-26 (1-acre well pad at Rifle), Figure 2-27 (1-acre well pad at BarD), Figure 2-28 (1-acre well pad at Anheuser-Busch), and Figure 2-29 (1-acre well pad at Ft. St Vrain). We have reversed the inset wind roses here as compared to those in Section 2.5, so that the ones shown here indicate where winds are blowing to rather than blowing from, to more easily indicate the direction of emission transport. The wind rose and the concentration plot should show similar patterns, although if a particular direction has considerably higher wind speeds than another then the higher-wind-speed direction should have lower concentrations, owing to the inverse relationship between wind speed and concentration. At Rifle, this explains why concentration contours to the east are not as elongated as those to the north, but overall the wind-flow pattern and concentration pattern show good agreement. There is good agreement also at BarD, with the concentration contours and the wind rose both having a prevailing northwestern direction. Similarly, the Anheuser-Busch concentration contours and wind rose show the prevailing flow to the south, and the Ft. St. Vrain plots show strong agreement with a narrow elongation to the northeast and a broad area of elongation to the southwest. This check required no changes to the methodology.



Notes: Wind rose made using WRPLOT View, by Lakes Environmental Software. Wind rose shows winds as "blowing toward". Concentration values inside of 150 feet from the center are not representative of the concentration, as the closest receptor to the source begins at 150 feet.

UTM = Universal Transverse Mercator; m = meters; ug/m^3 = micrograms per cubic meter; m/s = meters per second.

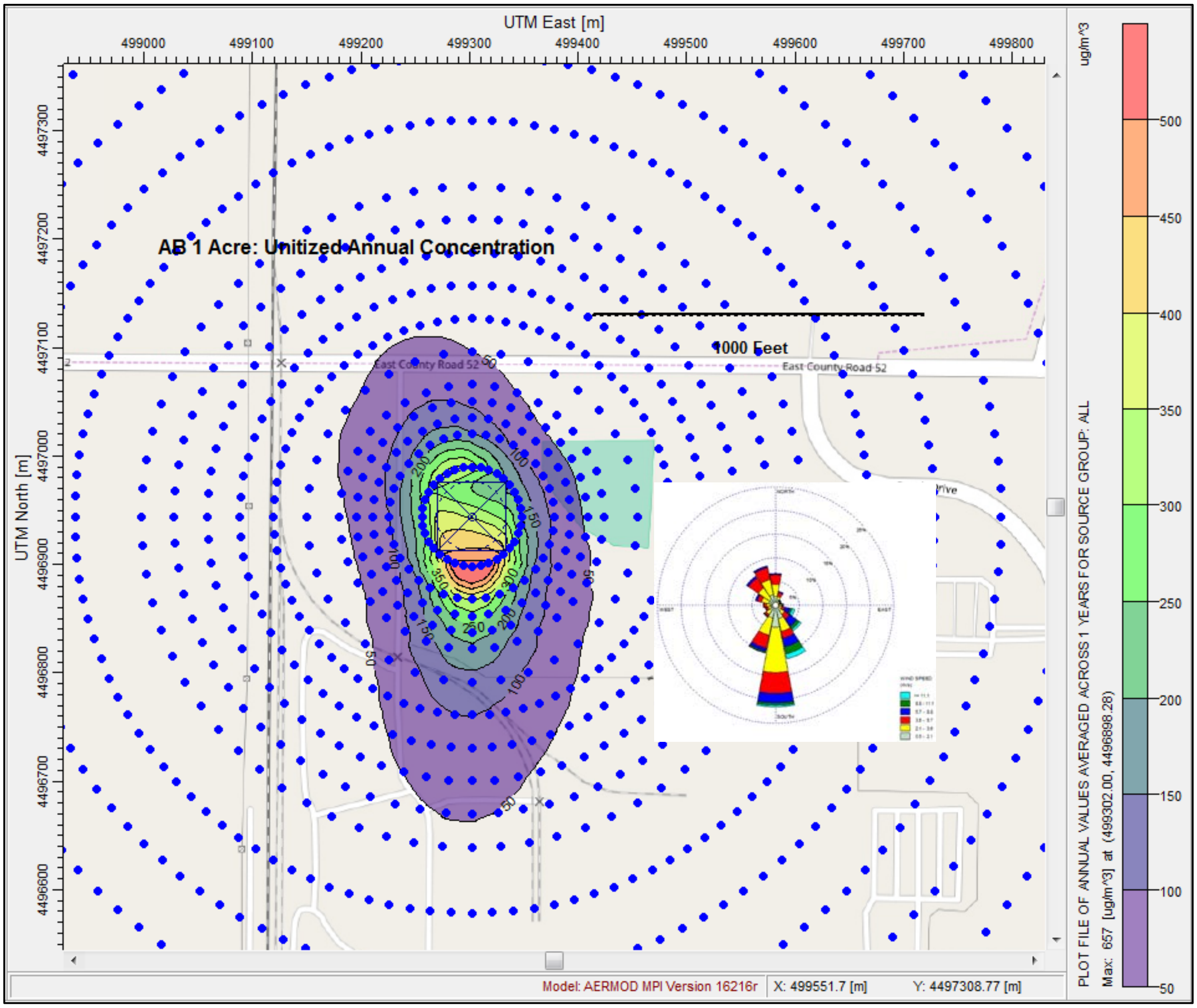
Figure 2-26. Rifle (Garfield County Valley Site) Annual-average Unit-emission Air Concentrations for 1-acre Well Pad, With Annual-average Wind Rose Insert



Notes: Wind rose made using WRPLOT View, by Lakes Environmental Software. Wind rose shows winds as "blowing toward". Concentration values inside of 150 feet from the center are not representative of the concentration, as the closest receptor to the source begins at 150 feet.

UTM = Universal Transverse Mercator; m = meters; ug/m^3 = micrograms per cubic meter; m/s = meters per second.

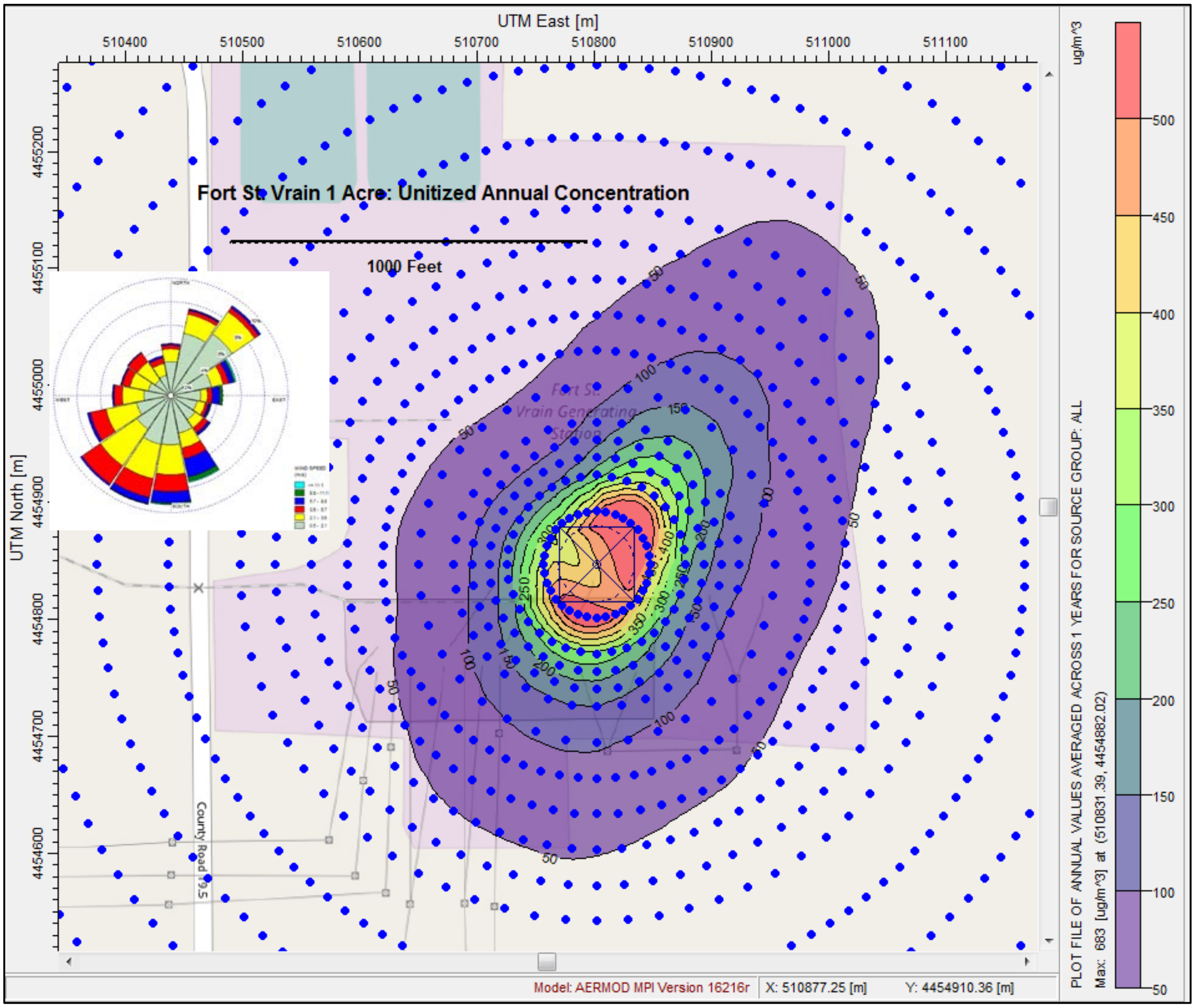
Figure 2-27. BarD (Garfield County Ridge-top Site) Annual-average Unit-emission Air Concentrations for 1-acre Well Pad, With Annual-average Wind Rose Insert



Notes: Wind rose made using WRPLOT View, by Lakes Environmental Software. Wind rose shows winds as "blowing toward". Concentration values inside of 150 feet from the center are not representative of the concentration, as the closest receptor to the source begins at 150 feet.

UTM = Universal Transverse Mercator; m = meters; ug/m^3 = micrograms per cubic meter; m/s = meters per second.

Figure 2-28. Anheuser-Busch (a Northern Front Range Site) Annual-average Unit-emission Air Concentrations for 1-acre Well Pad, With Annual-average Wind Rose Insert



Notes: Wind rose made using WRPLOT View, by Lakes Environmental Software. Wind rose shows winds as "blowing toward". Concentration values inside of 150 feet from the center are not representative of the concentration, as the closest receptor to the source begins at 150 feet.

UTM = Universal Transverse Mercator; m = meters; ug/m^3 = micrograms per cubic meter; m/s = meters per second.

Figure 2-29. Ft. St. Vrain (a Northern Front Range Site) Annual-average Unit-emission Air Concentrations for 1-acre Well Pad, With Annual-average Wind Rose Insert

2.10.3. Uncertainties and Variabilities in Modeling Approach

Uncertainties inherent in the AERMOD model should generally be smaller than the uncertainties in the model input data pertaining to emissions and meteorology. Like many models, AERMOD will usually be most accurate over longer averaging periods and across larger areas, compared to short averaging periods and specific point locations.

Still, AERMOD has a well-known tendency to underestimate dispersion (and, therefore, overestimate concentrations) during times of low wind speeds and stable conditions. As noted in Section 2.1, the number of model validation studies of AERMOD for near-ground-level sources is very limited. It is likely the AERMOD will have a tendency to overestimate given the difficulties of parameterizing low wind speed conditions in a Gaussian-formulated model. Additional low-wind-speed data sets are available (e.g., Sagendorf and Dickson, 1974; Wilson et al., 1976). EPA developed the **ADJ_U*** option in AERMOD to help adjust surface friction velocities (which is the u* parameter) to reduce these low-wind biases. This is a default feature of AERMOD when the meteorological data do not contain information on turbulence and vertical profiles of temperature. Except for the BarD station, the meteorological data used in these HHRAs do not have such information, so we utilized this ADJ_U* feature for the processing of Rifle, Ft. St. Vrain, and Anheuser-Busch meteorological data in these HHRAs. AERMOD contains several other features for adjustments to the model during low-wind conditions, but we elected to not use them due to their non-default (beta) status and due to uncertainties with their effects on modeled air concentrations without monitored air concentrations to compare against.

We also vary the **sizes of well pads** in the modeling, in an effort to reflect that **O&G site configurations** are highly variable depending on the type of drilling, the site operator, the stage of operations, the number of wells, etc. The precise locations where emissions originate on the well pad are equally variable. So as to not bias the air modeling toward one configuration or another, we assumed that emissions from the well pad come equally from all parts of the pad. At any given time at any real O&G site, emissions may come from only one corner of the pad, putting those emissions closer to anyone living or recreating near that corner (and farther away from people living/recreating near the opposite corner); our modeling will not capture those kinds of scenarios, which leads to some uncertainties in the subsequent exposure and risk assessments, especially for acute exposures. Instead, in our modeling, emissions from places on the well pad become immediately diffused across the modeled size of the well pad, and then the meteorology helps disperse that emission plume away from the pad. The size of the pad affects that initial plume diffusion—emissions from a larger pad are diffused across a larger area before being dispersed by meteorology. For simplicity, we modeled three sizes of well pad for development activities, determined by CDPHE to reasonably represent many current O&G sites in the state based on professional judgment and recent permits submitted to COGCC. However, some O&G sites will have smaller or larger layouts than what we have modeled, leading to reduced or enhanced initial diffusion of emissions, leading to different spatial patterns of air concentrations and exposure.

2.10.4.Sensitivity Analyses

Air dispersion models require many different elements in order to estimate ambient air concentrations. Here we describe qualitatively, and in some cases quantitatively, the sensitivity of AERMOD modeled concentrations to the elements listed below.

1. emissions
2. wind speed
3. surface roughness length
4. urbanization
5. seasonality
6. recirculation and terrain

Among these elements, **modeled air concentrations are probably most sensitive to inputs of emissions and wind speed. However, in these HHRAs the emissions and meteorology are considered "given"** in that they corresponded to site measurements. **Among the other elements, surface roughness length is perhaps the most influential**, indicating that air concentrations could be substantially lower for O&G activities in heavily forested areas, although we make no judgments about the likelihood of O&G activities in such areas. Urbanization also can substantially affect acute exposures, but chronic exposures are much less affected. Though air concentrations can vary by season, we already capture those variations in our HHRA methodology. We include reasonable terrain variations across about a 2,000-ft radius around a well pad, though more dramatic terrain features could have additional impacts not modeled here. Recirculation effects should be relatively minor. In the below subsections, we discuss these elements in more detail.

2.10.4.1. Emissions

One of the most important inputs to the dispersion model is specification of the emission source strength. **Air concentrations estimated by AERMOD are directly and proportionally sensitive to inputs of emission rate**. If emissions are doubled then the modeled concentrations are similarly doubled, and if emissions are reduced by half the concentrations are reduced by half. Across different samples and locations, CSU observed a wide range of 3-minute-average emission values for a given chemical (CSU, 2016a, 2016b), sometimes much more than one order of magnitude. For example, as discussed in Section 2.3, benzene emissions during drilling had a range of about 4.7 orders of magnitude (5th and 95th percentiles over 2.5 orders of magnitude apart), while toluene during Garfield County fracking had a range around 2.1 orders of magnitude (5th and 95th percentiles over 1.8 orders of magnitude apart), and isoprene during NFR flowback had a range around 1.9 orders of magnitude (5th and 95th percentiles 1.8 orders of magnitude apart). These emissions data were a "given" in these HHRAs, rather than a choice to be made in terms of assessment assumptions or model settings.

Regarding our derivations of 1-hour-average emission rates from the 3-minute-average samples, which we discuss in Section 2.3.1, we made the reasonable assumptions that emission rates are log-normally distributed and that 1-hour rates would have smaller ranges than 3-minute rates. For example, the ranges of rates for benzene during drilling, toluene during fracking in Garfield County, and isoprene during NFR flowback dropped to 1.5, 0.5, and 0.6 orders of magnitude, respectively, with the 1-hour-average rates relative to the 3-minute-average rates. These are the emission rates we used in the HHRA modeling, and these wide ranges in emission values lead to wide ranges in corresponding estimates of chemical air concentrations. Due to the small sample sizes of the 3-minute observations, the resulting means of the 1-hour distributions were sometimes noticeably different (by more than about 10 percent) than those of the 3-minute distributions. This should have the effect in these cases of proportionally changing the longer-term average air concentrations (by more than 10 percent) when utilizing 1-hour values instead of 3-minute values. Our modeling also does not capture the scenario of the highest 3-minute rates being sustained for an entire hour, nor does it capture the scenario of the lowest 3-minute rates being sustained; these scenarios would lead to higher peak acute exposures and lower minimum acute exposures, but we have no confidence in the probability of these scenarios.

2.10.4.2. Wind Speed

AERMOD modeled air concentrations are also particularly sensitive to inputs of wind speed, and as with emissions the relationship is simple: because AERMOD is a Gaussian-formulated dispersion model, the **concentration is inversely proportional to the wind speed**. That is, if the wind speed is reduced by half then the concentration is doubled, and similarly if the wind speed is doubled the concentration is reduced by half. These relationships are more influential for acute estimates of exposure, whereas differences in long-term averages of wind speed would be smaller and lead to smaller differences in chronic estimates of exposure. As with emissions data, these meteorology data were a “given” in these HHRAs, and they are quality controlled, consist of many months of observed data across several sites, and were selected to reflect many real meteorological patterns across the Garfield County and NFR regions.

2.10.4.3. Land Cover

Other elements that affect the modeled concentrations, such as **surface roughness** and **urbanization**, are not simple proportional adjustments. These require running the model for a given set of conditions and then varying only one element. In BAAQMD (2004), two source types that the authors studied were somewhat similar to the source types found at O&G operations in Colorado: a diesel generator modeled as a point source, and a typical gas dispensing facility modeled as a volume source. Differences in model sensitivity between the two source types were relatively small, but the gas dispensing facility exhibited slightly higher sensitivity, which may be particularly relevant to these HHRAs given that we modeled the O&G operations as a volume source and we would expect similar model sensitivities.

In Table 2-13, we show the AERMOD sensitivities found in BAAQMD (2004) for a gas-dispensing volume source. The table shows the maximum percent changes in concentration. **In their study, changing surface roughness by four-fold had up to an 85-percent effect on modeled annual-average concentrations**, with an inverse relationship. Surface roughness values can vary by land cover, which itself can vary by season, with the lowest roughness values associated with snow cover or water bodies (around 0.2 centimeters [cm]), as compared to values of 10 cm over grasslands, 50 cm for communities of single-family homes, and 130 cm for evergreen forests. The next most sensitive element is the urban population, which is used in the modeling of urban areas, which can be defined as having a population density greater than 750 people per square kilometer. **In their study, changing the urban population by 1.75-fold had up to a 19-percent effect on the peak modeled 1-hour concentration**, with an inverse relationship. Modeled air concentrations showed very little sensitivity to changes in the other three elements they studied (albedo, air temperature, and Bowen ratio).

Table 2-13. AERMOD Sensitivity to Input Parameters from a Typical Gas-dispensing Facility

Element	Variation	Maximum Change	Averaging Period
Surface roughness	0.25 x base case	+85 %	Annual
	4 x base case	-67 %	Annual
Urban population	-75 %	+19 %	1 hour
	+75%	-7 %	1 hour
Albedo	0.25 x base case	+1 %	1 hour
	4 x base case	+6 %	24 hour
Ambient temperature	-6 °C	-1 %	1 hour
	+6 °C	+0.6 %	24 hour
Bowen ratio	0.5 x base case	+0.7 %	24 hour
	2 x base case	-0.5 %	24 hour

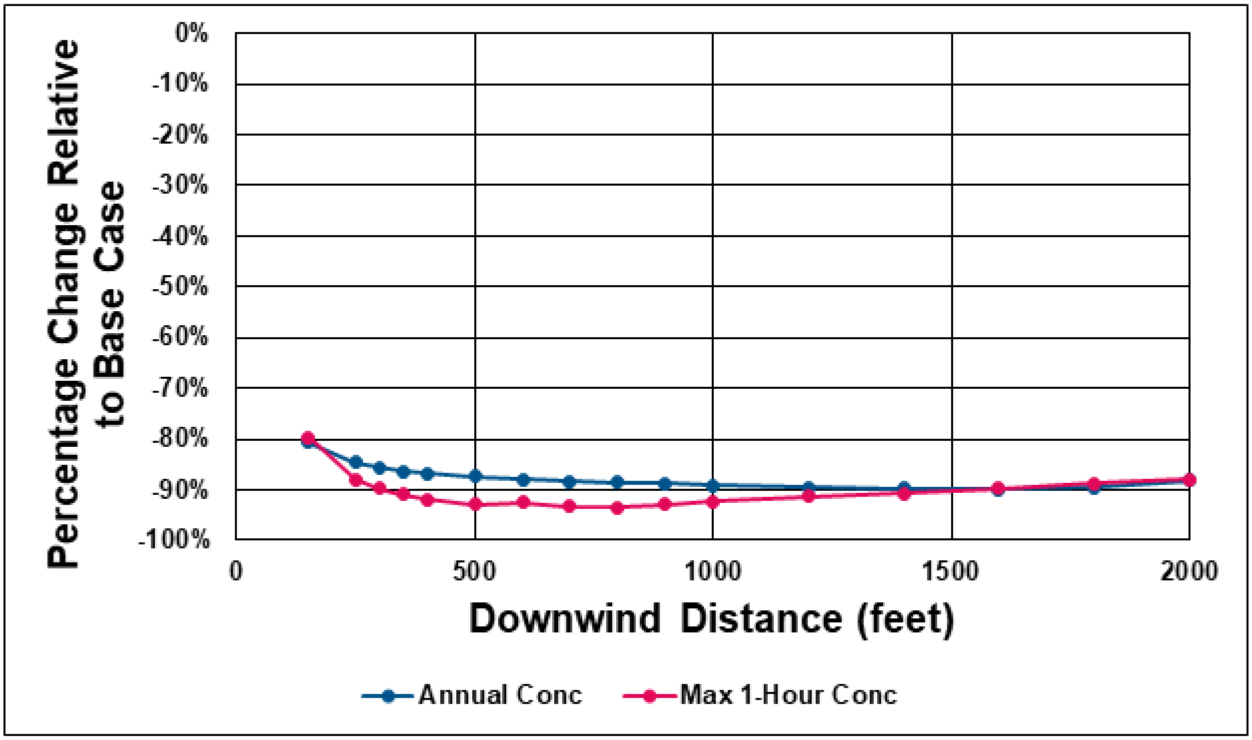
Source: Table 4 of BAAQMD (2004).
Note: °C = degrees Celsius

Because the surface roughness length exhibited such a strong sensitivity in the BAAQMD (2004) study, we conducted Colorado-specific model sensitivity runs for the Rifle site in Garfield County. In addition, BAAQMD (2004) did not evaluate the sensitivity of modeled air concentrations to whether or not the urban setting is used in AERMOD (a setting which affects estimates of pollutant mixing), so here we also conducted a site-specific analysis for the Anheuser-Busch meteorology but in an urban setting rather than the rural selection made in the HHRAs.

New Modeling of Sensitivity to Surface Roughness

In Garfield County, the site-specific surface roughness length near the Rifle site varies between 5 and 33 cm depending on season and location, with an average of 23 cm (base case). If this same site were located in forested area of evergreen trees, the surface roughness length would be 130 cm—a 5.7-fold increase. Since AERMOD's meteorological preprocessor (AERMET) uses the surface roughness length in determining atmospheric stability, it was necessary to re-run AERMET (Stage 2 and 3) to provide new meteorological input files to AERMOD. We then ran AERMOD to determine how the change in surface roughness length (a 5.7-fold increase from 23 cm to 130 cm) impacted modeled concentrations as a function of distance relative to the base case for each distance ring away from the O&G well pad for both the annual-average and the peak 1-hour concentration.

In Figure 2-30, we show the relative decrease at each receptor ring in the maximum 1-hour and maximum annual average associated with the increase surface roughness length. Both averages show similar **reductions in concentrations from increased surface roughness length, at nearly an 80-percent decrease at 150 ft followed by additional decreases, leveling off at about 90 percent by 500 ft**. The closer receptor rings show less relative decrease in concentration as the initial dispersion parameters of the volume source (the same in both simulations) are still important contributors to the near-field concentration. These are larger decreases in average concentration than were observed by BAAQMD (2004), likely due to utilizing a larger increase here in surface roughness length—about 5.7 x base case here, versus 4 x base case in BAAQMD (2004).



Notes: Conc = concentration; Max = maximum.

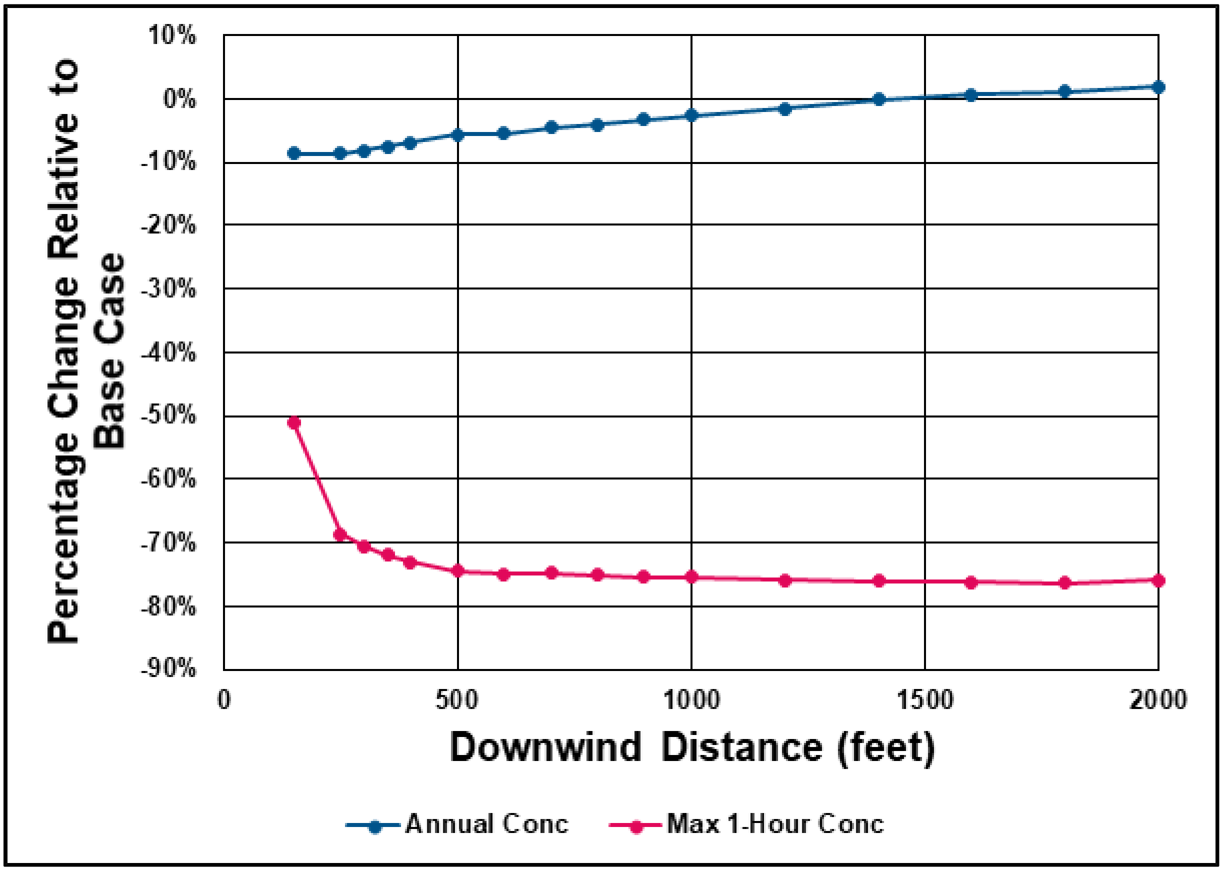
Figure 2-30. Percentage Change in Average Air Concentrations by Distance, Forested Case (Surface Roughness Length=130 centimeters) Relative to Base Case (Surface Roughness Length=23 centimeters)

New Modeling of Sensitivity to Urban versus Rural Dispersion

In all of the modeling for these HHRAs, we used the rural dispersion modeling option, as we assumed O&G development was not taking place in urbanized areas. However, the possibility exists that some O&G development may happen in fairly close proximity to a mostly urban setting. The Anheuser-Busch site, while relatively rural, is not far from the Ft. Collins metropolitan statistical area (MSA). We used this site to evaluate the impact on air concentrations utilizing the same base meteorology data but using the urban turbulent mixing dispersion coefficients that AERMOD estimates with the urban setting. To do so, we provided AERMOD with the population of the Ft. Collins MSA (about 340,000) and then ran AERMOD to identify the impact of this urban setting on annual-average and peak 1-hour concentrations by distance from the well pad.

In Figure 2-31, we show the relative increase or decrease in the maximum 1-hour and maximum annual-average concentrations for each receptor ring. **The maximum 1-hour concentration with the urban option is 50-percent lower than without the urban option at the first receptor ring (150 ft) and the difference grows to 75 percent at 500 ft** where it remains fairly constant for the remaining distances. The closer rings show less relative decrease in concentration because the initial dispersion of the O&G volume source is important in the near-field dilution. However, at 500 ft the initial dispersion becomes less important and the dilution is almost entirely due to the urban-rural dispersion parameters. **The annual average shows in the near-field that the urban setting results in slightly lower concentrations out to about**

1,400 ft, beyond which the annual concentrations are slightly higher with the urban setting than without the urban setting. This is a result of initial plume lateral and vertical mixing with the urban setting causing decreases in concentrations closer to the source, whereas this becomes less important at distances farther downwind where the urban setting causes slightly higher concentrations overall on average.



Notes: Conc = concentration; Max = maximum.

Figure 2-31. Percentage Change in Average Air Concentrations by Distance, Urbanized Case (Population=340,000) Relative to Base Case (Rural Setting)

2.10.4.4. Seasonality

Seasonal variation in the maximum short-term air concentrations could be of potential concern given changes in human activity levels and locations across seasons. Figure 2-25 shows month-by-month variation in the concentration distribution for all four meteorological sites utilized in these HHRAs. The figure shows that for Rifle and Ft. St. Vrain there is almost no seasonal variation in the average of maximum daily 1-hour concentrations. However, **both the Anheuser-Busch and BarD sites show about a 20-percent decrease in the summer (July–August) average daily-maximum 1-hour concentrations relative to the winter period**. **Our HHRA modeling captures air concentrations during all seasons.**

2.10.4.5. Recirculation and Terrain

Under stagnation conditions that occur most frequently during the fall and winter months, air may be trapped within an air basin and recirculated, leading to the accumulation of air pollutants. This meteorological phenomenon was not included in these HHRAs as AERMOD cannot simulate this type of airflow condition given its steady-state formulation. That is, every hour modeled is independent of the previous hour, so **we did not consider stagnation conditions or flow reversals in these HHRAs. Such conditions should not have a substantial impact for a single well pad as modeled in these HHRAs**—for a given well pad, the concentrations from a given hour's emissions will be larger relative to that due to recirculation from previous hours' emissions. These conditions would be far more important if we were assessing the cumulative impact of O&G well development and production across a region, as the recirculation occurs on those spatial scales.

Additionally, **we did not include sites that are strongly influenced by localized terrain affects** (e.g., slot canyons, narrow valleys, deep bowls) across the short distances utilized in these HHRAs.

3. Modeling of Inhalation Exposure

We conducted the inhalation exposure modeling using U.S. EPA's **Air Pollutants Exposure Model (APEX)**, which EPA uses primarily for inhalation exposure assessment for the criteria air pollutants (carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone, and particulate matter). APEX is not proprietary and is highly customizable, so it may be used without restriction by anyone inside or outside EPA and configured for a variety of exposure scenarios. Staff currently at ICF have been closely involved with APEX since its inception in 1999, including writing nearly all of the APEX code and conducting many of the practical applications, including customized scenarios.

APEX does not determine the outdoor (ambient) air quality. It must be given time series of ambient air quality data, most commonly at hourly time steps, for the duration of the simulation period (typically one year). APEX is a microenvironmental model in which each location with distinctive air quality is called a microenvironment (micro for short), with its own relationship to the ambient air.

We list below the main features of APEX.

- Stochastic sampling to characterize population variability
- Customizable micros
- Uses databases of human time-activity data to determine time spent in each micro
- Uses either of two methods—mass balance or linear regression—for estimating air concentrations of chemicals in each micro
- Produces detailed time series of exposure for each simulated individual

- Estimates time averages of exposure concentration

3.1. Overview of Approach

APEX is a **stochastic exposure model**[8] used by EPA since 2002 for assessments of criteria air pollutants and other airborne chemical-exposure scenarios. APEX assesses exposure by combining data on population, air quality, human activity, ambient temperature, and micros. APEX generates a set of modeled individuals, which collectively describe the population variability in exposure. Typically, each modeled individual has his/her exposure characterized hourly over the course of a year.

APEX is typically used to model specific geographical locations and the people living and working in the vicinity. For that purpose, it has default databases derived from the 2010 U.S. Census of home and work populations by census tract for the entire US. However, the current application is unusual in that it refers to the exposures of hypothetical individuals living at various distances from hypothetical O&G sites. Therefore, for these HHRAs we **customized several of the APEX input files and key parameters**, although no changes to the APEX code were required. We provide in Section 3.2 details on the inputs files, which we briefly summarize in the remainder of this section. We also provide in Section 3.1.1 a condensed list of key assumptions for the exposure modeling.

We replaced the census population data with a set of **hypothetical individuals whose houses are located at directions where our dispersion modeling estimated higher average air concentrations (and, therefore, higher average exposures) relative to other directions, indicating they are directly downwind from the hypothetical O&G sites relatively frequently**. For O&G development activities, these locations correspond to the direction with the largest mean-maximum 1-hour-average air concentrations at each modeled distance from the well pad, as modeled in the dispersion assessment (see Section 2.7.3). For O&G production activities, these locations correspond to the direction with the largest annual-average air concentration modeled with unit emissions at each distance from the well pad (see Section 2.8). These locations can change by modeled site, O&G activity, and, for development activities, emitted VOC. In our modeling for these HHRAs, APEX uses **stochastic sampling from U.S. data sets to assign physiological characteristics to the hypothetical individuals** living at these locations.

We customized the human activity data by selecting **activity diaries for adults surveyed from the Mountain West region of the US** (due to data limitations, for youth and older adults we selected activity diaries from the full U.S. survey data set). We selected three micros where these activities take place (**indoors, outdoors, and in-vehicle**), and, with no modeled indoor sources of pollution, the estimated VOC air concentrations in these micros are directly related to the outdoor ambient air at all times. We also do not include background pollution sources—the goal was to estimate population-level exposures to VOCs emitted by the O&G activities currently being evaluated.

[8] APEX is a stochastic (probabilistic) model because it samples from probability distributions for a variety of model inputs. Sampling from these distributions—for inputs such as the physiological and demographic characteristics of the simulated individuals and the manner in which outdoor air penetrates into buildings and vehicles—creates a variety of potential exposure scenarios across the simulated population and environments.

We utilized unit air concentrations (1 µg/m^3) for the APEX runs, and then we utilized custom post-processing algorithms to tailor the air quality (and, ultimately, the exposure) to the VOC air concentrations output from the dispersion assessment for each O&G site, O&G activity, distance from the well pad, and VOC. This tailoring in post-processing is possible because **the O&G activities modeled in the dispersion assessment are assumed to be the only sources of the modeled VOCs included in these HHRAs**, therefore making the APEX-modeled exposures directly proportional to the modeled air concentrations (a 50-percent increase in outdoor ambient air concentration causes a 50-percent increase in modeled exposure on that hour).

The result of the APEX modeling is an hourly time series (for one year) of exposure concentrations for each hypothetical individual exposed to 1 µg/m^3 of a generic airborne chemical. These output exposure concentrations can be interpreted as the hourly exposure concentration per unit air concentration. **Exposure concentrations are time-averaged air concentrations that the hypothetical individual experiences. They take into account time spent in various micros across a period of time (as dictated by stochastic sampling of activity diaries) and the estimated air concentrations in those micros (as estimated through stochastic sampling of penetration factors [PENs] of outdoor air moving into the micros)**.

Though most development activities on a well pad will last less than one year, we ran APEX for one year so that we could **generate many different hypothetical one-hour and multi-day exposure scenarios** that we could sample from across the year. A one-year model run allowed us to capture any seasonal differences in the activities individuals undertake in their daily lives, and through randomized sampling of many modeled air concentrations it also allowed us to generate many possible short- and longer-term sequences of air concentrations.

Because of the stochastic sampling involved in an APEX run, enough hypothetical individuals must be included to ensure convergence in the results (i.e., that the variability in modeled exposures across those individuals reasonably reflects the variability expected across a larger population). While about 500 individuals appeared to be sufficient based on our convergence testing, we have chosen to run **1,000 hypothetical individuals per age group** in each APEX run, which ensures convergence with a cushion to account for unique scenarios with higher variability (see Section 3.4.3 for details). We defined **broad age groups for youth (ages 0–17 years), adults (ages 18–59 years), and older adults (ages 60 years and above)**. With 8,760 hours per year[9], this results in 8.76 million hourly exposure values per age group per APEX run, which we post-process to obtain VOC- and location-specific exposures.

The post-processing initially creates **estimates of hourly exposures to each of 47 VOCs emitted by each modeled O&G activity from each hypothetical O&G site, for thousands of hypothetical individuals located across many distances from the sites**. This produces terabytes of data which must be summarized more succinctly to be manageable in a risk assessment. We condensed the hourly exposure data into daily averages and daily maxima for each hypothetical individual, and we utilized these distributions of daily exposures to estimate risks, as described in Sections 4 and 5.

[9] Throughout this report, we may refer to 365 days or 8,760 hours in a year. Correspondingly, we may also refer to how many days or hours we have across 1,000 modeled individuals (equaling 365,000 days or 8.76 million hours). In some cases, a leap year is also possible, but for simplicity of discussion in this report we refer to counts of days and hours for non-leap years.

3.1.1. Key Modeling Settings and Assumptions

In this section, we present a condensed list of the key settings and assumptions used in the exposure modeling in these HHRAs. We discuss these in more detail throughout Section 3.

- Inhalation was the only exposure pathway considered
- We simulated 1,000 hypothetical individuals in each of three distinct age groups at each modeled distance from the well pad
- We used modeled outdoor air concentrations from AERMOD (Section 2) as ambient outdoor concentrations at hypothetical residences. For development activities, on an hour-by-hour basis, we sampled from the database of maximum modeled concentrations (for acute exposure) or mean modeled concentrations (for subchronic and chronic exposure) from the Monte Carlo iterations used in the dispersion assessment. For production activities, we employed time series of concentrations derived from unit emissions mapped to randomly-sampled emission rates.
- The chemical concentration in air at the time of exposure depended on the outdoor (ambient) air concentration at the simulated individual's residential location, which of three micros the individual was in (outdoor, indoor, or in-vehicle), and how fully the chemical penetrated from outdoors into the micro (with PENs derived from literature sources and assigned to groups of the modeled VOCs)
- A simulated individual's micro location at a given time was assigned based on a national database of activity diaries (assigned probabilistically based on age and gender). For working-age adults, the diaries were specific to the Mountain West states.
- Simulated individuals remained at the same distance and cardinal direction from the source (well pad) at all times—even when assigned activities such as working or traveling—so the ambient outdoor concentrations were always sampled from that specific location
- Acute exposures occurred across one hour, while subchronic and chronic exposures occurred across some number of days as dictated by the assumed average O&G activity duration

3.2. APEX Modeling Inputs

In this section, we describe the various inputs required for APEX modeling and how we handle them (assumptions, settings, data sources, etc.) in these HHRAs. With the inputs, assumptions, and settings described below, we conducted a total of 18 APEX runs (with 1,000 simulated individuals each) using unit outdoor ambient air concentrations (1 µg/m^3) for each combination of groups of VOCs (grouped by PEN; n=2), O&G site (n=3), and age group (n=3). We then post-processed the results of these model runs as described in Section 3.3 to yield specific simulated exposure results for 1,000 hypothetical individuals for each combination of age group (n=3), distance from well pad (n=14 for development and 16 for production), O&G activity (n=3 for development and 1 for production), and size of well pad (n=3 for development and 1 for production).

3.2.1. Simulated Population Demographics

Typical APEX runs use actual population data (from the U.S. Census Bureau) in various census tracts. However, these are geographically large units (often many miles across for places outside cities), which would not provide the necessary level of detail in terms of distance from the well pad. Also, though we use real meteorology data from real sites in Garfield County and the NFR, **the simulated O&G sites and the hypothetical individuals living near them are intended to be generic (rather than real, specific sites and actual nearby neighborhoods)**. Therefore, for these APEX runs we consider hypothetical individuals at residences located at specific distances from the hypothetical well pad, at radial directions determined in the dispersion assessment to experience the highest average air concentrations as described earlier in Section 3.1 (customized by O&G site, O&G activity, and, for development activities, emitted VOC). Figure 2-18 in Section 2.8 depicts the selected receptors for the production activity at the modeled Rifle site in Garfield County. APEX considers the ambient air to be co-located with each residence (that is, the air concentrations from AERMOD modeling are assumed to reflect air directly outside the residences at these receptors and available to penetrate into the different micros as discussed below).

The population is divided into the three broad age groups listed below, with hypothetical heights and weights assigned from distributions of survey data collected nationally.

- **youth** (below 18 years old)
- **adults** (18–59 years old)
- **older adults** (age 60 years and above)

Ages have some relevance because people spend different amounts of time in the various micros at different life stages, therefore receiving different exposures. For example, we would expect a typical 30-year-old individual to be involved in more outdoor activities than a typical 75-year-old individual. Since the available toxicity criteria values (discussed in Section 4) were developed by the agencies to be protective of the general population including sensitive subgroups such as children and senior citizens, there was no practical need to evaluate exposures and risks for each year of age separately (which would have been computationally very intensive).

We did not model young children (say, ages 0–6 years) separately from older children for several reasons, including: the limited number of available activity diaries, the lack of separate health criteria, and the fact that such children are almost always accompanied by an adult. Two persons of different ages who are always at the same place at the same time will experience the same air concentrations. Therefore, young children will have the same exposures as the adults who are with them, and the adults are captured in the other age groups.

Convergence testing (described in Section 3.4.3) showed that a minimum of about 500 hypothetical individuals in each age group (at each modeled location) should be sufficient to capture most of the variability in exposure across the simulated population (variability related to stochastic sampling of the physiological characteristics and activities of modeled individuals). We chose to model **1,000 hypothetical individuals in each age group (at each modeled**

location) to provide a buffer for potential unique cases of higher variability that may cause exposure results to converge more slowly.

3.2.2. Activity Diaries

APEX uses activity data to estimate how much time modeled individuals spend in various micros. Different patterns of activities are expected between youth, adults, and older adults, and some differences may also be seen by geographic location (differences in activity patterns between locations of the country may lead to noticeable differences in exposure estimates).

The human activity data used in these APEX runs come from **EPA's Consolidated Human Activity Database** (CHAD; EPA, 2016a). CHAD is a collection of data from more than 20 different studies, with subjects located throughout the US. Many subjects supplied one diary day (24 hours of activities) to CHAD, but some supplied more. APEX treats each 24-hour diary from CHAD as separate. APEX **stochastically assigns CHAD diaries to a modeled individual based on several criteria: similarity of modeled demographics (age, sex, employment, etc.), matching each day by the weekend-weekday distinction, and matching the temperature bin based on the corresponding input meteorology (the temperature bins being maximum ambient temperature below 55, 55–83, and 84 ºF or warmer)**. The geographic locations of diaries are not considered in the diary-selection process in APEX, but the overall diary data set may be restricted to certain geographic areas to focus on activity patterns that may be unique to those areas.

For this application, we analyzed CHAD by the state of residence for each diary day. For youth, it is important to match the age of the simulated individual closely to the age of the diary subject, which limits the number of CHAD diaries available to be matched to a given simulated youth. Therefore, it was not possible to restrict CHAD geographically to Colorado or a region around Colorado (for youth) without unduly constraining the number of available diaries. Therefore, we used **diaries from youth across the US. For adults, diaries were sampled from the Mountain West states**, as the number of diaries from Colorado alone was too constraining, but the number of diaries from the Mountain West states (namely: Colorado, Arizona, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming) was sufficiently large for robust stochastic sampling. **For older adults, as with youth, we utilized the full U.S. set of CHAD diaries, due to the insufficient number of diaries available for this age group from Mountain West states alone**. Since the various age groups are co-located (at preset distances from the source), the only difference in activities between the age groups is the allocation of their time among the micros, based on their diary activities. We discuss the potential impacts of these diary assignments in Section 3.6.3.2.

3.2.2.1. Commuting

If "real" individuals were being modeled (that is, the set of people living in a particular census tract), then real commuting data may also be used in an APEX run. Commuting data would describe the distribution of work census tracts for each home census tract (where a person lives). APEX would then stochastically select one of the work locations for a simulated employed individual and account for exposure in that specific location for the hours in the activity diary that correspond to work.

However, our population and locations are hypothetical, so no workplace data exist for them. We therefore made the **conservative assumption that all the employed individuals essentially work at home in our simulations, and therefore they remain close to the well pad all day long**. During times when the activity diary indicated that the simulated individual was traveling in a vehicle (whether to/from work or other vehicle trips), we allowed the individual to be in the **in-vehicle micro**, which affects exposure during those times through PEN values unique to vehicles. However, the vehicle is simulated such that it never leaves the home location, so that the corresponding outdoor ambient air concentrations are always that of the home location. We discuss the potential impacts of these commuting assumptions in Section 3.6.3.1.

We did not utilize any site-specific employment-probability data in our modeling. Simulated individuals engaged in work-related activities (commuting to and from work, being at the office, etc.) based solely on their assigned activity diaries. Therefore, the probability of engaging in these activities is equal to the probability of being assigned an employed person's diary (i.e., the fraction of employed individuals represented in CHAD) rather than the geographically representative employment probability in the modeled regions of Colorado.

3.2.3. Microenvironments and Penetration Factors

Micros are locations in the modeled region with distinct air concentrations of modeled chemicals. APEX simulates the movement of individuals through time and space (based on activity diaries) to estimate their exposure to a modeled pollutant in a set of user-defined micros. We selected the three micros listed below.

- indoors
- outdoors
- in-vehicle

We selected the APEX "factors" (or linear-regression) method to characterize the penetration of chemicals in the outdoor ambient air into each micro. In this method, each micro's chemical air concentration has a linear relationship to the outdoor ambient air concentration at the same point in time and space. The regression intercept reflects the air concentration in the micro in the absence of any external source, which reflects the contribution only of sources within that micro. In this project, we set the intercepts to zero because we want to evaluate the exposure to VOCs from the O&G operations alone. The regression slope reflects the combined effects of two terms: proximity and PEN.

Proximity in APEX refers to any relationship between a modeled location of exposure and the location where outdoor ambient air concentrations were estimated. In these HHRAs, we have explicitly modeled this relationship using AERMOD—we place hypothetical populations at the locations where we estimated air concentrations in the dispersion assessment—so we set the proximity factor in APEX to 1.

The PENs are different for each micro and they vary between chemicals. PEN, or penetration factor, for any micro refers to the ratio of a chemical's concentration in the micro to the chemical's outdoor concentration. PEN is always set to 1 for the outdoor micro (micro air concentrations equal outdoor ambient air concentrations). For the indoor and in-vehicle micros, we conducted a **detailed literature analysis of PENs for the modeled VOCs**, as discussed in Section 3.2.3.1.

3.2.3.1. Penetration Factors for Indoor and In-vehicle Microenvironments

After APEX is given an hourly time series of outdoor ambient air concentrations, it chooses a PEN for each simulated individual and micro, and it estimates the air concentrations in the micros by multiplying the outdoor concentrations by the PENs (and by proximity factors, which we set to 1). Running APEX separately with different PENs for each of the 47 VOCs would be very computationally intensive and lead to data-management issues. Therefore, similar to the modeling of age groups, we reduced the number of APEX runs by grouping VOCs and running APEX at the VOC-group level. As a starting point, we grouped the 47 modeled VOCs into four initial groups (two final groups as discussed further below) based on vapor pressure (V_p), which is a measure of chemical volatility, and other chemical properties related to volatility (boiling point and octanol-to-air partition coefficient). Higher-V_p (more-volatile) chemicals are more likely to penetrate more fully into all typical micros. We used K-means, a commonly used clustering algorithm in the R programming language, for grouping VOCs by these chemical properties into the four initial groups listed below and shown in Table 3-1. The clusters corresponded well to ranges of log10(V_p) values, so here and in the table we define them by log10(V_p) values even though the clustering algorithm also considered boiling point and octanol-to-air partition coefficient.

a) benzene/toluene with functional groups, and very large alkanes: log10(V_p) around 0 to 5

b) benzene group: log10(V_p) around 6 to 9

c) large alkanes and alkenes (butane, pentane, butene, pentene): log10(V_p) around 5 to 12

d) smaller alkanes and alkenes: log10(V_p) greater than 12.5

Table 3-1. Selected Indoor Penetration Factors (Indoor-to-outdoor Ratios) for Modeled Chemical Groups

Final Group	Initial Group	Chemical Description	Modeled Range of PENs	Data Availability in Literature (number of studies with PEN data for at least 1 chemical within the chemical group)
1	a	benzene/toluene with functional groups and very large alkanes: log10(V_p)=0–5	0.1–1	yes (12)
	b	benzene group: log10(V_p)=6–9	0.1–1	yes (18)
2	c	large alkanes and alkenes-butane, pentane, butene, pentene: log10(V_p)=5–12)	0.9–1	only one point value for pentane (0.9)
	d	smaller alkanes and alkenes: log10(V_p)>12.5	0.9–1	no

Notes: log10 = logarithm base 10; V_p = vapor pressure; PEN = penetration factor.

To understand the distributions of PENs in each of the four VOC groups listed above, we conducted a search for literature with data on PENs for each of the 47 VOCs modeled in these HHRAs. The field studies captured by the search were conducted in various micros, such as residences, schools, offices, libraries, public buildings, non-smoking cafes and pubs, and industrial areas, among others. The studies together covered the four seasons, and seasonal variability seen in the PENs were potentially due to variations in building or vehicle ventilation rates, usage of heating systems in winter, increased volatilization/availability of VOCs in the warmer months, etc. A PEN less than 1 is correlated with mostly outdoor sources of the chemical, and a PEN greater than 1 is correlated with potential indoor sources. Since one of our chief assumptions in these HHRAs is that there are no indoor sources or background sources of the 47 VOCs, we restricted our search to only those studies which had results of measured/modeled PENs less than 1.

The differences between the PEN groups lie mainly in the lower limits of the distributions, which apply to “tight” houses. In all cases, a house with a very high air-exchange rate (due to open windows or doors) will have PENs close to 1.0 for all chemicals. We made the health-protective assumption that all chemicals could have these high PENs, although the groups with smaller lower limits (down to PEN=0.1) also have lower means.

For VOC groups a and b, numerous PENs were available in the literature. We identified the minimum-maximum range of PENs among all the VOCs in the group (see Table 3-1) and let APEX sample a value from the range at random for each modeled individual. For groups a and b, we expected some lower PEN values due to the lower V_p values of the constituent VOCs; indeed, the resulting ranges of PENs were 0.1–0.95 for group a and 0.1–1 for group b. In order to be computationally efficient, we combined the two groups of VOCs into **VOC group 1, assigning it a common indoor PEN range of 0.1–1** for the APEX runs. For group c (a group of VOCs with high V_p values), we would expect high PENs. We were able to find one point value of 0.9 for pentane that excludes indoor and background sources, so we conservatively assigned a PEN range of 0.9–1 for the VOCs in this group. For group d (VOCs with very high V_p values), due to a dearth of literature data where indoor and background sources were excluded, we conservatively assigned a range of high PENs from 0.9 to 1, assuming that due to their high volatility they will penetrate indoors quite easily. For computational efficiency, we combined VOC groups c and d into **VOC group 2, assigning it a common indoor PEN range of 0.9–1**. We show in Table 3-2 the chemicals modeled in penetration group 1 and penetration group 2.

Table 3-2. List of Modeled Chemicals by Final Indoor Penetration Group

Penetration Group 1 (Values 0.1–1)		Penetration Group 2 (Values 0.9–1)
1,2,3-trimethylbenzene	benzene	1-butene
1,2,4-trimethylbenzene	cyclohexane	1-pentene
1,3,5-trimethylbenzene	cyclopentane	2,3-dimethylpentane
1,3-diethylbenzene	ethylbenzene	cis-2-butene
1,4-diethylbenzene	isopropylbenzene	cis-2-pentene
2,2,4-trimethylpentane	m+p-xylene	ethane
2,3,4-trimethylpentane	methylcyclohexane	ethene
2,4 dimethylpentane	n-decane	isobutane
2-ethyltoluene	n-heptane	isopentane
2-methylheptane	n-hexane	isoprene
2-methylhexane	n-nonane	n-butane
3-ethyltoluene	n-octane	n-pentane
3-methylheptane	n-propylbenzene	propane
3-methylhexane	o-xylene	propene
4-ethyltoluene	styrene	trans-2-butene
	toluene	trans-2-pentene

With respect to the in-vehicle micro, our literature search typically suggested a high PEN, usually greater than 1 (owing to in-vehicle emissions/accumulation over time). We found a few cases of in-vehicle PENs between 0.9 and 1. Keeping in mind our assumption of no in-vehicle/background sources of VOCs, we chose an **in-vehicle PEN range of 0.9–1** for all VOCs.

We list in Appendix A the literature which we found relevant in our review of PENs. We discuss the potential impacts of PEN selections in Section 3.6.3.3.

3.2.4. Outdoor Ambient Air Concentrations

The APEX runs used constant unit air concentrations (1 µg/m^3) as inputs for all hours of a year and at all locations, resulting in ratios of microenvironmental exposures to a 1-µg/m^3 outdoor ambient air concentration for each modeled hour, which later in post-processing is converted to actual estimates of VOC exposure (as discussed in Section 3.3.2). We do this to reduce the computational complexity and the required number of model runs while increasing our flexibility to create many exposure scenarios in post-processing.

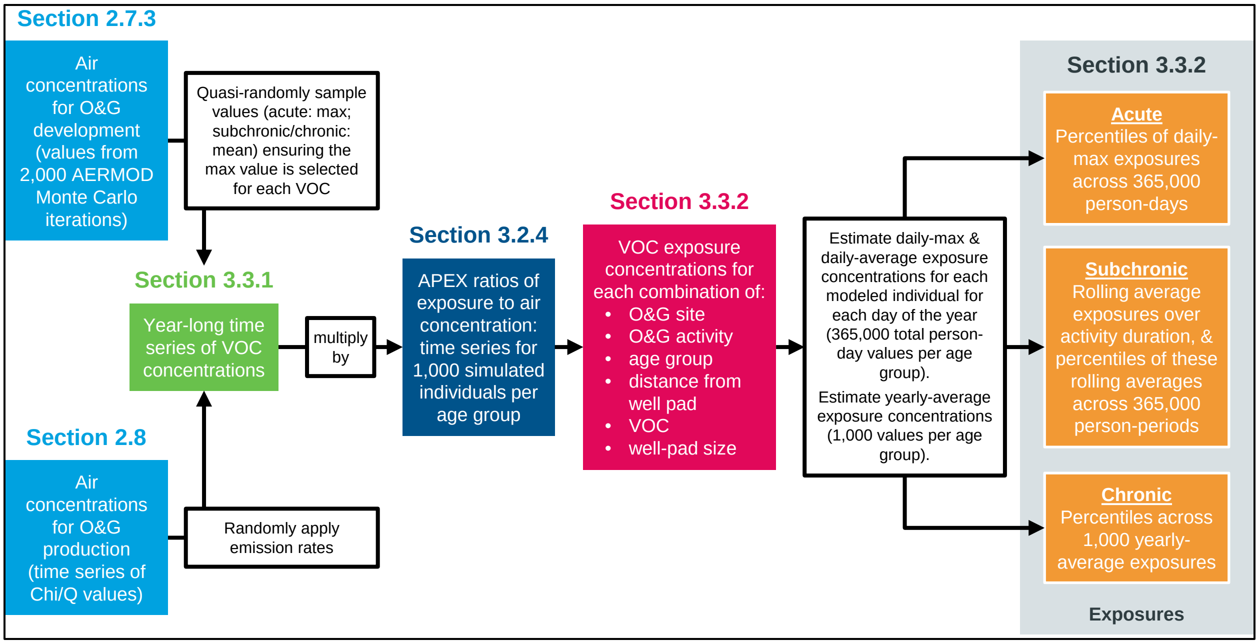
3.3. Generation of Exposure Outputs

In this section, we describe how we post-process the APEX outputs in order to produce estimates of exposure stratified by O&G site, well-pad size, O&G activity, VOC, distance from well pad, and individuals in each of the three age groups. Throughout this section, we refer to Figure 3-1, where we briefly illustrate the post-processing steps.

We list below the time frames of exposure that are relevant to these HHRAs. We discuss the health-protective toxicity criteria values, used to compare against exposure outputs, in Section 4.

- **Acute**: 1-hour-average exposures are compared to acute toxicity criteria values

- **Subchronic**: 24-hour- to 365-day-average exposures are compared to subchronic toxicity criteria values
- **Chronic**: exposures lasting more than 365 days are averaged and compared to chronic toxicity criteria values



Notes: Section numbers refer to this report.

O&G = oil and gas; Chi/Q = air concentration per unit emission; VOC = volatile organic compound; APEX = U.S. EPA Air Pollutants Exposure Model; max = maximum.

Figure 3-1. Overview of Steps for Post-processing APEX Outputs

3.3.1. Generation of Time Series of Outdoor Ambient Air Concentrations

The generation of scenario-specific exposure outputs involves multiplying the APEX outputs (year-long time series of modeled ratios of exposure to a 1-µg/m^3 outdoor ambient air concentration) with hourly estimated outdoor ambient air concentrations for each combination of O&G site, O&G activity, distance from the well pad, well-pad size, and VOC. We followed different steps to construct the time series of air concentrations for development activities versus production activities, as we explain below and as we illustrate in the left two sets of boxes in Figure 3-1.

3.3.1.1. Development

In the case of the three modeled O&G development activities, for each modeled VOC the dispersion assessment yielded summary values of air concentrations for 2,000 simulations (iterations) at the expected-maximum modeled receptor at each distance ring (as described in Section 2.7). For potential use in exposure modeling, the summary values saved from those iterations were the maximum, mean, median, and several percentiles of air concentrations calculated across the hours of each iteration (the number of hours in an iteration depended on the O&G site and the duration of the O&G development activity).

For the acute and subchronic/chronic estimates of exposure, we used different statistics from these iterations to create year-long time series of air concentrations for each exposure scenario, as we describe below.

- **Acute**: For each hour of the year-long time series of APEX air concentrations, randomly choose one of the 2,000 dispersion iterations and use its **maximum 1-hour-average VOC air concentrations**, specific to each distance from the well pad, using the same hour-to-iteration mapping at each distance ring. Ensure that each VOC's highest value from among the 2,000 maximum iteration values is included in the selections (these highest values being determined at the first distance ring).
- **Subchronic/chronic**: For each hour of the year-long time series of APEX air concentrations, randomly choose one of the 2,000 dispersion iterations and use its **mean VOC air concentrations**, specific to each distance from the well pad, using the same hour-to-iteration mapping at each distance ring. Ensure that each VOC's highest value from among the 2,000 mean iteration values is included in the selections (these highest values being determined at the first distance ring)..

3.3.1.2. Production

In the case of O&G production, as discussed in Section 2.8, the dispersion assessment yielded hourly Chi/Q values (values of concentrations per unit emissions) for one year at the receptor per distance where the annual-average Chi/Q was largest (where meteorological conditions on average lead to the highest air concentrations, if emissions are held constant). A total of 55 different hourly emission rates were available for each chemical derived from the 3-minute CSU measurements (55 different experiments). For each hour of the year, we **multiplied the Chi/Q value (specific to each distance from the well pad) by the hourly VOC emission rates from a randomly selected CSU experiment**, to arrive at a year-long air-concentration time series for each exposure scenario and VOC (employing emission rates derived from the same CSU experiment for all VOCs on a given hour).

For the hypothetical O&G sites in Garfield County (BarD and Rifle), distinct time series of Chi/Q values were available from the dispersion assessment. However, for the NFR site we created a hybrid time series of air concentrations by quasi-randomly merging the time series of Chi/Q values at the hypothetical Ft. St. Vrain site with that at the Anheuser-Busch site before applying the randomly selected emission rates per hour. This is similar to the dispersion assessment where for development activities we collected the 2,000 iterations of NFR air-concentration data by randomly selecting from either site approximately equally (see Section 2.7.2).

Unlike for development activities, for production activities we did not ensure that the maximum possible air concentration (according to our modeling) was included in our exposure modeling. On the hour of the year with the highest Chi/Q value, we multiplied the Chi/Q value by the hourly emissions corresponding to a randomly selected CSU emission experiment. That randomly selected experiment may or may not have the highest observed emission rate of a given VOC, and so we may or may not be simulating the highest possible air concentration of that VOC. Further, the highest emission rate of one VOC may not have been measured in the same experiment as the highest emission rate of another VOC, so it was not possible to both maximize potential air concentrations for all VOCs *and* have all the emissions on a given hour come from the same emission experiment. In a limited quality assurance step, we observed that the maximum chemical air concentration we produced with our methods could be 10- to 50-percent lower than the conservative, maximum-possible air concentrations that would have been produced by aligning maximum Chi/Q with maximum emissions.

3.3.2. Post-processing of Exposures

After generating the time series of VOC air concentrations, we multiplied them by the APEX outputs (time series of ratios of exposure to a 1-µg/m^3 outdoor ambient air concentration), resulting in a year-long time series of hourly VOC exposure concentrations (as illustrated in the pink box in the middle of Figure 3-1). We generated these time series of VOC exposures for each hypothetical individual at each modeled O&G site, O&G activity, distance from well pad, and well-pad size. Then, for use in risk assessment, **we processed the exposure time series as we described in Sections 3.3.2.1–3.3.2.3 to estimate acute, subchronic, and chronic exposures for the hypothetical individuals**. These steps correspond to the right two sets of boxes in Figure 3-1.

We produced estimates of acute, subchronic, and chronic exposures for all O&G activities and series of activities, as applicable. As noted in Table 3-3, new calculations of acute exposures are not needed for sequential series of activities (“back-to-back” activities) because the largest acute exposure from across the individual activities will also be the largest of those activities in series (see “Redundant” designations in the table).

Table 3-3. Durations of Activities for Exposure and Risk Modeling

Size of Well Pad / Number of Wells	Site	Activity	Weighted-average Activity Duration (days)	Acute	Subchronic	Chronic
1 acre / 1 well	Northern Front Range	Drilling	4	Evaluated	Evaluated	N/A
		Fracking	2	Evaluated	Evaluated	N/A
		Flowback	5	Evaluated	Evaluated	N/A
		All Development Back-to-back	11	Redundant	Evaluated	N/A
		Production	10,957	Evaluated	N/A	Evaluated
		All Activities Back-to-back	10,968	Redundant	N/A	Evaluated
	Garfield County	Drilling	4	Evaluated	Evaluated	N/A
		Fracking	1	Evaluated	Evaluated	N/A
		Flowback	14	Evaluated	Evaluated	N/A
		All Development Back-to-back	19	Redundant	Evaluated	N/A
		Production	10,957	Evaluated	N/A	Evaluated
		All Activities Back-to-back	10,976	Redundant	N/A	Evaluated
3 acres / 8 wells	Northern Front Range	Drilling	32	Evaluated	Evaluated	N/A
		Fracking	16	Evaluated	Evaluated	N/A
		Flowback	40	Evaluated	Evaluated	N/A
		All Development Back-to-back	88	Redundant	Evaluated	N/A
		Production[a]	10,957	N/A	N/A	N/A
		All Activities Back-to-back[a]	11,045	Redundant	N/A	Evaluated
3 acres / 16 wells	Garfield County	Drilling	64	Evaluated	Evaluated	N/A
		Fracking	16	Evaluated	Evaluated	N/A
		Flowback	224	Evaluated	Evaluated	N/A
		All Development Back-to-back	304	Redundant	Evaluated	N/A
		Production[a]	10,957	N/A	N/A	N/A
		All Activities Back-to-back[a]	11,261	Redundant	N/A	Evaluated
5 acres / 32 wells	Northern Front Range	Drilling	128	Evaluated	Evaluated	N/A
		Fracking	64	Evaluated	Evaluated	N/A
		Flowback	160	Evaluated	Evaluated	N/A
		All Development Back-to-back	352	Redundant	Evaluated	N/A
		Production[a]	10,957	N/A	N/A	N/A
		All Activities Back-to-back[a]	11,309	Redundant	N/A	Evaluated
	Garfield County	Drilling	128	Evaluated	Evaluated	N/A
		Fracking	32	Evaluated	Evaluated	N/A
		Flowback	448	Evaluated	N/A	Evaluated
		All Development Back-to-back	608	Redundant	N/A	Evaluated
		Production[a]	10,957	N/A	N/A	N/A
		All Activities Back-to-back[a]	11,565	Redundant	N/A	Evaluated

Notes: Evaluated (shaded green) = evaluated this exposure scenario. Redundant (shaded yellow) = the largest acute exposures during a sequence of activities will equal the largest acute exposure from across the activities making up the sequence, so a separate evaluation for the series was not needed. N/A (shaded gray) = not applicable: exposures lasting more than 365 days received a chronic evaluation (not subchronic), and exposures lasting 365 days or less received a subchronic evaluation (not chronic); also used to indicate that we did not evaluate hypothetical production sites other than 1 acre.

[a] We assessed oil and gas production only on 1-acre well pads, as discussed in Section 2.4. Following single- and multi-well development scenarios, the production phase was always 1 acre in our simulations.

We also show in Table 3-3 the assumed durations of each O&G activity or series of activities at each O&G site, which are relevant for estimating subchronic and chronic exposures. In the dispersion assessment, the Monte Carlo processing created simulated development-activity dispersion events (iterations) whose durations we sampled from the frequency distribution shown in Table 2-1. Then, as discussed in Section 3.3.1.1 above, we saved summaries of each iteration's air concentrations and used those to create time series of air concentrations for the exposure assessment. To calculate average subchronic and chronic exposures related to an O&G activity, for simplicity we utilized a single activity duration for each O&G site and activity, where we summarized the distribution of durations using frequency-weighted averaging. For example, for fracking in Garfield County, Table 2-1 indicates 85 percent of wells are fracked in 1 day, 13 percent in 2 days, and 2 percent in 4 days, so the weighted-average duration of fracking one well in Garfield County is 1 day (as indicated in Table 3-3 above). A one-day activity duration is appropriate for subchronic evaluation (see "Evaluate" designation in the table) but not chronic (see "Do not evaluate" designation in the table), which we define as exposures lasting more than 365 days.

Subchronic evaluation is not needed for O&G activities or series of activities lasting more than 365 days. For all scenarios, we assume that each well (if there is more than one) is drilled one-by-one with no overlap and no break between wells. Similarly, each well is then sequentially fracked, and subsequently each well undergoes flowback. All wells then simultaneously begin producing. For some multi-well scenarios, some individual development activities and series of development activities last more than 365 days, qualifying them for chronic evaluation rather than subchronic. We assume that a well produces for 30 years, which qualifies for chronic evaluation.

3.3.2.1. Acute Exposure Estimation

For each of the 1,000 hypothetical individuals modeled per age group and per distance from the well pad (at one selected receptor per distance) at a given hypothetical O&G site, we identified the **daily-maximum exposures** to emissions from each O&G activity across the whole year (the maximum value among the 24 hourly exposure values within a day, for all days of the year). This created a total of 365,000 unique estimates of acute exposure across the hypothetical population (per O&G site, well pad size, O&G activity, age group, VOC, and distance from the well pad). Put another way, we **identified each hypothetical individual's largest 1-hour-average exposure per day and O&G activity across a year of potential O&G activity, where the simulated activity can be occurring at any time of year.** For convenience, we refer to each of these 365,000 days as "**person-days**" because they correspond to each hypothetical person on each modeled day. The maximum value of acute exposure from a serial sequence of activities (e.g., drilling, fracking, and flowback back-to-back) will simply be the highest acute exposure estimated from across the individual activities (e.g., if flowback has the highest value, then that will be the highest value from all development activities in sequence).

Recall, however, that for development activities each calendar day in the exposure modeling comprises randomly selected air-concentration values, which means that each hour in the exposure assessment corresponds to a random hour of the year(s) in the dispersion assessment. Therefore, except for the production phase, calendar days in the exposure assessment do not correspond to contiguous hours of real observed meteorology on that day, and even the real contiguous meteorology reflected in the Chi/Q time series employed for production[10] is randomly combined with emission rates to produce the requisite time series of air

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[10] At the hypothetical Garfield County O&G sites in these HHRAs, the time series of Chi/Q values for use in the assessment of O&G production activities utilizes a real time series of contiguous hours of meteorology. The same is not true for the hypothetical NFR site because we constructed the NFR Chi/Q time series by randomly selecting from either the Ft. St. Vrain time series or the Anheuser-Busch time series hour-by-hour.

concentrations. As a result, for all O&G activities, a year's worth of daily-maximum exposures as identified above will not match a year's worth of daily-maximum exposures if calculated using contiguous hours of emissions (which we do not have), meteorology, and dispersion.

We utilized this daily-maximum approach to efficiently identify a wide range of possible acute exposures across various human activities and modeled air-concentration scenarios. Even though we constrain this collection of exposure results to one receptor per distance from the well pad and to each individual's highest exposure per day, the resulting set of values (365 per individual, 3,000 individuals per receptor) is still wide-ranging due to the different meteorological conditions and emissions values inherent in the air-concentration data and, to a lesser extent, due to different patterns across individuals of time spent outdoors versus indoors or in-vehicle. From these data, we identified the largest 1-hour-average exposure value from all person-days across the hypothetical population (the most-exposed simulated individual), which is the **worst-case potential acute exposure** according to our methodology (this corresponds to a real hour of meteorology combined with a real observed emission rate). The largest acute exposures in the modeling occur when the outdoor ambient air concentration is the highest (a combination of conservative meteorology and a high emission rate) and when the hypothetical individual experiences PEN=1 for that entire hour (he/she is either outside the whole hour, or is in micros where APEX assigned the individual a PEN=1). In collecting the daily-maximum exposures from all simulated persons (the maxima from all person-days), we can **put into context that worst-case potential acute exposure by relating it to the distribution of other potential daily-maximum acute exposures from across the simulated year and the hypothetical population**. As noted above, we do this with the caveat that the exposures are not the same as they would be if calculated using contiguous hours of emissions (which we do not have), meteorology, and dispersion.

3.3.2.2. Subchronic Exposure Estimation

We estimated subchronic exposures only during development activities, since the production activity has a long duration (30 years) that meets the definition of chronic exposure (more than 365 days). Some multi-well scenarios also have development activities that last more than 365 days, and sequences of development activities that last that long, and in those cases we evaluate chronic exposures instead of subchronic exposures.

Per age group and distance from the well pad at a given hypothetical O&G site, we identified the average exposure for each person-day (for each of the 1,000 hypothetical individuals, the average exposure from among the 24 hourly exposure values within a day, for each day of the year). Based on O&G activity durations unique to each O&G site and activity (see Table 3-3), we **calculated a series of average exposures starting on each calendar day and extending through the assumed activity duration**, leading to a total of 365,000 unique estimates of subchronic exposure across the hypothetical population (per O&G site, O&G activity, well-pad size, age group, VOC, and distance from well pad). That is, **for each possible multi-day period over which an O&G activity can occur in a year, we identify each hypothetical individual's average exposure for the activity**. Note that in calculating these "rolling averages", when the 'starting' day results in the rolling average crossing over into the following year, we employ exposure values from the beginning of the time series to account for this overlap between years (when at the end of the year, if needed we "wrap around" back to January). For convenience, we refer to each of these 365,000 multi-day periods as "**person-**

periods" because they correspond to each hypothetical individual in each modeled multi-day period of exposure.

As noted above for estimations of acute exposure, the calendar days in the exposure modeling of development activities do not reflect real calendar days made up of contiguous hours of real observed meteorology and dispersion. However, averaging the hourly modeled exposures across periods of time, especially across many days, will cause the average values to approach real potential average values of subchronic exposure, as they will incorporate variable meteorological conditions (meteorology can be highly variable hour-to-hour and day-to-day) and variability in emission rates (which was observed in the CSU measurements).

We utilized this approach of calculating multi-day average exposures (average person-period exposures) to efficiently identify a wide range of possible subchronic exposures across various series of human activities and modeled air-concentration scenarios. From that, we identified the largest person-period from across the simulated population (the most-exposed simulated individual), which is the **worst-case potential subchronic exposure** according to our methodology. The largest subchronic exposures in the modeling occur at the most conservative overlap of high average outdoor ambient air concentrations (a combination of conservative meteorology and high emission rates on average) and high average PENs across the micros where the hypothetical individual spends time. In collecting all simulated person-period exposures, we can **put into context that worst-case potential subchronic exposure by relating it to the distribution of other potential subchronic exposures from across the simulated year and the hypothetical population**.

After estimating subchronic exposures for drilling, fracking, and flowback activities individually, we can then calculate subchronic exposures during back-to-back sequences of development activities. These calculations utilize time-weighted averaging, where the subchronic exposures calculated for the individual drilling, fracking, and flowback activities are averaged together utilizing weights corresponding to their relative activity durations. We calculated these subchronic weighted-average exposures for back-to-back development activities by randomly selecting person-periods of drilling, fracking, and flowback from the exposure data available for each hypothetical individual, resulting in 365 randomized combinations of back-to-back development activities per individual. This leads to 365 different estimates of weighted-average exposures per person and 365,000 estimates of weighted-average exposures across the population of each age group at each distance from the well pad.

3.3.2.3. Chronic Exposure Estimation

We estimated chronic exposures only during individual O&G activities or back-to-back sequences of activities that last more than 365 days. This includes production activities (30-year duration) and individual development activities and series of development activities for some multi-well scenarios (see Table 3-3). We do not assess activities for both subchronic and chronic exposures—only one or the other based on duration.

For each of the 1,000 modeled individuals per age group and distance from the well pad at a hypothetical O&G site, we **calculated the annual-average exposures** to individual activities lasting more than 365 days. This leads to 1,000 unique estimates of chronic exposure (per O&G site, qualifying O&G activity and well-pad size, VOC, age group, and distance from well pad).

As described in Section 3.3.1.2, the individual hours of ambient air concentrations employed in the exposure modeling of production activities reflect real hours of meteorology combined with randomly selected emission rates, and these time series of air concentrations (and resulting exposure concentrations) reflect contiguous hours of meteorology. Despite the hour-to-hour randomness of the emission rates, the annual average of those hourly exposure concentrations approaches a real potential value of chronic exposure (the average of randomly selected data equals the average of ordered data). From the collection of annual-average exposures across the hypothetical population, we can **identify the most-exposed simulated individual and put that into context by relating it to the distribution of annual-average exposures from across the hypothetical population**. The hour-to-hour construction of the time series of air concentrations for development activities is randomized, but as with production the annual average of the resulting hourly exposure concentrations approaches a real potential value of chronic exposure.

As with estimating subchronic exposures for back-to-back sequences of O&G activities, for chronic exposures we calculated a time-weighted-average exposure utilizing the exposures of randomly selected individual activities, weighted by their respective durations. This results in 365 randomized combinations of back-to-back development activities per individual. The only development scenarios reaching chronic-level duration are in Garfield County with 32 wells on a 5-acre pad (see Table 3-3), and exposures during flowback likely account for the majority of the chronic back-to-back development exposure because flowback lasts substantially longer than drilling and fracking and because air concentrations during flowback tend to be higher. For the simulated back-to-back scenarios where production is included, we include in the time-weighted averaging the individual’s chronic exposure during the 30 years of O&G production. In those cases, the production exposures will account for most of the chronic exposure because of its 30-year time span, as compared to less than two years for the longest modeled development sequence.

3.4. Quality Assurance and Quality Control

Throughout the workflow of the exposure modeling, we took many steps to ensure the accuracy of modeling input and output data, as well as the proper functioning of data processing scripts. In this section, we provide a synthesis of these steps as well as the results of some of the quality assurance/quality control (QA/QC) procedures undertaken.

3.4.1. APEX Modeling Inputs

Several of the various APEX inputs, discussed in detail in Section 3.2, were identical to those that are provided with the publicly available version of APEX released by EPA[11] and are discussed in their documentation (EPA, 2017). For other inputs, either we modified the publicly available versions or we created custom new versions. Below, we discuss briefly how we generated these files and the QA steps we took prior to implementation in the APEX modeling. In most cases, separate people conducted input generation and input QA.

[11] The EPA website for APEX is https://www.epa.gov/fera/download-trimexpo-inhalation-apex.

3.4.1.1. Air Quality

As noted in Section 3.3.1, APEX requires complete, hourly input air-concentration data for the modeled time period (one year for these HHRAs). We generated these data with unit concentrations (values of 1) using the R programming language. We then reviewed the inputs to ensure they contained these hourly values of 1 for the full year.

3.4.1.2. Meteorology

APEX requires a continuous time series of hourly temperature data over the modeling time period for each modeled location. We employed a modified version of the meteorology data used in the dispersion-modeling portion of this study (which we discuss in Section 2.5). We first filled in any instances of missing temperature data using interpolation from surrounding hours or the same hours from surrounding days. We then used custom R scripts to put the data into the requisite format for APEX. We visually examined these APEX-ready meteorology data files to ensure that the defined time periods matched those of the corresponding site, and that the data were continuous and hourly.

3.4.1.3. Demographics

Several data files input to APEX denote the geographical patterns of employment probability and population counts on the basis of sex and age group. Due to the hypothetical nature of the exposure modeling, we employed simplified demographic inputs that assumed an equal distribution of ages and sexes across all individuals in the modeled domain. As we discuss in Section 3.2.2.1, we did not utilize employment probabilities in our modeling, and instead the diary-selection process (based on age, sex, day of week, etc.) determined whether the simulated individual engaged in work-related activities. We visually analyzed these input files to ensure proper formatting before model execution.

3.4.1.4. Geographical Locations

Several input files required by APEX denote the geospatial locations of all air-quality data sources, meteorological data sources, and points of reference for population counts. Due to the simplified and hypothetical nature of the APEX runs executed here, all geographical location files referred to a single arbitrary point (instead of, as would be the case in a typical APEX run, lists of latitude/longitude coordinates denoting locations of real data stations and census tract centroids). We later use multiplicative post-processing steps to convert the modeled exposure results (unit concentrations at a single location) to the results used for risk assessment (diverse air concentrations at many locations).

We visually analyzed geographical input files to ensure they referenced the same arbitrary location and that the arbitrary location names matched as necessary between files.

3.4.1.5. Activity Diaries

The publically available version of APEX contains activity diaries and corresponding demographics data that are based on a subset of all available CHAD activity diaries (diaries from certain human-activity studies in CHAD are not included in the APEX diaries in EPA's public release of the model). We employed a separate subset of all available CHAD diaries, tailored by age group as discussed in Section 3.2.2 using a SAS processing script.

We used custom R scripts to ensure that the criteria listed below were met in the age-group-specific diary files.

- All ages in the diaries correspond to the intended age group for modeling.
- All diary files needed per age group contain the same CHAD IDs.
- All CHAD IDs are denoted as unemployed (see Sections 3.2.2.1 and 3.4.1.3 for more information on how work-related activities were still included for many individuals).
- All CHAD IDs contain 1,440 minutes of activities (one full day of activities).
- All CHAD IDs have chronological start times.
- CHAD respondents ages 0–17 and 60–99 have approximately 50 unique states represented in their activity diaries, while ages 18–59 have Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming represented in their activity diaries.

Following these QA checks, for use in APEX, we combined the separate age-group diary files into a single set of files reflecting all age groups.

3.4.1.6. Microenvironmental Parameters

As discussed in Section 3.2.3.1, we defined the PENs for the three analyzed micros using two separate APEX input files: one for the low-PEN group of VOCs and one for the high-PEN group. We reviewed both of these files for correct formatting and to ensure that the values were set correctly for the corresponding files.

APEX requires that users define which of the user-defined microenvironmental parameters apply to the various activity locations defined throughout the activity diaries. This allows APEX to apply the correct PENs to the various micros. The publically available version of APEX denotes mappings for five separate micros, which we modified to reflect the three micros employed in these HHRAs (e.g., we mapped both the original “outdoor” and “near-road” micros to the “outdoor” micro for these HHRAs).

3.4.1.7. APEX Control Options Files

Separate APEX run files (or “Control Options Files”) were required for each of the 18 APEX runs. These run files were identical except for a few of the modeling parameters and input and output file paths. We constructed a template run file and visually reviewed it for correct parameter settings, and we generated all 18 APEX run files from this template. We further independently analyzed them to ensure that we correctly set all scenario-specific inputs for the given run file (e.g., the modeled age range, PEN factors employed, meteorology data, site-specific time span, output data locations, etc.).

3.4.1.8. Default Public Release Files

The input files for the following parameters were unchanged from the public release of APEX: physiology (distributions of weight, height, etc.), ventilation (distribution of breathing rates given a relative energy expenditure), and distributions of relative energy expenditure and how they map onto specific activities.

Additionally, APEX requires an input file that, among other things, defines how to apply different parameters to simulated individuals given variable environmental conditions (known as the "Profile Functions File"). We used a stripped-down version of this file that only contained the requisite temperature binning of activity diaries, and we ensured that this binning scheme was identical to the one used in the public release of APEX before executing the model runs.

3.4.2. APEX Modeling Outputs

We conducted several QC checks on the unit APEX exposure outputs to ensure that the modeling runs completed successfully. We synthesize these QC checks in Table 3-4 (for checks done on all model runs) and in Table 3-5 (for checks unique to each run).

Table 3-4. Quality-control Checks on All Exposure Simulations

Age Group	Number of Geographical Locations	All Modeled Individuals Unemployed?	Minimum Age	Maximum Age	% Males	% Females	Average % Population per Year of Age
0–17	1	Yes	0	17	49.40%	50.60%	5.56%
18–59	1	Yes	18	59	49.40%	50.60%	2.38%
60–99	1	Yes	60	99	49.40%	50.60%	2.50%

Table 3-5. Quality-control Checks on Specific Exposure Simulations

Chemical Group	Site	Age Group (yrs)	From Unit Exposure Concentrations		
			Annual Avg. (Avg. Across Pop.)	Lowest 1-hr Avg. (From Across Pop.)	% Individuals With 1-hr Avg.=1
High PEN	Garfield County Ridge-top Site (BarD)	0–17	0.954	0.945	97.50%
		18–59	0.953	0.942	92.30%
		60–99	0.953	0.933	92.00%
	Northern Front Range	0–17	0.955	0.959	97.50%
		18–59	0.953	0.942	93.50%
		60–99	0.954	0.941	94.30%
	Garfield County Valley Site (Rifle)	0–17	0.955	0.945	98.40%
		18–59	0.953	0.941	94.10%
		60–99	0.954	0.933	95.60%
Low PEN	Garfield County Ridge-top Site (BarD)	0–17	0.608	0.905	97.50%
		18–59	0.607	0.904	92.30%
		60–99	0.596	0.905	92.00%
	Northern Front Range	0–17	0.611	0.905	97.50%
		18–59	0.607	0.901	93.50%
		60–99	0.598	0.903	94.30%
	Garfield County Valley Site (Rifle)	0–17	0.611	0.908	98.40%
		18–59	0.608	0.904	94.10%
		60–99	0.598	0.901	95.60%

Notes: PEN = penetration factor; yrs = years; avg. = average; pop. = population; hr = hour; % = percentage.

From Table 3-4, it can be seen that all of the modeled individuals in each simulation were assigned the correct ages, and that for all runs the distribution of males and females was roughly equal. Additionally, the "Average % Population per Year of Age" column demonstrates that each distinct year of age was, on average, represented the expected number of times throughout the modeled population (based on uniform sampling of ages where each age is as likely as any other to be selected).

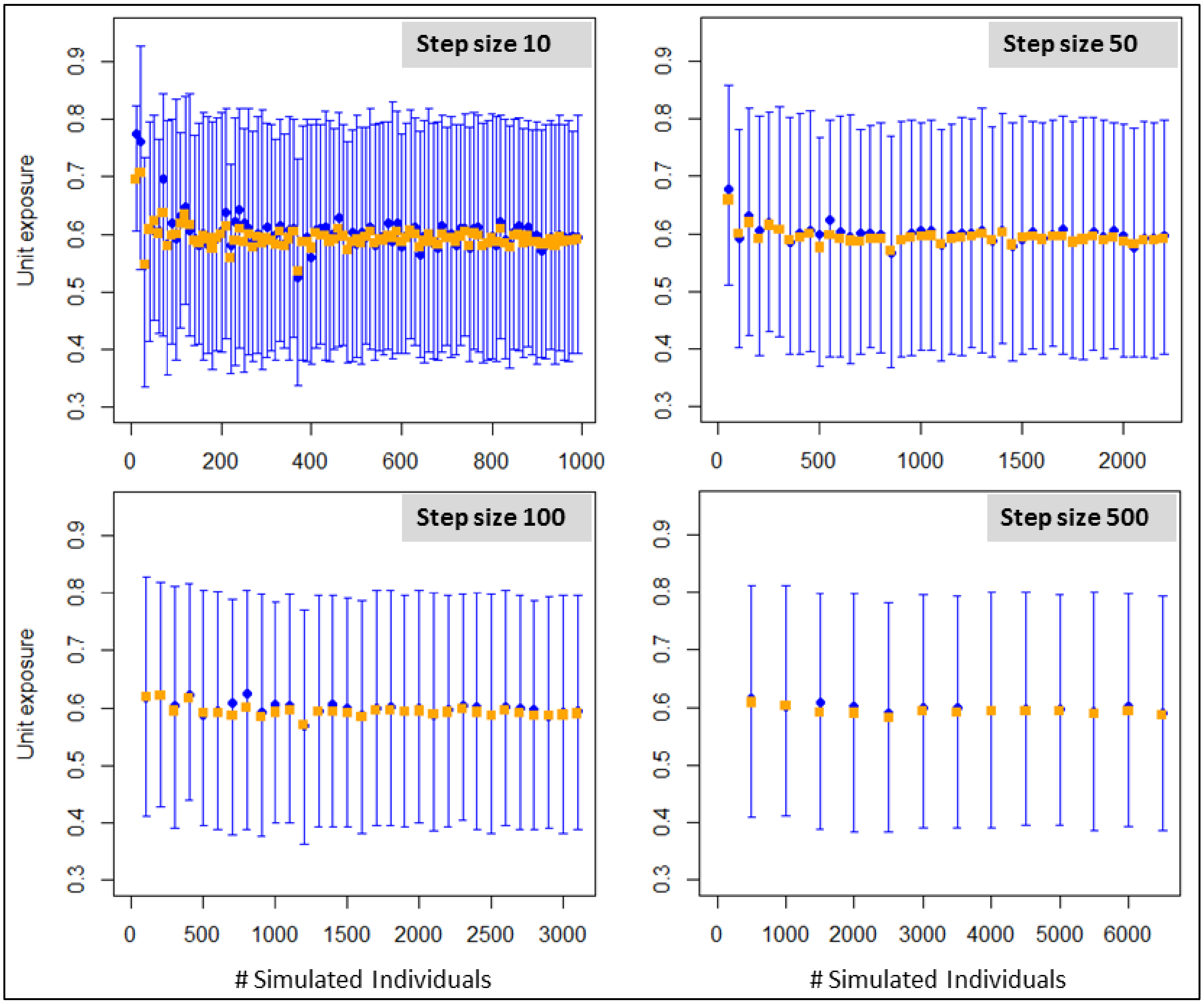
In Table 3-5, we provide the results of the QC checks that focused on parameters that differed between the various runs. For the high-PEN runs, the average simulation-long exposure across all modeled individuals (the "Annual Average (Average Across Population)" column) is about 0.95, which is expected given that most of an individual's time is spent in the indoor micro and that the PEN factors for this micro are assigned uniformly from between 0.9 and 1. Similarly, for the low-PEN runs, the average simulation-long exposure across all profiles is roughly 0.6, reflective of the indoor PEN varying between 0.1 and 1. In both of these groups of runs, the older age groups generally have slightly lower average exposures, reflective of the fact that on average the younger age groups spend more time outdoors. The "Lowest 1-hour Average (From Across Population)" column denotes the lowest maximum 1-hour-average exposure concentration experienced by any of the 1,000 simulated individuals (we collected each person's maximum 1-hour value, then found the lowest of these values). These values correspond to individuals that were not assigned a PEN of 1 for any micro and/or never went outside for a full hour. All of these values are above 0.9. Conversely, the "% Individuals With a 1-hour Average = 1" column denotes the percent of simulated individuals that achieved at least one occurrence of 1-hour exposure concentration equal to the outdoor ambient air concentration. Expectedly, these values are rather high (between 92 and 98.4 percent), and in each case the remainder of the population reflects those that were never in a PEN=1 micro for a full hour. Finally, we also ensured that the maximum 1-hour exposure concentration experienced by any simulated individual in each simulation was 1 µg/m^3 (that is, no higher than the outdoor ambient air concentration).

3.4.3. APEX Modeling Convergence Testing

As discussed in Section 3.1, the number of individuals simulated in each APEX run must be large enough that it captures the variability in exposure expected across a diverse population. We focus only on the variability in exposures to unit air concentrations for these purposes and not on the variability in the final analyzed exposures; that is, we analyze only the ratios of exposures to a 1 µg/m^3 outdoor ambient air concentration, and not exposures to actual VOC concentrations. The goal is to identify the number of individuals such that adding more individuals to the simulation does not substantially impact the population-wide average daily exposures (i.e., convergence in the daily-average exposure results). In the APEX modeling, the parameters that impact the variability in these unit-exposure values are the human activities (which in turn depend on the age group and the ambient outdoor temperature) and the PENs.

For the convergence testing, we selected temperature data from the modeled Rifle site because it had the largest variability in hourly temperature data. We also selected the low-PEN group because it had the largest variability in PENs. We chose the children age group (individuals below 18 years old) because the activity diaries from this group exhibit the highest average time spent outdoors (high exposure potential). We selected these higher-variability data so that the convergence testing utilized high variability in exposure, therefore ensuring convergence for high-variability scenarios.

We conducted one APEX run with these inputs, as well as all other inputs from the APEX modeling used in the exposure assessment, with 50,000 simulated individuals for one full year. We then determined the median, mean, and inner and outer quartile values of the daily-average exposure values across varying numbers of these simulated individuals (for the full year-long time series) to determine how these statistics varied with a variable number of simulated individuals being analyzed. We conducted this analysis for different step sizes in the numbers of individuals being analyzed. In Figure 3-2, we display these results with the use of step sizes of 10, 50, 100, and 500 individuals. Note that the statistics from each bin reflect data from a different subset of the modeled individuals, meaning that a larger step size results in a higher possible number of individuals being analyzed given that the simulated individuals are being sampled from a fixed number of 50,000.



Notes: Orange squares = means; blue circles = medians; top and bottom of blue lines = 75th and 25th percentiles, respectively; # = number.

Figure 3-2. Statistics of Daily-average Exposure Taken Across a Varying Number of Simulated Individuals (Exposure Concentration per Unit Air Concentration)

For daily-average exposures of fewer than 500 individuals, there are noticeable differences in the statistics between adjacent numbers of analyzed individuals. This is most apparent when the step size is 10 individuals, and is not discernable for step sizes of 100 or 500 individuals. When more than 500 individuals are analyzed, however, very little difference can be seen in the statistics from adjacent numbers of individuals, meaning the exposure values have converged (see the panels for step sizes 10 and 50). We analyzed step sizes of 100 and 500 individuals to ensure there were no major differences in the analyzed statistics when we considered much larger numbers of individuals.

Based on this analysis, we determined that 1,000 modeled individuals would be sufficient to capture the anticipated variability in exposures due to the unit air concentrations. We chose this high number relative to the apparent point of convergence (around 500) as a precaution against the possibility of higher variability in the inputs from the other scenarios.

3.4.4. Air Quality, Exposure, and Risk Processing Scripts

We developed a suite of post-APEX and post-AERMOD processing scripts in the R programming language to perform the necessary calculations for exposure and risk estimation. Generally, we structured our methodology such that one individual wrote most or all of the necessary processing code, after which a separate individual visually inspected the code to ensure it was constructed accurately. After this, we conducted numerical testing with the processing code, manually calculating a subset of the expected output given the known input values and comparing this expected output to the script output. We conducted this latter step by either using the actual AERMOD and/or APEX modeling data used throughout the exposure modeling, or by using a scaled-down version of these data to allow for easier manual calculation. We applied most, but not all, of these QA procedures to each of the processing scripts. In Table 3-6, we provide a brief description of each of the processing scripts used throughout the exposure and risk modeling calculations, as well as which of the QA/QC procedures described above we conducted to ensure the proper functioning of each.

Table 3-6. Quality-control and Quality-assurance Procedures for Post-processing Scripts

Processing Script	Description of Processing Code	Independent Review of Code	Numerical QA/QC using Full-scale Data	Numerical QA/QC using Scaled-down Data
Development AQ TS	Generates year-long TS of all VOC air conc. for development activities.	✓	✓	
Production AQ TS	Same as above, but for production activities.	✓	✓	
Acute Exposure and Risk Calc.	Scales TS of unit exposures by corresponding time series of VOC air conc., calc. daily-max. exposure per individual, & calc. population-wide %iles of daily acute exposure, HQ, HI.	✓		✓
Chronic Exposure Averaging	Scales TS of unit exposures by time series of VOC air conc., & calc. daily- and annual-avg. exposures for all individuals.	✓		✓
Subchronic Exposure and Risk Calc.	Calc. activity-duration rolling avg. & population-wide %iles of these subchronic exposures, HQs, HIs.	✓	✓	✓
Chronic Exposure and Risk Calc.	Calc. population-wide %iles of annual-avg. exposures, HQs, HIs.	✓	✓	
Back-to-back Exposure	Calc. population-wide %iles of subchronic and/or chronic exposures, HQs, & HIs for development activities & development + production activities that occur in sequence.	✓	✓	

Notes: Check mark indicates that we conducted that QA/QC step. In some instances, changes to scripts were not independently reviewed.
AQ = air quality; TS = time series; VOC = volatile organic compound; conc. = concentration; max. = maximum; calc. = calculate; %iles = percentiles; avg. = average; HQ = hazard quotient; HI = hazard index; QA/QC = quality control/quality assurance.

3.5. Exposure Modeling Results

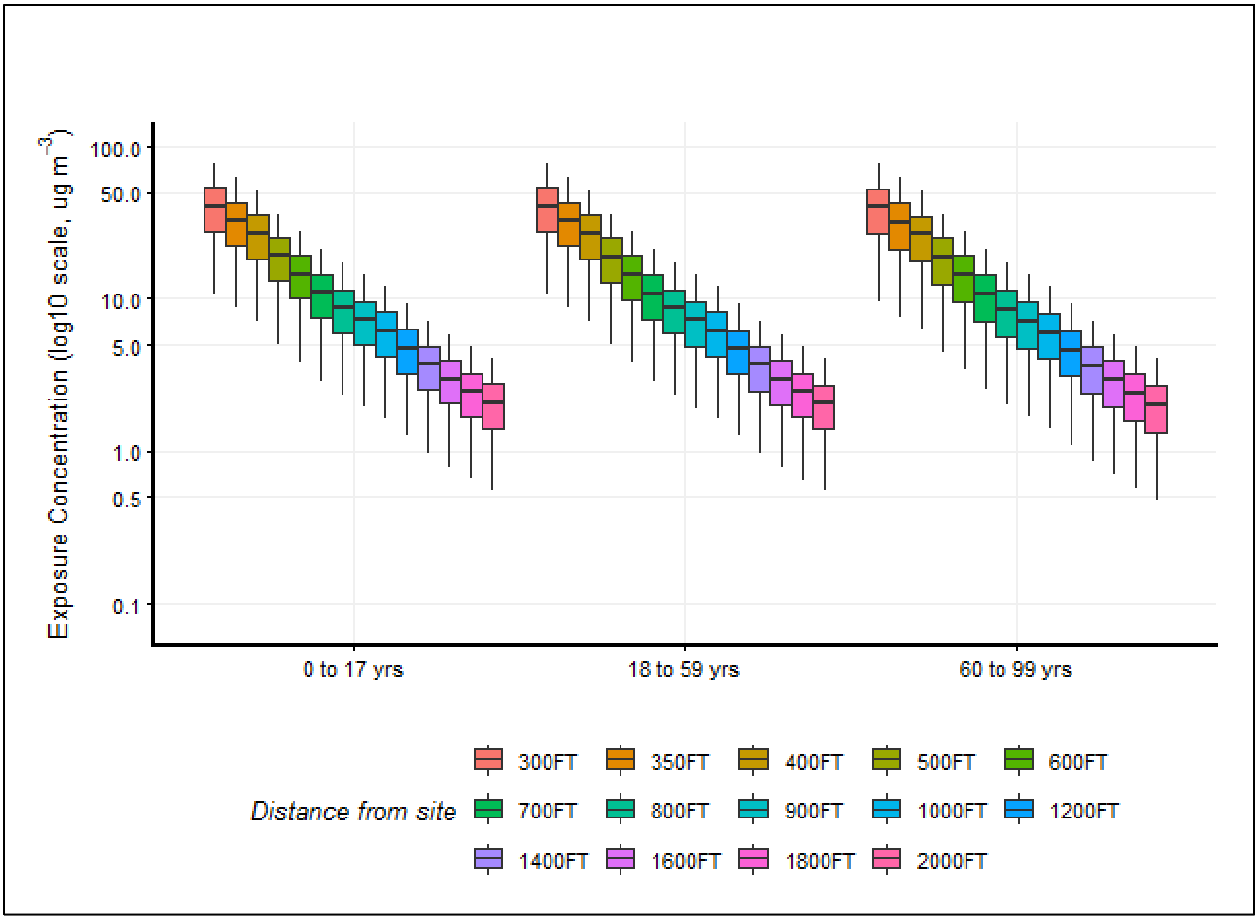
In this section, we present a sample of the results of the exposure modeling, created primarily for QA as our main focus will be on the resultant potential risks from these exposures (discussed in Section 5). In particular, in many cases here we compare ranges of exposure concentrations to ranges of the input air concentrations to ensure that the exposure results are logical given the air-concentration results. The observations we make here about the exposure results are pertinent to interpreting the risk results discussed in Section 5.

The structure of the box-and-whisker plots in this section are the same as those provided for hazard results later in Section 5.3, where values are plotted in log space and the shapes correspond to the 1st-percentile value (bottom whisker), 25th percentile (bottom of box), 50th percentile (i.e., median; line inside box), 75th percentile (top of box), and maximum (top whisker). Note that we define the boxes here and in Section 5.3 differently than in Section 2.9.

3.5.1. Variations in Exposure by Age

For most of the hypothetical simulated population, age has relatively little impact on distributions of exposure concentrations. As we discuss below and as illustrated in Figure 3-3 through Figure 3-6, this is true for comparisons of concentration distributions between modeled youth (ages up to 17 years) and adults (ages 18 to 59 years), and this is also true for comparisons of concentration distributions between all three age groups for VOCs modeled with higher PENs (those with indoor PEN values between 0.9 and 1). The exceptions where we see some noticeable differences in exposure concentrations between age groups are between older adults (60 years and older) and the rest of the population at lower ends of the exposure distributions, only for VOCs modeled with lower PENs (those with indoor PEN values between 0.1 and 1).

VOCs modeled with lower PENs typically penetrate into the indoor micro at lower rates than those modeled with higher PENs. For lower-PEN VOCs, the exposure concentrations were similar between age groups (to within about 1 percent) at most points of the distributions. This can be seen in Figure 3-3 for subchronic exposures to benzene emissions from NFR flowback operations on a 1-acre well pad, as an example. Figure 3-3 contains distributions of exposure concentrations for this scenario at the selected receptors at each distance from the well pad. These are distributions of person-period exposure concentrations across these simulated populations (365 values per individual, 1,000 individuals per age group and distance location). The negligible differences in the distributions between age groups suggest that many of the simulated individuals, no matter their age, are simulated to have similar basic patterns of activities in terms of time spent outdoors, indoors, and in-vehicle, and in terms of being in those micros during similar times of day, leading to similar subchronic averages of exposure concentration. As one moves toward the lower ends of the distributions of exposure concentrations, the concentrations for older adults become lower than those of the rest of the hypothetical population, approaching about 10 to 20 percent lower at the lowest exposures. This suggests that at least some hypothetical older adults were simulated to spend notably more time indoors as compared to youth and younger adults; indoor PENs can be as low as 0.1 (median 0.55), leading to lower average exposure concentrations for these people.

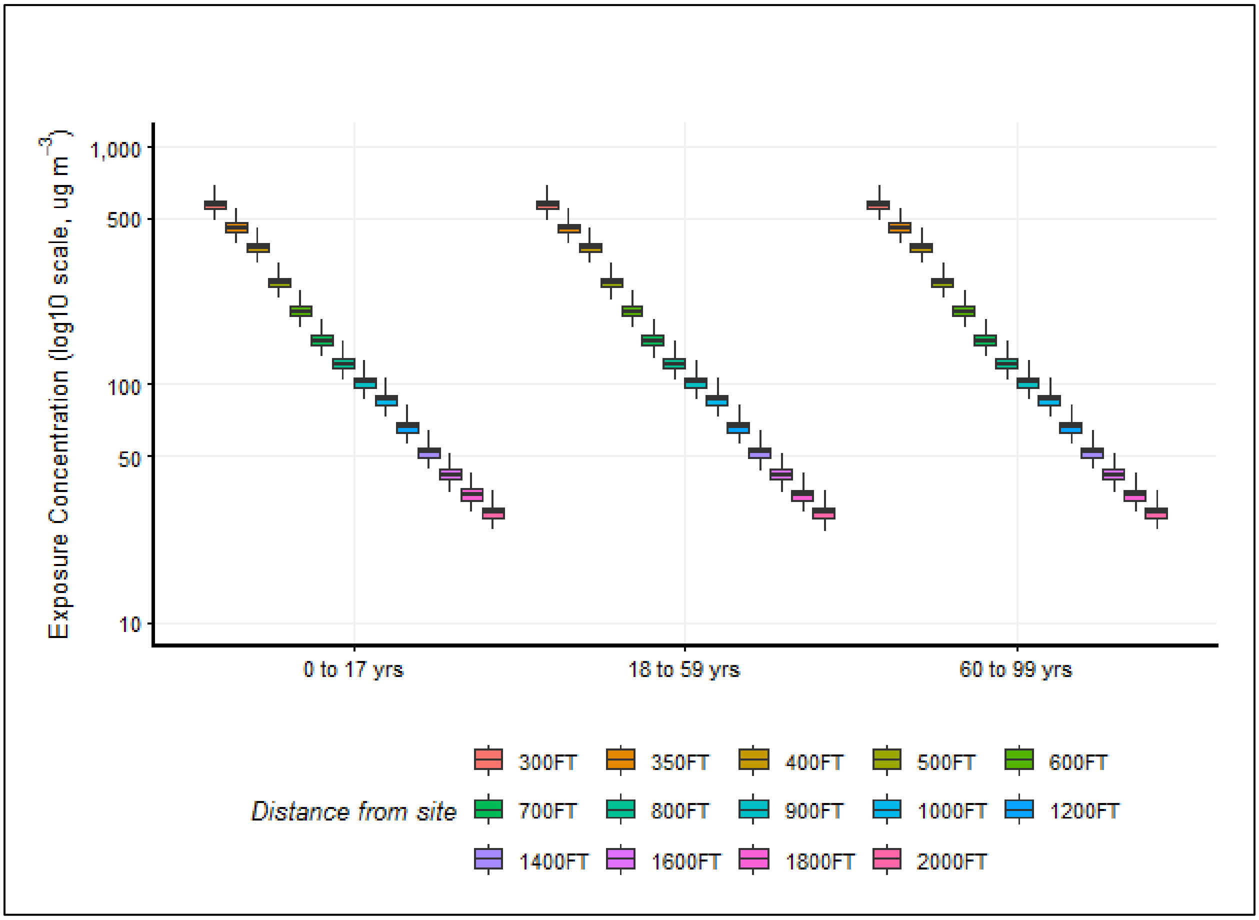


Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box).

log10 = logarithm base 10; ug m^{-3} = micrograms per cubic meter; FT = foot; yrs = years of age.

Figure 3-3. Distributions of Subchronic Benzene Exposure Concentrations by Distance and Age Group, for Flowback Activities at the Northern Front Range (1-acre Well Pad Only)

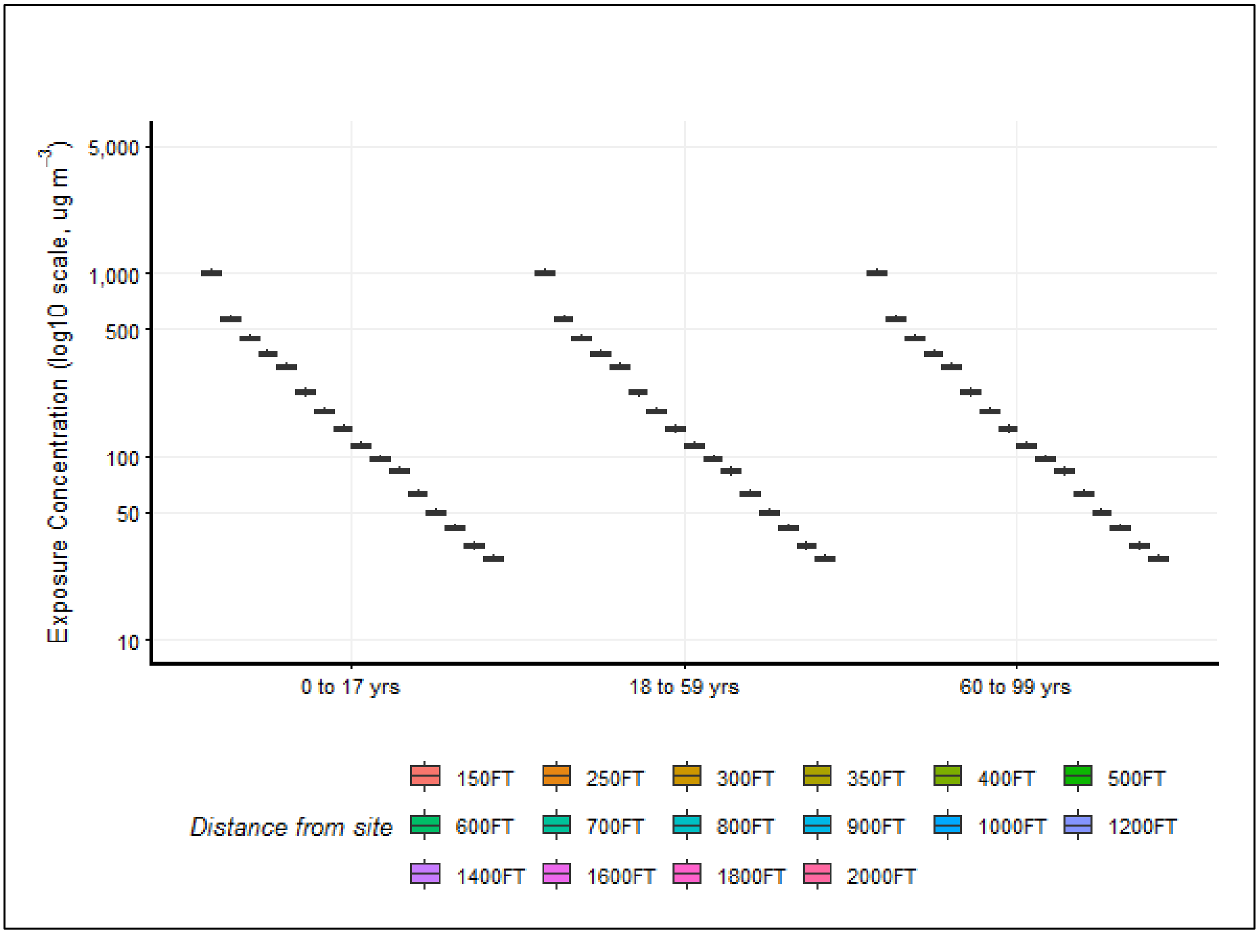
For higher-PEN VOCs, such as propane shown in Figure 3-4, indoor PENs vary between 0.9 and 1 (median 0.95), and, like all VOCs, in-vehicle PENs also vary between 0.9 and 1. This means that no matter what patterns of activities the hypothetical people are modeled with, and regardless of differences in those patterns by age, the differences in average exposure concentration between simulated individuals will be fairly small for a given ambient outdoor concentration. As can be seen in Figure 3-4, the distributions of modeled exposure concentrations are nearly identical between age groups at a given distance from the well pad. The effect of the narrow PEN ranges for high-PEN VOCs is especially apparent with distributions of chronic exposure during production activities, where all simulated individuals have almost the same chronic exposure concentrations for propane (see Figure 3-5, displaying the distributions of annual-average exposure concentrations across the simulated populations; 1,000 values per age group and distance location). For lower-PEN VOCs, however, the wider range of PENs leads to larger differences in exposure concentrations between people (see Figure 3-6, which is similar to Figure 3-5 but for benzene rather than propane).



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box).

log10 = logarithm base 10; ug m^{-3} = micrograms per cubic meter; FT = foot; yrs = years of age.

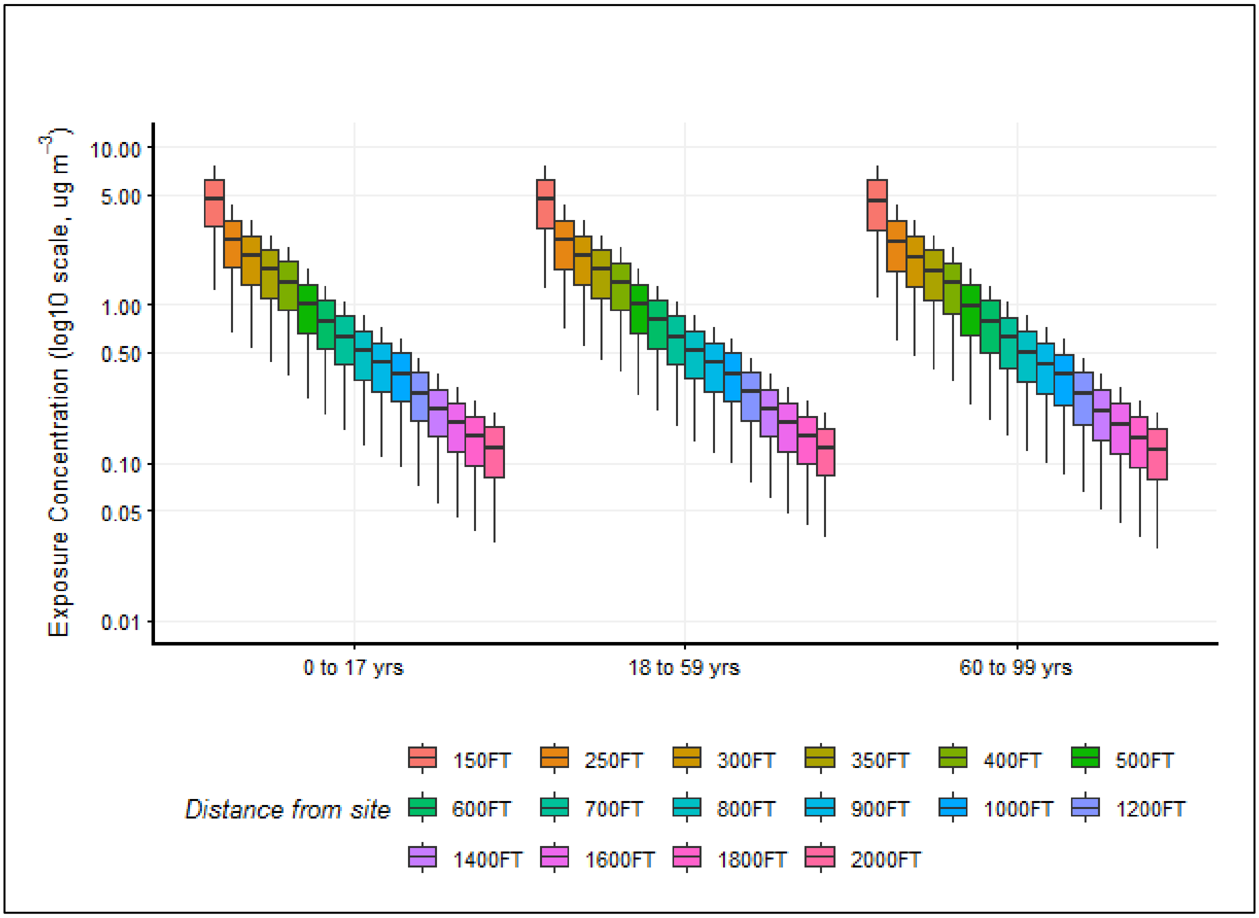
Figure 3-4. Distributions of Subchronic Propane Exposure Concentrations by Distance and Age Group, for Flowback Activities at the Northern Front Range (1-acre Well Pad Only)



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box).

log10 = logarithm base 10; ug m^{-3} = micrograms per cubic meter; FT = foot; yrs = years of age.

Figure 3-5. Distributions of Chronic Propane Exposure Concentrations by Distance and Age Group, for Production Activities at the Northern Front Range (1-acre Well Pad Only)



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box).

log10 = logarithm base 10; ug m^{-3} = micrograms per cubic meter; FT = foot; yrs = years of age.

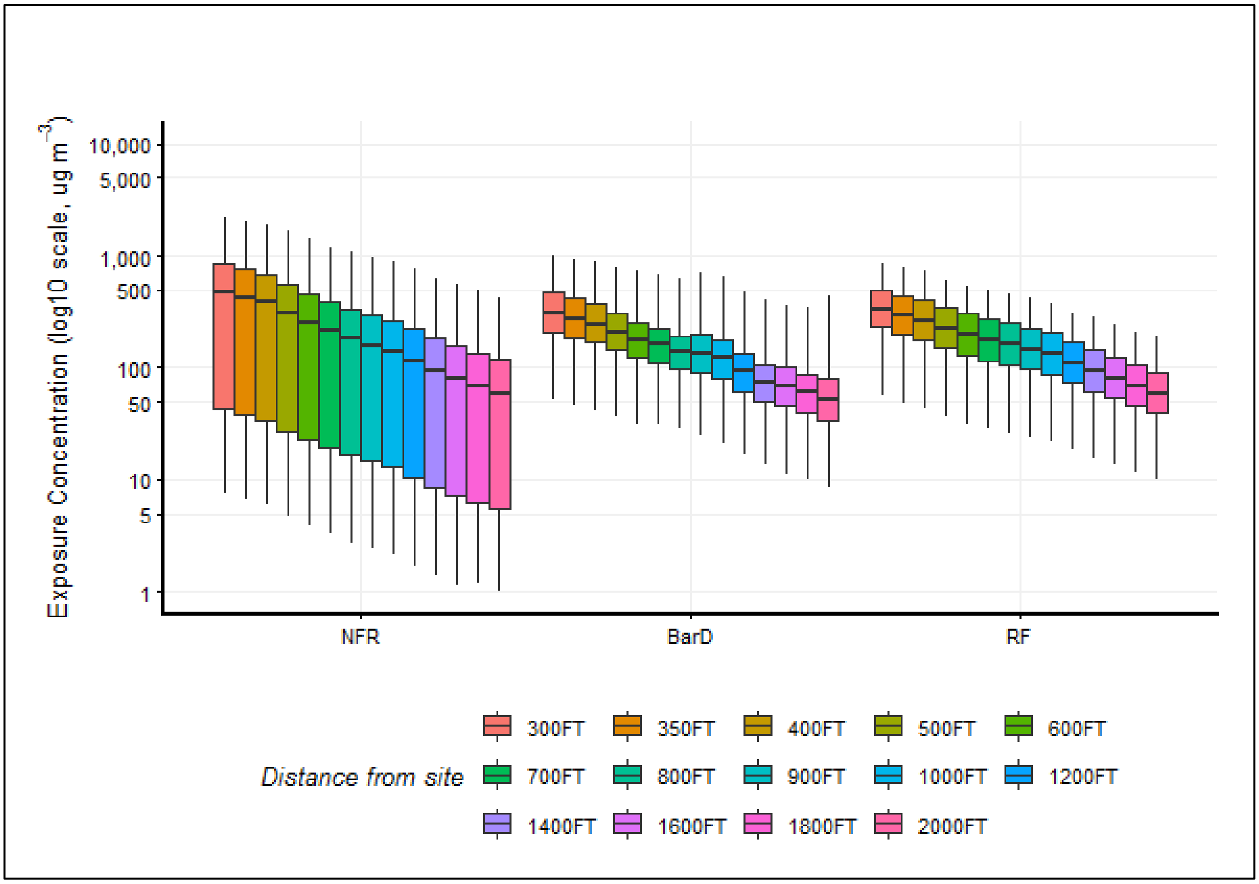
Figure 3-6. Distributions of Chronic Benzene Exposure Concentrations by Distance and Age Group, for Production Activities at the Northern Front Range (1-acre Well Pad Only)

The figures and text above directly reference certain chemicals, sites, activities, and exposure durations, but the overall patterns and observations we discuss above generally apply to all scenarios in these HHRAs.

3.5.2. Variations in Exposure by Distance

Exposures generally decline rapidly with distance from the well pad and there is a substantial range of values at each distance. These patterns are expected based on the patterns of air concentrations—see Section 2.9.1.1. We illustrate these declines and ranges in several figures in this section, utilizing exposure data for the youth age group, which are generally representative of the full set of modeled exposure results.

For ease of comparison, we generated Figure 3-7 to be roughly analogous to Figure 2-19, both showing VOC concentrations declining fairly consistently with distance from the well pad, and both also showing large ranges of concentration values at all distances. Figure 2-19 illustrates the distributions of benzene air concentrations during O&G development activities—specifically the maximum 1-hour-average values saved from each AERMOD Monte Carlo iteration, with data from all three development activities included in the distributions. These are the air-concentration data we used as ambient outdoor concentrations in the modeling of acute benzene exposures during development (with drilling air concentrations used for estimates of drilling exposure, and so on for fracking and flowback). In Figure 3-7, we illustrate the distributions of acute benzene exposure concentrations during development (drilling, fracking, and flowback are each included in this superset of benzene data). The distributions in Figure 3-7 utilize each hypothetical individual's maximum 1-hour exposure concentration from the 365-day time series (collected across the whole modeled population). Because Figure 3-7 shows collections of daily maxima rather than the full collection of all hourly acute values, the smallest of these daily-maximum exposure concentrations are larger than the smallest of the air concentrations shown in Figure 2-19, though the pattern of declining values with distance is similar in both figures. The maximum acute exposure concentrations shown in Figure 3-7 correspond well with the maximum air concentrations plotted in Figure 2-19, indicating as expected that the times of highest exposure in our modeling corresponded to a hypothetical individual either outside or in a situation of high VOC penetration into the micro during the hour of highest outdoor ambient air concentration.

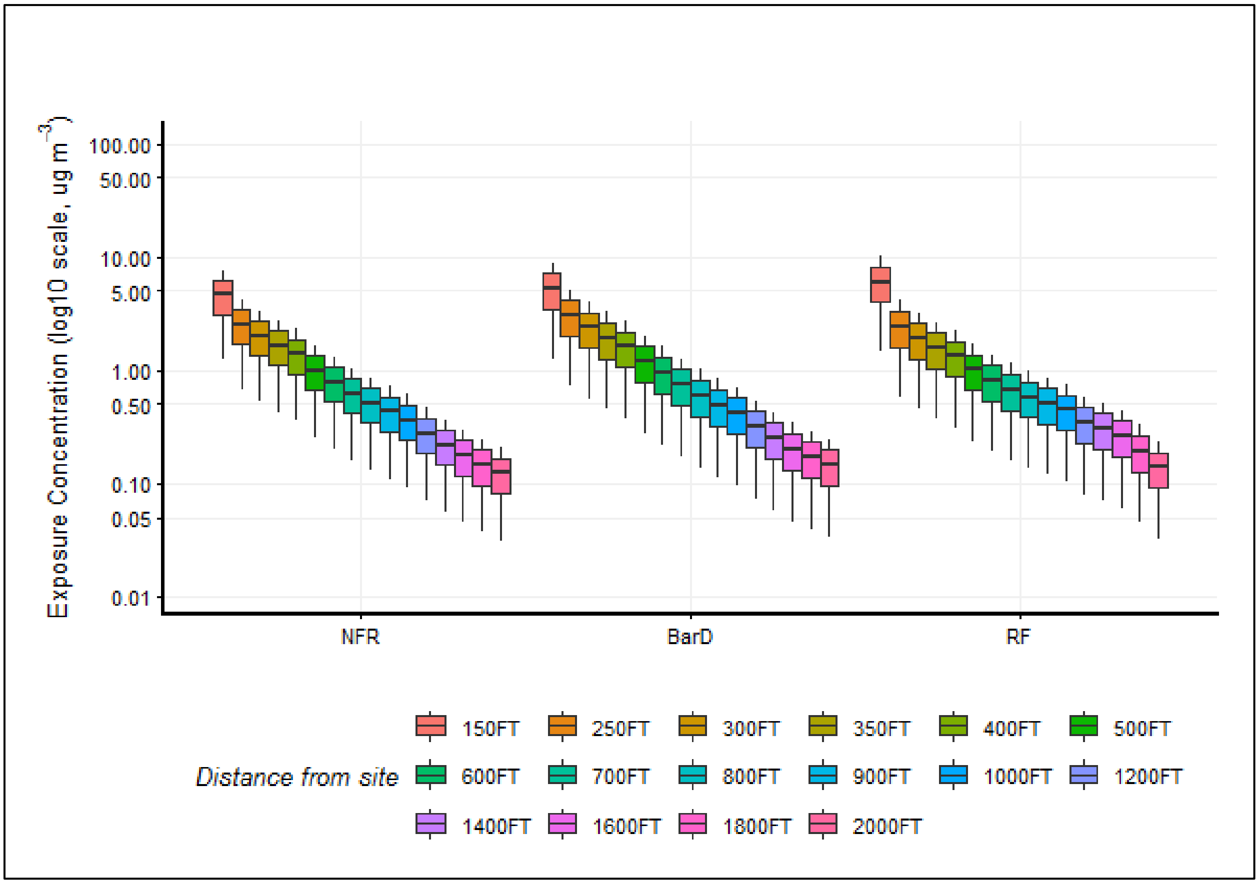


Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box).

log10 = logarithm base 10; ug m^{-3} = micrograms per cubic meter; FT = foot; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 3-7. Distributions of Acute Benzene Exposure Concentrations for Ages 0–17 Years, by Distance and Well-development Site (1-acre Well Pad Only), Across All Development Activity Types

Figure 3-8 is similar to Figure 3-7 but contains chronic exposure concentrations from emissions in the O&G production phase. All scenarios show generally consistent declining exposure with distance from the well pad. The ranges of chronic exposure concentrations are smaller than those of acute exposure, which is expected because the calculations in the chronic estimates average together the high and low hourly exposure concentrations, and all values in between, across a year. The air concentrations we used in chronic exposure modeling of O&G production were hourly values from modeled unit emissions (reflecting real hour-by-hour meteorology) multiplied by hourly production emissions randomly selected from the CSU VOC emission-rate data.



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box).

log10 = logarithm base 10; ug m^{-3} = micrograms per cubic meter; FT = foot; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

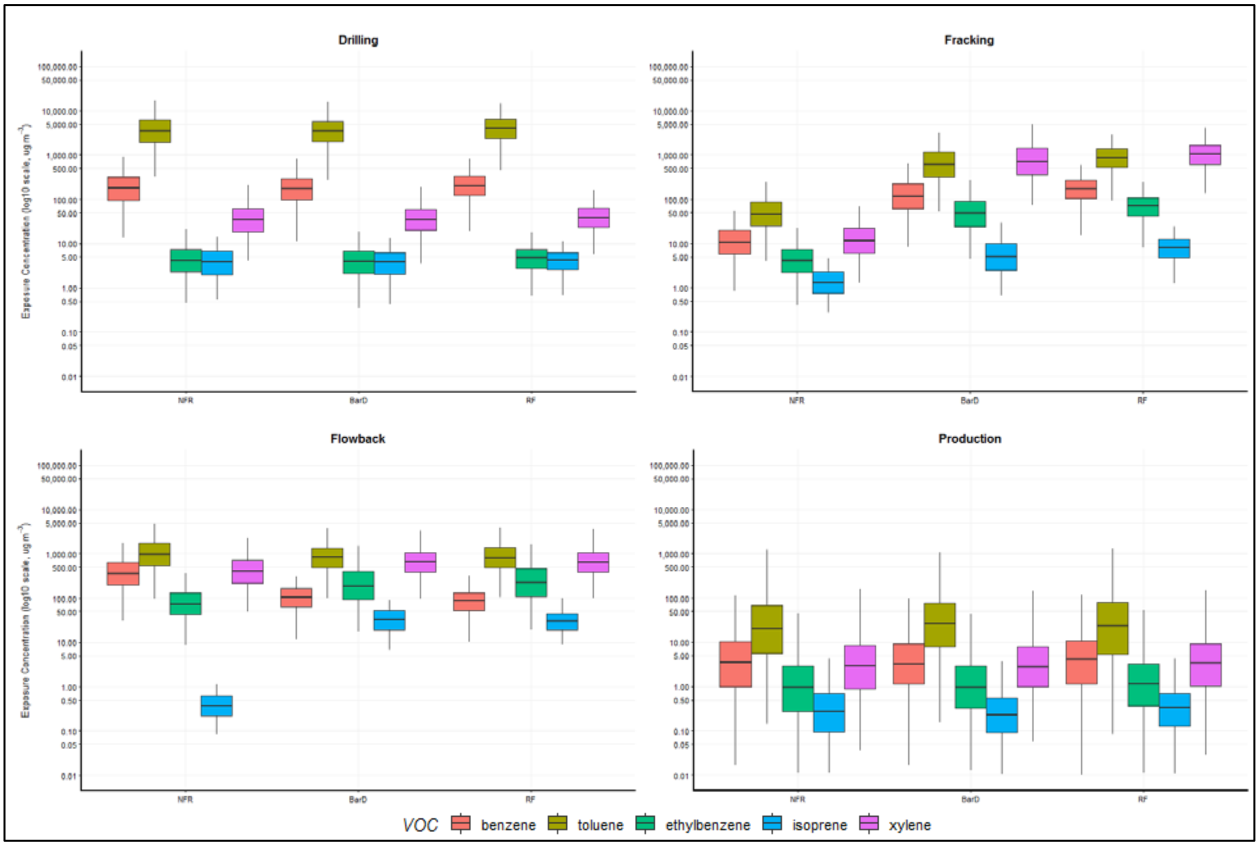
Figure 3-8. Distributions of Chronic Benzene Exposure Concentrations for Ages 0–17 Years, by Distance and Well-production Site

3.5.3. Variations in Exposure by Activity

As an additional QA check, we saw that **the variations in acute exposure concentrations generally follow the variations in the 1-hour-average air concentrations and the variations in the emissions**, as expected. Figure 3-9 is roughly analogous to Figure 2-21. Figure 2-21 is a plot of distributions of 1-hour-average concentrations for selected chemicals (benzene, toluene, ethylbenzene, isoprene, and m+p-xylene), stratified by O&G development activity and hypothetical O&G site, utilizing the 1-hour-maximum values from the AERMOD Monte Carlo iterations. We used these distributions of air concentrations in our modeling of acute exposure, and so we expect the resulting distributions of acute exposure concentrations to closely resemble these distributions in air concentrations. In Figure 3-9, we show distributions of acute exposure concentrations for the same chemicals as in Figure 2-21 and for the same O&G activities (plus production) and hypothetical sites. These exposure concentrations correspond to the youth age group modeled, though the adult values are nearly identical. Data from all modeled distances are included in these distributions.

In comparing Figure 3-9 to Figure 2-21, the distributions of acute exposure concentrations are generally consistent with the distributions of air concentrations used to estimate them. As we noted in discussing trends with distance in Section 3.5.2, the smallest values here are also taken from across all hypothetical individuals' maximum 1-hour exposure concentrations from the 365-day time series, rather than from all hours of the year, which is why the smallest values shown here are larger than those in Figure 2-21.

Other modeled chemicals will have distributions of air concentrations and exposures that are different from those shown here and in Figure 2-21, based on their respective distributions of emissions.



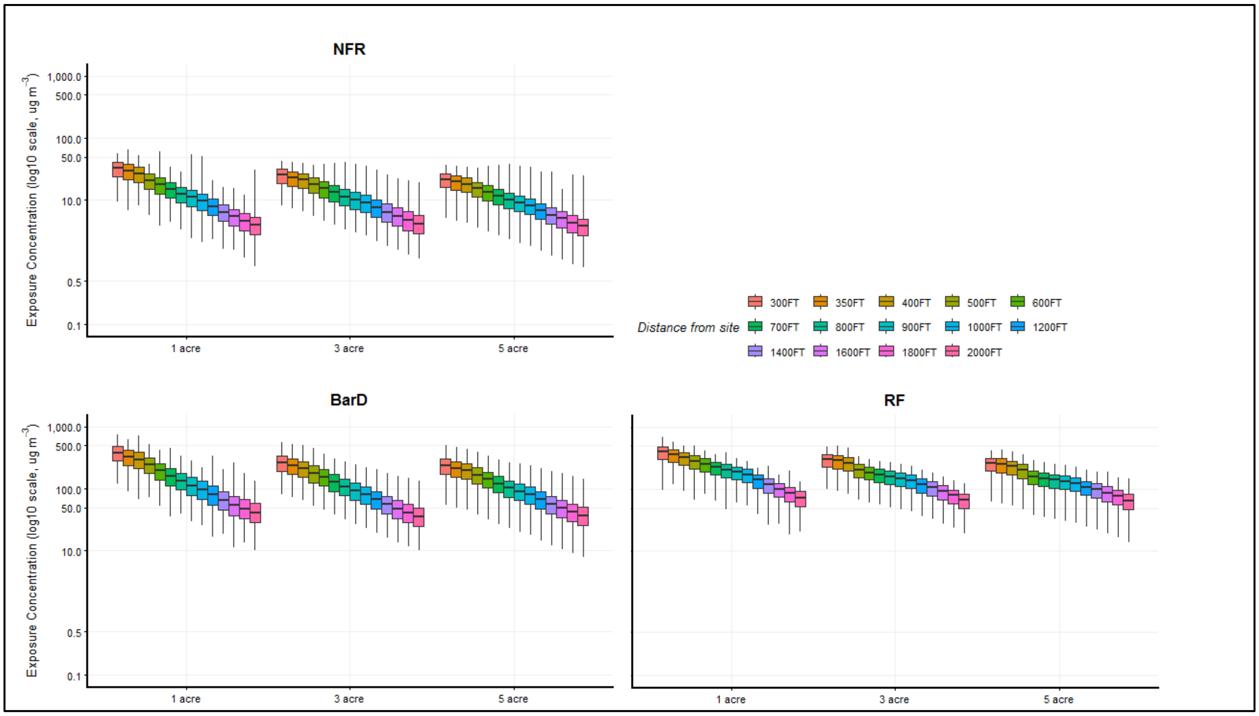
Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box).

log10 = logarithm base 10; ug m^{-3} = micrograms per cubic meter; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 3-9. Distributions of Acute Exposure Concentrations for Ages 0–17 Years, for Selected Chemicals by Oil and Gas Activity and Site (1-acre Well Pad Only), Across All Distances

3.5.4. Variations in Exposure by Size of Well Pad (Development Activities)

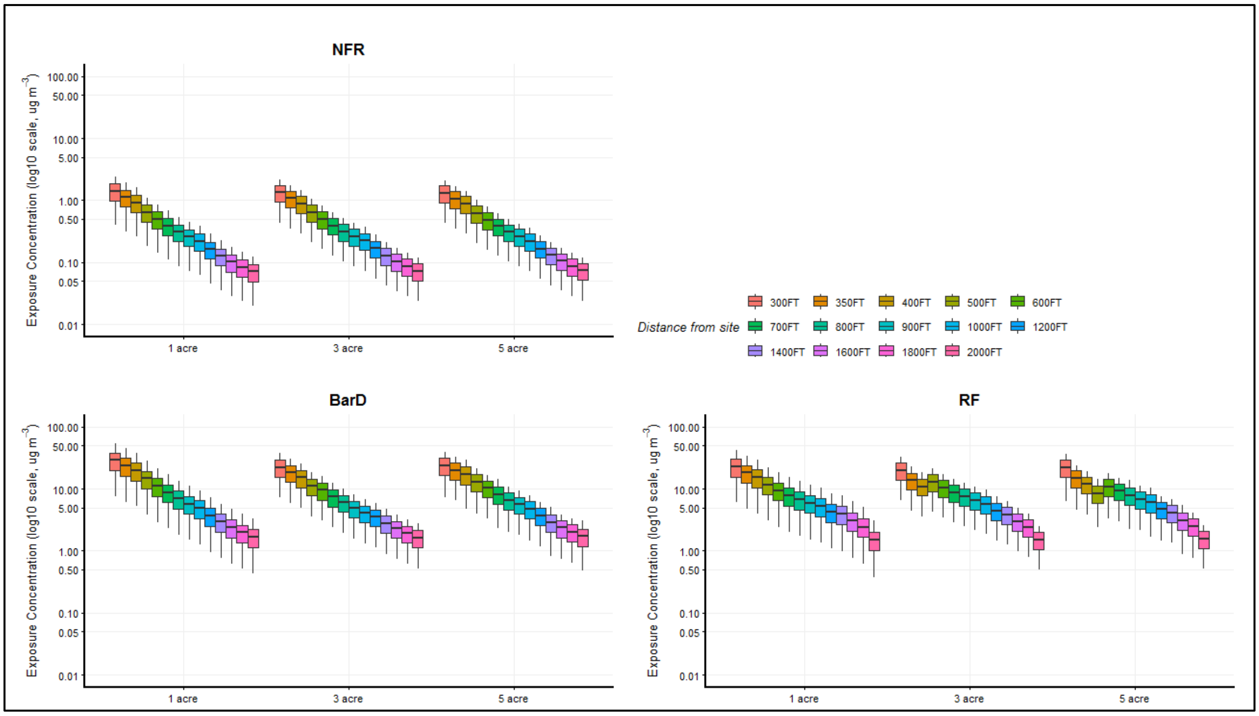
In Figure 3-10, we present distributions of acute benzene exposure concentrations during fracking, stratified by simulated O&G site, size of well pad, and distance from well pad (distances from well pad in these HHRAs are always relative to the center of the well pad). Figure 3-10 is similar to Figure 2-24 in Section 2.9.1.5, except Figure 2-24 includes data from all development activities (not just fracking), and those data are the maximum values from each Monte Carlo iteration (which we used in the acute exposure assessment, except here in Figure 3-10 the data comprise daily-maximum acute exposures). Figure 3-11 is similar to Figure 3-10 but for subchronic exposures. These values for youth are nearly identical to those for adults and older adults.



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box).

log10 = logarithm base 10; ug m^{-3} = micrograms per cubic meter; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 3-10. Distributions of Acute Benzene Exposure Concentrations between Different Sizes of Development Well Pads, for Fracking Activities (for Ages 0–17 Years)



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box).

log10 = logarithm base 10; ug m^{-3} = micrograms per cubic meter; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 3-11. Distributions of Subchronic Benzene Exposure Concentrations between Different Sizes of Development Well Pads, for Fracking Activities (for Ages 0–17 Years)

Maximum acute exposure concentrations related to 1-acre well pads tend to be somewhat higher than those related to 3-acre well pads, and values related to 3-acre well pads tend to be somewhat higher than those related to 5-acre well pads, although there are variations when stratified by distance from the well pad. The difference between 1-acre and 3-acre pads tends to be higher for maximum subchronic exposure concentrations relative to maximum acute exposure concentrations, with lower variability when stratified by distance. The subchronic concentrations tend to show relatively small differences when comparing 3- and 5-acre pads. For other chemicals and activities the differences can be larger in either direction.

Differences in these distributions between different O&G sites are likely related to differences in meteorological conditions, leading to different dispersion interactions between turbulence and wind flow and the initial well-pad emission plume. These general differences in exposures between different well-pad sizes, and how the O&G site and distance from well pad may affect these trends, were expected based on the dispersion results, as discussed in Section 2.9.1.5. A larger well pad will diffuse a fixed mass of emissions more than a smaller pad at locations close to the well pad, leading to lower initial concentrations in those areas, but also sometimes leading to mixed results farther from the well pad where atmospheric dispersion has a stronger effect.

3.5.5. Variations in Exposure by Duration of Exposure

The largest estimates of acute exposure from across the simulated population are always higher than the largest estimates of subchronic and chronic exposures for the same individuals, but that does not necessarily mean that estimates of potential health risks will follow that same pattern. The largest simulated acute exposure concentrations are always higher than the largest simulated subchronic and chronic exposure concentrations because those acute exposures correspond to single hours of high simulated VOC air concentrations, and across the longer subchronic and chronic averaging times those more extreme air concentrations are not sustained. During development activities, simulated maximum acute exposure concentrations (utilizing time series of air concentrations comprising the maximum values of the AERMOD Monte Carlo iterations) were about one to three orders of magnitude higher than simulated maximum subchronic exposure concentrations (utilizing time series of air concentrations comprising the mean values of the AERMOD Monte Carlo iterations), depending on the O&G site, activity, VOC, and distance from the well pad. Similarly, during production activities, simulated maximum acute exposure concentrations were about one to 2.5 orders of magnitude higher than simulated maximum chronic exposure concentrations.

The difference in a simulated individual's maximum acute and maximum subchronic or chronic exposure concentrations will depend on the amount of time the individual spends in different micros, how those times relate to the temporal patterns of ambient outdoor chemical concentrations, and how local meteorology affects dispersion. These differences will also depend on how much higher are the highest emission rates (more relevant for acute assessments) compared to the mean emission rates (more relevant for subchronic and chronic assessments). These differences do not necessarily mean that estimates of the potential for health risks will be larger for acute exposures relative to subchronic and chronic exposures; this is because the health-protective criteria concentration values (to which exposure concentrations are compared for estimates of health risks) change based on duration of exposure and expected critical effects.

3.5.6. Results Passed to the Risk Assessment

As shown in Table 3-7, for each O&G activity, we pass to the risk assessment various exposure-concentration metrics from across the modeled population, for all VOCs and sites, at the selected maximum receptor on each distance ring. These metrics are 1st percentiles, maxima, means, medians, and other percentiles, but as noted below the collection of data on which they are calculated differs between acute, subchronic, and chronic evaluations.

- For **acute** assessments, we calculated the means and percentiles of the collection, across the population, of each simulated individual's daily-maximum 1-hour-average exposure concentrations. That is 365,000 person-day values: 365 values per individual, 365,000 values across the 1,000 individuals of a given age group at each receptor location. Note that this is not the full collection of 8,760 hourly values in the year from each individual; we instead summarized the data by person-day to ease computational burdens while still being able to identify each individual's maximum 1-hour exposure, which is a primary metric for assessing the potential for acute exposures above health-protective levels.

- For **subchronic** assessments, we calculated the means and percentiles of the collection, across the population, of each simulated individual's multi-day-average exposure concentrations. The duration of multi-day exposure is specific to the O&G site, well-pad size, and activity, and we calculate these exposures based on contiguous calendar days for all possible periods in a year (e.g., for a four-day exposure, we calculated averages for January 1 through January 4, January 2 through January 5, and so on, with exposure periods at the end of the year being calculated as averages from December 29 through January 1, December 30 through January 2, and so on). This results in 365,000 person-period values: 365 values per individual, 365,000 values across the 1,000 individuals of a given age group at each receptor location. The exception to this methodology was for sequential development activities lasting a year or less, where we calculated exposures for the drilling, fracking, and flowback activities as a continuous exposure scenario. In these cases, we randomly paired an exposure period for the drilling activity with an exposure period for fracking, which in turn we paired with an exposure period for flowback. We performed these pairings 365 times for each of the 1,000 individuals of a given age group at a receptor. We averaged together the exposure concentrations for the individual activities, weighting based on the duration of each activity. As with subchronic exposures calculated for individual activities, we generated 365,000 person-period chemical exposure concentrations per receptor location for the sequential-activity scenarios. In some cases, based on activity durations, these sequential exposure scenarios exceeded 365 days in duration, making them subject to the chronic assessment rather than the subchronic assessment.

- For **chronic** assessments, we calculated the means and percentiles of the collection, across the population, of each simulated individual's annual-average exposure concentration. That is one value per simulated individual, totaling 1,000 values across the 1,000 individuals of a given age group at each receptor location. For sequential-activity scenarios that pair development activities with the production activity into a continuous exposure scenario, for each individual we paired each of the 365 sequential exposure scenarios for development activities (see previous bullet) with that individual's exposure scenario for production. We averaged together the exposure concentrations from each individual activity, weighting based on the duration of each activity, creating 365 chronic chemical exposure scenarios per individual at a receptor location for the sequential-activity scenarios. In a small number of cases, the flowback activity exceeded 365 days in duration. In these flowback cases, we calculated one exposure concentration per individual (the annual-average concentration), and for sequential-activity assessment we paired that concentration with the individual's production-activity concentration and randomly selected drilling and fracking concentrations for that individual, averaging together those concentrations with weighting based on the durations of the activities.

Table 3-7. Results Passed to the Risk Assessment for the Development and Production Stages

Variable	Development Stage	Production Stage
Sites	3 (Northern Front Range; BarD; Rifle)	3 (BarD; Rifle; we merged the Anheuser-Busch and Ft. St. Vrain data in the Northern Front Range exposure assessment)
Well-pad sizes[a]	3 (1, 3, and 5 acres)	1 (1 acre)
Data type for acute assessment	Metrics of daily-maximum 1-hour-average exposure concentrations	
Data type for subchronic assessment	Metrics of multi-day average exposure concentrations (duration depends on the site, well-pad size, and activity)	Not needed (the production stage lasts 30 years, so chronic assessment is most appropriate)
Data type for chronic assessment	Metrics of annual-average exposure concentrations (only required for activities or sequences of activities with durations longer than 365 days)	Metrics of annual-average exposure concentrations
Metrics	101 (mean, maximum, and percentiles 1st through 99th)	
Number of receptors per distance ring	14 rings with one receptor per ring, selected during the dispersion assessment as discussed in Section 2.7.3	16 rings (the same 14 as development, plus 2 closer in) with one receptor per ring selected during the dispersion assessment as discussed in Section 2.8

[a] When we calculate chronic exposures for the full sequence of development and production activities, the exposures to development emissions from 1-, 3-, and 5-acre well pads are each combined with exposures to production emissions from a 1-acre well pad.

3.6. Characterization of Data Gaps, Uncertainties, Variabilities, and Sensitivities

In general, the APEX exposure modeling is a hypothetical exercise where we create a synthetic population of individuals who reside, work, play, etc. in the same location (at a specific distance from the O&G activity). With any such hypothetical modeling, a number of assumptions are involved in the inputs, which in turn can introduce uncertainty/variability into the modeling.

In this section, we qualitatively discuss the various sources of uncertainty/variability in the input data used in the APEX exposure modeling, as well as potential sources of APEX model-based uncertainty, both of which can impact the estimated exposure concentrations. Additionally, we conducted some brief quantitative analyses to evaluate the sensitivity of the estimated exposure concentration results to some inputs/assumptions in the APEX modeling, as we discuss in detail in Section 3.6.3.

3.6.1. Gaps, Uncertainties, and Variabilities in Data

3.6.1.1. Air Concentration Inputs from AERMOD

APEX modeling uses air concentrations passed on by the air-dispersion modeling effort (Section 2), which essentially combines **emission rates** of specific O&G activities with the **meteorological data** from specific locations being modeled. These inputs into AERMOD are sources of uncertainty/variability, the nature of which was described in detail previously (see Section 2.10). **These uncertainties/variabilities will then be propagated into the APEX exposure modeling via the air concentrations**. Briefly, VOC emission rates used in these HHRAs are based on the limited, non-continuous air samples collected by CSU corresponding to certain specific O&G sites and activities. Although these can be assumed to be generally representative of the different activities and sites that we are trying to model, there is uncertainty introduced by the limited number of samples and the limited range of sampling times (sampling was done mostly during the day). For example, as a result of assuming the nighttime emission rates to be similar to those in the day, we might not be capturing any potential diurnal patterns in the VOC emissions, leading to possible under- or over-estimations of exposures. We believe our collaborative efforts with CDPHE resulted in choosing meteorology data representative of the variability between different sites to the best extent possible. As it is, any diurnal pattern seen in the modeled air concentrations from the air-dispersion modeling effort represents the diurnal pattern of meteorology of the site.

3.6.1.2. Penetration Factors

As discussed in Section 3.2.3.1, in this APEX modeling exercise we used the **factors method** of modeling penetration of the VOCs into the indoor and in-vehicle micros. This simply assumes that a fixed fraction, sampled from a distribution of factors, of the outdoor VOC concentration penetrates into the micro. The alternative method would have been a mass-balance-based method, which would have utilized more parameters such as the air-exchange rate, volume of the micro (for example, the house volume), and chemical sinks. Since our modeling exercise is mostly hypothetical, with a simulated population without any real data on building properties, **any assumptions about these additional input parameters would have introduced additional uncertainty into our exposure estimates**.

We have separated the 47 VOCs into two groups for indoor PENs: one with higher PENs (0.9–1) and the other with a larger range of PENs (0.1–1). Running the APEX model for each chemical separately would have been computationally prohibitive. We based these ranges on values obtained from scientific literature and on chemical properties that are relevant to chemical penetration. While the data available from the literature showed generally what we expected for the less-volatile group of VOCs (some lower PEN values), the data were much scarcer for the higher-volatility group and we assumed they followed a high-PEN distribution. Many of the studies were real-world measurements of micro/outdoor ratios where indoor sources, indoor sinks, and chemical build-up may have been present. The assumption of a maximum PEN restricted to 1 was based on the recommendation in the published studies that if there are no indoor emission sources (which we assume for these HHRAs), over a period of many hours a maximum PEN of 1 on average can be expected. An absolute restriction of maximum PEN=1 also neglects the possibility of lag time in air infiltration. We sampled from uniform distributions in the ranges of PENs, irrespective of time of year or any potential local patterns of building “tightness” in terms of chemical penetration, both of which can modify PEN distributions. **All of these issues and assumptions lead to uncertainty in our exposure modeling**. Therefore, we have further quantified the sensitivity of the estimated exposure concentrations to PEN distributions in a separate analysis discussed in Section 3.6.3.3, where we estimate sensitivities much less than a factor of 2 based on somewhat reasonable alternative assumptions.

3.6.1.3. Activity Diaries

As discussed in Section 3.2.2, we used a **hybrid set of CHAD activity diaries** due to CHAD data-availability restrictions: we employed in our modeling either diaries specific to the Mountain West states (adults) or from across the US (youth and older adults). Choosing activity diaries from across the US instead of those from just the Mountain West states could potentially mischaracterize expected activities for the region and in turn introduce uncertainty into the exposure estimates. If more age/region-specific CHAD activity data were available for children and older adults, that would reduce the uncertainty. In order to test if these assumptions had any impact on our exposure estimates, we did a simple quantitative sensitivity analysis (discussed below in Section 3.6.3.2) and found that there is virtually no difference between using adult activity diaries from the Mountain West and those from the entire US.

3.6.1.4. Commuting to Work

In our current modeling effort, we **assume that the modeled hypothetical children and adults commute** to a school/workplace (if the activity is present in the chosen CHAD diary), **but we also assume that the school/workplace is located at exactly the same location as the individual's residence**. This is a conservative assumption, since the schools/workplaces are almost certainly outside of the 2,000-foot modeling radius we use around the O&G site. This could impact the magnitude of the estimated VOC exposure concentrations. We ran a simple quantitative test with hypothetical individuals leaving the model domain for a period of the day. We describe this test in Section 3.6.3.1, where we saw relatively low impacts of daytime commuting on the modeled exposure estimates, mainly owing to lower concentrations near the O&G site during these times when the individuals were away at school/work.

3.6.2. Model Uncertainty

As it is, the estimation of exposure concentrations in the APEX modeling is a simple calculation of time spent in a micro and the air concentration in that micro, averaging across time and across micros. Therefore, there is **minimal model uncertainty for estimates of exposure concentrations**, with most of the uncertainty introduced by the model inputs/assumptions as discussed earlier.

3.6.3. Sensitivity Analyses

Exposure concentrations estimated by APEX are most sensitive to inputs of air concentrations and chemical PENs. We discuss estimated air concentrations in Section 2. In this section, we examine the sensitivity of the exposure modeling results to the three separate factors enumerated below.

1. spending time away from the well site during hours 8 am to 6 pm

2. expanding the database of activity diaries

3. expanding the range of PENs

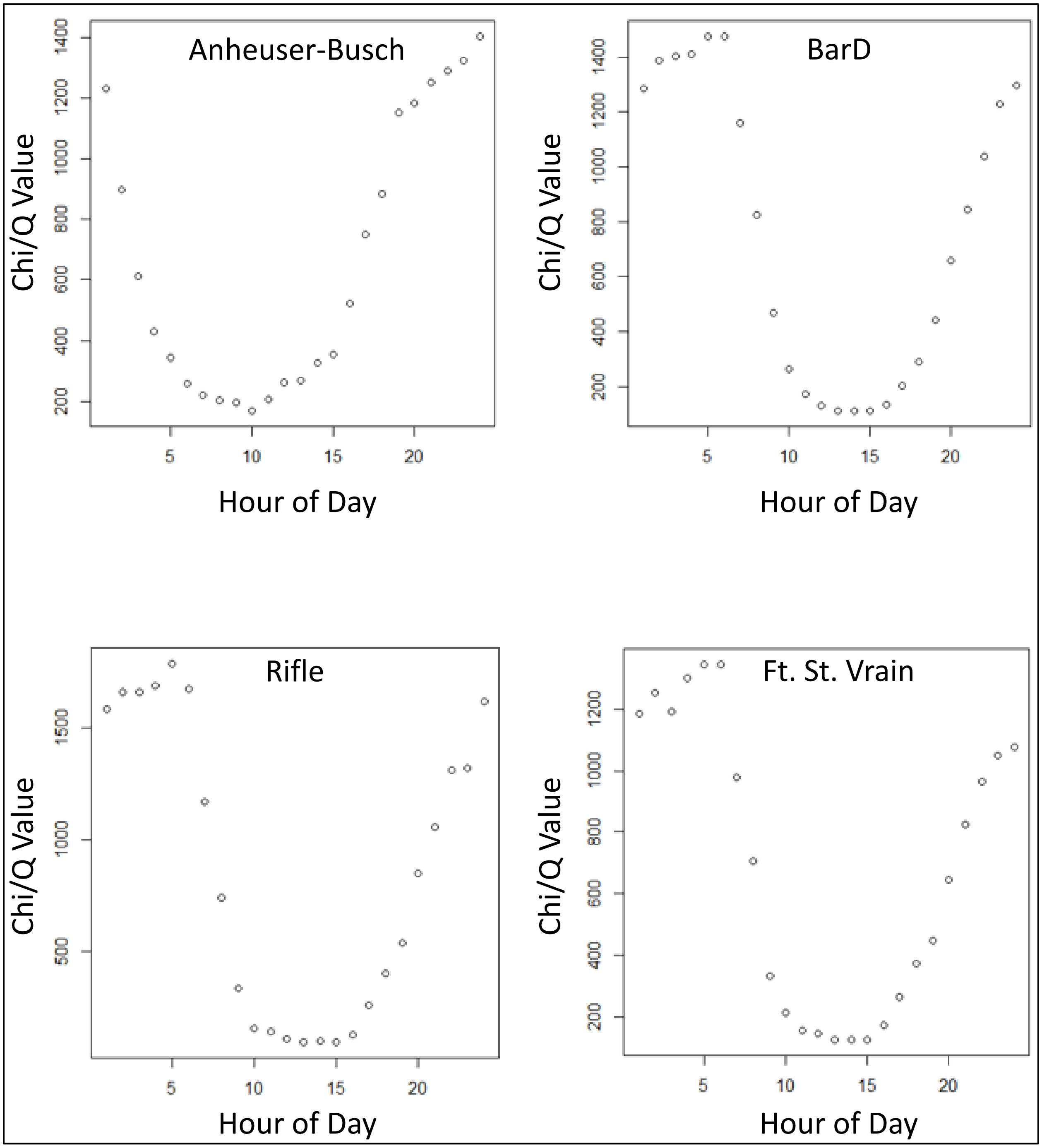
As discussed in the remainder of this section, **of these three factors the PENs may potentially be the most influential, although the estimated 41-percent reduction in mean chronic exposure required a fairly extreme assumption**. It is also unlikely that one could increase the mean exposure by more than this. Spending time away from home between 8 am and 6 pm reduced exposure between 3 and 25 percent, depending on site and distance from the source. If one worked on the night shift, this reduction would clearly be larger, but that would apply to a small fraction of the population. The geographical limitation of the database of activity diaries had a negligible effect on exposure.

3.6.3.1. Commuting

We conducted the APEX exposure modeling on hypothetical individuals who live and stay at the same location relative to the well pad at all times. This is straightforward to implement, compared to the alternative of constructing realistic workplace exposures without data collected on those individuals' places of employment. In the absence of such information, for nearly all simulated individuals the existing method of estimating exposure is health-protective, which means that it somewhat overstates the potential for exposure to emissions from the modeled well pads. The reason for this is that nearly everyone living close to a well pad will work, go to school, or otherwise spend time farther away from that pad (where VOC concentrations from the pad will be lower), and we are not considering exposure to other sources of the modeled VOCs.

The purpose of the first type of sensitivity analysis is to quantify the effect of this assumption. The simple, intuitive estimate is that if a person is near the well pad for just 14 hours per day (e.g., 6 pm to 8 am), and if there is no exposure to the evaluated VOCs during the remaining hours, then their exposure would be about 14/24, or 58 percent, of their exposure had they stayed home all day (a 42-percent reduction). This would be true (on average) if the time spent at home (or away from home) is not correlated with air concentrations.

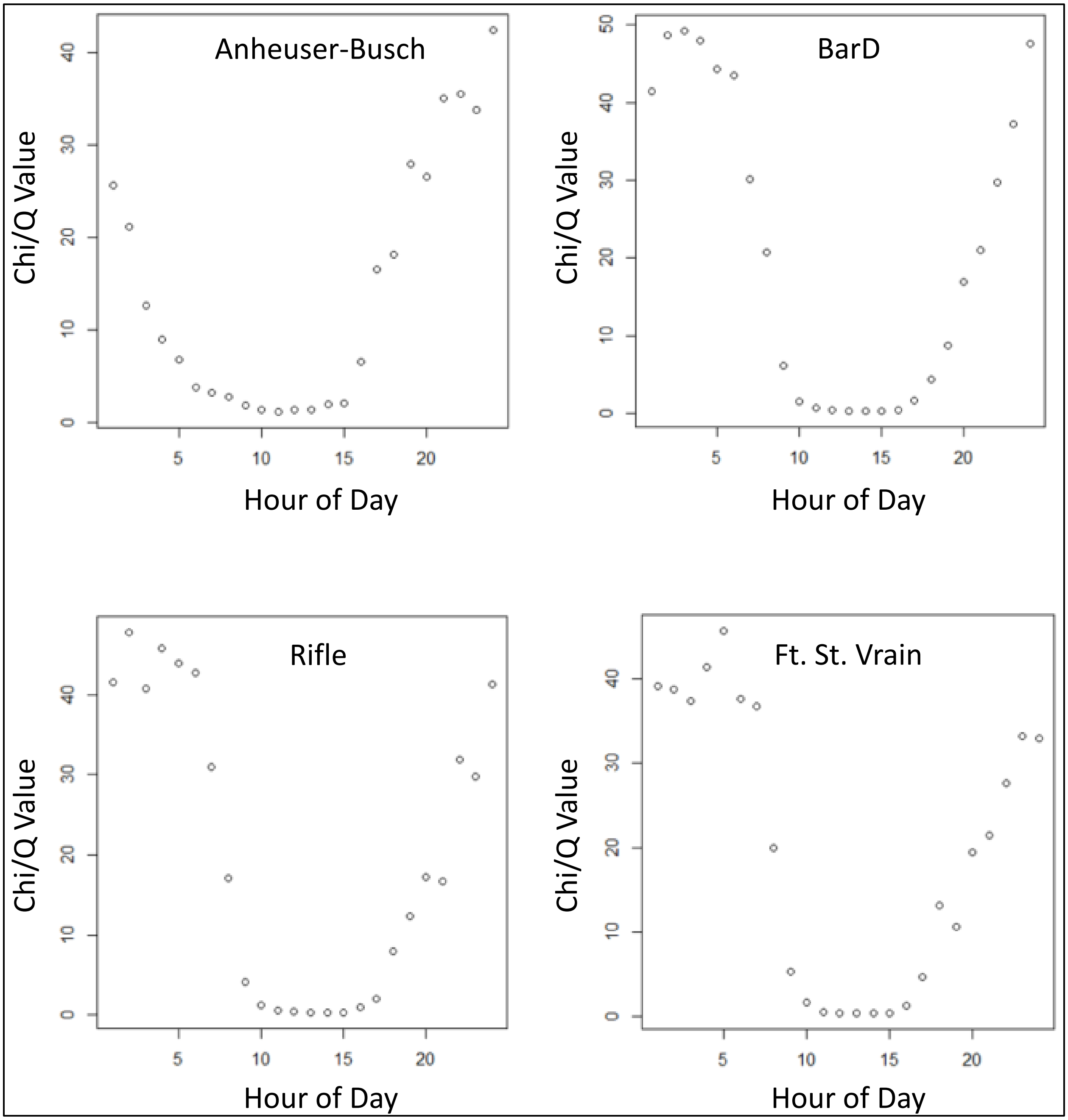
However, the air-dispersion modeling results show a strong diurnal pattern in concentrations that apply to all VOCs. This arises from the combination of a strong diurnal pattern in the dispersion measure Chi/Q (air concentration per unit emission strength), coupled with emission rates that are not dependent on time of day in our modeling. We show in Figure 3-12 and Figure 3-13 plots of mean Chi/Q values by hour of the day for the closest and farthest radial distances (150 and 2,000 feet), respectively, at each of the four meteorological sites. These are annual-average values by hour of day utilizing a 1-acre well pad, and the values correspond to the receptors selected as described in Section 2.8. The shapes of the profiles are generally similar between the two distances, indicating **substantially lower concentrations during daytime hours relative to nighttime**, with peaks in the early morning hours and minima near noon, plus or minus a few hours. This trend is likely due to higher mixing heights and greater turbulent mixing during the daytime, leading to more chemical dilution relative to nighttime when mixing heights and turbulent mixing tend to be lower. Variable wind speeds may also play a role.



Notes: Receptor selected as per methodology described in Section 2.8.

Chi/Q = air concentration (micrograms per cubic meter) per emission rate of 1 gram per second; Anheuser-Busch and Ft. St. Vrain = the Northern Front Range sites; BarD and Rifle = the Garfield County ridge-top and valley sites.

Figure 3-12. Average Air Concentration per Unit Emissions at Selected Receptor 150 feet from 1-acre Well Pad



Notes: Receptor selected as per methodology described in Section 2.8.

Chi/Q = air concentration (micrograms per cubic meter) per emission rate of 1 gram per second; Anheuser-Busch and Ft. St. Vrain = the Northern Front Range sites; BarD and Rifle = the Garfield County ridge-top and valley sites.

Figure 3-13. Average Air Concentration per Unit Emissions at Selected Receptor 2,000 feet from 1-acre Well Pad

The "No Commuting" column in Table 3-8 contains annual-average air concentrations for the scenario where modeled individuals spend all their time near the well pad (the scenario employed in the HHRAs). For the alternate scenario of commuting and spending time away from home, the time spent away should include work time plus travel (commute) time and lunch time. For simplicity, this is also applied on weekends, when the time away from home may include shopping, visits with friends or family, and other activities. The choice of time away from home was 8 am to 6 pm, or 10 hours per day. For data presented in the "With Commuting" column in Table 3-8, we replaced those hours with Chi/Q values of zero and recalculated the annual average. Since exposures per unit air concentration are nearly independent of the time of day in our modeling, these are reasonable estimates for the ratios of chronic or subchronic exposures when commuting is and is not accounted for.

Table 3-8. Annual-average Air Concentration per Unit Emissions at Selected 150-foot Receptor and Selected 2,000-foot Receptor (1-acre Well Pad)

Distance from Well Pad (feet)	Site	Annual-average Chi/Q		
		No Commuting	With Commuting	Ratio (With Commuting / No Commuting)
150	Anheuser-Busch	655.3	491.4	0.750
	BarD	746.7	663.8	0.889
	Ft. St. Vrain	681.2	596.8	0.876
	Rifle	853.6	777.2	0.911
2,000	Anheuser-Busch	14.15	11.95	0.844
	BarD	21.97	20.30	0.968
	Ft. St. Vrain	19.61	18.42	0.939
	Rifle	19.91	19.16	0.962

Notes: Chi/Q = air concentration (micrograms per cubic meter) per emission rate of 1 gram per second; Anheuser-Busch and Ft. St. Vrain = the Northern Front Range sites; BarD and Rifle = the Garfield County ridge-top and valley sites.

At the 150-foot location, the ratios ranged from 0.750 to 0.911 (concentrations with commuting were 9–25 percent lower than without commuting), which are much higher than the simple estimate of 0.58 (concentrations with commuting being 42 percent lower than without commuting) based on the fraction of time spent at home. At the 2,000-foot location, all the ratios were closer to one, ranging from 0.844 to 0.968. The conclusion is that **people who are away from home between 8 am and 6 pm every day and experiencing zero exposure during those times would have between 3- and 25-percent lower average exposures than people who are always near the well pad**, depending on the site and the distance from the pad. Individuals working the nightshift would experience a greater reduction in exposure by being away from the well pad overnight.

3.6.3.2. Choice of Activity Diaries

For the HHRAs, for the adult age group (ages 18–59 years) we used CHAD activity diaries (corresponding to suitable ages) from the eight Mountain West states (Colorado, Arizona, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming). The other two age groups used diaries from all states because of the relative paucity of diary data for their ages from the Mountain West states. This particular sensitivity analysis is meant to quantify the effect of geographically restricting the database of activity diaries when running the APEX model, whereby we conducted test runs of hypothetical adults (ages 18–59 years) at the Rifle site utilizing the full national database of activity diaries and compared the resulting exposures to those utilizing only the Mountain West database.

Average exposure concentrations were nearly unchanged between the Mountain West runs and the national runs. There was no difference in peak hourly exposure, and there were differences of less than 1 percent for annual-average exposures. The conclusion is that **the geographical extent of the activity database has a negligible effect on the exposure results**. This occurs because even when restricted to eight states, a large population's activities, in aggregate, do not differ very much from the rest of the country in either outdoor time or travel time. Other aspects of behavioral differences may exist but are not captured by the current calculations.

3.6.3.3. Changing the Penetration Factors

This sensitivity analysis examines the consequence of using lower PENs than in the HHRA runs, for indoor and in-vehicle micros. Each of the 1,000 simulated individuals in the run was randomly assigned one PEN value for the vehicle micro and one PEN value for the indoor micro, from their respective distributions of PENs. These values were assumed to remain constant over time, as people tend to have fairly consistent habits. For example, in some houses the windows will be opened regularly, and in others they will never be opened. This also applies to cars. This assumption creates wider variation in the chronic exposures across modeled individuals than if each simulated individual was assigned many random PENs over time. In the latter case, the annual-average exposure would reflect a time-averaged PEN, and this would have relatively little variation from one person to another.

Calculation of VOC concentrations during time spent in vehicles in the HHRA runs used PENs sampled from a uniform distribution between 0.9 and 1, which is written as U(0.9,1) for short. Higher PENs are health-protective in that the resulting exposure is relatively high. While many vehicles have high PENs, it is also possible to keep the windows closed and have the climate-control system on "recirculate". To account for "tighter" vehicles, in this sensitivity analysis we set the alternative distribution for the vehicle PEN as U(0.5,1). This results in a roughly 21-percent drop in the typically selected in-vehicle PEN.

Homes may also be relatively "tight", with reduced air exchange. However, in our literature searches for the HHRAs we found few (if any) observations indicating PEN<0.1, which was the lower bound we used for the lower-PEN VOCs in the HHRAs. The distribution for the HHRA APEX runs was U(0.1,1) for lower-PEN VOCs. For the sensitivity analysis, we utilized U(0.1,0.5), resulting in a roughly 45-percent drop in the typically selected indoor PEN for these VOCs.

In our test runs with adults (ages 18–59 years) at the Rifle site, **utilizing the altered PEN ranges (lower minimum PEN for vehicles, lower maximum PEN for indoors) made no difference in peak hourly exposure concentrations, but they resulted in a 41-percent reduction in the annual-average exposure concentrations**. This reduction makes sense given that people will usually spend most of their time indoors, so that the typical 45-percent reduction in indoor PEN will have a large impact on overall exposure. It is reasonable to conclude that the HHRA runs might overestimate exposure by up to 50 percent (but probably not more) for lower-PEN VOCs, in cases where highly energy-efficient home construction may significantly reduce infiltration of such VOCs. This may apply only to VOCs with low PENs; for high-PEN VOCs, it may be difficult to achieve much reduction by tightening houses.

We did not conduct sensitivity analyses with increased PENs because it is clear that they have an upper bound of 1 in the absence of indoor sources. Hence, even for a person who always has windows down/open in their vehicles and homes, exposures indoors and in vehicles will never exceed outdoor exposures given the chemical infiltration modeling assumptions. Compared to the PEN ranges used in the HHRAs, utilizing PEN=1 in all micros (constant exposure to outdoor levels of VOCs) would lead to a 65-percent increase in annual-average exposures for the low-PEN VOCs and a 5-percent increase for the high-PEN VOCs. Thus, **the potential for underestimating chronic exposure due to choice of PENs is no more than 65 percent, and probably much lower than 65 percent**.

4. Selection of Health Criteria Values for Assessment of Potential Health Risks

To characterize the potential for non-cancer health effects from acute, subchronic, and chronic exposures to the assessed VOCs, and to estimate lifetime cancer risks associated with chronic exposures to two VOCs believed to be carcinogenic to humans, **these HHRAs rely on toxicological and health-effects assessments conducted by EPA, Agency for Toxic Substances and Disease Registry (ATSDR), and state agencies charged with protecting the public health from adverse effects of chemical exposures**. In deriving these toxicological criteria, the agencies adopt health-protective assumptions to protect against adverse effects of chemical exposure. In this analysis, we estimate the potential for health risks from chemical exposure by **comparing our chemical exposure estimates to these protective health criteria values**.

4.1. Non-cancer Hazard Estimates for Individual Chemicals

We assessed the potential for non-cancer health effects by calculating hazard quotients (HQs) for exposure to individual VOCs. We calculated HQs for a VOC by dividing the estimated exposure by the corresponding VOC health criterion, as shown in Eq. 4-1 below.

$$\text{HQ} = \text{Exposure Concentration}/\text{Health Criterion Value} \qquad \text{Eq. 4-1}$$

The exposure concentration used in each calculation is unique to each modeled O&G scenario (site, size of well pad/number of wells, O&G activity) and each modeled distance of a simulated person relative to the well pad. The exposure concentration also changes based on the duration of exposure, and as does the health criterion value. **That is, the health criterion value in each HQ calculation is unique to each VOC and time frame of exposure**. We list in Section 3.3 the three time frames of exposure that are relevant to these HHRAs. Therefore, each VOC has up to three relevant health criteria values (see further discussion in Section 4.1.1).

HQ values do not provide numerical estimates of the incidence or severity of adverse effects; instead, they are intended as a **screening tool** used to identify chemical exposures that pose potential concern for adverse health effects. HQ values less than 1.0 (exposures below criteria values) are generally considered to indicate that adverse health effects are unlikely to occur, even in sensitive subpopulations, for the exposure durations being evaluated. **HQ values greater than 1.0 (exposures above criteria values) suggest the need for additional evaluation as to the potential for adverse effects**. The greater the HQ above a value of 1.0, the greater the potential for adverse effects. In Section 5.6, we provide additional discussion about uncertainties associated with these criteria values.

4.1.1. Sources and Selection of Health-based Criteria and Data Gaps

For the screening analysis of potential non-cancer effects, we conducted a review of the available health criteria values (exposure levels defined as being without appreciable risk of adverse effects) promulgated by EPA, ATSDR, and state regulatory and health agencies. Numerical criteria values for the same VOC often vary among agencies because they were derived based on different supporting data and studies, the agencies used different methods in the derivation of “no-effects levels,” and the agencies made different science policy decisions with regard to margin of safety for the general population and sensitive groups. **In selecting criteria values that were appropriately health-protective, we used a systematic approach to select the values for each of the assessed VOCs for acute, subchronic, and chronic exposures** (which we defined earlier in Section 3.3).

We list below the potential health criteria values included in our review.

- EPA Reference Concentration (RfC)
- ATSDR Minimal Risk Level (MRL)
- Other inhalation health criteria promulgated by EPA, principally the Provisional Peer-reviewed Toxicity Value (PPRTV)
- Inhalation health criteria by state agencies including those listed below.
  - Reference Value (ReV) promulgated by the Texas Commission on Environmental Quality (TCEQ)
  - Reference Exposure Level (REL) promulgated by the California Office of Environmental Health Hazard Assessment (OEHHA)
  - Effects Screening Levels (ESLs) promulgated by the TCEQ, where an ReV was not available

We based the selection of each health criterion value for each VOC on which values were the best documented, were based on the most recent studies, used current, generally accepted derivation methodologies, and had sufficient supporting documentation. When values meeting these criteria were unavailable, we used alternative values in their place (e.g., values with more limited supporting data or were not peer reviewed). Where available, we generally found EPA RfCs and ATSDR MRLs to be the best-documented of the reviewed values, having been subject to extensive scientific review, and derived in such a way as to be protective of both the general population and sensitive groups. When available, we preferred RfCs and MRLs as criteria values. PPRTVs are, by definition, provisional, and therefore intended for use when RfCs or MRLs were not available. We used criteria values promulgated by state agencies either when EPA or ATSDR had not promulgated criteria values or when state values were derived based on more recent data, analyses, or hazard-characterization methods (e.g., benchmark doses rather than no-observed- or lowest-observed-adverse effects levels). In addition, where two or more criteria values were available from sources derived using similar methodologies and approaches, we generally selected the more protective value or value derived from more recent data. In some cases, we used the same health criteria values for more than one chemical, following guidance from the various agencies as to which chemicals can be “grouped” together and reference the same data. When data are lacking on a specific chemical, data from a similar chemical or "surrogate" (e.g., based on chemical structure) can be used for decision making. We provide in Appendix B a complete table of the criteria values selected for these HHRAs. Table 4-1 contains a summary of the number and types of VOCs whose criteria values we selected from each source.

Table 4-1. Selected Sources of Non-cancer Health Criteria Values for the Assessed Chemicals

Source Hierarchy	Number of Chemicals	Types of Chemicals
Chronic		
EPA RfC	11	hexane, cyclohexane, substituted benzenes
ATSDR MRL	1	benzene
EPA PPRTV	5	C5-C9 alkanes
TCEQ ReV	20	mostly low-MW alkanes, alkenes
TCEQ ESL	7	disubstituted benzenes, isoprene, etc.
OEHHA REL	1	propane
NA	2	asphyxiants
Subchronic		
EPA RfC	3	trimethylbenzenes
EPA PPRTV	29	substituted benzenes, medium-MW alkanes, alkenes
NA	16	styrene, most low-MW alkanes, alkenes
Acute		
Literature Review	1	benzene
ATSDR MRL	1	toluene
TCEQ ReV	32	most aromatics, aliphatics, isoprene = proposed
TCEQ (interim) ESL	10	11 interim, 4 based on TCEQ surrogates
NA	3	ethane, propane, propene

Notes: RfC = Reference Concentration; MRL = Minimum Risk Level; PPRTV = Provisional Peer-reviewed Toxicity Value; ReV = Reference Value; ESL = Effects Screening Level; REL = Reference Exposure Level; EPA = U.S. Environmental Protection Agency; ATSDR = Agency for Toxic Substances and Disease Registry; TCEQ = Texas Commission on Environmental Quality; OEHHA = California Office of Environmental Health Hazard Assessment; MW = molecular weight; NA = not available.

As can be seen in Table 4-1 and Appendix B, for a given VOC we often selected the criterion value from different sources for acute, subchronic, and chronic exposure durations. For chronic exposures, TCEQ ReV and ESL values constituted a large proportion of selected criteria values; this is primarily because RfC or MRL values have not been promulgated by EPA or ATSDR, respectively, for most of the VOCs. For subchronic exposures, EPA PPRTVs were the only criteria values available for the majority of VOCs and no values were available for 16 of the VOCs. For acute exposures, most of the available criteria values were promulgated by TCEQ. If a criterion value was not available from any of these sources, we did not calculate the HQ for that VOC; this occurred for 2 VOCs for chronic non-cancer assessment, 16 VOCs for subchronic, and 3 VOCs for acute.

In the case of benzene, which is frequently detected near O&G operations, the available acute criteria values promulgated by different regulatory agencies (OEHHA and TCEQ) differed by more than a factor of 20—8 parts per billion (ppb) versus 180 ppb. We therefore conducted a detailed literature review to evaluate the basis for the acute criteria derivation (see Appendix C). We did not consider ATSDR acute MRL values in this analysis because they apply to durations of 14 days or less instead of 1-hour exposures. Based on the literature review, we chose to utilize a criterion value of 30 ppb to evaluate hazards associated with acute benzene exposure.

4.2. Hazard Characterization for Combined Exposures

HQ values characterize the potential for adverse effects from exposures to individual chemicals. Because a large number of VOCs are released concurrently from O&G well-development and production activities, it is also necessary to generate hazard estimates for multiple (simultaneous) exposures. Because there usually are little or no data related to the health hazards associated with a specific chemical mixture, **we calculated hazard indices (HIs) to estimate the combined effects of multiple VOCs that might act on the same target organ or show similar critical effects**.

In these HHRAs, we calculated the HI for a critical-effect group by summing the HQ values for all VOCs having that critical toxic effect, as shown in Eq. 4-2 below for *n* VOCs in each group.

$$\mathrm{HI} = \sum_{i=1}^{n} HQ_i \quad \text{Eq. 4-2}$$

Conventionally, HI values less than 1.0 are also considered to be health-protective because of the high degree of conservatism built into the constituent HQ calculations; however, the degree of uncertainty associated with interpreting the values is probably larger than for individual HQs. **As with HQs, instances where HI values exceed 1.0 are subject to further analysis**.

4.2.1. Selection of Critical-effect Groups

For each VOC, we assigned one or more critical-effect group based on the critical adverse effects reported in the literature for that VOC (effects occurring at the lowest exposures in the studies used to derive the criteria values). We assigned more than one critical-effect group if the effects were seen at similar exposure levels. In addition to effects noted in critical studies, we also identified other toxic effects that were well-documented to occur at similar exposures. We did not use toxicity occurring only at exposures far above the critical effects to inform the groups. We show in Table 4-2 the **ten non-cancer critical-effect groups** identified for the VOCs in these HHRAs. We provide in Appendix D the complete list of group assignments of each VOC.

Table 4-2. Hazard Index Critical-effect Groups

developmental
endocrine
hematological
hepatotoxicity
immune
nephrotoxicity
neurotoxicity
respiratory
sensory
systemic

We assigned these groups separately for acute, subchronic, and chronic effects. Often, the critical effects identified for a given VOC differed depending on exposure duration, and if no effect data were available in the supporting information, we did not assign the chemical to any effect group. Also, the individual group meanings may cover slightly different spectra of effects for different exposure durations (see Appendix D). Groups vary with regard to specificity, as noted below.

- The “neurotoxicity” group includes pathological changes in the central and peripheral nervous system, as well as neurobehavioral changes. For acute exposures, neurotoxicity may include reversible “intoxication” (blurred vision, diminished reflexes, decrease alertness), while subchronic and chronic neurotoxicity also covers less reversible pathological changes in the peripheral and central nervous system.
- The “hematological” group includes changes in both red and white blood-cell populations (short of overt immune effects).
- The “systemic” group is limited primarily to VOCs for which the observed critical effect is reported to be loss (or reduced gain) in body weight. The underlying cause for the observed effects is often not known.
- We applied the “sensory” group exclusively to acute exposures. Sensory effects include eye, nose, and throat irritation.
- For chemicals showing a lack of an effect at the levels used in the criteria-value calculations, we grouped them as best as possible based on known effects at higher doses according to the conventions described here.

4.3. Calculation of Potential Cancer Risks

In addition to non-cancer hazards, we assessed lifetime cancer risks for exposure to the VOC for which strong evidence of carcinogenicity was available. **A value of inhalation unit risk (IUR) for cancer has been promulgated by a federal agency for one VOC included in these HHRAs—benzene**.

Through the Integrated Risk Information System (IRIS) (EPA, 2018), **EPA has promulgated an IUR for benzene for leukemia risk, defined as a range from 2.2×10^{-6} to 7.8×10^{-6} per µg/m^3.** Using slightly different modeling assumptions, TCEQ independently derived a point estimate identical to the lower end of the EPA range. In estimating lifetime cancer risks from benzene exposure in these HHRAs, we used both the upper and lower end of the EPA range.

It is important to note that varying levels of evidence exist regarding the potential cancer-causing potential of several other chemicals included in these HHRAs. For example, the International Agency for Research on Cancer has classified ethylbenzene as “possibly carcinogenic to humans” (IARC, 2006), and the National Toxicity Program has indicated that both styrene and isoprene are “reasonably anticipated to be a human carcinogen” (NTP, 2016). In all three cases, however, the quantitative data regarding carcinogenicity come exclusively from animal studies, and information from epidemiological studies is limited or ambiguous. No federal agency has issued quantitative health criteria (IURs) for carcinogenic risks for any of the three chemicals, and, given the large uncertainties associated with the use of unit risk values derived solely the currently available data, no quantitative cancer risks estimates have been derived for these chemicals. These HHRAs also do not assess other chemicals that are suspected of increasing human cancer risks and that may be emitted by O&G operations (e.g., formaldehyde, acetaldehyde).

The "lifetime" exposure typically used in cancer risk calculations is a 70-year duration. In these HHRAs, no O&G activity or sequence of activities lasts for 70 years—individual development activities typically last days to weeks (except for flowback activities and sequences of development activities at 5-acre Garfield County sites, which last between 1 and 2 years), and we model the production activity to last 30 years. In these scenarios, the calculation of a lifetime-average exposure concentration is a time-weighted-average calculation of X years of exposure (e.g., 30 years of exposure to production emissions) and 70-X years of zero exposure (e.g., 40 years of zero exposure to production emissions). Seventy-year, time-weighted-average exposures for development activities would include at least 68 years of zero exposure, which would result in lifetime cancer risks very far below levels of concern. Therefore, we focused our cancer assessment on production activities (30 years of exposure, 40 years of zero exposure) and on sequences of development and production activities altogether (30–32 years of exposure, 38–40 years of zero exposure).

4.4. Sensitive Populations (Age Groups)

As discussed in Section 3.2.1, the exposure assessment in these HHRAs generates exposure estimates for three age groups: children through 17 years old, adults 18 to 59 years old, and people aged 60 years or older. Receptor populations are not further broken down by potential sensitivity to inhaled pollutants (e.g., gender, pregnancy status or coexisting conditions). **In evaluating potential risks, we have taken into account that the toxicity reference values selected for this analysis are intended to account for differences in sensitivity within the general population, from whatever cause**.[12]

The calculation of non-cancer criteria values generally includes the application of "uncertainty factors" (UFs) that take into account likely differences in sensitivity to a chemical between that of a "typical" human and members of the most sensitive subgroups. Support for the use of UFs is better documented for chronic criteria than for shorter-term criteria; in some cases, numerical values of the UFs used to derive subchronic and acute criteria values are increased by an agency to reflect this greater uncertainty. UFs are not intended to protect against extreme sensitivity due to rare genetic conditions. For the purposes of these HHRAs, **we have assumed, in the absence of data to the contrary, that the criteria values are adequately protective of all groups in the exposed population**. Thus, we assume that HQ and HI values have the same meaning for all age groups and for all exposure durations. That is, HQ or HI values greater than 1.0 indicate concern for potential adverse effects, while values below 1.0 indicate less cause for concern, and values less than 0.1 provide even greater assurance of the lack of adverse health consequences, irrespective of the age groups involved.

[12] The EPA IRIS program indicates that RfC values are estimated including consideration of "sensitive subgroups" (EPA, 2018). TCEQ (2015) guidance on establishing ReVs includes exactly the same language, and OEHHA (2014) states that the derivation of RELs "explicitly includes consideration of possible differential effects on the health of infants, children, and other sensitive subpopulations."

In the estimation of cancer risks, no quantitative adjustment has been made to account for differences in individual sensitivity or age of exposure. This is consistent with current practice in the absence of mechanistic evidence that could affect metabolism of the toxic compound or innate sensitivity to exposure. Lifetime exposures are weighted equally over the life stages when exposure takes place for each (hypothetical) individual in the simulation. EPA (2005) issued guidance suggesting that early-life exposures (below age 16 years) should be more heavily weighted in assessing cancer risks only for carcinogens known to be acting through a mutagenic mode of action. We have chosen not to implement this approach, because (1) the overall correction to lifetime risk is relatively small compared to uncertainty associated with the exposure assessment and other aspects of these HHRAs, and (2) there is insufficient information regarding the precise carcinogenic mode of action of benzene (the only VOC for which we are estimating cancer risks in these HHRAs) to justify the use of such an adjustment.

5. Results of the Risk Assessment

As we discuss in the previous sections, for these HHRAs **we focused principally on health-protective exposure scenarios where hypothetical individuals spend all of their time close to an O&G facility for the lifetime of the facility, and where they are frequently downwind of emissions from the facility**. We have also described how we estimate potential health risks from these exposures by **comparing our VOC exposure estimates to the VOCs' health-protective criteria values.** In this section, we describe the results of comparing modeled exposures to the criteria values, across all scenarios and locations included in the HHRAs. We also describe the potential cancer risks associated with chronic exposures to benzene.

In Section 5.1, we provide a summary of the key assumptions made during the risk assessment, which helps place the assessment results into proper context. Section 5.2 contains a broad summary discussion of the risk results, which we cover in more detail in Sections 5.3, 5.4, 5.5, and Appendix E. In Section 5.6, we discuss potential impacts on estimates of hazards and risks from data gaps, uncertainties, and variabilities related to the health-criteria values.

5.1. Key Assumptions of the Risk Assessment

In the course of conducting the HHRAs and calculating the risk values, we made a number key assumptions intended to provide a prudent (and conservative) degree of health protection, as described below.

O&G Development

Most of the modeled O&G development scenarios last several days to several weeks per activity (per period of drilling, fracking, or flowback), so we focused primarily on acute (1-hour) exposures when defining the areas of highest exposure for risk assessment of O&G development. More specifically, during O&G development activities, we identified these areas by distance from the facility for each modeled VOC during each O&G activity, with the criterion that **they most frequently experience the highest 1-hour-average VOC air concentrations in the simulations** (as discussed further in Section 2.7.3). This criterion particularly favors identifying locations where acute exposures will be highest. We also simulated subchronic exposures (and chronic exposures for a few scenarios lasting more than 365 days) for these same individuals during O&G development. We assumed that hypothetical individuals at these locations **spent all their time there, either indoors, outdoors, or in vehicles**. As discussed further in Section 2.4, O&G development analyses included three different configurations of well pads: 1-acre pad (corresponding to a single well under development) and 3- and 5-acre pads (where larger numbers of wells are being developed).

<u>O&G Production</u>

The modeled O&G production scenario lasts 30 years, so we focused primarily on chronic exposures when defining the areas of highest exposure for risk assessment of O&G production. More specifically, during O&G production activities, we identified these areas by distance from the facility, with the criterion that **they experience the highest annual-average air concentrations in the simulations** (as discussed further in Section 2.8). These production-assessment locations were the same for each VOC, and while it favors identifying locations where chronic exposures will be highest, we also simulated acute exposures for the same individuals during O&G production. We assumed that hypothetical individuals at these locations **spent all their time there, either indoors, outdoors, or in vehicles**. As discussed further in Section 2.4, O&G production analyses only included 1-acre well pad scenarios, as we assumed an average-size production pad according to the air monitoring conducted during production operations. Note that when we estimated chronic hazards and risks for development activities in sequence with the production activity (which is over 30 years of total exposure to O&G emissions), the receptor locations utilized for exposures during development activities may have been different from those utilized for exposures during production, though we treated them as the same individuals in our calculations.

<u>Acute Assessments</u>

For the acute assessment, the most-exposed individuals were those simulated to be outdoors or in a PEN=1 micro during the time of highest 1-hour-average air concentration. That is, the individuals were hypothetically outdoors or in a highly ventilated building or vehicle at a time when O&G emissions were at their peak in our modeling, and those emissions moved towards the individuals according to “worst-case” meteorological conditions. **These individuals experienced the worst potential combination of the micro location, peak 1-hour emissions of the O&G facility, and short-term unfavorable meteorological conditions**.

These higher-end conditions occurred quite infrequently in our modeling, much less than 10 percent of the time and likely less than a few percent of the time. For example, we looked at the full distribution of exposure concentrations related to benzene emitted from NFR flowback activities, at the selected “worst” receptor at 300 ft from the 1-acre well pad. In that example, only about 4 percent of the person-days (4 percent of the 365,000 daily-maximum values collected at that location) reached exposure concentrations within one standard deviation of the absolute maximum exposure there. The “real” frequency will be much lower than this, as this example calculation does not consider other receptors at the same distance where typical exposures are lower (e.g., at locations more commonly upwind of the O&G site; see Section 2.9.1.4), other hours of each day when exposure can be much lower than the daily peak (see Section 3.6.3.1), or other combinations of emissions and meteorology that were not part of the summary values passed from the dispersion assessment to the exposure and risk assessments.

<u>Subchronic and Chronic Assessments</u>

For the subchronic and chronic assessments, we simulated hypothetical exposed individuals to be outdoors very frequently or in a high-PEN micro during times of higher air concentrations. That is, the individuals were often hypothetically outdoors or in a highly ventilated building or vehicle during times when O&G emissions were higher than average, and those emissions moved towards the individuals at a relatively high frequency according to higher-end meteorological conditions. Again, **these individuals experienced the worst potential long-term combination of the activities of the modeled individual, the emissions of the O&G facility, and the local meteorological conditions**.

As with acute assessments, for longer-term assessments these higher-end conditions likely occurred less than a few percent of the time in our modeling. Using the same example as above for acute (benzene emitted from NFR flowback activities, at the selected "worst" receptor at 300 ft from the 1-acre well pad), about 11 percent of person-periods (11 percent of the 365,000 subchronic "rolling-average" exposure values collected at that location) reached exposure concentrations within one standard deviation of the absolute maximum exposure there. The "real" frequency will be much lower than this, as this example calculation does not consider other receptors at the same distance where typical exposures are lower (see Section 2.9.1.4).

<u>Health Criterion Values</u>

These HHRAs rely on toxicological and health-effects assessments conducted by agencies charged with protecting the public health from adverse effects of chemical exposures. Numerical criteria values for the same VOC often vary among agencies because they were derived based on different supporting data and studies and/or based on different estimations of "no-effects levels" and margins of safety. **In selecting criteria values that were appropriately health-protective, we used a systematic approach to select the values for each of the assessed VOCs for acute, subchronic, and chronic exposures that favored the most well documented and technically defensible values**. Further details on our selection approach can be found in Section 4.1.1.

<u>Characterizations of Hazards and Potential Cancer Risk</u>

We assessed the potential for non-cancer health effects by calculating HQs for exposure to individual VOCs. We calculated HQs for a VOC by dividing the estimated exposure by the corresponding VOC health criterion. **Rather than providing numerical estimates of the incidence or severity of adverse effects, HQs are intended as a screening tool** used to identify chemical exposures that pose potential concern for adverse health effects. Recognizing uncertainties in the derivation of the health criteria and in the exposure assessment, we utilize the convention that HQs less than 1.0 (exposures below criteria values) indicate that adverse health effects are unlikely to occur, even in sensitive subpopulations, for the exposure durations being evaluated. **HQs greater than 1.0 (exposures above criteria values) suggest the need for additional evaluation as to the**

potential for adverse effects. In addition to non-cancer hazards, we assessed **incremental lifetime cancer risks** for exposure to the O&G VOC for which strong evidence of carcinogenicity was available (**benzene**).

Combined Exposures

Because a large number of VOCs are released concurrently from O&G activities, it is also necessary to generate hazard estimates for multiple (simultaneous) exposures. Since there was usually little or no data related to the health hazards associated with a specific chemical mixtures, **we calculated HIs to characterize the combined effects of multiple VOCs that might act on the same target organ or show similar critical effects**. In these HHRAs, we calculated the HI for a critical-effect group by summing the HQ values for all VOCs having that critical toxic effect. Conventionally, HI values less than 1.0 are considered to be health-protective because of the high degree of conservatism built into the constituent HQ calculations; however, the degree of uncertainty associated with interpreting the values is probably larger than for individual HQs.

The results presented here in Section 5 follow from the decisions outlined above and **are chiefly concerned with the highest-exposed hypothetical individuals at locations of relatively high air concentrations for the exposure durations being considered**. We do this in order to address the primary objective of these HHRAs—to simulate a wide variety of exposure scenarios and **estimate if any have the potential for adverse risks and impacts to human health**. The discussions in the following sections focus primarily on scenarios of highest interest or that demonstrate the results, and they are broken down by O&G activity, duration, and well-pad size. A comprehensive presentation of maximum estimated chemical hazards can be found in Appendix E. The simulations across all of the exposure scenarios resulted in many thousands of hazard estimates, and in the following sections **we utilize these many estimates to also characterize the distributions of potential HQs and HIs across the simulated individuals at these locations of highest exposure**.

5.2. Summary of Risk Results

The results presented in this section align with the scenarios outlined above and described in detail in Section 3.3.2. In that section, we described how emissions data, sizes of well pads, O&G sites, duration of activities, and activity types all come together in specific scenarios for which we evaluated exposure and risk.

While discussing the highest potential exposures at specific distances and orientations with respect to the O&G facilities, it is important to put those exposures into context of the overall range of potential exposures for all hypothetical individuals at all hypothetical locations. The range of potential 1-hour-average (acute) exposures is quite large for each modeled individual, and for the lower-PEN VOCs the range is also high for multi-day (subchronic) exposures. For lower-PEN VOCs, the range of chronic exposures is also large across the modeled population. These large ranges mean that **modeled exposures, and therefore estimates of HQ, HI, and risk, are very frequently much lower than the peak values reported throughout Section 5**. In this section, we provide a high-level summary of the results, and in subsequent sections (including Appendix E) we provide further details. Several times here we refer to Figure 5-1, which summarizes the highest HQ and HIs at the 500-ft modeled distance (the distance of

COGCC's current Exception Zone Setback for well and production facilities relative to a building unit) and the 2,000-ft modeled distance (the farthest modeled distance)—medium and darker blue shades indicate if the highest HQ or HI of any chemical or critical-effect group reached 1 or 10, respectively, while light blue indicates values remaining below 1. The results shown in Figure 5-1 align with the scenarios outlined in Table 3-3.

Acute Exposures

Exposure modeling for most chemicals indicated that acute exposures to O&G emissions were below guideline levels for all hypothetical exposed individuals. **At the most-exposed (downwind) locations at 500 ft from the well pads, the highest estimated 1-hour exposures exceeded guideline levels for a small number of chemicals, including benzene during development and production activities, and toluene and ethyltoluenes during development activities.** At those locations, estimated exposures to benzene and 2-ethyltoluene were sometimes more than a factor of 10 above guideline levels during development activities, particularly during flowback activities at smaller well pads. These higher chemical exposures lead to estimates of maximum hematological HIs above 1 during development and production activities (sometimes above 10 during development activities), and also maximum neurotoxicity and respiratory HIs above 1 during development activities. These higher hazard estimates are reflected in the medium- and dark-blue shading for the acute scenarios in Figure 5-1. One-hour exposures decreased rapidly with distance from the hypothetical facilities, but some remained above guideline levels out to 2,000 ft. Exposures will be smaller, sometimes substantially smaller, at other locations that are less frequently downwind of the well pads.

While the highest values were largest at the NFR site, the average difference between sites in HQs and HIs was less than a factor of 2. HQs and HIs tended to become somewhat smaller as the size of the development well pad increased in the modeling. HQs and HIs were much smaller during production activities relative to development activities.

As noted above in Section 5.1, **our identification of these estimated exceedances of acute health guidelines is highly conservative**, in that these highest-estimated exposures occur relatively rarely. For example, at the 500-ft selected receptors, the median benzene HQs during flowback activities (the median of the 365,000 maximum person-day HQs at those locations) tended to be a factor of 1.6–2.7 smaller than the absolute maximum HQs, and while some of the highest benzene HQs were above 10 at the NFR site, they were below 10 for most people on most days.

Subchronic (Multi-Day) Exposures

Subchronic HQs and HIs were generally much lower than acute HQs and HIs. As summarized in Figure 5-1, **most modeled multi-day VOC exposures (and all such exposures at the 500-ft distance and beyond) were at or far below subchronic guideline levels during development activities** (not evaluated for production activities—see chronic results). **Emissions of trimethylbenzenes were of primary concern due to their contributions to maximum neurotoxicity and hematological HIs slightly above 1** at distances out to about 800 ft from the development well pads during fracking activities. During development activities in sequence (total exposures to development emissions, drilling through flowback), the highest subchronic HQs and HIs were generally lower than those during individual development activities, and they were all below 1 at 500+ ft from the well pads. Subchronic HQs and HIs generally decreased with increasing distances from the well pads.

While the highest values were largest at the Garfield County ridge-top site, the average difference between sites in HQs and HIs was generally less than a factor of 3 for individual development activities and generally less than a factor of 2 for development activities in sequence. Subchronic HQs and HIs tended to become somewhat smaller as the size of the development well pad increased from 1 to 3 acres in the modeling, though differences between 3- and 5-acre pads tended to be mixed.

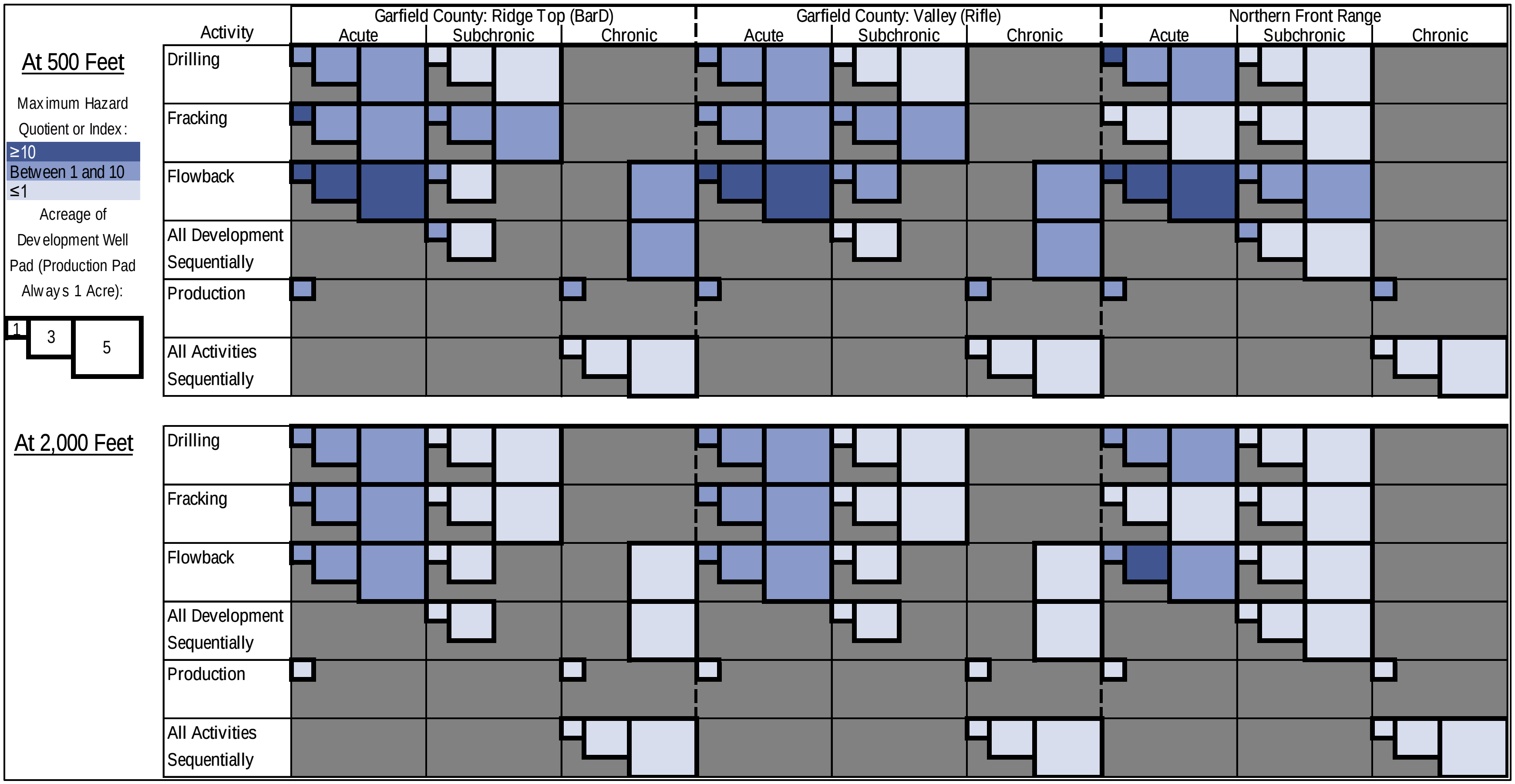
As with the highest 1-hour exposures, **our identification of these estimated exceedances of multi-day health guidelines is conservative,** corresponding to relatively rare exposure scenarios. For example, at the 500-ft selected receptors, the median neurotoxicity HIs during fracking activities (the median of the 365,000 person-period HIs at those locations) tended to be a factor of 1.7–2.5 smaller than the absolute maximum HQs, and while some of the highest neurotoxicity HIs were above 1 at the Garfield County sites, they were below 1 for the majority of people during most of the year.

Chronic Exposures

We also estimated chronic exposures for production operations (which we modeled for 30 years), for the sequence of all development and production activities (which lasts 30–32 years in our modeling), and for some long flowback operations that can last 14–15 months at the Garfield County sites.

At the 500-ft distance from the well pads, chronic exposures during these long, multi-well flowback activities were far below chemical guideline levels, though neurotoxicity and hematological HIs slightly exceeded 1 due primarily to the contributions of n-nonane, benzene, m+p-xylene, and trimethylbenzenes (see Figure 5-1). When exposures to these long flowback activities were aggregated with exposures to the preceding and shorter-duration drilling and fracking activities at the same sites, we saw generally the same results of all HQs below 1, and neurotoxicity and hematological HIs slightly above 1, at the 500-ft distance. These chronic HIs during flowback decreased with distance from the well pads, falling below 1 well before the 2,000-ft edge of our modeling domains, and such exposures will be much lower at locations away from these higher-impact locations (e.g., those more upwind of the well pad).

The chronic exposures during production operations (and when these chronic exposures include the preceding development operations) were below guideline levels at the 500-ft distance in all scenarios, and these HQs and HIs were generally the lowest from among all simulated exposures in the assessment. **Also at the 500-ft distance, incremental lifetime cancer risks due to benzene exposure were 5-in-one million or less for the average-exposed individuals, dropping below 1-in-one million before the 2,000-ft distance.**



Notes: This snapshot reflects the highest exposures in all our modeling scenarios, across all age groups at the indicted receptors. If there is no box indicating results, we did not evaluate that scenario. We did not evaluate acute exposure for sequential activities, as the largest acute results of the constituent activities will also be the largest for the activities in sequence. We did not evaluate subchronic exposures for activities or sequences of activities lasting longer than one year; that information is reflected in the chronic results. See Section 3.3.2 for further discussion of applicable scenarios.

Figure 5-1. Snapshot of Maximum Estimated Hazard Quotients and Hazard Indices at the Selected Receptors 500 feet (top) and 2,000 feet (bottom) from the Well Pads

5.3. Oil and Gas Development

In the subsections below, and relevant sections of Appendix E, we discuss estimates for acute, subchronic, and chronic non-cancer HQs and HIs for emissions during individual O&G development activities (see Section 5.5 for a discussion on development activities in sequence). **We focus particularly on the highest simulated potential values of these HQs and HIs, but we also discuss the ranges of potential values, to place the higher values in context**. We provide additional quantifications of HQs and HIs, both maximum values as well as frequencies of HQs and HIs above a value of 1, in Appendix E.1. We generally present the same types of tables and figures (the same basic content and purpose) in each individual subsection here. We provide the most comprehensive description of these tables and figures in the first subsection below (Section 5.3.1.1, which are acute non-cancer hazards related to a 1-acre development well pad). In later sections, we provide less description in order to reduce repetition; please reference the Section 5.3.1.1 descriptions as needed for interpretation.

As discussed further in Section 2.4, we evaluated three different configurations of the hypothetical O&G development well pads. The 1-acre pad corresponds to a single well under development. For scenarios where larger numbers of wells are being developed, the well pad necessarily grows in size: 3 acres for 8 wells at the hypothetical NFR site and 16 wells at the hypothetical Garfield County sites, and 5 acres for 32 wells at all hypothetical sites. Total emissions from the well pad per unit time do not change between well-pad configurations because we assume, based on typical practices, that wells are drilled one at a time, fracked one at a time, and undergo flowback one at a time. The differences between well pads, therefore, correspond to the duration of the various O&G activities (shorter for lower numbers of wells, longer for higher numbers of wells) and the size and diffusion of the initial emission plume at the well site. Longer activity durations (and larger numbers of wells) can correspond to longer exposure times, in a few cases lasting more than one year. A larger and more diffuse initial plume (associated with larger pads) typically will lower the highest concentrations and exposures compared to the plumes at smaller pads (see Section 3.5.4); that is, **HQs and HIs tend to be lower, and higher HQs and HIs tend to be less common, for emissions from larger O&G development operations relative to smaller operations**. We discuss this in the remainder of this section.

We also demonstrate below that **acute HQs and HIs tended to be substantially higher than subchronic HQs and HIs**. This result is expected, given the high variability in the O&G emissions data used in these HHRAs, where the larger 1-hour-average VOC air concentrations (which are relevant to the acute assessment) are generally much higher than the average concentrations across time (which are relevant to the subchronic and chronic assessments). This result is also expected given that the highest acute HQ and HI values are estimated for hypothetical individuals who live where the maximum 1-hour concentrations are highest, due to the chance combinations of highest estimated emissions and worst-case meteorological that occur only rarely in the simulations. While we do not make a direct comparison of subchronic and chronic HQs and HIs during individual development activities (because only flowback activities at the 5-acre Garfield County sites reach chronic duration; in those cases, we calculate only chronic values, not subchronic), we note that **in general most subchronic and chronic values are below 1 (and, at worst only a small amount above 1)**.

5.3.1. Acute Non-cancer Hazards

In this section, we discuss the potential for acute (1-hour) exposures above health-criteria levels, due to emissions from O&G individual development activities. We discuss the results of each size of well pad separately: 1 acre (Section 5.3.1.1), 3 acre (Section 5.3.1.2), and 5 acre (Section 5.3.1.3). Within each subsection, we stratify the results by O&G activity as well. Recall that all modeled sites are hypothetical.

Overall, benzene and 2-ethyltoluene were of primary concern for potential adverse effects from acute exposure. These were the VOCs for which modeled acute exposures were sometimes more than a factor of 10 above criteria levels at 500 ft from the pad (the distance of COGCC's current Exception Zone Setback for well and production facilities relative to a building unit), **particularly for the selected receptors most frequently downwind from the pad and during flowback operations**. Acute HQs for these chemicals were above 1 for most simulated individuals at least once during most simulated days, at the 500-ft selected receptor (e.g., Figure 5-3, Figure 5-7, and Figure 5-11 showing benzene from flowback activities). **Acute HQs were also sometimes above 1 for toluene and 3-ethyltoluene at the same locations**. The same is true of HIs reflecting multiple chemical exposures for critical-effect groups such as **hematological and neurotoxicity**, and occasionally respiratory (e.g., Table 5-2, Table 5-4, and Table 5-6). **HQs and HIs generally decreased with distance from the well pad** (e.g., Figure 5-2, Figure 5-6, and Figure 5-10)**, and for many chemicals the exposures were always well below criteria levels even during the worst simulated conditions.**

While the highest acute HQs and HIs were largest at the NFR site, on average across chemicals/critical-effect groups, distances, and O&G activities the differences in HQs and HIs between NFR and Garfield County sites were less than a factor of 2. Our modeling also indicated **small or negligible differences between simulated individuals in different age groups** in their typical and higher acute HQs and HIs, as expected based on the exposure modeling (see Section 3.5.1). Our discussion in this acute section does not differentiate results by age group (focusing on ages up to 17 years for convenience), though results stratified by age group can be found in Appendix E.1.1.

Differences in the maximum chemical HQs and critical-effect-group HIs by distance were more noticeable when comparing 1-, 3-, and 5-acre well-pad scenarios. We previously noted these differences in terms of air concentrations (Section 2.9.1.5) and acute exposures (Section 3.5.4). These comparisons **typically show smaller acute HQs and HIs at 3-acre pads relative to 1-acre pads (by about 20–30 percent on average across VOCs and O&G activities at the 500-ft distance), and at 5-acre pads relative to 3-acre pads (by about 20–60 percent on average across VOCs and O&G activities at the 500-ft distance). These differences tended to be smaller at farther distances from the well pad.** These are average differences, and for individual chemicals/critical-effect groups and activities the differences can be larger in either direction. These variations may be due to several factors, including: the complex interactions between the initial plume and meteorological parameters such as wind flow and turbulence, the focus here on maximum 1-hour values rather than averages or medians, and the identification of the selected receptor at each distance, which occurred independently by well-pad size.

We must use caution in interpreting these higher acute results, given the health-protective approach we selected for acute assessments. We built several layers of conservativeness into our acute assessment, as discussed in Sections 5.1 and 5.2, such that these higher acute results reflect narrow subsets of the potentially exposed population during relatively rare exposure scenarios. See discussions around Figure 5-4, Figure 5-8, and Figure 5-12 for more context about the maximum values and how they compare to more typical values in the simulations.

In each subsection below, we first discuss the potential for exposures above health-criteria levels, and the trend of that potential by distance of exposure relative to the center of the well pad. To assess this potential, we focused on the highest simulated exposures—**at the selected receptor at a given distance from the well, this highest value comes from the simulated individual with the highest single hour of exposure from among all simulated individuals and days of the year**. In the 1-acre section directly below, for example, we show these highest results in Table 5-1 and Figure 5-2 for HQs of individual VOCs, and in Table 5-2 and Figure 5-5 for HIs of critical-effect groups. We then take a broader look at the simulated chemical exposures across all individuals and days of the year, to **put the highest HQ results into context of the full distribution of results, giving a sense of what are the more typical HQs**. These HQ distributions, at the selected receptor at a given distance from the well, consist of the 365 daily-maximum acute HQs for each of the 1,000 simulated individuals. In the 1-acre section, for example, we show these distribution-based results in Figure 5-3 and Figure 5-4 for HQs of individual VOCs. The discussions generally focus on the 500-ft distance from the pad and the 2,000-ft distance (the farthest modeled distance). The discussions also generally stratify results by HQ and HI values of 10 or above, between 1 and 10, and between 0.1 and 1. HQs above 1 indicate modeled exposure concentrations (from specific simulated scenarios) above health-criteria levels. **We generally do not discuss the many chemicals whose HQs were below 0.1 at all times**. A more detailed presentation of HQs and HIs at various distances can be found in Appendix E.1.1.

5.3.1.1. 1-acre Well Pad

Overall Maximum Chemical Hazard Quotients by Distance

Benzene and 2-ethyltoluene were of primary concern, showing acute HQs above 10 at the selected receptors 500-ft downwind during development activities (Table 5-1). **Toluene and 3-ethyltoluene were of lesser concern, with HQs sometimes above 1 in the same locations**. This was particularly true during flowback activities. The bullets below pertain to maximum HQs at the selected receptor at the 500-ft distance.

- Benzene HQs reached as high as 20 during flowback activities at the simulated NFR site; they were also above 10 during drilling at NFR, and between 1 and 10 during all activities at the Garfield County sites. HQs below 1 during fracking at NFR.
- HQs for 2-ethyltoluene were up to 13 during flowback activities at the Garfield County sites, but they were below 1 in all other cases (all activities at the NFR site, and drilling and fracking at the Garfield County sites).
- Toluene HQs were slightly above 1 during drilling at all three sites but were below 1 in all other cases).

- HQs for 3-ethyltoluene were slightly above 1 during flowback activities at the Garfield County sites but were below 1 in all other cases.

However, at 2,000 ft, all chemicals had HQs less than 10 across all sites and activities. Maximum HQs were between 1 and 10 at the selected 2,000-ft receptor for

- benzene at all three sites (HQ=1.8–5.3; during all activities except for flowback at the Garfield County valley site and fracking at the NFR site, where HQs were below 1),
- toluene during drilling at the Garfield County ridge-top site (HQ=1.2; HQs below 1 in all other cases), and
- 2-ethyltoluene during flowback at the Garfield County sites (HQ=3.1–7.3; HQs below 1 in all other cases).

Comparing HQs between the three sites, while the highest maximum HQs at 500 ft from the well pad corresponded to the NFR site, and while there were notable other differences by chemical and activity, the HQs averaged across chemicals, activities, and distances were less than 50-percent different between the three sites.

In Figure 5-2, we plot maximum acute HQs by distance from the 1-acre well pad to illustrate more clearly the overall trend of decreasing HQs with increasing distance from the pad. As noted above, the highest acute HQ at the 500-ft distance during 1-acre development activities corresponded to benzene during flowback activities at the NFR site; Figure 5-2 plots these benzene HQs from flowback at NFR, and for comparison we also plot the HQs from flowback at the Garfield County sites. The values are also available in Table E-1. The lines connect the highest 1-hour HQ experienced by anyone at the selected receptor at the 300-ft distance with the highest value experienced by anyone at the selected 350-ft receptor, and so on out to 2,000 ft.

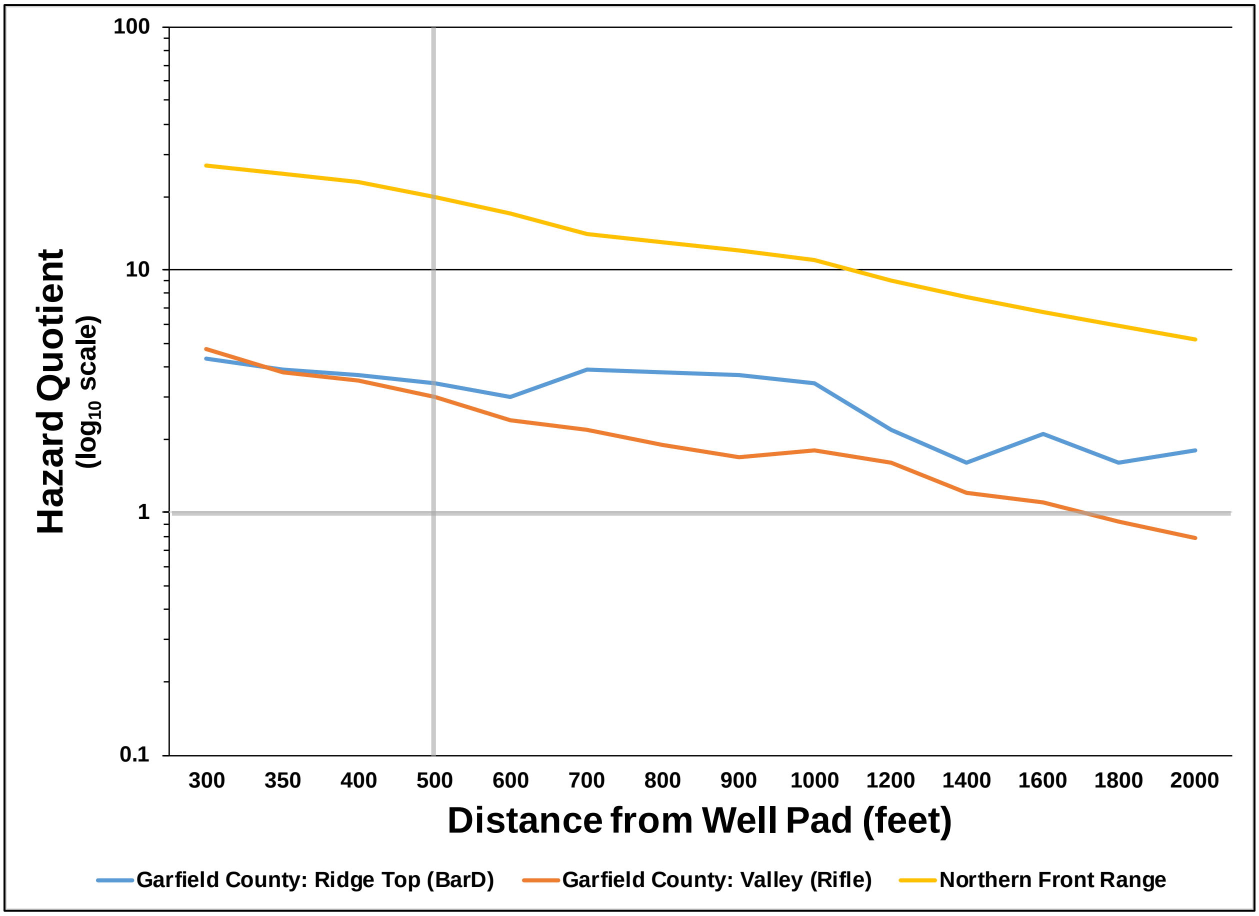
As noted above and illustrated here, these maximum benzene acute HQs during flowback activities remained above 1 at all modeled distances at the NFR and Garfield County ridge-top sites, while at the Garfield County valley site they dropped below 1 by the 1,800-ft distance. While the general trend in HQ is downward with increasing distance, there can be deviations in that trend from one distance to another (see Section 2.9.1.1), caused by the particular modeled dispersion patterns at a site and how those relate to the precise location of the selected receptor at each distance (see Section 2.7.3).

The decrease in HQs with distance for the 1-acre well pad was typical of most scenarios and activities, but there will be variations for each scenario in the specific chemicals that show HQs above 1, the numerical values of the maximum HQs, and the distance at which HQs might fall below 1. Table E-1 shows all modeled values for each site and VOC, including those used to create this graph.

Table 5-1. Overview of the Largest Acute Non-cancer Hazard Quotients during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 1-acre Well Pad

Range of Hazard Quotients	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none		benzene	none		
	Fracking	none			none		
	Flowback	2-ET	2-ET	benzene	none		
Between 1 and 10	Drilling	benzene toluene	benzene toluene	toluene	benzene toluene	benzene	benzene
	Fracking	benzene	benzene	none	benzene	benzene	none
	Flowback	3-ET benzene	3-ET benzene	none	2-ET benzene	2-ET	benzene
0.1 to 1	Drilling	2-ET	2-ET	2-ET	none	toluene	toluene
	Fracking	2-ET 3-ET 4-ET CHX m+p-xylene MCHX n-decane n-nonane n-octane T2B toluene	2-ET 3-ET 4-ET CHX m+p-xylene MCHX n-decane n-nonane n-octane T2B toluene	2-ET benzene	2-ET 3-ET m+p-xylene n-decane toluene	2-ET m+p-xylene toluene	benzene
	Flowback	123-TMB 124-TMB 135-TMB 13-DEB 4-ET CHX IPB m+p-xylene MCHX n-decane n-nonane n-PB o-xylene styrene toluene	123-TMB 124-TMB 135-TMB 13-DEB 4-ET CHX IPB m+p-xylene MCHX n-decane n-nonane n-PB o-xylene styrene toluene	2-ET 2-MHP 3-ET CHX m+p-xylene MCHX n-decane n-hexane n-nonane n-octane o-xylene toluene	123-TMB 124-TMB 135-TMB 13-DEB 3-ET 4-ET IPB m+p-xylene n-decane n-PB o-xylene toluene	13-DEB 3-ET 4-ET benzene IPB m+p-xylene n-decane n-PB toluene	CHX 3-ET m+p-xylene toluene

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
CHX = cyclohexane; DEB = diethylbenzene; DMP = dimethylpentane; ET = ethyltoluene; IPB = isopropylbenzene; MCHX = methylcyclohexane; PB = propylbenzene; T2B = trans-t-butene; TMB = trimethylbenzene; 123 = 1,2,3 and 124 = 1,2,4 and so on.



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard quotient=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10

Figure 5-2. Largest Acute Non-cancer Hazard Quotients for Benzene, for the Highest Exposed Hypothetical Individuals at Various Distances from the 1-acre Well Pad during Flowback Activities

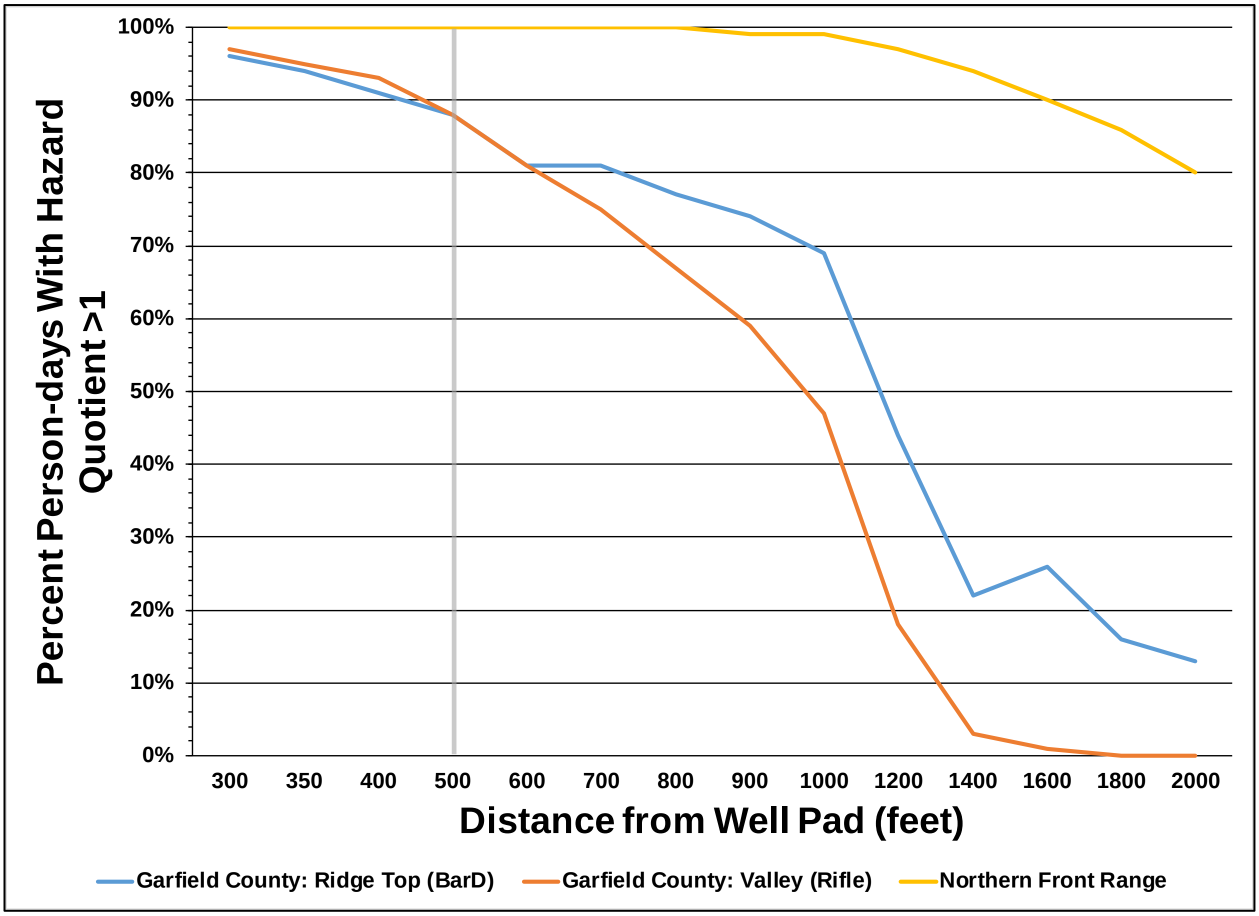
Analysis of Person-day Chemical Hazard Quotients by Distance

For the same scenarios used in Figure 5-2, in Figure 5-3 we illustrate the frequency of daily-maximum acute HQs reaching above a value of 1. These percentages are taken from the collection of each simulated individual's 365 daily-maximum acute HQs (which we term "person-days"), for 1,000 simulated youths up to 17 years old at each selected downwind receptor. The results for all age groups were nearly identical (see Section 3.5.1 and Section E.1). This analysis shows how often (on a daily basis) HQs above 1 occurred across a year of modeled acute scenarios for development activities at 1-acre well pads. A value of 100 percent indicates that every simulated individual experienced at least one acute HQ above 1 on every simulated day of the year. A value of 50 percent indicates that, among the 365,000 daily HQ data points across the population at a receptor, about half of them (about 182,500) were above 1.

In this example, under the conservative exposure assumptions used in this analysis (high emissions and unfavorable meteorology), the model results indicated the characteristics we note below.

- At distances 300–800 ft from the 1-acre NFR well pad, flowback activities during any day of the year produced at least one hourly acute benzene exposure above criteria levels (HQ above 1) for all simulated individuals.
  - By the 2,000-ft distance, flowback activities at the NFR site during most days of the year still produced at least one acute benzene HQ above 1 for most people (80 percent of all person-days modeled).
- Flowback activities during most days of the year produced at least one hourly acute benzene HQ above 1 for most people at 1,000 ft from the well pad or closer at the Garfield County ridge-top site (at 800 ft or closer at the Garfield County valley site). For example, at 500 ft from both sites, 88 percent of all person-days had HQs above 1. That percentage fell below 50 at the 1,000-ft distance (to 0 percent at 1,800 ft) at the valley site, and it fell below 50 at the 1,200-ft distance (to 13 percent at 2,000 ft) at the ridge-top site.

Generally, the rate of decline in these percentages with distance will vary across chemicals, sites, and O&G activities, depending on several factors. For these benzene HQs during flowback, the relatively slow rate of decline with distance at the NFR site, compared with the Garfield County sites, reflects the much higher benzene emission rates used for the NFR flowback modeling (see Table 2-5). Table E-2 shows the percentage of person-days with HQ above 1 for all chemicals, including those used to create this graph.



Notes: X-axis is not to scale. "Person-days" refers to the collection across the hypothetical population of each modeled individual's daily-maximum acute hazard quotients for a year of modeling. The data in this graph refer to the percentage of hazard quotients (in this collection of hazard quotients) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

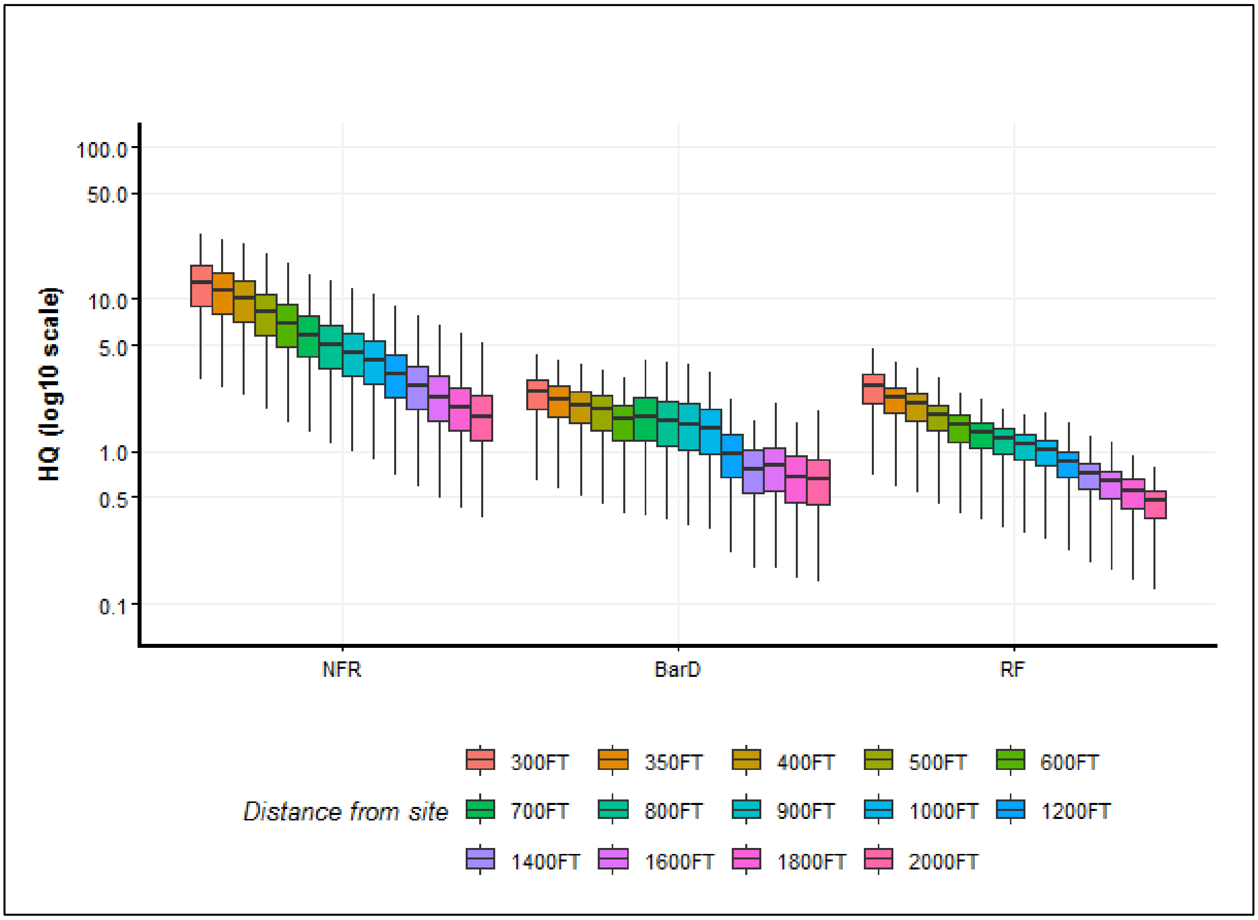
Figure 5-3. Percentage of Daily-maximum Acute Non-cancer Hazard Quotients for Benzene (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the 1-acre Well Pad during Flowback Activities

Figure 5-4 contains box-and-whisker plots reflecting the distributions of benzene HQs during flowback activities, across all person-days, stratified by O&G site and distance. The structure of these plots are the same as those provided for exposures in Section 3.5, where values are plotted in log space and the shapes correspond to the 1st-percentile value (bottom whisker), 25th percentile (bottom of box), 50th percentile (i.e., median; line inside box), 75th percentile (top of box), and maximum (top whisker). Note that we define the boxes here and in Section 3.5 differently than in Section 2.9.

The maximum HQ values discussed earlier and reflected in Table 5-1 are visible here as the tops of the whiskers (e.g., maximum HQ of 20 at NFR at the 500-ft distance; maximum HQ at the Garfield County valley site dropping below 1 at the 1,800-ft distance; etc.).

The boxes, providing a range of HQs between the 25th and 75th percentiles, can be considered to be reflective of a typical range of exposures at the respective receptor distance, and they can be compared against the maximum values discussed up to this point. As an example, the 25th-to-75th-percentile ranges of maximum person-day HQs for benzene were 1.4–2.3, 1.3–2, and 5.7–11 at 500 ft from the Garfield County ridge-top, Garfield County valley, and NFR well pads, respectively. These are notably lower than the absolute maximum values at that same distance: 3.4, 3, and 20, respectively. The median benzene HQs during flowback, represented by the line inside the box and corresponding to the central-tendency of the maximum person-day exposures, were 1.9, 1.7, and 8.1 at 500 ft from the three sites respectively, which were factors of 1.8–2.5 smaller than the absolute maximum values at the same distance.

For the scenario which had the highest HQs at the 500-ft distance (benzene from flowback at NFR), Figure 5-4 shows approximately 68 percent of all maximum person-day HQs at the 500-ft distance were below 10 (though, as shown in Figure 5-3, 100 percent of values at this distance and site were above 1). All maximum person-day benzene HQs during flowback activities at the Garfield County sites were already below 10 at the 500-ft distance, but approximately 10–11 percent of those values were below 1.



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HQ = hazard quotient; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-4. Distributions of Daily-maximum Acute Non-cancer Hazard Quotients for Benzene (Across the Hypothetical Population) at Various Distances from the 1-acre Well Pad during Flowback Activities

Overall Maximum Critical-effect-group Hazard Indices by Distance

For combined chemical exposures during development activities on a 1-acre well pad, **hematological health effects (driven by benzene exposure**; see Appendix B**) were of primary concern, followed by neurotoxicity effects (with several VOCs contributing substantially**; see Table 5-2). The bullets below pertain to the selected receptor at the 500-ft distance.

- Hematological HIs, as with benzene HQs that dominate the hematological HI calculation, reached as high as 20 during flowback activities at the simulated NFR site. They were also above 10 during drilling at NFR, and between 1 and 10 during all activities at the Garfield County sites (below 1 during fracking at NFR).

- The primary contribution of benzene to the hematological HI also can be seen in Figure 5-5, which represents approximate contributions of individual VOC HQs towards HIs of critical-effect groups. This plot uses HQs during flowback at the NFR site (specifically at 500 ft), which was the site and activity that produced the highest acute HQs and HIs at the 500-ft distance.

- HIs for neurotoxicity effects were slightly above 1 during all activities at all sites, except for fracking from the NFR site where they were below 1.
  - The HQs of several chemicals, including toluene, m+p-xylene, n-hexane, and n-decane, contributed substantially to the neurotoxicity HIs, as shown in Figure 5-5. Note that these VOC HQs were each less than 1 individually, but when aggregated they led to HIs above 1.

- HIs for respiratory effects were also slightly above 1 during fracking activities at the Garfield County ridge-top site, mostly as a result of m+p-xylene exposure (below 1 for all other cases).

However, at 2,000 ft, all chemicals had HIs less than 10 across sites and activities. HIs were between 1 and 10 at the selected 2,000-ft receptor for

- hematological effects at all three sites (HI=2–5.3; during all activities except for flowback at the Garfield County valley site and fracking at the NFR site where HIs were below 1), and

- neurotoxicity effects during drilling and flowback at the Garfield County ridge-top site (HI=1.3–1.5; HI below 1 in all other cases).

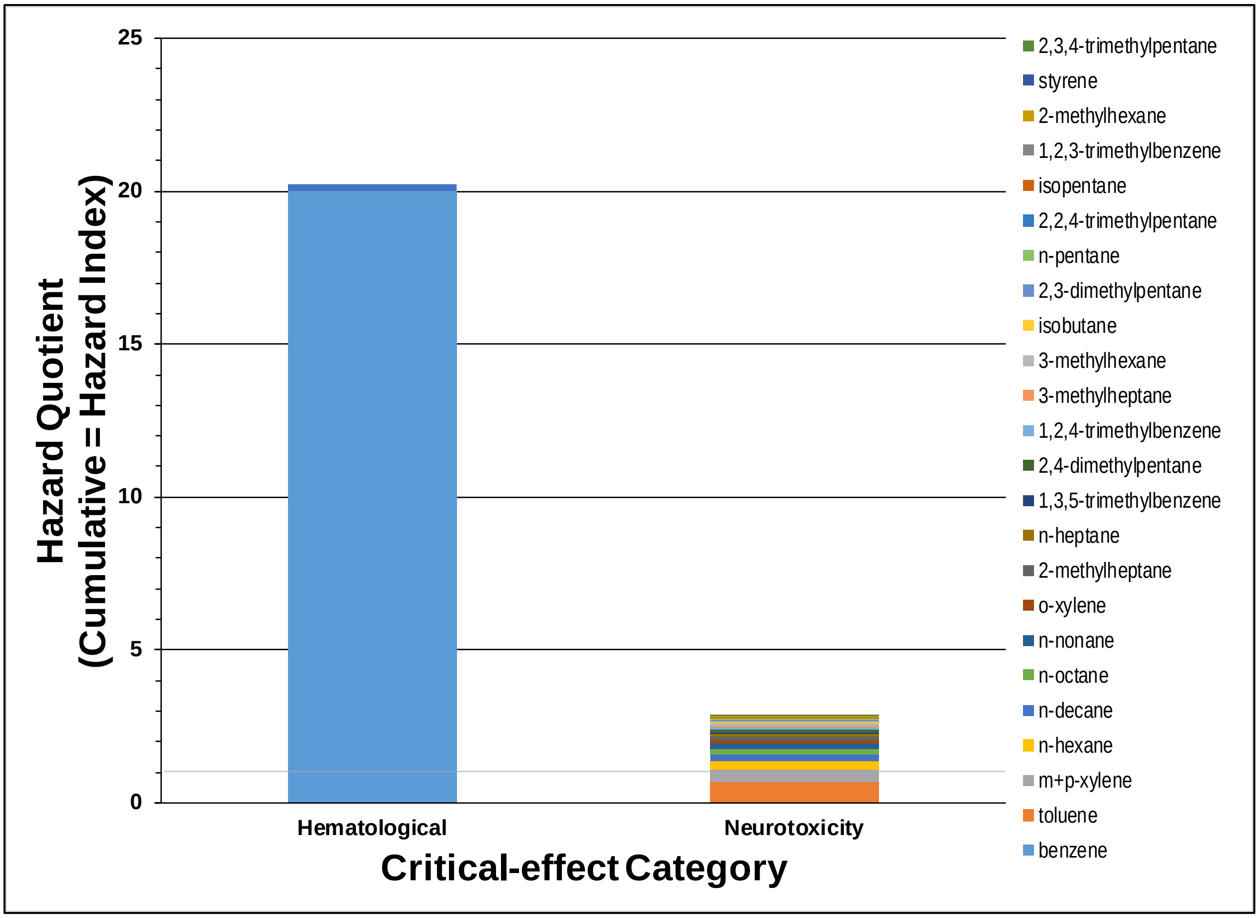
Note that we were unable, in our professional judgment based on available data, to assign ethyltoluenes to any acute critical-effect groups. This means that the acute HQs for ethyltoluenes (which sometimes were above 1) were not included in any acute HI results. Some other VOCs also were not assigned to any acute groups (see Appendix D).

A more detailed presentation of these HI values can be found in Table E-3, and Table E-4 contains data on the percentage of daily-maximum acute HIs above 1. The same HQ trends with distance discussed above existed also for HIs. Specifically, as distance from the well pad increased, HIs generally decreased and frequencies of HIs above 1 decreased for all modeled scenarios and critical-effect groups at the 1-acre development well pad.

Table 5-2. Overview of the Largest Acute Non-cancer Hazard Indices during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 1-acre Well Pad

<table>
<tr><th rowspan="2">Range of Hazard Indices</th><th rowspan="2">Activity</th><th colspan="3">500 feet from Well Pad</th><th colspan="3">2,000 feet from Well Pad</th></tr>
<tr><th>Garfield County: Ridge Top (BarD)</th><th>Garfield County: Valley (Rifle)</th><th>Northern Front Range</th><th>Garfield County: Ridge Top (BarD)</th><th>Garfield County: Valley (Rifle)</th><th>Northern Front Range</th></tr>
<tr><td rowspan="3">≥ 10</td><td>Drilling</td><td colspan="2">none</td><td>hematological</td><td colspan="3">none</td></tr>
<tr><td>Fracking</td><td colspan="3">none</td><td colspan="3">none</td></tr>
<tr><td>Flowback</td><td colspan="2">none</td><td>hematological</td><td colspan="3">none</td></tr>
<tr><td rowspan="3">Between 1 and 10</td><td>Drilling</td><td>hematological
neurotoxicity</td><td>hematological
neurotoxicity</td><td>neurotoxicity</td><td>hematological
neurotoxicity</td><td>hematological</td><td>hematological</td></tr>
<tr><td>Fracking</td><td>hematological
neurotoxicity
respiratory</td><td>hematological
neurotoxicity</td><td>none</td><td>hematological</td><td>hematological</td><td>none</td></tr>
<tr><td>Flowback</td><td>hematological
neurotoxicity</td><td>hematological
neurotoxicity</td><td>neurotoxicity</td><td>hematological
neurotoxicity</td><td>none</td><td>hematological</td></tr>
<tr><td rowspan="3">0.1 to 1</td><td>Drilling</td><td>respiratory</td><td>none</td><td>respiratory</td><td>none</td><td>neurotoxicity</td><td>neurotoxicity</td></tr>
<tr><td>Fracking</td><td>sensory
systemic</td><td>respiratory
sensory
systemic</td><td>hematological</td><td>neurotoxicity
respiratory
sensory</td><td>neurotoxicity
respiratory</td><td>hematological</td></tr>
<tr><td>Flowback</td><td>respiratory
sensory</td><td>respiratory
sensory</td><td>endocrine
respiratory
sensory
systemic</td><td>respiratory
sensory</td><td>hematological
neurotoxicity
respiratory
sensory</td><td>neurotoxicity
respiratory</td></tr>
</table>

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: Gray line emphasizes hazard quotient/index=1. The order of chemicals listed in the legend matches the order of plotting (e.g., benzene plotted first on the bottom if applicable to that critical-effect group, then toluene, etc.). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-5. Approximate Chemical Contributions to the Largest Hazard Indices of Selected Critical-effect Groups: Acute Non-cancer Assessment for the Highest Exposed Hypothetical Individuals at 500 Feet from the 1-acre Well Pad during Flowback Activities at the Northern Front Range Site

5.3.1.2. 3-acre Well Pad

For the 3-acre scenarios discussed here, compared to the 1-acre scenarios discussed in Section 5.3.1.1, HQs (Table 5-3, Figure 5-6) **and HIs** (Table 5-4)**, and frequencies of HQs and HIs above 1 on a daily basis** (Figure 5-7)**, tended to be lower.** The distributions of HQs (Figure 5-8) also tended to be shifted to lower values for the 3-acre scenarios relative to the 1-acre scenarios. This relationship between 3-acre and 1-acre results was not universal because the source size affects the spatial pattern of chemical dispersion, and because more than one aspect of the assessment was different between the acreage scenarios (i.e., this is not a true sensitivity test). While a change in source size resulted in different modeled air concentrations (which tended to be lower for larger sources as compared to smaller sources), those changes in air concentrations fluctuated depending on the receptor location relative to the emission source, which can cause a different selected effective-maximum receptor at a given distance. A change in the selected receptor leads to a different collection of air concentrations saved per Monte Carlo iteration, which directly affects the distribution of estimated HQs and HIs.

Overall Maximum Chemical Hazard Quotients by Distance

As with the 1-acre pads, for the 3-acre assessment **benzene and 2-ethyltoluene were of primary concern, some showing acute HQs above 10 at the selected receptors 500-ft downwind during development activities** (Table 5-3, Table E-5). **Toluene and 3-ethyltoluene were of lesser concern, with HQs sometimes above 1 in the same locations**. This was particularly true during flowback activities. Maximum chemical HQs at 500 ft were generally smaller for the 3-acre results relative to the 1-acre results (by less than about 20–30 percent on average across VOCs and O&G activities). The bullets below pertain to maximum HQs at the selected receptor at the 500-ft distance.

- Benzene HQs reached as high as 18 during flowback activities at the simulated NFR site (down from 20 at the 1-acre pad). While benzene HQs during drilling at NFR were also above 10 at the 1-acre pad, they were below 10 in that and all other scenarios at 3-acre pads, and, as with the 1-acre pad, below 1 during fracking at NFR.

- Comparing results between the 3-acre and 1-acre pads, while the HQ for 2-ethyltoluene was unchanged at 13 during flowback at the Garfield County ridge-top site, it decreased from 13 to 11 at the 3-acre pad for flowback at the Garfield County valley site. As with the 1-acre pad, 2-ethyltoluene HQs were below 1 in all other cases (all activities at the NFR site, and drilling and fracking at the Garfield County sites).

- As with the results at the 1-acre pad, toluene HQs at the 3-acre pad were slightly above 1 during drilling at all three sites, changing from 2.2, 1.6, and 2.4 at the 1-acre Garfield County ridge-top, Garfield County valley, and NFR pads, respectively, to 1.8, 1.7, and 1.7 at the 3-acre pads. HQs were below 1 in all other cases.

- As with the assessment of 1-acre pads, HQs for 3-ethyltoluene at the 3-acre pad were slightly above 1 during flowback activities at the Garfield County sites, changing from 1.3 and 1.4 at the 1-acre ridge-top and valley pads, respectively, to 1.4 and 1.1 at the 3-acre pads. HQs were below 1 in all other cases.

At the selected receptors at 2,000 ft, maximum benzene HQs remained above 10 (HQ=12) during flowback at the NFR site, as compared to HQ=5.2 at the 1-acre pad. However, as with the 1-acre pads, all other chemical HQs were below 10 across all sites and activities. Maximum HQs were between 1 and 10 at the selected 2,000-ft receptor for

- benzene at all three sites (HQ=1.5–4.9, as opposed to HQ=1.8–5.3 at the 1-acre pads), during all activities except for flowback at the NFR and Garfield County valley sites and fracking at the NFR site, where HQs were below 1;

- toluene during drilling at the Garfield County ridge-top site (HQ=1.1, as opposed to HQ=1.2 at the 1-acre pad), with HQs below 1 in all other cases; and

- 2-ethyltoluene during flowback at the Garfield County sites (HQ=2.9–6.7, as opposed to HQ=3.1–7.3 at the 1-acre pad), with HQs below 1 in all other cases.

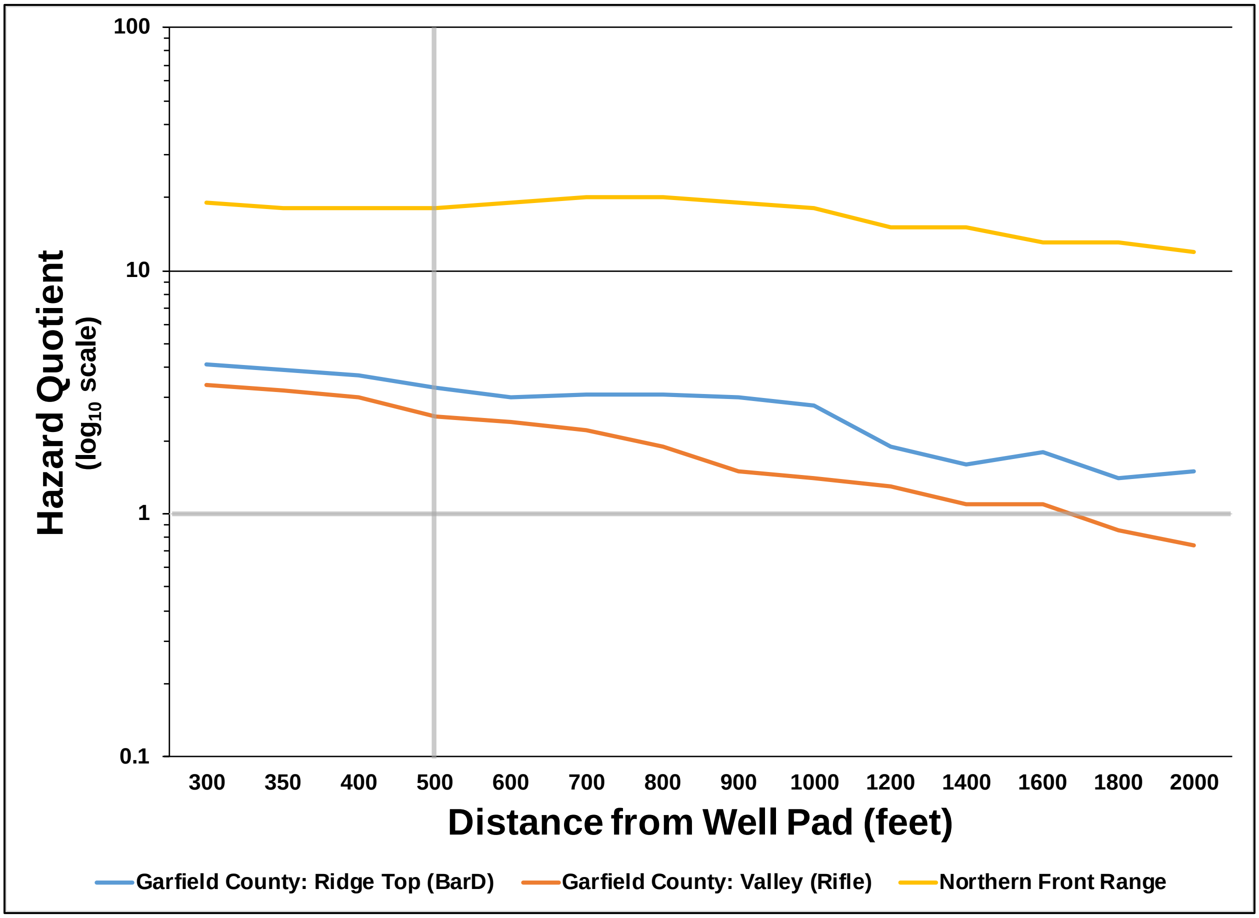
Comparing HQs between the three sites, while the highest maximum HQs at 500 ft from the well pad corresponded to the NFR site, and while there were notable other differences by chemical and activity, the HQs averaged across chemicals, activities, and distances were less than 40-percent different between the three sites.

Table 5-3. Overview of the Largest Acute Non-cancer Hazard Quotients during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 3-acre Well Pad

Range of Hazard Quotients	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	2-ET	2-ET	benzene	none		benzene
Between 1 and 10	Drilling	benzene toluene	benzene toluene	benzene toluene	benzene toluene	benzene	benzene
	Fracking	benzene	benzene	none	benzene	benzene	none
	Flowback	3-ET benzene	3-ET benzene	none	2-ET benzene	2-ET	none
0.1 to 1	Drilling	2-ET	2-ET	2-ET	none	toluene	toluene
	Fracking	2-ET 3-ET 4-ET CHX m+p-xylene MCHX n-decane n-nonane n-octane toluene T2B	2-ET 3-ET CHX m+p-xylene MCHX n-decane toluene T2B	2-ET benzene	2-ET 3-ET m+p-xylene toluene	2-ET m+p-xylene toluene	benzene
	Flowback	123-TMB 124-TMB 135-TMB 13-DEB 4-ET CHX IPB m+p-xylene MCHX n-decane n-nonane n-PB o-xylene styrene toluene	123-TMB 124-TMB 135-TMB 13-DEB 4-ET CHX IPB m+p-xylene MCHX n-decane n-nonane n-PB o-xylene styrene toluene	2-ET 3-ET CHX m+p-xylene MCHX n-decane n-hexane n-nonane n-octane o-xylene toluene	123-TMB 124-TMB 135-TMB 13-DEB 3-ET 4-ET IPB m+p-xylene n-decane n-PB toluene	13-DEB 3-ET 4-ET benzene IPB m+p-xylene n-decane n-PB toluene	3-ET CHX m+p-xylene MCHX n-decane n-hexane n-octane toluene

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
CHX = cyclohexane; DEB = diethylbenzene; DMP = dimethylpentane; ET = ethyltoluene; IPB = isopropylbenzene; MCHX = methylcyclohexane; PB = propylbenzene; T2B = trans-t-butene; TMB = trimethylbenzene; 123 = 1,2,3 and 124 = 1,2,4 and so on.

Figure 5-6 is analogous to the 1-acre Figure 5-2 (showing trends with distance in maximum benzene HQs at the selected receptors during flowback activities). Both figures show the same general trends in HQs with distance at the Garfield County sites, with HQs at the ridge-top site meandering somewhat between 300 and 1,000 ft before decreasing more steadily thereafter (due to complex interactions between the well-pad emission plume and local meteorology, as well as the exact locations of the selected receptors). For the same reasons, with the 3-acre pads, we also see meandering HQ values at the NFR site inside of 800 ft from the pad, while decreasing at farther distances. Table E-5 shows all modeled values for each site and VOC, including those used to create this graph.



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard quotient=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10.

Figure 5-6. Largest Acute Non-cancer Hazard Quotients for Benzene, for the Highest Exposed Hypothetical Individuals at Various Distances from the 3-acre Well Pad during Flowback Activities

Analysis of Person-day Chemical Hazard Quotients by Distance

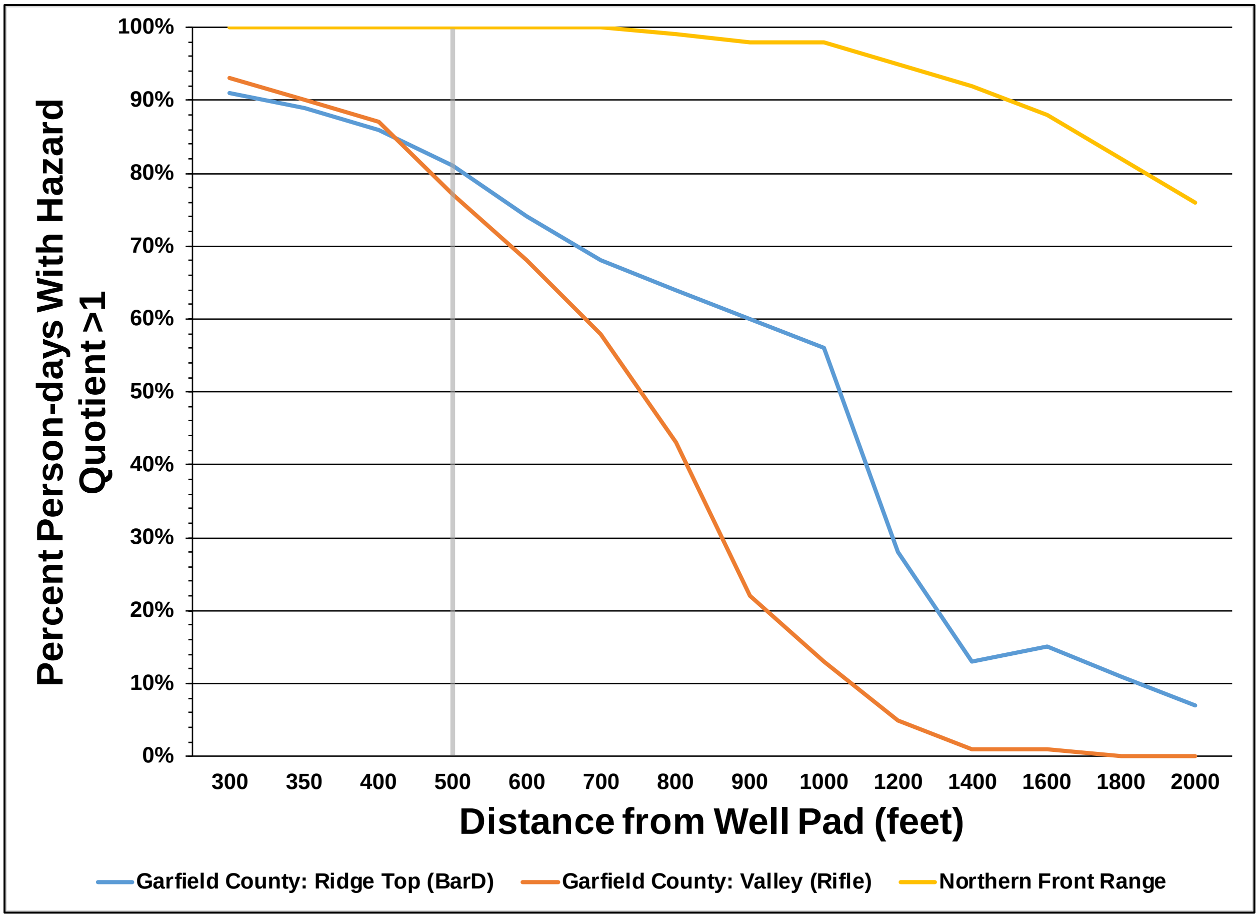
Figure 5-7 is analogous to the 1-acre Figure 5-3 (showing trends with distance in the percentage of population person-days with maximum benzene HQs at the selected receptors exceeding 1 during flowback activities). Both figures show that these daily-maximum HQs are above 1 for most hypothetical people on most days at distances closer to the well pad (at the Garfield County sites) or at all distances (at the NFR site). The slopes of these lines are generally steeper for the 3-acre pads relative to 1-acre, meaning that these percentages tend to drop more rapidly with distance, which is a reflection of the generally lower HQ values near 3-acre pads relative to 1-acre pads.

- At distances 300–700 ft from the 3-acre NFR well pad, flowback activities during any day of the year produced at least one hourly acute benzene exposure above criteria levels (HQ above 1) for all simulated individuals (this was also true at 800 ft for the 1-acre pad).
  - By the 2,000-ft distance, flowback activities at the NFR site during most days of the year still produced at least one acute benzene HQ above 1 for most people (76 percent of all person-days modeled, as opposed to 80 percent with the 1-acre pad).
- Flowback activities during most days of the year produced at least one hourly acute benzene HQ above 1 for most people at 900 ft from the well pad or closer at the Garfield County ridge-top site (at 600 ft or closer at the Garfield County valley site). These distances at the 1-acre pads were 1,000 ft and 800 ft, respectively. For example, at 500 ft from both Garfield County sites, 77–81 percent of all person-days had HQs above 1 (relative to 88 percent at the 1-acre pads). That percentage fell below 50 at the 800-ft distance at the 3-acre valley pad (relative to 1,000 ft at the 1-acre pad; to 0 percent at 1,800 ft at both the 1- and 3-acre pads) and at 1,200-ft distance at the ridge-top 3-acre pad (same as the 1-acre site; to 7 percent at 2,000 ft from the 3-acre pad, relative to 13 percent at the 1-acre pad).

The numbers used for this figure are available in Table E-6.

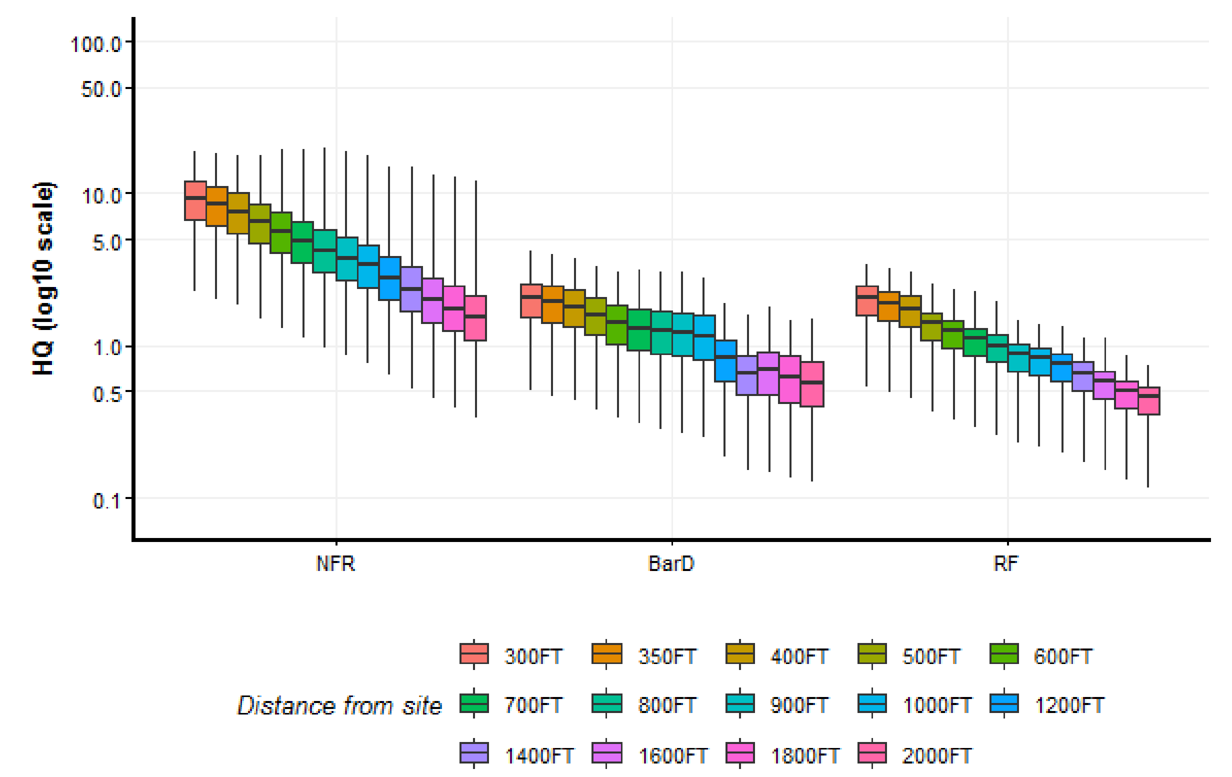
Figure 5-8 is analogous to Figure 5-4 in the 1-acre results, showing distributions of benzene HQs during flowback activities, across all person-days. The 25th-to-75th-percentile ranges of maximum person-day HQs for benzene at the 500-ft distance were 1.2–2.1, 1.1–1.6, and 4.6–8.6 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively (rather than 1.4–2.3, 1.3–2, and 5.7–11 at the 1-acre pads). These are notably lower than the absolute maximum values at that same distance: 3.3, 2.5, and 18, respectively. The median benzene HQs during flowback were 1.6, 1.4, and 6.4 at 500 ft from the three sites respectively (rather than 1.9, 1.7, and 8.1 at the 1-acre pads), which were factors of 1.9–2.7 smaller than the absolute maximum values at the same distance.

For the scenario which had the highest HQs at the 500-ft distance (benzene from flowback at NFR), Figure 5-8 shows approximately 86 percent of all maximum person-day HQs at the 500-ft distance were below 10 (up from 68 percent with the 1-acre pad), though, as shown in Figure 5-7, 100 percent of values at this distance and site were above 1. All maximum person-day benzene HQs during flowback activities at the Garfield County sites were already below 10 at the 500-ft distance, but approximately 17–20 percent of those values were below 1 (up from 10–11 percent with the 1-acre pads).



Notes: X-axis is not to scale. "Person-days" refers to the collection across the hypothetical population of each modeled individual's daily-maximum acute hazard quotients for a year of modeling. The data in this graph refer to the percentage of hazard quotients (in this collection of hazard quotients) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-7. Percentage of Daily-maximum Acute Non-cancer Hazard Quotients for Benzene (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the 3-acre Well Pad during Flowback Activities



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HQ = hazard quotient; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-8. Distributions of Daily-maximum Acute Non-cancer Hazard Quotients for Benzene (Across the Hypothetical Population) at Various Distances from the 3-acre Well Pad during Flowback Activities

Overall Maximum Critical-effect-group Hazard Indices by Distance

As with the 1-acre pads, **for combined chemical exposures during development activities on a 3-acre well pad**, **hematological health effects (driven by benzene exposure**; see Appendix B**) were of primary concern, followed by neurotoxicity effects (with several VOCs contributing substantially**; see Table 5-4). Maximum critical-effect-group HIs at 500-ft were generally smaller for the 3-acre results relative to the 1-acre results (by less than about 20–30 percent on average across VOCs and O&G activities). The bullets below pertain to the selected receptor at the 500-ft distance.

- Hematological HIs, as with benzene HQs that dominate the hematological HI calculation, reached as high as 18 during flowback activities at the simulated NFR site (down from 20 at the 1-acre pad). While they were above 10 during drilling at NFR for the 1-acre pad, they were between 1 and 10 in that scenario at the 3-acre pad and during all activities at the Garfield County 3-acre pads (below 1 during fracking at NFR).

  - The primary contribution of benzene to the hematological HI also can be seen in Figure 5-9, which is analogous to Figure 5-5 in the 1-acre results.

- As with the 1-acre pads, for the 3-acre pads the HIs for neurotoxicity effects were slightly above 1 during all activities at all sites, except for fracking from the NFR site where they were below 1.
  - The HQs of several chemicals, including toluene, m+p-xylene, n-hexane, and n-decane, contributed substantially to the neurotoxicity HIs, as shown in Figure 5-9.

- Whereas at the 1-acre pads the HIs for respiratory effects were slightly above 1 during fracking activities at the Garfield County ridge-top site, at the 3-acre pads all respiratory HIs were 1 or below.

At the selected receptor at 2,000 ft from the well pad, the hematological HI was 12 during flowback at the NFR site, corresponding to the benzene HQ of 12 there. Otherwise, all other HIs were less than 10. HIs were between 1 and 10 at the selected 2,000-ft receptor for

- hematological effects at all three sites (HI=1.7–4.9, rather than 2–5.3 at the 1-acre pads), during all activities except for flowback at the Garfield County valley site and fracking and flowback at the NFR site; and

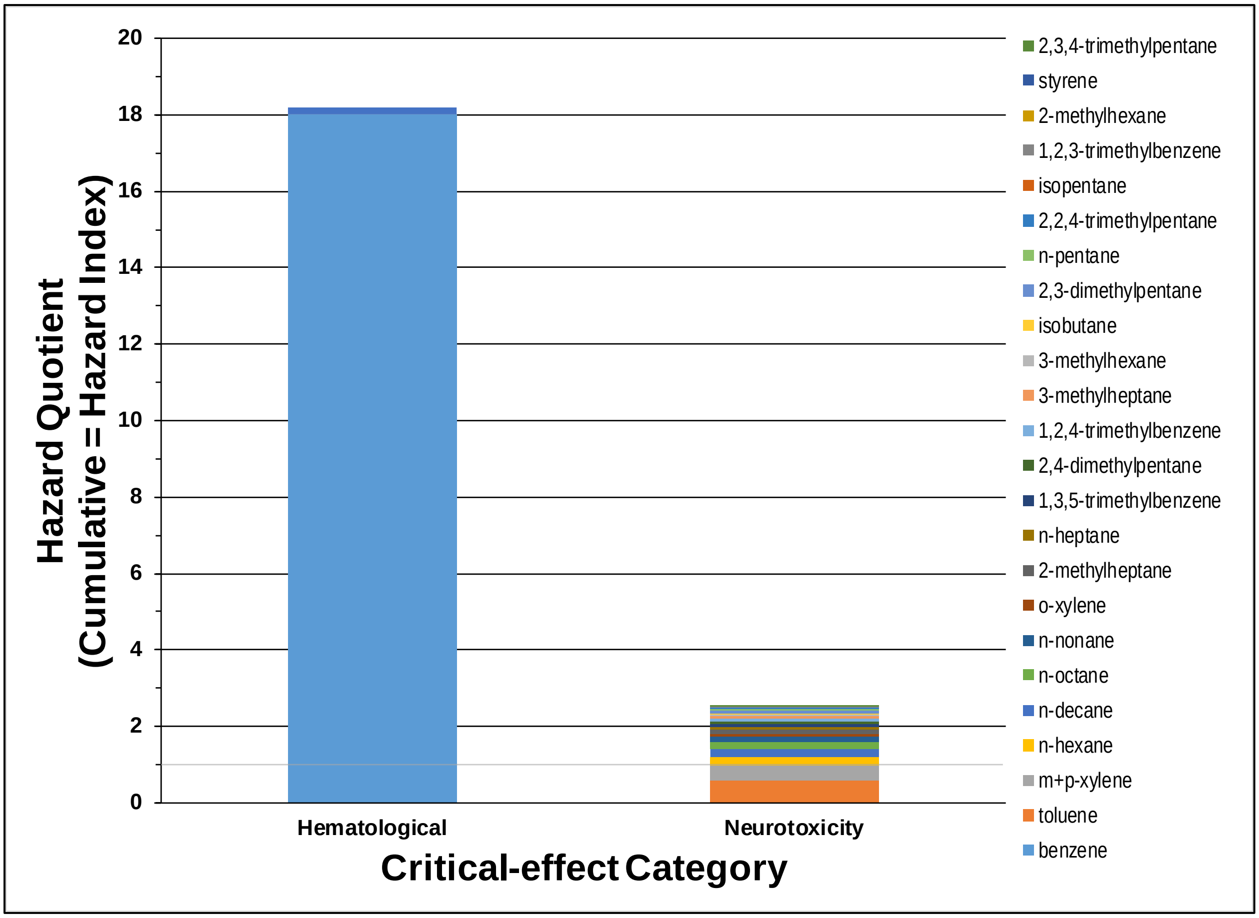
- neurotoxicity effects during drilling and flowback at the Garfield County ridge-top site, and, contrary to the 1-acre results, also during flowback at the NFR site (HI=1.1–1.6, rather than 0.68–1.5 at the 1-acre pads; HI below 1 in all other cases).

Note that we were not able to assign some chemicals, including ethyltoluenes, to any acute critical-effect groups (see Appendix B). A more detailed presentation of these HI values can be found in Table E-7, and Table E-8 contains data on the percentage of daily-maximum acute HIs above 1. The same HQ trends with distance discussed above exist also for HIs. Specifically, as distance increased, HIs generally decreased and frequencies of HIs above 1 decreased for all modeled scenarios and critical-effect groups at the 3-acre development well pad.

Table 5-4. Overview of the Largest Acute Non-cancer Hazard Indices during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 3-acre Well Pad

Range of Hazard Indices	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	none		hematological	none		hematological
Between 1 and 10	Drilling	hematological neurotoxicity	hematological neurotoxicity	hematological neurotoxicity	hematological neurotoxicity	hematological	hematological
	Fracking	hematological neurotoxicity	hematological neurotoxicity	none	hematological	hematological	none
	Flowback	hematological neurotoxicity	hematological neurotoxicity	neurotoxicity	hematological neurotoxicity	none	neurotoxicity
0.1 to 1	Drilling	none			none	neurotoxicity	neurotoxicity
	Fracking	respiratory sensory systemic	respiratory sensory systemic	hematological	neurotoxicity respiratory	neurotoxicity respiratory	hematological
	Flowback	respiratory sensory	respiratory sensory	endocrine respiratory sensory	respiratory sensory	hematological neurotoxicity respiratory sensory	endocrine respiratory sensory

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: Gray line emphasizes hazard quotient/index=1. The order of chemicals listed in the legend matches the order of plotting (e.g., benzene plotted first on the bottom if applicable to that critical-effect group, then toluene, etc.). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-9. Approximate Chemical Contributions to the Largest Hazard Indices of Selected Critical-effect Groups: Acute Non-cancer Assessment for the Highest Exposed Hypothetical Individuals at 500 Feet from the 3-acre Well Pad during Flowback Activities at the Northern Front Range Site

5.3.1.3. 5-acre Well Pad

For the 5-acre scenarios discussed here, compared to the 1-acre and 3-acre scenarios discussed in Sections 5.3.1.1 and 5.3.1.2, respectively, HQs (Table 5-5, Figure 5-10) **and HIs** (Table 5-6)**, and frequencies of HQs and HIs above 1 on a daily basis** (Figure 5-11)**, tended to be lower.** The distributions of HQs (Figure 5-12) also tended to be shifted to lower values for the 5-acre scenarios than the 1- and 3-acre scenarios. These relationships between 5-acre results and 1- and 3-acre results was not universal for reasons discussed in Section 5.3.1.2.

Overall Maximum Chemical Hazard Quotients by Distance

As with the 1- and 3-acre pads, for the 5-acre assessment **benzene and 2-ethyltoluene were of primary concern, sometimes showing acute HQs above 10 at the selected receptors**

500-ft downwind during development activities (Table 5-5, Table E-9). **Toluene and 3-ethyltoluene were of lesser concern, with HQs sometimes above 1 in the same locations**. This was particularly true during flowback activities. Maximum chemical HQs at 500 ft were generally smaller for the 5-acre results relative to the 3-acre results (by less than about 20–60 percent on average across VOCs and O&G activities), which themselves were generally smaller than the 1-acre results (as discussed in Section 5.3.1.2). The bullets below pertain to maximum HQs at the selected receptor at the 500-ft distance.

- Benzene HQs reached as high as 12 during flowback activities at the simulated NFR site (down from 18 at the 3-acre pad). As with the 3-acre pad, benzene HQs were below 10 in that and all other scenarios at 5-acre pads, and, as with the 3-acre pad, below 1 during fracking at NFR.

- Comparing results between the 5-acre and 3-acre pads, HQs for 2-ethyltoluene decreased from 13 to 11 and from 11 to 9.3 at the 5-acre pad for flowback at the Garfield County ridge-top and valley sites, respectively. As with the 3-acre pad, 2-ethyltoluene HQs were below 1 in all other cases (all activities at the NFR site, and drilling and fracking at the Garfield County sites).

- As with the results at the 3-acre pad, toluene HQs at the 5-acre pad were slightly above 1 during drilling at all three sites, changing from 1.8, 1.7, and 1.7 at the 3-acre Garfield County ridge-top, Garfield County valley, and NFR pads, respectively, to 1.4, 1.4, and 1.5 at the 5-acre pads. HQs were below 1 in all other cases.

- As with the assessment of 3-acre pads, HQs for 3-ethyltoluene at the 5-acre pad were slightly above 1 during flowback activities at the Garfield County ridge-top site (but not the valley site, where HQs were slightly above 1 at the 3-acre pad), changing from 1.4 and 1.1 at the 3-acre ridge-top and valley sites, respectively, to 1.2 and 0.97 at the 5-acre pads. HQs were below 1 in all other cases.

At the selected receptors at 2,000 ft, maximum HQs were between 1 and 10 at the selected 2,000-ft receptor for

- benzene at all three sites (HQ=1.6–4.4, as opposed to HQ=1.5–4.9 at the 3-acre pads), during all activities except for flowback at the Garfield County valley site and fracking at the NFR site, where HQs were below 1 (note that benzene HQs were above 10 in the 3-acre scenario, but not the 5-acre scenario, for flowback from the NFR site); and

- 2-ethyltoluene during flowback at the Garfield County sites (HQ=2.8–6.2, as opposed to HQ=2.9–6.7 at the 3-acre pad), with HQs below 1 in all other cases.

(Note that toluene HQs associated with the 5-acre pads were below 1 at the 2,000-ft distance, which was not the case with the 3-acre Garfield County ridge-top drilling scenario where HQ was 1.1.)

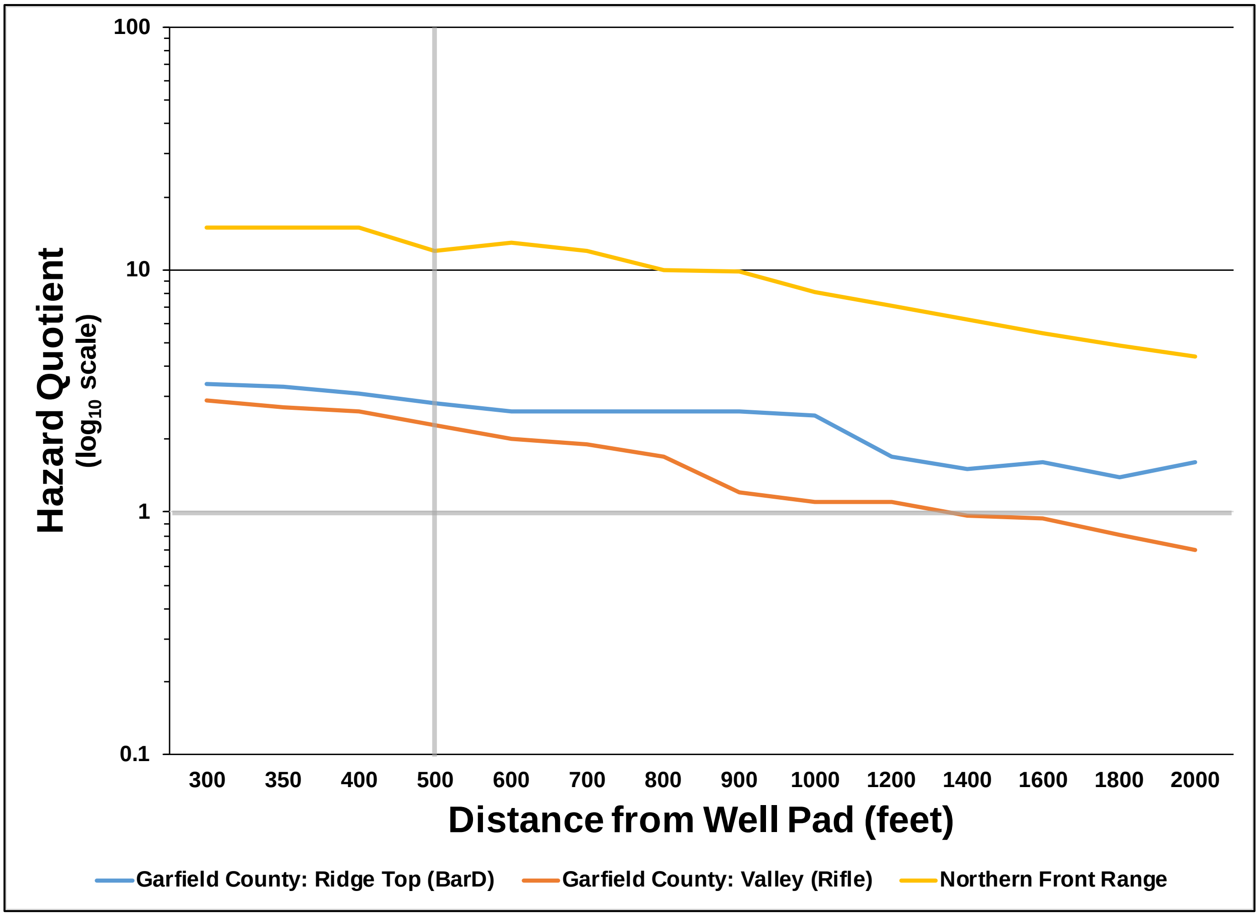
Comparing HQs between the three sites, while the highest maximum HQs at 500 ft from the well pad corresponded to the NFR site (e.g., the benzene HQ of 18 during flowback at NFR), and while there are notable other differences by chemical and activity, the HQs averaged across chemicals, activities, and distances were less than 60-percent different between the three sites.

Table 5-5. Overview of the Largest Acute Non-cancer Hazard Quotients during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Well Pad

Range of Hazard Quotients	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	2-ET	none	benzene	none		
Between 1 and 10	Drilling	benzene toluene	benzene toluene	benzene toluene	benzene	benzene	benzene
	Fracking	benzene	benzene	none	benzene	benzene	none
	Flowback	3-ET benzene	2-ET benzene	none	2-ET benzene	2-ET	benzene
0.1 to 1	Drilling	none		2-ET	toluene	toluene	toluene
	Fracking	2-ET 3-ET CHX m+p-xylene MCHX n-decane toluene T2B	2-ET 3-ET CHX m+p-xylene MCHX n-decane toluene T2B	benzene	2-ET m+p-xylene toluene	2-ET m+p-xylene toluene	benzene
	Flowback	123-TMB 124-TMB 135-TMB 13-DEB 4-ET CHX IPB m+p-xylene MCHX n-decane n-nonane n-PB o-xylene styrene toluene	123-TMB 124-TMB 135-TMB 13-DEB 3-ET 4-ET CHX IPB m+p-xylene MCHX n-decane n-nonane n-PB o-xylene styrene toluene	3-ET CHX m+p-xylene MCHX n-decane n-hexane n-nonane n-octane toluene	123-TMB 124-TMB 135-TMB 13-DEB 3-ET 4-ET IPB m+p-xylene n-decane n-PB toluene	13-DEB 3-ET 4-ET benzene IPB m+p-xylene n-decane n-PB toluene	3-ET CHX toluene

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
CHX = cyclohexane; DEB = diethylbenzene; ET = ethyltoluene; IPB = isopropylbenzene; MCHX = methylcyclohexane; PB = propylbenzene; T2B = trans-t-butene; TMB = trimethylbenzene; 123 = 1,2,3 and 124 = 1,2,4 and so on.

Figure 5-10 is analogous to the 3-acre Figure 5-6 (showing trends with distance in maximum benzene HQs at the selected receptors during flowback activities). Both figures show the same general trends in HQs with distance at the Garfield County sites, with HQs at the ridge-top site meandering somewhat between 300 and 1,000 ft before decreasing more steadily thereafter (due to complex interactions between the well-pad emission plume and local meteorology, as well as the exact locations of the selected receptors). As noted above, while the HQ remained above 10 at all distances for the 3-acre pad at the NFR site, it drops below 10 by 900 ft from the 5-acre pad. The HQ at the Garfield County valley site also drops below 1 at a closer distance from the 5-acre pad relative to the 3-acre pad (by 1,400 ft rather than 1,800 ft). Table E-9 shows all modeled values for each site and VOC, including those used to create this graph.



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard quotient=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10.

Figure 5-10. Largest Acute Non-cancer Hazard Quotients for Benzene, for the Highest Exposed Hypothetical Individuals at Various Distances from the 5-acre Well Pad during Flowback Activities

Analysis of Person-day Chemical Hazard Quotients by Distance

Figure 5-11 is analogous to the 3-acre Figure 5-7 (showing trends with distance in the percentage of population person-days with maximum benzene HQs at the selected receptors exceeding 1 during flowback activities). Both figures show that these daily-maximum HQs are above 1 for most hypothetical people on most days at distances closer to the well pad (at the Garfield County sites) or at all distances (at the NFR site). The slopes of these Garfield County lines are generally steeper for the 5-acre pads relative to 3-acres, meaning that these percentages tend to drop more rapidly with distance, which is a reflection of the generally lower HQ values near 5-acre pads relative to 3-acre pads.

- At distances 300–600 ft from the 5-acre NFR well pad, flowback activities during any day of the year produced at least one hourly acute benzene exposure above criteria levels (HQ above 1) for all simulated individuals (this was also true at 700 ft for the 3-acre pad).

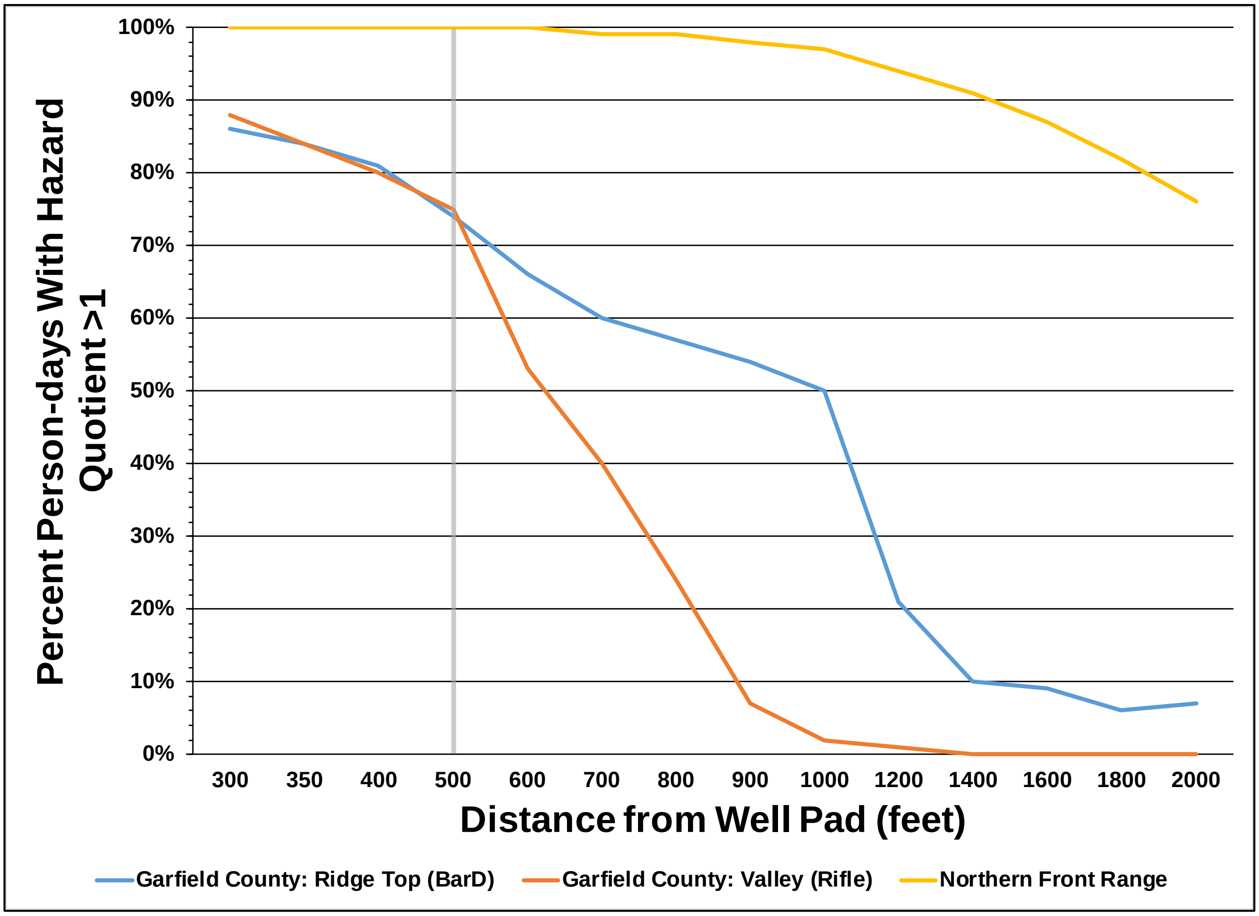
- By the 2,000-ft distance, flowback activities at the NFR site during most days of the year still produced at least one acute benzene HQ above 1 for most people (76 percent of all person-days modeled, same as with the 3-acre pad).

- Flowback activities during most days of the year produced at least one hourly acute benzene HQ above 1 for most people at 700 ft from the well pad or closer at the Garfield County ridge-top site (at 500 ft or closer at the Garfield County valley site). These distances at the 3-acre pads were 900 ft and 600 ft, respectively. For example, at 500 ft from both Garfield County sites, 74–75 percent of all person-days had HQs above 1 (relative to 77–81 percent at the 3-acre pads). That percentage fell below 50 at the 700-ft distance at the 5-acre valley pad (relative to 800 ft at the 3-acre pad; to 0 percent at 1,400 ft, relative to 1,800 ft at the 3-acre pads) and at 1,200-ft distance at the ridge-top 5-acre pad (same as the 1-acre site; to 7 percent at 2,000 ft from both the 3- and 5-acre pads).

The numbers used for this figure are available in Table E-10.

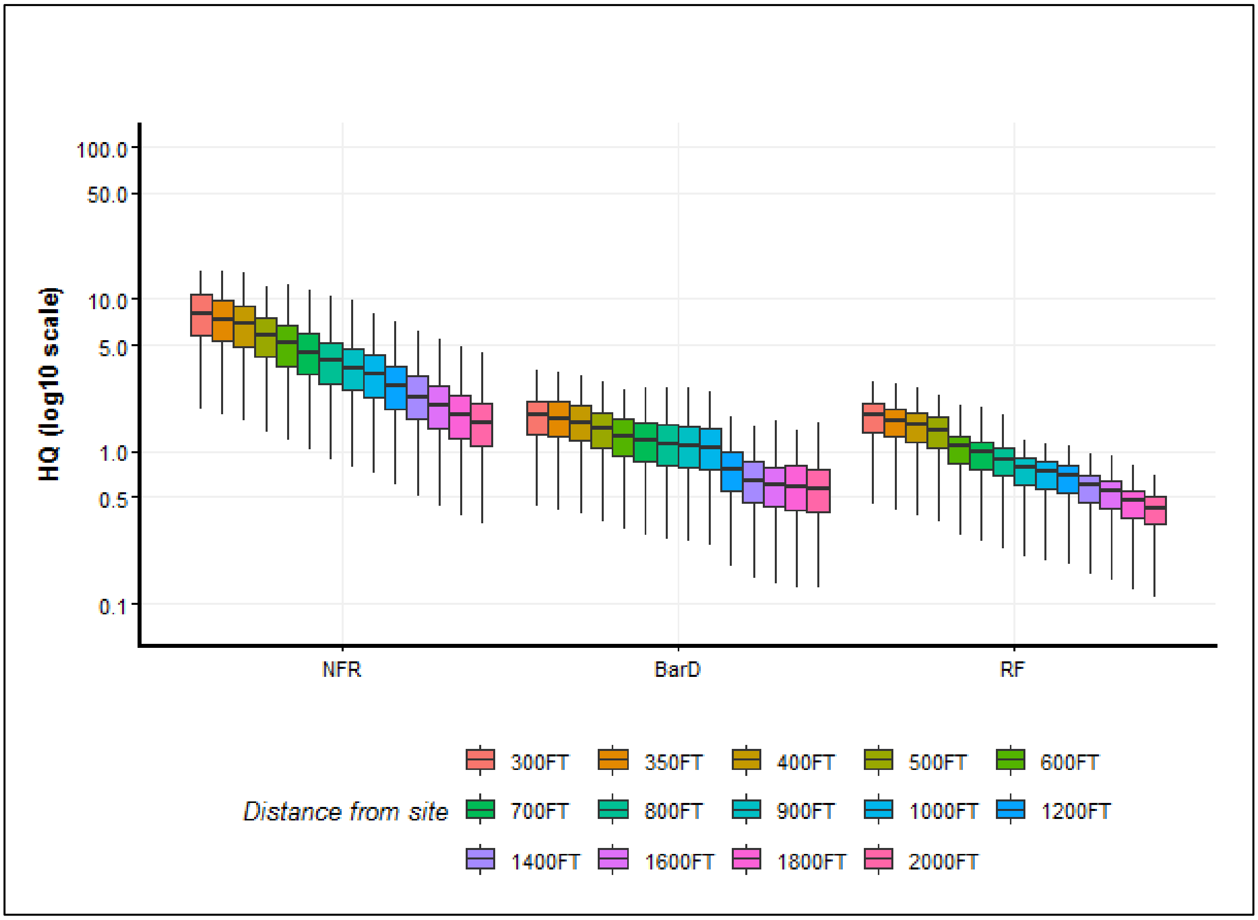
Figure 5-12 is analogous to Figure 5-8 in the 3-acre results, showing distributions of benzene HQs during flowback activities, across all person-days. The 25th-to-75th-percentile ranges of maximum person-day HQs for benzene at the 500-ft distance were 1–1.8, 1–1.7, and 4.1–7.6 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively (rather than 1.2–2.1, 1.1–1.6, and 4.6–8.6 at the 3-acre pads). These are notably lower than the absolute maximum values at that same distance: 2.8, 2.3, and 12, respectively. The median benzene HQs during flowback were 1.4, 1.4, and 5.8 at 500 ft from the three sites respectively (rather than 1.6, 1.4, and 6.4 at the 3-acre pads), which were factors of 1.6–2.1 smaller than the absolute maximum values at the same distance.

For the scenario which had the highest HQs at the 500-ft distance (benzene from flowback at NFR), Figure 5-12 shows that approximately 95 percent of all maximum person-day HQs at the 500-ft distance were below 10 (up from 86 percent with the 3-acre pad), though, as shown in Figure 5-11, 100 percent of values at this distance and site were above 1. All maximum person-day benzene HQs during flowback activities at the Garfield County sites were already below 10 at the 500-ft distance, but approximately 22–23 percent of those values were below 1 (up from 17–20 percent with the 3-acre pads).



Notes: X-axis is not to scale. "Person-days" refers to the collection across the hypothetical population of each modeled individual's daily-maximum acute hazard quotients for a year of modeling. The data in this graph refer to the percentage of hazard quotients (in this collection of hazard quotients) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-11. Percentage of Daily-maximum Acute Non-cancer Hazard Quotients for Benzene (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the 5-acre Well Pad during Flowback Activities



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HQ = hazard quotient; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-12. Distributions of Daily-maximum Acute Non-cancer Hazard Quotients for Benzene (Across the Hypothetical Population) at Various Distances from the 5-acre Well Pad during Flowback Activities

Overall Maximum Critical-effect-group Hazard Indices by Distance

As with the 3-acre pads, **for combined chemical exposures during development activities on a 5-acre well pad**, **hematological health effects (driven by benzene exposure**; see Appendix B**) were of primary concern, followed by neurotoxicity effects (with several VOCs contributing substantially**; see Table 5-6). Maximum critical-effect-group HIs at 500-ft were generally smaller for the 5-acre results relative to the 3-acre results (by less than about 30–60 percent on average across VOCs and O&G activities). The bullets below pertain to the selected receptor at the 500-ft distance.

- Hematological HIs, as with benzene HQs that dominate the hematological HI calculation, reached as high as 12 during flowback activities at the simulated NFR site (down from 18 at the 3-acre pad). As with the 3-acre pad, at the 5-acre pad they were between 1 and 10 during drilling at the NFR site and during all activities at the Garfield County sites (below 1 during fracking at NFR).

  - The primary contribution of benzene to the hematological HI also can be seen in Figure 5-13, which is analogous to Figure 5-9 in the 3-acre results.

- As with the 3-acre pads, for the 5-acre pads the HIs for neurotoxicity effects were slightly above 1 during all activities at all sites, except for fracking from the NFR site where they were below 1.
  - The HQs of several chemicals, including toluene, m+p-xylene, n-hexane, and n-decane, contributed substantially to the neurotoxicity HIs, as shown in Figure 5-13.

- Similar to the results on 3-acre pads, at the 5-acre pads all respiratory HIs were below 1.

At the selected receptor at 2,000 ft from the well pad, HIs were between 1 and 10 for

- hematological effects at all three sites (HI=1.7–4.5, rather than 1.7–12 at the 3-acre pads), during all activities except for flowback at the Garfield County valley site and fracking and flowback at the NFR site; and

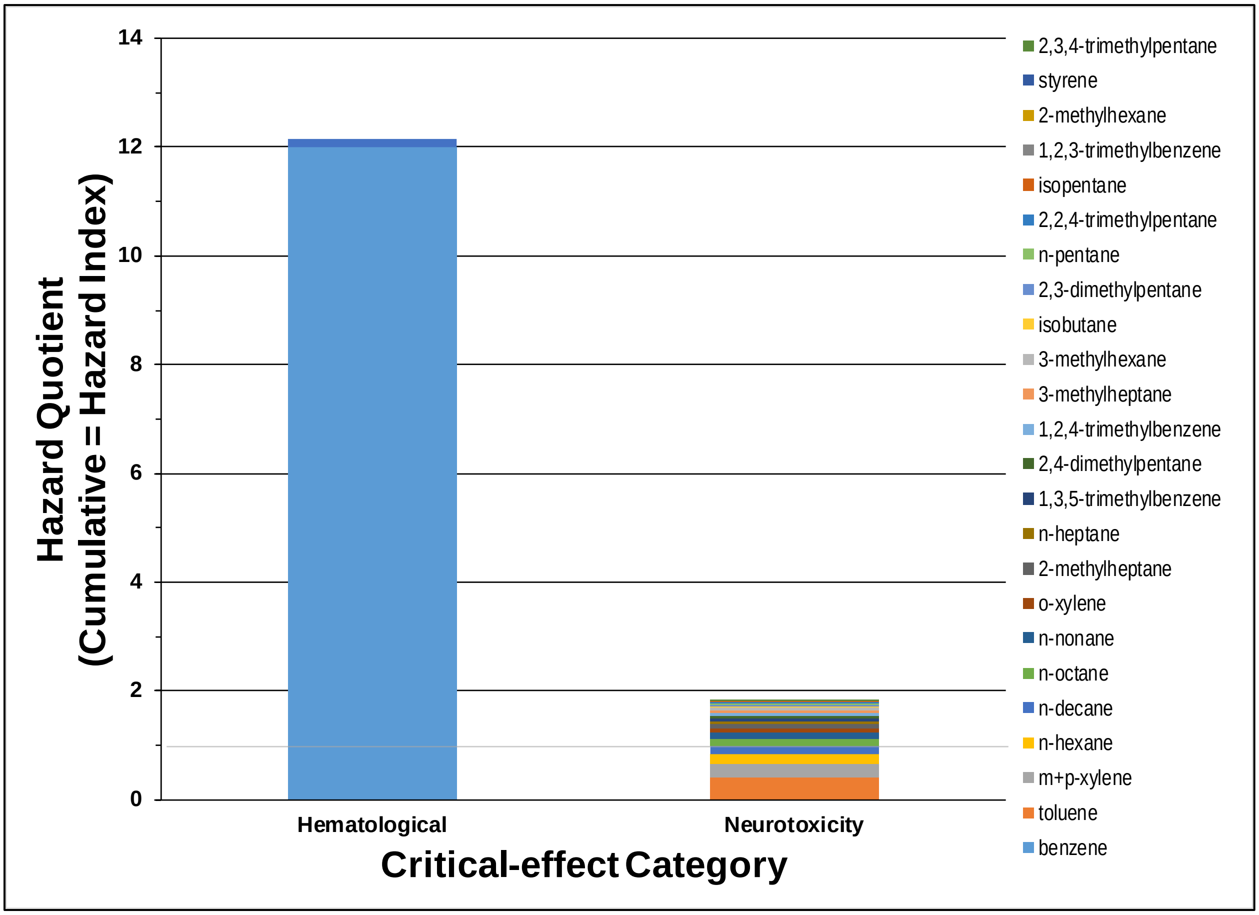
- neurotoxicity effects during flowback at the Garfield County ridge-top site (HI=1.2, rather than 1.3 at the 3-acre pad), but, contrary to the 3-acre results, not during drilling at the same site or flowback at the NFR site (where 5-acre HQs were below 1).

Note that we were not able to assign some chemicals, including ethyltoluenes, to any acute critical-effect groups (see Appendix B). A more detailed presentation of these HI values can be found in Table E-11, and Table E-12 contains data on the percentage of daily-maximum acute HIs above 1. The same HQ trends with distance discussed above exist also for HIs. Specifically, as distance increased, HIs generally decreased and frequencies of HIs above 1 decreased for all modeled scenarios and critical-effect groups at the 5-acre development well pad.

Table 5-6. Overview of the Largest Acute Non-cancer Hazard Indices during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Well Pad

Range of Hazard Indices	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	none		hematological	none		
Between 1 and 10	Drilling	hematological neurotoxicity	hematological neurotoxicity	hematological neurotoxicity	hematological	hematological	hematological
	Fracking	hematological neurotoxicity	hematological neurotoxicity	none	hematological	hematological	none
	Flowback	hematological neurotoxicity	hematological neurotoxicity	neurotoxicity	hematological neurotoxicity	none	hematological
0.1 to 1	Drilling	none			neurotoxicity	neurotoxicity	neurotoxicity
	Fracking	respiratory sensory systemic	respiratory sensory systemic	hematological	neurotoxicity respiratory	neurotoxicity respiratory	hematological
	Flowback	respiratory sensory	respiratory sensory	endocrine respiratory sensory	respiratory sensory	hematological neurotoxicity respiratory sensory	neurotoxicity respiratory

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: Gray line emphasizes hazard quotient/index=1. The order of chemicals listed in the legend matches the order of plotting (e.g., benzene plotted first on the bottom if applicable to that critical-effect group, then toluene, etc.). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-13. Approximate Chemical Contributions to the Largest Hazard Indices of Selected Critical-effect Groups: Acute Non-cancer Assessment for the Highest Exposed Hypothetical Individuals at 500 Feet from the 5-acre Well Pad during Flowback Activities at the Northern Front Range Site

5.3.2. Subchronic Non-cancer Hazards

In this section, we discuss the potential for subchronic (multi-day) exposures above health-criteria levels, due to emissions from individual O&G development activities (see Section 5.5.1 for a discussion on subchronic exposures during development activities in sequence). We discuss the results of each size of well pad separately: 1 acre (Section 5.3.2.1), 3 acre (Section 5.3.2.2), and 5 acre (Section 5.3.2.3). Within each subsection, we stratify the results by O&G activity as well. Recall that all modeled sites are hypothetical.

Emissions of all chemicals during all activities at all sites were at or below subchronic health-criteria levels at distances 500-ft from the well pad and beyond (e.g., Table 5-7, Table 5-9, and Table 5-11). **At distances closer than 500 ft from the well pad, exposures to m+p-xylene, n-nonane, and benzene were of primary concern, due to maximum HQs slightly above 1 during fracking and flowback** (e.g., Table E-13, Table E-17, and Table E-

21). **At distances out to about 800 ft from the well pad, exposures to trimethylbenzenes were also of concern due to their contributions to maximum neurotoxicity and hematological HI values that were slightly above 1** (e.g., Figure 5-14, Figure 5-18, Figure 5-22, Table E-15, Table E-19, and Table E-23). **HQs and HIs decreased with distance from the well pad** (e.g., Figure 5-15, Figure 5-19, and Figure 5-23)**, and for most chemicals the exposures were always well below criteria levels even during the worst simulated conditions.**

While the highest subchronic HQs and HIs were largest at the Garfield County ridge-top site, on average across chemicals/critical-effect groups, distances, and O&G activities the differences in HQs and HIs between that and the other two sites were less than a factor of 3, with values at the NFR site tending to be the lowest. As with the acute assessment, our modeling also indicated **small or negligible differences between simulated individuals in different age groups** in their typical and higher subchronic HQs and HIs, as expected based on the exposure modeling (see Section 3.5.1). Our discussion in this subchronic section does not differentiate results by age group (focusing on ages up to 17 years for convenience), though results stratified by age group can be found in Appendix E.1.2.

Differences in the maximum chemical HQs and critical-effect-group HIs by distance were noticeable when comparing 1-, 3-, and 5-acre well-pad scenarios. We previously noted these differences in terms of air concentrations (Section 2.9.1.5) and subchronic exposures (Section 3.5.4). These comparisons **typically showed smaller subchronic HQs and HIs at 3- and 5-acre pads relative to 1-acre pads. There is mixed comparison of maximum values stratified by distance, between 5- and 3-acre pads**: the 3-acre values were most often larger than the 5-acre values at the NFR site, while the 5-acre values tended to be larger at the Garfield County sites. As with acute HQs and HIs, **these differences tended to be smaller at farther distances from the well pad.** These are average differences, and for individual chemicals/critical-effect groups and activities the differences can be larger in either direction. These variations may be due to several factors, including: the complex interactions between the initial plume and meteorological parameters such as wind flow and turbulence, the focus here on maximum subchronic values rather than averages or medians, and the selection of the target receptor at each distance, which occurred independently by well-pad size.

The HQs and HIs were generally lower in subchronic evaluations compared to acute evaluations due to the effect of averaging hourly exposures (some high and some low, according to hour-by-hour variations in air concentrations) over multiple days (that is, subchronic scenarios are not as “conservative” as acute scenarios, which focus on the highest acute exposures). Though subchronic health criteria values tended to be more stringent (lower) than acute criteria values, the subchronic exposures were low enough so that no subchronic HQs were greater than 10, which was not the case for acute HQs. Similar to the acute assessment, the highest subchronic HQs still reflect narrow subsets of the potentially exposed population during relatively rare exposure scenarios (individuals assumed to live at the highest exposure locations during meteorological conditions favoring high exposures; see Section 5.1). When comparing an individual chemical’s HQs between the acute and subchronic assessment, one must keep in mind these differences in averaging time and criteria value, and also keep in mind that the air concentrations changed between these assessments—hour-by-hour air concentrations in the acute assessment were the maximum values found in the AERMOD Monte Carlo iterations, while those in the subchronic assessment were the mean values of those iterations. One chemical's maximum emissions may be higher than another's, but the opposite may be true of mean emissions.

As with the above sections on acute results, the subchronic results presented below focus first on the highest simulated exposures (especially at 500 and 2,000 ft from the well pad, and especially those leading to HQs and HIs above 1), and then we put those highest results into context of the full distributions of results. These distributions, at the selected receptor at a given distance from the well, consist of 365 multi-day periods for each of the 1,000 simulated individuals. Each multi-day period begins on a different day of the year and extends through the assumed duration of the O&G activity (see Table 3-3). We generally do not discuss the many chemicals whose maximum HQs were below 0.1. A more detailed presentation of HQs and HIs at various distances can be found in Section E.1.2.

5.3.2.1. 1-acre Well Pad

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

At the selected receptor at 500 ft from the well pad, contrary to the acute results discussed in Section 5.3.1, all VOC HQs were 1 or below (Table 5-7, Table E-13). At 2,000 ft from the pad, only the highest m+p-xylene exposures corresponded to an HQ slightly above 0.1 (all other HQs were below 0.1).

However, HQs for chemicals belonging to the hematological and neurotoxicity critical-effect groups sometimes aggregated to HIs slightly above 1 at the 500-ft distance (Table 5-8, Figure 5-14, Table E-15). **Due to these HQ aggregations, m+p-xylene, n-nonane, benzene, and trimethylbenzenes during fracking operations at the Garfield County sites were of primary concern for subchronic exposures at distances within about 800 ft of 1-acre well pads**. **All HIs were 1 or below at 900-ft distances and beyond, which was not the case with the acute HIs**. Figure 5-15 illustrates trends with distance in the maximum neurotoxicity HIs at the selected receptors during fracking activities. These HIs fell to 1 or below by the 900-ft distance at the Garfield County sites, and they were always below 1 at the NFR site and fell below the 0.01 level by the 1,400-ft distance. Table E-15 shows all modeled values for each site and critical-effect group, including those used to create this graph.

Comparing HQs and HIs between the three sites, the HQs and HIs averaged across chemicals, activities, and distances were within a factor of 3 between the Garfield County ridge-top site and the NFR site, and within about 15 percent between the two Garfield County sites.

Table 5-7. Overview of the Largest Subchronic Non-cancer Hazard Quotients during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 1-acre Well Pad

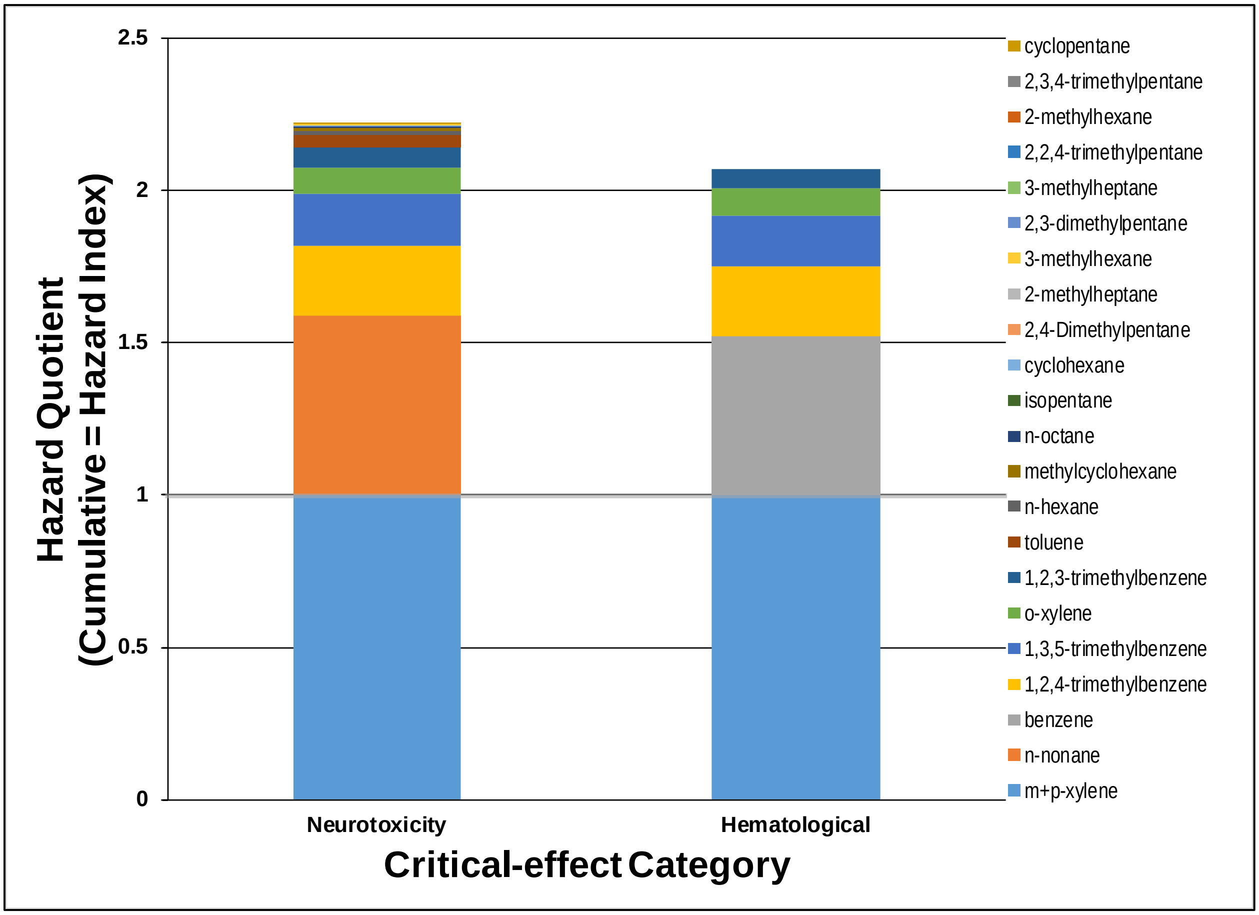
Range of Hazard Quotients	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	none			none		
Between 1 and 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	none			none		
0.1 to 1	Drilling	benzene toluene	benzene	benzene	none		
	Fracking	123-TMB 135-TMB benzene m+p-xylene n-nonane	124-TMB 135-TMB benzene n-nonane	none	m+p-xylene	m+p-xylene	none
	Flowback	123-TMB 124-TMB 135-TMB benzene m+p-xylene n-nonane	124-TMB 135-TMB m+p-xylene n-nonane	124-TMB 135-TMB benzene m+p-xylene n-nonane	none		

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
TMB = trimethylbenzene; 123 = 1,2,3 and 124 = 1,2,4 and so on.

Table 5-8. Overview of the Largest Subchronic Non-cancer Hazard Indices during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 1-acre Well Pad

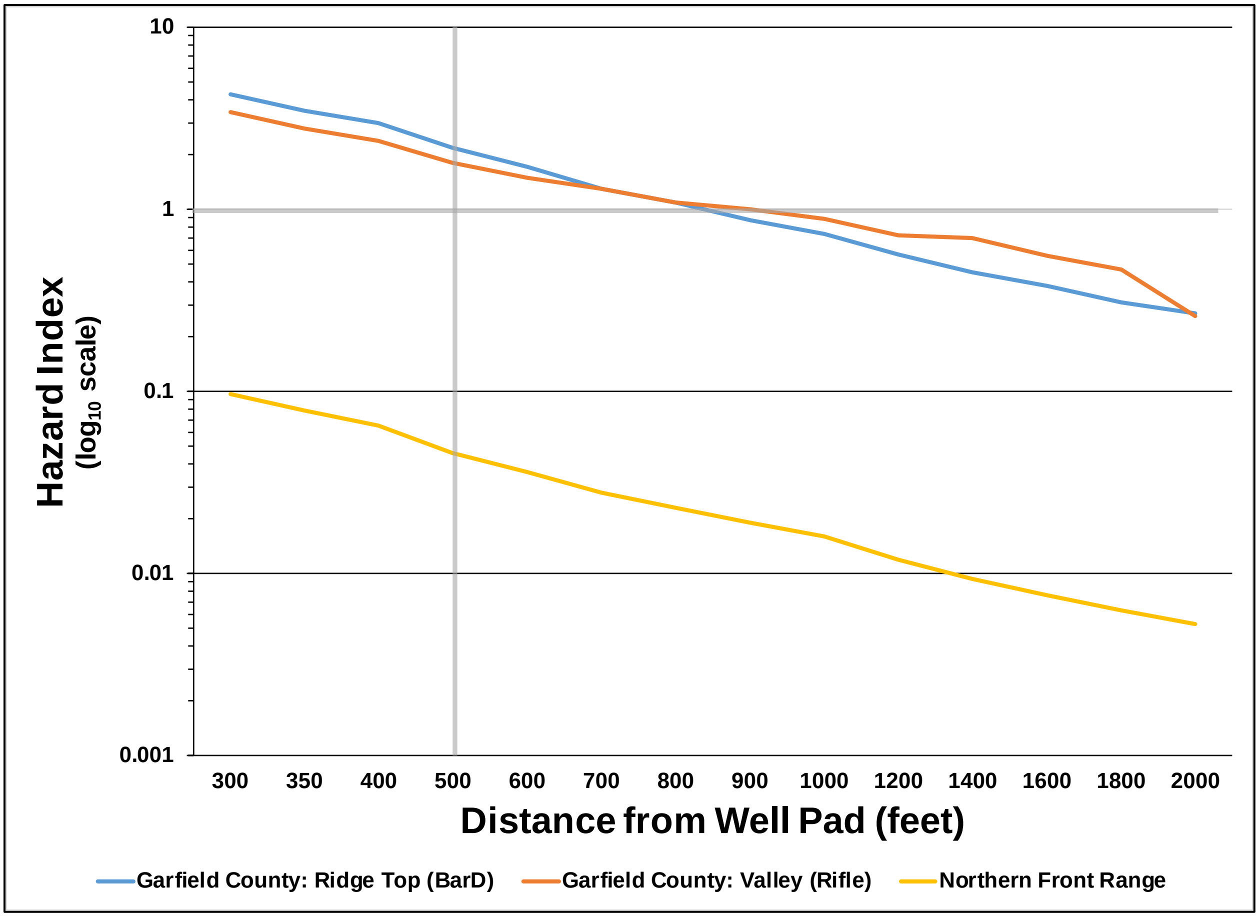
Range of Hazard Indices	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	none			none		
Between 1 and 10	Drilling	none			none		
	Fracking	hematological neurotoxicity	hematological neurotoxicity	none	none		
	Flowback	none			none		
0.1 to 1	Drilling	hematological neurotoxicity	hematological neurotoxicity	hematological neurotoxicity	none		
	Fracking	respiratory systemic	respiratory	none	hematological neurotoxicity	hematological neurotoxicity	none
	Flowback	hematological neurotoxicity respiratory systemic	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	none	neurotoxicity	hematological

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: Gray line emphasizes hazard quotient/index=1. The order of chemicals listed in the legend matches the order of plotting (e.g., m+p-xylene plotted first on the bottom if applicable to that critical-effect group, then n-nonane, etc.). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-14. Approximate Chemical Contributions to the Largest Hazard Indices of Selected Critical-effect Groups: Subchronic Non-cancer Assessment for the Highest Exposed Hypothetical Individuals at 500 Feet from the 1-acre Well Pad during Fracking Activities at the Garfield County Ridge-top Site



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10.

Figure 5-15. Largest Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the 1-acre Well Pad during Fracking Activities

Analysis of Person-period Critical-effect-group Hazard Indices by Distance

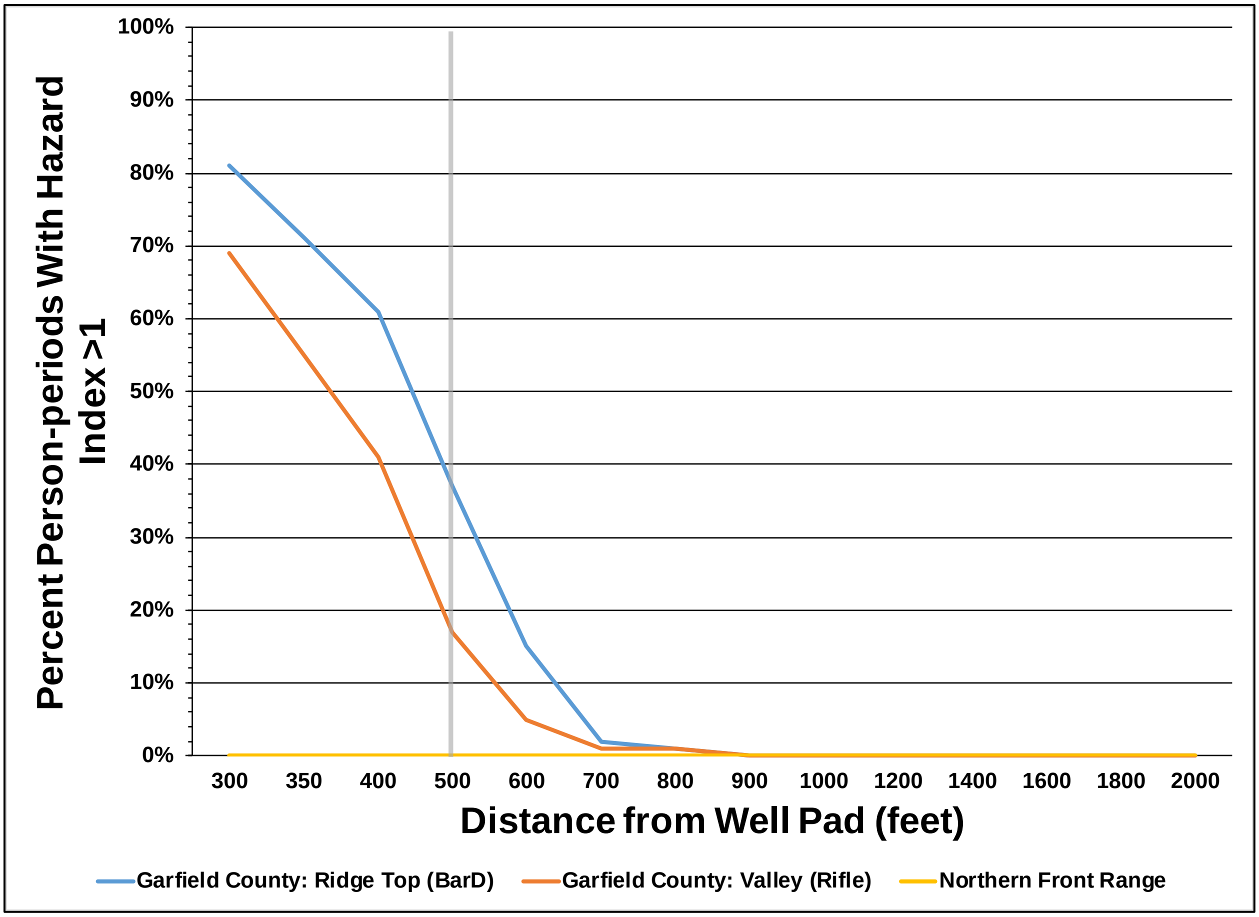
For the same scenarios used in Figure 5-15, in Figure 5-16 we illustrate the frequency of maximum subchronic HIs reaching above a value of 1. These percentages are taken from the collection of each simulated individual's 365 multi-day subchronic HIs (which we term "person-periods"), for 1,000 simulated youths up to 17 years old at each selected downwind receptor. The results for all age groups are nearly identical (see Sections 3.5.1 and E.1). This analysis shows how often (on a multi-day basis) HIs above 1 occurred across a year of modeled subchronic scenarios for development activities at 1-acre well pads. A value of 100 percent would indicate that every simulated individual experienced a subchronic HI above 1 on every multi-day period of the year. A value of 50 percent indicates that, among the 365,000 subchronic HI data points across the population at a receptor, about half of them (about 182,500) were above 1.

In this example, under the conservative exposure assumptions used in this analysis (high emissions and unfavorable meteorology), the model results indicated the characteristics we note below.

- As noted earlier, no neurotoxicity HIs were above 1 during fracking at the NFR site.
- At distances 300–400 ft from the 1-acre pad at the Garfield County ridge-top site, and at 300 ft from the pad at the Garfield County valley site, fracking activities during most multi-day periods of the year produced subchronic neurotoxicity HIs above 1 for most people.
  - By the 700-ft distance from the Garfield County pads, subchronic neurotoxicity HIs above 1 were rare, and they did not occur by the 900-ft distance (whereas acute neurotoxicity HIs above 1 did occur beyond these distances from the Garfield County pads).

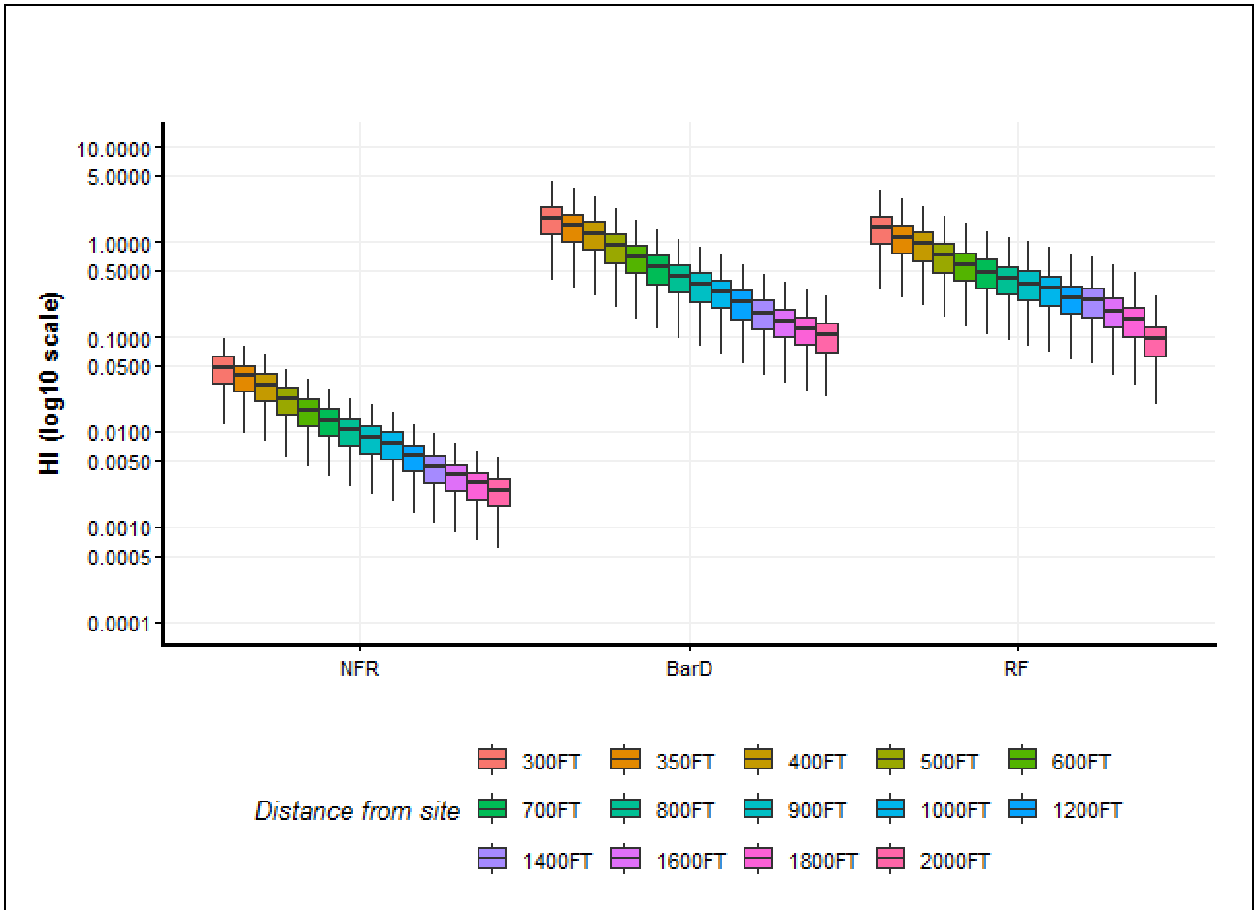
Generally, the rate of decline in these percentages with distance will vary across chemicals/critical-effect groups, sites, and O&G activities, depending on several factors. Table E-16 shows the percentage of person-periods with HI above 1 for all critical-effect groups, including those used to create this graph (see Table E-14 for HQs).

Figure 5-17 contains box-and-whisker plots reflecting the distributions of neurotoxicity HIs during fracking activities, across all person-periods, stratified by O&G site and distance. The 25th-to-75th-percentile ranges of person-period HIs for neurotoxicity at the 500-ft distance were 0.6–1.2, 0.48–0.95, and 0.015–0.029 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively. These were notably lower than the absolute maximum values at that same distance: 2.2, 1.8, and 0.046, respectively. The median neurotoxicity HIs during fracking were 0.9, 0.71, and 0.022 at 500 ft from the three sites respectively, which were factors of 2.1–2.5 smaller than the absolute maximum values at the same distance.



Notes: X-axis is not to scale. "Person-periods" refers to the collection across the hypothetical population of each modeled individual's subchronic hazard indices for a year of modeling (the "rolling averages" referred to in Section 3.3.2.2). The data in this graph refer to the percentage of hazard indices (in this collection of hazard indices) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-16. Percentage of Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the 1-acre Well Pad during Fracking Activities



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-17. Distributions of Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) at Various Distances from the 1-acre Well Pad during Fracking Activities

5.3.2.2. 3-acre Well Pad

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

At the selected receptor at 500 ft from the 3-acre well pad, as with the 1-acre results discussed in Section 5.3.2.1, all VOC HQs were 1 or below (Table 5-9, Table E-17). At 2,000 ft from the 3-acre pad, contrary to the 1-acre pad, all HQs were well below 0.1. Maximum chemical HQs and critical-effect-group HIs at 500 ft were generally smaller for the 3-acre results relative to the 1-acre results (by less than about a factor of 2 on average across VOCs/critical-effect groups, O&G activities, and sites).

However, HQs for chemicals belonging to the hematological and neurotoxicity critical-effect groups sometimes aggregated to HIs slightly above 1 at the 500-ft distance (Table 5-10, Figure 5-18, Table E-19). Note that Figure 5-18 illustrates data from the Garfield County valley site because that is where neurotoxicity HIs at the 500-ft distance were largest (rather than at the Garfield County ridge-top site, which was the case with 1-acre pads). **Due to these HQ aggregations, m+p-xylene, n-nonane, benzene, and trimethylbenzenes during fracking operations at the Garfield County sites were of primary concern for subchronic exposures at distances within about 600 ft of 3-acre well pads (down from within about 800 ft of the 1-acre pads)**. **All HIs were below 1 at 700-ft distances and beyond**. Figure 5-19 illustrates trends with distance in the maximum neurotoxicity HIs at the selected receptors during fracking activities. These HIs fell below 1 by the 700-ft distance at the Garfield County sites, and they were always below 1 at the NFR site and, as with the 1-acre pad, fell below the 0.01 level by the 1,400-ft distance. Table E-19 shows all modeled values for each site and critical-effect group, including those used to create this graph.

Table 5-9. Overview of the Largest Subchronic Non-cancer Hazard Quotients during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 3-acre Well Pad

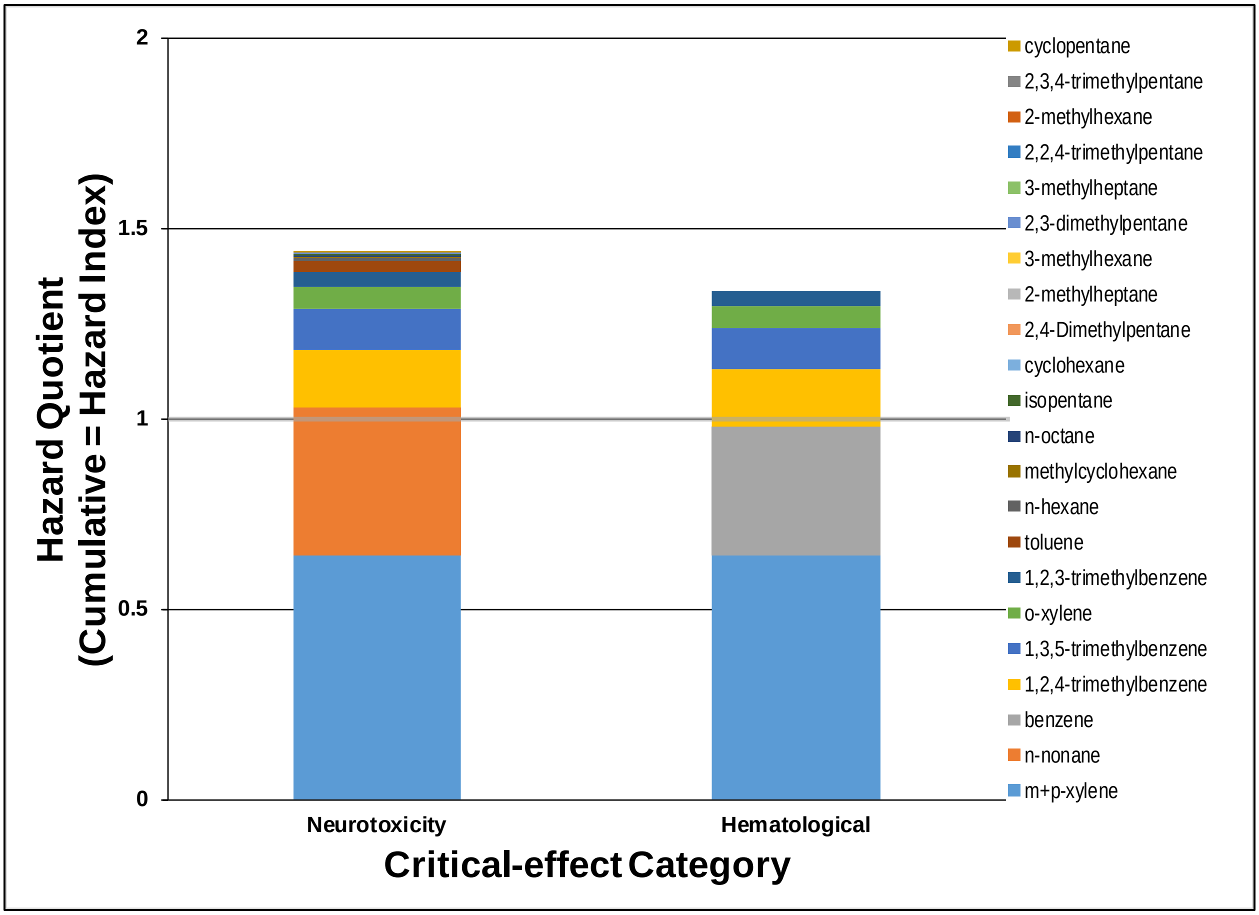
Range of Hazard Quotients	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	none			none		
Between 1 and 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	none			none		
0.1 to 1	Drilling	benzene	benzene	benzene	none		
	Fracking	124-TMB benzene m+p-xylene n-nonane	124-TMB 135-TMB benzene m+p-xylene n-nonane	none	none		
	Flowback	n-nonane	m+p-xylene n-nonane	benzene m+p-xylene n-nonane	none		

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
TMB = trimethylbenzene; 123 = 1,2,3 and 124 = 1,2,4 and so on.

Table 5-10. Overview of the Largest Subchronic Non-cancer Hazard Indices during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 3-acre Well Pad

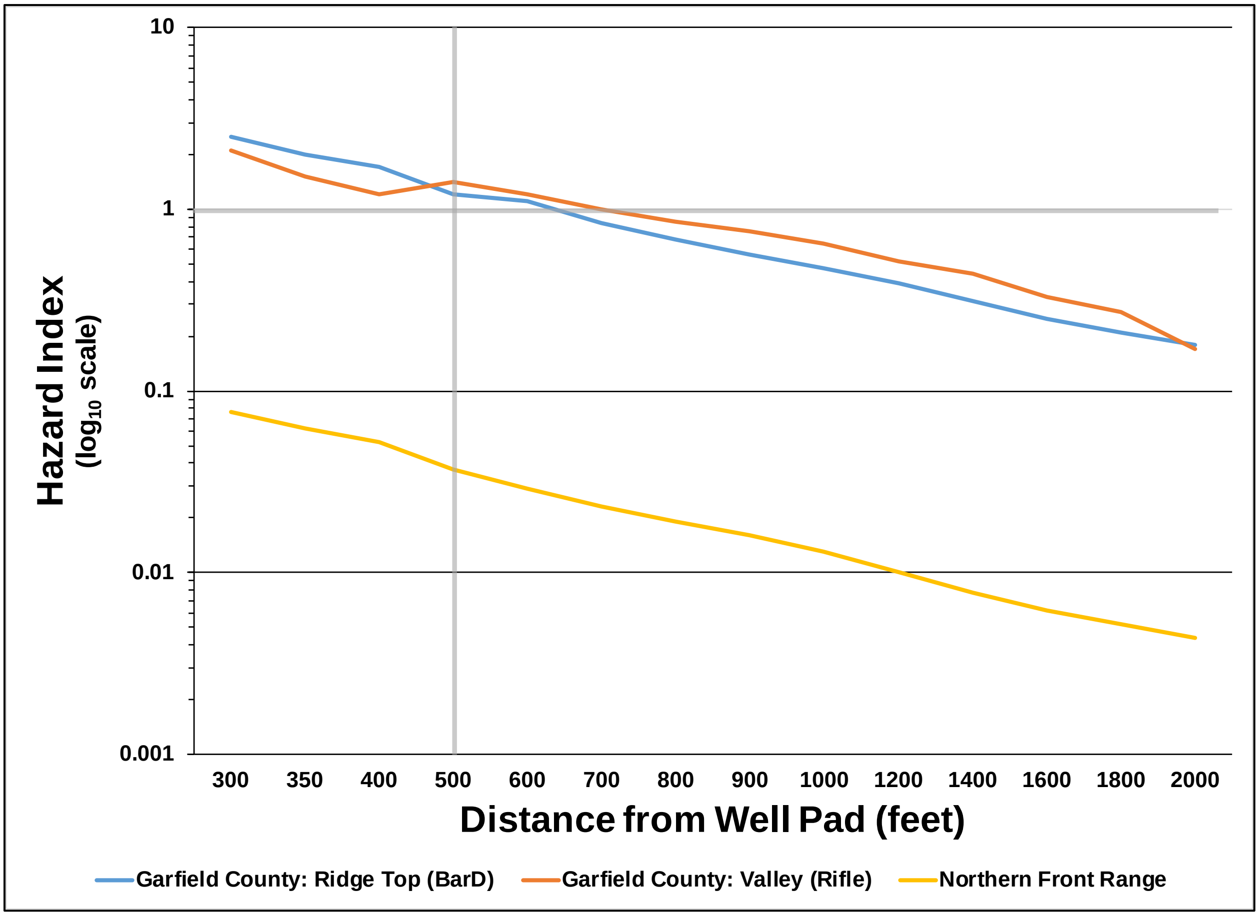
Range of Hazard Indices	Activity	500 feet from Well Pad: Garfield County: Ridge Top (BarD)	500 feet from Well Pad: Garfield County: Valley (Rifle)	500 feet from Well Pad: Northern Front Range	2,000 feet from Well Pad: Garfield County: Ridge Top (BarD)	2,000 feet from Well Pad: Garfield County: Valley (Rifle)	2,000 feet from Well Pad: Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	none			none		
Between 1 and 10	Drilling	none			none		
	Fracking	hematological neurotoxicity	hematological neurotoxicity	none	none		
	Flowback	none			none		
0.1 to 1	Drilling	hematological neurotoxicity	hematological	hematological	none		
	Fracking	respiratory	respiratory	none	hematological neurotoxicity	hematological neurotoxicity	none
	Flowback	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	none	neurotoxicity	none

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: Gray line emphasizes hazard quotient/index=1. The order of chemicals listed in the legend matches the order of plotting (e.g., m+p-xylene plotted first on the bottom if applicable to that critical-effect group, then n-nonane, etc.). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-18. Approximate Chemical Contributions to the Largest Hazard Indices of Selected Critical-effect Groups: Subchronic Non-cancer Assessment for the Highest Exposed Hypothetical Individuals at 500 Feet from the 3-acre Well Pad during Fracking Activities at the Garfield County Valley Site



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
log10 = logarithm base 10.

Figure 5-19. Largest Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the 3-acre Well Pad during Fracking Activities

Analysis of Person-period Critical-effect-group Hazard Indices by Distance

Figure 5-20 is analogous to the 1-acre Figure 5-16 (showing trends with distance in the percentage of population person-periods with neurotoxicity HIs at the selected receptors exceeding 1 during fracking activities).

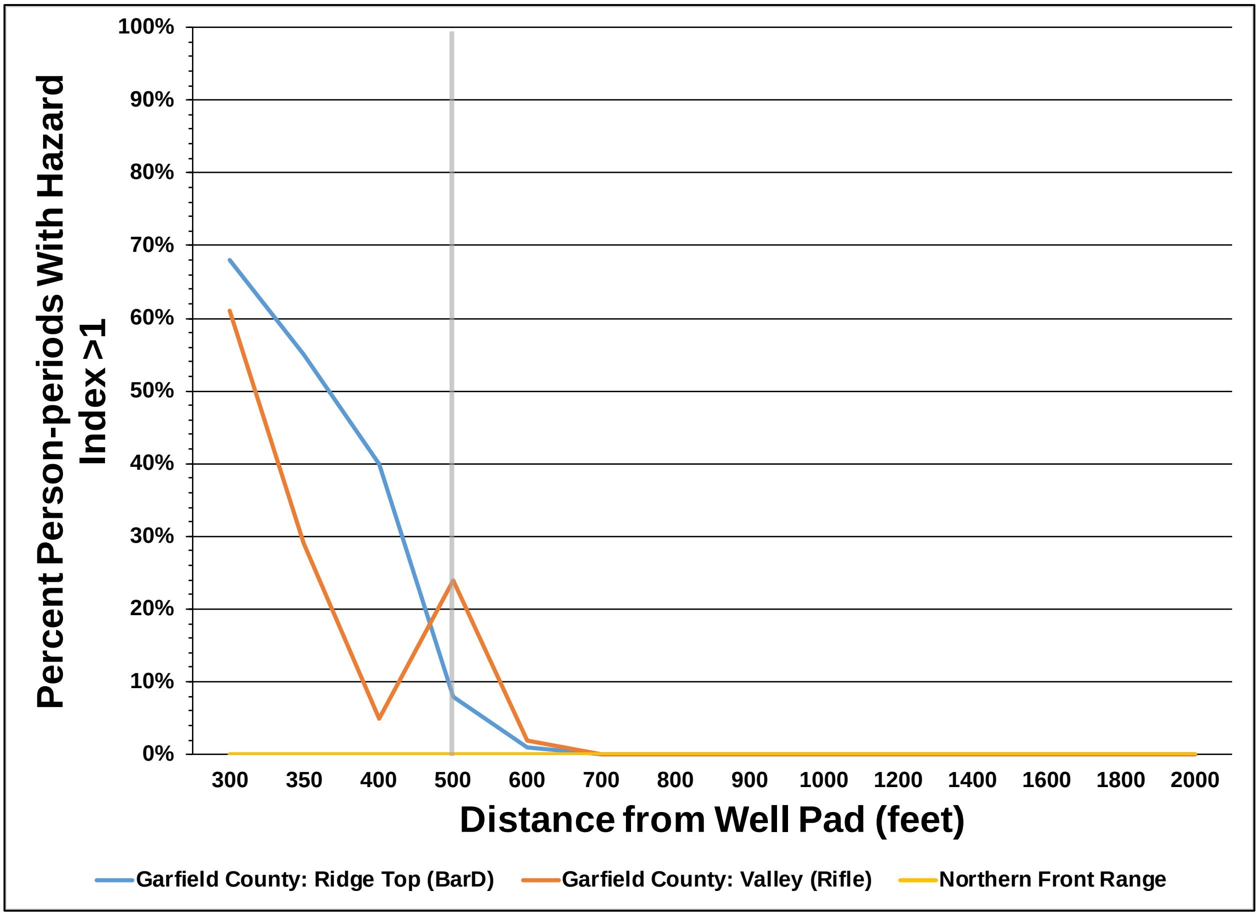
- As with the 1-acre pad, no neurotoxicity HIs were above 1 during fracking at the 3-acre NFR site.
- Only at the closest distance to the 3-acre Garfield County well pads did fracking activities during most multi-day periods of the year produce subchronic neurotoxicity HIs above 1 for most people (at the 1-acre pad, this extended to 400 ft at the Garfield County ridge-top site).

- By the 600-ft distance from the 3-acre Garfield County pads, subchronic neurotoxicity HIs above 1 were rare (this was at 700 ft at the 1-acre pads), and they did not occur by the 700-ft distance (this was at 900 ft at the 1-acre pads).

- The spike in percentages at the 500-ft distance from the Garfield County valley site corresponds to the spike seen with the HIs (Figure 5-19), and it also corresponds to spikes in the HQs of the primary chemical constituents of the neurotoxicity critical-effect group for the same site and distance (m+p-xylene, n-nonane, and trimethylbenzenes; see Table E-17). This reflects interactions between the 3-acre Garfield County valley pad and the local meteorological conditions particular to that site, and note that HIs continue to decrease beyond 500 ft.

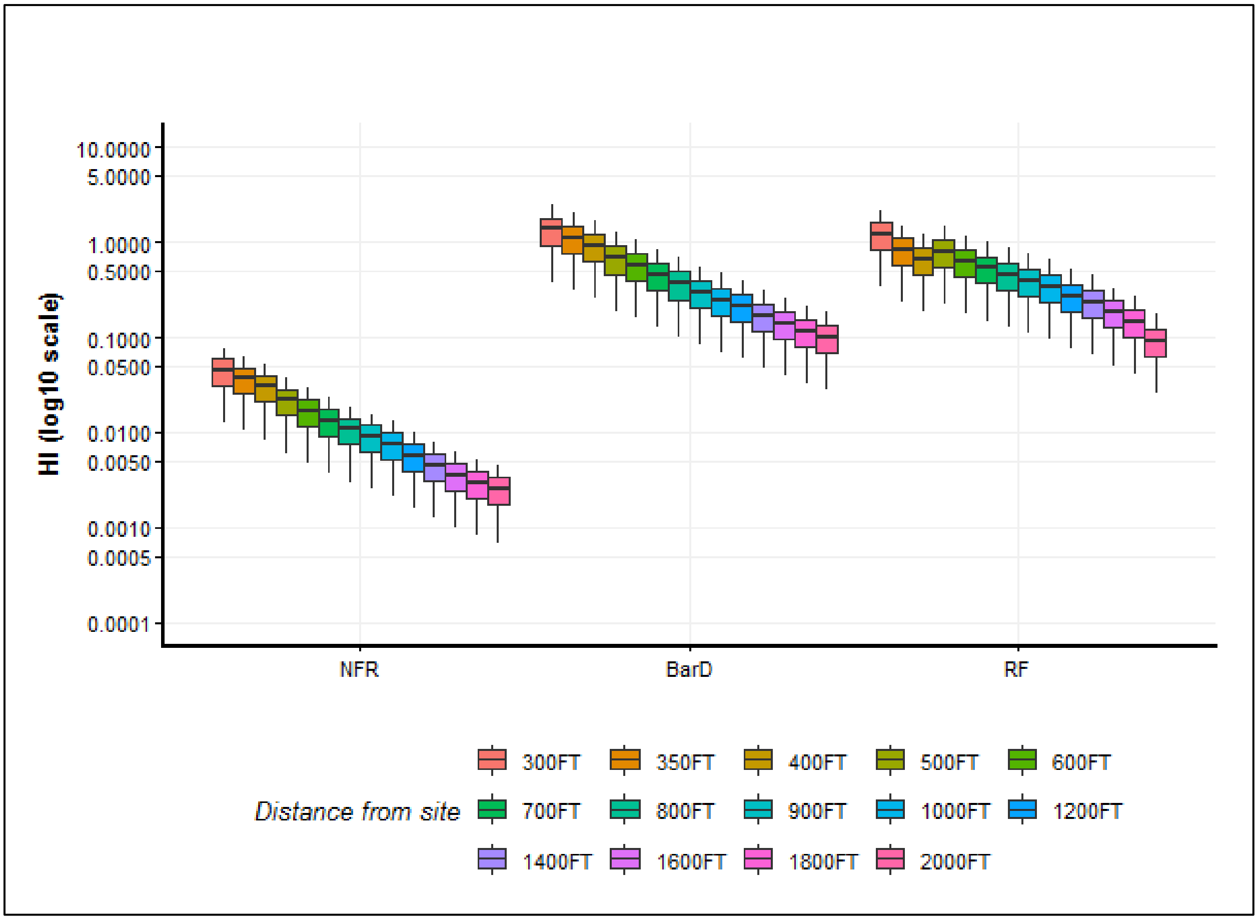
Generally, the rate of decline in these percentages with distance will vary across chemicals/critical-effect groups, sites, and O&G activities, depending on several factors. Table E-20 shows the percentage of person-periods with HI above 1 for all critical-effect groups, including those used to create this graph (see Table E-18 for HQs).

Figure 5-21 is analogous to Figure 5-17 in the 1-acre results, showing distributions of neurotoxicity HIs during fracking activities, across all person-periods. The 25th-to-75th-percentile ranges of person-period HIs for neurotoxicity at the 500-ft distance were 0.45–0.89, 0.53–1, and 0.015–0.029 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively (rather than 0.6–1.2, 0.48–0.95, and 0.015–0.029 at the 1-acre pads). These were lower than the absolute maximum values at that same distance: 1.2, 1.4, and 0.037, respectively. The median neurotoxicity HIs during fracking were 0.67, 0.78, and 0.022 at 500 ft from the three sites respectively (rather than 0.9, 0.71, and 0.022 at the 1-acre well pads), which were factors of 1.7–1.8 smaller than the absolute maximum values at the same distance.



Notes: X-axis is not to scale. "Person-periods" refers to the collection across the hypothetical population of each modeled individual's subchronic hazard indices for a year of modeling (the "rolling averages" referred to in Section 3.3.2.2). The data in this graph refer to the percentage of hazard indices (in this collection of hazard indices) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-20. Percentage of Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the 3-acre Well Pad during Fracking Activities



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-21. Distributions of Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) at Various Distances from the 3-acre Well Pad during Fracking Activities

5.3.2.3. 5-acre Well Pad

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

At the selected receptor at 500 ft from the 5-acre well pad, as with the 1- and 3-acre results discussed in Sections 5.3.2.1 and 5.3.2.2, all VOC HQs were 1 or below (Table 5-11, Table E-21). At 2,000 ft from the 5-acre pad, as with the 3-acre pad, all HQs were well below 0.1. Maximum chemical HQs and critical-effect-group HIs at 500 ft were generally smaller for the 5-acre results relative to the 3-acre results at the NFR and Garfield County valley sites (by less than about 70 percent on average across VOCs and O&G activities), but were generally larger for the 5-acre results at the Garfield County ridge-top site (by less than about 20 percent on average across VOCs/critical-effect groups, O&G activities, and sites).

However, HQs for chemicals belonging to the hematological and neurotoxicity critical-effect groups sometimes aggregated to HIs slightly above 1 at the 500-ft distance (Table 5-12, Figure 5-22, Table E-23). Note that Figure 5-22 illustrates data from the Garfield County ridge-top site because that is where neurotoxicity HIs at the 500-ft distance were largest (rather than at the Garfield County valley site, which was the case with 3-acre pads). **Due to these HQ aggregations, m+p-xylene, n-nonane, benzene, and trimethylbenzenes during fracking operations at the Garfield County sites were of primary concern for subchronic exposures at distances within about 600 ft of 5-acre well pads (similar to the 3-acre pads)**. **All HIs were below 1 at 700-ft distances and beyond**. Figure 5-23 illustrates trends with distance in the maximum neurotoxicity HIs at the selected receptors during fracking activities. These HIs fell below 1 by the 700-ft distance at the Garfield County sites, and they were always below 1 at the NFR site and fell below the 0.01 level by the 1,200-ft distance (rather than at 1,400 ft from the 3-acre pad). Table E-23 shows all modeled values for each site and critical-effect group, including those used to create this graph.

Table 5-11. Overview of the Largest Subchronic Non-cancer Hazard Quotients during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Well Pad

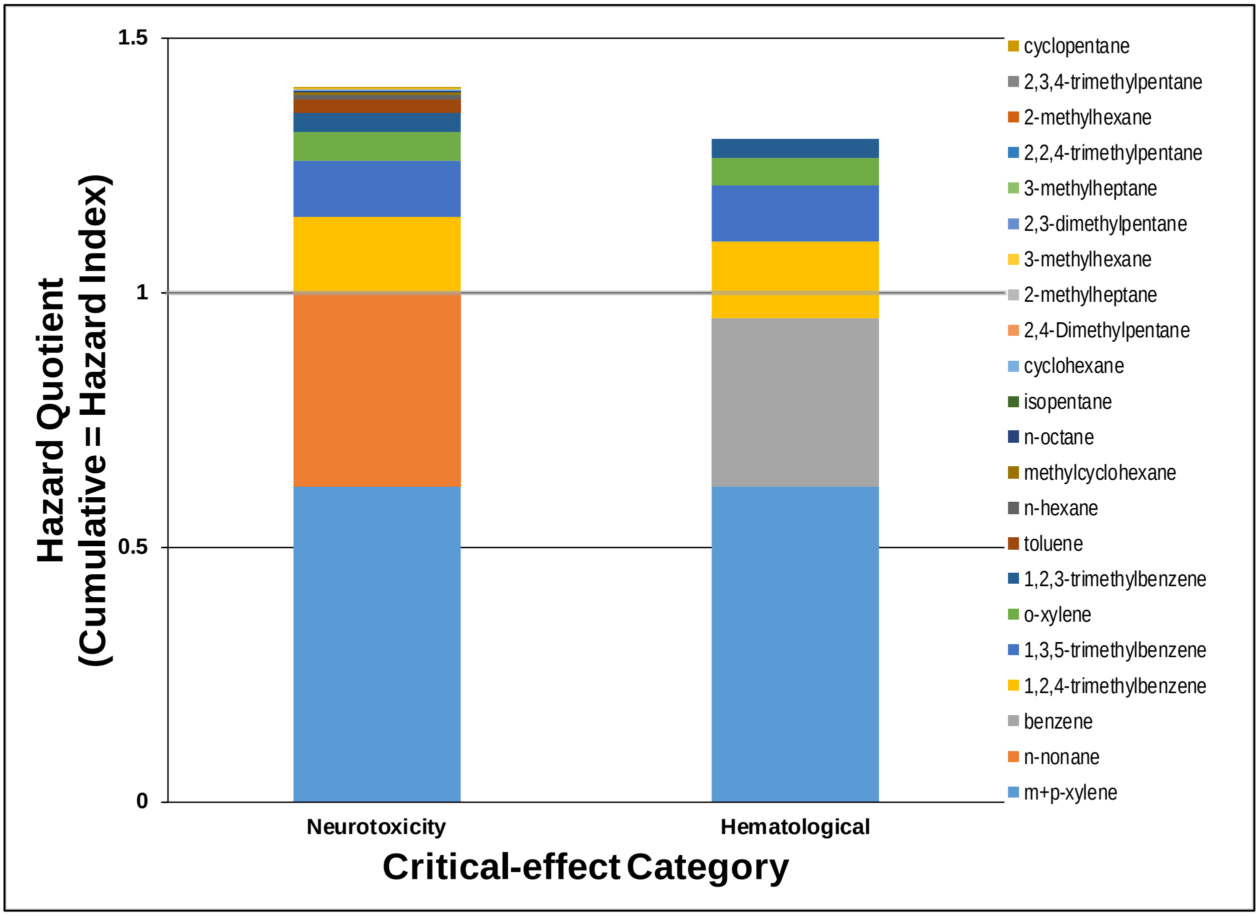
Range of Hazard Quotients	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	N/A	N/A	none	N/A	N/A	none
Between 1 and 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	N/A	N/A	none	N/A	N/A	none
0.1 to 1	Drilling	benzene	benzene	benzene	none		
	Fracking	124-TMB 135-TMB benzene m+p-xylene n-nonane	benzene m+p-xylene n-nonane		none		
	Flowback	N/A	N/A	benzene m+p-xylene n-nonane	N/A	N/A	none

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical). Flowback is "N/A" for Garfield County because it lasts more than 1 year in the 5-acre scenario with many wells being developed (so we defer to a chronic assessment).
TMB = trimethylbenzene; 123 = 1,2,3 and 124 = 1,2,4 and so on.

Table 5-12. Overview of the Largest Subchronic Non-cancer Hazard Indices during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Well Pad

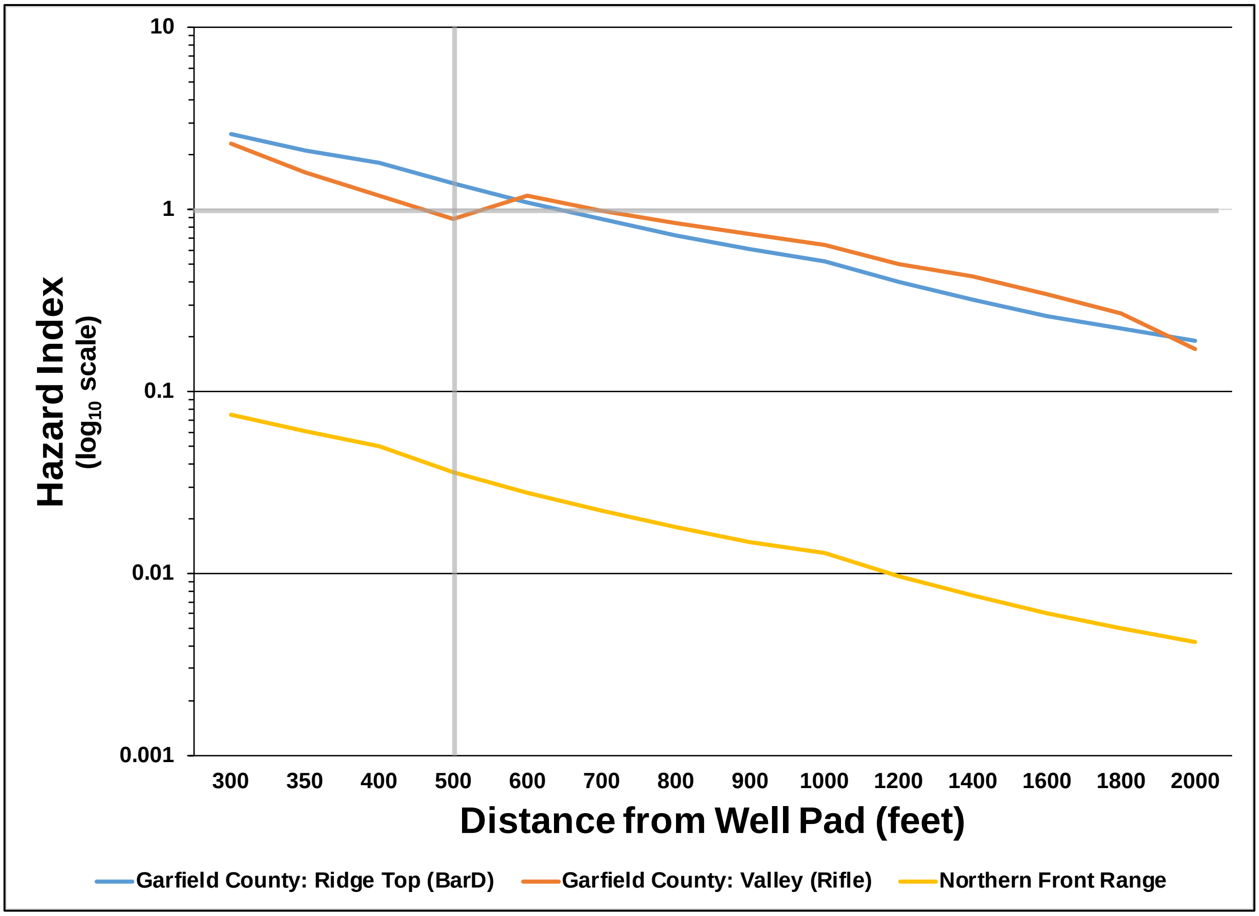
Range of Hazard Indices	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Drilling	none			none		
	Fracking	none			none		
	Flowback	N/A	N/A	none	N/A	N/A	none
Between 1 and 10	Drilling	none			none		
	Fracking	hematological neurotoxicity	none		none		
	Flowback	N/A	N/A	none	N/A	N/A	none
0.1 to 1	Drilling	hematological neurotoxicity	hematological	hematological	none		
	Fracking	respiratory	hematological neurotoxicity respiratory	none	hematological neurotoxicity	hematological neurotoxicity	none
	Flowback	N/A	N/A	hematological neurotoxicity respiratory	N/A	N/A	none

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical). Flowback is "N/A" for Garfield County because it lasts more than 1 year in the 5-acre scenario with many wells being developed (so we defer to a chronic assessment).



Notes: Gray line emphasizes hazard quotient/index=1. The order of chemicals listed in the legend matches the order of plotting (e.g., m+p-xylene plotted first on the bottom if applicable to that critical-effect group, then n-nonane, etc.). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-22. Approximate Chemical Contributions to the Largest Hazard Indices of Selected Critical-effect Groups: Subchronic Non-cancer Assessment for the Highest Exposed Hypothetical Individuals at 500 Feet from the 5-acre Well Pad during Fracking Activities at the Garfield County Ridge-top Site



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10.

Figure 5-23. Largest Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the 5-acre Well Pad during Fracking Activities

Analysis of Person-period Critical-effect-group Hazard Indices by Distance

Figure 5-24 is analogous to the 3-acre Figure 5-20 (showing trends with distance in the percentage of population person-periods with neurotoxicity HIs at the selected receptors exceeding 1 during fracking activities).

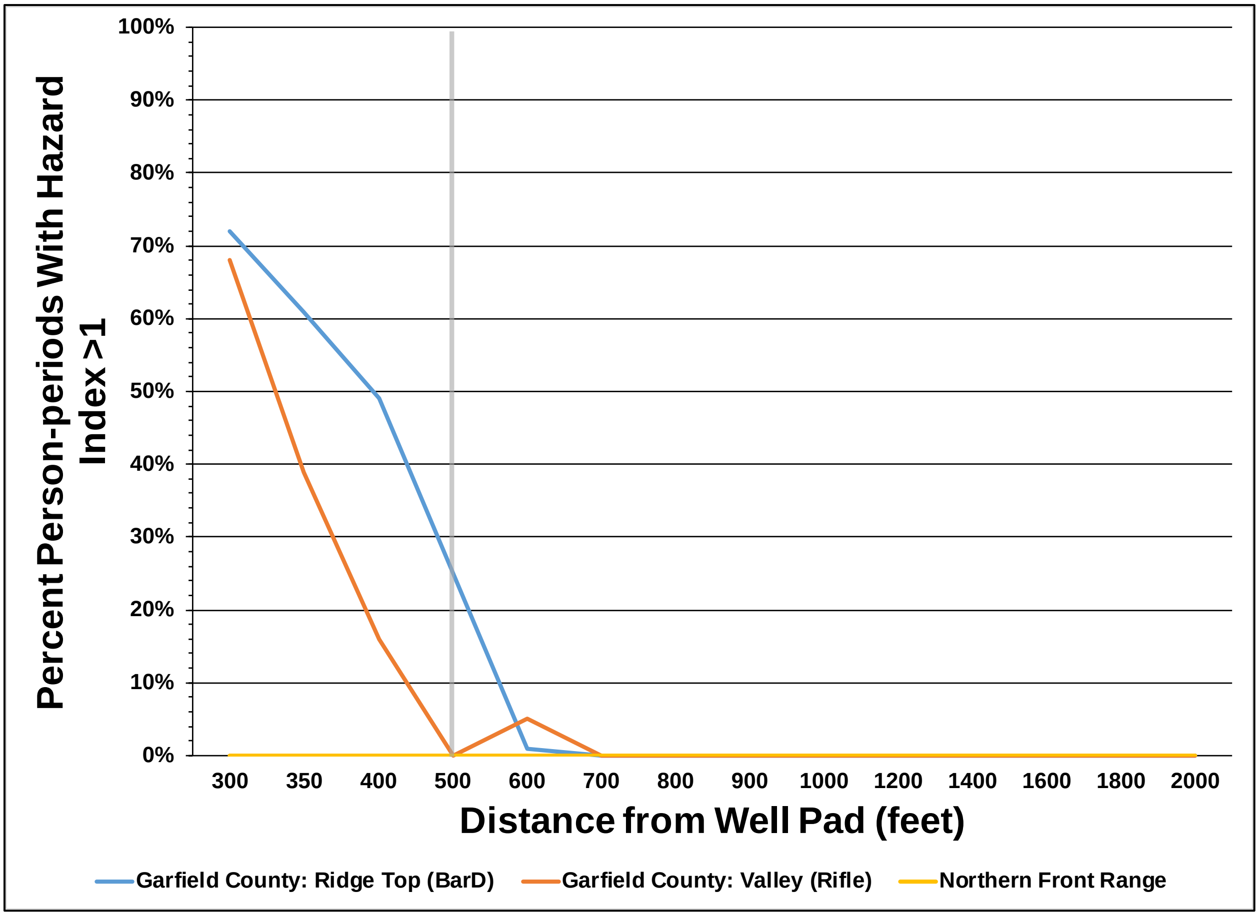
- As with the 3-acre pad, no neurotoxicity HIs were above 1 during fracking at the 5-acre NFR site.
- Only at the 300-ft distance from the Garfield County 5-acre well pads (and at 350 ft for the ridge-top site) did fracking activities during most multi-day periods of the year produce subchronic neurotoxicity HIs above 1 for most people (at the 3-acre pad, this was only at the 300-ft distance).

- By the 600-ft distance from the 5-acre Garfield County pads, subchronic neurotoxicity HIs above 1 were rare, and they did not occur by the 700-ft distance (same as with 3-acre pads).

- The spike in percentages at the 600-ft distance from the Garfield County valley site corresponds to spikes seen with the HIs (Figure 5-23), and it also corresponds to spikes in the HQs of the primary chemical constituents of the neurotoxicity critical-effect group for the same site and distance (m+p-xylene, n-nonane, and trimethylbenzenes; see Table E-21). This reflects interactions between the 5-acre Garfield County valley pad and the local meteorological conditions particular to that site, and note that HIs continue to decrease beyond 500 ft. This spike occurred at 500 ft from the 3-acre pad.

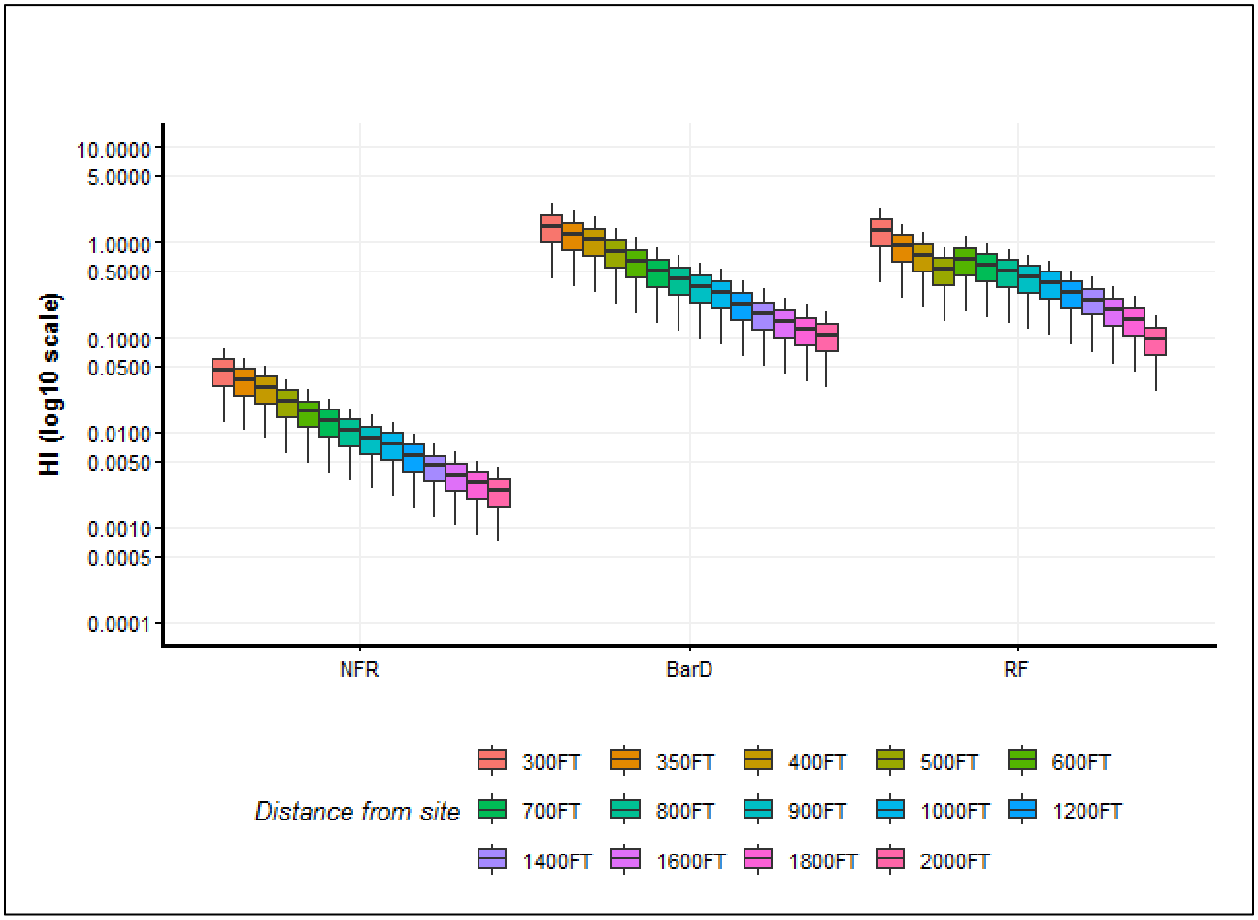
Generally, the rate of decline in these percentages with distance will vary across chemicals/critical-effect groups, sites, and O&G activities, depending on several factors. Table E-24 shows the percentage of person-periods with HI above 1 for all critical-effect groups, including those used to create this graph (see Table E-22 for HQs).

Figure 5-25 is analogous to Figure 5-21 in the 3-acre results, showing distributions of neurotoxicity HIs during fracking activities, across all person-periods. The 25th-to-75th-percentile ranges of person-period HIs for neurotoxicity at the 500-ft distance were 0.53–1, 0.35–0.68, and 0.014–0.028 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively (rather than 0.45–0.89, 0.53–1, and 0.015–0.029 at the 3-acre pads). These were lower than the absolute maximum values at that same distance: 1.4, 0.89, and 0.036, respectively. The median neurotoxicity HQs during fracking were 0.79, 0.52, and 0.021 at 500 ft from the three sites respectively (rather than 0.67, 0.78, and 0.022 at the 3-acre well pads), which were factors of 1.7–1.8 smaller than the absolute maximum values at the same distance.



Notes: X-axis is not to scale. "Person-periods" refers to the collection across the hypothetical population of each modeled individual's subchronic hazard indices for a year of modeling (the "rolling averages" referred to in Section 3.3.2.2). The data in this graph refer to the percentage of hazard indices (in this collection of hazard indices) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-24. Percentage of Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the 5-acre Well Pad during Fracking Activities



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-25. Distributions of Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) at Various Distances from the 5-acre Well Pad during Fracking Activities

5.3.3. Chronic Non-cancer Hazards

In this section, we discuss the potential for chronic exposures (more than 365 days) above health-protective non-cancer criteria levels, due to emissions from individual O&G development activities. Due to the limited duration of most development activities, at most well pads, chronic health hazards are most strongly related to production activities, which are assumed to continue for 30 years (we discuss production-related chronic exposures later in Section 5.4). Due to the nature of assumptions described in Section 3.3.2.3, **the only individual development scenarios reaching chronic-level duration are for flowback activities at 5-acre Garfield County sites where 32 wells are developed sequentially** (see Section 5.5 for a discussion on development activities in sequence).

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

Contrary to the acute results, emissions of all chemicals at the Garfield County sites were at or below chronic health-criteria levels at 500-ft from the 5-acre well pad during flowback activities (Table 5-13), although HQs for n-nonane rose to slightly above 1 at 600 and 900 ft from the valley pad (Table E-25). At 2,000 ft from the 5-acre pads, contrary to the acute results, all HQs were well below 1. The generally lower values with this chronic assessment, relative to the acute assessment, is largely a result of longer averaging times for exposure (hundreds of days versus one hour). There is no direct comparison to be made between subchronic and chronic HQs and HIs during flowback activities at the 5-acre Garfield County well pads (as they surpass subchronic duration, leading to chronic calculations only); however, it was true that all subchronic HQs and HIs at 500-ft from the well pads were 1 or below (for all pad sizes and O&G activities).

While all HIs were well below 1 at 2,000-ft from the 5-acre pads, HQs for some chemicals belonging to the neurotoxicity and hematological critical-effect groups sometimes aggregated to HIs slightly above 1 at the 500-ft distance (Table 5-14, Figure 5-26, Table E-27). **Due to these HQ aggregations, n-nonane, benzene, m+p-xylene, and trimethylbenzenes during flowback activities were of primary concern for chronic exposures at distances within about 1,400 ft of the 5-acre well pad at the Garfield County valley site (800 ft for the ridge-top site)**, beyond which all HIs were 1 or below (Figure 5-27). As sometimes seen at other sites for other exposure durations (see previous sections), there can be deviations in the downward trend of chronic HQs and HIs with increasing distance from the well pad (see Section 2.9.1.1), caused by the particular modeled dispersion patterns at a site and how those relate to the precise location of the selected receptor at each distance (see Section 2.7.3). Table E-27 shows all modeled HIs for each site and critical-effect group, including those used to create this graph (see Table E-25 for HQs).

The HQs and HIs averaged across chemicals, activities, and distances at the Garfield County valley site were about 45 percent larger than at the ridge-top site.

Table 5-13. Overview of the Largest Chronic Non-cancer Hazard Quotients during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Well Pad

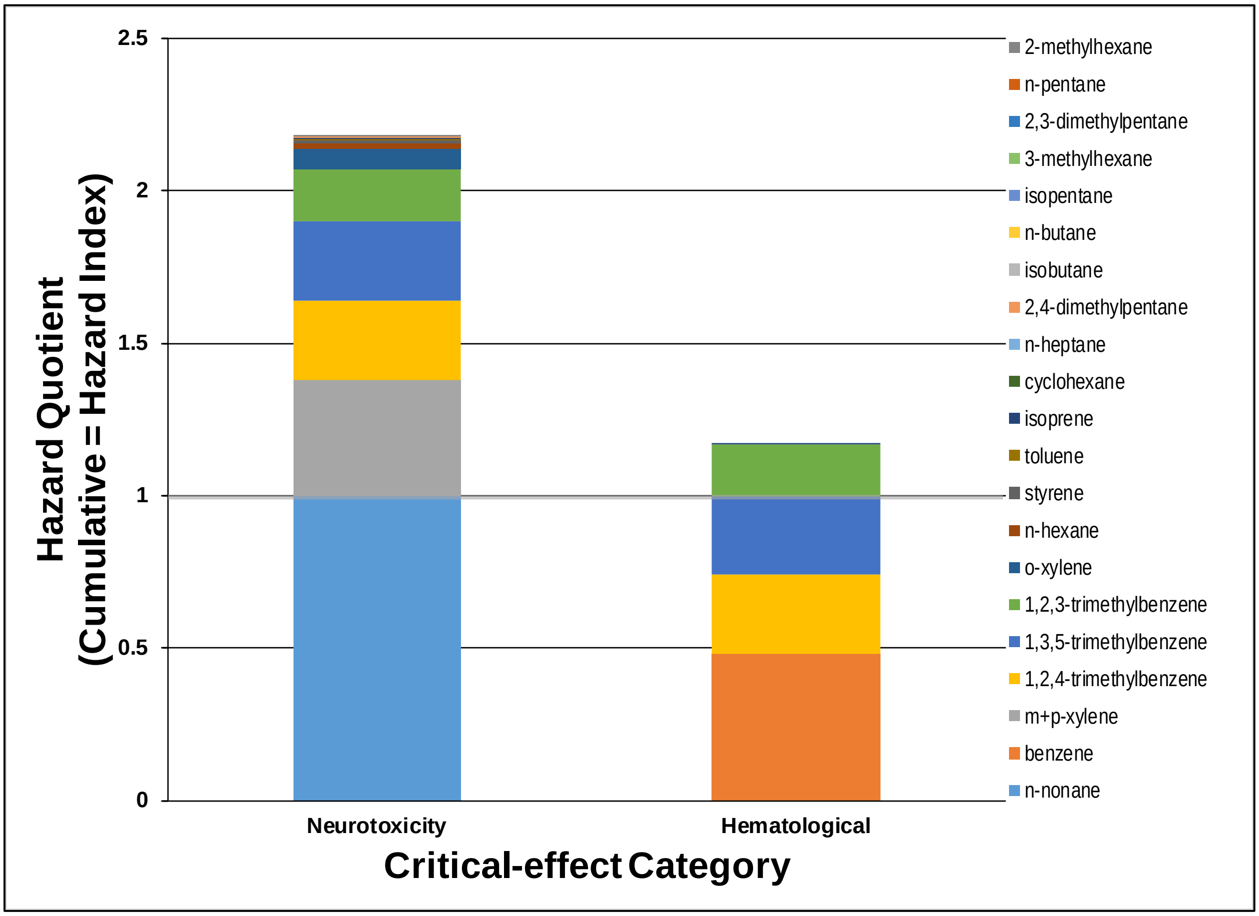
Range of Hazard Quotients	Activity	500 feet from Well Pad: Garfield County: Ridge Top (BarD)	500 feet from Well Pad: Garfield County: Valley (Rifle)	500 feet from Well Pad: Northern Front Range	2,000 feet from Well Pad: Garfield County: Ridge Top (BarD)	2,000 feet from Well Pad: Garfield County: Valley (Rifle)	2,000 feet from Well Pad: Northern Front Range
≥ 10	Drilling	N/A			N/A		
	Fracking	N/A			N/A		
	Flowback	none		N/A	none		N/A
Between 1 and 10	Drilling	N/A			N/A		
	Fracking	N/A			N/A		
	Flowback	none		N/A	none		N/A
0.1 to 1	Drilling	N/A			N/A		
	Fracking	N/A			N/A		
	Flowback	123-TMB 124-TMB 135-TMB 2-ET benzene m+p-xylene n-nonane	123-TMB 124-TMB 135-TMB 2-ET benzene m+p-xylene n-nonane	N/A	n-nonane	benzene n-nonane	N/A

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical). Drilling and fracking at the Garfield County sites, and all development activities at the Northern Front Range site, are "N/A" because they last less than 1 year in the 5-acre scenario with many wells being developed (so we defer to a subchronic assessment).
ET = ethyltoluene; TMB = trimethylbenzene; 123 = 1,2,3 and 124 = 1,2,4 and so on.

Table 5-14. Overview of the Largest Chronic Non-cancer Hazard Indices during Development Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Well Pad

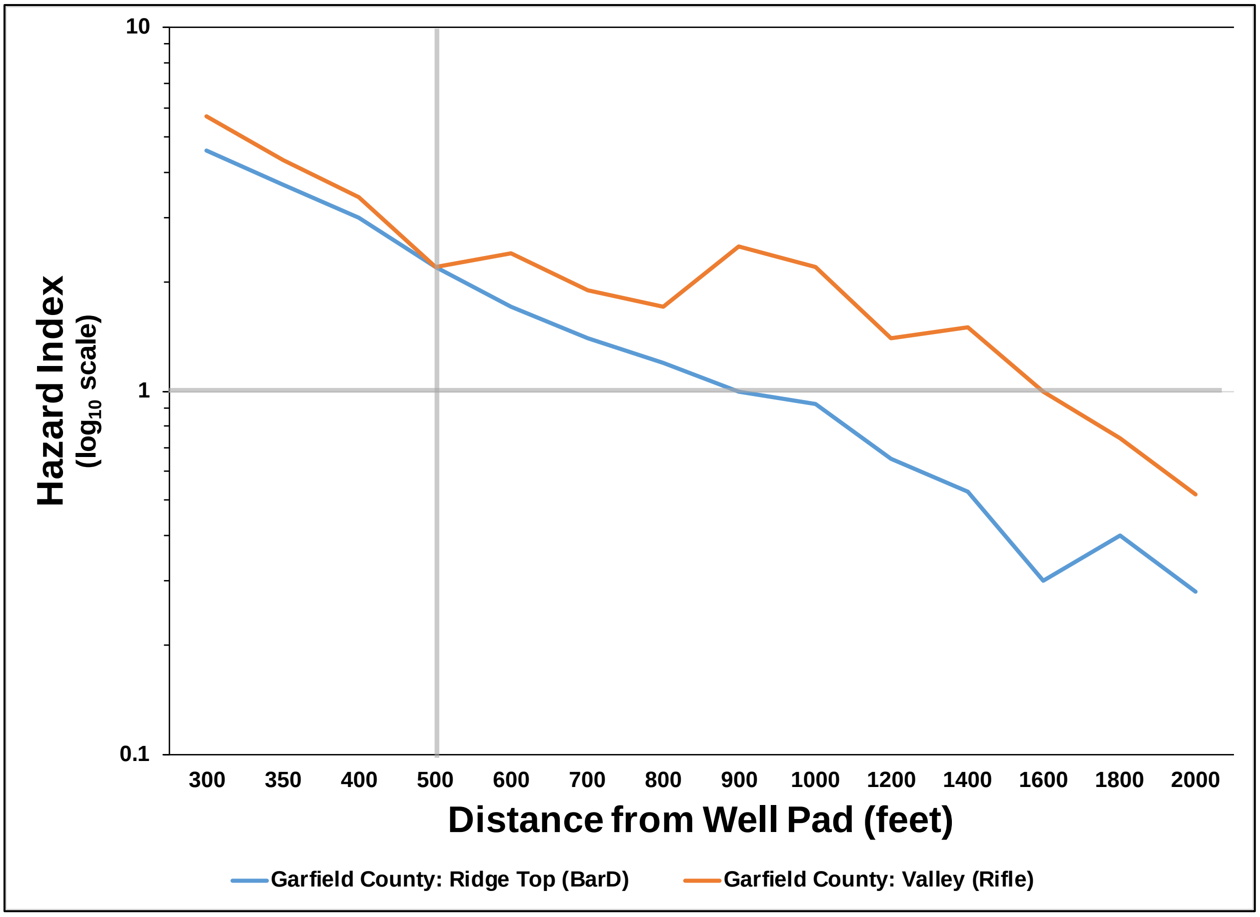
Range of Hazard Indices	Activity	500 feet from Well Pad: Garfield County: Ridge Top (BarD)	500 feet from Well Pad: Garfield County: Valley (Rifle)	500 feet from Well Pad: Northern Front Range	2,000 feet from Well Pad: Garfield County: Ridge Top (BarD)	2,000 feet from Well Pad: Garfield County: Valley (Rifle)	2,000 feet from Well Pad: Northern Front Range
≥ 10	Drilling	N/A			N/A		
	Fracking	N/A			N/A		
	Flowback	none		N/A	none		N/A
Between 1 and 10	Drilling	N/A			N/A		
	Fracking	N/A			N/A		
	Flowback	hematological neurotoxicity	hematological neurotoxicity	N/A	none		N/A
0.1 to 1	Drilling	N/A			N/A		
	Fracking	N/A			N/A		
	Flowback	respiratory systemic	respiratory systemic	N/A	hematological neurotoxicity	hematological neurotoxicity respiratory	N/A

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical). Drilling and fracking at the Garfield County sites, and all development activities at the Northern Front Range site, are "N/A" because they last less than 1 year in the 5-acre scenario with many wells being developed (so we defer to a subchronic assessment).



Notes: Gray line emphasizes hazard quotient/index=1. The order of chemicals listed in the legend matches the order of plotting (e.g., n-nonane plotted first on the bottom if applicable to that critical-effect group, then benzene, etc.). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-26. Approximate Chemical Contributions to the Largest Hazard Indices of Selected Critical-effect Groups: Chronic Non-cancer Assessment for the Highest Exposed Hypothetical Individuals at 500 Feet from the 5-acre Well Pad during Flowback Activities at the Garfield County Ridge-top Site



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10.

Figure 5-27. Largest Chronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the 5-acre Well Pad during Flowback Activities

Analysis of Critical-effect-group Hazard Indices by Distance

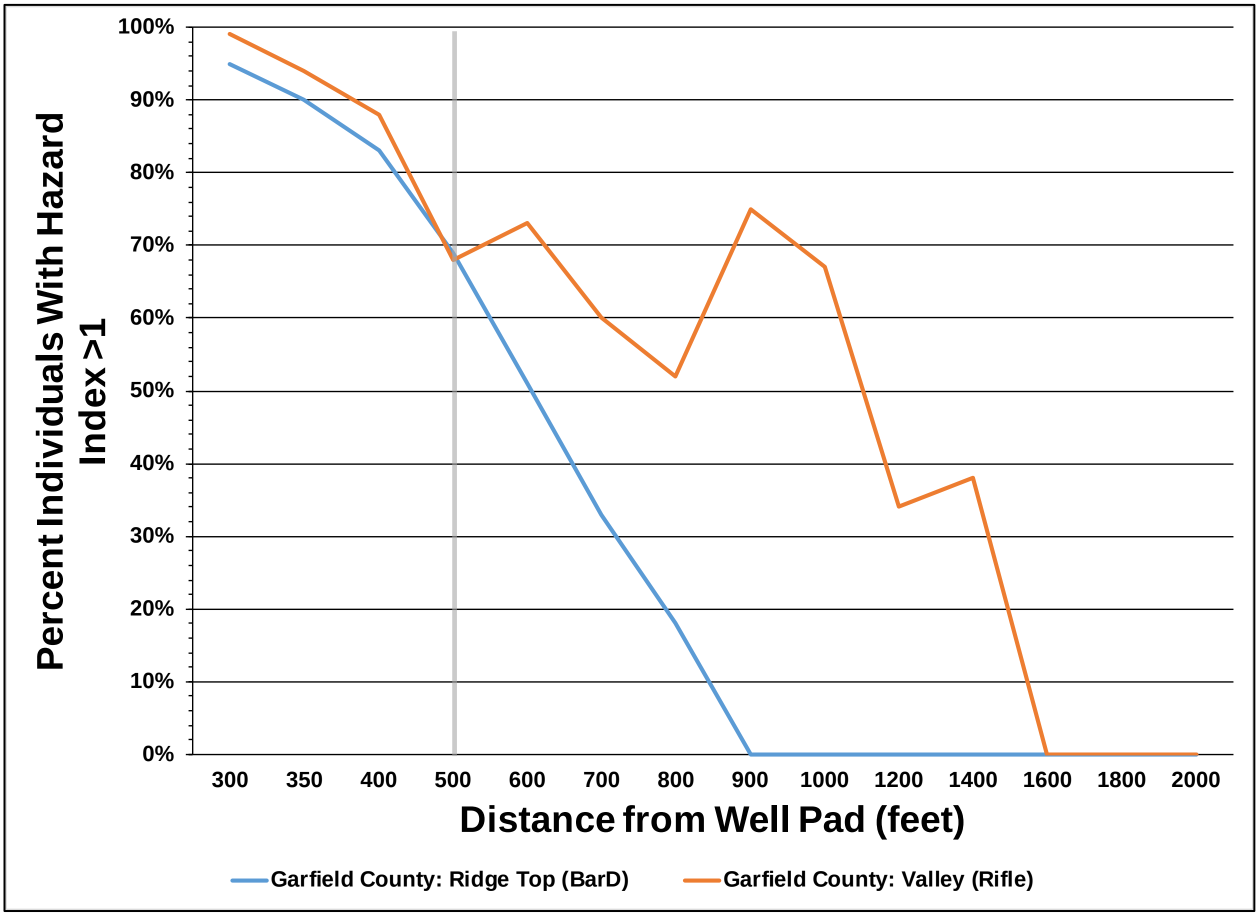
For the same scenarios used in Figure 5-27, in Figure 5-28 we illustrate the frequency of maximum chronic HIs reaching above a value of 1. These percentages are taken from the collection of each simulated individual's chronic HI, for 1,000 simulated youths up to 17 years old at each selected downwind receptor. The results for all age groups are nearly identical (see Sections 3.5.1 and E.1). This analysis shows how many simulated individuals have chronic HIs above 1 for flowback activities at 5-acre well pads.

In this example, the model results indicated the characteristics we note below.

- At distances 300–500 ft from the 5-acre pad at the Garfield County ridge-top site, and at 300–1,000 ft from the pad at the Garfield County valley site, flowback activities produced chronic neurotoxicity HIs above 1 for most people. Note a spike in the 600-ft value at the valley site, which was also seen with subchronic values from fracking activities at the same 5-acre site, and which corresponds to a spike in HIs at the same location (Figure 5-27).

- By 900 ft from the Garfield County ridge-top site, and by 1,600 ft from the valley site, no individuals had chronic neurotoxicity HIs above 1.

Generally, the rate of decline in these percentages with distance will vary across chemicals/critical-effect groups and sites, depending on several factors. Table E-28 shows the percentage of individuals with HI above 1 for all critical-effect groups, including those used to create this graph (see Table E-26 for HQs).

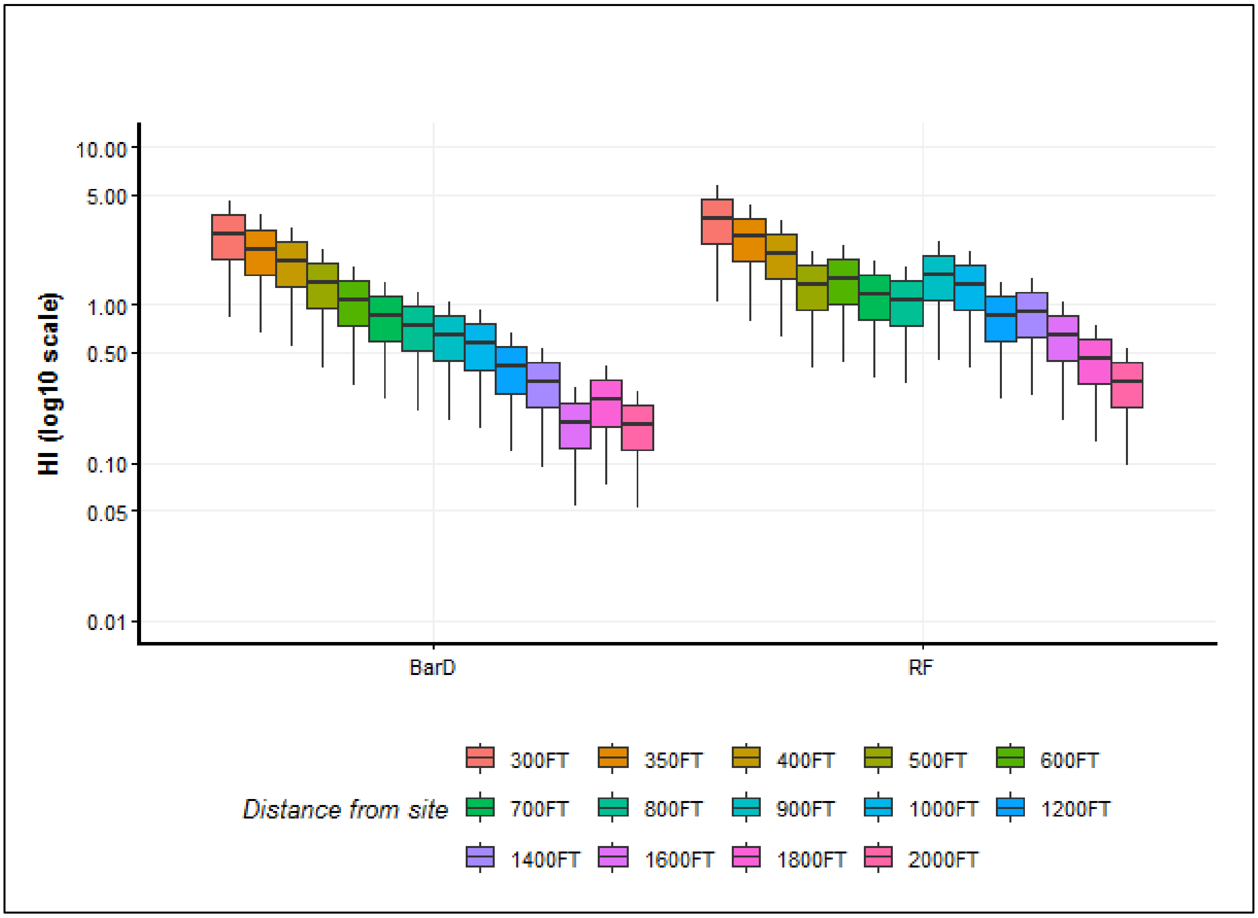


Notes: X-axis is not to scale. The data in this graph refer to the percentage of hazard indices (across all modeled individuals) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-28. Percentage of Chronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the 5-acre Well Pad during Flowback Activities

Figure 5-29 contains box-and-whisker plots reflecting the distributions of neurotoxicity chronic HIs during flowback activities, across all individuals, stratified by O&G site and distance. The 25th-to-75th-percentile ranges of chronic HIs for neurotoxicity at the 500-ft distance were 0.93–1.8 at both Garfield County sites. These were lower than the absolute maximum values at that same distance: 2.2 at both sites. The median neurotoxicity HIs during flowback were 1.3–1.4 at

500 ft from the Garfield County sites, which were a factor of 1.6–1.7 smaller than the absolute maximum values at the same distance.



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-29. Distributions of Chronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) at Various Distances from the 5-acre Well Pad during Flowback Activities

5.4. Oil and Gas Production

In the subsections below, we discuss estimates for acute and chronic non-cancer HQs and HIs for emissions during O&G production. We focus particularly on the highest simulated potential values of these HQs and HIs but we also discuss the range of potential values. We also discuss estimates of incremental lifetime cancer risk from O&G production emissions, focusing on the average potential risk at the locations of highest average air concentrations.

As discussed in Section 2.4, we only simulated 1-acre well pads for production, as this was the approximate average well-pad size for sites sampled for emissions during production activities. As mentioned in Section 3.3.2.2, we did not estimate subchronic exposures for production activities since the duration of production activities is 30 years. Note also that the production simulations included two receptors with smaller distances from the well pad than those used in the development simulations (at 150 and 250 ft from the center of the pad).

Finally, recall (as discussed in Section 3.3.1) that we constructed the time series of air concentrations utilized in the production modeling in a different and simpler manner than those utilized in the development modeling. Whereas the development time series comprised values from randomly selected Monte Carlo AERMOD iterations (maximum iteration values for acute assessment, mean iteration values for subchronic and chronic assessments), the production time series were a simpler construction of randomly selected production emission rates paired with each hour of AERMOD outputs run at unit emission rates. These differences between the development and production air-concentration time series (aside from differences in the emission rates themselves) will result in differences in the ranges of values seen in the risk estimates. This is likely particularly in the acute assessment where the maximum reasonable acute HQs and HIs are less likely to be captured in the production assessment relative to the development assessment (as noted in Section 3.3.1.2), and where lower acute values may also more frequently be captured in the production assessment. For these reasons, use caution in comparing distributions of HQs and HIs between the development and production assessments.

We provide additional quantifications of HQs and HIs, both maximum values as well as frequencies of HQs and HIs above a value of 1, in Appendix E.2. We generally present the same types of tables and figures (the same basic content and purpose) in each individual subsection here, with the exception of Section 5.4.3 discussing cancer risk. We provided the most comprehensive description of content and intent of these tables and figures in the first subsection of the O&G development results (Section 5.3.1.1, which are acute non-cancer hazards related to a 1-acre development well pad). In the following sections, we provide less description in order to reduce repetition; please reference the Section 5.3.1.1 descriptions as needed for interpretation. Note that we do not present the stacked bar charts indicating chemical contributions to some of the HIs (e.g., Figure 5-5 in Section 5.3.1.1) because chronic HIs during production did not exceed a value of 1 at the 500-ft distance, and because acute HIs during production only slightly exceeded 1 for one critical-effect group at 500 ft; HQs for each chemical constituent of each critical-effect group can still be found in Appendix E.2.

As noted in the subsections below, **estimated HQs and HIs during production were much lower than those during development activities**. **Benzene generally was the only chemical of concern during production activities, and only for the acute assessment** where maximum HQs were slightly above 1 at the selected downwind receptors 500 ft from the well pads. These slightly higher benzene acute HQs led to **maximum hematological acute HIs slightly above 1 at the same locations**. By contrast, benzene, 2-ethyltoluene, and the hematological critical-effect group sometimes had acute HQs and HIs above 10 at the same locations in the development assessment, and several other VOCs and critical-effect groups had maximum acute values above 1. While the chronic assessment during flowback development activities (Section 5.3.3) is not entirely comparable to the chronic assessment during production (due to the 5-acre pad utilized in the chronic flowback assessment versus the 1-acre pad utilized in the production assessment), we also note that chronic HQs and HIs for n-nonane and the neurotoxicity and hematological critical-effect groups were sometimes above 1 at 500+ ft from the development pads but not the production pads.

Also as noted below, **estimated incremental lifetime cancer risks from long-term exposure to benzene from the production pads were 4-in-one million or less for average hypothetical individuals at the selected downwind receptors 500 ft from the pads (less than 7-in-one million for the maximum-exposed individuals)**. Regardless of the IUR utilized and regardless of the individual's modeled exposure, estimated benzene risks were below 1-in-one million by 2,000 ft from the pads.

5.4.1. Acute Non-cancer Hazards

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

Benzene was of primary concern, showing acute HQs slightly above 1 at selected receptors 500-ft downwind during production activities (HQ=1.6 at NFR; Table 5-15, Table E-29). At 2,000 ft from the pad, all HQs were well below 1, and benzene was the only VOC with values above 0.1. The benzene HQs slightly above 1 also led to **hematological HIs slightly above 1 at the 500-ft distance** (HI=1.6 at NFR), but well below 1 by 2,000 ft (Table 5-16, Table E-31). Figure 5-30 illustrates trends with distance in the maximum benzene HQs at the selected receptors. These HQs fell below 1 by 600 ft from the Garfield County pads and by 1,200 ft from the NFR pad.

These acute HQs and HIs during production were much lower than those during development activities, where multiple chemicals and critical-effect groups had maximum values above 10 at 500 ft and above 1 at 2,000 ft. Comparing HQs and HIs between the three sites, the chronic values averaged across chemicals, activities, and distances differed by up to about 20 percent between the Garfield sites, and by up to about 70 percent between those sites and the NFR site (with the NFR site tending to have the largest values).

Table 5-15. Overview of the Largest Acute Non-cancer Hazard Quotients during Production Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the Well Pad

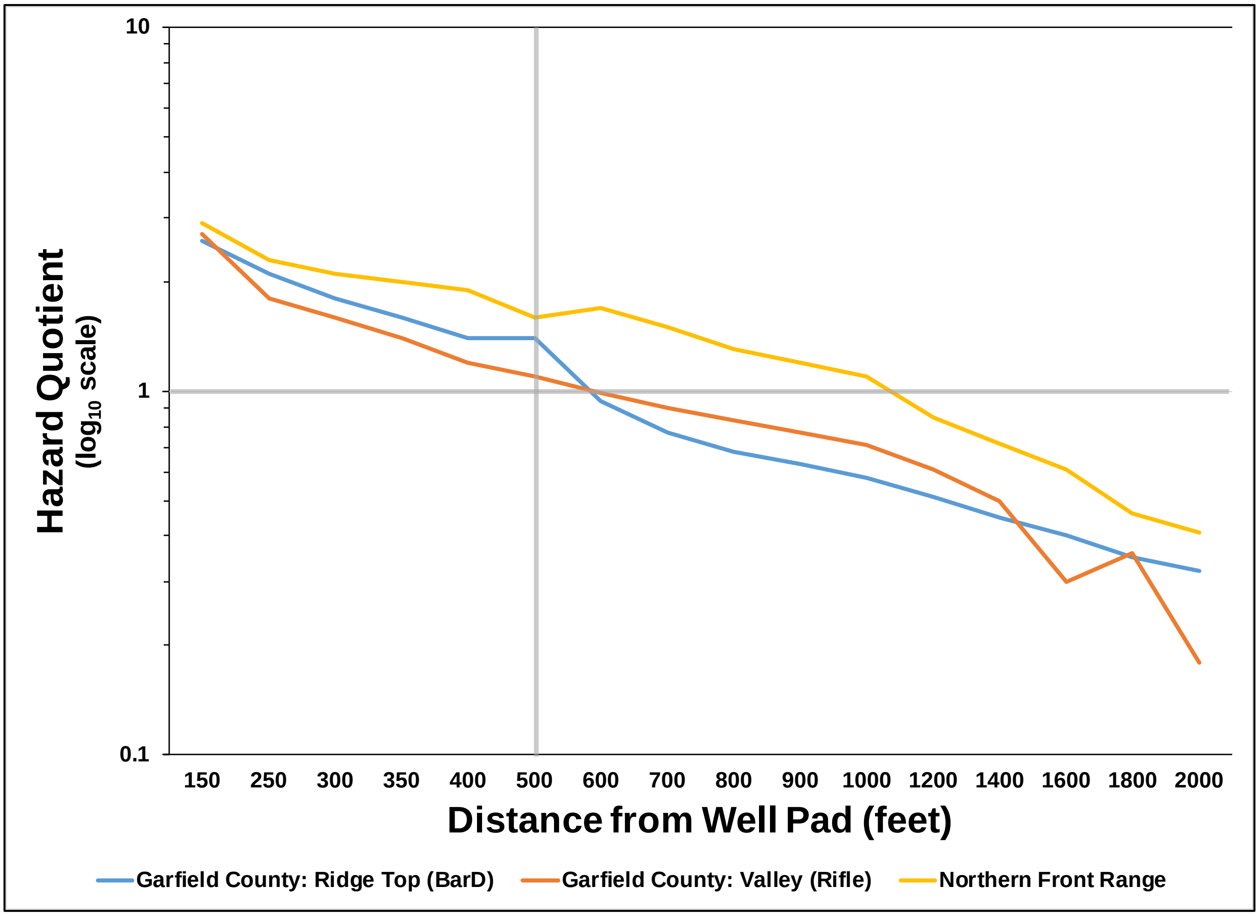
Range of Hazard Quotients	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	benzene	benzene	benzene	none		
0.1 to 1	2-ET toluene	2-ET toluene	2-ET toluene	benzene	benzene	benzene

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
ET = ethyltoluene.

Table 5-16. Overview of the Largest Acute Non-cancer Hazard Indices during Production Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the Well Pad

Range of Hazard Indices	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	hematological	hematological	hematological	none		
0.1 to 1	neurotoxicity	neurotoxicity	neurotoxicity respiratory systemic	hematological	hematological	hematological

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any acute critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard quotient=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10.

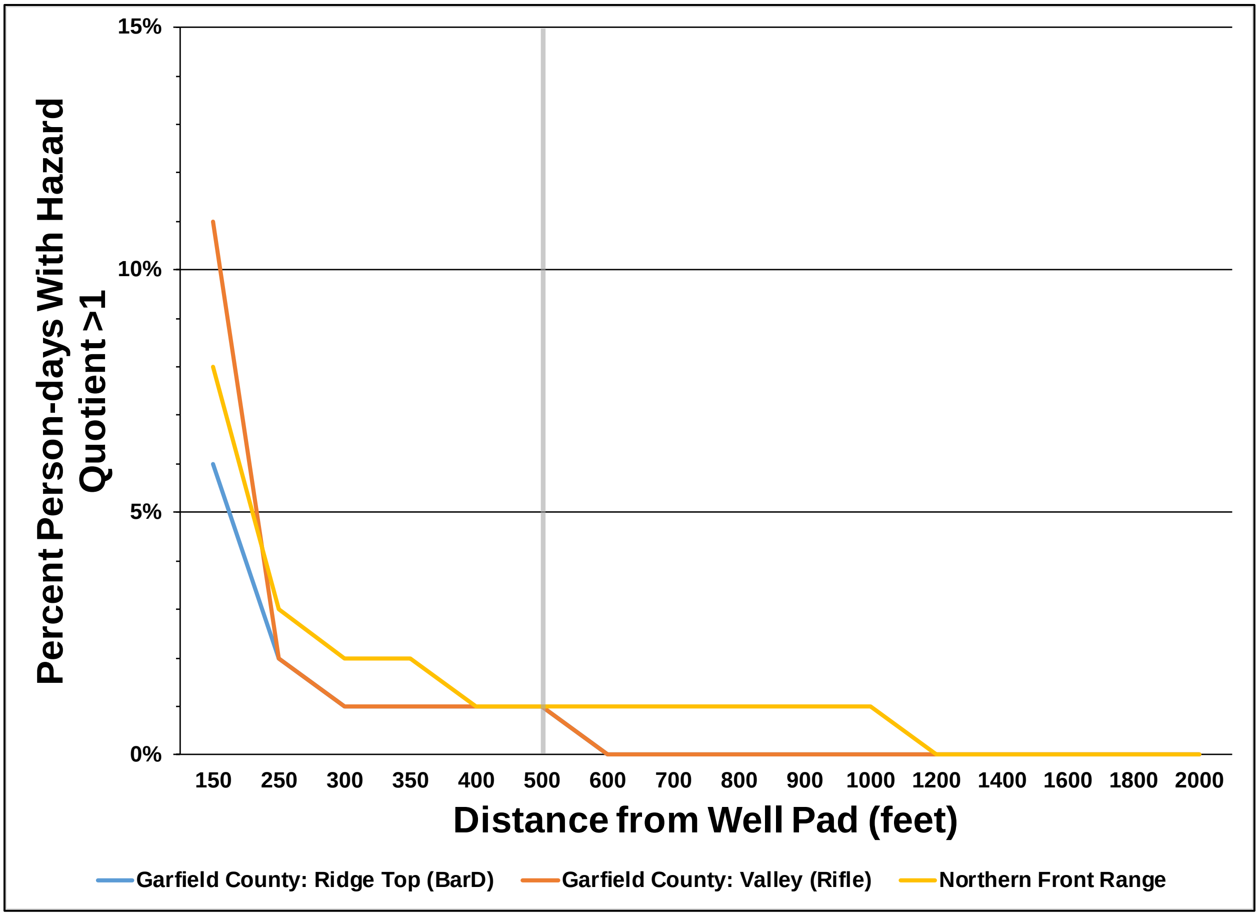
Figure 5-30. Largest Acute Non-cancer Benzene Hazard Quotients for the Highest Exposed Hypothetical Individuals at Various Distances from the Well Pad during Production Activities

Analysis of Person-period Critical-effect-group Hazard Indices by Distance

For the same scenarios used in Figure 5-30, in Figure 5-31 we illustrate the frequency of maximum acute HQs reaching above a value of 1 (analogous to Figure 5-3 for acute HQs during development, which showed much higher frequencies of HQs above 1 than during production). In this example, the model results indicated the characteristics we note below.

- For most people on most days, the maximum HQ is below 1.
- By the 250-ft distance from the well pad, occurrences of daily-maximum HQs above 1 are rare, dropping to a 1-percent frequency at all sites by the 400-ft distance.
- HQs are below 1 for all simulated individuals on all days by the 600-ft distance at the Garfield County sites, and by the 1,200-ft distance at the NFR site, as noted earlier.

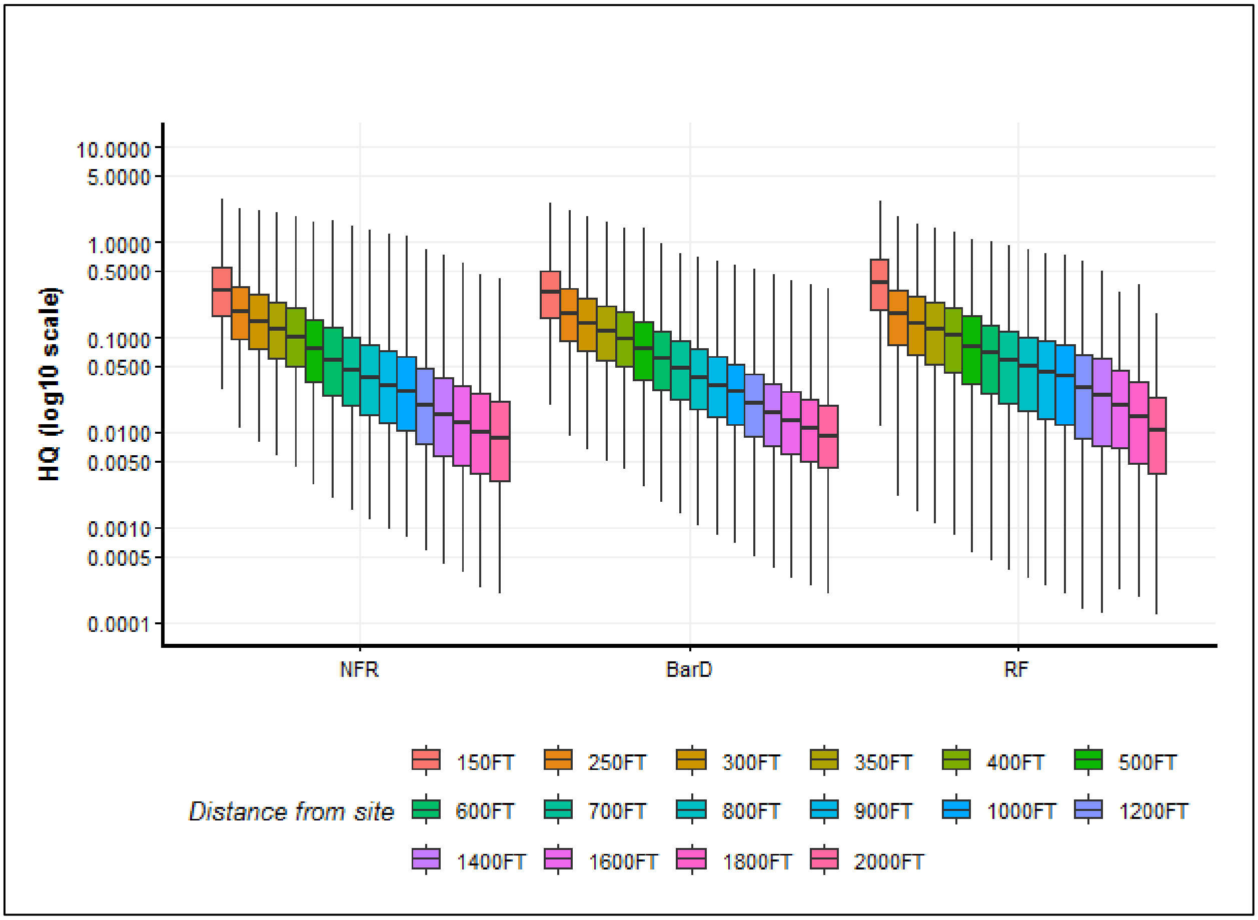
Generally, the rate of decline in these percentages with distance will vary across chemicals/critical-effect groups, sites, and O&G activities, depending on several factors. Table E-30 shows the percentage of person-days with maximum HQs above 1 for all chemicals, including those used to create this graph (see Table E-32 for HIs).



Notes: X-axis is not to scale. “Person-days” refers to the collection across the hypothetical population of each modeled individual’s daily-maximum acute hazard quotients for a year of modeling. The data in this graph refer to the percentage of hazard quotients (in this collection of hazard quotients) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-31. Percentage of Daily-maximum Acute Non-cancer Benzene Hazard Quotients (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the Well Pad During Production Activities

Figure 5-32 contains box-and-whisker plots reflecting distributions of benzene HQs during production activities, across all person-days, stratified by O&G site and distance. For acute benzene HQs at the 500-ft distance, the 25th-percentile values were 0.031–0.035 and the 75th-percentiles were 0.15–0.16 at the three sites. These were notably lower than the absolute maximum values at that same distance: 1.4, 1.1, and 1.6 at the Garfield County ridge-top site, Garfield County valley site, and NFR site, respectively. The median benzene HQs during production were 0.074, 0.079, and 0.073 at 500 ft from the three sites respectively, which were a factor of 14–22 lower than the absolute maximum values at the same distance.



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HQ = hazard quotient; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-32. Distributions of Daily-maximum Acute Non-cancer Benzene Hazard Quotients (Across the Hypothetical Population) at Various Distances from the Well Pad during Production Activities

5.4.2. Chronic Non-cancer Hazards

Contrary to the acute results, emissions of all chemicals were below chronic health-criteria levels at 500-ft from the 1-acre production well pad (Table 5-17), although HQs for benzene were to slightly above 1 at the 150-ft distance for 4 percent of simulated individuals at the Garfield County ridge-top site and for 19 percent at the valley site (Table E-33, Table E-34). At 2,000 ft from the pads, all HQs were well below 0.1, including for benzene (which was not the case with the acute results).

HIs followed this same pattern, with no values above 1 at the 250-ft distance and beyond (Table 5-18, Figure 5-33, Table E-35)**, benzene helping to produce hematological HIs slightly above 1 at the 150-ft distance at all three sites** (for 33–53 percent of the modeled individuals, depending on the site; Figure 5-34, Table E-36)**, and the aggregation of**

trimethylbenzenes, n-nonane, and xylenes helping to produce neurotoxicity HIs slightly above 1 also at the 150-ft distance at the Garfield County sites (for 10–24 percent of the modeled individuals, depending on the site; Table E-36).

Figure 5-35 contains box-and-whisker plots reflecting the distributions of hematological chronic HIs during production activities, across all individuals, stratified by O&G site and distance. The 25th-to-75th-percentile ranges of chronic HIs for hematological at the 500-ft distance were 0.14–0.29, 0.12–0.25, and 0.12–0.24 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively. These were lower than the absolute maximum values at the same distance: 0.37, 0.31, and 0.3, respectively. The median hematological HIs during production were 0.22, 0.18, and 0.18 at 500 ft from the three sites respectively, which were a factor of 1.7 smaller than the absolute maximum values at the same distance. Figure 5-35 shows that approximately 14–18 percent of all individuals had hematological HIs below 0.1 at the 500-ft distance, depending on the site.

The HQs and HIs averaged across chemicals, activities, and distances were about 8 percent larger at the Garfield County ridge-top site relative to the valley site, and about 19 percent larger at the ridge-top site than the NFR site. The generally lower values with this chronic assessment, relative to the acute assessment, is largely a result of longer averaging times for exposure (hundreds of days versus one hour). These chronic HQs and HIs during production activities at 1-acre pads are also generally lower than those during flowback development activities at 5-acre pads, due to generally lower emissions during production.

Table 5-17. Overview of the Largest Chronic Non-cancer Hazard Quotients during Production Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the Well Pad

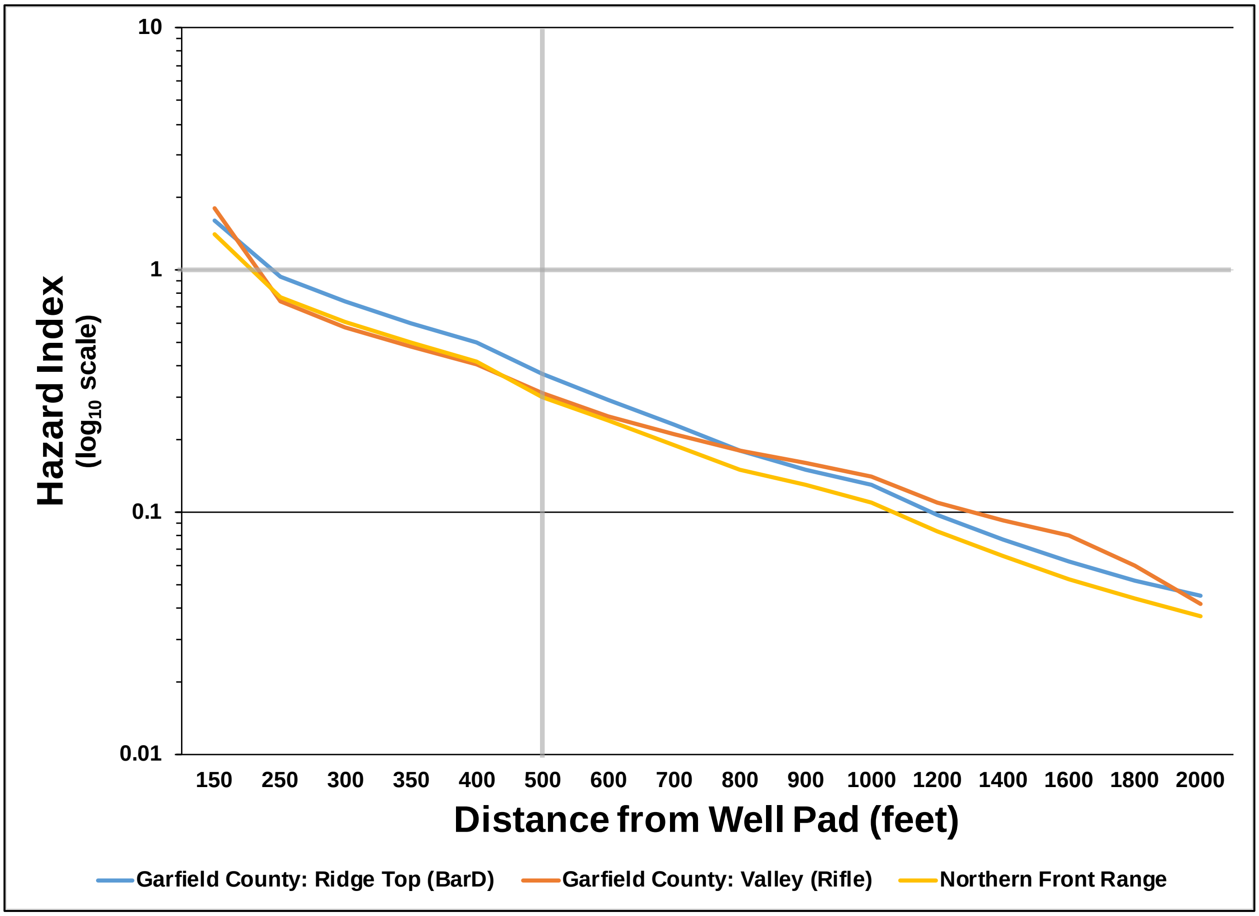
Range of Hazard Quotients	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	benzene	benzene	benzene	none		

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Table 5-18. Overview of the Largest Chronic Non-cancer Hazard Indices during Production Activities for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the Well Pad

Range of Hazard Indices	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	none		

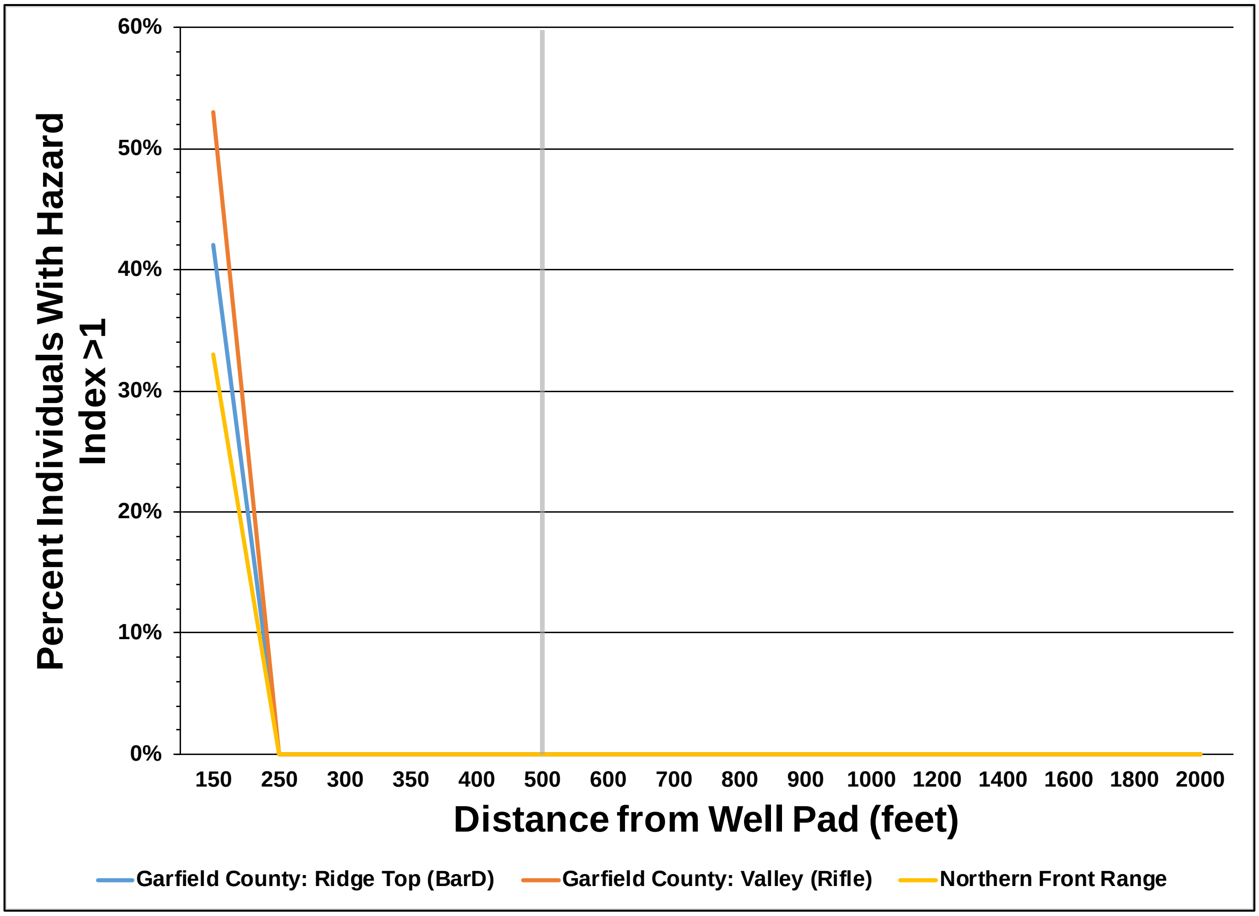
Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. The data in this graph refer to the percentage of hazard indices (across all modeled individuals) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

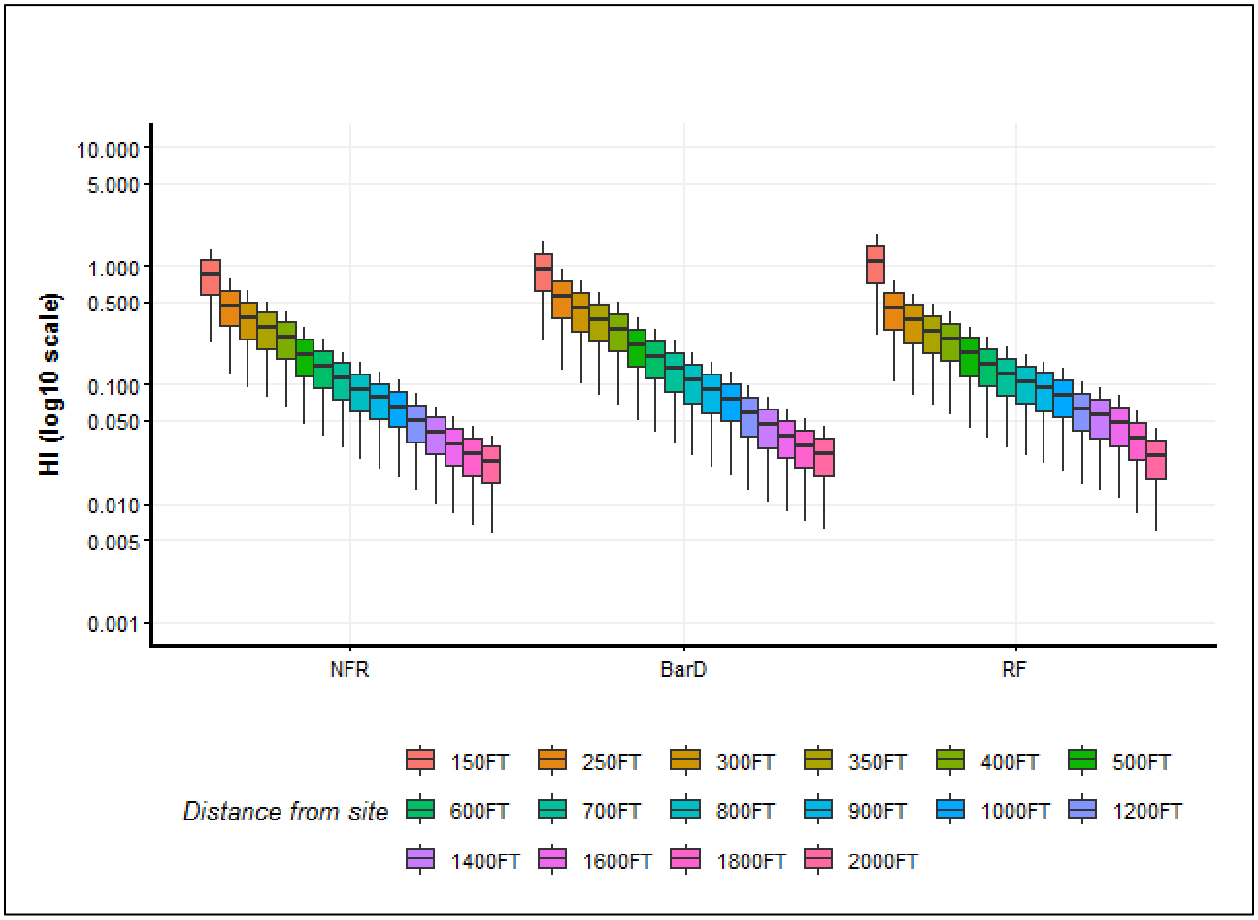
log10 = logarithm base 10.

Figure 5-33. Largest Chronic Non-cancer Hazard Indices for the Hematological Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the Well Pad during Production Activities



Notes: X-axis is not to scale. The data in this graph refer to the percentage of hazard quotients (in this collection of hazard quotients) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-34. Percentage of Chronic Non-cancer Hazard Indices for the Hematological Critical-effect Group (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the Well Pad during Production Activities



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-35. Distributions of Chronic Non-cancer Hazard Indices for the Hematological Critical-effect Group (Across the Hypothetical Population) at Various Distances from the Well Pad during Production Activities

5.4.3. Chronic Cancer Risks

We assessed incremental lifetime cancer risks for exposure to the VOC for which strong evidence of carcinogenicity was available (benzene; Section 4.3).[13] As discussed in Section 4.3, we focused our cancer assessment on O&G activities or sequences of activities lasting more

[13] The quantitative estimates of cancer risk only considers benzene, due to lack of reliable dose-response information for other VOCs which we evaluated in these HHRAs and which may increase cancer risks in humans. As discussed in Section 4.3, it was not possible to derive cancer risk estimates for several chemicals with emissions data (ethylbenzene, styrene, and isoprene) that are suspected to cause cancer in human. In addition (see Section 5.6), emissions data were not available for several chemicals (formaldehyde, acetaldehyde) that are suspected of increasing human cancer risks and which have been detected in the air near other O&G operations.

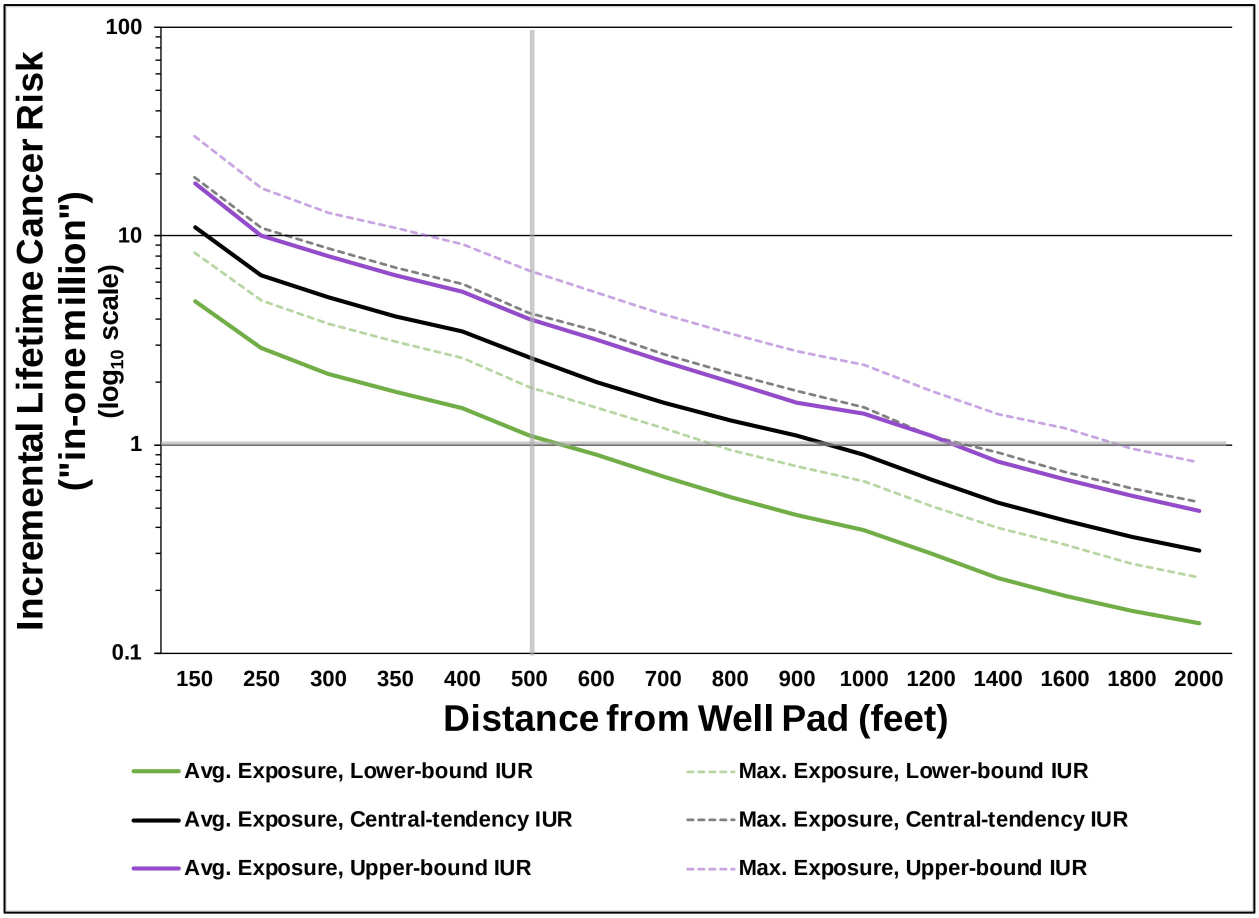
than several years—the 30-year production activity (discussed here), and the 30–32-year sequences of development and production activities (discussed later in Section 5.5.3).

As discussed below, **simulated cancer risks to the average simulated individuals were below 1-in-one million at distances 1,400+ ft from the well pads** at all sites (at 2,000 ft for the maximum-exposed individuals). Risks to average individuals were below 10-in-one million at 300+ ft from the pads (400+ ft for the maximum-exposed individuals). **At the 500-ft distance, risks to average individuals were 4-in-one million or less (less than 7-in-one million for the maximum-exposed individuals).**

In Figure 5-36, we plot the incremental lifetime cancer risks associated with benzene exposures at the selected receptors at the Garfield County ridge-top site. The main focus of the plot is the risk to the average simulated individual (the solid lines) based on the two EPA IURs as well as the midpoint between them ("central tendency"), but for supplemental analysis we also plot the risk to the maximum-exposed simulated individual (the dashed lines). In all of these scenarios (average vs. maximum-exposed individual; upper- and lower-bound IUR and central-tendency), the simulated risk to all individuals was well below 10-in-one million at the selected downwind 500-ft receptor—between 1.1- and 4-in-one million for the average individual (depending on the IUR) and between 1.9- and 6.8-in-one million for the maximum-exposed individual. All risks for the average individual fell below 1-in-one million by 1,400 ft from the well pad utilizing the upper-bound IUR (by 600 ft utilizing the lower-bound IUR). For the maximum-exposed individual, those distances respectively were 1,800 and 800 ft. Risks closer to the well pad were sometimes above 10-in-one million, up to 18-in-one million for the average individual at 150 ft from the pad utilizing the upper-bound IUR (30-in-one million for the maximum-exposed individual at the same distance), though both individuals were below 10-in-one million utilizing the lower-bound IUR. All simulated risks were below 10-in-one million by the 400-ft distance.

Similarly, in Figure 5-37 we plot the incremental lifetime cancer risks associated with benzene exposures at the selected receptors at the Garfield County valley site. The results were similar to those of the ridge-top site. Depending on the IUR and simulated individual, simulated risks were sometimes above 10-in-one million at distances 300 ft from the well pad and closer (values up to 20-in-one million for the average individual, 34-in-one million for the maximum-exposed individual, at the 150-ft distance utilizing the upper-bound IUR; risks below 10-in-one million utilizing the lower-bound IUR). However, risks at the 500-ft distance were no larger than 3.4-in-one million for the average individual (5.7 for the maximum-exposed individual), and risks dropped below 1-in-one million by the 1,400-ft distance for the average individual (2,000-ft distance for the maximum-exposed individual).

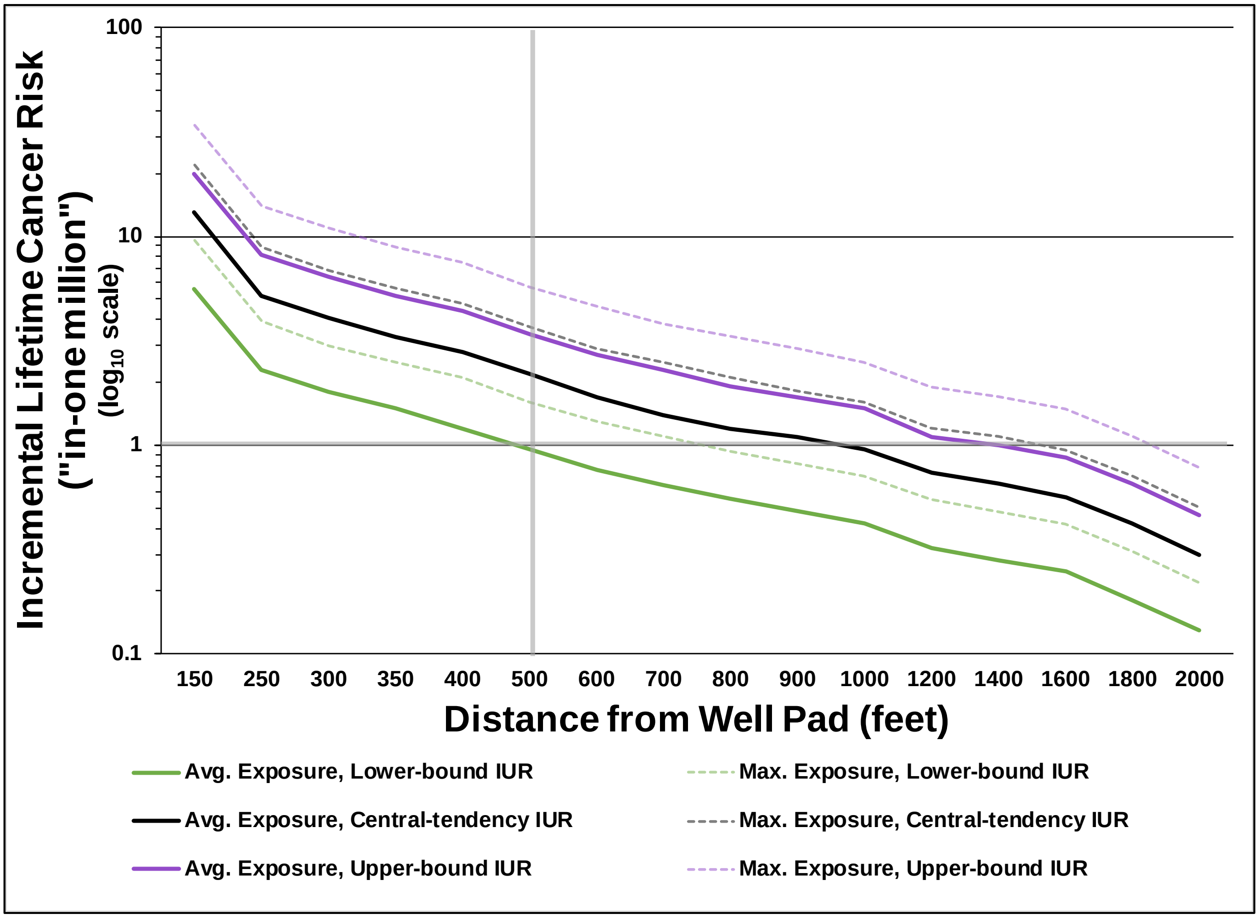
Finally, in Figure 5-38 we plot the incremental lifetime cancer risks associated with benzene exposures at the selected receptors at the NFR site. The results were similar to those of the Garfield County sites. Depending on the IUR and simulated individual, simulated risks were sometimes above 10-in-one million at distances 300 ft from the well pad and closer (values up to 15-in-one million for the average individual, 26-in-one million for the maximum-exposed individual, at the 150-ft distance utilizing the upper-bound IUR; risks below 10-in-one million utilizing the lower-bound IUR). However, risks at the 500-ft distance were no larger than 3.3-in-one million for the average individual (5.6 for the maximum-exposed individual), and risks dropped below 1-in-one million by the 1,200-ft distance for the average individual (1,600-ft distance for the maximum-exposed individual).



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

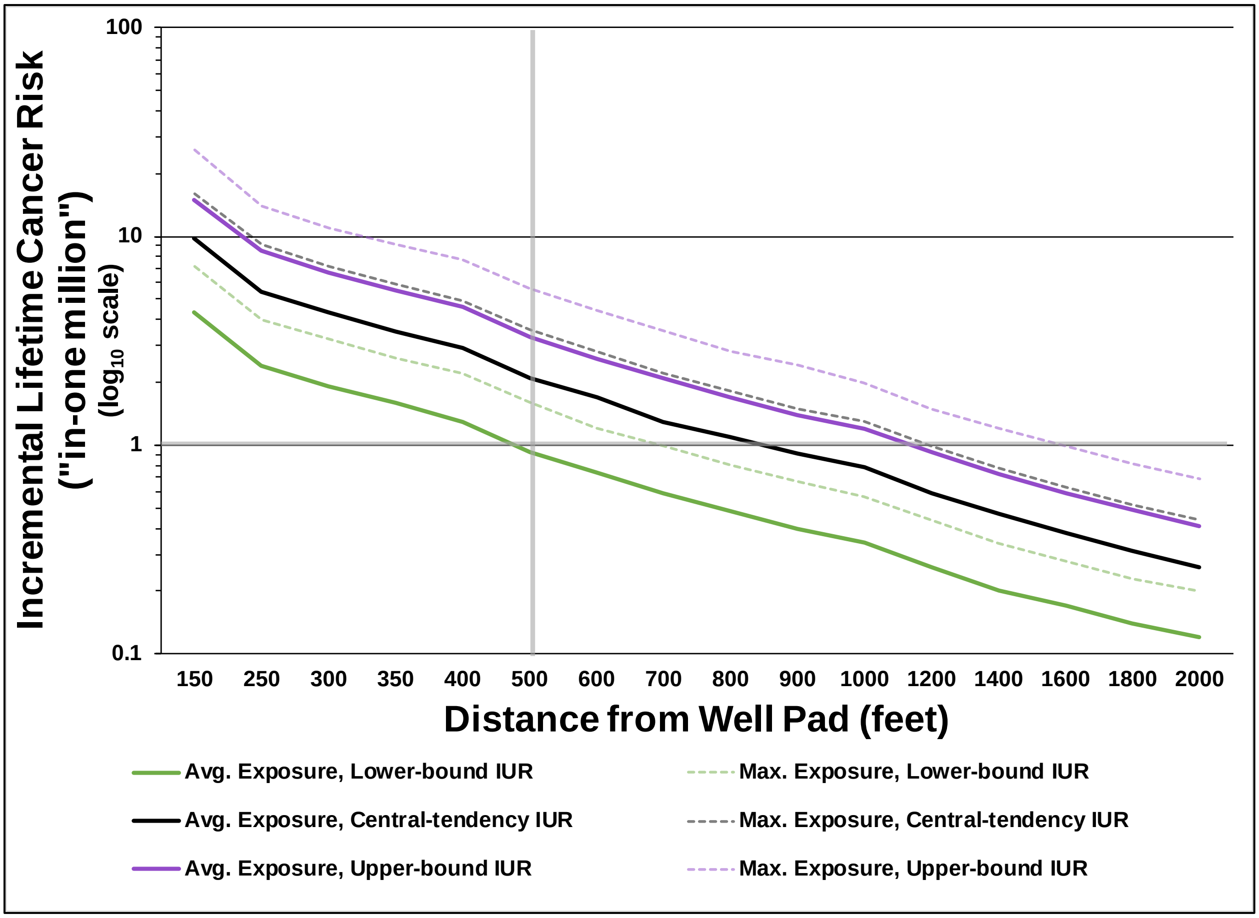
Figure 5-36. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during Production Activities at the Garfield County Ridge-top Site



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

Figure 5-37. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during Production Activities at the Garfield County Valley Site



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

Figure 5-38. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during Production Activities at the Northern Front Range Site

5.5. Sequential Oil and Gas Activities

In the subsections below, we discuss estimates for subchronic and chronic non-cancer HQs and HIs for sequential patterns of O&G development and production activities, covering drilling, fracking, and flowback together as an overall "development" exposure scenario, and covering development and production together as an overall "development+production" scenario. We discuss the context for these sequential activities further in Section 3.3.2. **Compared with assessing individual O&G activities, these assessments of sequential activities are more holistic because residential exposures likely are not isolated to just the drilling phase, just the fracking phase, etc.** However, the sequential assessment is also less conservative than assessments of individual O&G activities because the higher exposures during some activities will be averaged with lower exposures of other activities. Therefore, **the higher HQs**

and HIs in the sequential assessment will be lower than the higher HQs and HIs in the assessment of individual activities.

We focus particularly on the highest simulated potential values of HQs and HIs, but we also discuss the range of potential values. We also discuss estimates for incremental lifetime cancer risk for the multi-decade exposures of development+production activities, focusing on the average risk at the locations of highest average air concentrations.

All sequences of development activities (except for the 5-acre scenario at Garfield County) last less than 365 days in total, so we calculated only subchronic results for those scenarios. However, when we add production activities to the sequential development activities, the duration of exposures are more than 365 days and so we calculated chronic results for all such scenarios.

We provide additional quantifications of HQs and HIs, both maximum values as well as percentages of values above 1, in Appendix E.3. We generally present the same types of tables and figures (the same basic content and purpose) in each individual subsection here. We provide the most comprehensive description of these tables and figures in the first subsection of the O&G development results above (Section 5.3.1.1, which are acute non-cancer hazards related to a 1-acre development well pad). We provide less description here in order to reduce repetition; please reference the Section 5.3.1.1 descriptions as needed for interpretation.

5.5.1. Subchronic Non-cancer Hazards

In this section, we discuss the potential for subchronic (multi-day) exposures above health-criteria levels, due to emissions from O&G development activities that occur sequentially (covering drilling, fracking, and flowback together). We discuss the results of each size of well pad separately: 1 acre (Section 5.5.1.1), 3 acre (Section 5.5.1.2), and 5 acre (Section 5.5.1.3).

As noted in the subsections below, **the higher estimated subchronic HQs and HIs during development activities in sequence were generally lower than those during individual development activities**. This is due to the longer-term averaging of the generally higher fracking and flowback HQs and HIs with generally lower drilling HQs and HIs. **All subchronic HQs were below 1 at all distances from all well pads, and all subchronic HIs were below 1 at 500+ ft from the well pads**. Only with the Garfield County ridge-top 1-acre pad were subchronic neurotoxicity and hematological HIs above 1, and only at less than 500 ft from the pad (driven primarily by emissions of benzene, m+p-xylene, trimethylbenzenes, and n-nonane).

5.5.1.1. 1-acre Well Pad

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

Similar to the subchronic results presented in Section 5.3.2 for individual development activities, **when assessing the development activities in sequence all VOC HQs were below 1 at the selected receptors 500 ft from the 1-acre well pads** (Table 5-19, Table E-37). During development activities in sequence, **all HQs were below 0.1 at the selected 2,000-ft**

receptors (whereas some subchronic m+p-xylene HQs were slightly above 0.1 at the same locations during individual development activities).

Whereas some subchronic HIs were slightly above 1 at the selected 500-ft receptors during individual development activities at 1-acre pads (Section 5.3.2), during sequential development activities **all subchronic HIs were below 1 at 500 ft and at or below 0.1 at 2,000 ft** (Table 5-20, Table E-38). Figure 5-39 illustrates trends with distance in the maximum neurotoxicity HIs at the selected receptors (the critical-effect group with the highest maximum HIs in this 1-acre scenario of development activities in sequence). These HIs were always 1 or below at the Garfield County valley and NFR sites. At the ridge-top site, while these HIs were slightly above 1 at 300 ft from the well pads, they fell below 1 by the 500-ft distance. Maximum hematological HIs were also slightly above 1 at distances close to the ridge-top and NFR well pads (not shown in this figure). **These HIs slightly above 1 at close distances to the well pad were driven primarily by benzene, m+p-xylene, trimethylbenzenes, and n-nonane**. These HIs remained at or above 0.1 at the valley site at all selected receptors (all distances), while at the ridge-top site the HIs dropped below 0.1 by 1,600 ft (by 1,400 ft at the NFR site). Table E-38 shows all modeled values for each site and critical-effect group, including those used to create this graph.

Comparing HQs and HIs between the three sites, the HQs and HIs averaged across chemicals and distances were within about 25 percent between the two Garfield County sites (higher at ridge-top site), while the values at the Garfield County sites were up to a factor of 2 higher than those at the NFR site.

Table 5-19. Overview of the Largest Subchronic Non-cancer Hazard Quotients during Development Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 1-acre Well Pad

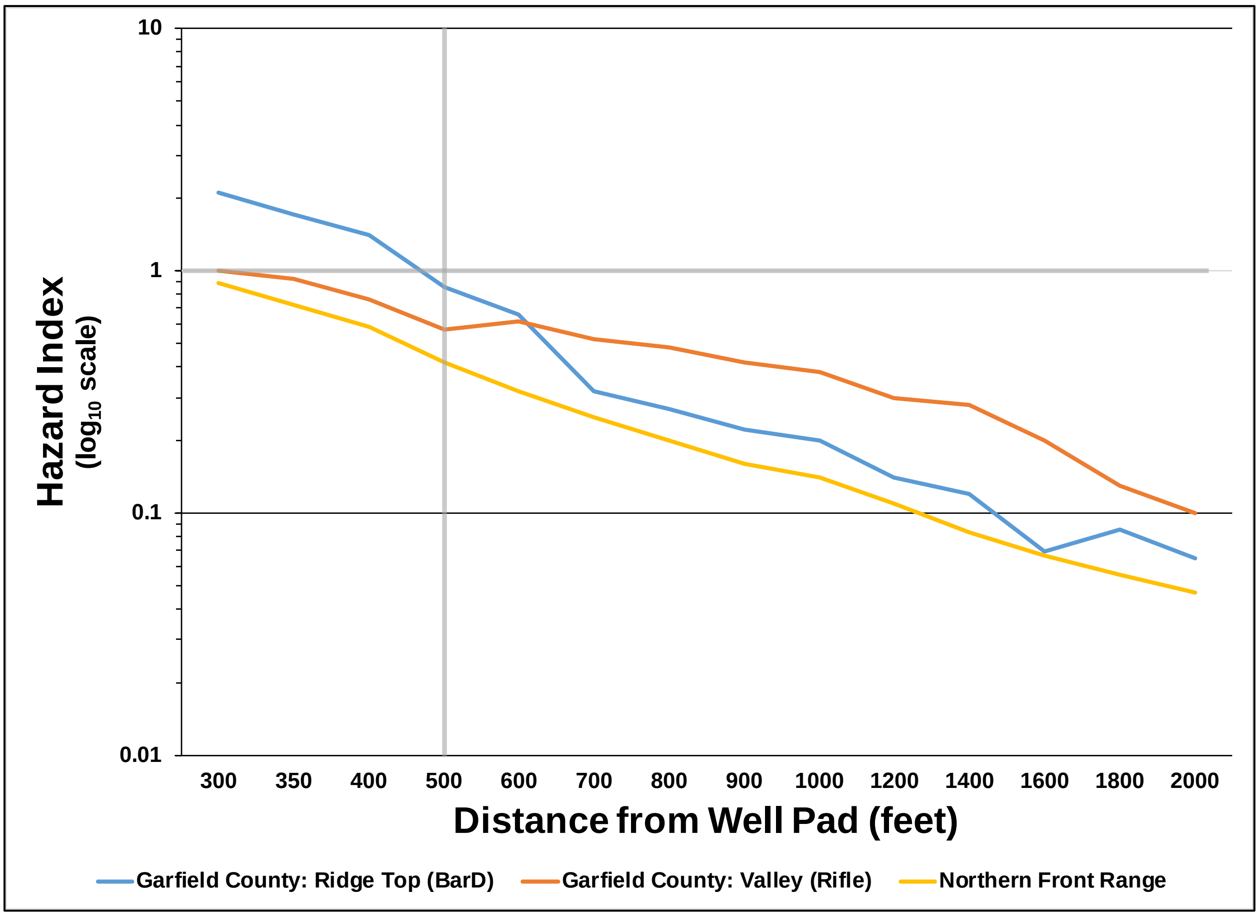
Range of Hazard Quotients	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	123-TMB 124-TMB 135-TMB benzene m+p-xylene n-nonane	benzene m+p-xylene n-nonane	benzene n-nonane	none		

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
TMB = trimethylbenzene; 123 = 1,2,3 and 124 = 1,2,4 and so on.

Table 5-20. Overview of the Largest Subchronic Non-cancer Hazard Indices during Development Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 1-acre Well Pad

Range of Hazard Indices	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	hematological neurotoxicity respiratory systemic	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	none	neurotoxicity	none

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



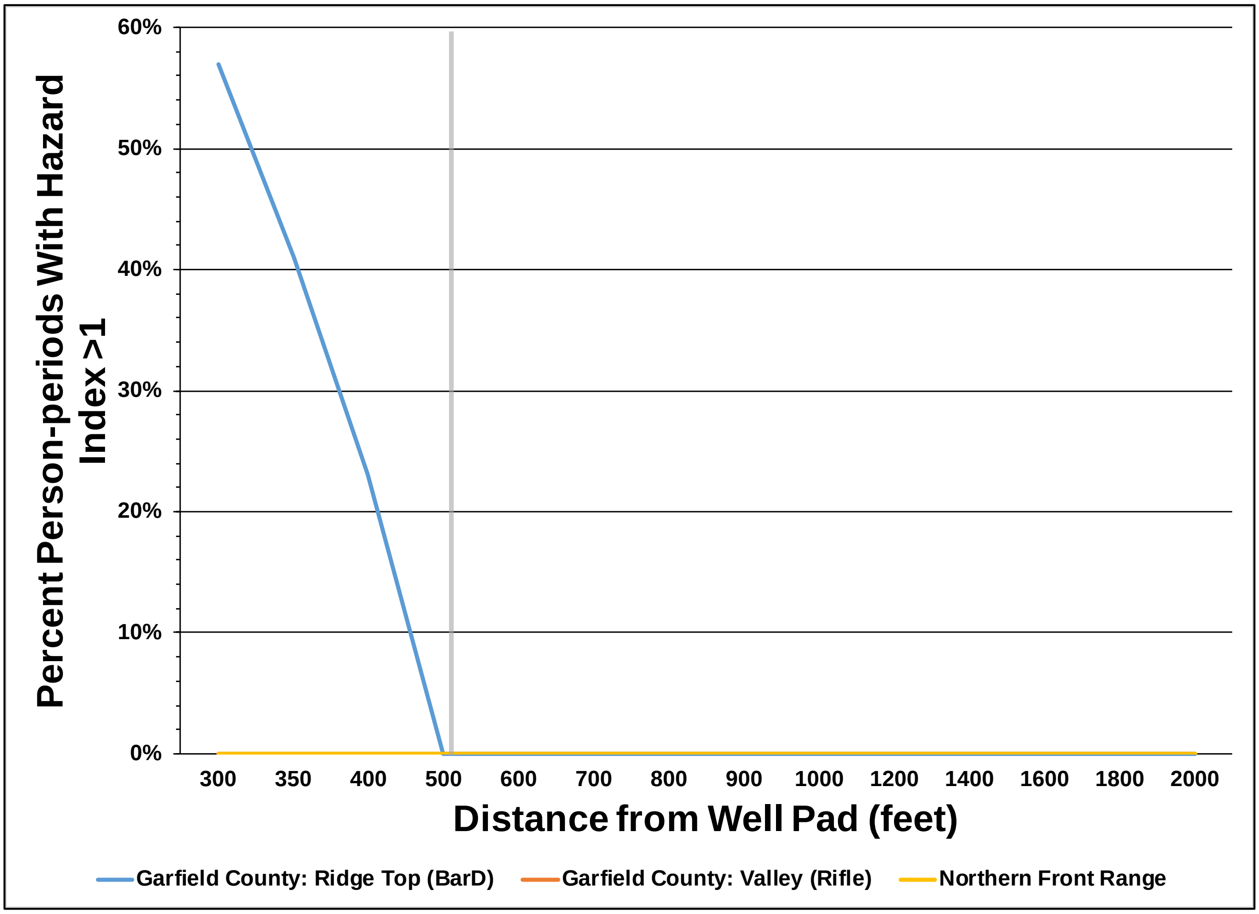
Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
log10 = logarithm base 10.

Figure 5-39. Largest Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the 1-acre Well Pad during Development Activities in Sequence

Analysis of Person-period Critical-effect-group Hazard Indices by Distance

For the same scenarios used in Figure 5-39, in Figure 5-40 we illustrate the frequency of maximum subchronic HIs reaching above a value of 1. This figure is analogous to Figure 5-16 in Section 5.3.2.1, and it shows that only at the closest distance to the Garfield County ridge-top pad did development activities in sequence produce subchronic neurotoxicity HIs above 1 for the majority of people on the majority of multi-day periods of the year. By the 500-ft distance, HIs above 1 occurred for no simulated individuals.

Generally, the rate of decline in these percentages with distance will vary across chemicals/critical-effect groups and sites, depending on several factors. Table E-39 shows the percentage of person-periods with HI above 1 for all critical-effect groups, including those used to create this graph (we do not show a similar table for HQs because all HQs were below 1).

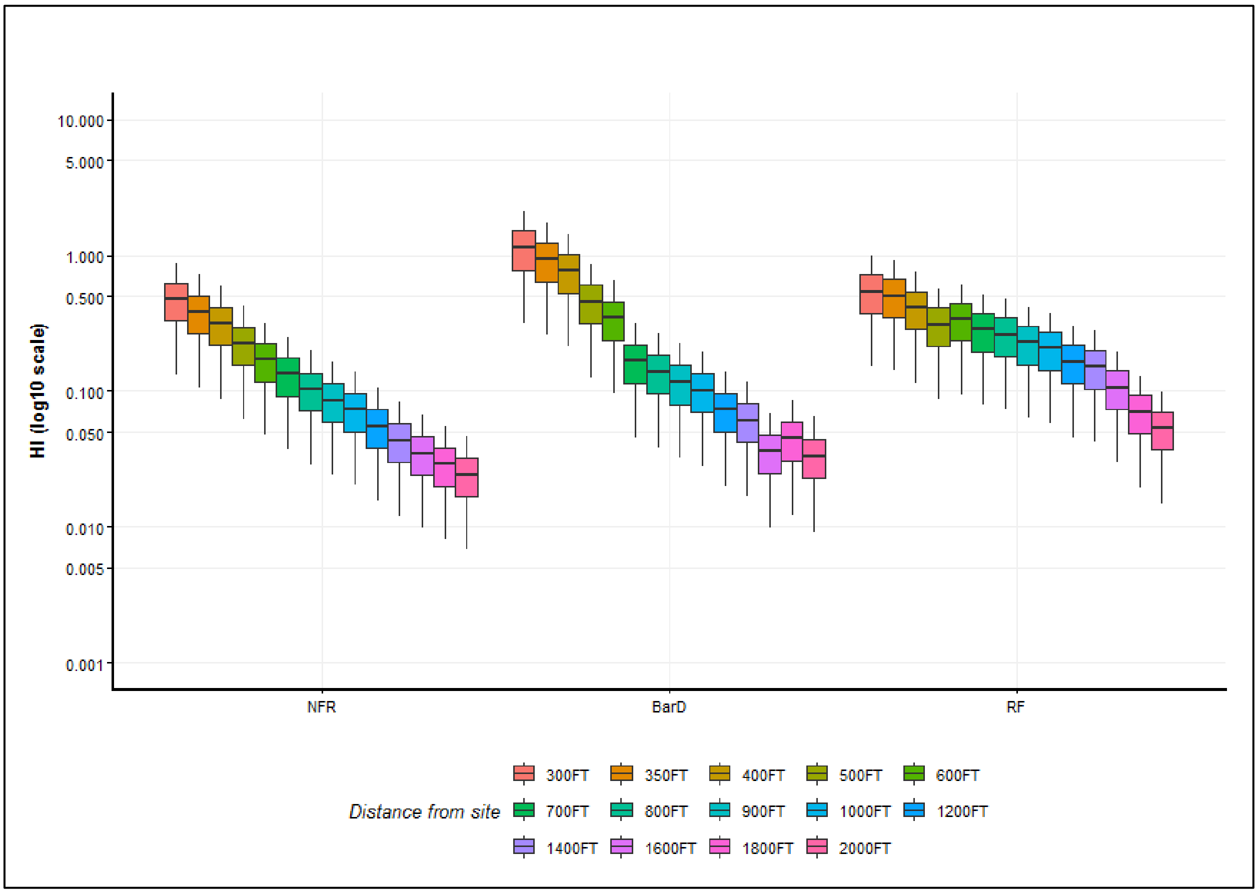


Notes: X-axis is not to scale. “Person-periods” refers to the collection across the hypothetical population of each modeled individual’s subchronic hazard indices for a year of modeling (the “rolling averages” referred to in Section 3.3.2.2). The data in this graph refer to the percentage of hazard indices (in this collection of hazard indices) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-40. Percentage of Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the 1-acre Well Pad during Development Activities in Sequence

Figure 5-41 is analogous to Figure 5-17 in Section 5.3.2.1, showing distributions of neurotoxicity HIs during development activities in sequence, across all person-periods. The 25th-to-75th-percentile ranges of subchronic HIs for neurotoxicity at the 500-ft distance were 0.31–0.61, 0.21–0.41, and 0.15–0.3 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively. These were lower than the absolute maximum values at the same distance: 0.86, 0.57, and 0.42, respectively. The median neurotoxicity HIs during development activities in sequence were 0.46, 0.31, and 0.22 at 500 ft from the three sites respectively, which were factors of 1.8–1.9 smaller than the absolute maximum values at the same distance.

For the scenario which had the highest HIs at the 500-ft distance (neurotoxicity HIs at the Garfield County ridge-top site), Figure 5-41 shows that approximately 57 percent of all person-period HIs at the 500-ft distance were below 0.5 (97 percent for the valley site, 100 percent for the NFR site).



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-41. Distributions of Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) at Various Distances from the 1-acre Well Pad during Development Activities in Sequence

5.5.1.2. 3-acre Well Pad

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

Maximum chemical HQs and critical-effect-group HIs at 500 ft were smaller for the 3-acre results relative to the 1-acre results (by less than about a factor of 2 on average across VOCs/critical-effect groups and sites).

As with the 1-acre results presented in Section 5.5.1.1, **when assessing the development activities in sequence all VOC subchronic HQs were below 1 at the selected receptors 500 ft from the 3-acre well pads, and all HQs were below 0.1 at the selected 2,000-ft receptors** (Table 5-21, Table E-40). Also similar to the 1-acre results, at 3-acre pads **all subchronic HIs were below 1 at 500 ft and below 0.1 at 2,000 ft** (Table 5-22, Table E-41). Figure 5-42 illustrates trends with distance in the maximum neurotoxicity HIs at the selected receptors (the critical-effect group with the highest maximum HIs in this 3-acre scenario of development activities in sequence). All HIs for all critical-effect groups were always below 1 at all three sites, contrary to the 1-acre results where neurotoxicity and hematological HIs were slightly above 1 at 300–400 ft from the pad at one or more sites. These HIs remained above 0.1 out to 1,000–1,800 ft from the well pads, depending on the site. Table E-41 shows all modeled values for each site and critical-effect group, including those used to create this graph.

Comparing HQs and HIs between the three sites, the HQs and HIs averaged across chemicals and distances were within about 30 percent between the two Garfield County sites and within about 45 percent between all three sites (highest at the valley site).

Table 5-21. Overview of the Largest Subchronic Non-cancer Hazard Quotients during Development Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 3-acre Well Pad

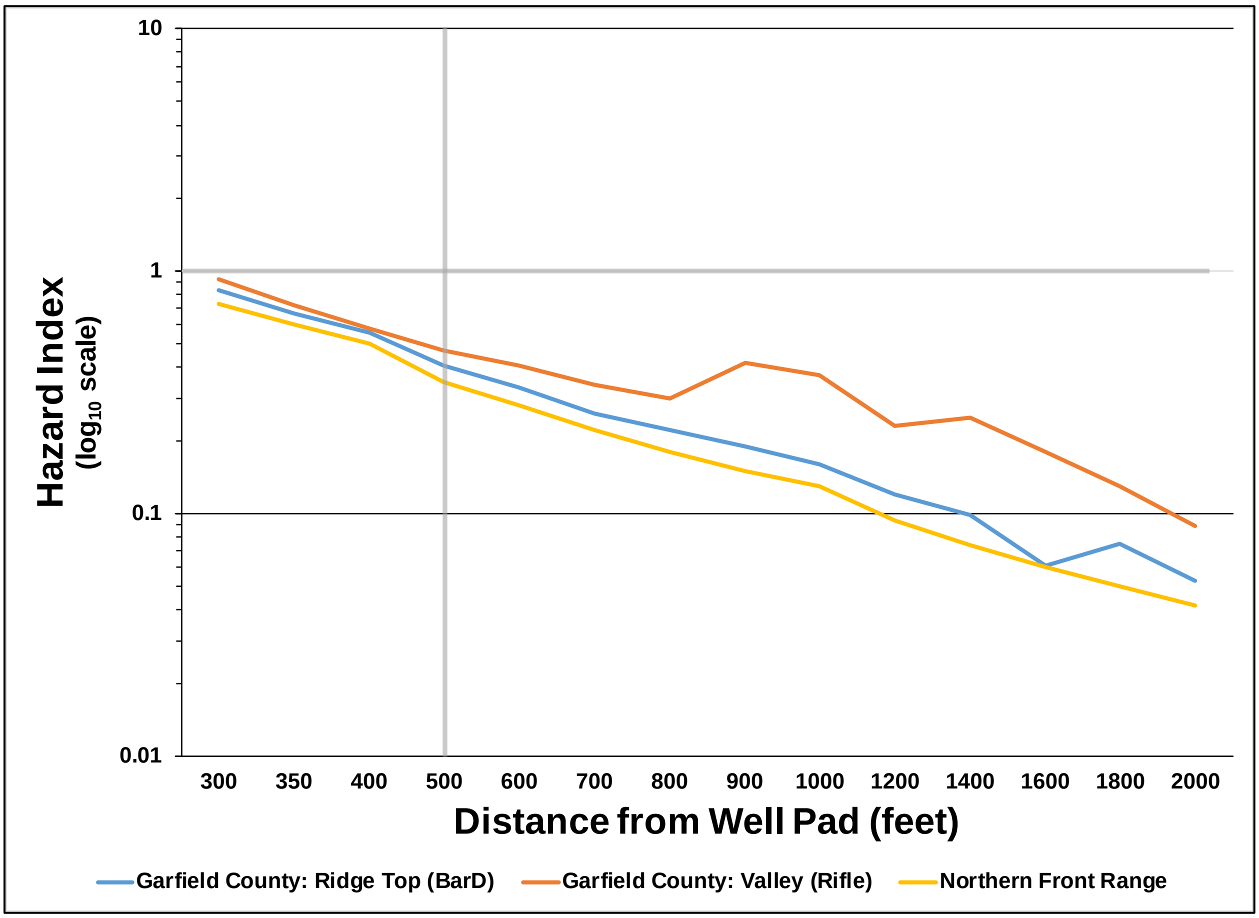
Range of Hazard Quotients	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	benzene m+p-xylene	benzene m+p-xylene n-nonane	benzene n-nonane	none		

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Table 5-22. Overview of the Largest Subchronic Non-cancer Hazard Indices during Development Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 3-acre Well Pad

	500 feet from Well Pad			2,000 feet from Well Pad		
Range of Hazard Indices	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	hematological neurotoxicity	none		

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10.

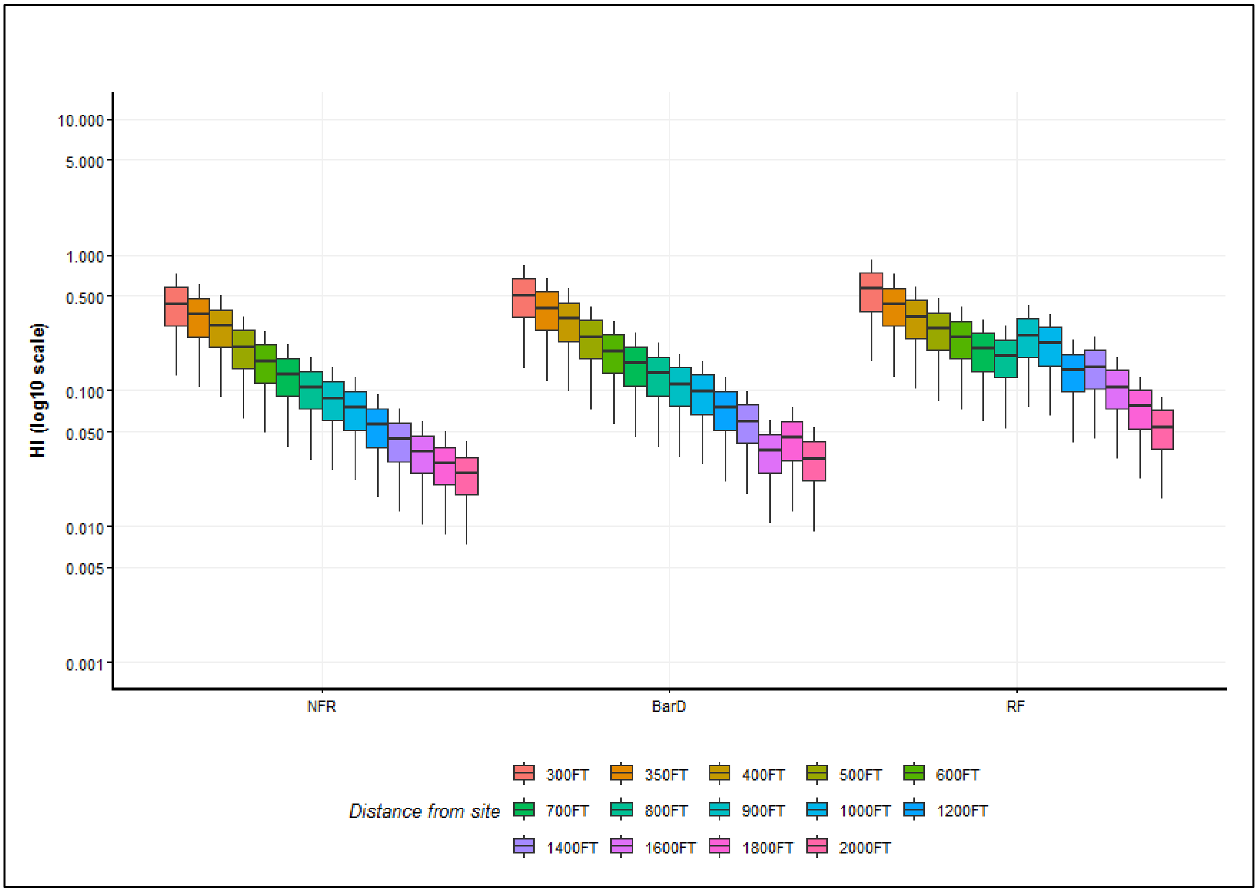
Figure 5-42. Largest Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the 3-acre Well Pad during Development Activities in Sequence

Analysis of Person-period Critical-effect-group Hazard Indices by Distance

Whereas in the 1-acre results some modeled individuals at the selected downwind receptors 300–500 ft from the Garfield County ridge-top pad had simulated HIs above 1, with the 3-acre results all HIs were below 1. Therefore, we do not present here a figure analogous to Figure 5-40 in Section 5.5.1.1.

Figure 5-43 is analogous to Figure 5-41 in the 1-acre results, showing distributions of neurotoxicity HIs during development activities in sequence, across all person-periods. The 25th-to-75th-percentile ranges of subchronic HIs for neurotoxicity at the 500-ft distance were 0.17–0.33, 0.2–0.38, and 0.14–0.28 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively (0.31–0.61, 0.21–0.41, and 0.15–0.3 at the 1-acre pads). These were lower than the absolute maximum values at the same distance: 0.41, 0.47, and 0.35, respectively. The median neurotoxicity HIs during development activities in sequence were 0.25, 0.29, and 0.21 at 500 ft from the three sites respectively (rather than 0.46, 0.31, and 0.22 at the 1-acre well pad), which were a factor of 1.6–1.7 smaller than the absolute maximum values at the same distance.

For the scenario which had the highest HIs at the 500-ft distance (neurotoxicity HIs at the Garfield County valley site), Figure 5-43 shows that approximately 3 percent of all person-period HIs at the 500-ft distance were below 0.1 (7 percent for the ridge-top site, 10 percent for the NFR site).



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-43. Distributions of Subchronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) at Various Distances from the 3-acre Well Pad during Development Activities in Sequence

5.5.1.3. 5-acre Well Pad

At the 5-acre pads during development activities in sequence, we analyzed subchronic exposures only at the NFR site where the total duration of development activities was less than 365 days (at the other sites, the total duration exceeded 365 days and so we conducted only chronic assessments there).

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

Maximum chemical HQs and critical-effect-group HIs at 500 ft were smaller for the 5-acre NFR results relative to the 3-acre NFR results (by less than about 5 percent on average across VOCs/critical-effect groups).

As with the 3-acre results presented in Section 5.5.1.2, **when assessing the development activities in sequence all subchronic VOC HQs were below 1 at the selected receptors 500 ft from the 5-acre NFR well pad, and all HQs were below 0.1 at the selected 2,000-ft receptor** (Table 5-23, Table E-42). Also similar to the 3-acre results, at 5-acre pads **all subchronic HIs were below 1 at 500 ft and below 0.1 at 2,000 ft** (Table 5-24, Table E-43). Figure 5-44 illustrates trends with distance in the maximum hematological HIs at the selected receptors (the critical-effect group with the highest maximum HIs in this 5-acre scenario of development activities in sequence at the NFR site), along with the two critical-effect groups with the next-highest maximum HIs (neurotoxicity and respiratory). Like with the 3-acre results, all HIs for all critical-effect groups were always below 1 at the 5-acre NFR site. These HIs remained above 0.1 out to 1,200 ft from the well pad for the hematological group (1,000 and 400 ft for the neurotoxicity and respiratory groups, respectively). Table E-43 shows all modeled values for each site and critical-effect group, including those used to create this graph.

Table 5-23. Overview of the Largest Subchronic Non-cancer Hazard Quotients during Development Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Well Pad

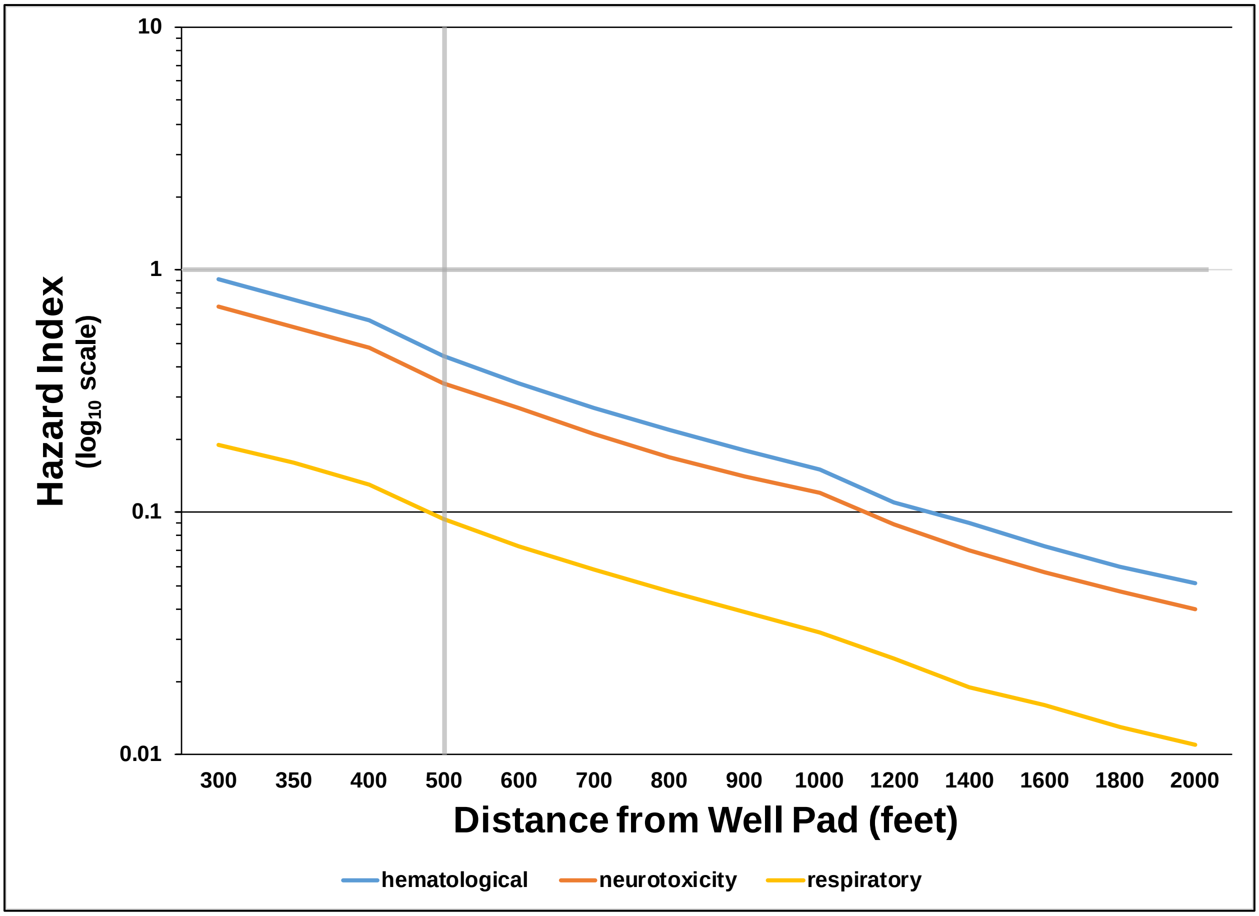
Range of Hazard Quotients	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	N/A	N/A	none	N/A	N/A	none
Between 1 and 10	N/A	N/A	none	N/A	N/A	none
0.1 to 1	N/A	N/A	benzene n-nonane	N/A	N/A	none

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical). Entries for Garfield County sites are "N/A" because development activities in sequence there last a total of more than 1 year in the 5-acre development scenario with many wells being developed (so we defer to a chronic assessment).

Table 5-24. Overview of the Largest Subchronic Non-cancer Hazard Indices during Development Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Well Pad

Range of Hazard Indices	300 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	N/A	N/A	none	N/A	N/A	none
Between 1 and 10	N/A	N/A	none	N/A	N/A	none
0.1 to 1	N/A	N/A	hematological neurotoxicity	N/A	N/A	none

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical). Entries for Garfield County sites are "N/A" because development activities in sequence there last a total of more than 1 year in the 5-acre development scenario with many wells being developed (so we defer to a chronic assessment).



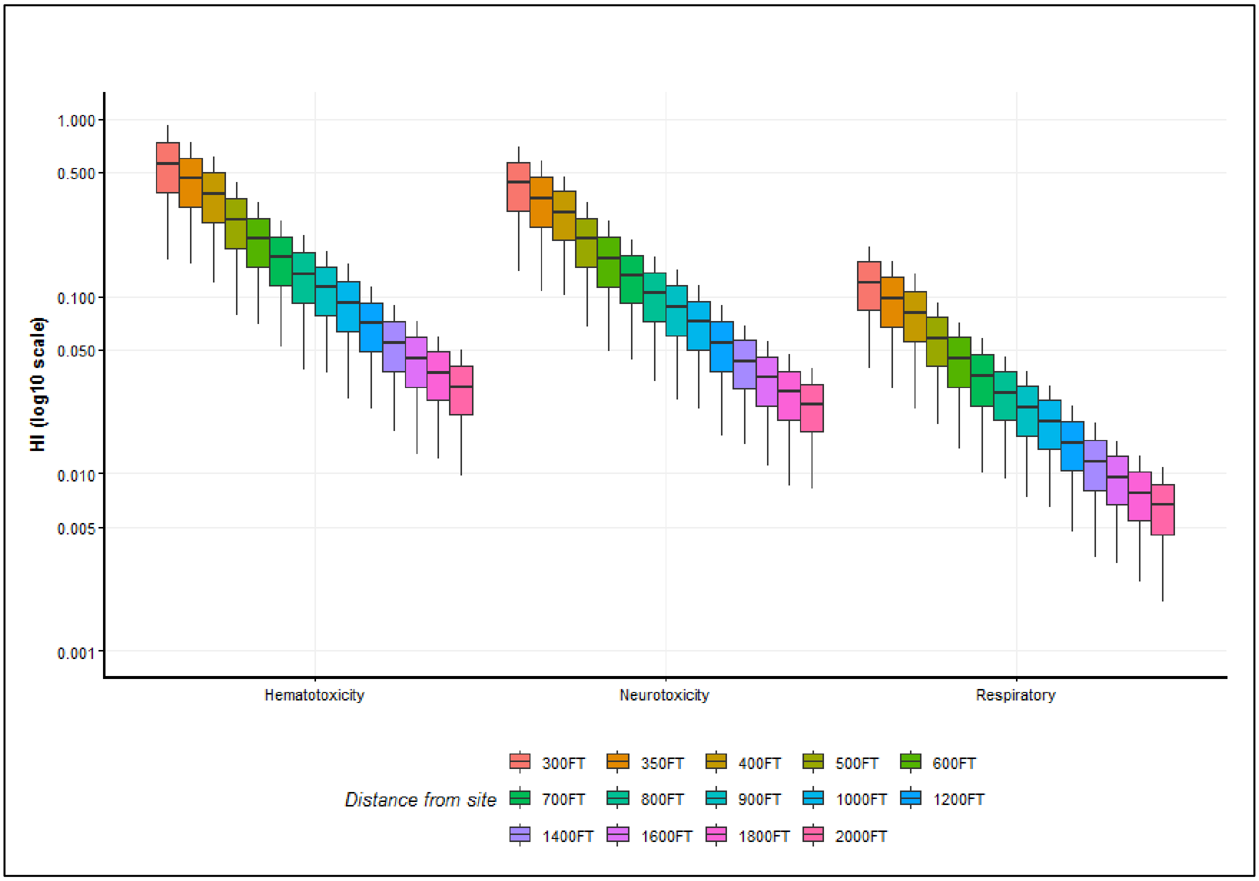
Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).
log10 = logarithm base 10.

Figure 5-44. Largest Subchronic Non-cancer Hazard Indices for the Hematological, Neurotoxicity, and Respiratory Critical-effect Groups, for the Highest Exposed Hypothetical Individuals at Various Distances from the 5-acre Well Pad during Development Activities in Sequence at the Northern Front Range Site

Analysis of Person-period Critical-effect-group Hazard Indices by Distance

As with the 3-acre results, all HIs were below 1 at the 5-acre NFR well pad. Therefore, we do not present here a figure analogous to Figure 5-40 in Section 5.5.1.1.

Figure 5-45 is analogous to Figure 5-43 in the 3-acre results, however here we show distributions of hematological, neurotoxicity, and respiratory HIs during development activities in sequence at the NFR site, across all person-periods (matching what we show in Figure 5-44). The 25th-to-75th-percentile ranges of subchronic HIs at the 500-ft distance were 0.18–0.35, 0.14–0.28, and 0.039–0.076 for the hematological, neurotoxicity, and respiratory groups, respectively (0.18–0.36, 0.14–0.28, and 0.039–0.076 at the 3-acre pads). These were lower than the absolute maximum values at the same distance: 0.44, 0.34, and 0.094, respectively. The median hematological, neurotoxicity, and respiratory HIs during development activities in sequence were 0.27, 0.21, and 0.058 at 500 ft from the three sites respectively, which were a factor of 1.6 smaller than the absolute maximum values. As shown in Figure 5-45, approximately 5 percent of all person-period HIs at the 500-ft distance were below 0.1 for the hematological group (10 percent for neurotoxicity, 100 percent for respiratory).



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range.

Figure 5-45. Distributions of Subchronic Non-cancer Hazard Indices for the Hematological, Neurotoxicity, and Respiratory Critical-effect Groups (Across the Hypothetical Population) at Various Distances from the 5-acre Well Pad during Development Activities in Sequence at the Northern Front Range Site

5.5.2. Chronic Non-cancer Hazards

In this section, we discuss the potential for chronic exposures above health-criteria levels, due to emissions from O&G development activities that occur sequentially (covering drilling, fracking, and flowback together), followed by production. We discuss the results of each size of development well pad separately: 1 acre (Section 5.5.2.1), 3 acre (Section 5.5.2.2), and 5 acre (Section 5.5.2.3).

As discussed in Section 5.4, production activities were estimated for 1-acre well pads only, so all development+production scenarios assume a 1-acre well pad for production. The 150- and 250-ft receptor distances only exist in the modeling during the production phase, so for these combined development+production calculations we show receptor distances of 300 ft and beyond. Note that we are utilizing exposures during development activities from the receptors selected for the development assessments discussed earlier (and in Section 2.7.3), and exposures during the production activity from the receptors selected for the production assessments discussed earlier (and in Section 2.8). This means that the exposure concentrations we utilize in our calculations may come from one 300-ft receptor for development activities (a location that tended to produce the highest average 1-hour concentrations during development) and a different 300-ft receptor during production activities (a location that tended to produce the highest annual-average concentration during production).

More than 96 percent of the total period of exposure during all activities in sequence was during production activities (see Table 3-3); because of this, the chronic HQs and HIs discussed here for all activities in sequence were very similar to those discussed in Section 5.4.2 for production alone. **All such HQs and HIs were below 1 at 500 ft from the well pads and below 0.1 at 2,000 ft**. At the 5-acre Garfield County Sites where flowback operations reach chronic duration, more than 70 percent of the total period of exposure during development activities in sequence at those sites was during flowback activities; because of this, the chronic HQs and HIs discussed here for development activities in sequence at 5-acre sites were very similar to those discussed in Section 5.3.3 for flowback alone. **All such HQs were below 1 at 500 ft from the well pads, and hematological and neurotoxicity HIs were slightly above 1 at the same locations.**

5.5.2.1. 1-acre Development Well Pad (1-acre Production Pad)

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

Similar to the chronic results for production activities presented in Section 5.4.2, **when assessing the all O&G activities in sequence all VOC HQs were below 1 at the selected receptors 500 ft from the 1-acre well pads and below 0.1 at 2,000 ft** (Table 5-25, Table E-44). **All chronic HIs were also below 1 at 500 ft and below 0.1 at 2,000 ft** (Table 5-26, Table E-45). Figure 5-46 illustrates trends with distance in the maximum hematological HIs at the selected receptors (the critical-effect group with the highest maximum HIs in this scenario of all activities in sequence). Differences in HIs were small between the three sites, with values falling below 0.1 by 1,200 ft from the Garfield County ridge-top site and the NFR site, and by 1,400 ft from the Garfield County valley site. Table E-45 shows all modeled values for each site and critical-effect group, including those used to create this graph.

Comparing HQs and HIs between the three sites, the HQs and HIs averaged across chemicals and distances were about 15 percent larger at the Garfield County ridge-top site compared with the valley site, and about 20 percent larger at the ridge-top site compared with the NFR site.

Table 5-25. Overview of the Largest Chronic Non-cancer Hazard Quotients during All Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 1-acre Development Well Pad/1-acre Production Pad

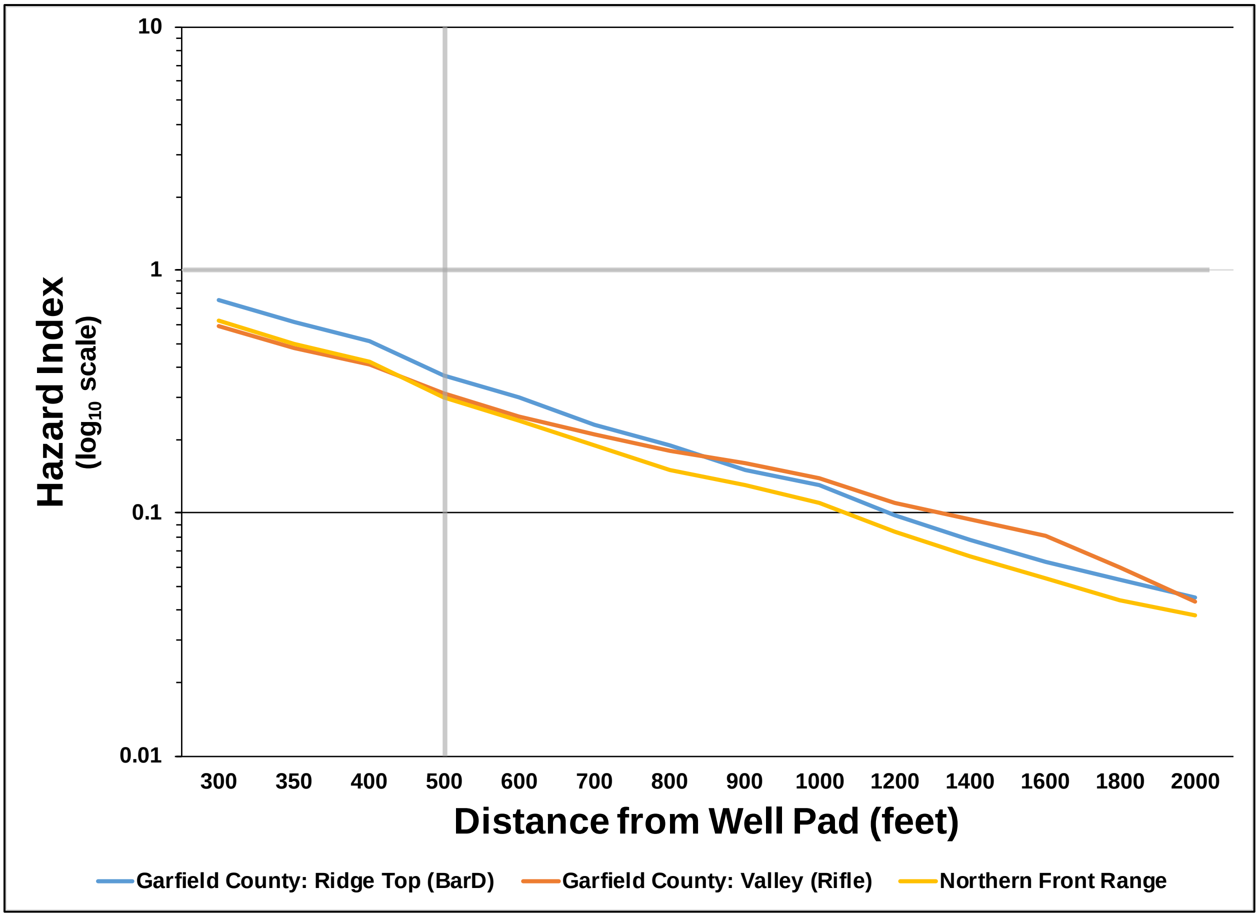
Range of Hazard Quotients	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	benzene	benzene	benzene	none		

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Table 5-26. Overview of the Largest Chronic Non-cancer Hazard Indices during All Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 1-acre Development Well Pad/1-acre Production Pad

Range of Hazard Indices	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	none		

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10.

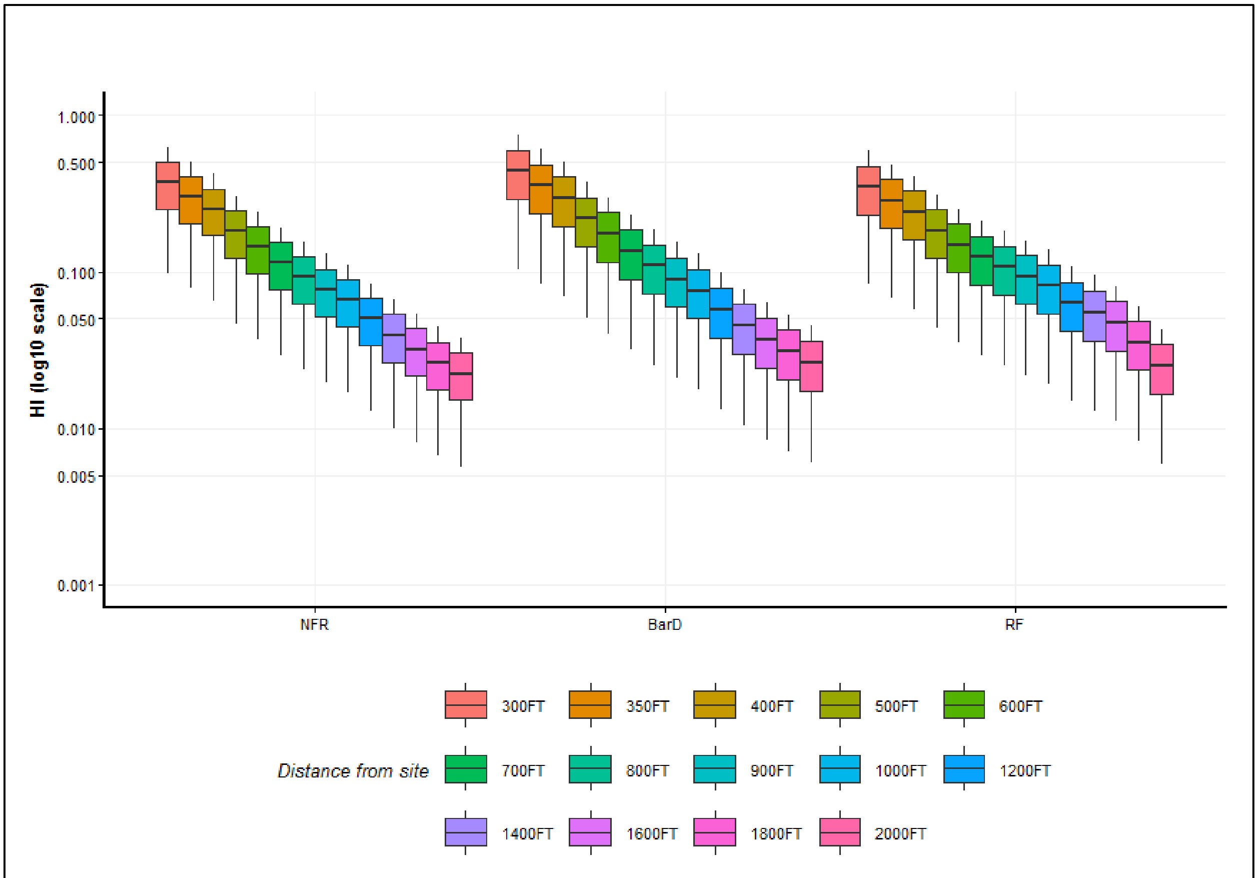
Figure 5-46. Largest Chronic Non-cancer Hazard Indices for the Hematological Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the 1-acre Development Well Pad/1-acre Production Pad during All Activities in Sequence

Analysis of Critical-effect-group Hazard Indices by Distance

All HQs and HIs were below 1; therefore, we do not present here a figure analogous to Figure 5-34 in Section 5.4.2.

Figure 5-47 is analogous to Figure 5-35 in Section 5.4.2, showing distributions of hematological HIs during all activities in sequence, across all modeled individuals. The 25th-to-75th-percentile ranges of chronic HIs for hematological at the 500-ft distance were 0.14–0.3, 0.12–0.25, and 0.12–0.24 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively. These were lower than the absolute maximum values at the same distance: 0.37, 0.31, and 0.3, respectively. The median hematological HIs during all activities in sequence were 0.22, 0.18, and 0.18 at 500 ft from the three sites respectively, which were a factor of 1.7 smaller than the absolute maximum values at the same distance.

For the scenario which had the highest HIs at the 500-ft distance (hematological HIs at the Garfield County ridge-top site), Figure 5-47 shows that approximately 14 percent of all chronic HIs at the 500-ft distance were below 0.1 (18 percent for the valley site, 18 percent for the NFR site).



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-47. Distributions of Chronic Non-cancer Hazard Indices for the Hematological Critical-effect Group (Across the Hypothetical Population) at Various Distances from the 1-acre Development Well Pad/1-acre Production Pad during All Activities in Sequence

5.5.2.2. 3-acre Development Well Pad (1-acre Production Pad)

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

Maximum chemical HQs and critical-effect-group HIs at 500 ft were larger for these results (3-acre development pad/1-acre production pad) relative to the results in the previous subsection

(1-acre development pad/1-acre production pad). The difference was less than about 10 percent on average across VOCs/critical-effect groups and sites.

As with the results for the 1-acre development pad/1-acre production pad presented in the previous subsection (Section 5.5.2.1), **when assessing all O&G activities in sequence all VOC HQs were below 1 at the selected receptors 500 ft from the 1-acre well pads and below 0.1 at 2,000 ft** (Table 5-27, Table E-46). **All chronic HIs were also below 1 at 500 ft and below 0.1 at 2,000 ft** (Table 5-28, Table E-47). Figure 5-48 illustrates trends with distance in the maximum hematological HIs at the selected receptors (the critical-effect group with the highest maximum HIs in this scenario of all activities in sequence). As with the results in the previous subsection, differences in HIs were small between the three sites, with values falling below 0.1 by 1,200 ft from the NFR site, by 1,400 ft from the Garfield County ridge-top site, and by 1,600 ft from the Garfield County valley site. Table E-47 shows all modeled values for each site and critical-effect group, including those used to create this graph.

Comparing HQs and HIs between the three sites, the HQs and HIs averaged across chemicals and distances were about 8 percent larger at the Garfield County ridge-top site compared with the valley site, and about 30 percent larger at the ridge-top site compared with the NFR site.

Table 5-27. Overview of the Largest Chronic Non-cancer Hazard Quotients during All Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 3-acre Development Well Pad/1-acre Production Pad

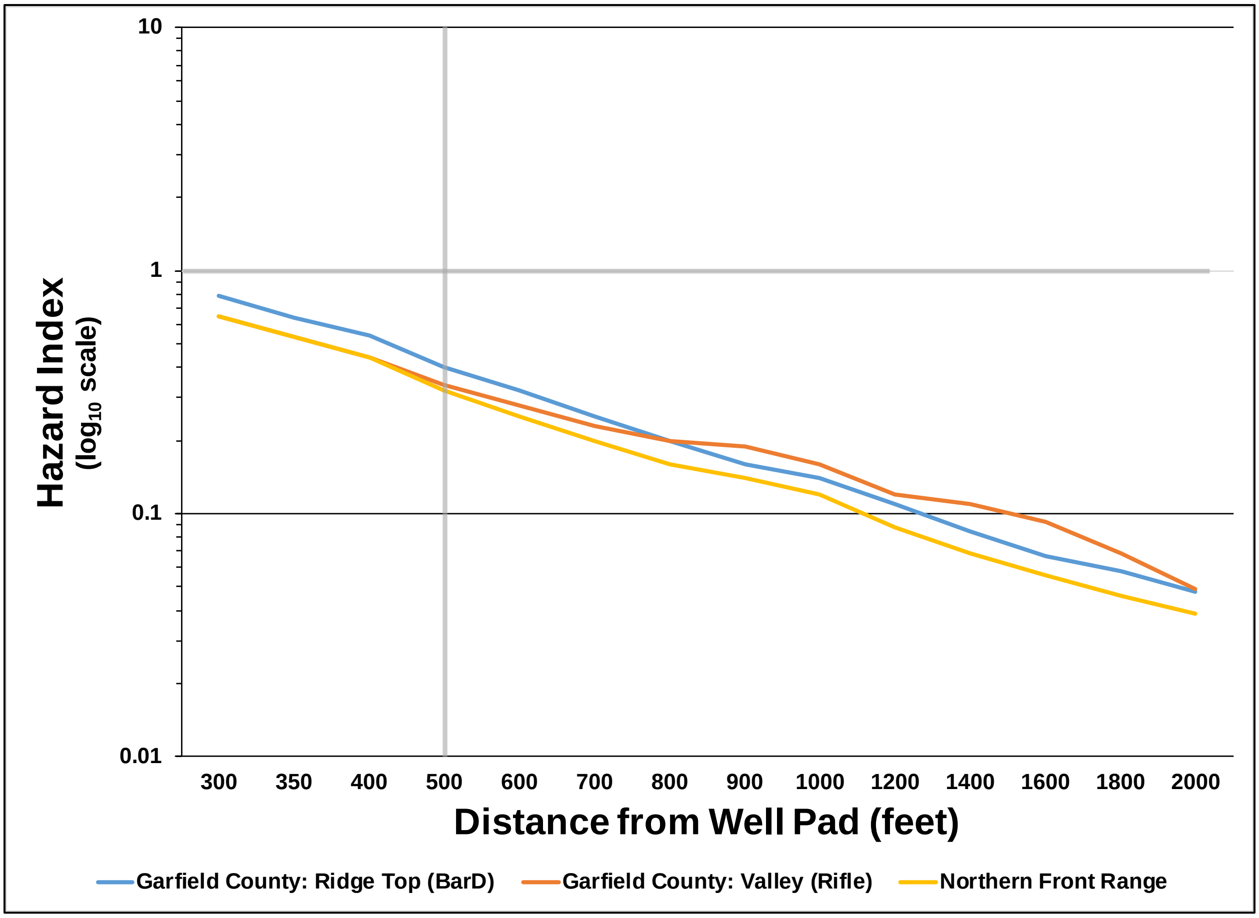
Range of Hazard Quotients	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	benzene	benzene	benzene	none		

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Table 5-28. Overview of the Largest Chronic Non-cancer Hazard Indices during All Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 3-acre Development Well Pad/1-acre Production Pad

Range of Hazard Indices	500 feet from Well Pad			2,000 feet from Well Pad		
	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	none			none		
Between 1 and 10	none			none		
0.1 to 1	hematological	hematological	hematological	none		
	neurotoxicity	neurotoxicity	neurotoxicity			
	respiratory	respiratory	respiratory			

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical).



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

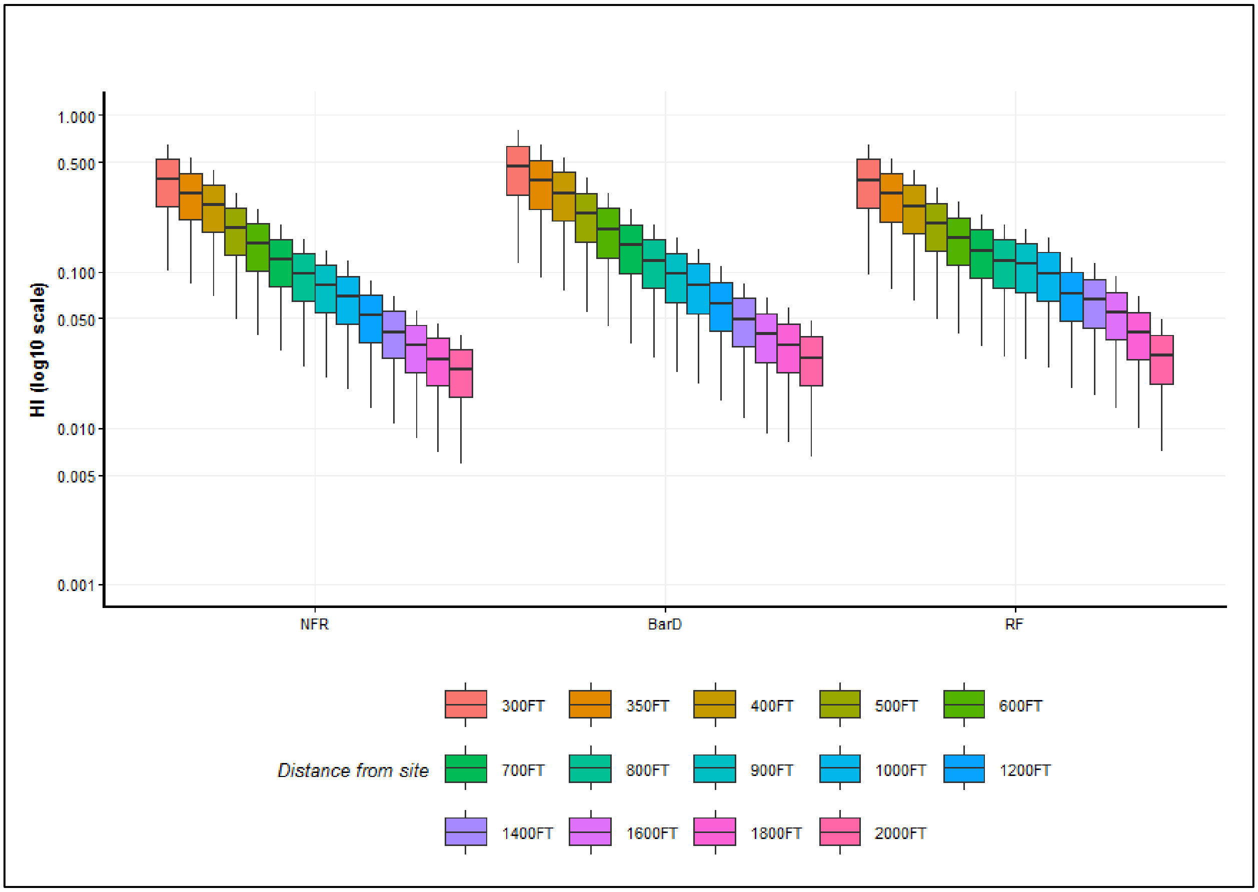
log10 = logarithm base 10.

Figure 5-48. Largest Chronic Non-cancer Hazard Indices for the Hematological Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the 3-acre Development Well Pad/1-acre Production Pad during All Activities in Sequence

Analysis of Critical-effect-group Hazard Indices by Distance

All HQs and HIs were below 1; therefore, we do not present here a figure analogous to Figure 5-34 in Section 5.4.2.

Figure 5-49 is analogous to Figure 5-47 in the previous subsection, showing distributions of hematological HIs during all activities in sequence, across all modeled individuals. The 25th-to-75th-percentile ranges of chronic HIs for hematological at the 500-ft distance were 0.15–0.32, 0.13–0.27, and 0.13–0.26 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively (compared with 0.14–0.3, 0.12–0.25, and 0.12–0.24 with all activities in sequence where development occurs on a 1-acre well pad). These were lower than the absolute maximum values at the same distance: 0.4, 0.34, and 0.32, respectively. The median hematological HIs during all activities in sequence were 0.23, 0.2, and 0.19 at 500 ft from the three sites respectively (rather than 0.22, 0.18, and 0.18 at the 1-acre well pads), which were a factor of 1.7 smaller than the absolute maximum values at the same distance. For the scenario which had the highest HIs at the 500-ft distance (hematological HIs at the Garfield County ridge-top site), Figure 5-49 shows that approximately 12 percent of all chronic HIs at the 500-ft distance were below 0.1 (16 percent for the valley site, 16 percent for the NFR site).



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-49. Distributions of Chronic Non-cancer Hazard Indices for the Hematological Critical-effect Group (Across the Hypothetical Population) at Various Distances from the 3-acre Development Well Pad/1-acre Production Pad during All Activities in Sequence

5.5.2.3. 5-acre Development Well Pad (1-acre Production Pad)

Overall Maximum Chemical Hazard Quotients and Critical-effect-group Hazard Indices by Distance

For all activities in sequence, maximum chemical HQs and critical-effect-group HIs at 500 ft were larger for these results (5-acre development pad/1-acre production pad) relative to the results in the previous subsection (3-acre development pad/1-acre production pad). The difference was less than about 10 percent on average across VOCs/critical-effect groups and sites.

Development activities in sequence also reach chronic duration at the 5-acre development pads at the Garfield County sites, due to long flowback durations (see Table 3-3). The chronic results presented in Section 5.3.3 only include exposure to flowback emissions, while the chronic development results presented in this section also include exposure to drilling and fracking emissions in a calculation of total exposure. Because flowback accounts for about 75 percent of the total duration of development activities in these scenarios, the chronic results of development activities presented here are similar to those presented just for flowback in Section 5.3.3.

As with the results for the 3-acre development pad/1-acre production pad presented in the previous subsection (Section 5.5.2.2), **when assessing all O&G activities in sequence all VOC HQs were below 1 at the selected receptors 500 ft from the 1-acre well pads and below 0.1 at 2,000 ft** (Table 5-29, Table E-48). **All chronic HIs were also below 1 at 500 ft and below 0.1 at 2,000 ft** (Table 5-30, Table E-50). Figure 5-50 illustrates trends with distance in the maximum hematological HIs at the selected receptors (the critical-effect group with the highest maximum HIs in this scenario of all activities in sequence). Similar to the results in the previous subsection, differences in HIs were small between the three sites, with values falling below 0.1 by 1,400 ft from the NFR and Garfield County ridge-top sites, and by 1,800 ft from the Garfield County valley site. Table E-50 shows all modeled values for each site and critical-effect group, including those used to create this graph.

Comparing HQs and HIs between the three sites, for all activities in sequence the HQs and HIs averaged across chemicals and distances were about 3 percent larger at the Garfield County ridge-top site compared with the valley site, and about 25 percent larger at the ridge-top site compared with the NFR site.

Table 5-29. Overview of the Largest Chronic Non-cancer Hazard Quotients during Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Development Well Pad/1-acre Production Pad

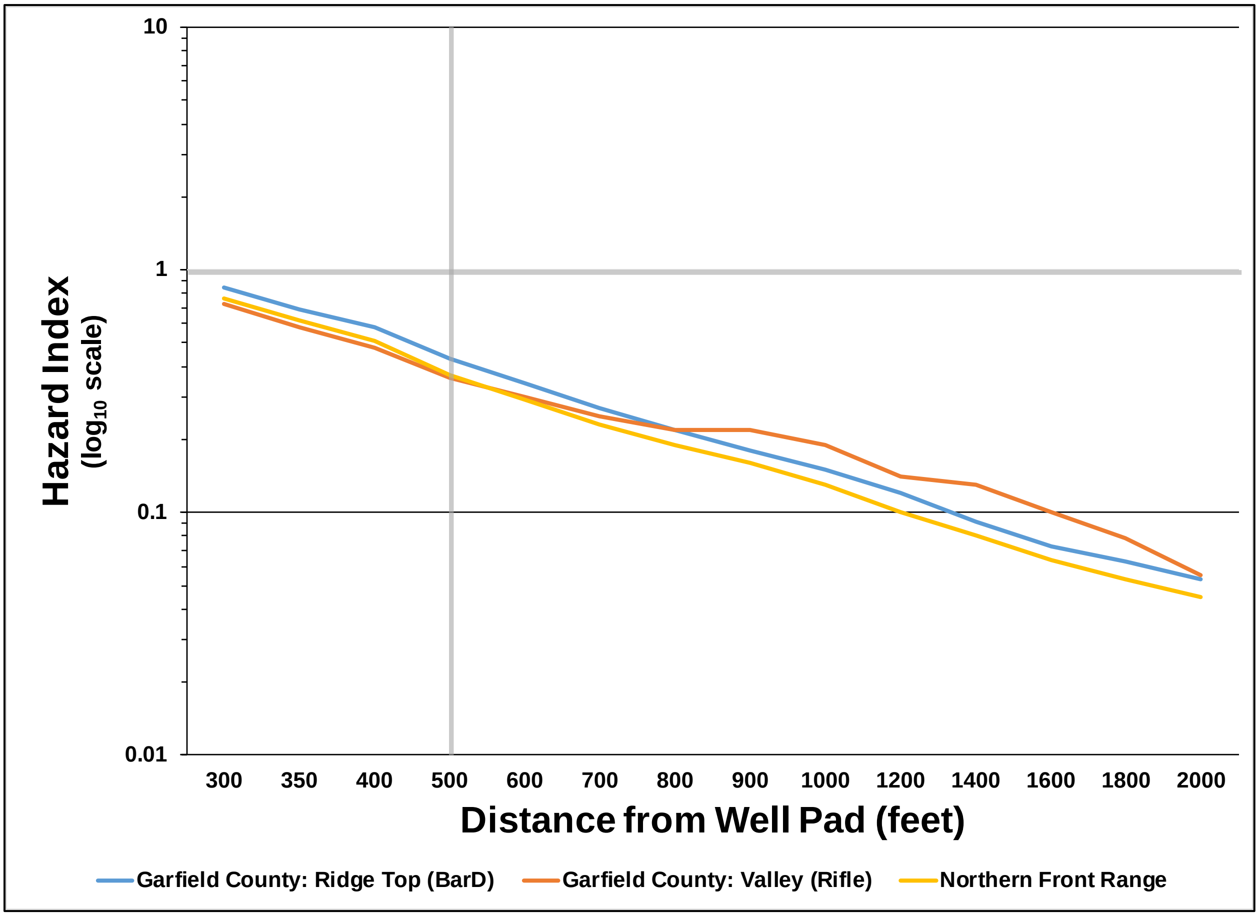
Range of Hazard Quotients	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Development	none		N/A	none		N/A
	All	none			none		
Between 1 and 10	Development	none		N/A	none		N/A
	All	none			none		
0.1 to 1	Development	123-TMB 124-TMB 135-TMB 2-ET benzene m+p-xylene n-nonane	123-TMB 124-TMB 135-TMB 2-ET benzene m+p-xylene n-nonane	N/A	benzene n-nonane	benzene n-nonane	N/A
	All	benzene n-nonane	benzene n-nonane	benzene	none		

Notes: Not showing chemicals with hazard quotients less than 0.1. Corresponds to ages 17 and younger (results for other age groups are nearly identical). Development activities in sequence at the Northern Front Range site are “N/A” because they last less than 1 year in the 5-acre scenario with many wells being developed (so we defer to a subchronic assessment).
ET = ethyltoluene; TMB = trimethylbenzene; 123 = 1,2,3 and 124 = 1,2,4 and so on.

Table 5-30. Overview of the Largest Chronic Non-cancer Hazard Indices during Activities in Sequence, for the Highest Exposed Hypothetical Individuals at 500 and 2,000 Feet from the 5-acre Development Well Pad/1-acre Production Pad

Range of Hazard Indices	Activity	500 feet from Well Pad			2,000 feet from Well Pad		
		Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range	Garfield County: Ridge Top (BarD)	Garfield County: Valley (Rifle)	Northern Front Range
≥ 10	Development	none		N/A	none		N/A
	All	none			none		
Between 1 and 10	Development	hematological neurotoxicity	hematological neurotoxicity	N/A	none		N/A
	All	none			none		
0.1 to 1	Development	respiratory systemic	respiratory systemic	N/A	hematological neurotoxicity	hematological neurotoxicity respiratory	N/A
	All	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	hematological neurotoxicity respiratory	none		

Notes: Not showing critical-effect groups with hazard indices less than 0.1. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Corresponds to ages 17 and younger (results for other age groups are nearly identical). Development activities in sequence at the Northern Front Range site are “N/A” because they last less than 1 year in the 5-acre scenario with many wells being developed (so we defer to a subchronic assessment).



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Thick lines emphasize hazard index=1 and the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10.

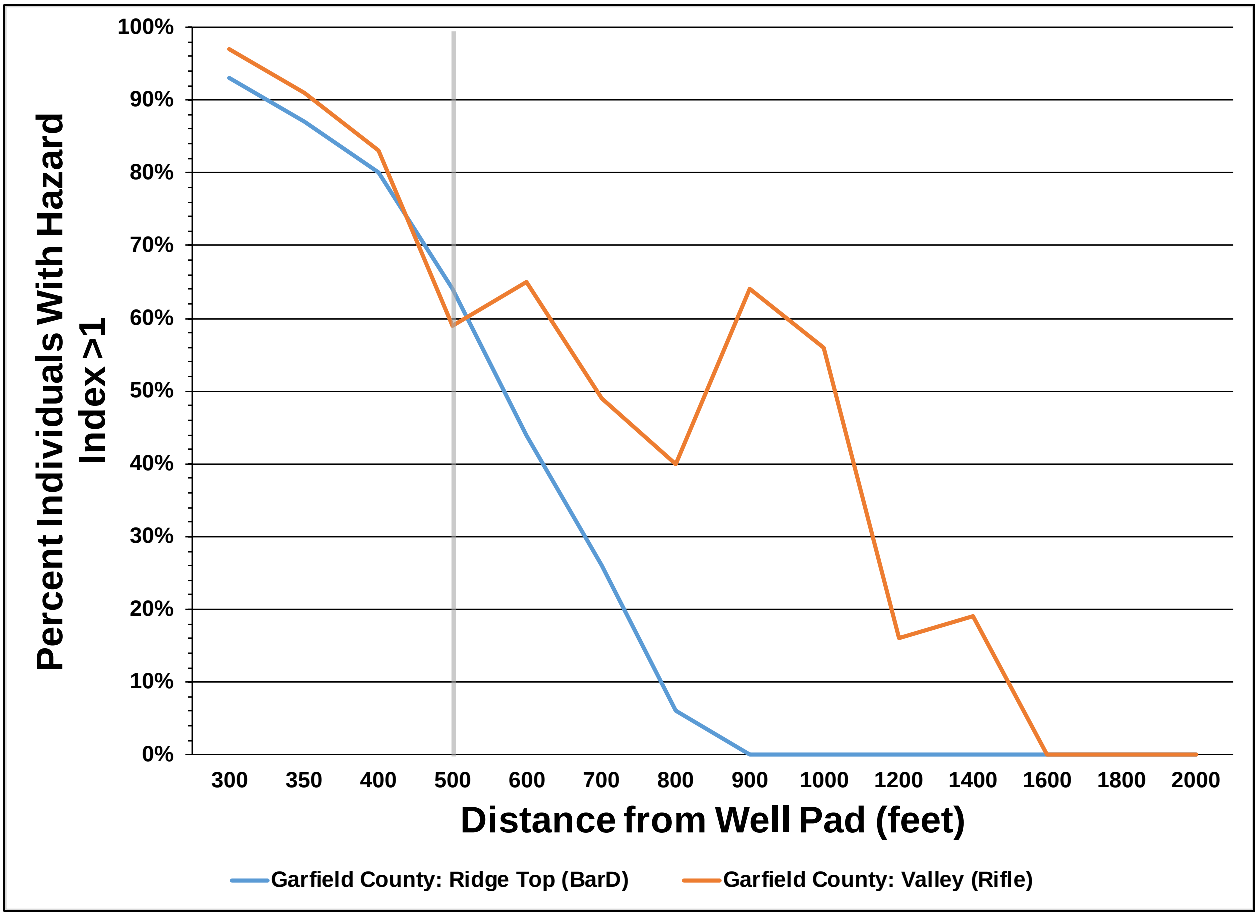
Figure 5-50. Largest Chronic Non-cancer Hazard Indices for the Hematological Critical-effect Group, for the Highest Exposed Hypothetical Individuals at Various Distances from the 5-acre Development Well Pad/1-acre Production Pad during All Activities in Sequence

Analysis of Critical-effect-group Hazard Indices by Distance

While all HQs and HIs were below 1 for all activities in sequence, some HIs were above 1 for development activities in sequence. In Figure 5-51 we illustrate the frequency of maximum chronic HIs reaching above a value of 1 for development activities in sequence. These percentages are taken from the collection of each simulated individual's chronic HI, for 1,000 simulated youths up to 17 years old at each selected downwind receptor. The results for all age groups are nearly identical (see Sections 3.5.1 and E.3.2.3). This analysis shows how many simulated individuals have chronic HIs above 1 for development activities in sequence at 5-acre well pads.

The averaging over time of drilling, fracking, and flowback exposures at the Garfield County sites creates lower chronic HQs and HIs relative to only the flowback exposures. This can be seen in comparing the frequencies of neurotoxicity HIs above 1 during flowback alone (Figure

5-28 in Section 5.3.3) to those during all development activities in sequence (Figure 5-51 below). Table E-51 shows the percentage of individuals with HI above 1 for all critical-effect groups, including those used to create this graph (see Table E-49 for HQs).

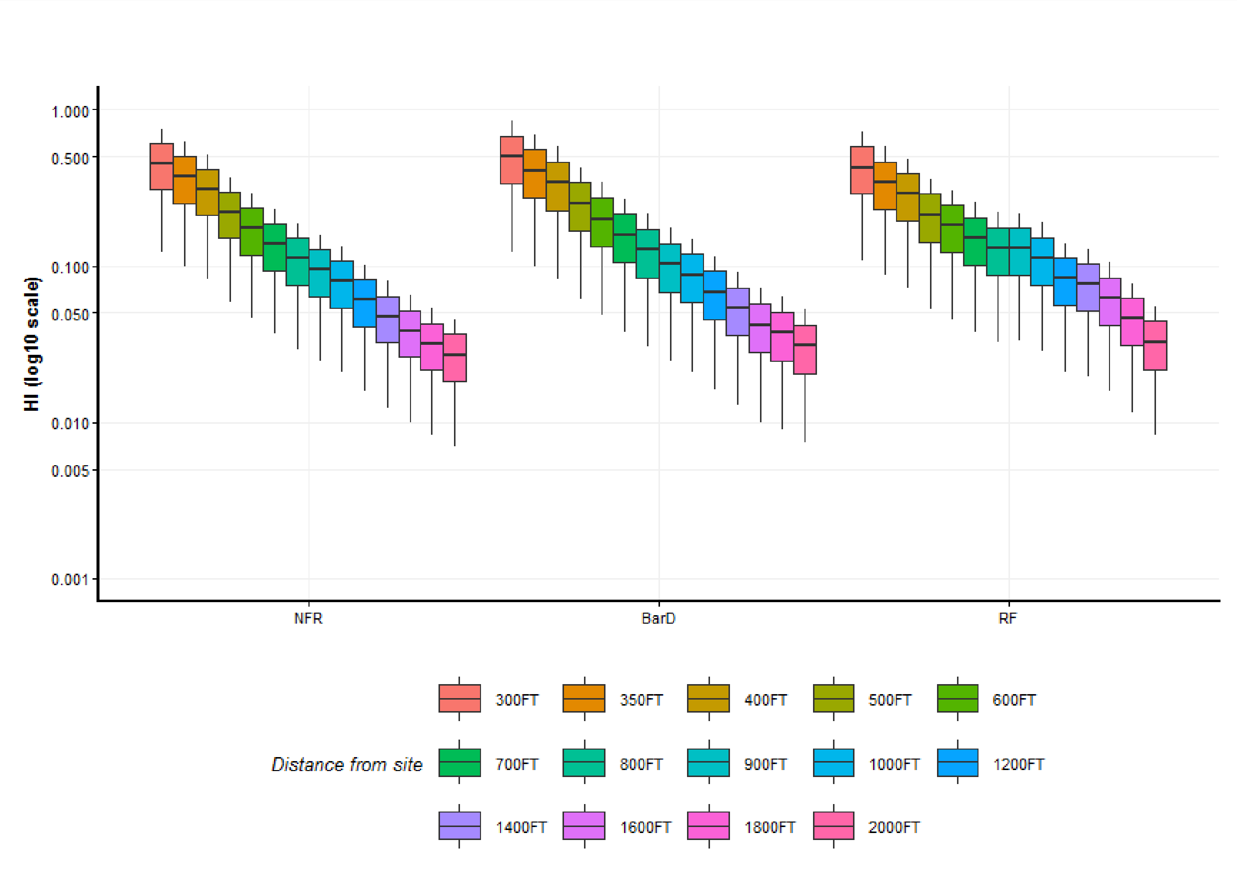


Notes: X-axis is not to scale. The data in this graph refer to the percentage of hazard indices (across all modeled individuals) greater than 1. Thick line emphasizes the 500-foot distance. Corresponds to ages 17 and younger (results for other age groups are nearly identical).

Figure 5-51. Percentage of Chronic Non-cancer Hazard Indices for the Neurotoxicity Critical-effect Group (Across the Hypothetical Population) that are Greater than 1 at Various Distances from the 5-acre Well Pad during Development Activities in Sequence

Figure 5-52 is analogous to Figure 5-49 in the previous subsection, showing distributions of hematological HIs during all activities in sequence, across all modeled individuals. The 25th-to-75th-percentile ranges of chronic HIs for hematological at the 500-ft distance were 0.16–0.34, 0.14–0.29, and 0.15–0.3 at the Garfield County ridge-top, Garfield County valley, and NFR sites, respectively (compared with 0.15–0.32, 0.13–0.27, and 0.13–0.26 with all activities in sequence where development occurs on a 3-acre well pad). These were lower than the absolute maximum values at the same distance: 0.43, 0.36, and 0.37, respectively. The median hematological HIs during all activities in sequence were 0.25, 0.21, and 0.22 at 500 ft from the three sites respectively, which were a factor of 1.7 lower than the absolute maximum values at the same distance. For the scenario which had the highest HIs at the 500-ft distance (hematological HIs at the Garfield County ridge-top site), Figure 5-52 shows that approximately

9 percent of all chronic HIs at the 500-ft distance were below 0.1 (13 percent for the valley site, 11 percent for the NFR site).



Notes: The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Each box-whisker plot indicates the maximum and 1st percentile (top and bottom whiskers), 75th and 25th percentiles (top and bottom of box), and 50th percentile (bar inside box). Corresponds to ages 17 and younger (results for other age groups are nearly identical).

log10 = logarithm base 10; HI = hazard index; FT = feet; NFR = Northern Front Range; BarD = Garfield County ridge-top site; RF = Garfield County valley site (Rifle).

Figure 5-52. Distributions of Chronic Non-cancer Hazard Indices for the Hematological Critical-effect Group (Across the Hypothetical Population) at Various Distances from the 5-acre Development Well Pad/1-acre Production Pad during All Activities in Sequence

5.5.3. Chronic Cancer Risks

We assessed incremental lifetime cancer risks for exposure to the VOC for which strong evidence of carcinogenicity was available (benzene; Section 4.3).[13] As discussed in Section 4.3, we focused our cancer assessment on O&G activities or sequences of activities lasting more than several years—the 30-year production activity (discussed earlier in Section 5.4.3), and the 30–32-year sequences of development and production activities (discussed here).

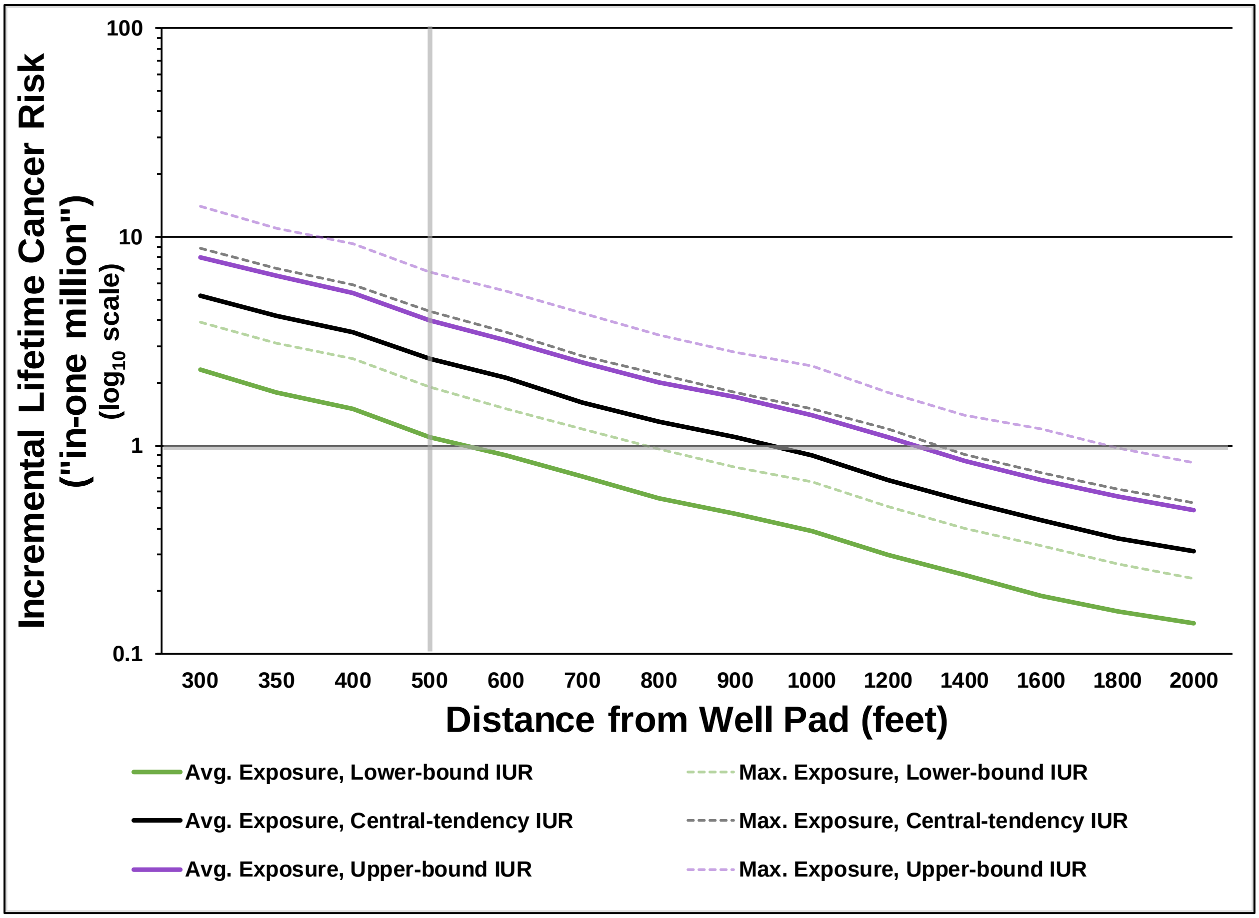
As discussed below, **simulated cancer risks to the average simulated individuals were below 1-in-one million by 1,800 ft from the well pads** at all sites and with all sizes of development pads (by 2,000 ft for the maximum-exposed individuals). Risks to average individuals were below 10-in-one million at all modeled distances 300–2,000 ft from the pads (at 500+ ft for the maximum-exposed individuals). **At the 500-ft distance, risks to average individuals were 5-in-one million or less (8-in-one million or less for the maximum-exposed individuals).** These risk metrics for all activities in sequence are generally slightly larger than those presented in Section 5.4.3 for the production activity alone.

On average, cancer risks from these activities were largest at the Garfield County ridge-top site—between about 10- and 15-percent larger than the risks at the valley site. In the scenarios with 1- and 3-acre development pads, risks at the valley site tended to be between about 5- and 10-percent larger than risks at the NFR site, though at sites with 5-acre development pads the difference in risks between those two sites narrowed (with values slightly larger at the NFR site). On average, cancer risks tended to be largest at the sites with 5-acre development pads (by an average of 14 percent relative to sites with 3-acre development pads) and smallest at the sites with 1-acre development pads (by an average of about 9 percent relative to sites with 3-acre development pads). This pattern of increasing risk with increasing size of development pad is likely due primarily to longer periods of positive chemical exposure at the larger sites and longer durations of development activities.

In Figure 5-53, Figure 5-54, and Figure 5-55, we plot the incremental lifetime cancer risks associated with benzene exposures at the selected receptors at the Garfield County ridge-top, Garfield County valley, and Northern Front Range sites which have 1-acre development pads. As with the figures in Section 5.4.3, the plots mainly focus on risks to average simulated individuals (the solid lines), but they also include risks to the maximum-exposed simulated individuals (the dashed lines), utilizing the two EPA IURs and the central-tendency between them. In all of these scenarios, simulated risks to all individuals were well below 10-in-one million at the selected downwind 500-ft receptor—between 0.93- and 4-in-one million for the average individual (depending on the IUR) and between 1.6- and 6.8-in-one million for the maximum-exposed individual. All risks for the average individual fell to 1-in-one million or below by 1,400 ft from the well pad utilizing the upper-bound IUR (by 600 ft utilizing the lower-bound IUR). For the maximum-exposed individual, those distances respectively were 2,000 and 800 ft. Risks closer to the well pad were sometimes above 10-in-one million but only for maximum-exposed individuals utilizing the upper-bound IUR (risk up to 14-in-one million at the 300-ft distance; 8-in-one million for the average individual with the same IUR); risks were below 4-in-one million utilizing the lower-bound IUR. All simulated risks were below 10-in-one million by the 400-ft distance.

Figure 5-56, Figure 5-57, and Figure 5-58 are analogous to Figure 5-53, Figure 5-54, and Figure 5-55, but for sites that have 3-acre development well pads. In all of these scenarios, simulated risks to all individuals were well below 10-in-one million at the selected downwind 500-ft receptor—between 1 and 4.4-in-one million the average individual (depending on the IUR; rather than 0.93- and 4-in-one million for locations with 1-acre development pads) and between 1.7- and 7.4-in-one million for the maximum-exposed individual (rather than 1.6- and 6.8-in-one million for locations with 1-acre development pads). All risks for the average individual fell to 1-in-one million or below by 1,600 ft from the well pad utilizing the upper-bound IUR (rather than 1,400 ft for locations with 1-acre development pads; by 600 ft utilizing the lower-bound IUR, same as with locations with 1-acre development pads). For the maximum-exposed individual, those distances respectively were 2,000 and 800 ft (rather than 2,000 ft and 900 ft at locations with 1-acre development pads). Similar to locations with 1-acre development pads, risks closer to the well pad were sometimes above 10-in-one million but only for maximum-exposed individuals utilizing the upper-bound IUR (risk up to 15-in-one million at the 300-ft distance; 8.7-in-one million for the average individual with the same IUR); risks were below 5-in-one million utilizing the lower-bound IUR. All simulated risks were at or below 10-in-one million by the 400-ft distance.

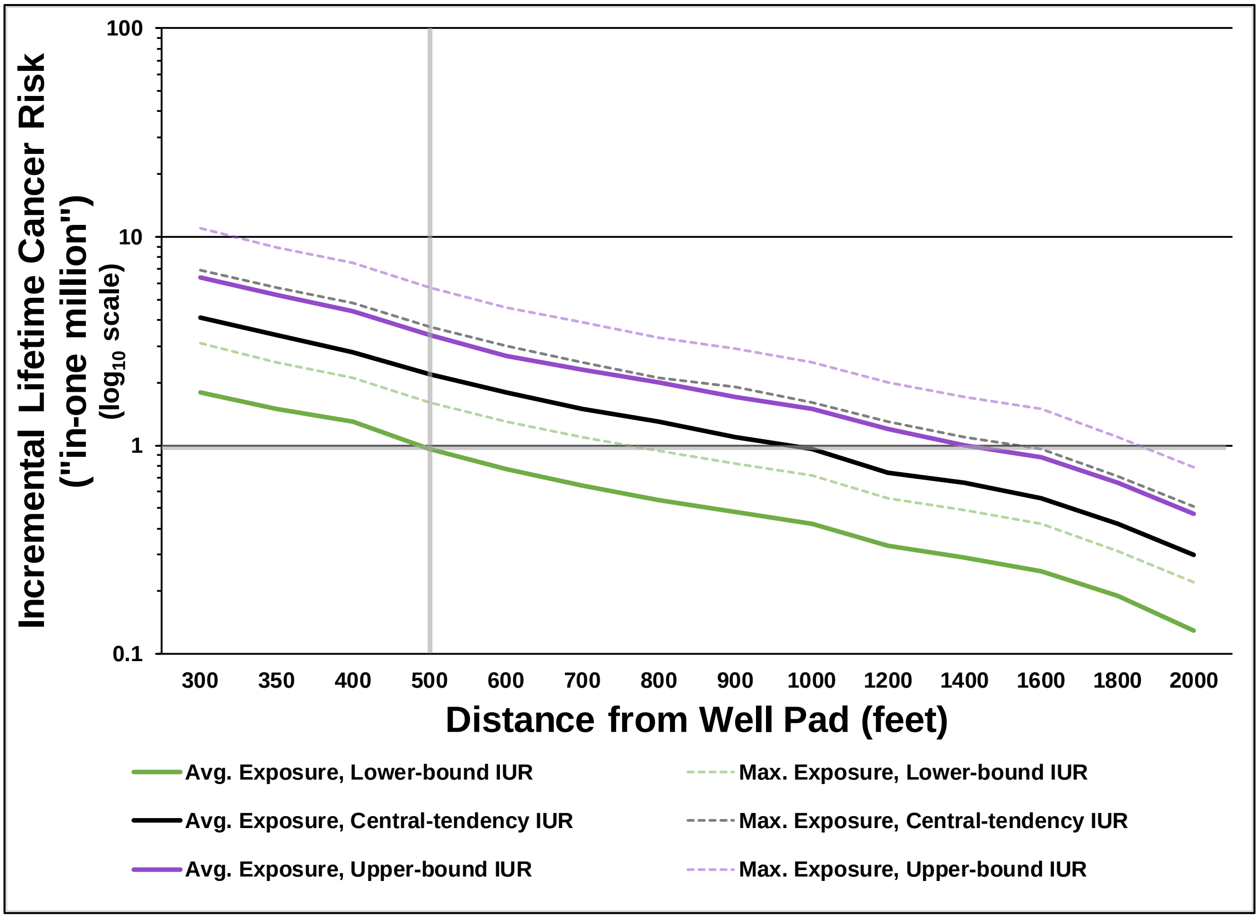
Figure 5-59, Figure 5-60, and Figure 5-61 are analogous to Figure 5-56, Figure 5-57, and Figure 5-58, but for sites that have 5-acre development well pads. In all of these scenarios, simulated risks to all individuals were below 10-in-one million at the selected downwind 500-ft receptor—between 1.1- and 4.8-in-one million the average individual (depending on the IUR; rather than 1 and 4.4-in-one million for locations with 3-acre development pads) and between 1.9- and 8.2-in-one million for the maximum-exposed individual (rather than 1.7- and 7.4-in-one million for locations with 3-acre development pads). All risks for the average individual fell to 1-in-one million or below by 1,800 ft from the well pad utilizing the upper-bound IUR (rather than 1,600 ft for locations with 3-acre development pads; by 700 ft utilizing the lower-bound IUR, rather than 600 ft at locations with 3-acre development pads). For the maximum-exposed individual, those distances respectively were 2,000 and 1,000 ft (rather than 2,000 ft and 800 ft at locations with 3-acre development pads). Similar to locations with 3-acre development pads, risks closer to the well pad were sometimes above 10-in-one million but only for maximum-exposed individuals utilizing the upper-bound IUR (risk up to 16-in-one million at the 300-ft distance; 9.6-in-one million for the average individual with the same IUR); risks were below 5-in-one million utilizing the lower-bound IUR. All simulated risks were at or below 10-in-one million by the 500-ft distance.



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

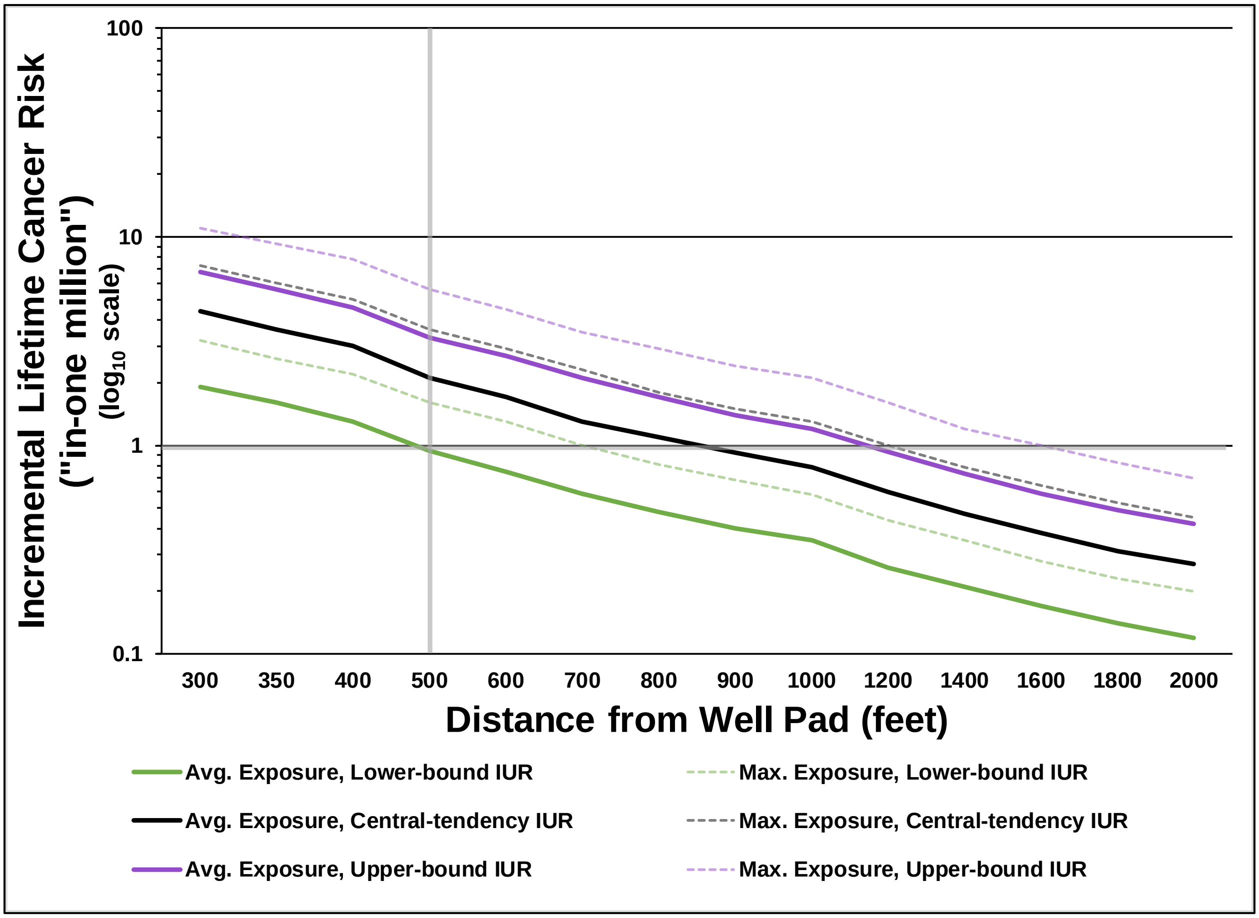
Figure 5-53. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during All Activities in Sequence at the Garfield County Ridge-top Site (1-acre Development Pad/1-acre Production Pad)



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

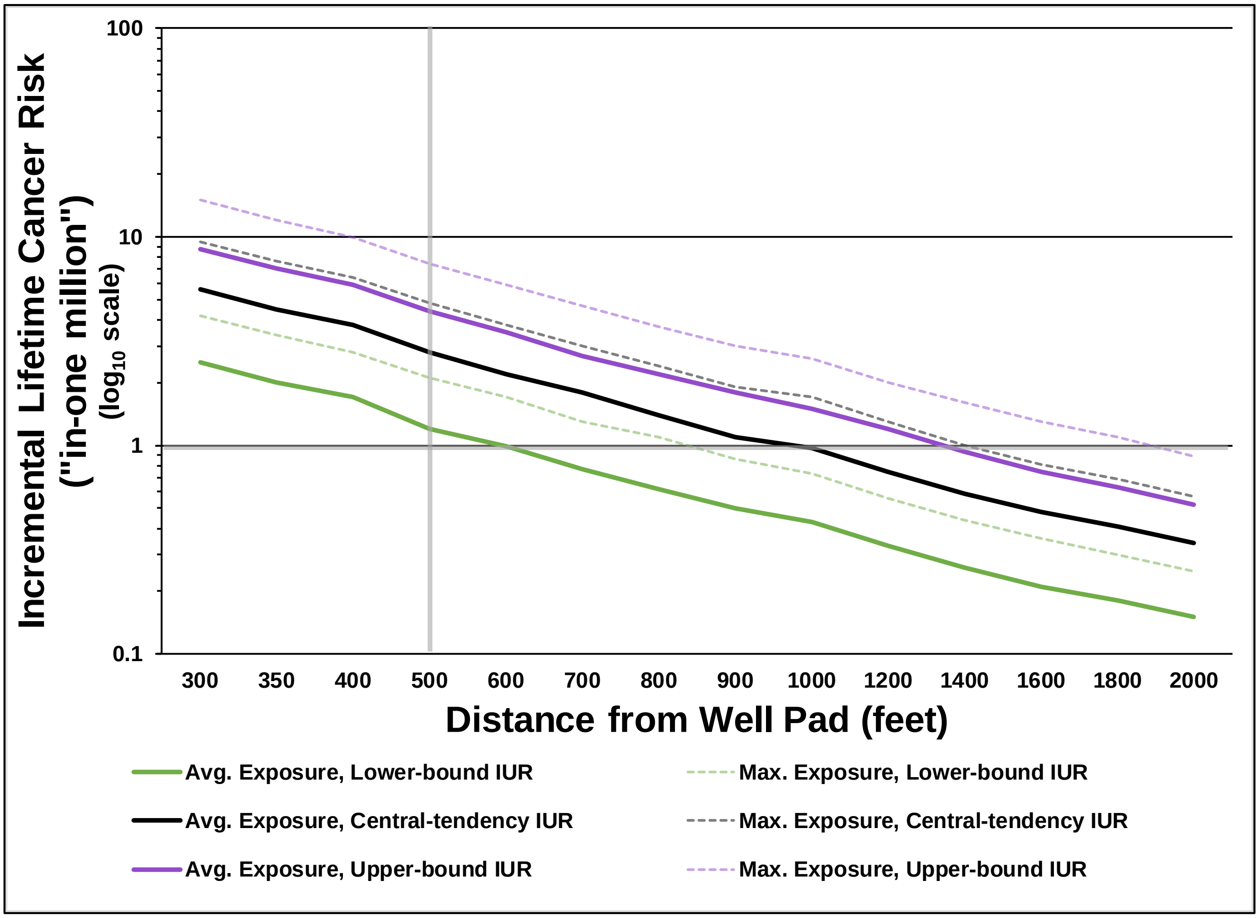
Figure 5-54. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during All Activities in Sequence at the Garfield County Valley Site (1-acre Development Pad/1-acre Production Pad)



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

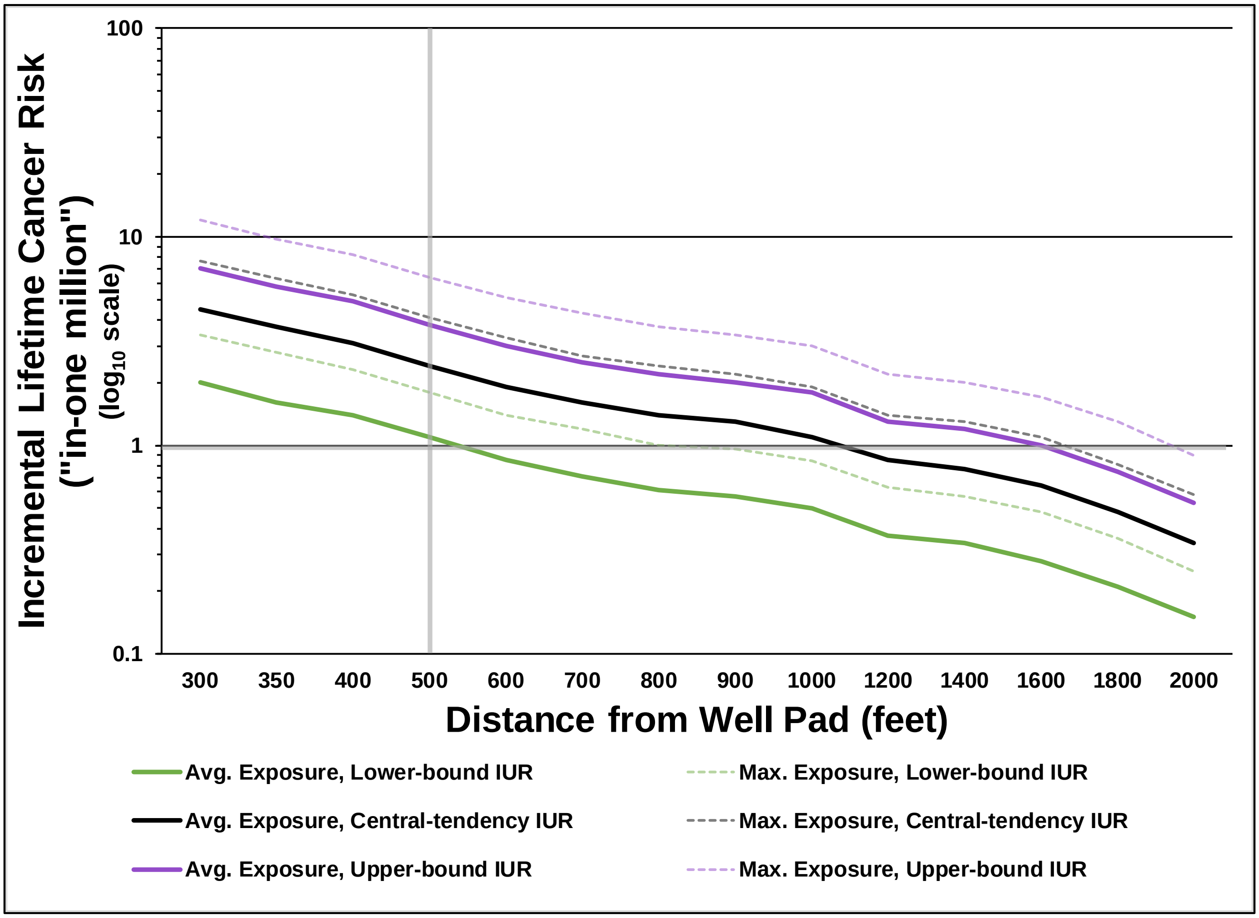
Figure 5-55. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during All Activities in Sequence at the Northern Front Range Site (1-acre Development Pad/1-acre Production Pad)



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

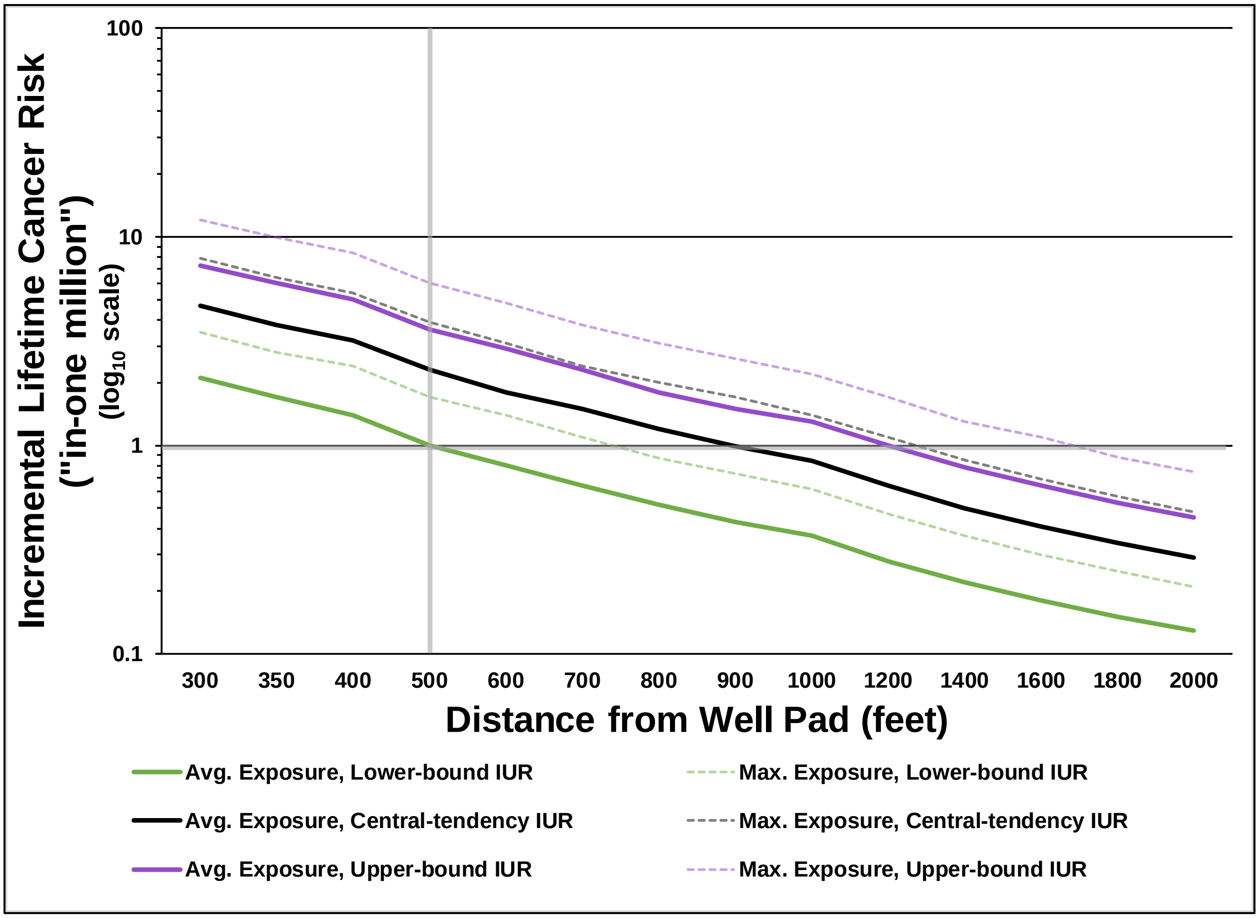
Figure 5-56. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during All Activities in Sequence at the Garfield County Ridge-top Site (3-acre Development Pad/1-acre Production Pad)



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

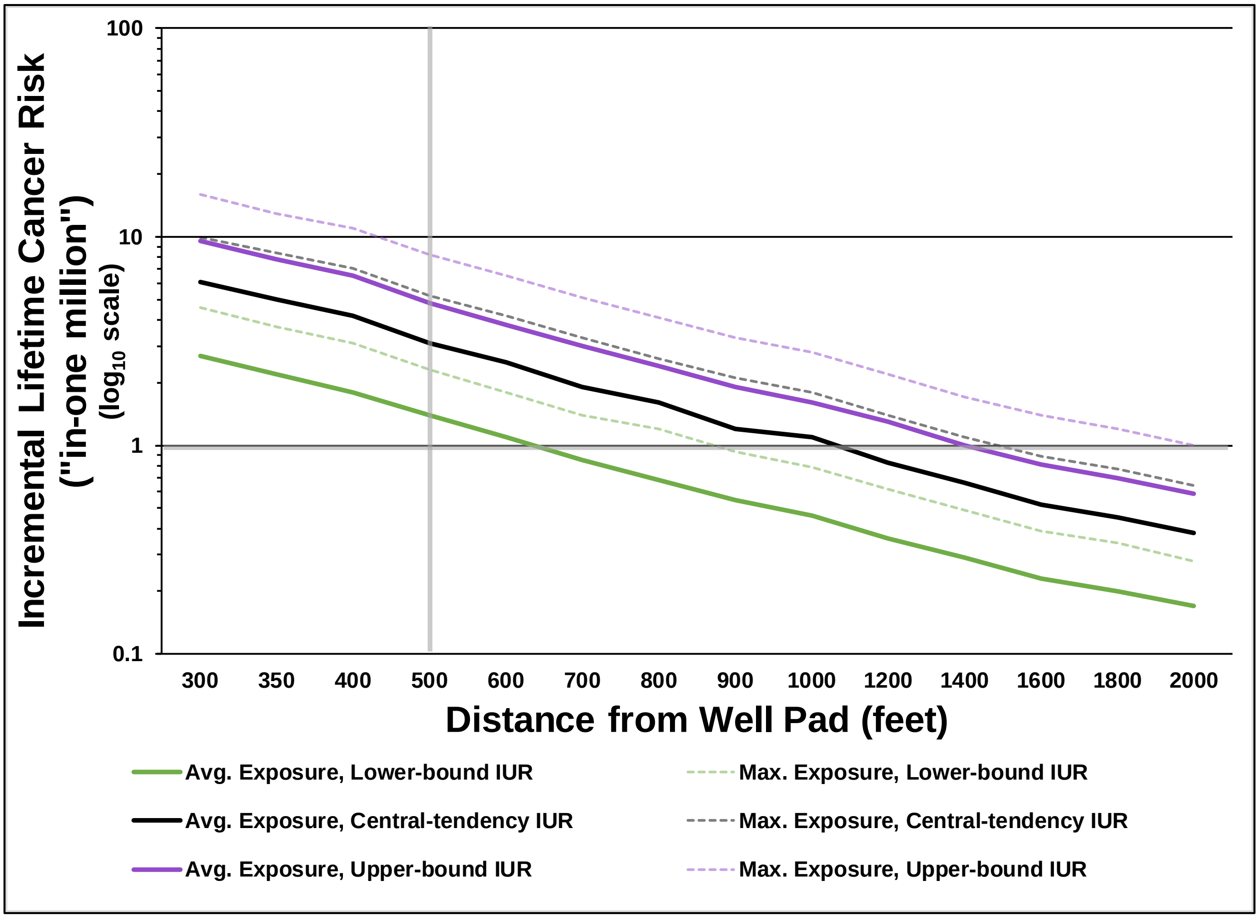
Figure 5-57. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during All Activities in Sequence at the Garfield County Valley Site (3-acre Development Pad/1-acre Production Pad)



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

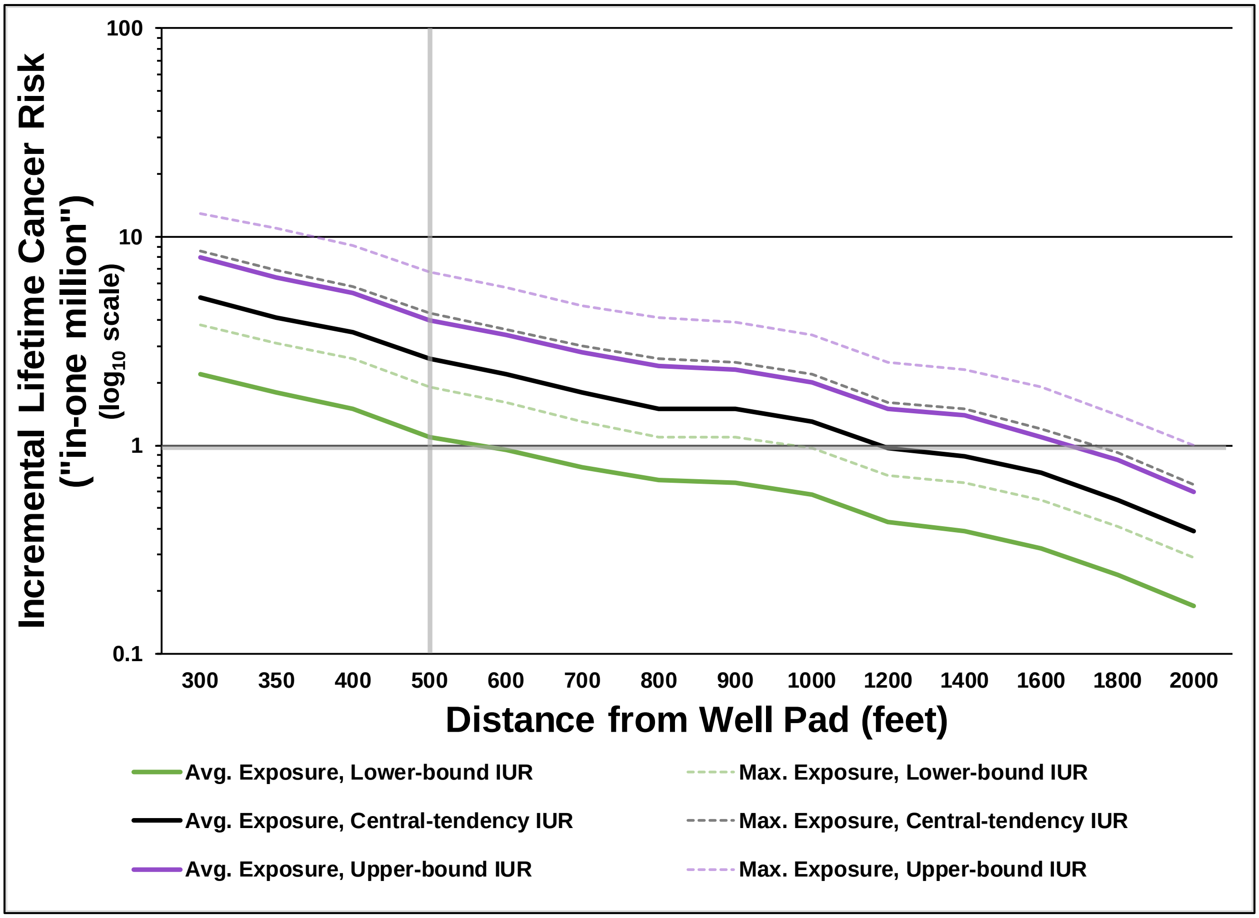
Figure 5-58. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during All Activities in Sequence at the Northern Front Range Site (3-acre Development Pad/1-acre Production Pad)



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

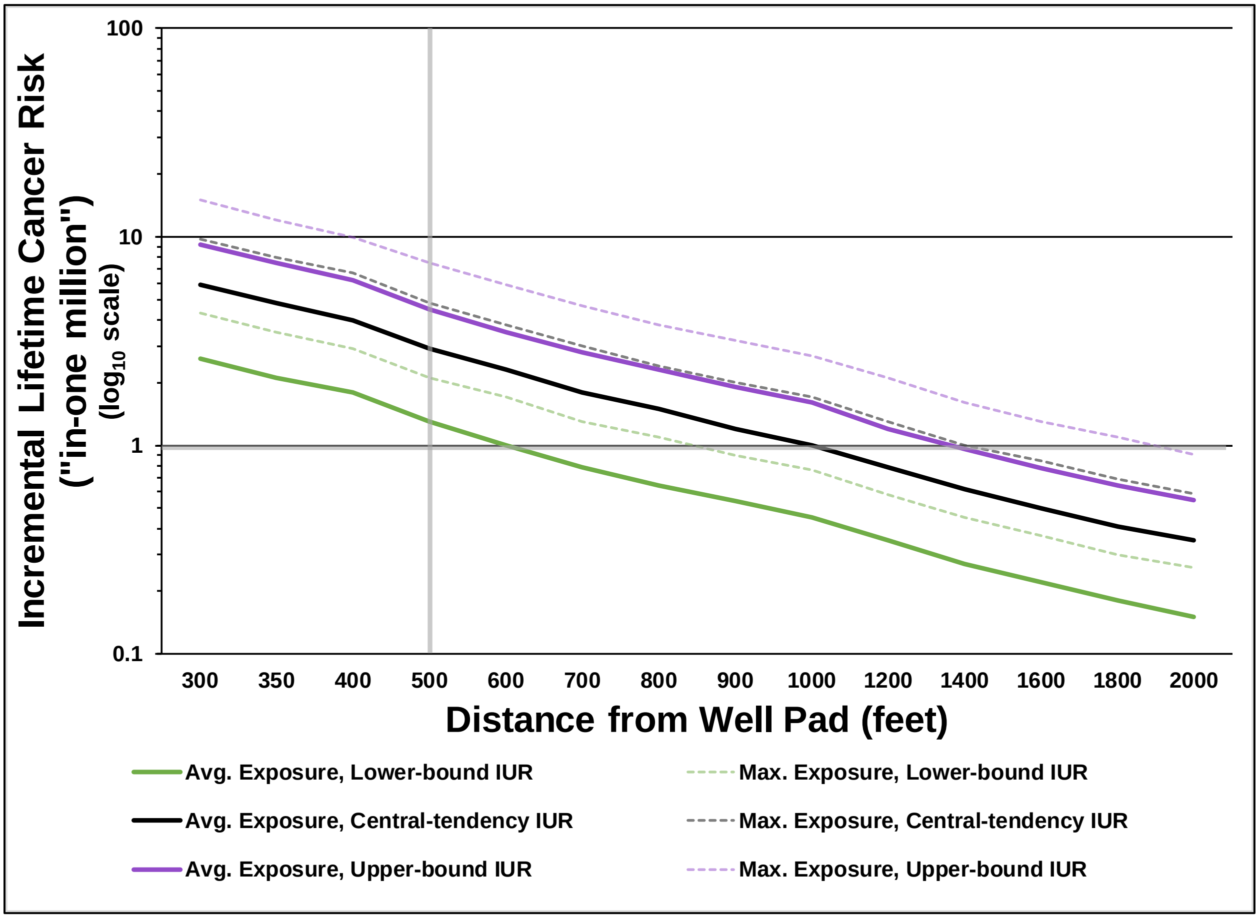
Figure 5-59. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during All Activities in Sequence at the Garfield County Ridge-top Site (5-acre Development Pad/1-acre Production Pad)



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to 1×10^{-6} ("1-in-one million"), so that a plotted value of 10 equals 10×10^{-6} (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

Figure 5-60. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during All Activities in Sequence at the Garfield County Valley Site (5-acre Development Pad/1-acre Production Pad)



Notes: X-axis is not to scale. The y-axis is in logarithm base 10 scale while the values plotted are not transformed. Risks are shown normalized to $1x10^{-6}$ ("1-in-one million"), so that a plotted value of 10 equals $10x10^{-6}$ (10-in-one million). Values refer to the average- and maximum-exposed adult individuals at each distance (exposure to emissions during ages 18–59 years; results for exposure during younger or older ages are nearly identical). Thick lines emphasize the 500-foot distance and the 1-in-one million risk level.

log10 = logarithm base 10; Avg. = average; Max. = maximum; IUR = inhalation unit risk.

Figure 5-61. Incremental Lifetime Cancer Risks from Benzene Exposure for Average- and Maximum-exposed Hypothetical Individuals at Various Distances from the Well Pad during All Activities in Sequence at the Northern Front Range Site (5-acre Development Pad/1-acre Production Pad)

5.6. Impact on Estimates of Hazards and Risks from the Derivation and Selection of Health Criteria: Data Gaps, Uncertainties, Variabilities, and Sensitivities

For the reasons discussed below, **HQ and HI values of 1.0 should not be interpreted as "bright lines" above which adverse effects will occur and below which they will not**. Nor do HQ and HI values provide numerical estimates of the probability or severity of potential risks.

The justification for use of HQs as indicators of non-cancer risk includes a large body of observational data and good mechanistic reasons to believe that such adverse effects are almost always “threshold” in nature. That is, below a given dose, no measureable health effects will occur. However, it is recognized that **sensitivity to certain chemicals or adverse effects can vary substantially in the general population**. **This variability is taken into account in the procedures used to derive health criteria**. UFs and other procedures are used to assure that EPA RfCs, ATSDR MRLs, and similar state health guidelines are health-protective even for sensitive groups (children, pregnant women, the elderly, and individuals with pre-existing health conditions). For example, EPA indicates that the level of uncertainty associated with their well-documented non-cancer RfC values is “perhaps an order of magnitude” (EPA, 2018). In the absence of data, individual UF values are customarily set at 10 or the square root of 10 for each source of uncertainty, so they only approximately account for potential overall uncertainty in the expected responses to exposure. For a number of VOCs addressed in these HHRAs, particularly in the case of subchronic and acute exposures, the data supporting health criteria values are quite limited, and the associated degree of uncertainty for subchronic and acute criteria values is almost certainly higher than that for chronic criteria values. Indeed, agencies’ usage of UFs (discussed in Section 4.4) reflect these high degrees of uncertainty, in particular for differences in effects between different subpopulations. In practice, inhalation health guidelines are usually set at concentrations 100–1,000 times lower than the lowest concentrations at which adverse effects are observed in the most sensitive animal species, or 10–300 times lower than the exposures where adverse effects are seen in humans (so, erring on the side of health protection). The intent is to build in an adequate “**margin of safety**,” and more UFs are included when the data sets are more limited. For these reasons, HQ values near 1.0 should be interpreted cautiously. HQ values less than 1.0 generally provide a high degree of health protection. We have assumed that these degrees of health protection apply adequately to all identifiable sensitive populations (characterized by age, gender, or common pre-existing conditions).

As discussed in Sections 4.1.1 and 4.3, different agencies have sometimes derived different health-protective criteria values for the same chemical. Differences arise from professional judgements related to the identity of the “critical” effect (the adverse effect seen at lowest exposures), the most reliable study, the exact exposure levels at which effects first occur, how to extrapolate animal exposures to humans, and how to estimate effects at different exposure durations. Criteria promulgated by different agencies also may vary because they are intended for different purposes, to protect different populations in different situations. We utilized a system that generally preferred values that were the best-documented, based on the most recent studies, and derived in such a way as to be health-protective of sensitive subpopulations. For most VOCs, there is general agreement regarding the general magnitude of chronic hazards, and the differences in criteria values are moderate (an order of magnitude or less). There tends to be somewhat less agreement with regard to acute and subchronic hazards. In the case of acute effects, data are often limited to occupational studies, and questions arise with regard to which effects are “critical” and how best to protect sensitive populations. A major source of uncertainty in the derivation of subchronic criteria is how best to account for variations in effect as a function of exposure duration; “subchronic” covers a broad range of exposure durations (in these HHRAs, 24 hours to 365 days) and assumptions related to corrections for duration may lead to large uncertainty.

Depending on the exposure duration, different agencies accounted for different proportions of the selected criteria values. We selected chronic RfCs or MRLs from federal agencies (EPA and ATSDR, respectively) for only 12 of the VOCs assessed in these HHRAs, plus EPA PPRTVs for five VOCs. On the other hand, we selected TCEQ-issued chronic ReVs for 20 of the assessed

VOCs, plus TCEQ ESLs for seven VOCs. In contrast, all of the selected subchronic criteria values were promulgated by EPA (3 RfCs and 29 PPRTVs). The bulk of the selected acute criteria were issued by TCEQ (32 ReVs [one proposed] and 10 interim ESLs).

As shown in Table 4-1, we were not able to identify adequately-documented criteria values for a number of chemicals and exposure durations (2 chronic, 16 subchronic, and 3 acute values). **We were unable to calculate HQs for these chemicals and exposure durations, and they could not be included in HI calculations, leading to an underestimation of health hazards that cannot be reasonably quantified**.

Varying levels of evidence exist regarding the potential cancer-causing potential of several chemicals included in these HHRAs. For example, the International Agency for Research on Cancer (IARC, 1982) has concluded that there is "sufficient evidence" for the human carcinogenicity of benzene, and EPA has promulgated an IUR value for estimating human cancer risks from benzene exposure (EPA, 1998). The IUR value is based on data from epidemiological studies. IARC (2000) also classified ethylbenzene as “possibly carcinogenic to humans”, and the National Toxicity Program (NTP 2016) has indicated that both styrene and isoprene are “reasonably anticipated to be a human carcinogen.” In all three of these cases, however, the quantitative data regarding carcinogenicity come exclusively from animal studies, and information from epidemiological studies is limited or ambiguous. No federal agency has issued quantitative health criteria (IURs) for carcinogenic risks for any of the three chemicals, and, given the large uncertainties associated with the use of unit risk values derived solely from the currently available data, no quantitative cancer risks estimates have been derived for these chemicals.

In evaluating the “sensitivity” of the non-cancer risk estimates to the selection of specific health criteria derived by the agencies, probably the most important consideration is the relatively high levels of conservatism (health protection) that are built into the derivation process. Experience suggests that criteria are highly likely to be protective with a reasonable margin of safety. Thus, **small disagreements between agencies, or small changes in health criteria values, are not likely to have major impacts on conclusions regarding estimates of public health impacts**. In practice (see Appendix B), we found that for chemicals where more than one agency had issued health criteria, **the differences between a chemical’s criteria values tended to be relatively small (almost always less than the order-of-magnitude uncertainty already considered in deriving the criteria)**. Also, even large differences in health criteria for a given chemical are not so important if the estimated exposure levels in the HHRAs are always far below the lowest criteria values. Thus, a key issue is whether use of alternative health criteria values could change HQ values to increase or decrease the level of concern for non-cancer effects. **Credible uncertainty in numerical criteria values will almost certainly not change the basic risk conclusions for chemicals with HQs far above 1.0 (e.g., greater than 10) or far below 1.0 (e.g., less than 0.1).**

For example, as discussed earlier in Section 5, for maximum acute exposures in these HHRAs, we estimated HQs far above 1.0 (above 10) for two chemicals at the 500-ft distance from well pads: benzene (20) and 2-ethyltoluene (13) during O&G development activities. As discussed in Appendix C, OEHHA and TCEQ have issued acute health criteria for benzene that differ by more than a factor of 20 (8 versus 180 ppb, respectively). After a review of the available data, we chose to employ an acute criterion of 30 ppb. Even using the higher (less-stringent) TCEQ value, however, the maximum acute HQ value for benzene would still be greater than 1.0.

Similarly, the HQ for 2-ethyltoluene was based on an interim TCEQ ESL; even if they promulgated a more refined ReV based on the same data, it would only be approximately three-fold higher (less stringent), and the resulting HQ for 2-ethyltoluene would likewise still be greater than 1.0. If we used less stringent criterion values to calculate HQs for these chemicals, however, the frequency of HQs above 1.0 might be lower, and the maximum distance from the well pad emissions at which HQ values were above 1.0 might be reduced for some activities and locations. Otherwise, maximum acute HQs for other chemicals were above 1.0, but closer to 1.0 than to 10.

In contrast, for maximum subchronic exposures, we estimated that HQs were close to 1.0 or far less. The highest subchronic HQ at the 500-ft distance was for m+p-xylenes (1.0), n-nonane (0.59), and benzene (0.53). For all three chemicals, small changes in how criteria were derived would not have resulted in HQs far above or below 1. For example, we calculated the HQ for xylenes based on the EPA subchronic PPRTV of 91 ppb; had we used the ATSDR intermediate MRL (600 ppb), the HQ would have been about six-fold lower (but still above 0.1). As another example, the benzene HQ would have been above 1.0 (but well below 10) if we had utilized the four-fold more stringent ATSDR MRL (6 ppb) rather than the EPA PPRTV (25 ppb).

Finally, for chronic exposures during O&G production, we estimated that HQs were close to 1.0 or far less. The chronic benzene HQ, for example, was 0.25 for the most exposed hypothetical individual at the 500-ft distance during production activities, based on the ATSDR MRL of 3 ppb. That value would have been three-fold higher (but still between 0.1 and 1) if we had selected the more stringent OEHHA chronic criterion (1 ppb), with HQs somewhat above 1.0 for additional hypothetical individuals at closer distances to the well pad. The chronic benzene HQ would have been approximately 28-fold lower (below 0.1) if we had selected the less stringent non-cancer TCEQ ReV (86 ppb). This is the largest difference in HQ value associated with criteria choice for chronic exposure to any VOC. On the other hand, at the 500-ft distance, the maximum estimated chronic HQ for toluene during production activities was about 0.003 based on our selection of the EPA RfC (1,328 ppb); the HQ would have remained below 0.1 had we used the 17-fold more stringent OEHHA REL (80 ppb).

As shown in the highlighted cells of Table 5-31, for all three exposure durations (acute, subchronic, and chronic) there are a number of chemicals whose highest HQs fall into the “grey area” range between 0.1 and 10 (shown for individual O&G activities on a 1-acre well pad). It is difficult to generalize about the potential effect of criteria selection on the HQs and HIs associated with this group of chemicals. However, all of the HQs between 1.0 and 10 are closer to 1.0 than to 10.0, and HQs between 0.1 and 1.0 tend to be closer to 0.1 than to 1.0. Thus, **shifts in criteria values are more likely to result in calculated HQs dropping below 1.0 rather than increasing above 10.0, or dropping below 0.1 rather than increasing above 1.0**.

Table 5-31. Evaluated Chemicals with Maximum Hazard Quotients near 1.0 during Simulations of Individual Oil and Gas Activities on 1-acre Well Pads

Chemical	Highest Hazard Quotient at 500 Feet			Criteria Derived for Neurotoxicity Effects?
	Acute	Subchronic	Chronic	
benzene	>10	0.53	0.25	no
toluene	2.4	0.11	<0.1	yes
3-ethyltoluene	1.4	<0.1	<0.1	no
m+p-xylene	1	1	<0.1	yes
4-ethyltoluene	0.91	<0.1	<0.1	no
n-decane	0.86	N/A	<0.1	no
n-propylbenzene	0.82	<0.1	<0.1	no
1,3-diethylbenzene	0.7	<0.1	<0.1	no
cyclohexane	0.58	<0.1	<0.1	yes
isopropylbenzene	0.54	<0.1	<0.1	no
1,2,3-trimethylbenzene	0.27	0.13	<0.1	yes
methylcyclohexane	0.27	<0.1	<0.1	yes
1,2,4-trimethylbenzene	0.26	0.23	<0.1	yes
n-hexane	0.26	<0.1	<0.1	yes
1,3,5-trimethylbenzene	0.26	0.19	<0.1	yes
trans-2-butene	0.2	N/A	<0.1	no
o-xylene	0.19	<0.1	<0.1	yes
n-octane	0.19	<0.1	<0.1	yes
n-nonane	0.16	0.59	<0.1	yes
styrene	0.15	N/A	<0.1	yes
2-methylheptane	0.11	<0.1	<0.1	yes

Notes: Highlighted cells indicate maximum hazard quotients between 0.1 and 10.
N/A = hazard quotient not calculated because we could not identify an appropriate health-criteria value.

In reviewing the available toxicity criteria for the 28 chemicals in Table 5-31, we have not identified any specific chemicals or groups of chemicals for which the criteria are particularly problematic, or for which numerical values are likely to be particularly uncertain. In these HHRAs, HIs for neurotoxicity effects may be the most susceptible (among all critical-effect groups) to differences in VOC criteria values. This is based on the fact that the selected criteria values for 27 (more than half) of the assessed VOCs were derived for neurotoxic effects at one or more exposure durations; 13 of these are in Table 5-31 (see last column). However, based on the patterns of estimated exposure and the span of credible criteria values, we expect that the use of alternative criteria would be unlikely to affect the HIs for neurotoxicity (or other effects) by a factor of as much as two-fold.

As for HIs, **the aggregation of individual VOC HQs into HIs for critical-effects groups is associated with a number of uncertainties**, as discussed in Section 4.2. Different agencies may identify different critical studies and effects, and data related to other effects near the critical exposures may be limited. Also, there is substantial uncertainty in assuming that all chemicals in a critical-effect group act cumulatively through the same or similar mechanisms, and in assuming no interactions (either positive [greater-than-additive] or negative [less-than-additive]) between the health effects of the different chemicals. In addition, we assume exposures to the multiple chemicals are simultaneous and continuous across the exposure period; however, the exposure-simulation approach used in these HHRAs does not specifically incorporate correlations in exposure to different VOCs over time.

As we discussed earlier in Section 5 regarding the incremental lifetime cancer risk for benzene, available IUR estimates (from EPA, TCEQ, and OEHHA) range over a factor of approximately four. We selected EPA's range of IURs from $2.2x10^{-6}$ to $7.8x10^{-6}$ $\mu g/m^3$, plus the central-tendency midpoint between those two values. **There does not appear to be any firm basis for selecting one IUR value over the other, and the span of the EPA range is considerably smaller than the uncertainty associated with release and exposure estimates**. Using one of these EPA IURs versus another does not make a substantive difference in the conclusion regarding estimated benzene cancer risks, which all fell between just below 1-in-one million to just below 10-in-one million at the 500-ft distance, depending on the site, activity, and whether the individual experienced average exposure or maximum exposure according to the modeling.

There is uncertainty in our assumption that exposure to carcinogens is equally weighted across an individual's stages of life in calculating the risk for cancer. However, the impact of unequal weighting is likely to be much smaller than the other uncertainties already part of these HHRAs, and the agencies have not found sufficient evidence of carcinogenic modes of action for the two assessed carcinogens in these HHRAs. Another source of uncertainty is the assumption of low-dose linearity that we applied for both chemicals. Low-dose linearity is a "default" assumption applied in the absence of information related to low-dose mechanism, and it is generally considered to be conservative. That is, risks are unlikely to be greater than the estimated value and could be far less.

Besides the aliphatic and aromatic hydrocarbons specifically measured by CSU (2016a, 2016b) and utilized in these HHRAs, **a previous CDPHE study of O&G operations (CDPHE, 2017) identified additional compounds which have been detected in the vicinity of O&G operations in Colorado**, particularly aldehydes and alcohols but also ketones, sulfur-containing compounds, and heterocyclic compounds. In these HHRAs, we do not quantitatively assess emissions, air concentrations, exposures, and hazards/risks for these additional compounds not measured in the CSU studies. Among the compounds assessed in the CDPHE (2017) interim assessment, estimated hazards were quite low for some of the compounds that are not included in these HHRAs (e.g., methanol, acetone), while formaldehyde and acetaldehyde (also not included in these HHRAs) accounted for the highest non-cancer HQs (which were well below 1.0) and had estimated lifetime cancer risks between 1- and 100-in-one million. The cancer risk estimated by CDPHE for formaldehyde was similar to that of benzene (which we included in these HHRAs).

6. Summary of Data Gaps, Uncertainties, Variabilities, and Sensitivities across the HHRAs

With respect to the input parameters we used and the modeling methodology we employed throughout the HHRAs, we made a number of choices or assumptions that must be accounted for in order to correctly interpret the numerical risk estimates. Two aspects of the modeling need to be understood, and they are

1. the overall "uncertainty" of the results, which may include contributions from both known data gaps/uncertainty/variability in the modeling and unknown factors which affect the accuracy of risk results, and

2. the potential for under- or over-estimation of health risks.

In some parts of the analysis, we used methods that are known, based on past experience, to be “conservative”—that is, they tend to produce exposure or risk estimates that are higher than “central-tendency” values might be. A good example is in the toxicological evaluation of VOCs, where UFs are applied where data are equivocal, to provide a high degree of assurance that HQ and HI values are health-protective. Some parts of the modeling, in contrast, do not have much built-in conservatism but are associated with a high degree of uncertainty. An example is the estimation of VOC emissions: owing to the relatively small number of data points for each chemical, the ranges of estimated emissions in any given hour can be very large.

In the previous sections of this document (Sections 2.10, 3.6, and 5.6), we have discussed these data gaps, uncertainties, variabilities, and sensitivities in detail. The two tables we present below serve as summaries of these sections, focusing on the key parameters and methods, along with the qualitative estimates of their potential influence on the simulated risks. We use the definitions below for these qualitative estimates of potential influence.

- High: at least a half an order of magnitude (about three-fold or more) of potential influence
- Medium: about a two-fold to half an order of magnitude of potential influence
- Low: no more than about a two-fold potential influence

These estimates should be interpreted with caution since the numerical ranges of the low, medium, and high categories are somewhat arbitrary. In some cases, the “High” category of uncertainty can be much greater than three-fold, and uncertainty tends to be higher in the case of acute exposures because of both the large variability in hourly emissions and the limited nature of the data sets supporting the health criteria. Factors affecting the magnitude and uncertainty of risk estimates include both “known unknowns” and “unknown unknowns”— these correspond roughly to “sensitivity” and “uncertainty,” respectively, as discussed below.

In Table 6-1, we give a qualitative estimate of the influence on the simulated health risk estimates in these HHRAs from various data gaps, uncertainties, and variabilities in the input data and methodologies. We have used color-coding for ease of readability, purples and reds corresponding to higher potential influence and oranges and yellows corresponding to lower potential influence on health risks. It is important to understand that the influence of the identified factors is generally not the same for estimated acute, subchronic, and chronic health risks. As noted above, we expect the numerical uncertainty in acute HIs and HQs to be considerably greater than for the subchronic and chronic time periods, because of both the conservative modeling methods (e.g., using maximum hourly exposures) and the greater uncertainty associated with the choice of acute health-criteria values.

In Table 6-2, we give a summary of the qualitative estimates of the sensitivity of simulated health risks to various input parameters used in the HHRAs, as well as whether these parameter choices are more likely to lead to over- or under-estimates of risks and hazards.

Table 6-1. Qualitative Summary of the Potential Influence on Simulated Risks from Data Gaps, Uncertainties, and Variabilities in Input Data and Methodologies

Input Data, Method, or Model Used	Description of Data Gap, Uncertainty, or Variability	Qualitative Estimate of the Potential Influence on Simulated Risks	Comment
Emission Rates of the Selected VOCs	• representativeness of the sampled emission rates (limited in number) to real emission rates across O&G operations in Garfield County and the NFR • non-continuous nature of the air sampling	High	
Meteorological Data	• missing key data or calm winds • selected meteorological data sets' representativeness of Garfield County and the NFR • inherent variability in weather conditions across Garfield County and across the NFR	Medium	
Hazard/Risk Estimation Methods	• commonly occurring chemicals excluded from risk characterization (non-hydrocarbons [aldehydes, ketones, alcohols, sulfur- and nitrogen-containing compounds] not sampled) • hourly exposures to multiple VOCs assumed to be uncorrelated (most important for acute HI estimation) • uncertainty associated with health-criteria values (derived from different databases, different "margins of safety") • criteria levels not available for some VOCs and exposure durations (especially subchronic) • assume affect additivity to derive HIs for adverse endpoint groups	Medium to High	Uncertainty is probably higher for acute toxicity criteria, may far exceed three-fold)
AERMOD Model	• handling of low-wind-speed conditions • inability to model the precise location of the emission source(s) on a well pad	Low to Medium	Handling of low winds may overall lean towards over-estimates of risk during low-wind times
PENs	• data gaps and variabilities in the PEN literature, and uncertainty with respect to their derivations and application across groups of VOCs	Low to Medium	
Activity Diaries	• use of hybrid set of activity diaries (for different age groups)	Low	
Commuting	• assuming that school/workplace is located at exactly the same location as the individual's residence	Low	
APEX Model	• calculation of exposures from APEX model inputs	Low	

Notes: NFR = Northern Front Range; VOCs = volatile organic compounds; O&G = oil and gas; PEN = penetration factor; APEX = U.S. EPA Air Pollutants Exposure Model; HI = hazard index; High = at least a half an order of magnitude (about three-fold or more) of potential influence on risk estimates; Medium = about a two-fold to half an order of magnitude of potential influence; Low = no more than about a two-fold potential influence.
Color-coding utilized for ease of readability, with purples and reds corresponding to higher potential influence and oranges and yellows corresponding to lower potential influence.

Table 6-2. Qualitative Summary of the Estimated Sensitivity of Simulated Health Risks to Input Parameters

Area of the HHRAs	Input Parameter	Qualitative Estimate of the Sensitivity of the Simulated Risks	Likely Influence of Current Assumption on estimated Health Risks	Comment
Air Modeling	VOC Emission Rates	High	Under-estimate or over-estimate	Being a multiplicative factor in the risk assessment, these might increase or decrease the estimated risks
Hazard/Risk Estimation	Degree of Protectiveness of Chosen Health-criteria Values	Medium	Over-estimate	The currently available health-criteria values are based on health-protective assumptions and generally provide conservative estimates of risk
Air Modeling	Surface Roughness	Low to Medium	Over-estimate	Currently use a lower surface-roughness value in modeling; an increase in surface roughness will decrease the health risk
Air Modeling	Urbanization	Low to Medium	Over-estimate	Modeled with rural dispersion-modeling setting; with the urban setting, in general, we would find a decrease in air concentrations and health risks
Exposure Modeling	PEN Factors	Low to Medium	Under-estimate or over-estimate	Modeled with broad PEN ranges for groups of VOCs. For any specific VOC, a more specific PEN might increase/decrease PEN, in turn increasing or decreasing health risks
Exposure Modeling	Commuting	Low to Medium	Over-estimate	Modeling did not include commuting. Commuting away from the well pads will reduce risks from well-pad emissions.

Notes: HHRA = human health risk assessment; VOC = volatile organic compound; PEN = penetration factor; High = at least a half an order of magnitude (about three-fold or more) of potential influence on risk estimates; Medium = about a two-fold to half an order of magnitude of potential influence; Low = no more than about a two-fold potential influence.
Color-coding utilized for ease of readability, with purples and reds corresponding to higher potential influence and orange corresponding to lower potential influence.

7. Possible Future Work to Further Refine Estimates of Human Health Risk

Additional, deeper analyses of the data generated in these HHRAs, or newly generated data utilizing a slightly different approach, may further refine the characterizations of potential exposures to O&G emissions. For example, examining the full set of hourly chemical exposures to a higher-impact chemical during a higher-impact scenario (e.g., benzene during flowback) may help better characterize the full distribution of acute HQs, relative to the computationally lighter method utilized in these HHRAs where we focused on the daily-maximum acute HQs. That kind of reexamination of acute HQs may also benefit from incorporating modeled hourly concentrations beyond those utilized in these HHRAs for acute assessment, which were the maximum values per AERMOD Monte Carlo run. Broadening that reexamination to lower-impact receptors would also better characterize the HQs throughout the modeling domain rather than just at those receptors most often downwind from the well pads.

Additionally, as described below, additional air monitoring near O&G sites may further elucidate potential air-quality and exposure impacts from emissions from O&G operations. Depending on the monitoring approach and the goals of a future risk assessment, the additional monitoring could lead to more robust distributions of O&G-attributable emissions, which could be used in probabilistic-type risk assessments like the ones we used in these HHRAs, and/or they could lead to a more site-specific assessment approach that may allow monitor-to-model comparisons/calibrations for validation/refinement of the risk results. The additional monitoring could also collect chemicals other than the VOCs utilized in these HHRAs, such as aldehydes and polycyclic aromatic hydrocarbons that may also originate from some O&G processes. Detailed, real-time monitoring may also lead to better estimates of concurrent exposures to multiple chemicals, especially for acute exposures. Data from the monitoring could be correlated with specific activities at the O&G sites in order to better understand what on-site activities may be producing higher emissions of certain chemicals.

New monitoring could be similar to those conducted by CSU (whose data we utilized in these HHRAs), where new air samples could be taken at carefully selected times and locations near O&G sites, with tracer and background methods allowing the derivation of emission rates. This additional monitoring would increase the number of data points collected for near-site air concentrations and emissions, which, together with the data already collected by CSU, would increase the measurements' representativeness of general O&G operations in the NFR and Garfield County. If the new superset of emissions rates derived from the new and existing measurements had a notably different distribution than the existing rates used in these HHRAs, additional risk modeling could be conducted to reflect the new distributions. Background air measurements could also be useful in a separate assessment of cumulative exposure to O&G sources and other sources at the same time.

A new HHRA could also be conducted on available or newly-conducted continuous air-monitoring experiments, whereby monitors collect a continuous time series of air samples across days, weeks, or longer near one or more O&G sites. If such monitoring were conducted in a way that allows derivation of O&G emission rates, then they could be use in air models such as AERMOD to simulate air concentrations. If meteorology data were collected concurrently, then the air simulations could utilize those data along with the emission rates to model air concentrations and compare them to the measured concentrations (a monitor-to-model comparison). Those on-site meteorological data could also be used to understand the conditions that may lead to higher downwind air concentrations from O&G emissions, and to better attribute the source(s) of the measured chemicals if tracer and background methods are not used to do so. The continuous time series of measured air concentrations could be used directly in an exposure model like APEX to simulate continuous time series of potential population exposures to those chemicals as the hypothetical individuals go about their daily lives. Such APEX runs could utilize hypothetical populations as we did for the HHRAs in this report, or they could utilize data on the populations living near the measurement sites, such as their demographics, residential locations, and distributions of employment locations. Continuous data could allow for a better understanding of “real-world” time patterns of exposure near O&G sites, as opposed to the probabilistic methods utilized in our HHRAs here that focused more on the potential for higher exposures, especially for acute exposures.

As a separate exercise, if monitoring of air concentrations at a range of distances (similar to those modeled in our HHRAs) from the modeled sites is possible, those measured air concentrations can then potentially be used to calibrate the AERMOD-estimated air concentrations. These calibrated air concentrations would be more realistic than purely modeled air concentrations (which are currently based on modeling using the emission rates back-calculated from limited measured air concentrations). These calibrated air concentrations can then be utilized in the APEX exposure modeling to arrive at more realistic exposures and risk estimates. Monitoring near the barriers often erected around development sites might also inform us about the effect they may have on local exposures and inform model calibration.

Personal exposure monitoring is a burgeoning field of study and could be utilized near O&G sites to better estimate individual exposures to O&G-attributable chemicals as people go about their daily lives. Great care must be taken with personal-exposure monitoring to collect the data in such a way that allows source attribution—distinctions between emissions from O&G sources, other non-O&G outdoor sources, indoor sources, etc. With a well-planned personal-monitoring study design (defining specific population demographics, activity patterns, source attribution, etc.), we could get more accurate personal-level data on exposure. Again, this could potentially be used to calibrate our APEX-model-based exposure estimations to arrive at more realistic estimates of exposure and, in turn, risk. Stationary monitors near sensitive receptors (e.g., schools, elder care facilities) could provide continuous air sampling in these important locations and provide better understanding of exposures there.

Monitoring both outside a building or residence and inside would help in deriving chemical PENs specific to the areas near these Colorado O&G sites—specific to the kinds of buildings in the area and the habits of the local population in terms of indoor air circulation systems, patterns of having windows open or closed, etc. These more site-specific PENs may follow different distributions (potentially more narrow and accurate) than those used in our HHRAs (gleaned from literature sources).

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Appendix A. Potentially Relevant Literature Identified for Chemical Penetration Factors

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Appendix B. Health-protective Non-cancer Criteria Values Selected for these HHRAs

Table B-1. Non-cancer Criteria Values

Chemical	Chronic Reference Value		Subchronic Reference Value		Acute Reference Value	
	Value (ppb)	Source[a]	Value (ppb)	Source[a]	Value (ppb)	Source[a]
1,2,3-trimethylbenzene	12	EPA RfC	41	EPA RfC	3000	TCEQ ReV
1,2,4-trimethylbenzene	12	EPA RfC	41	EPA RfC	3000	TCEQ ReV
1,3,5-trimethylbenzene	12	EPA RfC	41	EPA RfC	3000	TCEQ ReV
1,3-diethylbenzene	45	TCEQ ESL	182	EPA PPRTV	450	TCEQ interim ESL
1,4-diethylbenzene	45	TCEQ ESL	182	EPA PPRTV	450	TCEQ interim ESL, surr.
1-butene	2300	TCEQ ReV	NA	NA	27000	TCEQ ReV
1-pentene	560	TCEQ ReV	NA	NA	12000	TCEQ ReV
2,2,4-trimethylpentane	124	EPA PPRTV	5740	EPA PPRTV	4100	TCEQ ReV
2,3,4-trimethylpentane	124	EPA PPRTV	5740	EPA PPRTV	4100	TCEQ ReV
2,3-dimethylpentane	2200	TCEQ ReV	6543	EPA PPRTV	8200	TCEQ ReV
2,4-dimethylpentane	2200	TCEQ ReV	6543	EPA PPRTV	8200	TCEQ ReV
2-ethyltoluene	25	TCEQ ESL	204	EPA PPRTV	250	TCEQ interim ESL, surr.
2-methylheptane	390	TCEQ ReV	5740	EPA PPRTV	4100	TCEQ ReV
2-methylhexane	2200	TCEQ ReV	6543	EPA PPRTV	8200	TCEQ ReV
3-ethyltoluene	25	TCEQ ESL	204	EPA PPRTV	250	TCEQ interim ESL, surr.
3-methylheptane	390	TCEQ ReV	5740	EPA PPRTV	4100	TCEQ ReV
3-methylhexane	2200	TCEQ ReV	6543	EPA PPRTV	8200	TCEQ ReV
4-ethyltoluene	25	TCEQ ESL	204	EPA PPRTV	250	TCEQ interim ESL, surr.
benzene	3	ATSDR MRL	25	EPA PPRTV	30	Literature review
cis-2-butene	690	TCEQ ReV	NA	NA	15000	TCEQ ReV
cis-2-pentene	560	TCEQ ReV	NA	NA	12000	TCEQ ReV
cyclohexane	1744	EPA RfC	5232	EPA PPRTV	1000	TCEQ interim ESL
cyclopentane	202	EPA PPRTV	9348	EPA PPRTV	5900	TCEQ interim ESL
ethane	NA	NA	NA	NA	NA	NA
ethene	5300	TCEQ ReV	NA	NA	500000	TCEQ ReV
ethylbenzene	230	EPA RfC	2074	EPA PPRTV	20000	TCEQ ReV
isobutane	10000	TCEQ ReV	NA	NA	33000	TCEQ ReV
isopentane	8000	TCEQ ReV	9087	EPA PPRTV	68000	TCEQ ReV

Chemical	Chronic Reference Value		Subchronic Reference Value		Acute Reference Value	
	Value (ppb)	Source[a]	Value (ppb)	Source[a]	Value (ppb)	Source[a]
isoprene	140	TCEQ ReV	NA	NA	1400	TCEQ ReV, proposed
isopropyl benzene	81	EPA RfC	204	EPA PPRTV	510	TCEQ interim ESL
m+p-xylene	23	EPA RfC	91	EPA PPRTV	1700	TCEQ ReV
methylcyclohexane	400	TCEQ ESL	6677	EPA PPRTV	4000	TCEQ interim ESL
n-butane	10000	TCEQ ReV	NA	NA	92000	TCEQ ReV
n-decane	190	TCEQ ReV	NA	NA	1000	TCEQ ReV
n-heptane	2200	TCEQ ReV	977	EPA PPRTV	8200	TCEQ ReV
n-hexane	199	EPA RfC	625	EPA PPRTV	5500	TCEQ ReV
n-nonane	3.8	EPA PPRTV	38	EPA PPRTV	3000	TCEQ ReV
n-octane	124	EPA PPRTV	5740	EPA PPRTV	4100	TCEQ ReV
n-pentane	8000	TCEQ ReV	3391	EPA PPRTV	68000	TCEQ ReV
n-propylbenzene	51	TCEQ ESL	204	EPA PPRTV	510	TCEQ interim ESL
o-xylene	23	EPA RfC	92	EPA PPRTV	1700	TCEQ ReV
propane	NA	NA	NA	NA	NA	NA
propene	1744	OEHHA REL	NA	NA	NA	NA
styrene	235	EPA RfC	NA	NA	5100	TCEQ ReV
toluene	1328	EPA RfC	1328	EPA PPRTV	2000	ATSDR MRL
trans-2-butene	690	TCEQ ReV	NA	NA	15000	TCEQ ReV
trans-2-pentene	560	TCEQ ReV	NA	NA	12000	TCEQ ReV

Notes: ppb = parts per billion; RfC = Reference Concentration; MRL = Minimum Risk Level; PPRTV = Provisional Peer-reviewed Toxicity Value; ReV = Reference Value; ESL = Effects Screening Level; REL = Reference Exposure Level; EPA = U.S. Environmental Protection Agency; ATSDR = Agency for Toxic Substances and Disease Registry; TCEQ = Texas Commission on Environmental Quality; OEHHA = California Office of Environmental Health Hazard Assessment; NA = not available; surr. = data for a surrogate compound was used to derive the reference value.

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Appendix C. Recommended Acute Screening-level Criterion for Benzene Exposure

C.1 Introduction

Benzene is a ubiquitously occurring VOC and is one of many contaminants emitted by O&G development and production operations. Over the years, a number of regulatory agencies have proposed health-protective criteria for inhalation exposure to benzene. Unfortunately, the bulk of the human data associated with short-term exposures is not well-suited to establishing acute exposure criteria for the general population. Reasons include

- uncertainty in the measurement of exposure concentrations,
- uncertainty in exposure duration and frequency,
- incomplete evaluation of potential adverse outcomes, and
- limited statistical power associated with small numbers of subjects.

Also, most studies have been conducted in adult populations and provide little information regarding potential effects in more sensitive life stages.

For these reasons, recent efforts to establish protective acute criteria have used animal study results as the basis for their derivation (CalEPA, 2014, TCEQ, 2015). As more evidence became available that the blood-forming (hematopoietic) organs are the “critical” (most sensitive) targets of benzene toxicity, a number studies were conducted to investigate the nature and dose-response relationships for these effects in adult animals, pregnant females, and their offspring. We summarize in Table C-1 the studies that have been evaluated for use in the derivation of health criteria.

These studies focus on identifying low-dose effects on the hematopoietic system, and two studies include experiments on pregnant animals and fetuses exposed *in utero*. Thus, they are more likely to identify “critical” effects occurring during sensitive early life stages. However, none provide definitive information related to acute (1-hour) impacts; all reported effects in animals after exposures of six hours per day for multiple days.

This situation is not unprecedented; health-protective criteria often must be derived from non-ideal data. Standard procedures in such cases include

1. methods for “adjusting” the data from the exposure duration used in the critical study to the relevant exposure duration,
2. conversions to adjust for differences between animal and human doses for a given exposure, and

3. use of UFs based on professional judgement to account for differences between animal and human sensitivity, and variability in sensitivity among humans.

Different agencies have different policies regarding how these adjustments are made, and the approaches depend on factors including the severity of the effect being protected against and the degree of conservatism (risk aversion) that is to be built into the criteria in their intended uses. It is not surprising, therefore, that TCEQ and OEHHA have promulgated criteria which differ considerably, even though they are based on the same group of studies.

TCEQ has promulgated two criteria values for acute (1-hour) exposures to benzene. The TCEQ acute inhalation ReV has been set at **180 ppb** (0.18 ppm) while the acute ESL is set at 54 ppb. The ReV is defined as, "an estimate of an inhalation exposure concentration or oral exposure dose, respectively, for a given duration to the human population (including susceptible subgroups) that is likely to be without an appreciable risk of adverse effects", and TCEQ policy calls for its use in formal risk assessment. An ESL is calculated as 30 percent of the ReV and is used in screening assessments to trigger more in-depth analyses.

In contrast, OEHHA has established an acute REL of **8 ppb** (0.008 ppm) for 1-hour exposures to benzene. The REL is defined, similar to the TCEQ ReV, as, "an exposure that is not likely to cause adverse health effects in a human population, including sensitive subgroups, exposed to that concentration […] for the specified exposure duration on an intermittent basis."

In these HHRAs of O&G operations, we are faced with a decision regarding how to define a 1-hour, acute benzene benchmark with regard to adverse health effects to nearby residents. Given the difference between the TCEQ and OEHHA criteria, CDPHE has elected to review the underlying analyses supporting both values.[14]

In Section C.2, we analyze the TCEQ and OEHHA criteria derivations, specifically the key studies used, adjustments made for exposure duration and dosimetry, adversity of critical effects, and UFs. In Section C.3 we present our judgments on the TCEQ and OEHHA criteria derivations. Section C.4 contains a discussion on a sensitivity analysis we conducted, and Section C.5 contains a summary of this review.

[14] The EPA has also promulgated a 1-hour AEGL for benzene of **5,200 ppb**. We have chosen not to employ that value in these HHRAs because it is intended to protect against "discomfort, irritation, or certain asymptomatic, non-sensory effects…"; that is, it does not consider potential long-term consequences of acute exposures.

Table C-1. Effects of Short-term Benzene Exposure On Blood-forming Tissues in Rodents

Study	Species, Strain, Sex	Exposure Levels (ppm)	Exposure Duration and Frequency	Animals per Treatment Group (N)	Critical Effect	Selected POD for Derivation of Health Criteria	Selected as Basis for Health Criteria
(Rozen et al., 1984)	Adult male C57Bl mice	0, 10.2, 21, 100, 301	6 h/d, 6 d	10	Significantly reduced peripheral lymphocytes, femoral B-CFUs, B-lymphocytes	LOAEL (10.2 ppm)	TCEQ (primary study)
(Keller and Snyder, 1988)	Pregnant Swiss Webster mice	0, 5.1, 9.9, 20.4	6 h/d, gestational days 6-15	10	Peripheral early nucleated RBCs (%) in two-day old male and female neonates	LOAEL (5.1 ppm), significant trend	OEHHA
(Dempster and Snyder, 1991)	Adult male DBA/2J mice	0, 10.3	6 h/d, 5 d	10	Significantly reduced femoral CFU-E colonies, impaired CFU-E expansion	LOAEL (10.2 ppm)	TCEQ (supporting study)
(Corti and Snyder, 1996)	Adult male and female (virgin and pregnant) Swiss Webster mice	0, 10.2	6 h/d, 10 d	10	Significantly altered femoral CFU-E colonies in adult males (decreased), adult females (increased), and fetal or adult males exposed in utero (decreased)	LOAEL (10.2 ppm)	TCEQ (supporting study)

Notes: h = hour, d = day; ppm = parts per million; POD = point of departure; RBC = red blood cell; LOAEL = lowest observed adverse effect level; TCEQ = Texas Commission on Environmental Quality; OEHHA = California Office of Environmental Health Hazard Assessment.

C.2 Technical Analyses of TCEQ and OEHHA Criteria Derivations

After reviewing the supporting documents for the TCEQ and OEHHA criteria (CalEPA, 2014, TCEQ, 2015), we identified the issues discussed in the below subsections.

C.2.1 Selection of Critical and Supporting Studies

TCEQ chose to use data from the Rozen et al. (1984) study (a **10.2-ppm LOAEL** [lowest observed adverse effect level] in adult mice) as the basis for ReV calculation.

OEHHA, in contrast, used data from the Keller and Snyder (1988) study (a **5.1-ppm LOAEL** in two-day neonates) as the critical endpoint for REL calculation. Despite the fact that significant effects were only seen in the two-day neonates, and not in older offspring of exposed dams, it does not appear that the effect seen in the neonates is an artifact. The observed temporary decrease in peripheral early nucleated red blood cells (RBCs) can be explained as an effect of benzene on fetal blood formation (which occurs in the liver), which then is compensated for at later ages by hematopoiesis in bone marrow.

C.2.2 Adjustment for Exposure Duration

As noted previously, none of the studies in adults or pregnant female mice allow for direct assessment of the impacts of 1-hour benzene exposure.

In their derivation of the acute ReV, TCEQ chose to adjust the reported 6-hour daily exposure (from the Rozen et al. (1984) study) to an equivalent 1-hour exposure. This is appropriate for non-developmental effects, where time-integrated exposure may be an appropriate index of effect. In addition, the variation of Haber's law (employing the cube of exposure duration) applied by TCEQ results in a substantially lower human-equivalent exposure concentration than if a more conventional Haber's law correction (based on the product of concentration and time) had been used.

In contrast, OEHHA identified the critical effect in the Keller and Snyder (1988) study as "developmental," that is, involving some process during an unspecified crucial period of fetal growth and differentiation. For developmental effects, the argument for time-adjustment of exposures is much less clear-cut, since the observed impairment may have occurred at any time during the exposure period. It seems reasonable to accept that the critical effect is indeed developmental, not only based on Keller and Snyder (1988) but also on supporting data from Corti and Snyder (1996) who reported persistent effects in offspring of exposed pregnant dams.

C.2.3 Dosimetric Adjustment

Both TCEQ and OEHHA employed the same approach to adjusting animal exposures to equivalent human exposures. The regional gas dose ratio (RGDR) approach involves correcting for differences in absorption rates (reflected by air-blood partitioning coefficients) across the two species. If the animal partition coefficient is similar to or larger than that for humans, the default approach is to assume a ratio of 1.0 (EPA, 1994). Both state agencies employed this approach. However, in the absence of validated models, neither agency attempted to adjust for differences in specific ventilation rates (ventilation/minute per kilogram body weight) across the two species. This is understandable, but available data indicate that specific ventilation rates may be as much as five-fold greater in mice than in “typical” humans. Thus, similar exposure concentrations might be expected to result in larger doses per body weight for mice than for humans, and not correcting for this difference may have resulted in an added degree of conservatism for the 1-hour TCEQ and OEHHA benzene benchmarks.

C.2.4 Adversity of the Critical Effects

None of the studies in Table C-1 report overt “adverse” effects of benzene in experimental animals; that is, no clear effects on mortality or morbidity were seen. Rather, the critical effects identified in these studies are precursor effects, such as decreased levels of circulating blood cells, which are considered “early biomarkers of benzene-induced hematotoxicity” (TCEQ, 2015). Abnormal hematological values alone do not constitute an adverse effect, but in human populations they can be indicators or precursor effects for more serious, clinical adverse effects, including leukemia (ATSDR, 2007, CalEPA, 2014).

Both TCEQ and OEHHA derived acute benzene benchmarks based on these precursor effects. The underlying rationale for their selection as critical is reasonable because precursor effects may develop into adverse effects. However, using LOAELs for precursor effects as points of departure (PODs) for health-criteria derivation is somewhat at odds with current practice and may have resulted in an additional level of conservatism in the derived criteria (see Section C.2.5).

C.2.5 Values of Uncertainty Factors

As noted above, UFs are commonly employed in health-criteria development to assure that an adequate level of health-protectiveness is achieved by taking into account the nature of the POD, animal-human differences, and human variability. A substantial amount of effort has been expended in developing supporting rationales for specific UF values; modern practice is to employ UFs only where specific sources of uncertainty cannot be adequately quantified.

Unfortunately, the database supporting specific UF values for acute effects is much less well-developed than that for chronic exposures. In deriving their ReV, TCEQ employs an aggregate UF value of 100, composed of the three individual UF values itemized below.

1. An approximate UF of 3 (the square root of 10) for using a LOAEL.
   a. While a UF value of 10 for using a LOAEL is often selected, TCEQ argued that the data from supporting studies (including Keller and Snyder (1988)) support the use of a lower value (3) in this case.

2. UF=3 for interspecies (animal-human) differences.
   a. The value of 3 for animal-human differences is lower than commonly employed, but TCEQ argued that it is reasonable since the default dosimetric correction had been employed. As noted above, the actual dosimetric difference between animals and humans (based on specific ventilation differences) may also support this choice.

3. UF=10 for intraspecies (human) variability.
    a. TCEQ's selection of 10 for the human variability UF is a routine default and is consistent with the endpoint they selected being observed in adult animals.

OEHHA, in contrast, employed a composite UF value of 600, composed of the three individual UF values itemized below.

1. UF=3 for using a LOAEL.

2. UF=2 and 3, respectively, for the toxicokinetic and toxicodynamic differences between animals and humans.

3. UF=10 and 3, respectively, for toxicokinetic and toxicodynamic variability within the human population.
    a. Using more than a total factor of 10 for human variability is uncommon; OEHHA suggests that this choice is justified by findings of large toxicokinetic variability, associated with genetically determined metabolic differences, in several human populations.

C.3 Evaluation of Criteria Derivation

Having reviewed the approaches taken by TCEQ and OEHHA in deriving acute hazard criteria for benzene, the judgements described below are supported by the data.

- It is reasonable to select the two-day neonate results from Keller and Snyder (1988) rather than use the results of Rozen et al. (1984). The data from Keller and Snyder (1988) have the additional advantage that they are suitable for benchmark-dose (concentration) analysis.

- Given the developmental nature of the selected endpoint, using a large correction for duration of exposure is probably not justified. (Since TCEQ identified their endpoint as non-developmental, however, some form of correction may be appropriate.)

- Because the reduction in early nucleated RBCs seen in Keller and Snyder (1988) is a precursor effect (not accompanied by demonstrated effects on the health or survival in experimental animals), current best practices suggest that a relatively large reduction in RBC counts should be used in benchmark-concentration modeling. Since the level of reduction that would be biologically significant is not known, a change of 1 standard deviation from controls (rather than 0.5 standard deviations) would be appropriate. Identifying a benchmark concentration as the POD for criteria derivation obviates the need for a UF for the use of a LOAEL.

- Given the likely conservative nature of the RGDR correction, an additional large UF to account for differences between animal and human toxicokinetics does not appear justified.

- Because the critical study was performed in pregnant animals, with fetuses representing a presumed sensitive population, default adjustments are appropriate for toxicodynamic differences between animals and humans (UF = square root of 10, or approximately 3) and among humans.

- While a large UF of 10 for toxicodynamic variation in humans has been proposed by OEHHA, it is not clear that this value is adequately supported by the available data; while the variability in human benzene metabolism may indeed by large, it is by no means clear that this uncertainty points toward a more conservative UF value.

Based on these considerations, it appears that the acute health criteria derived by TCEQ (180 and 54 ppb) are not acceptably health protective, primarily owing to the duration adjustment used to calculate human-equivalent 1-hour concentrations. Similarly, the OEHHA UF of 10 for human toxicokinetic variability is very conservative, and it results in a criterion value (8 ppb) that is too far-removed from the human equivalent concentration (600-fold) to be very reliable.

Roughly speaking, the effect of the TCEQ duration adjustment was to increase the criteria by about three-fold compared to criteria derived using a more conventional adjustment method. Use of the cubic time-exposure adjustment model (Section C.2.2) resulted in an adjustment factor of approximately 1.8, compared to the six-fold adjustment that would have resulted from a simple (linear) Haber's law correction. Similarly, reduction to the square root of 10 of the OEHHA UF for human toxicokinetic variability would increase their acute criterion value by 3.2-fold.

Replicating the TCEQ criteria calculations, substituting the six-fold Haber's law adjustment yields a "modified" ReV of 53 ppb and a "modified" ESL of 16 ppb. Similarly, reducing the UF for human variability from 10 to 3.2 in the OEHHA criterion derivation gives a "modified" REL of approximately 26 ppb. That is, criteria values converge to the range of about 16–50 ppb.

C.4 Sensitivity Analyses

We have also conducted limited sensitivity analyses of acute-criteria derivation for benzene based on different PODs, duration adjustments, use of LOAELs versus a calculated benchmark concentration-low (BMCL), and different approaches to defining UF values. Because these calculations are all based on the same data sets used by TCEQ and OEHHA, it is not surprising that the range of results (calculated criteria values) are close to the "modified" values given above. Table C-2 shows an example analysis in which we derived an acute criterion based on the BMCL from Keller and Snyder (1988), with no duration adjustment (since the critical endpoint is developmental) and mostly standard default UF values. The resulting criterion value is approximately 26 ppb, close to the "modified" OEHHA value discussed above. Similar analyses, based on the LOAEL from Rozen et al. (1984), depending on the specific values for duration adjustments and UFs that are applied, also yield criteria values in the range of 30–60 ppb.

Table C-2. Example Acute Criteria Derivation Based on the BMCL from Keller and Snyder (1988)

Element	Value	Comment
POD (ppm)	1.61	1.0 standard deviation BMCL (Exp2 model) based on Keller and Snyder (1988)
Duration adjustment (1-hour)	NA	(developmental effect; default = no Haber's law correction)
Dosimetry adjustment:		
Ventilation/kg	1	(Even though mouse ventilation rate/kg is higher than in humans)
Absorption/partitioning	1	Default, defensible RGDR method (EPA, 1994)
UF (LOAEL)	NA	Because a BMCL is used as the POD
UF (interspecies):		
PK	2.0	Relatively low value because of likely animal-human differences in inhalation dosimetry
PD	3.2	< 10 because endpoint is measured at sensitive life stage
UF (intraspecies):		
PK	3.2	Default
PD	3.2	Default
Acute Criterion	0.026	ppm
	26	ppb

Notes: kg = kilogram; PK = pharmacokinetic adjustment; PD = pharmacodynamics adjustment; POD = point of departure; BMCL = benchmark concentration-low; UF = uncertainty factor; LOAEL = lowest observed adverse effect level; ppm = parts per million; ppb = parts per billion; RGDR = regional gas dose ratio; NA = not applicable.

C.5 Summary

Based on the analyses presented here, we conclude that the data support **a 1-hour health screening value of 30 ppb for benzene exposure**. In applying this value in these HHRAs, the intent is to provide a high but reasonable degree of protectiveness. This is assured by selection of a precursor effect (in a sensitive life stage) as the POD, using a BMCL instead of a LOAEL, and the inclusion of appropriate UF values to account for potential differences between experimental animal and humans and variability within the human population.

Because of the many sources of uncertainty and variability in its derivation, the numerical criterion value is associated with a high degree of uncertainty. One-hour exposures above this value should not be construed to automatically indicate that adverse health effects will occur; rather, frequent exposures above 30 ppb and isolated exposures far above this value need to be evaluated in more detail (with regard to meteorological conditions and exposure assumptions) to adequately evaluate the degree of hazard and health risk.

C.6 References

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Appendix D. Hazard-index Groups

Table D-1. Hazard-index Groups for Each Chemical

Chemical	Chronic Groups	Subchronic Groups	Acute Groups
1,2,3-trimethylbenzene	neurotoxicity, hematological, respiratory*	neurotoxicity, hematological, respiratory*	neurotoxicity
1,2,4-trimethylbenzene	neurotoxicity, hematological, respiratory*	neurotoxicity, hematological, respiratory*	neurotoxicity
1,3,5-trimethylbenzene	neurotoxicity, hematological, respiratory	neurotoxicity, hematological, respiratory*	neurotoxicity
1,3-diethylbenzene	systemic#	systemic#	unassigned
1,4-diethylbenzene	systemic	systemic	unassigned
1-butene	systemic	--	systemic
1-pentene	systemic	--	systemic
2,2,4-trimethylpentane	respiratory**	neurotoxicity, systemic	neurotoxicity
2,3,4-trimethylpentane	respiratory**	neurotoxicity, systemic	neurotoxicity
2,3-dimethylpentane	systemic, neurotoxicity	neurotoxicity, systemic	neurotoxicity
2,4-dimethylpentane	systemic, neurotoxicity	neurotoxicity, systemic	neurotoxicity
2-ethyltoluene	systemic	systemic	unassigned
2-methylheptane	systemic	neurotoxicity, systemic	neurotoxicity
2-methylhexane	systemic, neurotoxicity	neurotoxicity, systemic	neurotoxicity
3-ethyltoluene	systemic	systemic	unassigned
3-methylheptane	systemic	neurotoxicity, systemic	neurotoxicity
3-methylhexane	systemic, neurotoxicity	neurotoxicity, systemic	neurotoxicity
4-ethyltoluene	systemic	systemic	unassigned
benzene	hematological	hematological	hematological
cis-2-butene	systemic	--	systemic
cis-2-pentene	systemic	--	systemic
cyclohexane	developmental, hepatotoxicity, neurotoxicity	developmental, neurotoxicity	unassigned
cyclopentane	respiratory**	neurotoxicity, systemic	unassigned
ethane	--	--	--
ethene	hepatotoxicity	--	hepatotoxicity
ethylbenzene	developmental	sensory‡ , developmental	sensory
isobutane	neurotoxicity	--	respiratory, neurotoxicity
isopentane	neurotoxicity	neurotoxicity, systemic	neurotoxicity
isoprene	neurotoxicity, hematological	--	developmental, sensory
isopropyl benzene	nephrotoxicity, endocrine***	systemic	unassigned
m+p-xylene	neurotoxicity	neurotoxicity, hematological	respiratory, neurotoxicity
methylcyclohexane	unassigned	neurotoxicity, systemic	unassigned

Chemical	Chronic Groups	Subchronic Groups	Acute Groups
n-butane	neurotoxicity	--	systemic
n-decane	systemic, immune	--	sensory, hematological
n-heptane	neurotoxicity, systemic	sensory‡	neurotoxicity
n-hexane	neurotoxicity	neurotoxicity	neurotoxicity, endocrine
n-nonane	neurotoxicity	neurotoxicity	neurotoxicity
n-octane	respiratory**	neurotoxicity, systemic	neurotoxicity
n-pentane	neurotoxicity	systemic	neurotoxicity
n-propylbenzene	nephrotoxicity, endocrine	systemic	unassigned
o-xylene	neurotoxicity	neurotoxicity, hematological	respiratory, neurotoxicity
propane	--	--	--
propene	respiratory**	--	--
styrene	neurotoxicity	--	respiratory, neurotoxicity
toluene	neurotoxicity	neurotoxicity	neurotoxicity
trans-2-butene	systemic	--	systemic
trans-2-pentene	systemic	--	systemic

Notes: * = histological changes in the lung (alveoli); **= histological changes in the nasal cavity; *** endocrine = increased adrenal weight; **** endocrine = HPA axis changes; # = effect seen in critical study was change in organism weight or weight gain; ‡ = ototoxicity; unassigned = promulgating authority does not identify the critical effects (usually TCEQ ESL).

Table D-2. Chemicals for Each Hazard Index Group

Exposure Duration	Group	Chemical(s)
Acute	Developmental	isoprene
	Endocrine	n-hexane
	Hematological	benzene; n-decane
	Hepatotoxicity	ethene
	Neurotoxicity	1,2,3-trimethylbenzene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; 2,2,4-trimethylpentane; 2,3,4-trimethylpentane; 2,3-dimethylpentane; 2,4-dimethylpentane; 2-methylheptane; 2-methylhexane; 3-methylheptane; 3-methylhexane; isobutane; isopentane; m+p-xylene; n-heptane; n-hexane; n-nonane; n-octane; n-pentane; o-xylene; styrene; toluene
	Respiratory	isobutane; m+p-xylene; o-xylene; styrene
	Sensory	ethylbenzene; isoprene; n-decane
	Systemic	1-butene; 1-pentene; cis-2-butene; cis-2-pentene; n-butane; trans-2-butene; trans-2-pentene
	Unassigned	1,3-diethylbenzene; 1,4-diethylbenzene; 2-ethyltoluene; 3-ethyltoluene; 4-ethyltoluene; cyclohexane; cyclopentane; isopropyl benzene; methylcyclohexane; n-propylbenzene
Subchronic	Developmental	cyclohexane; ethylbenzene
	Hematological	1,2,3-trimethylbenzene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; benzene; m+p-xylene; o-xylene

Exposure Duration	Group	Chemical(s)
	Neurotoxicity	1,2,3-trimethylbenzene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; 2,2,4-trimethylpentane; 2,3,4-trimethylpentane; 2,3-dimethylpentane; 2,4-dimethylpentane; 2-methylheptane; 2-methylhexane; 3-methylheptane; 3-methylhexane; cyclohexane; cyclopentane; isopentane; m+p-xylene; methylcyclohexane; n-hexane; n-nonane; n-octane; o-xylene; toluene
	Respiratory	1,2,3-trimethylbenzene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene
	Sensory	ethylbenzene; n-heptane
	Systemic	1,3-diethylbenzene; 1,4-diethylbenzene; 2,2,4-trimethylpentane; 2,3,4-trimethylpentane; 2,3-dimethylpentane; 2,4-dimethylpentane; 2-ethyltoluene; 2-methylheptane; 2-methylhexane; 3-ethyltoluene; 3-methylheptane; 3-methylhexane; 4-ethyltoluene; cyclopentane; isopentane; isopropyl benzene; methylcyclohexane; n-octane; n-pentane; n-propylbenzene
Chronic	Developmental	cyclohexane; ethylbenzene
	Endocrine	isopropyl benzene; n-propylbenzene
	Hematological	1,2,3-trimethylbenzene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; benzene; isoprene
	Hepatotoxicity	cyclohexane; ethene
	Immune	n-decane
	Nephrotoxicity	isopropyl benzene; n-propylbenzene
	Neurotoxicity	1,2,3-trimethylbenzene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; 2,3-dimethylpentane; 2,4-dimethylpentane; 2-methylhexane; 3-methylhexane; cyclohexane; isobutane; isopentane; isoprene; m+p-xylene; n-butane; n-heptane; n-hexane; n-nonane; n-pentane; o-xylene; styrene; toluene
	Respiratory	1,2,3-trimethylbenzene; 1,2,4-trimethylbenzene; 1,3,5-trimethylbenzene; 2,2,4-trimethylpentane; 2,3,4-trimethylpentane; cyclopentane; n-octane; propene
	Systemic	1,3-diethylbenzene; 1,4-diethylbenzene; 1-butene; 1-pentene; 2,3-dimethylpentane; 2,4-dimethylpentane; 2-ethyltoluene; 2-methylheptane; 2-methylhexane; 3-ethyltoluene; 3-methylheptane; 3-methylhexane; 4-ethyltoluene; cis-2-butene; cis-2-pentene; n-decane; n-heptane; trans-2-butene; trans-2-pentene
	Unassigned	methylcyclohexane

Appendix E. Additional Quantifications of Estimated Hazard Quotients and Hazard Indices

This appendix contains **detailed tables of estimates of non-cancer HQs and HIs across the various scenarios modeled in these HHRAs**. They supplement the more abbreviated, summary-level tables and figures presented in Section 5. Each subsection of tables corresponds to a stratification by O&G activity type (development and production), exposure duration (acute [short term], subchronic [medium term], and chronic [long term]), and size of well pad (1, 3, and 5 acres for development activities; 1 acre for production). We also include tables at the end for subchronic and chronic exposures to sequences of O&G activities (drilling, fracking, and flowback activities in sequence, and those activities and production in sequence).

Each subsection generally has the four tables listed below. We stratify each table by the simulated age group, hypothetical O&G site, O&G activity, VOC or critical-effect group, and distance from the well pad.

1. The single maximum simulated HQ from among all hypothetical individuals simulated at the selected receptors at each distance from the well pad. **Since these are the single largest HQs from among the simulated population, they do not necessarily represent typical or average HQs for all simulated individuals and, for exposures below the chronic duration, these higher HQs may be relatively uncommon for any individual.**

   We only show VOCs with at least one HQ above 0.1, so **in some tables we do not show many VOCs because their HQs are below 0.1 for all hypothetical individuals at all times in the modeling, at the selected receptors**.

   For acute assessments, these are the largest 1-hour-average simulated exposures to any hypothetical individual during the course of the modeling, at the selected receptors.

   For subchronic assessments, these are the largest multi-day-average simulated exposures to any hypothetical individual during the course of the modeling, at the selected receptors.

   For chronic assessments, these are the largest annual-average or multi-year-average simulated exposures to any hypothetical individual, at the selected receptors.

2. The percentage of simulated HQs that are above 1 at the selected receptors at each distance from the well pad. We only show VOCs with at least one HQ above 1, so in some tables we do not show many VOCs because their HQs are below 1 for all hypothetical individuals at the selected receptors during the course of the modeling.

   For acute assessments, the percentage is calculated from the collection across all modeled individuals of each individual's 365 daily-maximum 1-hour-average simulated HQs, totaling 365,000 values per age group and selected receptor. Recall, as discussed earlier in this report, that we designed the acute modeling to assess the potential for acute exposures above health-protective criteria. This means that **these 1-hour values that we produced**

reflect the highest exposures that may be possible during many types of local meteorological conditions combined with randomly sampled emission rates. They do not reflect every possible 1-hour combination of meteorology and emissions.

For subchronic assessments, the percentage is calculated from the collection across all modeled individuals of each individual's 365 multi-day-average simulated HQs, totaling 365,000 values per age group and selected receptor.

For chronic assessments, the percentage is calculated from the collection of each modeled individual's annual- or multi-year-average simulated HQs, totaling 1,000 values per age group and selected receptor.

3. Same as Bullet 1 above but for HIs for critical-effect groups. We do not show critical-effect groups whose HIs are below 0.1 for all simulated individuals at the selected receptors.

4. Same as Bullet 2 above but for HIs for critical-effect groups. We do not show critical-effect groups whose HIs are below 1 for all simulated individuals at the selected receptors.

The tables use color shading to call attention to different bins of HQ, HI, and percentage values. Tables of HQ and HI values utilize darker blue shading with white font for values above 10, medium blue shading for values between 1 and 10, light blue shading for values between 0.1 and 1, gray shading for values between 0.01 and 0.1, and light gray shading for values below 0.01. Tables of percentages utilize red shadings for higher values, orange and yellow shadings for medium values, greens for lower values, and gray for values of 0. Recall, as discussed earlier in this report, that HQs and HIs do not provide numerical estimates of the probability or severity of potential risks, meaning that an HQ of 20 does not mean 20 times the probability or severity of an adverse health impact of an HQ of 10. We intend the color-coding of different ranges of HQs and HIs to help the reader better synthesize the results and identify which VOCs and scenarios may be of greater concern and which are likely not of concern.

Each table is sorted within each combination of age group, O&G site, and O&G activity, so that VOCs and critical-effect groups with the highest values appear first while the lowest values appear last.

E.1 Oil and Gas Development

E.1.1 Acute Non-cancer Hazards

E.1.1.1 1-acre Well Pad

Table E-1. Largest Acute Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 1-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	12	11	11	9.8	8.9	8.2	7.6	8.5	7.9	5.7	5	4.5	4.1	5.3
			toluene	NA	NA	2.8	2.6	2.5	2.2	2	1.9	1.7	1.9	1.8	1.3	1.1	1	0.94	1.2
			2-ethyltoluene	NA	NA	0.2	0.18	0.17	0.14	0.12	0.1	0.089	0.14	0.13	0.066	0.058	0.052	0.067	0.043
		Fracking	benzene	NA	NA	10	9.4	8.7	7.6	6.5	5.6	5.1	4.8	4.2	4.2	3.5	3.2	3	2.8
			m+p-xylene	NA	NA	1.4	1.3	1.2	1	0.9	0.79	0.73	0.68	0.64	0.59	0.53	0.45	0.43	0.39
			2-ethyltoluene	NA	NA	0.77	0.72	0.68	0.61	0.56	0.51	0.48	0.42	0.39	0.37	0.33	0.29	0.27	0.24
			toluene	NA	NA	0.62	0.56	0.52	0.46	0.42	0.39	0.36	0.33	0.29	0.29	0.25	0.22	0.21	0.19
			3-ethyltoluene	NA	NA	0.47	0.43	0.4	0.34	0.3	0.28	0.26	0.24	0.23	0.21	0.18	0.16	0.15	0.14
			n-decane	NA	NA	0.33	0.3	0.28	0.25	0.23	0.21	0.19	0.18	0.17	0.16	0.13	0.12	0.11	0.1
			cyclohexane	NA	NA	0.27	0.25	0.23	0.21	0.19	0.18	0.16	0.15	0.14	0.13	0.11	0.1	0.097	0.088
			methylcyclohexane	NA	NA	0.27	0.25	0.23	0.2	0.18	0.17	0.15	0.14	0.13	0.12	0.11	0.095	0.09	0.082
			trans-2-butene	NA	NA	0.25	0.23	0.22	0.2	0.17	0.16	0.15	0.13	0.12	0.12	0.11	0.094	0.085	0.077
			n-nonane	NA	NA	0.19	0.17	0.16	0.14	0.12	0.11	0.099	0.092	0.086	0.08	0.072	0.061	0.058	0.053
			n-octane	NA	NA	0.19	0.18	0.16	0.14	0.12	0.11	0.1	0.096	0.089	0.083	0.071	0.063	0.06	0.055
			4-ethyltoluene	NA	NA	0.17	0.16	0.15	0.13	0.12	0.11	0.1	0.095	0.084	0.079	0.07	0.063	0.06	0.055
			o-xylene	NA	NA	0.12	0.11	0.099	0.085	0.074	0.065	0.061	0.056	0.053	0.049	0.044	0.037	0.036	0.032
		Flowback	2-ethyltoluene	NA	NA	17	16	15	13	11	13	12	15	13	8.9	7	6.3	6.2	7.3
			benzene	NA	NA	4.3	3.9	3.7	3.4	3	3.9	3.8	3.7	3.4	2.2	1.6	2.1	1.6	1.8
			3-ethyltoluene	NA	NA	1.8	1.6	1.5	1.3	1.2	1.4	1.6	1.5	1.4	0.92	0.72	0.85	0.65	0.76
			4-ethyltoluene	NA	NA	1.2	1.1	1	0.9	0.79	1.1	1.1	1	0.93	0.61	0.48	0.57	0.43	0.51
			n-decane	NA	NA	1.1	1	0.97	0.85	0.75	0.88	1	0.97	0.88	0.58	0.46	0.54	0.41	0.48
			n-propylbenzene	NA	NA	1.1	0.97	0.93	0.81	0.71	0.83	0.94	0.91	0.83	0.55	0.43	0.51	0.39	0.45
			1,3-diethylbenzene	NA	NA	0.9	0.83	0.79	0.69	0.6	0.71	0.81	0.78	0.71	0.47	0.37	0.44	0.33	0.39
			m+p-xylene	NA	NA	0.8	0.74	0.7	0.61	0.53	0.73	0.71	0.69	0.63	0.42	0.33	0.39	0.29	0.34
			isopropylbenzene	NA	NA	0.71	0.65	0.61	0.54	0.47	0.55	0.63	0.61	0.55	0.37	0.29	0.34	0.26	0.3
			toluene	NA	NA	0.67	0.62	0.58	0.51	0.45	0.61	0.6	0.58	0.53	0.35	0.27	0.32	0.25	0.29

		1,2,3-trimethylbenzene	NA	NA	0.36	0.33	0.31	0.27	0.24	0.28	0.32	0.31	0.28	0.18	0.14	0.17	0.13	0.15
		1,2,4-trimethylbenzene	NA	NA	0.34	0.32	0.3	0.26	0.23	0.31	0.31	0.3	0.27	0.18	0.14	0.17	0.13	0.15
		1,3,5-trimethylbenzene	NA	NA	0.34	0.31	0.29	0.26	0.22	0.26	0.3	0.29	0.26	0.17	0.14	0.16	0.12	0.14
		o-xylene	NA	NA	0.25	0.23	0.22	0.19	0.17	0.23	0.22	0.21	0.19	0.13	0.1	0.12	0.091	0.11
		cyclohexane	NA	NA	0.23	0.21	0.2	0.18	0.16	0.21	0.2	0.19	0.18	0.12	0.085	0.11	0.082	0.097
		methylcyclohexane	NA	NA	0.23	0.21	0.2	0.18	0.15	0.21	0.21	0.2	0.18	0.12	0.094	0.11	0.085	0.099
		n-nonane	NA	NA	0.21	0.19	0.18	0.16	0.14	0.19	0.19	0.18	0.16	0.11	0.085	0.1	0.076	0.089
		styrene	NA	NA	0.19	0.18	0.17	0.15	0.13	0.15	0.17	0.17	0.15	0.1	0.078	0.093	0.07	0.082
Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	10	9.8	8.9	7.3	6.6	6	5.5	5	4.6	3.8	3.4	2.8	2.5	2.3
		toluene	NA	NA	2.4	2.2	2	1.6	1.5	1.3	1.2	1.1	1	0.86	0.77	0.67	0.58	0.52
		2-ethyltoluene	NA	NA	0.17	0.19	0.17	0.12	0.11	0.096	0.088	0.081	0.072	0.061	0.055	0.047	0.042	0.038
	Fracking	benzene	NA	NA	8.4	7.6	7	6.2	5.6	5.1	4.7	4.4	4	3.2	2.9	2.9	2.4	2
		m+p-xylene	NA	NA	1.2	1	0.97	0.86	0.78	0.71	0.65	0.6	0.55	0.45	0.4	0.4	0.33	0.28
		2-ethyltoluene	NA	NA	0.61	0.55	0.5	0.44	0.4	0.36	0.33	0.3	0.28	0.23	0.21	0.21	0.17	0.12
		toluene	NA	NA	0.5	0.45	0.42	0.37	0.34	0.31	0.28	0.26	0.24	0.19	0.17	0.17	0.14	0.12
		3-ethyltoluene	NA	NA	0.38	0.34	0.32	0.28	0.26	0.23	0.21	0.2	0.18	0.15	0.13	0.13	0.11	0.093
		n-decane	NA	NA	0.27	0.24	0.22	0.2	0.18	0.16	0.15	0.14	0.13	0.1	0.091	0.093	0.076	0.065
		methylcyclohexane	NA	NA	0.22	0.2	0.18	0.16	0.15	0.13	0.12	0.11	0.1	0.085	0.075	0.077	0.063	0.054
		cyclohexane	NA	NA	0.21	0.19	0.18	0.16	0.14	0.13	0.12	0.11	0.1	0.086	0.076	0.075	0.062	0.051
		trans-2-butene	NA	NA	0.19	0.17	0.16	0.14	0.13	0.11	0.1	0.096	0.089	0.072	0.065	0.064	0.05	0.047
		n-octane	NA	NA	0.16	0.14	0.13	0.12	0.11	0.096	0.089	0.082	0.075	0.06	0.054	0.055	0.045	0.038
		n-nonane	NA	NA	0.15	0.14	0.13	0.11	0.1	0.092	0.085	0.078	0.072	0.058	0.052	0.052	0.043	0.037
		4-ethyltoluene	NA	NA	0.14	0.13	0.12	0.1	0.094	0.086	0.079	0.073	0.067	0.054	0.048	0.049	0.04	0.034
	Flowback	2-ethyltoluene	NA	NA	19	16	15	13	9	8.1	7.5	6.9	6.3	5.2	4.6	4	3.7	3.1
		benzene	NA	NA	4.7	3.8	3.5	3	2.4	2.2	1.9	1.7	1.8	1.6	1.2	1.1	0.92	0.79
		3-ethyltoluene	NA	NA	1.9	1.7	1.5	1.4	0.94	0.85	0.77	0.71	0.64	0.54	0.47	0.42	0.38	0.33
		4-ethyltoluene	NA	NA	1.3	1.1	1	0.91	0.63	0.57	0.52	0.48	0.44	0.36	0.32	0.28	0.26	0.22
		n-decane	NA	NA	1.2	1.1	0.97	0.86	0.59	0.54	0.49	0.45	0.4	0.34	0.3	0.26	0.24	0.21
		n-propylbenzene	NA	NA	1.2	1	0.92	0.82	0.56	0.51	0.46	0.43	0.39	0.32	0.28	0.25	0.23	0.19
		1,3-diethylbenzene	NA	NA	0.99	0.86	0.78	0.7	0.48	0.43	0.4	0.36	0.33	0.28	0.24	0.21	0.2	0.17
		m+p-xylene	NA	NA	0.88	0.76	0.7	0.62	0.42	0.39	0.35	0.32	0.29	0.24	0.22	0.19	0.17	0.15
		isopropylbenzene	NA	NA	0.78	0.67	0.61	0.54	0.37	0.34	0.31	0.28	0.26	0.21	0.19	0.17	0.15	0.13
		toluene	NA	NA	0.74	0.64	0.58	0.52	0.36	0.32	0.29	0.27	0.24	0.2	0.18	0.16	0.15	0.12
		1,2,3-trimethylbenzene	NA	NA	0.39	0.34	0.31	0.27	0.19	0.17	0.16	0.14	0.13	0.11	0.096	0.084	0.077	0.065
		1,2,4-trimethylbenzene	NA	NA	0.38	0.33	0.3	0.26	0.18	0.16	0.15	0.14	0.13	0.1	0.092	0.081	0.075	0.063
		1,3,5-trimethylbenzene	NA	NA	0.37	0.32	0.29	0.26	0.18	0.16	0.15	0.14	0.12	0.1	0.09	0.079	0.073	0.062
		o-xylene	NA	NA	0.27	0.24	0.22	0.19	0.13	0.12	0.11	0.1	0.09	0.076	0.067	0.058	0.054	0.046

			cyclohexane	NA	NA	0.25	0.2	0.18	0.16	0.13	0.12	0.099	0.09	0.094	0.082	0.065	0.06	0.049	0.041
			methylcyclohexane	NA	NA	0.25	0.22	0.2	0.18	0.12	0.11	0.1	0.093	0.083	0.07	0.062	0.054	0.05	0.043
			n-nonane	NA	NA	0.23	0.2	0.18	0.16	0.11	0.1	0.091	0.084	0.075	0.063	0.056	0.049	0.045	0.038
			styrene	NA	NA	0.21	0.18	0.17	0.15	0.1	0.092	0.084	0.078	0.071	0.059	0.052	0.045	0.042	0.035
	Northern Front Range	Drilling	benzene	NA	NA	14	13	12	11	9	7.9	7.1	6.3	5.7	4.8	4.1	3.6	3.1	2.8
			toluene	NA	NA	3.2	3	2.8	2.4	2	1.8	1.6	1.4	1.3	1.1	0.93	0.81	0.71	0.62
			2-ethyltoluene	NA	NA	0.23	0.21	0.2	0.17	0.15	0.13	0.11	0.1	0.092	0.078	0.066	0.058	0.05	0.044
			cyclohexane	NA	NA	0.11	0.1	0.097	0.084	0.072	0.063	0.056	0.05	0.046	0.038	0.033	0.028	0.025	0.022
		Fracking	benzene	NA	NA	0.85	0.79	0.74	0.66	0.73	0.73	0.73	0.66	0.61	0.51	0.49	0.43	0.41	0.38
			2-ethyltoluene	NA	NA	0.19	0.18	0.16	0.14	0.12	0.11	0.093	0.084	0.076	0.059	0.051	0.045	0.043	0.04
		Flowback	benzene	NA	NA	27	25	23	20	17	14	13	12	11	9.1	7.7	6.7	5.9	5.2
			toluene	NA	NA	0.89	0.83	0.77	0.67	0.58	0.49	0.44	0.4	0.36	0.3	0.26	0.23	0.2	0.17
			3-ethyltoluene	NA	NA	0.88	0.82	0.77	0.66	0.57	0.51	0.43	0.39	0.36	0.3	0.26	0.22	0.2	0.17
			cyclohexane	NA	NA	0.78	0.72	0.67	0.58	0.5	0.42	0.38	0.35	0.32	0.26	0.23	0.2	0.17	0.15
			m+p-xylene	NA	NA	0.56	0.52	0.49	0.42	0.36	0.32	0.28	0.25	0.23	0.19	0.16	0.14	0.12	0.11
			methylcyclohexane	NA	NA	0.36	0.34	0.31	0.27	0.23	0.2	0.18	0.16	0.15	0.12	0.1	0.091	0.08	0.07
			n-hexane	NA	NA	0.35	0.32	0.3	0.26	0.23	0.19	0.17	0.16	0.14	0.12	0.1	0.088	0.077	0.068
			n-decane	NA	NA	0.3	0.28	0.26	0.23	0.2	0.18	0.15	0.14	0.12	0.1	0.089	0.077	0.067	0.06
			n-octane	NA	NA	0.25	0.23	0.22	0.19	0.16	0.16	0.12	0.11	0.1	0.085	0.072	0.063	0.055	0.049
			n-nonane	NA	NA	0.21	0.2	0.18	0.16	0.14	0.12	0.1	0.094	0.086	0.072	0.061	0.053	0.047	0.041
			2-ethyltoluene	NA	NA	0.16	0.15	0.14	0.12	0.1	0.091	0.081	0.073	0.066	0.055	0.046	0.04	0.035	0.031
			o-xylene	NA	NA	0.15	0.14	0.13	0.11	0.098	0.094	0.074	0.068	0.062	0.052	0.044	0.038	0.033	0.03
			2-methylheptane	NA	NA	0.14	0.13	0.12	0.11	0.091	0.077	0.069	0.063	0.058	0.048	0.041	0.036	0.031	0.028
			n-heptane	NA	NA	0.13	0.12	0.11	0.095	0.082	0.069	0.062	0.056	0.052	0.043	0.037	0.032	0.028	0.025
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	12	11	11	9.8	8.9	8.2	7.6	8.5	7.9	5.7	5	4.5	4.1	5.3
			toluene	NA	NA	2.8	2.6	2.5	2.2	2	1.9	1.7	1.9	1.8	1.3	1.1	1	0.94	1.2
			2-ethyltoluene	NA	NA	0.2	0.18	0.17	0.14	0.12	0.1	0.089	0.14	0.13	0.066	0.058	0.052	0.067	0.043
		Fracking	benzene	NA	NA	10	9.4	8.7	7.6	6.5	5.6	5.1	4.8	4.2	4.2	3.5	3.2	3	2.8
			m+p-xylene	NA	NA	1.4	1.3	1.2	1	0.9	0.79	0.73	0.68	0.64	0.59	0.53	0.45	0.43	0.39
			2-ethyltoluene	NA	NA	0.77	0.72	0.68	0.61	0.56	0.51	0.48	0.42	0.39	0.37	0.33	0.29	0.27	0.24
			toluene	NA	NA	0.62	0.56	0.52	0.46	0.42	0.39	0.36	0.33	0.29	0.29	0.25	0.22	0.21	0.19
			3-ethyltoluene	NA	NA	0.47	0.43	0.4	0.34	0.3	0.28	0.26	0.24	0.23	0.21	0.18	0.16	0.15	0.14
			n-decane	NA	NA	0.33	0.3	0.28	0.25	0.23	0.21	0.19	0.18	0.17	0.16	0.13	0.12	0.11	0.1
			cyclohexane	NA	NA	0.27	0.25	0.23	0.21	0.19	0.18	0.16	0.15	0.14	0.13	0.11	0.1	0.097	0.088
			methylcyclohexane	NA	NA	0.27	0.25	0.23	0.2	0.18	0.17	0.15	0.14	0.13	0.12	0.11	0.095	0.09	0.082
			trans-2-butene	NA	NA	0.25	0.23	0.22	0.2	0.17	0.16	0.15	0.13	0.12	0.12	0.11	0.094	0.085	0.077
			n-nonane	NA	NA	0.19	0.17	0.16	0.14	0.12	0.11	0.099	0.092	0.086	0.08	0.072	0.061	0.058	0.053

			n-octane	NA	NA	0.19	0.18	0.16	0.14	0.12	0.11	0.1	0.096	0.089	0.083	0.071	0.063	0.06	0.055
			4-ethyltoluene	NA	NA	0.17	0.16	0.15	0.13	0.12	0.11	0.1	0.095	0.084	0.079	0.07	0.063	0.06	0.055
			o-xylene	NA	NA	0.12	0.11	0.099	0.085	0.074	0.065	0.061	0.056	0.053	0.049	0.044	0.037	0.036	0.032
		Flowback	2-ethyltoluene	NA	NA	17	16	15	13	11	13	12	15	13	8.9	7	6.3	6.2	7.3
			benzene	NA	NA	4.3	3.9	3.7	3.4	3	3.9	3.8	3.7	3.4	2.2	1.6	2.1	1.6	1.8
			3-ethyltoluene	NA	NA	1.8	1.6	1.5	1.3	1.2	1.4	1.6	1.5	1.4	0.92	0.72	0.85	0.65	0.76
			4-ethyltoluene	NA	NA	1.2	1.1	1	0.9	0.79	1.1	1.1	1	0.93	0.61	0.48	0.57	0.43	0.51
			n-decane	NA	NA	1.1	1	0.97	0.85	0.75	0.88	1	0.97	0.88	0.58	0.46	0.54	0.41	0.48
			n-propylbenzene	NA	NA	1.1	0.97	0.93	0.81	0.71	0.83	0.94	0.91	0.83	0.55	0.43	0.51	0.39	0.45
			1,3-diethylbenzene	NA	NA	0.9	0.83	0.79	0.69	0.6	0.71	0.81	0.78	0.71	0.47	0.37	0.44	0.33	0.39
			m+p-xylene	NA	NA	0.8	0.74	0.7	0.61	0.53	0.73	0.71	0.69	0.63	0.42	0.33	0.39	0.29	0.34
			isopropylbenzene	NA	NA	0.71	0.65	0.61	0.54	0.47	0.55	0.63	0.61	0.55	0.37	0.29	0.34	0.26	0.3
			toluene	NA	NA	0.67	0.62	0.58	0.51	0.45	0.61	0.6	0.58	0.53	0.35	0.27	0.32	0.25	0.29
			1,2,3-trimethylbenzene	NA	NA	0.36	0.33	0.31	0.27	0.24	0.28	0.32	0.31	0.28	0.18	0.14	0.17	0.13	0.15
			1,2,4-trimethylbenzene	NA	NA	0.34	0.32	0.3	0.26	0.23	0.31	0.31	0.3	0.27	0.18	0.14	0.17	0.13	0.15
			1,3,5-trimethylbenzene	NA	NA	0.34	0.31	0.29	0.26	0.22	0.26	0.3	0.29	0.26	0.17	0.14	0.16	0.12	0.14
			o-xylene	NA	NA	0.25	0.23	0.22	0.19	0.17	0.23	0.22	0.21	0.19	0.13	0.1	0.12	0.091	0.11
			cyclohexane	NA	NA	0.23	0.21	0.2	0.18	0.16	0.21	0.2	0.19	0.18	0.12	0.085	0.11	0.082	0.097
			methylcyclohexane	NA	NA	0.23	0.21	0.2	0.18	0.15	0.21	0.21	0.2	0.18	0.12	0.094	0.11	0.085	0.099
			n-nonane	NA	NA	0.21	0.19	0.18	0.16	0.14	0.19	0.19	0.18	0.16	0.11	0.085	0.1	0.076	0.089
			styrene	NA	NA	0.19	0.18	0.17	0.15	0.13	0.15	0.17	0.17	0.15	0.1	0.078	0.093	0.07	0.082
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	10	9.8	8.9	7.3	6.6	6	5.5	5	4.6	3.8	3.4	2.8	2.5	2.3
			toluene	NA	NA	2.4	2.2	2	1.6	1.5	1.3	1.2	1.1	1	0.86	0.77	0.67	0.58	0.52
			2-ethyltoluene	NA	NA	0.17	0.19	0.17	0.12	0.11	0.096	0.088	0.081	0.072	0.061	0.055	0.047	0.042	0.038
		Fracking	benzene	NA	NA	8.4	7.6	7	6.2	5.6	5.1	4.7	4.4	4	3.2	2.9	2.9	2.4	2
			m+p-xylene	NA	NA	1.2	1	0.97	0.86	0.78	0.71	0.65	0.6	0.55	0.45	0.4	0.4	0.33	0.28
			2-ethyltoluene	NA	NA	0.61	0.55	0.5	0.44	0.4	0.36	0.33	0.3	0.28	0.23	0.21	0.21	0.17	0.12
			toluene	NA	NA	0.5	0.45	0.42	0.37	0.34	0.31	0.28	0.26	0.24	0.19	0.17	0.17	0.14	0.12
			3-ethyltoluene	NA	NA	0.38	0.34	0.32	0.28	0.26	0.23	0.21	0.2	0.18	0.15	0.13	0.13	0.11	0.093
			n-decane	NA	NA	0.27	0.24	0.22	0.2	0.18	0.16	0.15	0.14	0.13	0.1	0.091	0.093	0.076	0.065
			methylcyclohexane	NA	NA	0.22	0.2	0.18	0.16	0.15	0.13	0.12	0.11	0.1	0.085	0.075	0.077	0.063	0.054
			cyclohexane	NA	NA	0.21	0.19	0.18	0.16	0.14	0.13	0.12	0.11	0.1	0.086	0.076	0.075	0.062	0.051
			trans-2-butene	NA	NA	0.19	0.17	0.16	0.14	0.13	0.11	0.1	0.096	0.089	0.072	0.065	0.064	0.05	0.047
			n-octane	NA	NA	0.16	0.14	0.13	0.12	0.11	0.096	0.089	0.082	0.075	0.06	0.054	0.055	0.045	0.038
			n-nonane	NA	NA	0.15	0.14	0.13	0.11	0.1	0.092	0.085	0.078	0.072	0.058	0.052	0.052	0.043	0.037
			4-ethyltoluene	NA	NA	0.14	0.13	0.12	0.1	0.094	0.086	0.079	0.073	0.067	0.054	0.048	0.049	0.04	0.034
		Flowback	2-ethyltoluene	NA	NA	19	16	15	13	9	8.1	7.5	6.9	6.3	5.2	4.6	4	3.7	3.1

			benzene	NA	NA	4.7	3.8	3.5	3	2.4	2.2	1.9	1.7	1.8	1.6	1.2	1.1	0.92	0.79
			3-ethyltoluene	NA	NA	1.9	1.7	1.5	1.4	0.94	0.85	0.77	0.71	0.64	0.54	0.47	0.42	0.38	0.33
			4-ethyltoluene	NA	NA	1.3	1.1	1	0.91	0.63	0.57	0.52	0.48	0.44	0.36	0.32	0.28	0.26	0.22
			n-decane	NA	NA	1.2	1.1	0.97	0.86	0.59	0.54	0.49	0.45	0.4	0.34	0.3	0.26	0.24	0.21
			n-propylbenzene	NA	NA	1.2	1	0.92	0.82	0.56	0.51	0.46	0.43	0.39	0.32	0.28	0.25	0.23	0.19
			1,3-diethylbenzene	NA	NA	0.99	0.86	0.78	0.7	0.48	0.43	0.4	0.36	0.33	0.28	0.24	0.21	0.2	0.17
			m+p-xylene	NA	NA	0.88	0.76	0.7	0.62	0.42	0.39	0.35	0.32	0.29	0.24	0.22	0.19	0.17	0.15
			isopropylbenzene	NA	NA	0.78	0.67	0.61	0.54	0.37	0.34	0.31	0.28	0.26	0.21	0.19	0.17	0.15	0.13
			toluene	NA	NA	0.74	0.64	0.58	0.52	0.36	0.32	0.29	0.27	0.24	0.2	0.18	0.16	0.15	0.12
			1,2,3-trimethylbenzene	NA	NA	0.39	0.34	0.31	0.27	0.19	0.17	0.16	0.14	0.13	0.11	0.096	0.084	0.077	0.065
			1,2,4-trimethylbenzene	NA	NA	0.38	0.33	0.3	0.26	0.18	0.16	0.15	0.14	0.13	0.1	0.092	0.081	0.075	0.063
			1,3,5-trimethylbenzene	NA	NA	0.37	0.32	0.29	0.26	0.18	0.16	0.15	0.14	0.12	0.1	0.09	0.079	0.073	0.062
			o-xylene	NA	NA	0.27	0.24	0.22	0.19	0.13	0.12	0.11	0.1	0.09	0.076	0.067	0.058	0.054	0.046
			cyclohexane	NA	NA	0.25	0.2	0.18	0.16	0.13	0.12	0.099	0.09	0.094	0.082	0.065	0.06	0.049	0.041
			methylcyclohexane	NA	NA	0.25	0.22	0.2	0.18	0.12	0.11	0.1	0.093	0.083	0.07	0.062	0.054	0.05	0.043
			n-nonane	NA	NA	0.23	0.2	0.18	0.16	0.11	0.1	0.091	0.084	0.075	0.063	0.056	0.049	0.045	0.038
			styrene	NA	NA	0.21	0.18	0.17	0.15	0.1	0.092	0.084	0.078	0.071	0.059	0.052	0.045	0.042	0.035
	Northern Front Range	Drilling	benzene	NA	NA	14	13	12	11	9	7.9	7.1	6.3	5.7	4.8	4.1	3.6	3.1	2.8
			toluene	NA	NA	3.2	3	2.8	2.4	2	1.8	1.6	1.4	1.3	1.1	0.93	0.81	0.71	0.62
			2-ethyltoluene	NA	NA	0.23	0.21	0.2	0.17	0.15	0.13	0.11	0.1	0.092	0.078	0.066	0.058	0.05	0.044
			cyclohexane	NA	NA	0.11	0.1	0.097	0.084	0.072	0.063	0.056	0.05	0.046	0.038	0.033	0.028	0.025	0.022
		Fracking	benzene	NA	NA	0.85	0.79	0.74	0.66	0.73	0.73	0.73	0.66	0.61	0.51	0.49	0.43	0.41	0.38
			2-ethyltoluene	NA	NA	0.19	0.18	0.16	0.14	0.12	0.11	0.093	0.084	0.076	0.059	0.051	0.045	0.043	0.04
		Flowback	benzene	NA	NA	27	25	23	20	17	14	13	12	11	9.1	7.7	6.7	5.9	5.2
			toluene	NA	NA	0.89	0.83	0.77	0.67	0.58	0.49	0.44	0.4	0.36	0.3	0.26	0.23	0.2	0.17
			3-ethyltoluene	NA	NA	0.88	0.82	0.77	0.66	0.57	0.51	0.43	0.39	0.36	0.3	0.26	0.22	0.2	0.17
			cyclohexane	NA	NA	0.78	0.72	0.67	0.58	0.5	0.42	0.38	0.35	0.32	0.26	0.23	0.2	0.17	0.15
			m+p-xylene	NA	NA	0.56	0.52	0.49	0.42	0.36	0.32	0.28	0.25	0.23	0.19	0.16	0.14	0.12	0.11
			methylcyclohexane	NA	NA	0.36	0.34	0.31	0.27	0.23	0.2	0.18	0.16	0.15	0.12	0.1	0.091	0.08	0.07
			n-hexane	NA	NA	0.35	0.32	0.3	0.26	0.23	0.19	0.17	0.16	0.14	0.12	0.1	0.088	0.077	0.068
			n-decane	NA	NA	0.3	0.28	0.26	0.23	0.2	0.18	0.15	0.14	0.12	0.1	0.089	0.077	0.067	0.06
			n-octane	NA	NA	0.25	0.23	0.22	0.19	0.16	0.16	0.12	0.11	0.1	0.085	0.072	0.063	0.055	0.049
			n-nonane	NA	NA	0.21	0.2	0.18	0.16	0.14	0.12	0.1	0.094	0.086	0.072	0.061	0.053	0.047	0.041
			2-ethyltoluene	NA	NA	0.16	0.15	0.14	0.12	0.1	0.091	0.081	0.073	0.066	0.055	0.046	0.04	0.035	0.031
			o-xylene	NA	NA	0.15	0.14	0.13	0.11	0.098	0.094	0.074	0.068	0.062	0.052	0.044	0.038	0.033	0.03
			2-methylheptane	NA	NA	0.14	0.13	0.12	0.11	0.091	0.077	0.069	0.063	0.058	0.048	0.041	0.036	0.031	0.028
			n-heptane	NA	NA	0.13	0.12	0.11	0.095	0.082	0.069	0.062	0.056	0.052	0.043	0.037	0.032	0.028	0.025

60+ Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	12	11	11	9.8	8.9	8.2	7.6	8.5	7.9	5.7	5	4.5	4.1	5.3
			toluene	NA	NA	2.8	2.6	2.5	2.2	2	1.9	1.7	1.9	1.8	1.3	1.1	1	0.94	1.2
			2-ethyltoluene	NA	NA	0.2	0.18	0.17	0.14	0.12	0.1	0.089	0.14	0.13	0.066	0.058	0.052	0.067	0.043
		Fracking	benzene	NA	NA	10	9.4	8.7	7.6	6.5	5.6	5.1	4.8	4.2	4.2	3.5	3.2	3	2.8
			m+p-xylene	NA	NA	1.4	1.3	1.2	1	0.9	0.79	0.73	0.68	0.64	0.59	0.53	0.45	0.43	0.39
			2-ethyltoluene	NA	NA	0.77	0.72	0.68	0.61	0.56	0.51	0.48	0.42	0.39	0.37	0.33	0.29	0.27	0.24
			toluene	NA	NA	0.62	0.56	0.52	0.46	0.42	0.39	0.36	0.33	0.29	0.29	0.25	0.22	0.21	0.19
			3-ethyltoluene	NA	NA	0.47	0.43	0.4	0.34	0.3	0.28	0.26	0.24	0.23	0.21	0.18	0.16	0.15	0.14
			n-decane	NA	NA	0.33	0.3	0.28	0.25	0.23	0.21	0.19	0.18	0.17	0.16	0.13	0.12	0.11	0.1
			cyclohexane	NA	NA	0.27	0.25	0.23	0.21	0.19	0.18	0.16	0.15	0.14	0.13	0.11	0.1	0.097	0.088
			methylcyclohexane	NA	NA	0.27	0.25	0.23	0.2	0.18	0.17	0.15	0.14	0.13	0.12	0.11	0.095	0.09	0.082
			trans-2-butene	NA	NA	0.25	0.23	0.22	0.2	0.17	0.16	0.15	0.13	0.12	0.12	0.11	0.094	0.085	0.077
			n-nonane	NA	NA	0.19	0.17	0.16	0.14	0.12	0.11	0.099	0.092	0.086	0.08	0.072	0.061	0.058	0.053
			n-octane	NA	NA	0.19	0.18	0.16	0.14	0.12	0.11	0.1	0.096	0.089	0.083	0.071	0.063	0.06	0.055
			4-ethyltoluene	NA	NA	0.17	0.16	0.15	0.13	0.12	0.11	0.1	0.095	0.084	0.079	0.07	0.063	0.06	0.055
			o-xylene	NA	NA	0.12	0.11	0.099	0.085	0.074	0.065	0.061	0.056	0.053	0.049	0.044	0.037	0.036	0.032
		Flowback	2-ethyltoluene	NA	NA	17	16	15	13	11	13	12	15	13	8.9	7	6.3	6.2	7.3
			benzene	NA	NA	4.3	3.9	3.7	3.4	3	3.9	3.8	3.7	3.4	2.2	1.6	2.1	1.6	1.8
			3-ethyltoluene	NA	NA	1.8	1.6	1.5	1.3	1.2	1.4	1.6	1.5	1.4	0.92	0.72	0.85	0.65	0.76
			4-ethyltoluene	NA	NA	1.2	1.1	1	0.9	0.79	1.1	1.1	1	0.93	0.61	0.48	0.57	0.43	0.51
			n-decane	NA	NA	1.1	1	0.97	0.85	0.75	0.88	1	0.97	0.88	0.58	0.46	0.54	0.41	0.48
			n-propylbenzene	NA	NA	1.1	0.97	0.93	0.81	0.71	0.83	0.94	0.91	0.83	0.55	0.43	0.51	0.39	0.45
			1,3-diethylbenzene	NA	NA	0.9	0.83	0.79	0.69	0.6	0.71	0.81	0.78	0.71	0.47	0.37	0.44	0.33	0.39
			m+p-xylene	NA	NA	0.8	0.74	0.7	0.61	0.53	0.73	0.71	0.69	0.63	0.42	0.33	0.39	0.29	0.34
			isopropylbenzene	NA	NA	0.71	0.65	0.61	0.54	0.47	0.55	0.63	0.61	0.55	0.37	0.29	0.34	0.26	0.3
			toluene	NA	NA	0.67	0.62	0.58	0.51	0.45	0.61	0.6	0.58	0.53	0.35	0.27	0.32	0.25	0.29
			1,2,3-trimethylbenzene	NA	NA	0.36	0.33	0.31	0.27	0.24	0.28	0.32	0.31	0.28	0.18	0.14	0.17	0.13	0.15
			1,2,4-trimethylbenzene	NA	NA	0.34	0.32	0.3	0.26	0.23	0.31	0.31	0.3	0.27	0.18	0.14	0.17	0.13	0.15
			1,3,5-trimethylbenzene	NA	NA	0.34	0.31	0.29	0.26	0.22	0.26	0.3	0.29	0.26	0.17	0.14	0.16	0.12	0.14
			o-xylene	NA	NA	0.25	0.23	0.22	0.19	0.17	0.23	0.22	0.21	0.19	0.13	0.1	0.12	0.091	0.11
			cyclohexane	NA	NA	0.23	0.21	0.2	0.18	0.16	0.21	0.2	0.19	0.18	0.12	0.085	0.11	0.082	0.097
			methylcyclohexane	NA	NA	0.23	0.21	0.2	0.18	0.15	0.21	0.21	0.2	0.18	0.12	0.094	0.11	0.085	0.099
			n-nonane	NA	NA	0.21	0.19	0.18	0.16	0.14	0.19	0.19	0.18	0.16	0.11	0.085	0.1	0.076	0.089
			styrene	NA	NA	0.19	0.18	0.17	0.15	0.13	0.15	0.17	0.17	0.15	0.1	0.078	0.093	0.07	0.082
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	10	9.8	8.9	7.3	6.6	6	5.5	5	4.6	3.8	3.4	2.8	2.5	2.3
			toluene	NA	NA	2.4	2.2	2	1.6	1.5	1.3	1.2	1.1	1	0.86	0.77	0.67	0.58	0.52
			2-ethyltoluene	NA	NA	0.17	0.19	0.17	0.12	0.11	0.096	0.088	0.081	0.072	0.061	0.055	0.047	0.042	0.038

(Rifle)	Fracking	benzene	NA	NA	8.4	7.6	7	6.2	5.6	5.1	4.7	4.4	4	3.2	2.9	2.9	2.4	2
		m+p-xylene	NA	NA	1.2	1	0.97	0.86	0.78	0.71	0.65	0.6	0.55	0.45	0.4	0.4	0.33	0.28
		2-ethyltoluene	NA	NA	0.61	0.55	0.5	0.44	0.4	0.36	0.33	0.3	0.28	0.23	0.21	0.21	0.17	0.12
		toluene	NA	NA	0.5	0.45	0.42	0.37	0.34	0.31	0.28	0.26	0.24	0.19	0.17	0.17	0.14	0.12
		3-ethyltoluene	NA	NA	0.38	0.34	0.32	0.28	0.26	0.23	0.21	0.2	0.18	0.15	0.13	0.13	0.11	0.093
		n-decane	NA	NA	0.27	0.24	0.22	0.2	0.18	0.16	0.15	0.14	0.13	0.1	0.091	0.093	0.076	0.065
		methylcyclohexane	NA	NA	0.22	0.2	0.18	0.16	0.15	0.13	0.12	0.11	0.1	0.085	0.075	0.077	0.063	0.054
		cyclohexane	NA	NA	0.21	0.19	0.18	0.16	0.14	0.13	0.12	0.11	0.1	0.086	0.076	0.075	0.062	0.051
		trans-2-butene	NA	NA	0.19	0.17	0.16	0.14	0.13	0.11	0.1	0.096	0.089	0.072	0.065	0.064	0.05	0.047
		n-octane	NA	NA	0.16	0.14	0.13	0.12	0.11	0.096	0.089	0.082	0.075	0.06	0.054	0.055	0.045	0.038
		n-nonane	NA	NA	0.15	0.14	0.13	0.11	0.1	0.092	0.085	0.078	0.072	0.058	0.052	0.052	0.043	0.037
		4-ethyltoluene	NA	NA	0.14	0.13	0.12	0.1	0.094	0.086	0.079	0.073	0.067	0.054	0.048	0.049	0.04	0.034
	Flowback	2-ethyltoluene	NA	NA	19	16	15	13	9	8.1	7.5	6.9	6.3	5.2	4.6	4	3.7	3.1
		benzene	NA	NA	4.7	3.8	3.5	3	2.4	2.2	1.9	1.7	1.8	1.6	1.2	1.1	0.92	0.79
		3-ethyltoluene	NA	NA	1.9	1.7	1.5	1.4	0.94	0.85	0.77	0.71	0.64	0.54	0.47	0.42	0.38	0.33
		4-ethyltoluene	NA	NA	1.3	1.1	1	0.91	0.63	0.57	0.52	0.48	0.44	0.36	0.32	0.28	0.26	0.22
		n-decane	NA	NA	1.2	1.1	0.97	0.86	0.59	0.54	0.49	0.45	0.4	0.34	0.3	0.26	0.24	0.21
		n-propylbenzene	NA	NA	1.2	1	0.92	0.82	0.56	0.51	0.46	0.43	0.39	0.32	0.28	0.25	0.23	0.19
		1,3-diethylbenzene	NA	NA	0.99	0.86	0.78	0.7	0.48	0.43	0.4	0.36	0.33	0.28	0.24	0.21	0.2	0.17
		m+p-xylene	NA	NA	0.88	0.76	0.7	0.62	0.42	0.39	0.35	0.32	0.29	0.24	0.22	0.19	0.17	0.15
		isopropylbenzene	NA	NA	0.78	0.67	0.61	0.54	0.37	0.34	0.31	0.28	0.26	0.21	0.19	0.17	0.15	0.13
		toluene	NA	NA	0.74	0.64	0.58	0.52	0.36	0.32	0.29	0.27	0.24	0.2	0.18	0.16	0.15	0.12
		1,2,3-trimethylbenzene	NA	NA	0.39	0.34	0.31	0.27	0.19	0.17	0.16	0.14	0.13	0.11	0.096	0.084	0.077	0.065
		1,2,4-trimethylbenzene	NA	NA	0.38	0.33	0.3	0.26	0.18	0.16	0.15	0.14	0.13	0.1	0.092	0.081	0.075	0.063
		1,3,5-trimethylbenzene	NA	NA	0.37	0.32	0.29	0.26	0.18	0.16	0.15	0.14	0.12	0.1	0.09	0.079	0.073	0.062
		o-xylene	NA	NA	0.27	0.24	0.22	0.19	0.13	0.12	0.11	0.1	0.09	0.076	0.067	0.058	0.054	0.046
		cyclohexane	NA	NA	0.25	0.2	0.18	0.16	0.13	0.12	0.099	0.09	0.094	0.082	0.065	0.06	0.049	0.041
		methylcyclohexane	NA	NA	0.25	0.22	0.2	0.18	0.12	0.11	0.1	0.093	0.083	0.07	0.062	0.054	0.05	0.043
		n-nonane	NA	NA	0.23	0.2	0.18	0.16	0.11	0.1	0.091	0.084	0.075	0.063	0.056	0.049	0.045	0.038
		styrene	NA	NA	0.21	0.18	0.17	0.15	0.1	0.092	0.084	0.078	0.071	0.059	0.052	0.045	0.042	0.035
Northern Front Range	Drilling	benzene	NA	NA	14	13	12	11	9	7.9	7.1	6.3	5.7	4.8	4.1	3.6	3.1	2.8
		toluene	NA	NA	3.2	3	2.8	2.4	2	1.8	1.6	1.4	1.3	1.1	0.93	0.81	0.71	0.62
		2-ethyltoluene	NA	NA	0.23	0.21	0.2	0.17	0.15	0.13	0.11	0.1	0.092	0.078	0.066	0.058	0.05	0.044
		cyclohexane	NA	NA	0.11	0.1	0.097	0.084	0.072	0.063	0.056	0.05	0.046	0.038	0.033	0.028	0.025	0.022
	Fracking	benzene	NA	NA	0.85	0.79	0.74	0.66	0.73	0.73	0.73	0.66	0.61	0.51	0.49	0.43	0.41	0.38
		2-ethyltoluene	NA	NA	0.19	0.18	0.16	0.14	0.12	0.11	0.093	0.084	0.076	0.059	0.051	0.045	0.043	0.04
	Flowback	benzene	NA	NA	27	25	23	20	17	14	13	12	11	9.1	7.7	6.7	5.9	5.2

			toluene	NA	NA	0.89	0.83	0.77	0.67	0.58	0.49	0.44	0.4	0.36	0.3	0.26	0.23	0.2	0.17
			3-ethyltoluene	NA	NA	0.88	0.82	0.77	0.66	0.57	0.51	0.43	0.39	0.36	0.3	0.26	0.22	0.2	0.17
			cyclohexane	NA	NA	0.78	0.72	0.67	0.58	0.5	0.42	0.38	0.35	0.32	0.26	0.23	0.2	0.17	0.15
			m+p-xylene	NA	NA	0.56	0.52	0.49	0.42	0.36	0.32	0.28	0.25	0.23	0.19	0.16	0.14	0.12	0.11
			methylcyclohexane	NA	NA	0.36	0.34	0.31	0.27	0.23	0.2	0.18	0.16	0.15	0.12	0.1	0.091	0.08	0.07
			n-hexane	NA	NA	0.35	0.32	0.3	0.26	0.23	0.19	0.17	0.16	0.14	0.12	0.1	0.088	0.077	0.068
			n-decane	NA	NA	0.3	0.28	0.26	0.23	0.2	0.18	0.15	0.14	0.12	0.1	0.089	0.077	0.067	0.06
			n-octane	NA	NA	0.25	0.23	0.22	0.19	0.16	0.16	0.12	0.11	0.1	0.085	0.072	0.063	0.055	0.049
			n-nonane	NA	NA	0.21	0.2	0.18	0.16	0.14	0.12	0.1	0.094	0.086	0.072	0.061	0.053	0.047	0.041
			2-ethyltoluene	NA	NA	0.16	0.15	0.14	0.12	0.1	0.091	0.081	0.073	0.066	0.055	0.046	0.04	0.035	0.031
			o-xylene	NA	NA	0.15	0.14	0.13	0.11	0.098	0.094	0.074	0.068	0.062	0.052	0.044	0.038	0.033	0.03
			2-methylheptane	NA	NA	0.14	0.13	0.12	0.11	0.091	0.077	0.069	0.063	0.058	0.048	0.041	0.036	0.031	0.028
			n-heptane	NA	NA	0.13	0.12	0.11	0.095	0.082	0.069	0.062	0.056	0.052	0.043	0.037	0.032	0.028	0.025

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-2. Percentage of Daily-maximum Acute Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 1-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	100%	100%	99%	98%	95%	91%	86%	89%	87%	76%	66%	57%	51%	39%
			toluene	NA	NA	71%	62%	53%	32%	16%	6%	3%	14%	12%	4%	1%	0%	0%	1%
		Fracking	benzene	NA	NA	100%	99%	98%	96%	92%	86%	79%	70%	60%	45%	28%	18%	14%	10%
			m+p-xylene	NA	NA	6%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	96%	94%	91%	88%	81%	81%	77%	74%	69%	44%	22%	26%	16%	13%
			2-ethyltoluene	NA	NA	82%	78%	75%	69%	65%	61%	58%	58%	55%	48%	48%	43%	42%	39%
			3-ethyltoluene	NA	NA	21%	14%	10%	7%	3%	4%	3%	3%	3%	0%	0%	0%	0%	0%
			4-ethyltoluene	NA	NA	3%	1%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%
			n-decane	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-propylbenzene	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	100%	100%	100%	99%	98%	97%	96%	95%	93%	89%	82%	74%	64%	52%
			toluene	NA	NA	77%	71%	63%	44%	32%	19%	9%	2%	0%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	100%	99%	99%	98%	97%	96%	94%	93%	90%	84%	76%	65%	51%	32%
			m+p-xylene	NA	NA	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	97%	95%	93%	88%	81%	75%	67%	59%	47%	18%	3%	1%	0%	0%
			2-ethyltoluene	NA	NA	86%	82%	78%	72%	67%	66%	65%	65%	64%	62%	59%	57%	55%	51%

			3-ethyltoluene	NA	NA	28%	20%	13%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			4-ethyltoluene	NA	NA	4%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-decane	NA	NA	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-propylbenzene	NA	NA	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	benzene	NA	NA	100%	100%	100%	99%	97%	95%	92%	88%	84%	76%	64%	53%	41%	30%
			toluene	NA	NA	79%	73%	65%	48%	29%	14%	6%	4%	2%	1%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	100%	100%	100%	100%	100%	100%	100%	99%	99%	97%	94%	90%	86%	80%
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	100%	100%	99%	97%	95%	91%	86%	89%	87%	76%	66%	57%	51%	39%
			toluene	NA	NA	70%	61%	52%	32%	16%	6%	3%	14%	11%	4%	1%	0%	0%	1%
		Fracking	benzene	NA	NA	100%	99%	98%	96%	92%	86%	78%	70%	60%	44%	28%	18%	14%	10%
			m+p-xylene	NA	NA	6%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	96%	94%	91%	87%	81%	80%	76%	73%	69%	43%	22%	26%	15%	13%
			2-ethyltoluene	NA	NA	82%	78%	75%	69%	65%	61%	58%	58%	55%	48%	48%	43%	42%	39%
			3-ethyltoluene	NA	NA	20%	14%	10%	7%	3%	4%	3%	3%	3%	0%	0%	0%	0%	0%
			4-ethyltoluene	NA	NA	3%	1%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%
			n-decane	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-propylbenzene	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	100%	100%	100%	99%	98%	97%	96%	94%	92%	88%	81%	73%	63%	51%
			toluene	NA	NA	76%	70%	62%	42%	31%	18%	9%	2%	0%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	100%	99%	99%	98%	97%	96%	94%	92%	90%	83%	74%	63%	49%	31%
			m+p-xylene	NA	NA	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	97%	95%	92%	87%	79%	72%	64%	55%	43%	17%	3%	1%	0%	0%
			2-ethyltoluene	NA	NA	86%	81%	78%	71%	67%	66%	65%	65%	64%	62%	59%	57%	55%	51%
			3-ethyltoluene	NA	NA	27%	20%	12%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			4-ethyltoluene	NA	NA	4%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-decane	NA	NA	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-propylbenzene	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	benzene	NA	NA	100%	100%	100%	98%	97%	94%	91%	88%	84%	75%	63%	52%	40%	30%
			toluene	NA	NA	78%	71%	64%	46%	28%	14%	6%	4%	2%	1%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	100%	100%	100%	100%	100%	100%	100%	99%	98%	96%	93%	90%	85%	79%
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	99%	99%	98%	96%	93%	89%	83%	87%	85%	74%	64%	55%	49%	38%
			toluene	NA	NA	66%	58%	49%	30%	15%	6%	3%	13%	11%	4%	1%	0%	0%	1%
		Fracking	benzene	NA	NA	99%	97%	96%	93%	89%	83%	76%	67%	57%	43%	27%	17%	13%	10%
			m+p-xylene	NA	NA	6%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	92%	89%	87%	83%	77%	77%	74%	70%	66%	41%	20%	25%	14%	13%
			2-ethyltoluene	NA	NA	81%	77%	74%	69%	65%	60%	58%	57%	55%	47%	47%	42%	41%	38%
			3-ethyltoluene	NA	NA	19%	13%	9%	6%	2%	4%	3%	3%	2%	0%	0%	0%	0%	0%

			4-ethyltoluene	NA	NA	2%	1%	0%	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%
			n-decane	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-propylbenzene	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	100%	100%	99%	97%	96%	95%	93%	92%	90%	85%	78%	70%	60%	49%
			toluene	NA	NA	72%	67%	59%	40%	29%	17%	8%	2%	0%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	99%	98%	97%	96%	95%	93%	91%	89%	86%	79%	70%	60%	46%	29%
			m+p-xylene	NA	NA	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	94%	90%	88%	82%	74%	67%	60%	51%	41%	16%	3%	1%	0%	0%
			2-ethyltoluene	NA	NA	85%	80%	77%	71%	67%	66%	65%	64%	63%	61%	59%	56%	54%	50%
			3-ethyltoluene	NA	NA	26%	19%	12%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			4-ethyltoluene	NA	NA	4%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-decane	NA	NA	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-propylbenzene	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	benzene	NA	NA	100%	100%	99%	97%	95%	92%	89%	86%	81%	73%	61%	50%	39%	29%
			toluene	NA	NA	75%	68%	61%	44%	27%	13%	6%	4%	2%	1%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	100%	100%	100%	100%	100%	100%	99%	98%	97%	95%	91%	87%	83%	77%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity.

Table E-3. Largest Acute Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 1-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	12	11	11	9.8	8.9	8.2	7.7	8.5	7.9	5.7	5	4.5	4.1	5.3
			neurotoxicity	NA	NA	3	2.8	2.6	2.4	2.2	2	1.9	2.1	1.9	1.4	1.2	1.1	1	1.3
			respiratory	NA	NA	0.14	0.13	0.12	0.11	0.1	0.095	0.088	0.098	0.091	0.066	0.058	0.051	0.048	0.049
		Fracking	hematological	NA	NA	11	9.7	9	7.8	6.7	5.8	5.3	4.9	4.3	4.3	3.6	3.3	3.1	2.8
			neurotoxicity	NA	NA	2.9	2.7	2.5	2.1	1.9	1.7	1.6	1.4	1.3	1.3	1.1	0.96	0.91	0.83
			respiratory	NA	NA	1.6	1.4	1.3	1.1	0.98	0.87	0.8	0.75	0.7	0.65	0.58	0.5	0.47	0.43
			sensory	NA	NA	0.33	0.3	0.28	0.25	0.23	0.21	0.2	0.18	0.17	0.16	0.14	0.12	0.12	0.11
			systemic	NA	NA	0.25	0.23	0.22	0.2	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.095	0.085	0.077
		Flowback	hematological	NA	NA	4.6	4.2	4	3.7	3.2	4.1	4.1	4	3.6	2.4	1.8	2.2	1.7	2
			neurotoxicity	NA	NA	3.4	3.1	3	2.6	2.3	2.9	3	2.9	2.7	1.8	1.4	1.6	1.2	1.5
			respiratory	NA	NA	1.3	1.2	1.1	0.96	0.84	1.1	1.1	1.1	0.99	0.66	0.51	0.61	0.46	0.54
			sensory	NA	NA	1.2	1.1	1	0.88	0.77	0.91	1	1	0.91	0.6	0.47	0.56	0.42	0.5
	Garfield	Drilling	hematological	NA	NA	10	9.8	8.9	7.3	6.6	6	5.5	5	4.6	3.8	3.4	2.8	2.5	2.3

	County: Valley (Rifle)		neurotoxicity	NA	NA	2.5	2.4	2.2	1.8	1.6	1.5	1.3	1.2	1.1	0.92	0.83	0.69	0.62	0.56
			respiratory	NA	NA	0.12	0.11	0.1	0.084	0.075	0.069	0.063	0.058	0.052	0.043	0.039	0.033	0.029	0.026
		Fracking	hematological	NA	NA	8.7	7.8	7.2	6.4	5.8	5.3	4.9	4.5	4.1	3.3	3	3	2.5	2.1
			neurotoxicity	NA	NA	2.4	2.2	2	1.8	1.6	1.5	1.3	1.2	1.1	0.91	0.81	0.83	0.68	0.58
			respiratory	NA	NA	1.3	1.1	1.1	0.94	0.85	0.77	0.71	0.66	0.6	0.49	0.43	0.44	0.36	0.31
			sensory	NA	NA	0.27	0.25	0.23	0.2	0.18	0.17	0.15	0.14	0.13	0.1	0.093	0.095	0.078	0.066
			systemic	NA	NA	0.19	0.17	0.16	0.14	0.13	0.12	0.11	0.097	0.09	0.072	0.065	0.064	0.05	0.048
		Flowback	hematological	NA	NA	5.1	4.2	3.8	3.4	2.6	2.4	2	1.9	1.9	1.7	1.3	1.2	0.99	0.85
			neurotoxicity	NA	NA	3.7	3.3	3	2.6	1.8	1.6	1.5	1.4	1.2	1	0.91	0.8	0.74	0.63
			respiratory	NA	NA	1.4	1.2	1.1	0.97	0.67	0.61	0.55	0.51	0.46	0.38	0.34	0.3	0.27	0.23
			sensory	NA	NA	1.3	1.1	1	0.89	0.61	0.56	0.51	0.47	0.42	0.35	0.31	0.27	0.25	0.21
	Northern Front Range	Drilling	hematological	NA	NA	14	13	12	11	9	7.9	7.1	6.4	5.7	4.8	4.1	3.6	3.1	2.8
			neurotoxicity	NA	NA	3.4	3.2	3	2.6	2.2	1.9	1.7	1.5	1.4	1.2	1	0.87	0.76	0.67
			respiratory	NA	NA	0.16	0.15	0.14	0.12	0.1	0.081	0.077	0.066	0.058	0.055	0.047	0.041	0.036	0.032
		Fracking	hematological	NA	NA	0.87	0.81	0.76	0.68	0.75	0.75	0.74	0.67	0.62	0.52	0.5	0.44	0.41	0.39
		Flowback	hematological	NA	NA	27	25	23	20	17	15	13	12	11	9.2	7.8	6.8	6	5.3
			neurotoxicity	NA	NA	3.5	3.2	3	2.6	2.2	1.9	1.7	1.5	1.4	1.2	1	0.88	0.77	0.68
			respiratory	NA	NA	0.79	0.74	0.69	0.6	0.51	0.45	0.39	0.35	0.32	0.27	0.23	0.2	0.18	0.15
			endocrine	NA	NA	0.35	0.32	0.3	0.26	0.23	0.19	0.17	0.16	0.14	0.12	0.1	0.088	0.077	0.068
			sensory	NA	NA	0.31	0.29	0.27	0.23	0.2	0.18	0.15	0.14	0.13	0.11	0.09	0.079	0.069	0.061
			systemic	NA	NA	0.14	0.13	0.12	0.1	0.09	0.076	0.068	0.062	0.057	0.047	0.04	0.035	0.031	0.027
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	12	11	11	9.8	8.9	8.2	7.7	8.5	7.9	5.7	5	4.5	4.1	5.3
			neurotoxicity	NA	NA	3	2.8	2.6	2.4	2.2	2	1.9	2.1	1.9	1.4	1.2	1.1	1	1.3
			respiratory	NA	NA	0.14	0.13	0.12	0.11	0.1	0.095	0.088	0.098	0.091	0.066	0.058	0.051	0.048	0.049
		Fracking	hematological	NA	NA	11	9.7	9	7.8	6.7	5.8	5.3	4.9	4.3	4.3	3.6	3.3	3.1	2.8
			neurotoxicity	NA	NA	2.9	2.7	2.5	2.1	1.9	1.7	1.6	1.4	1.3	1.3	1.1	0.96	0.91	0.83
			respiratory	NA	NA	1.6	1.4	1.3	1.1	0.98	0.87	0.8	0.75	0.7	0.65	0.58	0.5	0.47	0.43
			sensory	NA	NA	0.33	0.3	0.28	0.25	0.23	0.21	0.2	0.18	0.17	0.16	0.14	0.12	0.12	0.11
			systemic	NA	NA	0.25	0.23	0.22	0.2	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.095	0.085	0.077
		Flowback	hematological	NA	NA	4.6	4.2	4	3.7	3.2	4.1	4.1	4	3.6	2.4	1.8	2.2	1.7	2
			neurotoxicity	NA	NA	3.4	3.1	3	2.6	2.3	2.9	3	2.9	2.7	1.8	1.4	1.6	1.2	1.5
			respiratory	NA	NA	1.3	1.2	1.1	0.96	0.84	1.1	1.1	1.1	0.99	0.66	0.51	0.61	0.46	0.54
			sensory	NA	NA	1.2	1.1	1	0.88	0.77	0.91	1	1	0.91	0.6	0.47	0.56	0.42	0.5
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	10	9.8	8.9	7.3	6.6	6	5.5	5	4.6	3.8	3.4	2.8	2.5	2.3
			neurotoxicity	NA	NA	2.5	2.4	2.2	1.8	1.6	1.5	1.3	1.2	1.1	0.92	0.83	0.69	0.62	0.56
			respiratory	NA	NA	0.12	0.11	0.1	0.084	0.075	0.069	0.063	0.058	0.052	0.043	0.039	0.033	0.029	0.026
		Fracking	hematological	NA	NA	8.7	7.8	7.2	6.4	5.8	5.3	4.9	4.5	4.1	3.3	3	3	2.5	2.1

			neurotoxicity	NA	NA	2.4	2.2	2	1.8	1.6	1.5	1.3	1.2	1.1	0.91	0.81	0.83	0.68	0.58
			respiratory	NA	NA	1.3	1.1	1.1	0.94	0.85	0.77	0.71	0.66	0.6	0.49	0.43	0.44	0.36	0.31
			sensory	NA	NA	0.27	0.25	0.23	0.2	0.18	0.17	0.15	0.14	0.13	0.1	0.093	0.095	0.078	0.066
			systemic	NA	NA	0.19	0.17	0.16	0.14	0.13	0.12	0.11	0.097	0.09	0.072	0.065	0.064	0.05	0.048
		Flowback	hematological	NA	NA	5.1	4.2	3.8	3.4	2.6	2.4	2	1.9	1.9	1.7	1.3	1.2	0.99	0.85
			neurotoxicity	NA	NA	3.7	3.3	3	2.6	1.8	1.6	1.5	1.4	1.2	1	0.91	0.8	0.74	0.63
			respiratory	NA	NA	1.4	1.2	1.1	0.97	0.67	0.61	0.55	0.51	0.46	0.38	0.34	0.3	0.27	0.23
			sensory	NA	NA	1.3	1.1	1	0.89	0.61	0.56	0.51	0.47	0.42	0.35	0.31	0.27	0.25	0.21
	Northern Front Range	Drilling	hematological	NA	NA	14	13	12	11	9	7.9	7.1	6.4	5.7	4.8	4.1	3.6	3.1	2.8
			neurotoxicity	NA	NA	3.4	3.2	3	2.6	2.2	1.9	1.7	1.5	1.4	1.2	1	0.87	0.76	0.67
			respiratory	NA	NA	0.16	0.15	0.14	0.12	0.1	0.081	0.077	0.066	0.058	0.055	0.047	0.041	0.036	0.032
		Fracking	hematological	NA	NA	0.87	0.81	0.76	0.68	0.75	0.75	0.74	0.67	0.62	0.52	0.5	0.44	0.41	0.39
		Flowback	hematological	NA	NA	27	25	23	20	17	15	13	12	11	9.2	7.8	6.8	6	5.3
			neurotoxicity	NA	NA	3.5	3.2	3	2.6	2.2	1.9	1.7	1.5	1.4	1.2	1	0.88	0.77	0.68
			respiratory	NA	NA	0.79	0.74	0.69	0.6	0.51	0.45	0.39	0.35	0.32	0.27	0.23	0.2	0.18	0.15
			endocrine	NA	NA	0.35	0.32	0.3	0.26	0.23	0.19	0.17	0.16	0.14	0.12	0.1	0.088	0.077	0.068
			sensory	NA	NA	0.31	0.29	0.27	0.23	0.2	0.18	0.15	0.14	0.13	0.11	0.09	0.079	0.069	0.061
			systemic	NA	NA	0.14	0.13	0.12	0.1	0.09	0.076	0.068	0.062	0.057	0.047	0.04	0.035	0.031	0.027
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	12	11	11	9.8	8.9	8.2	7.7	8.5	7.9	5.7	5	4.5	4.1	5.3
			neurotoxicity	NA	NA	3	2.8	2.6	2.4	2.2	2	1.9	2.1	1.9	1.4	1.2	1.1	1	1.3
			respiratory	NA	NA	0.14	0.13	0.12	0.11	0.1	0.095	0.088	0.098	0.091	0.066	0.058	0.051	0.048	0.049
		Fracking	hematological	NA	NA	11	9.7	9	7.8	6.7	5.8	5.3	4.9	4.3	4.3	3.6	3.3	3.1	2.8
			neurotoxicity	NA	NA	2.9	2.7	2.5	2.1	1.9	1.7	1.6	1.4	1.3	1.3	1.1	0.96	0.91	0.83
			respiratory	NA	NA	1.6	1.4	1.3	1.1	0.98	0.87	0.8	0.75	0.7	0.65	0.58	0.5	0.47	0.43
			sensory	NA	NA	0.33	0.3	0.28	0.25	0.23	0.21	0.2	0.18	0.17	0.16	0.14	0.12	0.12	0.11
			systemic	NA	NA	0.25	0.23	0.22	0.2	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.095	0.085	0.077
		Flowback	hematological	NA	NA	4.6	4.2	4	3.7	3.2	4.1	4.1	4	3.6	2.4	1.8	2.2	1.7	2
			neurotoxicity	NA	NA	3.4	3.1	3	2.6	2.3	2.9	3	2.9	2.7	1.8	1.4	1.6	1.2	1.5
			respiratory	NA	NA	1.3	1.2	1.1	0.96	0.84	1.1	1.1	1.1	0.99	0.66	0.51	0.61	0.46	0.54
			sensory	NA	NA	1.2	1.1	1	0.88	0.77	0.91	1	1	0.91	0.6	0.47	0.56	0.42	0.5
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	10	9.8	8.9	7.3	6.6	6	5.5	5	4.6	3.8	3.4	2.8	2.5	2.3
			neurotoxicity	NA	NA	2.5	2.4	2.2	1.8	1.6	1.5	1.3	1.2	1.1	0.92	0.83	0.69	0.62	0.56
			respiratory	NA	NA	0.12	0.11	0.1	0.084	0.075	0.069	0.063	0.058	0.052	0.043	0.039	0.033	0.029	0.026
		Fracking	hematological	NA	NA	8.7	7.8	7.2	6.4	5.8	5.3	4.9	4.5	4.1	3.3	3	3	2.5	2.1
			neurotoxicity	NA	NA	2.4	2.2	2	1.8	1.6	1.5	1.3	1.2	1.1	0.91	0.81	0.83	0.68	0.58
			respiratory	NA	NA	1.3	1.1	1.1	0.94	0.85	0.77	0.71	0.66	0.6	0.49	0.43	0.44	0.36	0.31
			sensory	NA	NA	0.27	0.25	0.23	0.2	0.18	0.17	0.15	0.14	0.13	0.1	0.093	0.095	0.078	0.066

			systemic	NA	NA	0.19	0.17	0.16	0.14	0.13	0.12	0.11	0.097	0.09	0.072	0.065	0.064	0.05	0.048
		Flowback	hematological	NA	NA	5.1	4.2	3.8	3.4	2.6	2.4	2	1.9	1.9	1.7	1.3	1.2	0.99	0.85
			neurotoxicity	NA	NA	3.7	3.3	3	2.6	1.8	1.6	1.5	1.4	1.2	1	0.91	0.8	0.74	0.63
			respiratory	NA	NA	1.4	1.2	1.1	0.97	0.67	0.61	0.55	0.51	0.46	0.38	0.34	0.3	0.27	0.23
			sensory	NA	NA	1.3	1.1	1	0.89	0.61	0.56	0.51	0.47	0.42	0.35	0.31	0.27	0.25	0.21
	Northern Front Range	Drilling	hematological	NA	NA	14	13	12	11	9	7.9	7.1	6.4	5.7	4.8	4.1	3.6	3.1	2.8
			neurotoxicity	NA	NA	3.4	3.2	3	2.6	2.2	1.9	1.7	1.5	1.4	1.2	1	0.87	0.76	0.67
			respiratory	NA	NA	0.16	0.15	0.14	0.12	0.1	0.081	0.077	0.066	0.058	0.055	0.047	0.041	0.036	0.032
		Fracking	hematological	NA	NA	0.87	0.81	0.76	0.68	0.75	0.75	0.74	0.67	0.62	0.52	0.5	0.44	0.41	0.39
		Flowback	hematological	NA	NA	27	25	23	20	17	15	13	12	11	9.2	7.8	6.8	6	5.3
			neurotoxicity	NA	NA	3.5	3.2	3	2.6	2.2	1.9	1.7	1.5	1.4	1.2	1	0.88	0.77	0.68
			respiratory	NA	NA	0.79	0.74	0.69	0.6	0.51	0.45	0.39	0.35	0.32	0.27	0.23	0.2	0.18	0.15
			endocrine	NA	NA	0.35	0.32	0.3	0.26	0.23	0.19	0.17	0.16	0.14	0.12	0.1	0.088	0.077	0.068
			sensory	NA	NA	0.31	0.29	0.27	0.23	0.2	0.18	0.15	0.14	0.13	0.11	0.09	0.079	0.069	0.061
			systemic	NA	NA	0.14	0.13	0.12	0.1	0.09	0.076	0.068	0.062	0.057	0.047	0.04	0.035	0.031	0.027

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D).

Table E-4. Percentage of Daily-maximum Acute Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 1-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	100%	100%	99%	98%	95%	91%	86%	89%	87%	76%	66%	57%	51%	39%
			neurotoxicity	NA	NA	75%	66%	58%	38%	20%	8%	3%	17%	13%	5%	2%	1%	0%	1%
		Fracking	hematological	NA	NA	100%	99%	98%	96%	93%	87%	80%	72%	62%	47%	31%	20%	15%	11%
			neurotoxicity	NA	NA	68%	58%	48%	28%	14%	6%	3%	1%	1%	1%	1%	0%	0%	0%
			respiratory	NA	NA	10%	5%	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	97%	95%	94%	91%	86%	84%	82%	79%	75%	52%	31%	35%	24%	20%
			neurotoxicity	NA	NA	63%	53%	46%	37%	28%	23%	19%	15%	12%	6%	3%	2%	2%	1%
			respiratory	NA	NA	4%	2%	1%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%
			sensory	NA	NA	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	100%	100%	100%	99%	98%	97%	96%	95%	93%	89%	82%	75%	65%	52%
			neurotoxicity	NA	NA	80%	75%	68%	49%	38%	27%	15%	7%	2%	0%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	100%	100%	99%	98%	97%	96%	95%	93%	91%	85%	77%	67%	53%	36%
			neurotoxicity	NA	NA	75%	66%	58%	43%	28%	15%	7%	3%	1%	0%	0%	0%	0%	0%

			respiratory	NA	NA	7%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	98%	96%	95%	91%	86%	81%	75%	68%	60%	37%	11%	1%	0%	0%
			neurotoxicity	NA	NA	71%	59%	51%	41%	35%	30%	24%	18%	10%	0%	0%	0%	0%	0%
			respiratory	NA	NA	7%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			sensory	NA	NA	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	hematological	NA	NA	100%	100%	100%	99%	97%	95%	92%	88%	84%	76%	65%	53%	41%	31%
			neurotoxicity	NA	NA	82%	76%	69%	53%	35%	19%	9%	5%	3%	1%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	100%	100%	100%	100%	100%	100%	100%	99%	99%	97%	94%	91%	86%	81%
			neurotoxicity	NA	NA	85%	78%	71%	54%	39%	21%	12%	8%	5%	1%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	100%	100%	99%	97%	95%	91%	86%	89%	87%	76%	66%	57%	51%	39%
			neurotoxicity	NA	NA	74%	66%	57%	37%	20%	8%	3%	16%	13%	5%	2%	1%	0%	1%
		Fracking	hematological	NA	NA	100%	99%	98%	96%	93%	87%	80%	71%	62%	47%	31%	20%	15%	11%
			neurotoxicity	NA	NA	68%	57%	48%	28%	13%	6%	3%	1%	1%	1%	1%	0%	0%	0%
			respiratory	NA	NA	10%	5%	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	97%	95%	93%	90%	85%	84%	81%	78%	74%	51%	30%	34%	23%	20%
			neurotoxicity	NA	NA	62%	53%	46%	37%	27%	23%	18%	15%	12%	5%	3%	2%	2%	1%
			respiratory	NA	NA	4%	2%	1%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%
			sensory	NA	NA	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	100%	100%	100%	99%	98%	97%	96%	94%	92%	88%	81%	73%	63%	51%
			neurotoxicity	NA	NA	79%	74%	67%	48%	37%	26%	15%	7%	1%	0%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	100%	100%	99%	98%	97%	96%	95%	93%	91%	84%	76%	65%	52%	34%
			neurotoxicity	NA	NA	73%	64%	56%	42%	27%	15%	6%	2%	1%	0%	0%	0%	0%	0%
			respiratory	NA	NA	6%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	98%	96%	94%	90%	85%	79%	73%	66%	57%	34%	10%	1%	0%	0%
			neurotoxicity	NA	NA	70%	58%	51%	41%	34%	29%	24%	18%	10%	0%	0%	0%	0%	0%
			respiratory	NA	NA	7%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			sensory	NA	NA	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	hematological	NA	NA	100%	100%	100%	99%	97%	94%	91%	88%	84%	75%	64%	52%	40%	30%
			neurotoxicity	NA	NA	81%	75%	68%	52%	34%	19%	8%	5%	3%	1%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	100%	100%	100%	100%	100%	100%	100%	99%	98%	96%	94%	90%	85%	80%
			neurotoxicity	NA	NA	83%	77%	70%	53%	38%	21%	12%	7%	5%	1%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	99%	99%	98%	96%	93%	89%	83%	87%	85%	74%	64%	55%	49%	38%
			neurotoxicity	NA	NA	70%	62%	54%	35%	19%	8%	3%	16%	13%	4%	2%	1%	0%	1%
		Fracking	hematological	NA	NA	99%	98%	97%	94%	90%	84%	77%	69%	60%	45%	29%	19%	14%	11%
			neurotoxicity	NA	NA	64%	54%	45%	27%	13%	6%	3%	1%	1%	1%	1%	0%	0%	0%
			respiratory	NA	NA	9%	5%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	94%	92%	89%	86%	81%	81%	78%	75%	72%	49%	29%	33%	22%	19%

			neurotoxicity	NA	NA	60%	51%	44%	36%	26%	22%	18%	15%	12%	5%	3%	2%	2%	1%
			respiratory	NA	NA	4%	2%	1%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%
			sensory	NA	NA	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	100%	100%	99%	97%	96%	95%	93%	92%	90%	85%	78%	70%	60%	49%
			neurotoxicity	NA	NA	76%	71%	64%	45%	35%	24%	14%	6%	1%	0%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	99%	98%	98%	96%	95%	94%	92%	90%	87%	81%	72%	62%	49%	32%
			neurotoxicity	NA	NA	69%	60%	53%	39%	25%	14%	6%	2%	1%	0%	0%	0%	0%	0%
			respiratory	NA	NA	6%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	95%	92%	90%	86%	80%	74%	68%	61%	53%	32%	10%	1%	0%	0%
			neurotoxicity	NA	NA	68%	57%	49%	40%	33%	28%	22%	17%	9%	0%	0%	0%	0%	0%
			respiratory	NA	NA	7%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			sensory	NA	NA	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	hematological	NA	NA	100%	100%	99%	97%	95%	92%	89%	86%	81%	73%	62%	50%	39%	29%
			neurotoxicity	NA	NA	78%	72%	65%	49%	33%	18%	8%	5%	3%	1%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	100%	100%	100%	100%	100%	100%	99%	98%	97%	95%	92%	88%	83%	77%
			neurotoxicity	NA	NA	81%	74%	67%	50%	36%	20%	12%	7%	4%	1%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D).

E.1.1.2 3-acre Well Pad

Table E-5. Largest Acute Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 3-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	9.5	8.9	8.7	8	6.6	5.6	5	8	7.7	5.1	4.7	4.3	3.9	4.9
			toluene	NA	NA	2.2	2.1	2	1.8	1.5	1.3	1.1	1.8	1.7	1.2	1.1	0.96	0.87	1.1
			2-ethyltoluene	NA	NA	0.16	0.15	0.14	0.12	0.098	0.083	0.072	0.13	0.12	0.059	0.054	0.049	0.045	0.056
		Fracking	benzene	NA	NA	8.4	7.9	7.5	6.7	5.1	4.2	3.6	3.3	3	3.7	3.4	3.1	2.8	2.6
			m+p-xylene	NA	NA	1.2	1.1	1	0.93	0.71	0.59	0.52	0.47	0.43	0.53	0.48	0.44	0.4	0.37
			2-ethyltoluene	NA	NA	0.58	0.56	0.54	0.5	0.4	0.35	0.31	0.28	0.26	0.22	0.19	0.17	0.15	0.13
			toluene	NA	NA	0.5	0.47	0.45	0.4	0.31	0.25	0.22	0.2	0.19	0.23	0.21	0.19	0.17	0.16
			3-ethyltoluene	NA	NA	0.38	0.36	0.34	0.3	0.23	0.19	0.17	0.16	0.15	0.18	0.16	0.15	0.13	0.12
			n-decane	NA	NA	0.27	0.25	0.24	0.21	0.16	0.14	0.12	0.11	0.1	0.12	0.11	0.1	0.093	0.085
			methylcyclohexane	NA	NA	0.22	0.21	0.2	0.18	0.13	0.11	0.1	0.091	0.084	0.098	0.089	0.081	0.074	0.068

		cyclohexane	NA	NA	0.21	0.2	0.19	0.17	0.14	0.12	0.11	0.097	0.089	0.093	0.084	0.077	0.07	0.064
		trans-2-butene	NA	NA	0.19	0.18	0.17	0.15	0.13	0.11	0.099	0.089	0.082	0.075	0.065	0.057	0.05	0.044
		n-octane	NA	NA	0.16	0.15	0.14	0.13	0.096	0.08	0.069	0.063	0.058	0.071	0.065	0.059	0.054	0.049
		n-nonane	NA	NA	0.15	0.14	0.13	0.12	0.092	0.076	0.067	0.061	0.056	0.068	0.062	0.057	0.052	0.047
		4-ethyltoluene	NA	NA	0.14	0.13	0.13	0.11	0.087	0.074	0.066	0.06	0.055	0.068	0.062	0.056	0.051	0.047
	Flowback	2-ethyltoluene	NA	NA	16	16	15	13	13	12	12	12	11	7.6	6.4	7.1	5.3	6.7
		benzene	NA	NA	4.1	3.9	3.7	3.3	3	3.1	3.1	3	2.8	1.9	1.6	1.8	1.4	1.5
		3-ethyltoluene	NA	NA	1.7	1.6	1.5	1.4	1.3	1.3	1.3	1.2	1.2	0.79	0.66	0.74	0.59	0.69
		4-ethyltoluene	NA	NA	1.1	1.1	1	0.92	0.89	0.85	0.85	0.84	0.77	0.53	0.44	0.49	0.39	0.46
		n-decane	NA	NA	1.1	1	0.97	0.87	0.84	0.81	0.8	0.79	0.73	0.5	0.42	0.47	0.37	0.44
		n-propylbenzene	NA	NA	1	0.97	0.92	0.83	0.8	0.76	0.76	0.75	0.69	0.47	0.4	0.44	0.33	0.42
		1,3-diethylbenzene	NA	NA	0.87	0.83	0.78	0.7	0.68	0.65	0.65	0.64	0.59	0.4	0.34	0.38	0.3	0.35
		m+p-xylene	NA	NA	0.77	0.73	0.7	0.62	0.56	0.58	0.57	0.57	0.52	0.36	0.3	0.33	0.27	0.31
		isopropylbenzene	NA	NA	0.68	0.65	0.61	0.55	0.53	0.51	0.51	0.5	0.46	0.31	0.26	0.29	0.23	0.28
		toluene	NA	NA	0.65	0.62	0.58	0.52	0.47	0.48	0.48	0.48	0.44	0.3	0.25	0.28	0.22	0.26
		1,2,3-trimethylbenzene	NA	NA	0.34	0.33	0.31	0.28	0.27	0.26	0.26	0.25	0.23	0.16	0.13	0.15	0.12	0.14
		1,2,4-trimethylbenzene	NA	NA	0.33	0.31	0.3	0.27	0.26	0.25	0.25	0.24	0.22	0.15	0.13	0.14	0.11	0.13
		1,3,5-trimethylbenzene	NA	NA	0.32	0.31	0.29	0.26	0.25	0.24	0.24	0.24	0.22	0.15	0.13	0.14	0.11	0.13
		o-xylene	NA	NA	0.24	0.23	0.22	0.19	0.19	0.18	0.18	0.18	0.16	0.11	0.093	0.1	0.082	0.097
		cyclohexane	NA	NA	0.22	0.21	0.2	0.18	0.16	0.16	0.16	0.16	0.15	0.1	0.084	0.094	0.076	0.079
		methylcyclohexane	NA	NA	0.22	0.21	0.2	0.18	0.16	0.17	0.17	0.16	0.15	0.1	0.086	0.096	0.077	0.091
		n-nonane	NA	NA	0.2	0.19	0.18	0.16	0.15	0.15	0.15	0.15	0.14	0.093	0.078	0.087	0.069	0.082
		styrene	NA	NA	0.19	0.18	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.086	0.072	0.08	0.059	0.075
Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	8.3	8.7	8.1	7.4	6.2	5.8	5.6	4	3.8	3.4	3.1	2.6	2.4	2.2
		toluene	NA	NA	1.9	2	1.8	1.7	1.4	1.3	1.3	0.91	0.86	0.77	0.71	0.61	0.54	0.5
		2-ethyltoluene	NA	NA	0.14	0.12	0.11	0.1	0.086	0.08	0.076	0.065	0.061	0.055	0.05	0.047	0.038	0.035
	Fracking	benzene	NA	NA	6	7.5	7	4.4	4.1	3.9	3.7	3.5	3.3	2.9	2.7	2.2	1.9	1.8
		m+p-xylene	NA	NA	0.83	1	0.96	0.61	0.56	0.53	0.51	0.48	0.45	0.4	0.37	0.32	0.27	0.25
		2-ethyltoluene	NA	NA	0.5	0.54	0.5	0.32	0.3	0.28	0.26	0.25	0.24	0.21	0.2	0.16	0.14	0.13
		toluene	NA	NA	0.36	0.45	0.42	0.26	0.24	0.23	0.22	0.21	0.2	0.17	0.16	0.14	0.12	0.11
		3-ethyltoluene	NA	NA	0.27	0.34	0.32	0.2	0.19	0.17	0.17	0.16	0.15	0.13	0.12	0.11	0.09	0.081
		n-decane	NA	NA	0.19	0.24	0.22	0.14	0.13	0.12	0.12	0.11	0.1	0.092	0.086	0.074	0.062	0.057
		methylcyclohexane	NA	NA	0.16	0.2	0.18	0.11	0.11	0.1	0.096	0.091	0.086	0.076	0.071	0.059	0.05	0.047
		cyclohexane	NA	NA	0.17	0.19	0.17	0.11	0.11	0.1	0.095	0.09	0.084	0.075	0.07	0.058	0.052	0.049
		trans-2-butene	NA	NA	0.16	0.15	0.14	0.12	0.092	0.086	0.081	0.077	0.072	0.072	0.06	0.047	0.042	0.045
		n-nonane	NA	NA	0.11	0.14	0.13	0.079	0.074	0.069	0.066	0.062	0.059	0.052	0.049	0.041	0.035	0.032
		n-octane	NA	NA	0.11	0.14	0.13	0.082	0.077	0.072	0.069	0.065	0.061	0.054	0.051	0.043	0.036	0.034

			4-ethyltoluene	NA	NA	0.1	0.13	0.12	0.073	0.069	0.065	0.061	0.058	0.055	0.049	0.045	0.041	0.034	0.03
		Flowback	2-ethyltoluene	NA	NA	14	13	12	11	8.5	7.9	6.5	5.8	5.5	5.2	4.4	4.4	3.4	2.9
			benzene	NA	NA	3.4	3.2	3	2.5	2.4	2.2	1.9	1.5	1.4	1.3	1.1	1.1	0.86	0.74
			3-ethyltoluene	NA	NA	1.4	1.3	1.3	1.1	0.88	0.81	0.67	0.61	0.57	0.54	0.46	0.46	0.36	0.3
			4-ethyltoluene	NA	NA	0.95	0.89	0.84	0.75	0.59	0.54	0.45	0.4	0.38	0.36	0.31	0.3	0.24	0.2
			n-decane	NA	NA	0.9	0.85	0.8	0.61	0.56	0.52	0.43	0.38	0.36	0.34	0.29	0.29	0.23	0.19
			n-propylbenzene	NA	NA	0.85	0.8	0.75	0.67	0.53	0.49	0.4	0.36	0.34	0.32	0.27	0.27	0.21	0.18
			1,3-diethylbenzene	NA	NA	0.72	0.68	0.64	0.57	0.45	0.42	0.34	0.31	0.29	0.28	0.23	0.23	0.18	0.16
			m+p-xylene	NA	NA	0.64	0.61	0.57	0.44	0.4	0.37	0.3	0.27	0.26	0.25	0.21	0.21	0.16	0.14
			isopropylbenzene	NA	NA	0.56	0.53	0.5	0.45	0.35	0.32	0.27	0.24	0.23	0.22	0.18	0.18	0.14	0.12
			toluene	NA	NA	0.54	0.51	0.48	0.37	0.33	0.31	0.26	0.23	0.22	0.21	0.17	0.17	0.14	0.12
			1,2,3-trimethylbenzene	NA	NA	0.28	0.27	0.25	0.23	0.18	0.16	0.14	0.12	0.11	0.11	0.092	0.092	0.072	0.061
			1,2,4-trimethylbenzene	NA	NA	0.27	0.26	0.24	0.22	0.17	0.16	0.13	0.12	0.11	0.11	0.089	0.088	0.069	0.059
			1,3,5-trimethylbenzene	NA	NA	0.27	0.25	0.24	0.21	0.17	0.15	0.13	0.11	0.11	0.1	0.087	0.087	0.067	0.058
			o-xylene	NA	NA	0.2	0.19	0.18	0.14	0.12	0.11	0.094	0.085	0.08	0.076	0.064	0.064	0.05	0.043
			cyclohexane	NA	NA	0.18	0.17	0.16	0.13	0.12	0.12	0.1	0.077	0.073	0.069	0.058	0.058	0.045	0.039
			methylcyclohexane	NA	NA	0.18	0.17	0.16	0.13	0.12	0.11	0.088	0.079	0.075	0.071	0.06	0.06	0.046	0.04
			n-nonane	NA	NA	0.17	0.16	0.15	0.11	0.1	0.096	0.079	0.071	0.067	0.064	0.054	0.054	0.042	0.036
			styrene	NA	NA	0.15	0.15	0.14	0.12	0.096	0.088	0.073	0.066	0.062	0.059	0.05	0.05	0.039	0.033
	Northern Front Range	Drilling	benzene	NA	NA	9.3	8.8	8.4	7.7	7.1	6.5	5.9	5.5	4.2	4.2	3.7	3.2	2.9	2.6
			toluene	NA	NA	2.1	2	1.9	1.7	1.6	1.5	1.2	1.2	0.98	0.95	0.83	0.73	0.65	0.58
			2-ethyltoluene	NA	NA	0.16	0.16	0.15	0.13	0.12	0.11	0.098	0.085	0.079	0.068	0.059	0.052	0.046	0.041
		Fracking	benzene	NA	NA	0.59	0.56	0.53	0.51	0.55	0.57	0.58	0.53	0.51	0.43	0.36	0.31	0.29	0.27
			2-ethyltoluene	NA	NA	0.13	0.13	0.12	0.13	0.14	0.14	0.14	0.13	0.13	0.092	0.09	0.078	0.073	0.067
		Flowback	benzene	NA	NA	19	18	18	18	19	20	20	19	18	15	15	13	13	12
			toluene	NA	NA	0.63	0.62	0.59	0.6	0.64	0.66	0.67	0.62	0.59	0.5	0.49	0.45	0.43	0.41
			3-ethyltoluene	NA	NA	0.62	0.61	0.59	0.59	0.63	0.65	0.66	0.61	0.58	0.49	0.49	0.44	0.42	0.4
			cyclohexane	NA	NA	0.55	0.54	0.52	0.52	0.56	0.57	0.58	0.54	0.51	0.43	0.43	0.39	0.37	0.35
			m+p-xylene	NA	NA	0.4	0.39	0.37	0.38	0.4	0.41	0.42	0.39	0.37	0.31	0.31	0.28	0.27	0.26
			methylcyclohexane	NA	NA	0.25	0.25	0.24	0.24	0.26	0.27	0.27	0.25	0.24	0.2	0.2	0.18	0.17	0.16
			n-hexane	NA	NA	0.25	0.24	0.23	0.23	0.25	0.26	0.26	0.24	0.23	0.19	0.19	0.17	0.17	0.16
			n-decane	NA	NA	0.22	0.21	0.2	0.2	0.22	0.22	0.23	0.21	0.2	0.17	0.17	0.15	0.15	0.14
			n-octane	NA	NA	0.18	0.17	0.17	0.17	0.18	0.18	0.19	0.17	0.16	0.14	0.14	0.12	0.12	0.11
			n-nonane	NA	NA	0.15	0.15	0.14	0.14	0.15	0.16	0.16	0.15	0.14	0.12	0.12	0.11	0.1	0.096
			2-ethyltoluene	NA	NA	0.12	0.12	0.11	0.11	0.11	0.12	0.12	0.11	0.1	0.088	0.087	0.079	0.075	0.072
			2-methylheptane	NA	NA	0.099	0.098	0.094	0.095	0.1	0.1	0.11	0.098	0.093	0.079	0.078	0.07	0.067	0.064
			o-xylene	NA	NA	0.11	0.1	0.1	0.1	0.11	0.11	0.11	0.11	0.1	0.084	0.084	0.075	0.072	0.069

18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	9.5	8.9	8.7	8	6.6	5.6	5	8	7.7	5.1	4.7	4.3	3.9	4.9
			toluene	NA	NA	2.2	2.1	2	1.8	1.5	1.3	1.1	1.8	1.7	1.2	1.1	0.96	0.87	1.1
			2-ethyltoluene	NA	NA	0.16	0.15	0.14	0.12	0.098	0.083	0.072	0.13	0.12	0.059	0.054	0.049	0.045	0.056
		Fracking	benzene	NA	NA	8.4	7.9	7.5	6.7	5.1	4.2	3.6	3.3	3	3.7	3.4	3.1	2.8	2.6
			m+p-xylene	NA	NA	1.2	1.1	1	0.93	0.71	0.59	0.52	0.47	0.43	0.53	0.48	0.44	0.4	0.37
			2-ethyltoluene	NA	NA	0.58	0.56	0.54	0.5	0.4	0.35	0.31	0.28	0.26	0.22	0.19	0.17	0.15	0.13
			toluene	NA	NA	0.5	0.47	0.45	0.4	0.31	0.25	0.22	0.2	0.19	0.23	0.21	0.19	0.17	0.16
			3-ethyltoluene	NA	NA	0.38	0.36	0.34	0.3	0.23	0.19	0.17	0.16	0.15	0.18	0.16	0.15	0.13	0.12
			n-decane	NA	NA	0.27	0.25	0.24	0.21	0.16	0.14	0.12	0.11	0.1	0.12	0.11	0.1	0.093	0.085
			methylcyclohexane	NA	NA	0.22	0.21	0.2	0.18	0.13	0.11	0.1	0.091	0.084	0.098	0.089	0.081	0.074	0.068
			cyclohexane	NA	NA	0.21	0.2	0.19	0.17	0.14	0.12	0.11	0.097	0.089	0.093	0.084	0.077	0.07	0.064
			trans-2-butene	NA	NA	0.19	0.18	0.17	0.15	0.13	0.11	0.099	0.089	0.082	0.075	0.065	0.057	0.05	0.044
			n-octane	NA	NA	0.16	0.15	0.14	0.13	0.096	0.08	0.069	0.063	0.058	0.071	0.065	0.059	0.054	0.049
			n-nonane	NA	NA	0.15	0.14	0.13	0.12	0.092	0.076	0.067	0.061	0.056	0.068	0.062	0.057	0.052	0.047
			4-ethyltoluene	NA	NA	0.14	0.13	0.13	0.11	0.087	0.074	0.066	0.06	0.055	0.068	0.062	0.056	0.051	0.047
		Flowback	2-ethyltoluene	NA	NA	16	16	15	13	13	12	12	12	11	7.6	6.4	7.1	5.3	6.7
			benzene	NA	NA	4.1	3.9	3.7	3.3	3	3.1	3.1	3	2.8	1.9	1.6	1.8	1.4	1.5
			3-ethyltoluene	NA	NA	1.7	1.6	1.5	1.4	1.3	1.3	1.3	1.2	1.2	0.79	0.66	0.74	0.59	0.69
			4-ethyltoluene	NA	NA	1.1	1.1	1	0.92	0.89	0.85	0.85	0.84	0.77	0.53	0.44	0.49	0.39	0.46
			n-decane	NA	NA	1.1	1	0.97	0.87	0.84	0.81	0.8	0.79	0.73	0.5	0.42	0.47	0.37	0.44
			n-propylbenzene	NA	NA	1	0.97	0.92	0.83	0.8	0.76	0.76	0.75	0.69	0.47	0.4	0.44	0.33	0.42
			1,3-diethylbenzene	NA	NA	0.87	0.83	0.78	0.7	0.68	0.65	0.65	0.64	0.59	0.4	0.34	0.38	0.3	0.35
			m+p-xylene	NA	NA	0.77	0.73	0.7	0.62	0.56	0.58	0.57	0.57	0.52	0.36	0.3	0.33	0.27	0.31
			isopropylbenzene	NA	NA	0.68	0.65	0.61	0.55	0.53	0.51	0.51	0.5	0.46	0.31	0.26	0.29	0.23	0.28
			toluene	NA	NA	0.65	0.62	0.58	0.52	0.47	0.48	0.48	0.48	0.44	0.3	0.25	0.28	0.22	0.26
			1,2,3-trimethylbenzene	NA	NA	0.34	0.33	0.31	0.28	0.27	0.26	0.26	0.25	0.23	0.16	0.13	0.15	0.12	0.14
			1,2,4-trimethylbenzene	NA	NA	0.33	0.31	0.3	0.27	0.26	0.25	0.25	0.24	0.22	0.15	0.13	0.14	0.11	0.13
			1,3,5-trimethylbenzene	NA	NA	0.32	0.31	0.29	0.26	0.25	0.24	0.24	0.24	0.22	0.15	0.13	0.14	0.11	0.13
			o-xylene	NA	NA	0.24	0.23	0.22	0.19	0.19	0.18	0.18	0.18	0.16	0.11	0.093	0.1	0.082	0.097
			cyclohexane	NA	NA	0.22	0.21	0.2	0.18	0.16	0.16	0.16	0.16	0.15	0.1	0.084	0.094	0.076	0.079
			methylcyclohexane	NA	NA	0.22	0.21	0.2	0.18	0.16	0.17	0.17	0.16	0.15	0.1	0.086	0.096	0.077	0.091
			n-nonane	NA	NA	0.2	0.19	0.18	0.16	0.15	0.15	0.15	0.15	0.14	0.093	0.078	0.087	0.069	0.082
			styrene	NA	NA	0.19	0.18	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.086	0.072	0.08	0.059	0.075
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	8.3	8.7	8.1	7.4	6.2	5.8	5.6	4	3.8	3.4	3.1	2.6	2.4	2.2
			toluene	NA	NA	1.9	2	1.8	1.7	1.4	1.3	1.3	0.91	0.86	0.77	0.71	0.61	0.54	0.5
			2-ethyltoluene	NA	NA	0.14	0.12	0.11	0.1	0.086	0.08	0.076	0.065	0.061	0.055	0.05	0.047	0.038	0.035
		Fracking	benzene	NA	NA	6	7.5	7	4.4	4.1	3.9	3.7	3.5	3.3	2.9	2.7	2.2	1.9	1.8

		m+p-xylene	NA	NA	0.83	1	0.96	0.61	0.56	0.53	0.51	0.48	0.45	0.4	0.37	0.32	0.27	0.25
		2-ethyltoluene	NA	NA	0.5	0.54	0.5	0.32	0.3	0.28	0.26	0.25	0.24	0.21	0.2	0.16	0.14	0.13
		toluene	NA	NA	0.36	0.45	0.42	0.26	0.24	0.23	0.22	0.21	0.2	0.17	0.16	0.14	0.12	0.11
		3-ethyltoluene	NA	NA	0.27	0.34	0.32	0.2	0.19	0.17	0.17	0.16	0.15	0.13	0.12	0.11	0.09	0.081
		n-decane	NA	NA	0.19	0.24	0.22	0.14	0.13	0.12	0.12	0.11	0.1	0.092	0.086	0.074	0.062	0.057
		methylcyclohexane	NA	NA	0.16	0.2	0.18	0.11	0.11	0.1	0.096	0.091	0.086	0.076	0.071	0.059	0.05	0.047
		cyclohexane	NA	NA	0.17	0.19	0.17	0.11	0.11	0.1	0.095	0.09	0.084	0.075	0.07	0.058	0.052	0.049
		trans-2-butene	NA	NA	0.16	0.15	0.14	0.12	0.092	0.086	0.081	0.077	0.072	0.072	0.06	0.047	0.042	0.045
		n-nonane	NA	NA	0.11	0.14	0.13	0.079	0.074	0.069	0.066	0.062	0.059	0.052	0.049	0.041	0.035	0.032
		n-octane	NA	NA	0.11	0.14	0.13	0.082	0.077	0.072	0.069	0.065	0.061	0.054	0.051	0.043	0.036	0.034
		4-ethyltoluene	NA	NA	0.1	0.13	0.12	0.073	0.069	0.065	0.061	0.058	0.055	0.049	0.045	0.041	0.034	0.03
	Flowback	2-ethyltoluene	NA	NA	14	13	12	11	8.5	7.9	6.5	5.8	5.5	5.2	4.4	4.4	3.4	2.9
		benzene	NA	NA	3.4	3.2	3	2.5	2.4	2.2	1.9	1.5	1.4	1.3	1.1	1.1	0.86	0.74
		3-ethyltoluene	NA	NA	1.4	1.3	1.3	1.1	0.88	0.81	0.67	0.61	0.57	0.54	0.46	0.46	0.36	0.3
		4-ethyltoluene	NA	NA	0.95	0.89	0.84	0.75	0.59	0.54	0.45	0.4	0.38	0.36	0.31	0.3	0.24	0.2
		n-decane	NA	NA	0.9	0.85	0.8	0.61	0.56	0.52	0.43	0.38	0.36	0.34	0.29	0.29	0.23	0.19
		n-propylbenzene	NA	NA	0.85	0.8	0.75	0.67	0.53	0.49	0.4	0.36	0.34	0.32	0.27	0.27	0.21	0.18
		1,3-diethylbenzene	NA	NA	0.72	0.68	0.64	0.57	0.45	0.42	0.34	0.31	0.29	0.28	0.23	0.23	0.18	0.16
		m+p-xylene	NA	NA	0.64	0.61	0.57	0.44	0.4	0.37	0.3	0.27	0.26	0.25	0.21	0.21	0.16	0.14
		isopropylbenzene	NA	NA	0.56	0.53	0.5	0.45	0.35	0.32	0.27	0.24	0.23	0.22	0.18	0.18	0.14	0.12
		toluene	NA	NA	0.54	0.51	0.48	0.37	0.33	0.31	0.26	0.23	0.22	0.21	0.17	0.17	0.14	0.12
		1,2,3-trimethylbenzene	NA	NA	0.28	0.27	0.25	0.23	0.18	0.16	0.14	0.12	0.11	0.11	0.092	0.092	0.072	0.061
		1,2,4-trimethylbenzene	NA	NA	0.27	0.26	0.24	0.22	0.17	0.16	0.13	0.12	0.11	0.11	0.089	0.088	0.069	0.059
		1,3,5-trimethylbenzene	NA	NA	0.27	0.25	0.24	0.21	0.17	0.15	0.13	0.11	0.11	0.1	0.087	0.087	0.067	0.058
		o-xylene	NA	NA	0.2	0.19	0.18	0.14	0.12	0.11	0.094	0.085	0.08	0.076	0.064	0.064	0.05	0.043
		cyclohexane	NA	NA	0.18	0.17	0.16	0.13	0.12	0.12	0.1	0.077	0.073	0.069	0.058	0.058	0.045	0.039
		methylcyclohexane	NA	NA	0.18	0.17	0.16	0.13	0.12	0.11	0.088	0.079	0.075	0.071	0.06	0.06	0.046	0.04
		n-nonane	NA	NA	0.17	0.16	0.15	0.11	0.1	0.096	0.079	0.071	0.067	0.064	0.054	0.054	0.042	0.036
		styrene	NA	NA	0.15	0.15	0.14	0.12	0.096	0.088	0.073	0.066	0.062	0.059	0.05	0.05	0.039	0.033
Northern Front Range	Drilling	benzene	NA	NA	9.3	8.8	8.4	7.7	7.1	6.5	5.9	5.5	4.2	4.2	3.7	3.2	2.9	2.6
		toluene	NA	NA	2.1	2	1.9	1.7	1.6	1.5	1.2	1.2	0.98	0.95	0.83	0.73	0.65	0.58
		2-ethyltoluene	NA	NA	0.16	0.16	0.15	0.13	0.12	0.11	0.098	0.085	0.079	0.068	0.059	0.052	0.046	0.041
	Fracking	benzene	NA	NA	0.59	0.56	0.53	0.51	0.55	0.57	0.58	0.53	0.51	0.43	0.36	0.31	0.29	0.27
		2-ethyltoluene	NA	NA	0.13	0.13	0.12	0.13	0.14	0.14	0.14	0.13	0.13	0.092	0.09	0.078	0.073	0.067
	Flowback	benzene	NA	NA	19	18	18	18	19	20	20	19	18	15	15	13	13	12
		toluene	NA	NA	0.63	0.62	0.59	0.6	0.64	0.66	0.67	0.62	0.59	0.5	0.49	0.45	0.43	0.41
		3-ethyltoluene	NA	NA	0.62	0.61	0.59	0.59	0.63	0.65	0.66	0.61	0.58	0.49	0.49	0.44	0.42	0.4

			cyclohexane	NA	NA	0.55	0.54	0.52	0.52	0.56	0.57	0.58	0.54	0.51	0.43	0.43	0.39	0.37	0.35
			m+p-xylene	NA	NA	0.4	0.39	0.37	0.38	0.4	0.41	0.42	0.39	0.37	0.31	0.31	0.28	0.27	0.26
			methylcyclohexane	NA	NA	0.25	0.25	0.24	0.24	0.26	0.27	0.27	0.25	0.24	0.2	0.2	0.18	0.17	0.16
			n-hexane	NA	NA	0.25	0.24	0.23	0.23	0.25	0.26	0.26	0.24	0.23	0.19	0.19	0.17	0.17	0.16
			n-decane	NA	NA	0.22	0.21	0.2	0.2	0.22	0.22	0.23	0.21	0.2	0.17	0.17	0.15	0.15	0.14
			n-octane	NA	NA	0.18	0.17	0.17	0.17	0.18	0.18	0.19	0.17	0.16	0.14	0.14	0.12	0.12	0.11
			n-nonane	NA	NA	0.15	0.15	0.14	0.14	0.15	0.16	0.16	0.15	0.14	0.12	0.12	0.11	0.1	0.096
			2-ethyltoluene	NA	NA	0.12	0.12	0.11	0.11	0.11	0.12	0.12	0.11	0.1	0.088	0.087	0.079	0.075	0.072
			2-methylheptane	NA	NA	0.099	0.098	0.094	0.095	0.1	0.1	0.11	0.098	0.093	0.079	0.078	0.07	0.067	0.064
			o-xylene	NA	NA	0.11	0.1	0.1	0.1	0.11	0.11	0.11	0.11	0.1	0.084	0.084	0.075	0.072	0.069
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	9.5	8.9	8.7	8	6.6	5.6	5	8	7.7	5.1	4.7	4.3	3.9	4.9
			toluene	NA	NA	2.2	2.1	2	1.8	1.5	1.3	1.1	1.8	1.7	1.2	1.1	0.96	0.87	1.1
			2-ethyltoluene	NA	NA	0.16	0.15	0.14	0.12	0.098	0.083	0.072	0.13	0.12	0.059	0.054	0.049	0.045	0.056
		Fracking	benzene	NA	NA	8.4	7.9	7.5	6.7	5.1	4.2	3.6	3.3	3	3.7	3.4	3.1	2.8	2.6
			m+p-xylene	NA	NA	1.2	1.1	1	0.93	0.71	0.59	0.52	0.47	0.43	0.53	0.48	0.44	0.4	0.37
			2-ethyltoluene	NA	NA	0.58	0.56	0.54	0.5	0.4	0.35	0.31	0.28	0.26	0.22	0.19	0.17	0.15	0.13
			toluene	NA	NA	0.5	0.47	0.45	0.4	0.31	0.25	0.22	0.2	0.19	0.23	0.21	0.19	0.17	0.16
			3-ethyltoluene	NA	NA	0.38	0.36	0.34	0.3	0.23	0.19	0.17	0.16	0.15	0.18	0.16	0.15	0.13	0.12
			n-decane	NA	NA	0.27	0.25	0.24	0.21	0.16	0.14	0.12	0.11	0.1	0.12	0.11	0.1	0.093	0.085
			methylcyclohexane	NA	NA	0.22	0.21	0.2	0.18	0.13	0.11	0.1	0.091	0.084	0.098	0.089	0.081	0.074	0.068
			cyclohexane	NA	NA	0.21	0.2	0.19	0.17	0.14	0.12	0.11	0.097	0.089	0.093	0.084	0.077	0.07	0.064
			trans-2-butene	NA	NA	0.19	0.18	0.17	0.15	0.13	0.11	0.099	0.089	0.082	0.075	0.065	0.057	0.05	0.044
			n-octane	NA	NA	0.16	0.15	0.14	0.13	0.096	0.08	0.069	0.063	0.058	0.071	0.065	0.059	0.054	0.049
			n-nonane	NA	NA	0.15	0.14	0.13	0.12	0.092	0.076	0.067	0.061	0.056	0.068	0.062	0.057	0.052	0.047
			4-ethyltoluene	NA	NA	0.14	0.13	0.13	0.11	0.087	0.074	0.066	0.06	0.055	0.068	0.062	0.056	0.051	0.047
		Flowback	2-ethyltoluene	NA	NA	16	16	15	13	13	12	12	12	11	7.6	6.4	7.1	5.3	6.7
			benzene	NA	NA	4.1	3.9	3.7	3.3	3	3.1	3.1	3	2.8	1.9	1.6	1.8	1.4	1.5
			3-ethyltoluene	NA	NA	1.7	1.6	1.5	1.4	1.3	1.3	1.3	1.2	1.2	0.79	0.66	0.74	0.59	0.69
			4-ethyltoluene	NA	NA	1.1	1.1	1	0.92	0.89	0.85	0.85	0.84	0.77	0.53	0.44	0.49	0.39	0.46
			n-decane	NA	NA	1.1	1	0.97	0.87	0.84	0.81	0.8	0.79	0.73	0.5	0.42	0.47	0.37	0.44
			n-propylbenzene	NA	NA	1	0.97	0.92	0.83	0.8	0.76	0.76	0.75	0.69	0.47	0.4	0.44	0.33	0.42
			1,3-diethylbenzene	NA	NA	0.87	0.83	0.78	0.7	0.68	0.65	0.65	0.64	0.59	0.4	0.34	0.38	0.3	0.35
			m+p-xylene	NA	NA	0.77	0.73	0.7	0.62	0.56	0.58	0.57	0.57	0.52	0.36	0.3	0.33	0.27	0.31
			isopropylbenzene	NA	NA	0.68	0.65	0.61	0.55	0.53	0.51	0.51	0.5	0.46	0.31	0.26	0.29	0.23	0.28
			toluene	NA	NA	0.65	0.62	0.58	0.52	0.47	0.48	0.48	0.48	0.44	0.3	0.25	0.28	0.22	0.26
			1,2,3-trimethylbenzene	NA	NA	0.34	0.33	0.31	0.28	0.27	0.26	0.26	0.25	0.23	0.16	0.13	0.15	0.12	0.14
			1,2,4-trimethylbenzene	NA	NA	0.33	0.31	0.3	0.27	0.26	0.25	0.25	0.24	0.22	0.15	0.13	0.14	0.11	0.13

		1,3,5-trimethylbenzene	NA	NA	0.32	0.31	0.29	0.26	0.25	0.24	0.24	0.24	0.22	0.15	0.13	0.14	0.11	0.13
		o-xylene	NA	NA	0.24	0.23	0.22	0.19	0.19	0.18	0.18	0.18	0.16	0.11	0.093	0.1	0.082	0.097
		cyclohexane	NA	NA	0.22	0.21	0.2	0.18	0.16	0.16	0.16	0.16	0.15	0.1	0.084	0.094	0.076	0.079
		methylcyclohexane	NA	NA	0.22	0.21	0.2	0.18	0.16	0.17	0.17	0.16	0.15	0.1	0.086	0.096	0.077	0.091
		n-nonane	NA	NA	0.2	0.19	0.18	0.16	0.15	0.15	0.15	0.15	0.14	0.093	0.078	0.087	0.069	0.082
		styrene	NA	NA	0.19	0.18	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.086	0.072	0.08	0.059	0.075
Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	8.3	8.7	8.1	7.4	6.2	5.8	5.6	4	3.8	3.4	3.1	2.6	2.4	2.2
		toluene	NA	NA	1.9	2	1.8	1.7	1.4	1.3	1.3	0.91	0.86	0.77	0.71	0.61	0.54	0.5
		2-ethyltoluene	NA	NA	0.14	0.12	0.11	0.1	0.086	0.08	0.076	0.065	0.061	0.055	0.05	0.047	0.038	0.035
	Fracking	benzene	NA	NA	6	7.5	7	4.4	4.1	3.9	3.7	3.5	3.3	2.9	2.7	2.2	1.9	1.8
		m+p-xylene	NA	NA	0.83	1	0.96	0.61	0.56	0.53	0.51	0.48	0.45	0.4	0.37	0.32	0.27	0.25
		2-ethyltoluene	NA	NA	0.5	0.54	0.5	0.32	0.3	0.28	0.26	0.25	0.24	0.21	0.2	0.16	0.14	0.13
		toluene	NA	NA	0.36	0.45	0.42	0.26	0.24	0.23	0.22	0.21	0.2	0.17	0.16	0.14	0.12	0.11
		3-ethyltoluene	NA	NA	0.27	0.34	0.32	0.2	0.19	0.17	0.17	0.16	0.15	0.13	0.12	0.11	0.09	0.081
		n-decane	NA	NA	0.19	0.24	0.22	0.14	0.13	0.12	0.12	0.11	0.1	0.092	0.086	0.074	0.062	0.057
		methylcyclohexane	NA	NA	0.16	0.2	0.18	0.11	0.11	0.1	0.096	0.091	0.086	0.076	0.071	0.059	0.05	0.047
		cyclohexane	NA	NA	0.17	0.19	0.17	0.11	0.11	0.1	0.095	0.09	0.084	0.075	0.07	0.058	0.052	0.049
		trans-2-butene	NA	NA	0.16	0.15	0.14	0.12	0.092	0.086	0.081	0.077	0.072	0.072	0.06	0.047	0.042	0.045
		n-nonane	NA	NA	0.11	0.14	0.13	0.079	0.074	0.069	0.066	0.062	0.059	0.052	0.049	0.041	0.035	0.032
		n-octane	NA	NA	0.11	0.14	0.13	0.082	0.077	0.072	0.069	0.065	0.061	0.054	0.051	0.043	0.036	0.034
		4-ethyltoluene	NA	NA	0.1	0.13	0.12	0.073	0.069	0.065	0.061	0.058	0.055	0.049	0.045	0.041	0.034	0.03
	Flowback	2-ethyltoluene	NA	NA	14	13	12	11	8.5	7.9	6.5	5.8	5.5	5.2	4.4	4.4	3.4	2.9
		benzene	NA	NA	3.4	3.2	3	2.5	2.4	2.2	1.9	1.5	1.4	1.3	1.1	1.1	0.86	0.74
		3-ethyltoluene	NA	NA	1.4	1.3	1.3	1.1	0.88	0.81	0.67	0.61	0.57	0.54	0.46	0.46	0.36	0.3
		4-ethyltoluene	NA	NA	0.95	0.89	0.84	0.75	0.59	0.54	0.45	0.4	0.38	0.36	0.31	0.3	0.24	0.2
		n-decane	NA	NA	0.9	0.85	0.8	0.61	0.56	0.52	0.43	0.38	0.36	0.34	0.29	0.29	0.23	0.19
		n-propylbenzene	NA	NA	0.85	0.8	0.75	0.67	0.53	0.49	0.4	0.36	0.34	0.32	0.27	0.27	0.21	0.18
		1,3-diethylbenzene	NA	NA	0.72	0.68	0.64	0.57	0.45	0.42	0.34	0.31	0.29	0.28	0.23	0.23	0.18	0.16
		m+p-xylene	NA	NA	0.64	0.61	0.57	0.44	0.4	0.37	0.3	0.27	0.26	0.25	0.21	0.21	0.16	0.14
		isopropylbenzene	NA	NA	0.56	0.53	0.5	0.45	0.35	0.32	0.27	0.24	0.23	0.22	0.18	0.18	0.14	0.12
		toluene	NA	NA	0.54	0.51	0.48	0.37	0.33	0.31	0.26	0.23	0.22	0.21	0.17	0.17	0.14	0.12
		1,2,3-trimethylbenzene	NA	NA	0.28	0.27	0.25	0.23	0.18	0.16	0.14	0.12	0.11	0.11	0.092	0.092	0.072	0.061
		1,2,4-trimethylbenzene	NA	NA	0.27	0.26	0.24	0.22	0.17	0.16	0.13	0.12	0.11	0.11	0.089	0.088	0.069	0.059
		1,3,5-trimethylbenzene	NA	NA	0.27	0.25	0.24	0.21	0.17	0.15	0.13	0.11	0.11	0.1	0.087	0.087	0.067	0.058
		o-xylene	NA	NA	0.2	0.19	0.18	0.14	0.12	0.11	0.094	0.085	0.08	0.076	0.064	0.064	0.05	0.043
		cyclohexane	NA	NA	0.18	0.17	0.16	0.13	0.12	0.12	0.1	0.077	0.073	0.069	0.058	0.058	0.045	0.039
		methylcyclohexane	NA	NA	0.18	0.17	0.16	0.13	0.12	0.11	0.088	0.079	0.075	0.071	0.06	0.06	0.046	0.04

			n-nonane	NA	NA	0.17	0.16	0.15	0.11	0.1	0.096	0.079	0.071	0.067	0.064	0.054	0.054	0.042	0.036
			styrene	NA	NA	0.15	0.15	0.14	0.12	0.096	0.088	0.073	0.066	0.062	0.059	0.05	0.05	0.039	0.033
	Northern Front Range	Drilling	benzene	NA	NA	9.3	8.8	8.4	7.7	7.1	6.5	5.9	5.5	4.2	4.2	3.7	3.2	2.9	2.6
			toluene	NA	NA	2.1	2	1.9	1.7	1.6	1.5	1.2	1.2	0.98	0.95	0.83	0.73	0.65	0.58
			2-ethyltoluene	NA	NA	0.16	0.16	0.15	0.13	0.12	0.11	0.098	0.085	0.079	0.068	0.059	0.052	0.046	0.041
		Fracking	benzene	NA	NA	0.59	0.56	0.53	0.51	0.55	0.57	0.58	0.53	0.51	0.43	0.36	0.31	0.29	0.27
			2-ethyltoluene	NA	NA	0.13	0.13	0.12	0.13	0.14	0.14	0.14	0.13	0.13	0.092	0.09	0.078	0.073	0.067
		Flowback	benzene	NA	NA	19	18	18	18	19	20	20	19	18	15	15	13	13	12
			toluene	NA	NA	0.63	0.62	0.59	0.6	0.64	0.66	0.67	0.62	0.59	0.5	0.49	0.45	0.43	0.41
			3-ethyltoluene	NA	NA	0.62	0.61	0.59	0.59	0.63	0.65	0.66	0.61	0.58	0.49	0.49	0.44	0.42	0.4
			cyclohexane	NA	NA	0.55	0.54	0.52	0.52	0.56	0.57	0.58	0.54	0.51	0.43	0.43	0.39	0.37	0.35
			m+p-xylene	NA	NA	0.4	0.39	0.37	0.38	0.4	0.41	0.42	0.39	0.37	0.31	0.31	0.28	0.27	0.26
			methylcyclohexane	NA	NA	0.25	0.25	0.24	0.24	0.26	0.27	0.27	0.25	0.24	0.2	0.2	0.18	0.17	0.16
			n-hexane	NA	NA	0.25	0.24	0.23	0.23	0.25	0.26	0.26	0.24	0.23	0.19	0.19	0.17	0.17	0.16
			n-decane	NA	NA	0.22	0.21	0.2	0.2	0.22	0.22	0.23	0.21	0.2	0.17	0.17	0.15	0.15	0.14
			n-octane	NA	NA	0.18	0.17	0.17	0.17	0.18	0.18	0.19	0.17	0.16	0.14	0.14	0.12	0.12	0.11
			n-nonane	NA	NA	0.15	0.15	0.14	0.14	0.15	0.16	0.16	0.15	0.14	0.12	0.12	0.11	0.1	0.096
			2-ethyltoluene	NA	NA	0.12	0.12	0.11	0.11	0.11	0.12	0.12	0.11	0.1	0.088	0.087	0.079	0.075	0.072
			2-methylheptane	NA	NA	0.099	0.098	0.094	0.095	0.1	0.1	0.11	0.098	0.093	0.079	0.078	0.07	0.067	0.064
			o-xylene	NA	NA	0.11	0.1	0.1	0.1	0.11	0.11	0.11	0.11	0.1	0.084	0.084	0.075	0.072	0.069

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-6. Percentage of Daily-maximum Acute Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 3-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	99%	98%	97%	94%	92%	86%	80%	84%	82%	55%	41%	29%	19%	38%
			toluene	NA	NA	45%	35%	27%	16%	8%	3%	1%	8%	7%	1%	1%	0%	0%	1%
		Fracking	benzene	NA	NA	97%	95%	94%	89%	85%	77%	67%	55%	43%	29%	17%	10%	5%	4%
			m+p-xylene	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	91%	89%	86%	81%	74%	68%	64%	60%	56%	28%	13%	15%	11%	7%
			2-ethyltoluene	NA	NA	71%	68%	66%	62%	60%	58%	56%	55%	53%	47%	40%	35%	34%	31%
			3-ethyltoluene	NA	NA	11%	8%	6%	5%	3%	2%	2%	2%	1%	0%	0%	0%	0%	0%
			4-ethyltoluene	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-decane	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	100%	99%	99%	98%	96%	95%	93%	91%	88%	84%	79%	70%	62%	47%
			toluene	NA	NA	59%	51%	43%	29%	14%	4%	1%	0%	0%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	99%	98%	97%	95%	93%	91%	88%	86%	83%	75%	68%	56%	41%	24%
		Flowback	benzene	NA	NA	93%	90%	87%	77%	68%	58%	43%	22%	13%	5%	1%	1%	0%	0%
			2-ethyltoluene	NA	NA	75%	71%	68%	65%	62%	61%	60%	59%	58%	57%	55%	53%	50%	47%
			3-ethyltoluene	NA	NA	13%	8%	5%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	benzene	NA	NA	100%	99%	98%	97%	95%	92%	88%	84%	79%	71%	59%	46%	34%	23%
			toluene	NA	NA	61%	53%	43%	27%	13%	5%	2%	2%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	100%	100%	100%	100%	100%	100%	99%	98%	98%	95%	92%	88%	82%	76%
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	99%	98%	97%	94%	91%	86%	79%	84%	81%	54%	41%	28%	19%	38%
			toluene	NA	NA	44%	35%	27%	16%	8%	3%	1%	8%	8%	1%	1%	0%	0%	1%
		Fracking	benzene	NA	NA	97%	95%	94%	89%	85%	76%	66%	54%	43%	29%	17%	10%	5%	3%
			m+p-xylene	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	90%	88%	86%	80%	73%	67%	63%	59%	56%	28%	13%	15%	10%	7%
			2-ethyltoluene	NA	NA	71%	68%	66%	62%	60%	58%	56%	55%	53%	47%	40%	35%	33%	31%
			3-ethyltoluene	NA	NA	10%	8%	7%	5%	3%	2%	2%	2%	1%	0%	0%	0%	0%	0%
			4-ethyltoluene	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-decane	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	99%	99%	99%	97%	96%	95%	93%	90%	88%	83%	78%	69%	61%	46%
			toluene	NA	NA	57%	50%	42%	28%	14%	3%	1%	0%	0%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	98%	98%	97%	94%	92%	90%	88%	85%	82%	73%	67%	54%	40%	23%
		Flowback	benzene	NA	NA	92%	89%	86%	75%	65%	55%	40%	20%	11%	5%	1%	1%	0%	0%
			2-ethyltoluene	NA	NA	74%	71%	68%	65%	62%	61%	60%	59%	58%	57%	55%	53%	50%	47%
			3-ethyltoluene	NA	NA	12%	8%	5%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	benzene	NA	NA	99%	99%	98%	97%	94%	92%	87%	83%	78%	69%	57%	45%	33%	22%
			toluene	NA	NA	59%	51%	41%	26%	13%	5%	2%	2%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	100%	100%	100%	100%	100%	100%	99%	98%	97%	95%	91%	87%	81%	75%
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	97%	96%	95%	92%	89%	83%	77%	82%	79%	52%	39%	27%	18%	37%
			toluene	NA	NA	41%	33%	25%	15%	7%	3%	1%	8%	7%	1%	1%	0%	0%	1%
		Fracking	benzene	NA	NA	95%	93%	91%	86%	82%	73%	63%	51%	41%	27%	16%	9%	5%	3%
			m+p-xylene	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	86%	84%	82%	76%	69%	64%	60%	57%	53%	26%	12%	14%	9%	7%
			2-ethyltoluene	NA	NA	71%	68%	65%	62%	59%	57%	56%	54%	52%	47%	39%	34%	33%	31%
			3-ethyltoluene	NA	NA	10%	7%	6%	5%	3%	2%	2%	2%	1%	0%	0%	0%	0%	0%
			4-ethyltoluene	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-decane	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield	Drilling	benzene	NA	NA	99%	98%	97%	96%	94%	92%	91%	87%	85%	80%	75%	66%	58%	44%

	County: Valley (Rifle)		toluene	NA	NA	54%	47%	39%	26%	13%	3%	1%	0%	0%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	97%	96%	95%	91%	89%	87%	84%	81%	78%	70%	63%	51%	38%	22%
		Flowback	benzene	NA	NA	88%	85%	82%	70%	61%	51%	38%	19%	11%	5%	1%	1%	0%	0%
			2-ethyltoluene	NA	NA	74%	70%	68%	65%	62%	61%	60%	58%	57%	56%	54%	52%	49%	46%
			3-ethyltoluene	NA	NA	12%	8%	5%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	benzene	NA	NA	99%	98%	97%	95%	92%	89%	85%	81%	76%	67%	55%	44%	32%	21%
			toluene	NA	NA	57%	48%	40%	25%	13%	5%	2%	2%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	100%	100%	100%	100%	100%	99%	98%	97%	96%	93%	89%	84%	79%	73%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity.

Table E-7. Largest Acute Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 3-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	9.5	9	8.7	8	6.6	5.6	5	8	7.7	5.1	4.7	4.3	3.9	4.9
			neurotoxicity	NA	NA	2.3	2.2	2.1	2	1.6	1.4	1.2	1.9	1.9	1.3	1.1	1	0.93	1.1
			respiratory	NA	NA	0.11	0.1	0.1	0.093	0.076	0.065	0.058	0.085	0.089	0.059	0.054	0.049	0.027	0.041
		Fracking	hematological	NA	NA	8.6	8.1	7.7	6.9	5.3	4.4	3.8	3.4	3.1	3.9	3.5	3.2	2.9	2.7
			neurotoxicity	NA	NA	2.4	2.2	2.1	1.9	1.5	1.2	1.1	0.96	0.88	1.1	0.99	0.9	0.82	0.75
			respiratory	NA	NA	1.3	1.2	1.1	1	0.77	0.64	0.56	0.51	0.47	0.58	0.52	0.48	0.44	0.4
			sensory	NA	NA	0.27	0.26	0.24	0.22	0.17	0.14	0.12	0.11	0.1	0.13	0.11	0.1	0.095	0.087
			systemic	NA	NA	0.19	0.18	0.17	0.15	0.13	0.11	0.1	0.09	0.083	0.075	0.065	0.057	0.05	0.045
		Flowback	hematological	NA	NA	4.5	4.2	4	3.6	3.2	3.3	3.3	3.3	3	2.1	1.7	1.9	1.6	1.7
			neurotoxicity	NA	NA	3.3	3.1	3	2.7	2.4	2.4	2.4	2.4	2.2	1.5	1.3	1.4	1.1	1.3
			respiratory	NA	NA	1.2	1.2	1.1	0.98	0.89	0.91	0.91	0.89	0.83	0.56	0.47	0.53	0.39	0.5
			sensory	NA	NA	1.1	1.1	1	0.9	0.87	0.83	0.83	0.82	0.76	0.52	0.43	0.48	0.38	0.45
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	8.3	8.7	8.1	7.4	6.2	5.8	5.6	4	3.8	3.4	3.1	2.6	2.4	2.2
			neurotoxicity	NA	NA	2	2.1	2	1.8	1.5	1.4	1.4	0.98	0.92	0.84	0.76	0.64	0.58	0.53
		Fracking	hematological	NA	NA	6.2	7.8	7.2	4.5	4.2	4	3.8	3.6	3.4	3	2.8	2.3	1.9	1.8
			neurotoxicity	NA	NA	1.7	2.1	2	1.2	1.2	1.1	1	0.99	0.93	0.82	0.77	0.65	0.55	0.51
			respiratory	NA	NA	0.9	1.1	1.1	0.66	0.62	0.58	0.55	0.52	0.49	0.44	0.41	0.35	0.29	0.27
			sensory	NA	NA	0.19	0.24	0.23	0.14	0.13	0.12	0.12	0.11	0.11	0.094	0.088	0.075	0.063	0.058
			systemic	NA	NA	0.16	0.15	0.14	0.12	0.093	0.087	0.082	0.077	0.073	0.073	0.06	0.048	0.043	0.046
		Flowback	hematological	NA	NA	3.7	3.5	3.3	2.7	2.5	2.4	2.1	1.6	1.5	1.4	1.2	1.2	0.93	0.79
			neurotoxicity	NA	NA	2.7	2.6	2.4	1.9	1.7	1.6	1.3	1.2	1.1	1	0.88	0.88	0.68	0.59

			respiratory	NA	NA	1	0.95	0.9	0.69	0.63	0.58	0.48	0.43	0.41	0.39	0.33	0.33	0.25	0.22
			sensory	NA	NA	0.93	0.87	0.82	0.63	0.58	0.53	0.44	0.4	0.37	0.35	0.3	0.3	0.23	0.2
	Northern Front Range	Drilling	hematological	NA	NA	9.3	8.9	8.4	7.7	7.1	6.5	5.9	5.5	4.2	4.2	3.7	3.3	2.9	2.6
			neurotoxicity	NA	NA	2.3	2.2	2	1.8	1.7	1.6	1.2	1.3	1	1	0.89	0.79	0.7	0.62
			respiratory	NA	NA	0.11	0.1	0.096	0.085	0.082	0.075	0.06	0.06	0.056	0.048	0.042	0.037	0.033	0.03
		Fracking	hematological	NA	NA	0.61	0.57	0.54	0.53	0.56	0.58	0.59	0.55	0.52	0.44	0.38	0.32	0.3	0.28
		Flowback	hematological	NA	NA	19	19	18	18	19	20	20	19	18	15	15	13	13	12
			neurotoxicity	NA	NA	2.4	2.4	2.3	2.3	2.5	2.6	2.6	2.4	2.3	1.9	1.9	1.7	1.7	1.6
			respiratory	NA	NA	0.56	0.55	0.53	0.53	0.57	0.58	0.59	0.55	0.52	0.44	0.44	0.4	0.38	0.36
			endocrine	NA	NA	0.25	0.24	0.23	0.23	0.25	0.26	0.26	0.24	0.23	0.19	0.19	0.17	0.17	0.16
			sensory	NA	NA	0.22	0.22	0.21	0.21	0.22	0.23	0.23	0.22	0.21	0.17	0.17	0.16	0.15	0.14
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	9.5	9	8.7	8	6.6	5.6	5	8	7.7	5.1	4.7	4.3	3.9	4.9
			neurotoxicity	NA	NA	2.3	2.2	2.1	2	1.6	1.4	1.2	1.9	1.9	1.3	1.1	1	0.93	1.1
			respiratory	NA	NA	0.11	0.1	0.1	0.093	0.076	0.065	0.058	0.085	0.089	0.059	0.054	0.049	0.027	0.041
		Fracking	hematological	NA	NA	8.6	8.1	7.7	6.9	5.3	4.4	3.8	3.4	3.1	3.9	3.5	3.2	2.9	2.7
			neurotoxicity	NA	NA	2.4	2.2	2.1	1.9	1.5	1.2	1.1	0.96	0.88	1.1	0.99	0.9	0.82	0.75
			respiratory	NA	NA	1.3	1.2	1.1	1	0.77	0.64	0.56	0.51	0.47	0.58	0.52	0.48	0.44	0.4
			sensory	NA	NA	0.27	0.26	0.24	0.22	0.17	0.14	0.12	0.11	0.1	0.13	0.11	0.1	0.095	0.087
			systemic	NA	NA	0.19	0.18	0.17	0.15	0.13	0.11	0.1	0.09	0.083	0.075	0.065	0.057	0.05	0.045
		Flowback	hematological	NA	NA	4.5	4.2	4	3.6	3.2	3.3	3.3	3.3	3	2.1	1.7	1.9	1.6	1.7
			neurotoxicity	NA	NA	3.3	3.1	3	2.7	2.4	2.4	2.4	2.4	2.2	1.5	1.3	1.4	1.1	1.3
			respiratory	NA	NA	1.2	1.2	1.1	0.98	0.89	0.91	0.91	0.89	0.83	0.56	0.47	0.53	0.39	0.5
			sensory	NA	NA	1.1	1.1	1	0.9	0.87	0.83	0.83	0.82	0.76	0.52	0.43	0.48	0.38	0.45
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	8.3	8.7	8.1	7.4	6.2	5.8	5.6	4	3.8	3.4	3.1	2.6	2.4	2.2
			neurotoxicity	NA	NA	2	2.1	2	1.8	1.5	1.4	1.4	0.98	0.92	0.84	0.76	0.64	0.58	0.53
		Fracking	hematological	NA	NA	6.2	7.8	7.2	4.5	4.2	4	3.8	3.6	3.4	3	2.8	2.3	1.9	1.8
			neurotoxicity	NA	NA	1.7	2.1	2	1.2	1.2	1.1	1	0.99	0.93	0.82	0.77	0.65	0.55	0.51
			respiratory	NA	NA	0.9	1.1	1.1	0.66	0.62	0.58	0.55	0.52	0.49	0.44	0.41	0.35	0.29	0.27
			sensory	NA	NA	0.19	0.24	0.23	0.14	0.13	0.12	0.12	0.11	0.11	0.094	0.088	0.075	0.063	0.058
			systemic	NA	NA	0.16	0.15	0.14	0.12	0.093	0.087	0.082	0.077	0.073	0.073	0.06	0.048	0.043	0.046
		Flowback	hematological	NA	NA	3.7	3.5	3.3	2.7	2.5	2.4	2.1	1.6	1.5	1.4	1.2	1.2	0.93	0.79
			neurotoxicity	NA	NA	2.7	2.6	2.4	1.9	1.7	1.6	1.3	1.2	1.1	1	0.88	0.88	0.68	0.59
			respiratory	NA	NA	1	0.95	0.9	0.69	0.63	0.58	0.48	0.43	0.41	0.39	0.33	0.33	0.25	0.22
			sensory	NA	NA	0.93	0.87	0.82	0.63	0.58	0.53	0.44	0.4	0.37	0.35	0.3	0.3	0.23	0.2
	Northern Front Range	Drilling	hematological	NA	NA	9.3	8.9	8.4	7.7	7.1	6.5	5.9	5.5	4.2	4.2	3.7	3.3	2.9	2.6
			neurotoxicity	NA	NA	2.3	2.2	2	1.8	1.7	1.6	1.2	1.3	1	1	0.89	0.79	0.7	0.62
			respiratory	NA	NA	0.11	0.1	0.096	0.085	0.082	0.075	0.06	0.06	0.056	0.048	0.042	0.037	0.033	0.03

		Fracking	hematological	NA	NA	0.61	0.57	0.54	0.53	0.56	0.58	0.59	0.55	0.52	0.44	0.38	0.32	0.3	0.28
		Flowback	hematological	NA	NA	19	19	18	18	19	20	20	19	18	15	15	13	13	12
			neurotoxicity	NA	NA	2.4	2.4	2.3	2.3	2.5	2.6	2.6	2.4	2.3	1.9	1.9	1.7	1.7	1.6
			respiratory	NA	NA	0.56	0.55	0.53	0.53	0.57	0.58	0.59	0.55	0.52	0.44	0.44	0.4	0.38	0.36
			endocrine	NA	NA	0.25	0.24	0.23	0.23	0.25	0.26	0.26	0.24	0.23	0.19	0.19	0.17	0.17	0.16
			sensory	NA	NA	0.22	0.22	0.21	0.21	0.22	0.23	0.23	0.22	0.21	0.17	0.17	0.16	0.15	0.14
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	9.5	9	8.7	8	6.6	5.6	5	8	7.7	5.1	4.7	4.3	3.9	4.9
			neurotoxicity	NA	NA	2.3	2.2	2.1	2	1.6	1.4	1.2	1.9	1.9	1.3	1.1	1	0.93	1.1
			respiratory	NA	NA	0.11	0.1	0.1	0.093	0.076	0.065	0.058	0.085	0.089	0.059	0.054	0.049	0.027	0.041
		Fracking	hematological	NA	NA	8.6	8.1	7.7	6.9	5.3	4.4	3.8	3.4	3.1	3.9	3.5	3.2	2.9	2.7
			neurotoxicity	NA	NA	2.4	2.2	2.1	1.9	1.5	1.2	1.1	0.96	0.88	1.1	0.99	0.9	0.82	0.75
			respiratory	NA	NA	1.3	1.2	1.1	1	0.77	0.64	0.56	0.51	0.47	0.58	0.52	0.48	0.44	0.4
			sensory	NA	NA	0.27	0.26	0.24	0.22	0.17	0.14	0.12	0.11	0.1	0.13	0.11	0.1	0.095	0.087
			systemic	NA	NA	0.19	0.18	0.17	0.15	0.13	0.11	0.1	0.09	0.083	0.075	0.065	0.057	0.05	0.045
		Flowback	hematological	NA	NA	4.5	4.2	4	3.6	3.2	3.3	3.3	3.3	3	2.1	1.7	1.9	1.6	1.7
			neurotoxicity	NA	NA	3.3	3.1	3	2.7	2.4	2.4	2.4	2.4	2.2	1.5	1.3	1.4	1.1	1.3
			respiratory	NA	NA	1.2	1.2	1.1	0.98	0.89	0.91	0.91	0.89	0.83	0.56	0.47	0.53	0.39	0.5
			sensory	NA	NA	1.1	1.1	1	0.9	0.87	0.83	0.83	0.82	0.76	0.52	0.43	0.48	0.38	0.45
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	8.3	8.7	8.1	7.4	6.2	5.8	5.6	4	3.8	3.4	3.1	2.6	2.4	2.2
			neurotoxicity	NA	NA	2	2.1	2	1.8	1.5	1.4	1.4	0.98	0.92	0.84	0.76	0.64	0.58	0.53
		Fracking	hematological	NA	NA	6.2	7.8	7.2	4.5	4.2	4	3.8	3.6	3.4	3	2.8	2.3	1.9	1.8
			neurotoxicity	NA	NA	1.7	2.1	2	1.2	1.2	1.1	1	0.99	0.93	0.82	0.77	0.65	0.55	0.51
			respiratory	NA	NA	0.9	1.1	1.1	0.66	0.62	0.58	0.55	0.52	0.49	0.44	0.41	0.35	0.29	0.27
			sensory	NA	NA	0.19	0.24	0.23	0.14	0.13	0.12	0.12	0.11	0.11	0.094	0.088	0.075	0.063	0.058
			systemic	NA	NA	0.16	0.15	0.14	0.12	0.093	0.087	0.082	0.077	0.073	0.073	0.06	0.048	0.043	0.046
		Flowback	hematological	NA	NA	3.7	3.5	3.3	2.7	2.5	2.4	2.1	1.6	1.5	1.4	1.2	1.2	0.93	0.79
			neurotoxicity	NA	NA	2.7	2.6	2.4	1.9	1.7	1.6	1.3	1.2	1.1	1	0.88	0.88	0.68	0.59
			respiratory	NA	NA	1	0.95	0.9	0.69	0.63	0.58	0.48	0.43	0.41	0.39	0.33	0.33	0.25	0.22
			sensory	NA	NA	0.93	0.87	0.82	0.63	0.58	0.53	0.44	0.4	0.37	0.35	0.3	0.3	0.23	0.2
	Northern Front Range	Drilling	hematological	NA	NA	9.3	8.9	8.4	7.7	7.1	6.5	5.9	5.5	4.2	4.2	3.7	3.3	2.9	2.6
			neurotoxicity	NA	NA	2.3	2.2	2	1.8	1.7	1.6	1.2	1.3	1	1	0.89	0.79	0.7	0.62
			respiratory	NA	NA	0.11	0.1	0.096	0.085	0.082	0.075	0.06	0.06	0.056	0.048	0.042	0.037	0.033	0.03
		Fracking	hematological	NA	NA	0.61	0.57	0.54	0.53	0.56	0.58	0.59	0.55	0.52	0.44	0.38	0.32	0.3	0.28
		Flowback	hematological	NA	NA	19	19	18	18	19	20	20	19	18	15	15	13	13	12
			neurotoxicity	NA	NA	2.4	2.4	2.3	2.3	2.5	2.6	2.6	2.4	2.3	1.9	1.9	1.7	1.7	1.6
			respiratory	NA	NA	0.56	0.55	0.53	0.53	0.57	0.58	0.59	0.55	0.52	0.44	0.44	0.4	0.38	0.36
			endocrine	NA	NA	0.25	0.24	0.23	0.23	0.25	0.26	0.26	0.24	0.23	0.19	0.19	0.17	0.17	0.16

			sensory	NA	NA	0.22	0.22	0.21	0.21	0.22	0.23	0.23	0.22	0.21	0.17	0.17	0.16	0.15	0.14

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D).

Table E-8. Percentage of Daily-maximum Acute Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 3-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	99%	98%	97%	94%	92%	86%	80%	84%	82%	55%	41%	29%	19%	38%
			neurotoxicity	NA	NA	50%	41%	33%	20%	11%	4%	2%	10%	9%	1%	1%	0%	0%	1%
		Fracking	hematological	NA	NA	97%	96%	94%	90%	86%	78%	69%	57%	46%	31%	19%	11%	6%	4%
			neurotoxicity	NA	NA	35%	25%	18%	10%	5%	2%	1%	0%	0%	1%	0%	0%	0%	0%
			respiratory	NA	NA	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	93%	91%	89%	85%	79%	75%	71%	67%	64%	37%	19%	21%	18%	11%
			neurotoxicity	NA	NA	45%	40%	35%	27%	19%	15%	13%	12%	10%	4%	2%	2%	1%	1%
			respiratory	NA	NA	2%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			sensory	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	100%	99%	99%	98%	96%	95%	93%	91%	89%	84%	79%	70%	62%	48%
			neurotoxicity	NA	NA	64%	57%	48%	36%	21%	10%	2%	0%	0%	0%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	99%	98%	97%	95%	93%	91%	89%	87%	84%	76%	70%	58%	45%	27%
			neurotoxicity	NA	NA	48%	43%	32%	6%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	95%	93%	90%	82%	76%	68%	57%	40%	29%	16%	2%	1%	0%	0%
			neurotoxicity	NA	NA	48%	42%	37%	29%	22%	15%	8%	1%	1%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	hematological	NA	NA	100%	99%	98%	97%	95%	92%	88%	84%	79%	71%	59%	47%	34%	23%
			neurotoxicity	NA	NA	66%	58%	49%	32%	18%	8%	3%	3%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	100%	100%	100%	100%	100%	100%	99%	99%	98%	95%	92%	88%	83%	77%
			neurotoxicity	NA	NA	66%	57%	48%	32%	20%	11%	8%	7%	6%	3%	3%	2%	2%	2%
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	99%	98%	97%	94%	91%	86%	80%	84%	82%	55%	41%	29%	19%	38%
			neurotoxicity	NA	NA	49%	40%	32%	20%	11%	4%	2%	10%	9%	1%	1%	0%	0%	1%
		Fracking	hematological	NA	NA	97%	96%	94%	90%	86%	78%	68%	56%	45%	31%	19%	11%	6%	4%
			neurotoxicity	NA	NA	34%	25%	18%	10%	5%	2%	1%	0%	0%	1%	0%	0%	0%	0%
			respiratory	NA	NA	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	93%	91%	89%	84%	78%	74%	70%	67%	63%	36%	19%	21%	17%	11%
			neurotoxicity	NA	NA	45%	40%	35%	26%	19%	15%	13%	12%	10%	4%	2%	2%	1%	1%

			respiratory	NA	NA	2%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			sensory	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	99%	99%	99%	97%	96%	95%	93%	90%	88%	84%	78%	69%	61%	46%
			neurotoxicity	NA	NA	62%	55%	47%	35%	20%	9%	2%	0%	0%	0%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	99%	98%	97%	95%	93%	91%	89%	86%	83%	75%	69%	57%	43%	26%
			neurotoxicity	NA	NA	47%	41%	31%	6%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	94%	92%	89%	81%	73%	65%	54%	37%	27%	15%	2%	1%	0%	0%
			neurotoxicity	NA	NA	48%	42%	37%	29%	22%	15%	7%	1%	1%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	hematological	NA	NA	99%	99%	98%	97%	94%	92%	87%	83%	78%	70%	58%	45%	33%	22%
			neurotoxicity	NA	NA	64%	56%	47%	31%	17%	8%	3%	3%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	100%	100%	100%	100%	100%	100%	99%	98%	97%	95%	91%	87%	82%	76%
			neurotoxicity	NA	NA	64%	55%	46%	31%	20%	11%	8%	7%	6%	3%	3%	2%	2%	2%
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	97%	96%	95%	92%	89%	83%	77%	82%	80%	52%	39%	27%	18%	37%
			neurotoxicity	NA	NA	47%	38%	30%	19%	10%	4%	2%	10%	9%	1%	1%	0%	0%	1%
		Fracking	hematological	NA	NA	95%	94%	92%	87%	83%	74%	65%	54%	43%	30%	18%	10%	6%	4%
			neurotoxicity	NA	NA	32%	23%	17%	10%	4%	2%	1%	0%	0%	1%	0%	0%	0%	0%
			respiratory	NA	NA	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	89%	88%	86%	81%	75%	70%	67%	64%	60%	34%	18%	20%	16%	10%
			neurotoxicity	NA	NA	43%	38%	34%	26%	18%	14%	12%	11%	10%	4%	2%	2%	1%	1%
			respiratory	NA	NA	2%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			sensory	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	99%	98%	97%	96%	94%	92%	91%	87%	85%	80%	75%	66%	58%	44%
			neurotoxicity	NA	NA	59%	52%	45%	33%	19%	8%	2%	0%	0%	0%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	97%	96%	95%	92%	90%	88%	85%	82%	79%	71%	65%	54%	41%	25%
			neurotoxicity	NA	NA	44%	39%	29%	5%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	91%	88%	85%	76%	69%	61%	51%	35%	25%	14%	2%	1%	0%	0%
			neurotoxicity	NA	NA	47%	41%	36%	28%	21%	14%	7%	1%	1%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	hematological	NA	NA	99%	98%	97%	95%	92%	89%	85%	81%	76%	67%	55%	44%	32%	21%
			neurotoxicity	NA	NA	61%	53%	45%	29%	17%	8%	3%	3%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	100%	100%	100%	100%	100%	99%	98%	97%	96%	93%	89%	85%	79%	73%
			neurotoxicity	NA	NA	62%	53%	45%	30%	19%	11%	8%	6%	5%	3%	3%	2%	2%	2%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D).

E.1.1.3 5-acre Well Pad

Table E-9. Largest Acute Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	7.3	6.6	6.4	6	5.8	5.6	5.2	5.9	5.8	4.6	4.2	3.9	3.6	3.3
			toluene	NA	NA	1.7	1.5	1.4	1.4	1.3	1.3	1.2	1.6	1.5	1	0.95	0.88	0.81	0.75
			2-ethyltoluene	NA	NA	0.12	0.11	0.1	0.097	0.093	0.09	0.084	0.083	0.08	0.074	0.068	0.063	0.058	0.054
		Fracking	benzene	NA	NA	6.2	5.7	5.4	4.8	4.2	3.6	3.2	3.1	2.9	2.6	2.4	2.1	1.9	1.8
			m+p-xylene	NA	NA	0.85	0.79	0.75	0.66	0.58	0.5	0.44	0.36	0.33	0.27	0.24	0.22	0.19	0.17
			2-ethyltoluene	NA	NA	0.45	0.41	0.39	0.35	0.31	0.28	0.26	0.27	0.25	0.23	0.2	0.18	0.17	0.15
			toluene	NA	NA	0.37	0.34	0.32	0.29	0.25	0.22	0.19	0.2	0.19	0.17	0.15	0.14	0.12	0.11
			3-ethyltoluene	NA	NA	0.28	0.26	0.25	0.22	0.19	0.17	0.15	0.12	0.11	0.093	0.084	0.076	0.069	0.064
			n-decane	NA	NA	0.2	0.18	0.17	0.15	0.13	0.12	0.1	0.083	0.076	0.067	0.062	0.057	0.052	0.048
			cyclohexane	NA	NA	0.16	0.15	0.14	0.12	0.11	0.1	0.095	0.098	0.093	0.084	0.075	0.068	0.062	0.056
			methylcyclohexane	NA	NA	0.16	0.15	0.14	0.13	0.11	0.096	0.089	0.092	0.087	0.079	0.071	0.064	0.058	0.053
			trans-2-butene	NA	NA	0.14	0.13	0.12	0.11	0.095	0.084	0.075	0.077	0.072	0.063	0.056	0.05	0.045	0.04
			n-octane	NA	NA	0.12	0.11	0.1	0.09	0.079	0.068	0.06	0.054	0.052	0.047	0.042	0.038	0.034	0.031
			n-nonane	NA	NA	0.11	0.1	0.097	0.086	0.076	0.066	0.058	0.047	0.043	0.039	0.035	0.032	0.029	0.026
		Flowback	2-ethyltoluene	NA	NA	14	13	13	11	10	9.6	9.3	11	9.8	6.8	5.9	5.2	5	6.2
			benzene	NA	NA	3.4	3.3	3.1	2.8	2.6	2.6	2.6	2.6	2.5	1.7	1.5	1.6	1.4	1.6
			3-ethyltoluene	NA	NA	1.4	1.4	1.3	1.2	1.1	0.99	1.1	1.1	1	0.7	0.61	0.66	0.57	0.64
			4-ethyltoluene	NA	NA	0.96	0.91	0.87	0.78	0.71	0.67	0.73	0.73	0.68	0.47	0.41	0.44	0.38	0.43
			n-decane	NA	NA	0.91	0.86	0.82	0.74	0.67	0.63	0.69	0.69	0.64	0.44	0.39	0.42	0.36	0.41
			n-propylbenzene	NA	NA	0.86	0.82	0.78	0.7	0.64	0.6	0.58	0.56	0.61	0.42	0.36	0.32	0.34	0.39
			1,3-diethylbenzene	NA	NA	0.73	0.7	0.66	0.6	0.54	0.51	0.49	0.48	0.52	0.36	0.31	0.28	0.29	0.33
			m+p-xylene	NA	NA	0.64	0.62	0.59	0.53	0.48	0.49	0.5	0.49	0.46	0.32	0.28	0.3	0.26	0.29
			isopropylbenzene	NA	NA	0.57	0.54	0.52	0.47	0.42	0.4	0.44	0.43	0.41	0.28	0.24	0.26	0.23	0.26
			toluene	NA	NA	0.54	0.52	0.49	0.44	0.4	0.41	0.42	0.41	0.39	0.27	0.23	0.25	0.22	0.24
			1,2,3-trimethylbenzene	NA	NA	0.29	0.27	0.26	0.24	0.21	0.2	0.19	0.19	0.2	0.14	0.12	0.13	0.11	0.13
			1,2,4-trimethylbenzene	NA	NA	0.28	0.26	0.25	0.23	0.21	0.19	0.21	0.21	0.2	0.14	0.12	0.13	0.11	0.12
			1,3,5-trimethylbenzene	NA	NA	0.27	0.26	0.25	0.22	0.2	0.19	0.21	0.21	0.19	0.13	0.12	0.12	0.11	0.12
			o-xylene	NA	NA	0.2	0.19	0.18	0.16	0.15	0.14	0.15	0.15	0.14	0.099	0.085	0.092	0.08	0.09
			cyclohexane	NA	NA	0.18	0.17	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.09	0.077	0.084	0.073	0.082
			methylcyclohexane	NA	NA	0.18	0.18	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.092	0.079	0.086	0.075	0.084

		n-nonane	NA	NA	0.17	0.16	0.15	0.14	0.13	0.13	0.13	0.13	0.12	0.083	0.072	0.077	0.067	0.076
		styrene	NA	NA	0.16	0.15	0.14	0.13	0.12	0.11	0.1	0.1	0.11	0.076	0.066	0.059	0.062	0.07
Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	7.2	6.1	5.7	5.2	4.6	4.3	4.1	3.6	3.4	3.2	2.9	2.9	2.2	2.1
		toluene	NA	NA	1.6	1.6	1.5	1.4	1.2	1.2	1.1	0.81	0.77	0.72	0.66	0.65	0.51	0.47
		2-ethyltoluene	NA	NA	0.12	0.1	0.095	0.086	0.074	0.069	0.066	0.058	0.055	0.05	0.047	0.043	0.036	0.034
	Fracking	benzene	NA	NA	5.1	5.3	5	4.5	3.6	3.3	3.1	2.9	2.8	2.5	2.4	2.3	1.9	1.8
		m+p-xylene	NA	NA	0.71	0.74	0.69	0.62	0.49	0.46	0.43	0.41	0.38	0.34	0.33	0.32	0.26	0.25
		2-ethyltoluene	NA	NA	0.41	0.38	0.36	0.32	0.26	0.24	0.23	0.22	0.21	0.19	0.18	0.18	0.15	0.13
		toluene	NA	NA	0.31	0.32	0.3	0.27	0.21	0.2	0.19	0.18	0.17	0.15	0.14	0.14	0.11	0.11
		3-ethyltoluene	NA	NA	0.23	0.24	0.23	0.2	0.16	0.15	0.14	0.13	0.13	0.11	0.11	0.11	0.087	0.082
		n-decane	NA	NA	0.16	0.17	0.16	0.14	0.11	0.11	0.1	0.094	0.088	0.079	0.076	0.074	0.061	0.057
		cyclohexane	NA	NA	0.13	0.14	0.13	0.12	0.091	0.087	0.084	0.08	0.076	0.068	0.065	0.058	0.048	0.046
		methylcyclohexane	NA	NA	0.13	0.14	0.13	0.12	0.094	0.088	0.082	0.077	0.073	0.065	0.062	0.061	0.05	0.047
		trans-2-butene	NA	NA	0.12	0.12	0.11	0.1	0.082	0.077	0.072	0.068	0.064	0.057	0.055	0.045	0.04	0.041
	Flowback	2-ethyltoluene	NA	NA	11	11	10	9.3	6.4	5.8	5.4	4.9	4.7	4.3	3.9	3.4	3.2	2.8
		benzene	NA	NA	2.9	2.7	2.6	2.3	2	1.9	1.7	1.2	1.1	1.1	0.97	0.94	0.81	0.7
		3-ethyltoluene	NA	NA	1.2	1.1	1.1	0.97	0.66	0.6	0.56	0.51	0.48	0.45	0.4	0.36	0.33	0.29
		4-ethyltoluene	NA	NA	0.8	0.76	0.72	0.65	0.44	0.4	0.38	0.34	0.32	0.3	0.27	0.24	0.22	0.19
		n-decane	NA	NA	0.75	0.72	0.68	0.61	0.42	0.38	0.36	0.32	0.31	0.28	0.25	0.23	0.21	0.18
		n-propylbenzene	NA	NA	0.71	0.68	0.64	0.58	0.4	0.36	0.34	0.3	0.29	0.27	0.24	0.21	0.2	0.17
		1,3-diethylbenzene	NA	NA	0.61	0.58	0.55	0.49	0.34	0.31	0.29	0.26	0.25	0.23	0.2	0.18	0.17	0.15
		m+p-xylene	NA	NA	0.54	0.51	0.49	0.44	0.3	0.27	0.25	0.23	0.22	0.2	0.18	0.16	0.15	0.13
		isopropylbenzene	NA	NA	0.47	0.45	0.43	0.39	0.26	0.24	0.22	0.2	0.19	0.18	0.16	0.14	0.13	0.12
		toluene	NA	NA	0.45	0.43	0.41	0.37	0.25	0.23	0.21	0.19	0.18	0.17	0.15	0.14	0.13	0.11
		1,2,3-trimethylbenzene	NA	NA	0.24	0.23	0.22	0.19	0.13	0.12	0.11	0.1	0.097	0.09	0.081	0.072	0.067	0.058
		1,2,4-trimethylbenzene	NA	NA	0.23	0.22	0.21	0.19	0.13	0.12	0.11	0.098	0.093	0.087	0.078	0.069	0.065	0.056
		1,3,5-trimethylbenzene	NA	NA	0.23	0.22	0.2	0.18	0.13	0.11	0.11	0.096	0.091	0.085	0.076	0.068	0.063	0.055
		o-xylene	NA	NA	0.17	0.16	0.15	0.14	0.093	0.085	0.079	0.071	0.068	0.063	0.056	0.05	0.047	0.041
		methylcyclohexane	NA	NA	0.16	0.15	0.14	0.13	0.091	0.088	0.078	0.066	0.063	0.059	0.052	0.046	0.044	0.038
		cyclohexane	NA	NA	0.15	0.14	0.14	0.12	0.11	0.1	0.091	0.063	0.059	0.058	0.051	0.049	0.042	0.037
		n-nonane	NA	NA	0.14	0.13	0.13	0.11	0.078	0.071	0.066	0.06	0.057	0.053	0.047	0.042	0.039	0.034
		styrene	NA	NA	0.13	0.12	0.12	0.11	0.072	0.065	0.061	0.055	0.052	0.049	0.044	0.039	0.036	0.031
Northern Front Range	Drilling	benzene	NA	NA	8.3	8	7.7	6.8	6.5	5.9	5.3	4.9	4.6	3.8	3.3	2.9	2.6	2.3
		toluene	NA	NA	1.9	1.8	1.8	1.5	1.5	1.3	1.2	1.1	1	0.84	0.74	0.66	0.59	0.53
		2-ethyltoluene	NA	NA	0.13	0.13	0.12	0.11	0.097	0.089	0.081	0.076	0.071	0.059	0.051	0.045	0.04	0.036
	Fracking	benzene	NA	NA	0.45	0.43	0.41	0.41	0.43	0.45	0.46	0.43	0.41	0.35	0.36	0.18	0.31	0.3
	Flowback	benzene	NA	NA	15	15	15	12	13	12	10	9.8	8.1	7.1	6.2	5.5	4.9	4.4

			3-ethyltoluene	NA	NA	0.5	0.51	0.49	0.4	0.42	0.38	0.35	0.32	0.27	0.24	0.21	0.18	0.16	0.15
			toluene	NA	NA	0.51	0.51	0.5	0.41	0.42	0.39	0.36	0.34	0.27	0.24	0.21	0.19	0.16	0.15
			cyclohexane	NA	NA	0.44	0.45	0.43	0.4	0.37	0.34	0.35	0.33	0.27	0.21	0.18	0.16	0.14	0.13
			m+p-xylene	NA	NA	0.32	0.32	0.31	0.26	0.27	0.24	0.22	0.21	0.17	0.15	0.13	0.12	0.1	0.093
			methylcyclohexane	NA	NA	0.2	0.21	0.2	0.19	0.17	0.16	0.16	0.15	0.12	0.096	0.084	0.075	0.067	0.06
			n-hexane	NA	NA	0.2	0.2	0.19	0.16	0.16	0.16	0.16	0.15	0.12	0.092	0.081	0.072	0.064	0.058
			n-decane	NA	NA	0.17	0.18	0.17	0.16	0.14	0.13	0.12	0.11	0.093	0.081	0.071	0.063	0.056	0.051
			n-octane	NA	NA	0.14	0.14	0.14	0.13	0.12	0.11	0.1	0.095	0.085	0.066	0.058	0.052	0.046	0.041
			n-nonane	NA	NA	0.12	0.12	0.12	0.11	0.1	0.091	0.083	0.077	0.064	0.056	0.049	0.044	0.039	0.035
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	7.3	6.6	6.4	6	5.8	5.6	5.2	5.9	5.8	4.6	4.2	3.9	3.6	3.3
			toluene	NA	NA	1.7	1.5	1.4	1.4	1.3	1.3	1.2	1.6	1.5	1	0.95	0.88	0.81	0.75
			2-ethyltoluene	NA	NA	0.12	0.11	0.1	0.097	0.093	0.09	0.084	0.083	0.08	0.074	0.068	0.063	0.058	0.054
		Fracking	benzene	NA	NA	6.2	5.7	5.4	4.8	4.2	3.6	3.2	3.1	2.9	2.6	2.4	2.1	1.9	1.8
			m+p-xylene	NA	NA	0.85	0.79	0.75	0.66	0.58	0.5	0.44	0.36	0.33	0.27	0.24	0.22	0.19	0.17
			2-ethyltoluene	NA	NA	0.45	0.41	0.39	0.35	0.31	0.28	0.26	0.27	0.25	0.23	0.2	0.18	0.17	0.15
			toluene	NA	NA	0.37	0.34	0.32	0.29	0.25	0.22	0.19	0.2	0.19	0.17	0.15	0.14	0.12	0.11
			3-ethyltoluene	NA	NA	0.28	0.26	0.25	0.22	0.19	0.17	0.15	0.12	0.11	0.093	0.084	0.076	0.069	0.064
			n-decane	NA	NA	0.2	0.18	0.17	0.15	0.13	0.12	0.1	0.083	0.076	0.067	0.062	0.057	0.052	0.048
			cyclohexane	NA	NA	0.16	0.15	0.14	0.12	0.11	0.1	0.095	0.098	0.093	0.084	0.075	0.068	0.062	0.056
			methylcyclohexane	NA	NA	0.16	0.15	0.14	0.13	0.11	0.096	0.089	0.092	0.087	0.079	0.071	0.064	0.058	0.053
			trans-2-butene	NA	NA	0.14	0.13	0.12	0.11	0.095	0.084	0.075	0.077	0.072	0.063	0.056	0.05	0.045	0.04
			n-octane	NA	NA	0.12	0.11	0.1	0.09	0.079	0.068	0.06	0.054	0.052	0.047	0.042	0.038	0.034	0.031
			n-nonane	NA	NA	0.11	0.1	0.097	0.086	0.076	0.066	0.058	0.047	0.043	0.039	0.035	0.032	0.029	0.026
		Flowback	2-ethyltoluene	NA	NA	14	13	13	11	10	9.6	9.3	11	9.8	6.8	5.9	5.2	5	6.2
			benzene	NA	NA	3.4	3.3	3.1	2.8	2.6	2.6	2.6	2.6	2.5	1.7	1.5	1.6	1.4	1.6
			3-ethyltoluene	NA	NA	1.4	1.4	1.3	1.2	1.1	0.99	1.1	1.1	1	0.7	0.61	0.66	0.57	0.64
			4-ethyltoluene	NA	NA	0.96	0.91	0.87	0.78	0.71	0.67	0.73	0.73	0.68	0.47	0.41	0.44	0.38	0.43
			n-decane	NA	NA	0.91	0.86	0.82	0.74	0.67	0.63	0.69	0.69	0.64	0.44	0.39	0.42	0.36	0.41
			n-propylbenzene	NA	NA	0.86	0.82	0.78	0.7	0.64	0.6	0.58	0.56	0.61	0.42	0.36	0.32	0.34	0.39
			1,3-diethylbenzene	NA	NA	0.73	0.7	0.66	0.6	0.54	0.51	0.49	0.48	0.52	0.36	0.31	0.28	0.29	0.33
			m+p-xylene	NA	NA	0.64	0.62	0.59	0.53	0.48	0.49	0.5	0.49	0.46	0.32	0.28	0.3	0.26	0.29
			isopropylbenzene	NA	NA	0.57	0.54	0.52	0.47	0.42	0.4	0.44	0.43	0.41	0.28	0.24	0.26	0.23	0.26
			toluene	NA	NA	0.54	0.52	0.49	0.44	0.4	0.41	0.42	0.41	0.39	0.27	0.23	0.25	0.22	0.24
			1,2,3-trimethylbenzene	NA	NA	0.29	0.27	0.26	0.24	0.21	0.2	0.19	0.19	0.2	0.14	0.12	0.13	0.11	0.13
			1,2,4-trimethylbenzene	NA	NA	0.28	0.26	0.25	0.23	0.21	0.19	0.21	0.21	0.2	0.14	0.12	0.13	0.11	0.12
			1,3,5-trimethylbenzene	NA	NA	0.27	0.26	0.25	0.22	0.2	0.19	0.21	0.21	0.19	0.13	0.12	0.12	0.11	0.12
			o-xylene	NA	NA	0.2	0.19	0.18	0.16	0.15	0.14	0.15	0.15	0.14	0.099	0.085	0.092	0.08	0.09

		cyclohexane	NA	NA	0.18	0.17	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.09	0.077	0.084	0.073	0.082
		methylcyclohexane	NA	NA	0.18	0.18	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.092	0.079	0.086	0.075	0.084
		n-nonane	NA	NA	0.17	0.16	0.15	0.14	0.13	0.13	0.13	0.13	0.12	0.083	0.072	0.077	0.067	0.076
		styrene	NA	NA	0.16	0.15	0.14	0.13	0.12	0.11	0.1	0.1	0.11	0.076	0.066	0.059	0.062	0.07
Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	7.2	6.1	5.7	5.2	4.6	4.3	4.1	3.6	3.4	3.2	2.9	2.9	2.2	2.1
		toluene	NA	NA	1.6	1.6	1.5	1.4	1.2	1.2	1.1	0.81	0.77	0.72	0.66	0.65	0.51	0.47
		2-ethyltoluene	NA	NA	0.12	0.1	0.095	0.086	0.074	0.069	0.066	0.058	0.055	0.05	0.047	0.043	0.036	0.034
	Fracking	benzene	NA	NA	5.1	5.3	5	4.5	3.6	3.3	3.1	2.9	2.8	2.5	2.4	2.3	1.9	1.8
		m+p-xylene	NA	NA	0.71	0.74	0.69	0.62	0.49	0.46	0.43	0.41	0.38	0.34	0.33	0.32	0.26	0.25
		2-ethyltoluene	NA	NA	0.41	0.38	0.36	0.32	0.26	0.24	0.23	0.22	0.21	0.19	0.18	0.18	0.15	0.13
		toluene	NA	NA	0.31	0.32	0.3	0.27	0.21	0.2	0.19	0.18	0.17	0.15	0.14	0.14	0.11	0.11
		3-ethyltoluene	NA	NA	0.23	0.24	0.23	0.2	0.16	0.15	0.14	0.13	0.13	0.11	0.11	0.11	0.087	0.082
		n-decane	NA	NA	0.16	0.17	0.16	0.14	0.11	0.11	0.1	0.094	0.088	0.079	0.076	0.074	0.061	0.057
		cyclohexane	NA	NA	0.13	0.14	0.13	0.12	0.091	0.087	0.084	0.08	0.076	0.068	0.065	0.058	0.048	0.046
		methylcyclohexane	NA	NA	0.13	0.14	0.13	0.12	0.094	0.088	0.082	0.077	0.073	0.065	0.062	0.061	0.05	0.047
		trans-2-butene	NA	NA	0.12	0.12	0.11	0.1	0.082	0.077	0.072	0.068	0.064	0.057	0.055	0.045	0.04	0.041
	Flowback	2-ethyltoluene	NA	NA	11	11	10	9.3	6.4	5.8	5.4	4.9	4.7	4.3	3.9	3.4	3.2	2.8
		benzene	NA	NA	2.9	2.7	2.6	2.3	2	1.9	1.7	1.2	1.1	1.1	0.97	0.94	0.81	0.7
		3-ethyltoluene	NA	NA	1.2	1.1	1.1	0.97	0.66	0.6	0.56	0.51	0.48	0.45	0.4	0.36	0.33	0.29
		4-ethyltoluene	NA	NA	0.8	0.76	0.72	0.65	0.44	0.4	0.38	0.34	0.32	0.3	0.27	0.24	0.22	0.19
		n-decane	NA	NA	0.75	0.72	0.68	0.61	0.42	0.38	0.36	0.32	0.31	0.28	0.25	0.23	0.21	0.18
		n-propylbenzene	NA	NA	0.71	0.68	0.64	0.58	0.4	0.36	0.34	0.3	0.29	0.27	0.24	0.21	0.2	0.17
		1,3-diethylbenzene	NA	NA	0.61	0.58	0.55	0.49	0.34	0.31	0.29	0.26	0.25	0.23	0.2	0.18	0.17	0.15
		m+p-xylene	NA	NA	0.54	0.51	0.49	0.44	0.3	0.27	0.25	0.23	0.22	0.2	0.18	0.16	0.15	0.13
		isopropylbenzene	NA	NA	0.47	0.45	0.43	0.39	0.26	0.24	0.22	0.2	0.19	0.18	0.16	0.14	0.13	0.12
		toluene	NA	NA	0.45	0.43	0.41	0.37	0.25	0.23	0.21	0.19	0.18	0.17	0.15	0.14	0.13	0.11
		1,2,3-trimethylbenzene	NA	NA	0.24	0.23	0.22	0.19	0.13	0.12	0.11	0.1	0.097	0.09	0.081	0.072	0.067	0.058
		1,2,4-trimethylbenzene	NA	NA	0.23	0.22	0.21	0.19	0.13	0.12	0.11	0.098	0.093	0.087	0.078	0.069	0.065	0.056
		1,3,5-trimethylbenzene	NA	NA	0.23	0.22	0.2	0.18	0.13	0.11	0.11	0.096	0.091	0.085	0.076	0.068	0.063	0.055
		o-xylene	NA	NA	0.17	0.16	0.15	0.14	0.093	0.085	0.079	0.071	0.068	0.063	0.056	0.05	0.047	0.041
		methylcyclohexane	NA	NA	0.16	0.15	0.14	0.13	0.091	0.088	0.078	0.066	0.063	0.059	0.052	0.046	0.044	0.038
		cyclohexane	NA	NA	0.15	0.14	0.14	0.12	0.11	0.1	0.091	0.063	0.059	0.058	0.051	0.049	0.042	0.037
		n-nonane	NA	NA	0.14	0.13	0.13	0.11	0.078	0.071	0.066	0.06	0.057	0.053	0.047	0.042	0.039	0.034
		styrene	NA	NA	0.13	0.12	0.12	0.11	0.072	0.065	0.061	0.055	0.052	0.049	0.044	0.039	0.036	0.031
Northern Front Range	Drilling	benzene	NA	NA	8.3	8	7.7	6.8	6.5	5.9	5.3	4.9	4.6	3.8	3.3	2.9	2.6	2.3
		toluene	NA	NA	1.9	1.8	1.8	1.5	1.5	1.3	1.2	1.1	1	0.84	0.74	0.66	0.59	0.53
		2-ethyltoluene	NA	NA	0.13	0.13	0.12	0.11	0.097	0.089	0.081	0.076	0.071	0.059	0.051	0.045	0.04	0.036

		Fracking	benzene	NA	NA	0.45	0.43	0.41	0.41	0.43	0.45	0.46	0.43	0.41	0.35	0.36	0.18	0.31	0.3
		Flowback	benzene	NA	NA	15	15	15	12	13	12	10	9.8	8.1	7.1	6.2	5.5	4.9	4.4
			3-ethyltoluene	NA	NA	0.5	0.51	0.49	0.4	0.42	0.38	0.35	0.32	0.27	0.24	0.21	0.18	0.16	0.15
			toluene	NA	NA	0.51	0.51	0.5	0.41	0.42	0.39	0.36	0.34	0.27	0.24	0.21	0.19	0.16	0.15
			cyclohexane	NA	NA	0.44	0.45	0.43	0.4	0.37	0.34	0.35	0.33	0.27	0.21	0.18	0.16	0.14	0.13
			m+p-xylene	NA	NA	0.32	0.32	0.31	0.26	0.27	0.24	0.22	0.21	0.17	0.15	0.13	0.12	0.1	0.093
			methylcyclohexane	NA	NA	0.2	0.21	0.2	0.19	0.17	0.16	0.16	0.15	0.12	0.096	0.084	0.075	0.067	0.06
			n-hexane	NA	NA	0.2	0.2	0.19	0.16	0.16	0.16	0.16	0.15	0.12	0.092	0.081	0.072	0.064	0.058
			n-decane	NA	NA	0.17	0.18	0.17	0.16	0.14	0.13	0.12	0.11	0.093	0.081	0.071	0.063	0.056	0.051
			n-octane	NA	NA	0.14	0.14	0.14	0.13	0.12	0.11	0.1	0.095	0.085	0.066	0.058	0.052	0.046	0.041
			n-nonane	NA	NA	0.12	0.12	0.12	0.11	0.1	0.091	0.083	0.077	0.064	0.056	0.049	0.044	0.039	0.035
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	7.3	6.6	6.4	6	5.8	5.6	5.2	5.9	5.8	4.6	4.2	3.9	3.6	3.3
			toluene	NA	NA	1.7	1.5	1.4	1.4	1.3	1.3	1.2	1.6	1.5	1	0.95	0.88	0.81	0.75
			2-ethyltoluene	NA	NA	0.12	0.11	0.1	0.097	0.093	0.09	0.084	0.083	0.08	0.074	0.068	0.063	0.058	0.054
		Fracking	benzene	NA	NA	6.2	5.7	5.4	4.8	4.2	3.6	3.2	3.1	2.9	2.6	2.4	2.1	1.9	1.8
			m+p-xylene	NA	NA	0.85	0.79	0.75	0.66	0.58	0.5	0.44	0.36	0.33	0.27	0.24	0.22	0.19	0.17
			2-ethyltoluene	NA	NA	0.45	0.41	0.39	0.35	0.31	0.28	0.26	0.27	0.25	0.23	0.2	0.18	0.17	0.15
			toluene	NA	NA	0.37	0.34	0.32	0.29	0.25	0.22	0.19	0.2	0.19	0.17	0.15	0.14	0.12	0.11
			3-ethyltoluene	NA	NA	0.28	0.26	0.25	0.22	0.19	0.17	0.15	0.12	0.11	0.093	0.084	0.076	0.069	0.064
			n-decane	NA	NA	0.2	0.18	0.17	0.15	0.13	0.12	0.1	0.083	0.076	0.067	0.062	0.057	0.052	0.048
			cyclohexane	NA	NA	0.16	0.15	0.14	0.12	0.11	0.1	0.095	0.098	0.093	0.084	0.075	0.068	0.062	0.056
			methylcyclohexane	NA	NA	0.16	0.15	0.14	0.13	0.11	0.096	0.089	0.092	0.087	0.079	0.071	0.064	0.058	0.053
			trans-2-butene	NA	NA	0.14	0.13	0.12	0.11	0.095	0.084	0.075	0.077	0.072	0.063	0.056	0.05	0.045	0.04
			n-octane	NA	NA	0.12	0.11	0.1	0.09	0.079	0.068	0.06	0.054	0.052	0.047	0.042	0.038	0.034	0.031
			n-nonane	NA	NA	0.11	0.1	0.097	0.086	0.076	0.066	0.058	0.047	0.043	0.039	0.035	0.032	0.029	0.026
		Flowback	2-ethyltoluene	NA	NA	14	13	13	11	10	9.6	9.3	11	9.8	6.8	5.9	5.2	5	6.2
			benzene	NA	NA	3.4	3.3	3.1	2.8	2.6	2.6	2.6	2.6	2.5	1.7	1.5	1.6	1.4	1.6
			3-ethyltoluene	NA	NA	1.4	1.4	1.3	1.2	1.1	0.99	1.1	1.1	1	0.7	0.61	0.66	0.57	0.64
			4-ethyltoluene	NA	NA	0.96	0.91	0.87	0.78	0.71	0.67	0.73	0.73	0.68	0.47	0.41	0.44	0.38	0.43
			n-decane	NA	NA	0.91	0.86	0.82	0.74	0.67	0.63	0.69	0.69	0.64	0.44	0.39	0.42	0.36	0.41
			n-propylbenzene	NA	NA	0.86	0.82	0.78	0.7	0.64	0.6	0.58	0.56	0.61	0.42	0.36	0.32	0.34	0.39
			1,3-diethylbenzene	NA	NA	0.73	0.7	0.66	0.6	0.54	0.51	0.49	0.48	0.52	0.36	0.31	0.28	0.29	0.33
			m+p-xylene	NA	NA	0.64	0.62	0.59	0.53	0.48	0.49	0.5	0.49	0.46	0.32	0.28	0.3	0.26	0.29
			isopropylbenzene	NA	NA	0.57	0.54	0.52	0.47	0.42	0.4	0.44	0.43	0.41	0.28	0.24	0.26	0.23	0.26
			toluene	NA	NA	0.54	0.52	0.49	0.44	0.4	0.41	0.42	0.41	0.39	0.27	0.23	0.25	0.22	0.24
			1,2,3-trimethylbenzene	NA	NA	0.29	0.27	0.26	0.24	0.21	0.2	0.19	0.19	0.2	0.14	0.12	0.13	0.11	0.13
			1,2,4-trimethylbenzene	NA	NA	0.28	0.26	0.25	0.23	0.21	0.19	0.21	0.21	0.2	0.14	0.12	0.13	0.11	0.12

		1,3,5-trimethylbenzene	NA	NA	0.27	0.26	0.25	0.22	0.2	0.19	0.21	0.21	0.19	0.13	0.12	0.12	0.11	0.12
		o-xylene	NA	NA	0.2	0.19	0.18	0.16	0.15	0.14	0.15	0.15	0.14	0.099	0.085	0.092	0.08	0.09
		cyclohexane	NA	NA	0.18	0.17	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.09	0.077	0.084	0.073	0.082
		methylcyclohexane	NA	NA	0.18	0.18	0.17	0.15	0.14	0.14	0.14	0.14	0.13	0.092	0.079	0.086	0.075	0.084
		n-nonane	NA	NA	0.17	0.16	0.15	0.14	0.13	0.13	0.13	0.13	0.12	0.083	0.072	0.077	0.067	0.076
		styrene	NA	NA	0.16	0.15	0.14	0.13	0.12	0.11	0.1	0.1	0.11	0.076	0.066	0.059	0.062	0.07
Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	7.2	6.1	5.7	5.2	4.6	4.3	4.1	3.6	3.4	3.2	2.9	2.9	2.2	2.1
		toluene	NA	NA	1.6	1.6	1.5	1.4	1.2	1.2	1.1	0.81	0.77	0.72	0.66	0.65	0.51	0.47
		2-ethyltoluene	NA	NA	0.12	0.1	0.095	0.086	0.074	0.069	0.066	0.058	0.055	0.05	0.047	0.043	0.036	0.034
	Fracking	benzene	NA	NA	5.1	5.3	5	4.5	3.6	3.3	3.1	2.9	2.8	2.5	2.4	2.3	1.9	1.8
		m+p-xylene	NA	NA	0.71	0.74	0.69	0.62	0.49	0.46	0.43	0.41	0.38	0.34	0.33	0.32	0.26	0.25
		2-ethyltoluene	NA	NA	0.41	0.38	0.36	0.32	0.26	0.24	0.23	0.22	0.21	0.19	0.18	0.18	0.15	0.13
		toluene	NA	NA	0.31	0.32	0.3	0.27	0.21	0.2	0.19	0.18	0.17	0.15	0.14	0.14	0.11	0.11
		3-ethyltoluene	NA	NA	0.23	0.24	0.23	0.2	0.16	0.15	0.14	0.13	0.13	0.11	0.11	0.11	0.087	0.082
		n-decane	NA	NA	0.16	0.17	0.16	0.14	0.11	0.11	0.1	0.094	0.088	0.079	0.076	0.074	0.061	0.057
		cyclohexane	NA	NA	0.13	0.14	0.13	0.12	0.091	0.087	0.084	0.08	0.076	0.068	0.065	0.058	0.048	0.046
		methylcyclohexane	NA	NA	0.13	0.14	0.13	0.12	0.094	0.088	0.082	0.077	0.073	0.065	0.062	0.061	0.05	0.047
		trans-2-butene	NA	NA	0.12	0.12	0.11	0.1	0.082	0.077	0.072	0.068	0.064	0.057	0.055	0.045	0.04	0.041
	Flowback	2-ethyltoluene	NA	NA	11	11	10	9.3	6.4	5.8	5.4	4.9	4.7	4.3	3.9	3.4	3.2	2.8
		benzene	NA	NA	2.9	2.7	2.6	2.3	2	1.9	1.7	1.2	1.1	1.1	0.97	0.94	0.81	0.7
		3-ethyltoluene	NA	NA	1.2	1.1	1.1	0.97	0.66	0.6	0.56	0.51	0.48	0.45	0.4	0.36	0.33	0.29
		4-ethyltoluene	NA	NA	0.8	0.76	0.72	0.65	0.44	0.4	0.38	0.34	0.32	0.3	0.27	0.24	0.22	0.19
		n-decane	NA	NA	0.75	0.72	0.68	0.61	0.42	0.38	0.36	0.32	0.31	0.28	0.25	0.23	0.21	0.18
		n-propylbenzene	NA	NA	0.71	0.68	0.64	0.58	0.4	0.36	0.34	0.3	0.29	0.27	0.24	0.21	0.2	0.17
		1,3-diethylbenzene	NA	NA	0.61	0.58	0.55	0.49	0.34	0.31	0.29	0.26	0.25	0.23	0.2	0.18	0.17	0.15
		m+p-xylene	NA	NA	0.54	0.51	0.49	0.44	0.3	0.27	0.25	0.23	0.22	0.2	0.18	0.16	0.15	0.13
		isopropylbenzene	NA	NA	0.47	0.45	0.43	0.39	0.26	0.24	0.22	0.2	0.19	0.18	0.16	0.14	0.13	0.12
		toluene	NA	NA	0.45	0.43	0.41	0.37	0.25	0.23	0.21	0.19	0.18	0.17	0.15	0.14	0.13	0.11
		1,2,3-trimethylbenzene	NA	NA	0.24	0.23	0.22	0.19	0.13	0.12	0.11	0.1	0.097	0.09	0.081	0.072	0.067	0.058
		1,2,4-trimethylbenzene	NA	NA	0.23	0.22	0.21	0.19	0.13	0.12	0.11	0.098	0.093	0.087	0.078	0.069	0.065	0.056
		1,3,5-trimethylbenzene	NA	NA	0.23	0.22	0.2	0.18	0.13	0.11	0.11	0.096	0.091	0.085	0.076	0.068	0.063	0.055
		o-xylene	NA	NA	0.17	0.16	0.15	0.14	0.093	0.085	0.079	0.071	0.068	0.063	0.056	0.05	0.047	0.041
		methylcyclohexane	NA	NA	0.16	0.15	0.14	0.13	0.091	0.088	0.078	0.066	0.063	0.059	0.052	0.046	0.044	0.038
		cyclohexane	NA	NA	0.15	0.14	0.14	0.12	0.11	0.1	0.091	0.063	0.059	0.058	0.051	0.049	0.042	0.037
		n-nonane	NA	NA	0.14	0.13	0.13	0.11	0.078	0.071	0.066	0.06	0.057	0.053	0.047	0.042	0.039	0.034
		styrene	NA	NA	0.13	0.12	0.12	0.11	0.072	0.065	0.061	0.055	0.052	0.049	0.044	0.039	0.036	0.031
Northern	Drilling	benzene	NA	NA	8.3	8	7.7	6.8	6.5	5.9	5.3	4.9	4.6	3.8	3.3	2.9	2.6	2.3

	Front Range		toluene	NA	NA	1.9	1.8	1.8	1.5	1.5	1.3	1.2	1.1	1	0.84	0.74	0.66	0.59	0.53
			2-ethyltoluene	NA	NA	0.13	0.13	0.12	0.11	0.097	0.089	0.081	0.076	0.071	0.059	0.051	0.045	0.04	0.036
		Fracking	benzene	NA	NA	0.45	0.43	0.41	0.41	0.43	0.45	0.46	0.43	0.41	0.35	0.36	0.18	0.31	0.3
		Flowback	benzene	NA	NA	15	15	15	12	13	12	10	9.8	8.1	7.1	6.2	5.5	4.9	4.4
			3-ethyltoluene	NA	NA	0.5	0.51	0.49	0.4	0.42	0.38	0.35	0.32	0.27	0.24	0.21	0.18	0.16	0.15
			toluene	NA	NA	0.51	0.51	0.5	0.41	0.42	0.39	0.36	0.34	0.27	0.24	0.21	0.19	0.16	0.15
			cyclohexane	NA	NA	0.44	0.45	0.43	0.4	0.37	0.34	0.35	0.33	0.27	0.21	0.18	0.16	0.14	0.13
			m+p-xylene	NA	NA	0.32	0.32	0.31	0.26	0.27	0.24	0.22	0.21	0.17	0.15	0.13	0.12	0.1	0.093
			methylcyclohexane	NA	NA	0.2	0.21	0.2	0.19	0.17	0.16	0.16	0.15	0.12	0.096	0.084	0.075	0.067	0.06
			n-hexane	NA	NA	0.2	0.2	0.19	0.16	0.16	0.16	0.16	0.15	0.12	0.092	0.081	0.072	0.064	0.058
			n-decane	NA	NA	0.17	0.18	0.17	0.16	0.14	0.13	0.12	0.11	0.093	0.081	0.071	0.063	0.056	0.051
			n-octane	NA	NA	0.14	0.14	0.14	0.13	0.12	0.11	0.1	0.095	0.085	0.066	0.058	0.052	0.046	0.041
			n-nonane	NA	NA	0.12	0.12	0.12	0.11	0.1	0.091	0.083	0.077	0.064	0.056	0.049	0.044	0.039	0.035

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-10. Percentage of Daily-maximum Acute Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	98%	97%	96%	93%	90%	84%	78%	83%	80%	51%	37%	25%	16%	10%
			toluene	NA	NA	33%	25%	19%	6%	2%	1%	1%	5%	4%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	96%	95%	93%	89%	83%	75%	65%	55%	45%	29%	16%	8%	4%	2%
		Flowback	benzene	NA	NA	86%	84%	81%	74%	66%	60%	57%	54%	50%	21%	10%	9%	6%	7%
			2-ethyltoluene	NA	NA	66%	64%	63%	60%	59%	57%	56%	55%	53%	47%	44%	40%	37%	34%
			3-ethyltoluene	NA	NA	7%	6%	4%	2%	1%	0%	1%	1%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	99%	98%	97%	96%	95%	93%	91%	88%	85%	83%	75%	68%	59%	46%
			toluene	NA	NA	44%	34%	25%	10%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	98%	97%	96%	94%	90%	87%	85%	82%	78%	70%	64%	53%	38%	22%
		Flowback	benzene	NA	NA	88%	84%	80%	75%	53%	40%	24%	7%	2%	1%	0%	0%	0%	0%
			2-ethyltoluene	NA	NA	71%	69%	68%	66%	64%	63%	62%	61%	60%	59%	57%	54%	51%	49%
			3-ethyltoluene	NA	NA	3%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	benzene	NA	NA	99%	98%	98%	96%	93%	90%	86%	82%	77%	67%	56%	45%	34%	24%
			toluene	NA	NA	47%	39%	31%	16%	6%	3%	1%	1%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	100%	100%	100%	100%	100%	99%	99%	98%	97%	94%	91%	87%	82%	76%
18 to 59	Garfield	Drilling	benzene	NA	NA	98%	97%	96%	93%	89%	84%	78%	82%	80%	50%	37%	25%	16%	10%

Years	County: Ridge Top (BarD)		toluene	NA	NA	33%	25%	18%	6%	2%	1%	1%	5%	4%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	96%	95%	93%	88%	83%	74%	64%	54%	45%	29%	15%	8%	4%	2%
		Flowback	benzene	NA	NA	85%	83%	80%	73%	65%	59%	56%	53%	50%	21%	10%	9%	6%	7%
			2-ethyltoluene	NA	NA	66%	64%	62%	60%	59%	57%	56%	54%	53%	47%	44%	40%	37%	34%
			3-ethyltoluene	NA	NA	7%	6%	4%	2%	1%	0%	1%	1%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	99%	98%	97%	96%	94%	93%	91%	87%	84%	82%	74%	67%	58%	44%
			toluene	NA	NA	42%	32%	24%	9%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	98%	97%	96%	94%	89%	86%	84%	81%	77%	68%	62%	51%	37%	21%
		Flowback	benzene	NA	NA	87%	83%	78%	73%	50%	37%	22%	6%	2%	1%	0%	0%	0%	0%
			2-ethyltoluene	NA	NA	71%	69%	67%	65%	64%	63%	62%	61%	60%	58%	56%	54%	51%	49%
			3-ethyltoluene	NA	NA	3%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	benzene	NA	NA	99%	98%	97%	95%	93%	89%	85%	81%	76%	66%	55%	44%	33%	23%
			toluene	NA	NA	46%	37%	29%	15%	6%	2%	1%	1%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	100%	100%	100%	100%	100%	99%	99%	98%	97%	94%	90%	86%	81%	75%
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	96%	95%	94%	91%	87%	81%	75%	80%	77%	48%	35%	23%	15%	10%
			toluene	NA	NA	31%	23%	17%	6%	1%	1%	1%	4%	4%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	93%	92%	90%	85%	79%	71%	61%	51%	42%	27%	15%	7%	4%	2%
		Flowback	benzene	NA	NA	81%	79%	76%	69%	62%	56%	53%	51%	47%	20%	9%	8%	6%	7%
			2-ethyltoluene	NA	NA	65%	63%	62%	60%	58%	57%	55%	54%	52%	47%	43%	39%	36%	33%
			3-ethyltoluene	NA	NA	7%	6%	4%	2%	1%	0%	1%	1%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	97%	96%	95%	94%	92%	90%	88%	84%	81%	79%	71%	64%	55%	42%
			toluene	NA	NA	40%	30%	22%	9%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%
		Fracking	benzene	NA	NA	95%	95%	93%	91%	85%	83%	80%	77%	73%	65%	59%	48%	35%	20%
		Flowback	benzene	NA	NA	82%	78%	74%	68%	47%	35%	21%	6%	2%	1%	0%	0%	0%	0%
			2-ethyltoluene	NA	NA	71%	69%	67%	65%	64%	63%	62%	60%	59%	58%	56%	53%	49%	47%
			3-ethyltoluene	NA	NA	3%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	benzene	NA	NA	98%	97%	96%	93%	91%	87%	83%	78%	73%	64%	53%	42%	32%	22%
			toluene	NA	NA	44%	35%	28%	15%	5%	2%	1%	1%	0%	0%	0%	0%	0%	0%
		Flowback	benzene	NA	NA	100%	100%	100%	100%	99%	98%	97%	96%	95%	92%	88%	84%	78%	72%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity.

Table E-11. Largest Acute Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	7.3	6.6	6.4	6.1	5.8	5.6	5.2	5.9	5.8	4.6	4.2	3.9	3.6	3.3
			neurotoxicity	NA	NA	1.8	1.6	1.5	1.5	1.4	1.4	1.3	1.7	1.6	1.1	1	0.94	0.82	0.81
		Fracking	hematological	NA	NA	6.4	5.9	5.6	4.9	4.3	3.8	3.3	3.2	3	2.7	2.4	2.2	2	1.8
			neurotoxicity	NA	NA	1.7	1.6	1.5	1.4	1.2	1	0.91	0.77	0.72	0.65	0.59	0.53	0.48	0.44
			respiratory	NA	NA	0.93	0.86	0.81	0.72	0.63	0.55	0.48	0.39	0.36	0.3	0.26	0.24	0.21	0.19
			sensory	NA	NA	0.2	0.19	0.18	0.16	0.14	0.12	0.1	0.085	0.078	0.069	0.063	0.058	0.053	0.049
			systemic	NA	NA	0.14	0.13	0.12	0.11	0.096	0.084	0.076	0.078	0.073	0.064	0.057	0.05	0.045	0.041
		Flowback	hematological	NA	NA	3.7	3.6	3.4	3	2.8	2.8	2.8	2.8	2.6	1.8	1.6	1.7	1.5	1.7
			neurotoxicity	NA	NA	2.7	2.6	2.5	2.3	2.1	2	2.1	2	2	1.3	1.2	1.2	1.1	1.2
			respiratory	NA	NA	1	0.97	0.93	0.83	0.76	0.74	0.76	0.75	0.73	0.49	0.43	0.44	0.41	0.46
			sensory	NA	NA	0.94	0.89	0.85	0.76	0.7	0.65	0.72	0.71	0.66	0.46	0.4	0.43	0.37	0.42
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	7.2	6.1	5.7	5.2	4.6	4.3	4.1	3.6	3.4	3.2	2.9	2.9	2.3	2.1
			neurotoxicity	NA	NA	1.8	1.7	1.6	1.5	1.3	1.2	1.2	0.87	0.83	0.77	0.71	0.7	0.55	0.51
		Fracking	hematological	NA	NA	5.3	5.5	5.1	4.6	3.7	3.4	3.2	3	2.9	2.6	2.4	2.4	2	1.9
			neurotoxicity	NA	NA	1.5	1.5	1.4	1.3	1	0.95	0.89	0.84	0.79	0.7	0.67	0.66	0.54	0.51
			respiratory	NA	NA	0.77	0.8	0.75	0.67	0.54	0.5	0.47	0.44	0.42	0.37	0.36	0.35	0.29	0.27
			sensory	NA	NA	0.17	0.17	0.16	0.14	0.12	0.11	0.1	0.095	0.09	0.08	0.077	0.075	0.062	0.058
			systemic	NA	NA	0.12	0.12	0.11	0.1	0.083	0.078	0.073	0.068	0.065	0.058	0.055	0.045	0.041	0.042
		Flowback	hematological	NA	NA	3.1	3	2.8	2.5	2.2	2.1	1.9	1.3	1.2	1.2	1	1	0.87	0.75
			neurotoxicity	NA	NA	2.3	2.2	2.1	1.9	1.3	1.2	1.1	0.98	0.93	0.87	0.77	0.69	0.64	0.56
			respiratory	NA	NA	0.85	0.81	0.77	0.69	0.47	0.43	0.4	0.36	0.34	0.32	0.29	0.25	0.24	0.21
			sensory	NA	NA	0.78	0.74	0.7	0.63	0.43	0.39	0.37	0.33	0.32	0.29	0.26	0.23	0.22	0.19
	Northern Front Range	Drilling	hematological	NA	NA	8.3	8.1	7.8	6.8	6.5	5.9	5.3	4.9	4.6	3.8	3.3	2.9	2.6	2.3
			neurotoxicity	NA	NA	2	2	1.9	1.7	1.6	1.4	1.3	1.2	1.1	0.91	0.8	0.71	0.64	0.57
		Fracking	hematological	NA	NA	0.46	0.44	0.43	0.42	0.44	0.46	0.47	0.44	0.42	0.36	0.36	0.19	0.32	0.31
		Flowback	hematological	NA	NA	15	16	15	12	13	12	11	9.9	8.2	7.2	6.3	5.6	5	4.5
			neurotoxicity	NA	NA	2	2	1.9	1.7	1.6	1.5	1.4	1.3	1	0.92	0.81	0.72	0.64	0.57
			respiratory	NA	NA	0.45	0.46	0.44	0.37	0.37	0.34	0.31	0.29	0.24	0.21	0.18	0.16	0.15	0.13
			endocrine	NA	NA	0.2	0.2	0.19	0.16	0.16	0.16	0.16	0.15	0.12	0.092	0.081	0.072	0.064	0.058
			sensory	NA	NA	0.18	0.18	0.17	0.16	0.15	0.13	0.12	0.11	0.094	0.083	0.073	0.065	0.057	0.052
18 to 59 Years	Garfield County:	Drilling	hematological	NA	NA	7.3	6.6	6.4	6.1	5.8	5.6	5.2	5.9	5.8	4.6	4.2	3.9	3.6	3.3
			neurotoxicity	NA	NA	1.8	1.6	1.5	1.5	1.4	1.4	1.3	1.7	1.6	1.1	1	0.94	0.82	0.81

	Ridge Top (BarD)	Fracking	hematological	NA	NA	6.4	5.9	5.6	4.9	4.3	3.8	3.3	3.2	3	2.7	2.4	2.2	2	1.8
			neurotoxicity	NA	NA	1.7	1.6	1.5	1.4	1.2	1	0.91	0.77	0.72	0.65	0.59	0.53	0.48	0.44
			respiratory	NA	NA	0.93	0.86	0.81	0.72	0.63	0.55	0.48	0.39	0.36	0.3	0.26	0.24	0.21	0.19
			sensory	NA	NA	0.2	0.19	0.18	0.16	0.14	0.12	0.1	0.085	0.078	0.069	0.063	0.058	0.053	0.049
			systemic	NA	NA	0.14	0.13	0.12	0.11	0.096	0.084	0.076	0.078	0.073	0.064	0.057	0.05	0.045	0.041
		Flowback	hematological	NA	NA	3.7	3.6	3.4	3	2.8	2.8	2.8	2.8	2.6	1.8	1.6	1.7	1.5	1.7
			neurotoxicity	NA	NA	2.7	2.6	2.5	2.3	2.1	2	2.1	2	2	1.3	1.2	1.2	1.1	1.2
			respiratory	NA	NA	1	0.97	0.93	0.83	0.76	0.74	0.76	0.75	0.73	0.49	0.43	0.44	0.41	0.46
			sensory	NA	NA	0.94	0.89	0.85	0.76	0.7	0.65	0.72	0.71	0.66	0.46	0.4	0.43	0.37	0.42
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	7.2	6.1	5.7	5.2	4.6	4.3	4.1	3.6	3.4	3.2	2.9	2.9	2.3	2.1
			neurotoxicity	NA	NA	1.8	1.7	1.6	1.5	1.3	1.2	1.2	0.87	0.83	0.77	0.71	0.7	0.55	0.51
		Fracking	hematological	NA	NA	5.3	5.5	5.1	4.6	3.7	3.4	3.2	3	2.9	2.6	2.4	2.4	2	1.9
			neurotoxicity	NA	NA	1.5	1.5	1.4	1.3	1	0.95	0.89	0.84	0.79	0.7	0.67	0.66	0.54	0.51
			respiratory	NA	NA	0.77	0.8	0.75	0.67	0.54	0.5	0.47	0.44	0.42	0.37	0.36	0.35	0.29	0.27
			sensory	NA	NA	0.17	0.17	0.16	0.14	0.12	0.11	0.1	0.095	0.09	0.08	0.077	0.075	0.062	0.058
			systemic	NA	NA	0.12	0.12	0.11	0.1	0.083	0.078	0.073	0.068	0.065	0.058	0.055	0.045	0.041	0.042
		Flowback	hematological	NA	NA	3.1	3	2.8	2.5	2.2	2.1	1.9	1.3	1.2	1.2	1	1	0.87	0.75
			neurotoxicity	NA	NA	2.3	2.2	2.1	1.9	1.3	1.2	1.1	0.98	0.93	0.87	0.77	0.69	0.64	0.56
			respiratory	NA	NA	0.85	0.81	0.77	0.69	0.47	0.43	0.4	0.36	0.34	0.32	0.29	0.25	0.24	0.21
			sensory	NA	NA	0.78	0.74	0.7	0.63	0.43	0.39	0.37	0.33	0.32	0.29	0.26	0.23	0.22	0.19
	Northern Front Range	Drilling	hematological	NA	NA	8.3	8.1	7.8	6.8	6.5	5.9	5.3	4.9	4.6	3.8	3.3	2.9	2.6	2.3
			neurotoxicity	NA	NA	2	2	1.9	1.7	1.6	1.4	1.3	1.2	1.1	0.91	0.8	0.71	0.64	0.57
		Fracking	hematological	NA	NA	0.46	0.44	0.43	0.42	0.44	0.46	0.47	0.44	0.42	0.36	0.36	0.19	0.32	0.31
		Flowback	hematological	NA	NA	15	16	15	12	13	12	11	9.9	8.2	7.2	6.3	5.6	5	4.5
			neurotoxicity	NA	NA	2	2	1.9	1.7	1.6	1.5	1.4	1.3	1	0.92	0.81	0.72	0.64	0.57
			respiratory	NA	NA	0.45	0.46	0.44	0.37	0.37	0.34	0.31	0.29	0.24	0.21	0.18	0.16	0.15	0.13
			endocrine	NA	NA	0.2	0.2	0.19	0.16	0.16	0.16	0.16	0.15	0.12	0.092	0.081	0.072	0.064	0.058
			sensory	NA	NA	0.18	0.18	0.17	0.16	0.15	0.13	0.12	0.11	0.094	0.083	0.073	0.065	0.057	0.052
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	7.3	6.6	6.4	6.1	5.8	5.6	5.2	5.9	5.8	4.6	4.2	3.9	3.6	3.3
			neurotoxicity	NA	NA	1.8	1.6	1.5	1.5	1.4	1.4	1.3	1.7	1.6	1.1	1	0.94	0.82	0.81
		Fracking	hematological	NA	NA	6.4	5.9	5.6	4.9	4.3	3.8	3.3	3.2	3	2.7	2.4	2.2	2	1.8
			neurotoxicity	NA	NA	1.7	1.6	1.5	1.4	1.2	1	0.91	0.77	0.72	0.65	0.59	0.53	0.48	0.44
			respiratory	NA	NA	0.93	0.86	0.81	0.72	0.63	0.55	0.48	0.39	0.36	0.3	0.26	0.24	0.21	0.19
			sensory	NA	NA	0.2	0.19	0.18	0.16	0.14	0.12	0.1	0.085	0.078	0.069	0.063	0.058	0.053	0.049
			systemic	NA	NA	0.14	0.13	0.12	0.11	0.096	0.084	0.076	0.078	0.073	0.064	0.057	0.05	0.045	0.041
		Flowback	hematological	NA	NA	3.7	3.6	3.4	3	2.8	2.8	2.8	2.8	2.6	1.8	1.6	1.7	1.5	1.7
			neurotoxicity	NA	NA	2.7	2.6	2.5	2.3	2.1	2	2.1	2	2	1.3	1.2	1.2	1.1	1.2

			respiratory	NA	NA	1	0.97	0.93	0.83	0.76	0.74	0.76	0.75	0.73	0.49	0.43	0.44	0.41	0.46
			sensory	NA	NA	0.94	0.89	0.85	0.76	0.7	0.65	0.72	0.71	0.66	0.46	0.4	0.43	0.37	0.42
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	7.2	6.1	5.7	5.2	4.6	4.3	4.1	3.6	3.4	3.2	2.9	2.9	2.3	2.1
			neurotoxicity	NA	NA	1.8	1.7	1.6	1.5	1.3	1.2	1.2	0.87	0.83	0.77	0.71	0.7	0.55	0.51
		Fracking	hematological	NA	NA	5.3	5.5	5.1	4.6	3.7	3.4	3.2	3	2.9	2.6	2.4	2.4	2	1.9
			neurotoxicity	NA	NA	1.5	1.5	1.4	1.3	1	0.95	0.89	0.84	0.79	0.7	0.67	0.66	0.54	0.51
			respiratory	NA	NA	0.77	0.8	0.75	0.67	0.54	0.5	0.47	0.44	0.42	0.37	0.36	0.35	0.29	0.27
			sensory	NA	NA	0.17	0.17	0.16	0.14	0.12	0.11	0.1	0.095	0.09	0.08	0.077	0.075	0.062	0.058
			systemic	NA	NA	0.12	0.12	0.11	0.1	0.083	0.078	0.073	0.068	0.065	0.058	0.055	0.045	0.041	0.042
		Flowback	hematological	NA	NA	3.1	3	2.8	2.5	2.2	2.1	1.9	1.3	1.2	1.2	1	1	0.87	0.75
			neurotoxicity	NA	NA	2.3	2.2	2.1	1.9	1.3	1.2	1.1	0.98	0.93	0.87	0.77	0.69	0.64	0.56
			respiratory	NA	NA	0.85	0.81	0.77	0.69	0.47	0.43	0.4	0.36	0.34	0.32	0.29	0.25	0.24	0.21
			sensory	NA	NA	0.78	0.74	0.7	0.63	0.43	0.39	0.37	0.33	0.32	0.29	0.26	0.23	0.22	0.19
	Northern Front Range	Drilling	hematological	NA	NA	8.3	8.1	7.8	6.8	6.5	5.9	5.3	4.9	4.6	3.8	3.3	2.9	2.6	2.3
			neurotoxicity	NA	NA	2	2	1.9	1.7	1.6	1.4	1.3	1.2	1.1	0.91	0.8	0.71	0.64	0.57
		Fracking	hematological	NA	NA	0.46	0.44	0.43	0.42	0.44	0.46	0.47	0.44	0.42	0.36	0.36	0.19	0.32	0.31
		Flowback	hematological	NA	NA	15	16	15	12	13	12	11	9.9	8.2	7.2	6.3	5.6	5	4.5
			neurotoxicity	NA	NA	2	2	1.9	1.7	1.6	1.5	1.4	1.3	1	0.92	0.81	0.72	0.64	0.57
			respiratory	NA	NA	0.45	0.46	0.44	0.37	0.37	0.34	0.31	0.29	0.24	0.21	0.18	0.16	0.15	0.13
			endocrine	NA	NA	0.2	0.2	0.19	0.16	0.16	0.16	0.16	0.15	0.12	0.092	0.081	0.072	0.064	0.058
			sensory	NA	NA	0.18	0.18	0.17	0.16	0.15	0.13	0.12	0.11	0.094	0.083	0.073	0.065	0.057	0.052

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D).

Table E-12. Percentage of Daily-maximum Acute Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	98%	97%	96%	93%	90%	84%	78%	83%	80%	51%	37%	25%	16%	10%
			neurotoxicity	NA	NA	39%	30%	24%	11%	3%	1%	1%	6%	5%	1%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	97%	95%	94%	90%	84%	77%	67%	57%	48%	32%	18%	9%	5%	3%
			neurotoxicity	NA	NA	24%	15%	10%	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	89%	87%	85%	80%	73%	68%	65%	62%	59%	30%	19%	13%	13%	12%
			neurotoxicity	NA	NA	34%	30%	27%	21%	16%	12%	11%	10%	10%	4%	2%	1%	1%	1%
	Garfield	Drilling	hematological	NA	NA	99%	98%	98%	96%	95%	93%	91%	88%	85%	83%	76%	68%	59%	46%

	County: Valley (Rifle)		neurotoxicity	NA	NA	49%	40%	32%	17%	5%	1%	1%	0%	0%	0%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	98%	97%	96%	94%	90%	88%	86%	83%	80%	72%	66%	55%	42%	25%
			neurotoxicity	NA	NA	33%	29%	18%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	91%	88%	85%	81%	65%	55%	42%	22%	12%	5%	0%	0%	0%	0%
			neurotoxicity	NA	NA	41%	36%	31%	25%	15%	6%	1%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	hematological	NA	NA	99%	98%	98%	96%	93%	90%	86%	82%	77%	67%	56%	45%	34%	24%
			neurotoxicity	NA	NA	53%	44%	36%	22%	10%	4%	2%	2%	1%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	100%	100%	100%	100%	100%	99%	99%	98%	97%	95%	92%	87%	82%	77%
			neurotoxicity	NA	NA	53%	44%	36%	19%	10%	4%	3%	2%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	98%	97%	96%	93%	89%	84%	78%	82%	80%	50%	37%	25%	16%	10%
			neurotoxicity	NA	NA	39%	30%	23%	10%	3%	1%	1%	6%	5%	1%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	97%	95%	93%	89%	84%	76%	66%	56%	47%	31%	17%	9%	5%	3%
			neurotoxicity	NA	NA	23%	15%	10%	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	89%	87%	84%	79%	72%	67%	64%	61%	58%	30%	18%	13%	13%	12%
			neurotoxicity	NA	NA	33%	30%	27%	21%	16%	12%	11%	10%	9%	4%	2%	1%	1%	1%
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	99%	98%	97%	96%	94%	93%	91%	87%	84%	82%	74%	67%	58%	44%
			neurotoxicity	NA	NA	48%	39%	31%	16%	4%	1%	1%	0%	0%	0%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	98%	97%	96%	94%	90%	87%	85%	82%	79%	70%	64%	54%	40%	24%
			neurotoxicity	NA	NA	31%	27%	17%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	90%	87%	84%	79%	62%	52%	39%	20%	10%	5%	0%	0%	0%	0%
			neurotoxicity	NA	NA	41%	35%	30%	24%	14%	6%	1%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Drilling	hematological	NA	NA	99%	98%	97%	95%	93%	89%	85%	81%	76%	67%	55%	44%	33%	23%
			neurotoxicity	NA	NA	51%	43%	35%	21%	9%	4%	2%	1%	1%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	100%	100%	100%	100%	100%	99%	99%	98%	97%	94%	91%	86%	81%	75%
			neurotoxicity	NA	NA	52%	43%	35%	19%	10%	4%	3%	2%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	96%	95%	94%	91%	87%	81%	75%	80%	78%	48%	35%	23%	15%	10%
			neurotoxicity	NA	NA	37%	28%	22%	9%	3%	1%	1%	6%	5%	1%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	94%	92%	90%	86%	81%	73%	63%	54%	45%	30%	16%	9%	4%	3%
			neurotoxicity	NA	NA	22%	14%	9%	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	85%	83%	81%	75%	69%	64%	61%	59%	55%	28%	17%	12%	12%	11%
			neurotoxicity	NA	NA	32%	29%	26%	20%	15%	12%	11%	10%	9%	4%	2%	1%	1%	1%
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	97%	96%	95%	94%	92%	90%	88%	84%	81%	79%	71%	64%	55%	42%
			neurotoxicity	NA	NA	45%	37%	29%	15%	4%	1%	1%	0%	0%	0%	0%	0%	0%	0%
		Fracking	hematological	NA	NA	96%	95%	94%	92%	86%	84%	81%	79%	75%	67%	61%	51%	38%	23%
			neurotoxicity	NA	NA	30%	26%	17%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	86%	83%	79%	75%	57%	49%	37%	19%	10%	5%	0%	0%	0%	0%
			neurotoxicity	NA	NA	39%	34%	29%	23%	13%	6%	1%	0%	0%	0%	0%	0%	0%	0%

Age Group	Site	Activity	Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
	Northern Front Range	Drilling	hematological	NA	NA	98%	97%	96%	93%	91%	87%	83%	78%	73%	64%	53%	43%	32%	22%
			neurotoxicity	NA	NA	49%	41%	33%	20%	9%	4%	2%	1%	1%	0%	0%	0%	0%	0%
		Flowback	hematological	NA	NA	100%	100%	100%	100%	99%	98%	97%	96%	95%	92%	88%	84%	79%	73%
			neurotoxicity	NA	NA	50%	41%	34%	18%	9%	4%	2%	2%	0%	0%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D).

E.1.2 Subchronic Non-cancer Hazards

E.1.2.1 1-acre Well Pad

Table E-13. Largest Subchronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 1-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	0.62	0.51	0.43	0.32	0.24	0.19	0.15	0.065	0.057	0.04	0.032	0.026	0.023	0.022
			toluene	NA	NA	0.21	0.17	0.14	0.11	0.081	0.063	0.051	0.02	0.018	0.013	0.01	<0.01	<0.01	<0.01
		Fracking	m+p-xylene	NA	NA	2	1.6	1.4	1	0.78	0.61	0.49	0.4	0.34	0.26	0.21	0.17	0.14	0.12
			n-nonane	NA	NA	1.1	0.95	0.8	0.59	0.46	0.36	0.29	0.24	0.2	0.15	0.12	0.1	0.085	0.074
			benzene	NA	NA	0.99	0.82	0.69	0.52	0.4	0.31	0.25	0.21	0.18	0.14	0.11	0.095	0.079	0.068
			1,2,4-trimethylbenzene	NA	NA	0.43	0.36	0.3	0.23	0.17	0.14	0.11	0.092	0.08	0.061	0.05	0.041	0.034	0.029
			1,3,5-trimethylbenzene	NA	NA	0.33	0.27	0.23	0.17	0.14	0.11	0.085	0.07	0.059	0.046	0.036	0.03	0.026	0.022
			o-xylene	NA	NA	0.17	0.14	0.12	0.087	0.068	0.053	0.042	0.035	0.029	0.023	0.018	0.015	0.012	0.011
			1,2,3-trimethylbenzene	NA	NA	0.12	0.1	0.085	0.064	0.049	0.039	0.031	0.025	0.021	0.017	0.014	0.011	<0.01	<0.01
		Flowback	n-nonane	NA	NA	0.59	0.48	0.41	0.23	0.17	0.075	0.064	0.056	0.05	0.035	0.029	0.016	0.022	0.016
			m+p-xylene	NA	NA	0.54	0.45	0.37	0.21	0.16	0.07	0.06	0.052	0.046	0.032	0.027	0.015	0.02	0.014
			1,3,5-trimethylbenzene	NA	NA	0.48	0.4	0.33	0.19	0.14	0.061	0.052	0.045	0.04	0.028	0.025	0.013	0.018	0.013
			1,2,4-trimethylbenzene	NA	NA	0.47	0.39	0.32	0.18	0.14	0.06	0.051	0.044	0.039	0.028	0.024	0.012	0.018	0.013
			1,2,3-trimethylbenzene	NA	NA	0.34	0.28	0.19	0.13	0.1	0.043	0.037	0.032	0.028	0.02	0.018	<0.01	0.013	0.01
			benzene	NA	NA	0.32	0.26	0.22	0.12	0.095	0.04	0.034	0.03	0.027	0.019	0.016	<0.01	0.012	<0.01
			2-ethyltoluene	NA	NA	0.23	0.19	0.13	0.091	0.069	0.029	0.025	0.022	0.019	0.013	0.012	0.01	<0.01	<0.01
			o-xylene	NA	NA	0.11	0.087	0.073	0.041	0.031	0.013	0.012	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	0.42	0.31	0.26	0.28	0.22	0.19	0.16	0.14	0.13	0.1	0.094	0.072	0.05	0.03
			toluene	NA	NA	0.13	0.1	0.084	0.09	0.073	0.061	0.053	0.046	0.041	0.034	0.03	0.023	0.016	<0.01
		Fracking	m+p-xylene	NA	NA	1.6	1.3	1.1	0.85	0.69	0.59	0.51	0.45	0.4	0.33	0.32	0.26	0.21	0.12

	(Rifle)		n-nonane	NA	NA	0.91	0.74	0.63	0.49	0.41	0.35	0.3	0.27	0.24	0.19	0.19	0.15	0.12	0.07
			benzene	NA	NA	0.8	0.65	0.56	0.43	0.36	0.3	0.27	0.23	0.21	0.17	0.16	0.13	0.11	0.063
			1,2,4-trimethylbenzene	NA	NA	0.36	0.29	0.25	0.19	0.16	0.13	0.11	0.1	0.09	0.073	0.071	0.057	0.046	0.028
			1,3,5-trimethylbenzene	NA	NA	0.27	0.22	0.19	0.15	0.12	0.1	0.089	0.079	0.07	0.056	0.056	0.045	0.037	0.022
			o-xylene	NA	NA	0.13	0.11	0.094	0.073	0.06	0.051	0.045	0.04	0.035	0.029	0.027	0.022	0.018	0.01
		Flowback	n-nonane	NA	NA	0.25	0.24	0.2	0.15	0.17	0.14	0.13	0.11	0.11	0.082	0.077	0.054	0.034	0.027
			m+p-xylene	NA	NA	0.23	0.23	0.18	0.14	0.15	0.13	0.12	0.11	0.097	0.076	0.071	0.05	0.032	0.025
			1,3,5-trimethylbenzene	NA	NA	0.2	0.19	0.16	0.11	0.13	0.11	0.1	0.089	0.078	0.064	0.06	0.042	0.027	0.021
			1,2,4-trimethylbenzene	NA	NA	0.19	0.19	0.15	0.11	0.13	0.11	0.098	0.086	0.076	0.062	0.058	0.041	0.026	0.02
			1,2,3-trimethylbenzene	NA	NA	0.14	0.13	0.11	0.081	0.089	0.075	0.07	0.062	0.055	0.045	0.041	0.029	0.018	0.015
			benzene	NA	NA	0.14	0.13	0.11	0.08	0.093	0.077	0.072	0.063	0.058	0.045	0.042	0.03	0.019	0.015
	Northern Front Range	Drilling	benzene	NA	NA	0.49	0.39	0.32	0.23	0.17	0.14	0.11	0.092	0.078	0.057	0.044	0.036	0.03	0.025
			toluene	NA	NA	0.16	0.13	0.1	0.075	0.057	0.045	0.036	0.03	0.026	0.018	0.014	0.012	<0.01	<0.01
		Flowback	benzene	NA	NA	1.1	0.9	0.75	0.53	0.4	0.31	0.25	0.21	0.18	0.13	0.11	0.085	0.07	0.059
			n-nonane	NA	NA	0.58	0.47	0.39	0.28	0.21	0.16	0.13	0.11	0.092	0.07	0.055	0.044	0.037	0.031
			m+p-xylene	NA	NA	0.35	0.29	0.24	0.17	0.13	0.099	0.079	0.066	0.056	0.042	0.033	0.027	0.022	0.019
			1,3,5-trimethylbenzene	NA	NA	0.25	0.2	0.17	0.12	0.089	0.07	0.056	0.047	0.04	0.03	0.024	0.019	0.016	0.013
			1,2,4-trimethylbenzene	NA	NA	0.22	0.18	0.15	0.1	0.079	0.062	0.049	0.041	0.035	0.027	0.021	0.017	0.014	0.012
			n-hexane	NA	NA	0.12	0.097	0.08	0.057	0.044	0.033	0.027	0.022	0.019	0.014	0.011	<0.01	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	0.63	0.51	0.43	0.32	0.24	0.19	0.15	0.065	0.057	0.04	0.032	0.026	0.023	0.022
			toluene	NA	NA	0.21	0.17	0.14	0.11	0.081	0.064	0.051	0.02	0.018	0.013	0.01	<0.01	<0.01	<0.01
		Fracking	m+p-xylene	NA	NA	2	1.6	1.4	1	0.78	0.61	0.49	0.4	0.34	0.26	0.21	0.17	0.14	0.12
			n-nonane	NA	NA	1.1	0.95	0.8	0.59	0.46	0.36	0.29	0.24	0.2	0.15	0.12	0.1	0.085	0.073
			benzene	NA	NA	0.99	0.82	0.69	0.52	0.4	0.31	0.25	0.21	0.18	0.14	0.11	0.094	0.079	0.068
			1,2,4-trimethylbenzene	NA	NA	0.43	0.36	0.3	0.23	0.17	0.14	0.11	0.092	0.08	0.061	0.05	0.041	0.034	0.029
			1,3,5-trimethylbenzene	NA	NA	0.33	0.27	0.23	0.17	0.14	0.11	0.085	0.07	0.059	0.046	0.036	0.03	0.026	0.022
			o-xylene	NA	NA	0.17	0.14	0.12	0.087	0.068	0.053	0.042	0.035	0.029	0.023	0.018	0.015	0.012	0.011
			1,2,3-trimethylbenzene	NA	NA	0.12	0.1	0.085	0.064	0.049	0.039	0.031	0.025	0.021	0.017	0.014	0.011	<0.01	<0.01
		Flowback	n-nonane	NA	NA	0.59	0.48	0.41	0.23	0.17	0.076	0.064	0.056	0.05	0.035	0.029	0.016	0.022	0.016
			m+p-xylene	NA	NA	0.54	0.45	0.37	0.21	0.16	0.07	0.06	0.052	0.046	0.032	0.027	0.015	0.02	0.014
			1,3,5-trimethylbenzene	NA	NA	0.48	0.4	0.33	0.19	0.14	0.061	0.052	0.045	0.04	0.028	0.025	0.013	0.018	0.013
			1,2,4-trimethylbenzene	NA	NA	0.47	0.39	0.32	0.18	0.14	0.06	0.051	0.044	0.039	0.028	0.024	0.012	0.018	0.013
			1,2,3-trimethylbenzene	NA	NA	0.34	0.28	0.19	0.13	0.1	0.043	0.037	0.032	0.028	0.02	0.018	<0.01	0.013	0.01
			benzene	NA	NA	0.32	0.26	0.22	0.12	0.095	0.04	0.034	0.03	0.027	0.019	0.016	<0.01	0.012	<0.01
			2-ethyltoluene	NA	NA	0.23	0.19	0.13	0.091	0.069	0.029	0.025	0.022	0.019	0.013	0.012	0.01	<0.01	<0.01
			o-xylene	NA	NA	0.11	0.087	0.073	0.041	0.031	0.013	0.012	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Garfield	Drilling	benzene	NA	NA	0.42	0.31	0.26	0.27	0.22	0.19	0.16	0.14	0.13	0.1	0.094	0.072	0.05	0.03

	County: Valley (Rifle)		toluene	NA	NA	0.14	0.1	0.084	0.089	0.073	0.061	0.053	0.046	0.041	0.034	0.03	0.023	0.016	<0.01
		Fracking	m+p-xylene	NA	NA	1.5	1.3	1.1	0.84	0.69	0.58	0.51	0.45	0.4	0.33	0.32	0.26	0.21	0.12
			n-nonane	NA	NA	0.91	0.74	0.63	0.49	0.41	0.35	0.3	0.27	0.24	0.19	0.19	0.15	0.12	0.07
			benzene	NA	NA	0.8	0.65	0.56	0.43	0.36	0.3	0.26	0.23	0.21	0.17	0.16	0.13	0.11	0.063
			1,2,4-trimethylbenzene	NA	NA	0.36	0.29	0.25	0.19	0.16	0.13	0.11	0.1	0.09	0.073	0.071	0.056	0.046	0.028
			1,3,5-trimethylbenzene	NA	NA	0.27	0.22	0.18	0.15	0.12	0.1	0.089	0.079	0.07	0.056	0.056	0.045	0.037	0.022
			o-xylene	NA	NA	0.13	0.11	0.093	0.073	0.06	0.051	0.045	0.04	0.035	0.029	0.027	0.022	0.018	0.01
		Flowback	n-nonane	NA	NA	0.25	0.24	0.2	0.14	0.17	0.14	0.13	0.11	0.11	0.082	0.077	0.054	0.034	0.027
			m+p-xylene	NA	NA	0.23	0.22	0.18	0.14	0.15	0.13	0.12	0.11	0.097	0.076	0.071	0.05	0.032	0.025
			1,3,5-trimethylbenzene	NA	NA	0.2	0.19	0.15	0.11	0.13	0.11	0.1	0.088	0.078	0.064	0.06	0.042	0.027	0.021
			1,2,4-trimethylbenzene	NA	NA	0.19	0.19	0.15	0.11	0.13	0.11	0.098	0.086	0.076	0.062	0.058	0.041	0.026	0.02
			1,2,3-trimethylbenzene	NA	NA	0.14	0.13	0.11	0.081	0.089	0.074	0.07	0.062	0.054	0.045	0.041	0.029	0.018	0.015
			benzene	NA	NA	0.14	0.13	0.11	0.08	0.093	0.077	0.072	0.063	0.058	0.045	0.042	0.03	0.019	0.015
	Northern Front Range	Drilling	benzene	NA	NA	0.49	0.39	0.32	0.23	0.17	0.14	0.11	0.092	0.078	0.057	0.044	0.036	0.03	0.025
			toluene	NA	NA	0.16	0.13	0.1	0.074	0.057	0.045	0.036	0.03	0.026	0.018	0.014	0.012	<0.01	<0.01
		Flowback	benzene	NA	NA	1.1	0.91	0.75	0.53	0.4	0.31	0.25	0.21	0.18	0.13	0.11	0.085	0.07	0.059
			n-nonane	NA	NA	0.59	0.47	0.39	0.28	0.21	0.16	0.13	0.11	0.092	0.07	0.055	0.044	0.037	0.031
			m+p-xylene	NA	NA	0.35	0.29	0.24	0.17	0.13	0.099	0.079	0.066	0.056	0.042	0.033	0.027	0.022	0.019
			1,3,5-trimethylbenzene	NA	NA	0.25	0.2	0.17	0.12	0.089	0.07	0.056	0.047	0.04	0.03	0.024	0.019	0.016	0.013
			1,2,4-trimethylbenzene	NA	NA	0.22	0.18	0.15	0.1	0.079	0.062	0.049	0.041	0.035	0.027	0.021	0.017	0.014	0.012
			n-hexane	NA	NA	0.12	0.097	0.08	0.057	0.044	0.033	0.027	0.022	0.019	0.014	0.011	<0.01	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	0.63	0.51	0.43	0.32	0.25	0.19	0.15	0.065	0.057	0.04	0.032	0.026	0.023	0.022
			toluene	NA	NA	0.21	0.17	0.14	0.11	0.081	0.064	0.051	0.02	0.018	0.013	0.01	<0.01	<0.01	<0.01
		Fracking	m+p-xylene	NA	NA	2	1.6	1.4	1	0.78	0.61	0.49	0.4	0.34	0.26	0.21	0.17	0.14	0.12
			n-nonane	NA	NA	1.1	0.95	0.8	0.59	0.46	0.36	0.29	0.24	0.2	0.15	0.12	0.1	0.085	0.074
			benzene	NA	NA	0.99	0.82	0.69	0.52	0.4	0.31	0.25	0.21	0.18	0.14	0.11	0.095	0.079	0.068
			1,2,4-trimethylbenzene	NA	NA	0.43	0.35	0.3	0.23	0.17	0.14	0.11	0.092	0.08	0.061	0.05	0.041	0.034	0.029
			1,3,5-trimethylbenzene	NA	NA	0.33	0.27	0.23	0.17	0.13	0.11	0.085	0.07	0.059	0.046	0.036	0.03	0.026	0.022
			o-xylene	NA	NA	0.17	0.14	0.12	0.087	0.068	0.053	0.042	0.035	0.029	0.022	0.018	0.015	0.012	0.011
			1,2,3-trimethylbenzene	NA	NA	0.12	0.1	0.085	0.064	0.049	0.039	0.031	0.025	0.021	0.017	0.014	0.011	<0.01	<0.01
		Flowback	n-nonane	NA	NA	0.59	0.48	0.41	0.23	0.17	0.076	0.065	0.056	0.05	0.035	0.029	0.016	0.022	0.016
			m+p-xylene	NA	NA	0.55	0.45	0.38	0.21	0.16	0.07	0.06	0.052	0.046	0.032	0.027	0.015	0.02	0.014
			1,3,5-trimethylbenzene	NA	NA	0.48	0.4	0.33	0.19	0.14	0.061	0.052	0.045	0.04	0.028	0.025	0.013	0.018	0.013
			1,2,4-trimethylbenzene	NA	NA	0.47	0.39	0.32	0.18	0.14	0.06	0.051	0.045	0.039	0.028	0.024	0.012	0.018	0.013
			1,2,3-trimethylbenzene	NA	NA	0.34	0.28	0.19	0.13	0.1	0.043	0.037	0.032	0.028	0.02	0.018	<0.01	0.013	0.01
			benzene	NA	NA	0.32	0.26	0.22	0.12	0.095	0.04	0.034	0.03	0.027	0.019	0.016	<0.01	0.012	<0.01
			2-ethyltoluene	NA	NA	0.23	0.19	0.13	0.091	0.069	0.029	0.025	0.022	0.019	0.013	0.012	0.01	<0.01	<0.01

			o-xylene	NA	NA	0.11	0.087	0.073	0.041	0.031	0.013	0.012	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	0.42	0.31	0.26	0.28	0.22	0.19	0.16	0.14	0.13	0.1	0.094	0.072	0.05	0.03
			toluene	NA	NA	0.14	0.1	0.084	0.09	0.073	0.061	0.053	0.046	0.041	0.034	0.03	0.023	0.016	<0.01
		Fracking	m+p-xylene	NA	NA	1.6	1.3	1.1	0.85	0.69	0.59	0.51	0.45	0.4	0.33	0.32	0.26	0.21	0.12
			n-nonane	NA	NA	0.91	0.74	0.63	0.49	0.41	0.35	0.3	0.27	0.24	0.19	0.19	0.15	0.12	0.07
			benzene	NA	NA	0.8	0.65	0.56	0.44	0.36	0.3	0.27	0.23	0.21	0.17	0.16	0.13	0.11	0.063
			1,2,4-trimethylbenzene	NA	NA	0.36	0.29	0.25	0.19	0.16	0.13	0.11	0.1	0.09	0.073	0.071	0.057	0.046	0.028
			1,3,5-trimethylbenzene	NA	NA	0.27	0.22	0.18	0.15	0.12	0.1	0.089	0.079	0.07	0.056	0.056	0.045	0.037	0.022
			o-xylene	NA	NA	0.13	0.11	0.094	0.073	0.06	0.051	0.045	0.04	0.035	0.029	0.027	0.022	0.018	0.01
		Flowback	n-nonane	NA	NA	0.25	0.24	0.2	0.15	0.17	0.14	0.13	0.11	0.11	0.082	0.077	0.054	0.034	0.027
			m+p-xylene	NA	NA	0.23	0.23	0.18	0.14	0.15	0.13	0.12	0.11	0.097	0.076	0.071	0.05	0.032	0.025
			1,3,5-trimethylbenzene	NA	NA	0.2	0.19	0.16	0.11	0.13	0.11	0.1	0.089	0.078	0.064	0.06	0.042	0.027	0.021
			1,2,4-trimethylbenzene	NA	NA	0.19	0.19	0.15	0.11	0.13	0.11	0.098	0.086	0.076	0.062	0.058	0.041	0.026	0.02
			1,2,3-trimethylbenzene	NA	NA	0.14	0.13	0.11	0.081	0.089	0.075	0.07	0.062	0.055	0.045	0.041	0.029	0.018	0.015
			benzene	NA	NA	0.14	0.13	0.11	0.08	0.093	0.078	0.072	0.063	0.058	0.045	0.042	0.03	0.019	0.015
	Northern Front Range	Drilling	benzene	NA	NA	0.49	0.39	0.32	0.23	0.17	0.14	0.11	0.092	0.078	0.057	0.044	0.036	0.03	0.025
			toluene	NA	NA	0.16	0.13	0.1	0.074	0.057	0.045	0.036	0.03	0.026	0.018	0.014	0.012	<0.01	<0.01
		Flowback	benzene	NA	NA	1.1	0.91	0.75	0.53	0.4	0.31	0.25	0.21	0.18	0.13	0.11	0.085	0.07	0.059
			n-nonane	NA	NA	0.58	0.47	0.39	0.28	0.21	0.16	0.13	0.11	0.092	0.07	0.055	0.044	0.037	0.031
			m+p-xylene	NA	NA	0.35	0.29	0.24	0.17	0.13	0.099	0.079	0.066	0.056	0.042	0.033	0.027	0.022	0.019
			1,3,5-trimethylbenzene	NA	NA	0.25	0.2	0.17	0.12	0.089	0.07	0.056	0.047	0.04	0.03	0.024	0.019	0.016	0.013
			1,2,4-trimethylbenzene	NA	NA	0.22	0.18	0.15	0.1	0.079	0.063	0.049	0.041	0.035	0.027	0.021	0.017	0.014	0.012
			n-hexane	NA	NA	0.12	0.097	0.08	0.057	0.044	0.033	0.027	0.022	0.019	0.014	0.011	<0.01	<0.01	<0.01

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-14. Percentage of Subchronic Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 1-acre Well Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet): 150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Fracking	m+p-xylene	NA	NA	25%	10%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-nonane	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Garfield County: Valley (Rifle)		m+p-xylene	NA	NA	7%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Flowback	benzene	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)	Fracking	m+p-xylene	NA	NA	25%	10%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-nonane	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		m+p-xylene	NA	NA	7%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Flowback	benzene	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)	Fracking	m+p-xylene	NA	NA	24%	10%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			n-nonane	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		m+p-xylene	NA	NA	7%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Flowback	benzene	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity.

Table E-15. Largest Subchronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 1-acre Well Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet)															
				150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	0.71	0.58	0.49	0.36	0.28	0.22	0.17	0.075	0.065	0.048	0.038	0.031	0.026	0.026
			neurotoxicity	NA	NA	0.31	0.25	0.21	0.16	0.12	0.095	0.076	0.033	0.028	0.022	0.017	0.014	0.011	0.012
		Fracking	neurotoxicity	NA	NA	4.3	3.5	3	2.2	1.7	1.3	1.1	0.87	0.74	0.57	0.45	0.38	0.31	0.27
			hematological	NA	NA	4	3.3	2.8	2	1.6	1.2	0.99	0.82	0.69	0.53	0.42	0.35	0.29	0.25
			respiratory	NA	NA	0.87	0.72	0.61	0.46	0.35	0.28	0.22	0.18	0.16	0.12	0.1	0.082	0.068	0.059
			systemic	NA	NA	0.21	0.17	0.15	0.11	0.084	0.066	0.053	0.044	0.037	0.029	0.023	0.019	0.016	0.014
		Flowback	neurotoxicity	NA	NA	2.6	2.1	1.8	1	0.77	0.33	0.29	0.25	0.22	0.15	0.13	0.07	0.099	0.072
			hematological	NA	NA	2.3	1.8	1.5	0.87	0.66	0.29	0.24	0.21	0.19	0.13	0.11	0.06	0.085	0.062
			respiratory	NA	NA	1.3	1.1	0.84	0.5	0.38	0.16	0.14	0.12	0.11	0.076	0.066	0.034	0.05	0.037
			systemic	NA	NA	0.43	0.35	0.25	0.17	0.13	0.054	0.046	0.04	0.035	0.025	0.022	0.016	0.017	0.012
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	0.47	0.35	0.29	0.31	0.25	0.21	0.18	0.16	0.14	0.12	0.11	0.082	0.057	0.034
			neurotoxicity	NA	NA	0.2	0.15	0.12	0.14	0.11	0.093	0.081	0.071	0.063	0.052	0.046	0.035	0.024	0.015
		Fracking	neurotoxicity	NA	NA	3.4	2.8	2.4	1.8	1.5	1.3	1.1	1	0.89	0.72	0.7	0.56	0.47	0.26
			hematological	NA	NA	3.2	2.6	2.2	1.7	1.4	1.2	1	0.93	0.83	0.67	0.64	0.52	0.43	0.24
			respiratory	NA	NA	0.72	0.58	0.5	0.39	0.31	0.27	0.23	0.2	0.18	0.15	0.15	0.12	0.095	0.057
			systemic	NA	NA	0.16	0.13	0.11	0.087	0.072	0.061	0.053	0.047	0.042	0.034	0.032	0.025	0.021	0.013
		Flowback	neurotoxicity	NA	NA	1.1	1	0.86	0.63	0.71	0.6	0.56	0.49	0.44	0.35	0.33	0.23	0.15	0.12
			hematological	NA	NA	0.94	0.9	0.74	0.54	0.61	0.51	0.48	0.42	0.38	0.3	0.28	0.2	0.13	0.099
			respiratory	NA	NA	0.53	0.51	0.42	0.31	0.34	0.29	0.27	0.24	0.21	0.17	0.16	0.11	0.071	0.056
			systemic	NA	NA	0.17	0.16	0.13	0.098	0.11	0.098	0.087	0.076	0.068	0.055	0.051	0.036	0.023	0.018
	Northern Front Range	Drilling	hematological	NA	NA	0.55	0.45	0.37	0.26	0.2	0.16	0.13	0.1	0.089	0.065	0.05	0.041	0.034	0.028
			neurotoxicity	NA	NA	0.24	0.19	0.16	0.11	0.087	0.068	0.055	0.045	0.039	0.028	0.022	0.018	0.015	0.012
		Fracking	hematological	NA	NA	0.11	0.092	0.076	0.054	0.042	0.033	0.027	0.022	0.019	0.014	0.011	<0.01	<0.01	<0.01
		Flowback	hematological	NA	NA	2.1	1.7	1.4	0.99	0.74	0.58	0.46	0.39	0.33	0.25	0.2	0.16	0.13	0.11
			neurotoxicity	NA	NA	1.8	1.4	1.2	0.84	0.63	0.49	0.39	0.33	0.28	0.21	0.17	0.13	0.11	0.094
			respiratory	NA	NA	0.51	0.41	0.34	0.24	0.18	0.14	0.11	0.095	0.081	0.061	0.048	0.039	0.032	0.027
			systemic	NA	NA	0.16	0.13	0.1	0.074	0.056	0.044	0.035	0.029	0.025	0.019	0.015	0.012	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	0.71	0.58	0.49	0.36	0.28	0.22	0.17	0.075	0.065	0.048	0.038	0.031	0.026	0.026
			neurotoxicity	NA	NA	0.31	0.25	0.21	0.16	0.12	0.095	0.076	0.033	0.028	0.022	0.017	0.014	0.011	0.012
		Fracking	neurotoxicity	NA	NA	4.3	3.5	3	2.2	1.7	1.3	1.1	0.87	0.74	0.57	0.45	0.38	0.31	0.27
			hematological	NA	NA	4	3.3	2.8	2	1.6	1.2	0.99	0.82	0.69	0.53	0.42	0.35	0.29	0.25
			respiratory	NA	NA	0.87	0.72	0.61	0.46	0.35	0.28	0.22	0.18	0.16	0.12	0.099	0.082	0.069	0.059

			systemic	NA	NA	0.21	0.17	0.15	0.11	0.084	0.066	0.053	0.044	0.037	0.029	0.023	0.019	0.016	0.014
		Flowback	neurotoxicity	NA	NA	2.6	2.1	1.8	1	0.78	0.33	0.29	0.25	0.22	0.15	0.13	0.07	0.099	0.072
			hematological	NA	NA	2.3	1.8	1.5	0.87	0.67	0.29	0.24	0.21	0.19	0.13	0.11	0.06	0.085	0.062
			respiratory	NA	NA	1.3	1.1	0.84	0.5	0.38	0.16	0.14	0.12	0.11	0.076	0.066	0.034	0.05	0.036
			systemic	NA	NA	0.43	0.35	0.25	0.17	0.13	0.054	0.046	0.04	0.035	0.025	0.022	0.016	0.017	0.012
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	0.47	0.35	0.29	0.31	0.25	0.21	0.18	0.16	0.14	0.12	0.11	0.082	0.057	0.034
			neurotoxicity	NA	NA	0.2	0.15	0.12	0.14	0.11	0.093	0.081	0.071	0.063	0.052	0.046	0.035	0.024	0.015
		Fracking	neurotoxicity	NA	NA	3.4	2.8	2.4	1.8	1.5	1.3	1.1	0.99	0.89	0.72	0.69	0.56	0.46	0.26
			hematological	NA	NA	3.2	2.6	2.2	1.7	1.4	1.2	1	0.93	0.82	0.67	0.64	0.52	0.43	0.24
			respiratory	NA	NA	0.72	0.58	0.5	0.39	0.31	0.27	0.23	0.2	0.18	0.15	0.14	0.12	0.095	0.057
			systemic	NA	NA	0.16	0.13	0.11	0.087	0.072	0.061	0.053	0.047	0.042	0.034	0.032	0.025	0.021	0.013
		Flowback	neurotoxicity	NA	NA	1.1	1	0.86	0.63	0.71	0.6	0.56	0.49	0.44	0.35	0.33	0.23	0.15	0.12
			hematological	NA	NA	0.93	0.9	0.74	0.54	0.61	0.51	0.48	0.42	0.38	0.3	0.28	0.2	0.13	0.099
			respiratory	NA	NA	0.53	0.51	0.42	0.31	0.34	0.29	0.27	0.24	0.21	0.17	0.16	0.11	0.071	0.056
			systemic	NA	NA	0.17	0.16	0.13	0.098	0.11	0.098	0.087	0.076	0.068	0.055	0.051	0.036	0.023	0.018
	Northern Front Range	Drilling	hematological	NA	NA	0.55	0.45	0.37	0.26	0.2	0.16	0.12	0.1	0.088	0.064	0.05	0.041	0.033	0.028
			neurotoxicity	NA	NA	0.24	0.19	0.16	0.11	0.087	0.068	0.055	0.045	0.039	0.028	0.022	0.018	0.015	0.012
		Fracking	hematological	NA	NA	0.11	0.092	0.076	0.054	0.042	0.033	0.027	0.022	0.019	0.014	0.011	<0.01	<0.01	<0.01
		Flowback	hematological	NA	NA	2.1	1.7	1.4	0.99	0.74	0.58	0.46	0.39	0.33	0.25	0.2	0.16	0.13	0.11
			neurotoxicity	NA	NA	1.8	1.4	1.2	0.84	0.63	0.49	0.39	0.33	0.28	0.21	0.17	0.13	0.11	0.094
			respiratory	NA	NA	0.51	0.41	0.34	0.24	0.18	0.14	0.11	0.095	0.081	0.061	0.048	0.039	0.032	0.027
			systemic	NA	NA	0.16	0.13	0.1	0.074	0.056	0.044	0.035	0.029	0.025	0.019	0.015	0.012	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	0.71	0.58	0.49	0.36	0.28	0.22	0.17	0.075	0.065	0.048	0.038	0.031	0.026	0.026
			neurotoxicity	NA	NA	0.31	0.25	0.21	0.16	0.12	0.095	0.076	0.033	0.028	0.022	0.017	0.014	0.011	0.012
		Fracking	neurotoxicity	NA	NA	4.3	3.5	3	2.2	1.7	1.3	1.1	0.87	0.74	0.57	0.45	0.38	0.31	0.27
			hematological	NA	NA	4	3.3	2.8	2	1.6	1.2	0.99	0.81	0.69	0.53	0.42	0.35	0.29	0.25
			respiratory	NA	NA	0.87	0.72	0.61	0.46	0.35	0.28	0.22	0.18	0.16	0.12	0.1	0.082	0.068	0.059
			systemic	NA	NA	0.21	0.17	0.15	0.11	0.084	0.066	0.053	0.044	0.037	0.029	0.023	0.019	0.016	0.014
		Flowback	neurotoxicity	NA	NA	2.6	2.1	1.8	1	0.78	0.33	0.29	0.25	0.22	0.15	0.13	0.07	0.1	0.072
			hematological	NA	NA	2.3	1.8	1.5	0.88	0.67	0.29	0.24	0.21	0.19	0.13	0.11	0.06	0.085	0.062
			respiratory	NA	NA	1.3	1.1	0.84	0.51	0.38	0.16	0.14	0.12	0.11	0.076	0.066	0.034	0.05	0.037
			systemic	NA	NA	0.43	0.35	0.25	0.17	0.13	0.054	0.046	0.04	0.035	0.025	0.022	0.016	0.017	0.012
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	0.47	0.35	0.29	0.31	0.25	0.21	0.18	0.16	0.14	0.12	0.11	0.082	0.057	0.034
			neurotoxicity	NA	NA	0.2	0.15	0.13	0.14	0.11	0.093	0.081	0.071	0.063	0.052	0.046	0.035	0.024	0.015
		Fracking	neurotoxicity	NA	NA	3.4	2.8	2.4	1.8	1.5	1.3	1.1	0.99	0.89	0.72	0.7	0.56	0.47	0.26
			hematological	NA	NA	3.2	2.6	2.2	1.7	1.4	1.2	1	0.93	0.83	0.67	0.64	0.52	0.43	0.24
			respiratory	NA	NA	0.72	0.58	0.5	0.39	0.31	0.27	0.23	0.2	0.18	0.15	0.14	0.12	0.095	0.057

			systemic	NA	NA	0.16	0.13	0.11	0.087	0.072	0.061	0.053	0.047	0.042	0.034	0.032	0.025	0.021	0.013
		Flowback	neurotoxicity	NA	NA	1.1	1.1	0.86	0.63	0.71	0.6	0.56	0.49	0.44	0.35	0.33	0.23	0.15	0.12
			hematological	NA	NA	0.94	0.9	0.74	0.54	0.61	0.51	0.48	0.42	0.38	0.3	0.28	0.2	0.13	0.099
			respiratory	NA	NA	0.53	0.51	0.42	0.31	0.34	0.29	0.27	0.24	0.21	0.17	0.16	0.11	0.071	0.056
			systemic	NA	NA	0.17	0.16	0.13	0.098	0.11	0.098	0.087	0.076	0.068	0.055	0.051	0.036	0.023	0.018
	Northern Front Range	Drilling	hematological	NA	NA	0.55	0.45	0.37	0.26	0.2	0.16	0.13	0.1	0.088	0.065	0.05	0.041	0.034	0.028
			neurotoxicity	NA	NA	0.24	0.19	0.16	0.11	0.087	0.068	0.055	0.045	0.039	0.028	0.022	0.018	0.015	0.012
		Fracking	hematological	NA	NA	0.11	0.092	0.076	0.054	0.042	0.033	0.027	0.022	0.019	0.014	0.011	<0.01	<0.01	<0.01
		Flowback	hematological	NA	NA	2.1	1.7	1.4	0.99	0.74	0.58	0.46	0.39	0.33	0.25	0.2	0.16	0.13	0.11
			neurotoxicity	NA	NA	1.8	1.4	1.2	0.84	0.63	0.49	0.39	0.33	0.28	0.21	0.17	0.13	0.11	0.094
			respiratory	NA	NA	0.51	0.41	0.34	0.24	0.18	0.14	0.11	0.095	0.081	0.061	0.048	0.039	0.032	0.027
			systemic	NA	NA	0.16	0.13	0.1	0.074	0.056	0.044	0.035	0.029	0.025	0.019	0.015	0.012	<0.01	<0.01

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D).

Table E-16. Percentage of Subchronic Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 1-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Fracking	neurotoxicity	NA	NA	81%	71%	61%	37%	15%	2%	1%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	78%	68%	56%	31%	10%	1%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	neurotoxicity	NA	NA	69%	56%	40%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	59%	43%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	4%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Fracking	neurotoxicity	NA	NA	69%	55%	41%	17%	5%	1%	1%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	65%	50%	35%	12%	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	neurotoxicity	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range		hematological	NA	NA	54%	36%	16%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	NA	NA	40%	19%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge	Fracking	neurotoxicity	NA	NA	80%	71%	61%	37%	15%	2%	1%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	77%	67%	56%	31%	10%	1%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	neurotoxicity	NA	NA	69%	56%	40%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Top (BarD)		hematological	NA	NA	59%	43%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Fracking	neurotoxicity	NA	NA	69%	55%	40%	17%	5%	1%	1%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	65%	49%	34%	12%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	neurotoxicity	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range		hematological	NA	NA	53%	35%	15%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	NA	NA	40%	19%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)	Fracking	neurotoxicity	NA	NA	79%	69%	59%	36%	14%	2%	1%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	76%	66%	55%	30%	10%	1%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	neurotoxicity	NA	NA	67%	54%	39%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	57%	42%	24%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)	Fracking	neurotoxicity	NA	NA	67%	53%	39%	17%	5%	1%	1%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	63%	48%	34%	12%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	neurotoxicity	NA	NA	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range		hematological	NA	NA	52%	35%	15%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	NA	NA	39%	18%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D).

E.1.2.2 3-acre Well Pad

Table E-17. Largest Subchronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 3-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	0.43	0.35	0.29	0.21	0.19	0.14	0.12	0.053	0.047	0.069	0.055	0.045	0.037	0.014
			toluene	NA	NA	0.14	0.11	0.094	0.068	0.059	0.046	0.037	0.017	0.015	0.022	0.017	0.014	0.012	<0.01
		Fracking	m+p-xylene	NA	NA	1.1	0.91	0.76	0.56	0.48	0.37	0.3	0.25	0.21	0.18	0.14	0.11	0.095	0.081
			n-nonane	NA	NA	0.67	0.55	0.46	0.34	0.29	0.23	0.18	0.15	0.13	0.11	0.084	0.068	0.057	0.049

	(BarD)		benzene	NA	NA	0.58	0.48	0.4	0.29	0.25	0.2	0.16	0.13	0.11	0.092	0.073	0.06	0.05	0.043
			1,2,4-trimethylbenzene	NA	NA	0.26	0.21	0.18	0.13	0.11	0.087	0.071	0.058	0.049	0.041	0.033	0.027	0.022	0.019
			1,3,5-trimethylbenzene	NA	NA	0.2	0.16	0.13	0.098	0.085	0.066	0.054	0.044	0.037	0.031	0.025	0.02	0.017	0.015
		Flowback	n-nonane	NA	NA	0.22	0.17	0.14	0.11	0.083	0.067	0.057	0.05	0.044	0.032	0.025	0.014	0.019	0.014
			m+p-xylene	NA	NA	0.2	0.16	0.13	0.099	0.076	0.062	0.053	0.046	0.041	0.029	0.023	0.013	0.018	0.013
			1,2,4-trimethylbenzene	NA	NA	0.16	0.13	0.1	0.077	0.06	0.049	0.042	0.036	0.032	0.023	0.018	0.01	0.014	<0.01
			1,3,5-trimethylbenzene	NA	NA	0.16	0.13	0.11	0.079	0.061	0.05	0.042	0.037	0.033	0.023	0.019	0.01	0.014	0.01
			benzene	NA	NA	0.12	0.096	0.08	0.059	0.046	0.037	0.032	0.028	0.024	0.017	0.014	<0.01	0.011	<0.01
			1,2,3-trimethylbenzene	NA	NA	0.11	0.085	0.071	0.052	0.04	0.033	0.028	0.024	0.022	0.015	0.012	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	0.3	0.26	0.21	0.15	0.12	0.1	0.086	0.13	0.11	0.068	0.075	0.054	0.042	0.03
		Fracking	m+p-xylene	NA	NA	0.95	0.65	0.53	0.64	0.52	0.44	0.38	0.33	0.29	0.23	0.2	0.15	0.12	0.076
			n-nonane	NA	NA	0.58	0.4	0.32	0.39	0.32	0.27	0.23	0.2	0.18	0.14	0.12	0.089	0.072	0.046
			benzene	NA	NA	0.52	0.36	0.29	0.34	0.28	0.23	0.2	0.18	0.15	0.12	0.1	0.079	0.064	0.041
			1,2,4-trimethylbenzene	NA	NA	0.23	0.16	0.13	0.15	0.12	0.1	0.089	0.078	0.068	0.054	0.046	0.036	0.029	0.019
			1,3,5-trimethylbenzene	NA	NA	0.17	0.12	0.095	0.11	0.094	0.079	0.068	0.059	0.052	0.041	0.035	0.027	0.022	0.014
		Flowback	n-nonane	NA	NA	0.26	0.2	0.16	0.14	0.11	0.09	0.081	0.12	0.11	0.066	0.071	0.05	0.036	0.025
			m+p-xylene	NA	NA	0.24	0.18	0.15	0.13	0.1	0.083	0.075	0.11	0.097	0.061	0.066	0.046	0.033	0.023
			1,3,5-trimethylbenzene	NA	NA	0.19	0.15	0.12	0.077	0.081	0.066	0.059	0.089	0.078	0.048	0.052	0.037	0.026	0.019
			1,2,4-trimethylbenzene	NA	NA	0.18	0.14	0.12	0.076	0.079	0.065	0.058	0.087	0.076	0.047	0.051	0.036	0.026	0.018
			benzene	NA	NA	0.14	0.11	0.089	0.079	0.061	0.05	0.045	0.067	0.058	0.037	0.039	0.028	0.02	0.014
			1,2,3-trimethylbenzene	NA	NA	0.12	0.096	0.078	0.051	0.053	0.043	0.039	0.059	0.051	0.031	0.034	0.024	0.017	0.012
	Northern Front Range	Drilling	benzene	NA	NA	0.41	0.33	0.27	0.19	0.15	0.12	0.097	0.081	0.068	0.05	0.039	0.032	0.026	0.022
			toluene	NA	NA	0.13	0.11	0.088	0.062	0.049	0.039	0.031	0.026	0.022	0.016	0.013	0.01	<0.01	<0.01
		Flowback	benzene	NA	NA	0.9	0.75	0.62	0.44	0.34	0.27	0.22	0.18	0.16	0.12	0.092	0.074	0.062	0.052
			n-nonane	NA	NA	0.47	0.39	0.32	0.23	0.18	0.14	0.11	0.095	0.081	0.061	0.048	0.039	0.032	0.027
			m+p-xylene	NA	NA	0.28	0.23	0.19	0.14	0.11	0.085	0.069	0.058	0.049	0.037	0.029	0.023	0.019	0.016
			1,3,5-trimethylbenzene	NA	NA	0.2	0.16	0.14	0.096	0.076	0.06	0.048	0.04	0.034	0.026	0.02	0.016	0.014	0.012
			1,2,4-trimethylbenzene	NA	NA	0.18	0.15	0.12	0.086	0.067	0.053	0.043	0.036	0.031	0.023	0.018	0.015	0.012	0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	0.43	0.35	0.29	0.21	0.19	0.14	0.12	0.053	0.047	0.069	0.055	0.045	0.037	0.014
			toluene	NA	NA	0.14	0.11	0.094	0.068	0.059	0.046	0.037	0.017	0.015	0.022	0.017	0.014	0.012	<0.01
		Fracking	m+p-xylene	NA	NA	1.1	0.91	0.76	0.56	0.48	0.37	0.3	0.25	0.21	0.17	0.14	0.11	0.095	0.081
			n-nonane	NA	NA	0.67	0.55	0.46	0.33	0.29	0.23	0.18	0.15	0.12	0.11	0.084	0.068	0.057	0.049
			benzene	NA	NA	0.58	0.47	0.4	0.29	0.25	0.2	0.16	0.13	0.11	0.092	0.073	0.06	0.05	0.043
			1,2,4-trimethylbenzene	NA	NA	0.26	0.21	0.18	0.13	0.11	0.087	0.071	0.058	0.048	0.041	0.033	0.027	0.022	0.019
			1,3,5-trimethylbenzene	NA	NA	0.2	0.16	0.13	0.098	0.085	0.066	0.054	0.044	0.037	0.031	0.025	0.02	0.017	0.014
		Flowback	n-nonane	NA	NA	0.21	0.17	0.14	0.11	0.082	0.067	0.057	0.05	0.044	0.031	0.025	0.014	0.019	0.014
			m+p-xylene	NA	NA	0.2	0.16	0.13	0.098	0.076	0.062	0.053	0.046	0.041	0.029	0.023	0.013	0.018	0.013

			1,2,4-trimethylbenzene	NA	NA	0.16	0.13	0.1	0.077	0.059	0.049	0.041	0.036	0.032	0.023	0.018	0.01	0.014	<0.01
			1,3,5-trimethylbenzene	NA	NA	0.16	0.13	0.11	0.079	0.061	0.05	0.042	0.037	0.033	0.023	0.018	0.01	0.014	0.01
			benzene	NA	NA	0.12	0.096	0.08	0.059	0.046	0.037	0.032	0.028	0.024	0.017	0.014	<0.01	0.011	<0.01
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	0.3	0.25	0.21	0.15	0.12	0.1	0.086	0.13	0.11	0.068	0.074	0.053	0.042	0.029
		Fracking	m+p-xylene	NA	NA	0.95	0.65	0.53	0.64	0.52	0.44	0.38	0.33	0.29	0.23	0.2	0.15	0.12	0.076
			n-nonane	NA	NA	0.58	0.4	0.32	0.39	0.32	0.27	0.23	0.2	0.18	0.14	0.12	0.089	0.072	0.046
			benzene	NA	NA	0.52	0.36	0.29	0.34	0.28	0.23	0.2	0.18	0.15	0.12	0.1	0.079	0.064	0.041
			1,2,4-trimethylbenzene	NA	NA	0.23	0.16	0.13	0.15	0.12	0.1	0.089	0.078	0.068	0.054	0.046	0.036	0.029	0.019
			1,3,5-trimethylbenzene	NA	NA	0.17	0.12	0.094	0.11	0.093	0.079	0.068	0.059	0.052	0.041	0.035	0.027	0.022	0.014
		Flowback	n-nonane	NA	NA	0.25	0.2	0.16	0.14	0.11	0.089	0.081	0.12	0.1	0.066	0.071	0.05	0.036	0.025
			m+p-xylene	NA	NA	0.24	0.18	0.15	0.13	0.1	0.083	0.075	0.11	0.097	0.061	0.065	0.046	0.033	0.023
			1,3,5-trimethylbenzene	NA	NA	0.19	0.15	0.12	0.077	0.081	0.066	0.059	0.089	0.078	0.048	0.052	0.037	0.026	0.019
			1,2,4-trimethylbenzene	NA	NA	0.18	0.14	0.12	0.075	0.079	0.064	0.058	0.087	0.076	0.047	0.051	0.036	0.026	0.018
			benzene	NA	NA	0.14	0.11	0.089	0.079	0.061	0.049	0.045	0.067	0.058	0.036	0.039	0.028	0.02	0.014
			1,2,3-trimethylbenzene	NA	NA	0.12	0.096	0.078	0.051	0.053	0.043	0.039	0.058	0.051	0.031	0.034	0.024	0.017	0.012
	Northern Front Range	Drilling	benzene	NA	NA	0.41	0.33	0.27	0.19	0.15	0.12	0.097	0.081	0.068	0.05	0.039	0.031	0.026	0.022
			toluene	NA	NA	0.13	0.11	0.088	0.062	0.049	0.039	0.031	0.026	0.022	0.016	0.012	0.01	<0.01	<0.01
		Flowback	benzene	NA	NA	0.91	0.75	0.62	0.44	0.34	0.27	0.22	0.18	0.16	0.12	0.092	0.074	0.062	0.052
			n-nonane	NA	NA	0.47	0.39	0.32	0.23	0.18	0.14	0.11	0.095	0.081	0.061	0.048	0.039	0.032	0.027
			m+p-xylene	NA	NA	0.28	0.24	0.19	0.14	0.11	0.085	0.069	0.058	0.049	0.037	0.029	0.023	0.019	0.016
			1,3,5-trimethylbenzene	NA	NA	0.2	0.16	0.14	0.096	0.076	0.06	0.048	0.041	0.034	0.026	0.02	0.016	0.014	0.012
			1,2,4-trimethylbenzene	NA	NA	0.18	0.15	0.12	0.086	0.067	0.053	0.043	0.036	0.031	0.023	0.018	0.015	0.012	0.01
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	0.43	0.35	0.29	0.21	0.19	0.14	0.12	0.053	0.047	0.069	0.055	0.045	0.037	0.014
			toluene	NA	NA	0.14	0.11	0.094	0.069	0.059	0.046	0.037	0.017	0.015	0.022	0.017	0.014	0.012	<0.01
		Fracking	m+p-xylene	NA	NA	1.1	0.91	0.76	0.56	0.48	0.37	0.3	0.25	0.21	0.18	0.14	0.11	0.095	0.081
			n-nonane	NA	NA	0.67	0.55	0.46	0.33	0.29	0.23	0.18	0.15	0.13	0.11	0.084	0.068	0.057	0.049
			benzene	NA	NA	0.58	0.48	0.4	0.29	0.25	0.2	0.16	0.13	0.11	0.092	0.073	0.06	0.05	0.043
			1,2,4-trimethylbenzene	NA	NA	0.26	0.21	0.18	0.13	0.11	0.087	0.071	0.058	0.049	0.041	0.033	0.027	0.022	0.019
			1,3,5-trimethylbenzene	NA	NA	0.2	0.16	0.13	0.098	0.085	0.066	0.054	0.044	0.037	0.031	0.025	0.02	0.017	0.014
		Flowback	n-nonane	NA	NA	0.22	0.17	0.14	0.11	0.083	0.067	0.057	0.05	0.044	0.032	0.025	0.014	0.019	0.014
			m+p-xylene	NA	NA	0.2	0.16	0.13	0.099	0.076	0.062	0.053	0.046	0.041	0.029	0.023	0.013	0.018	0.013
			1,2,4-trimethylbenzene	NA	NA	0.16	0.13	0.1	0.077	0.06	0.049	0.042	0.036	0.032	0.023	0.018	0.01	0.014	<0.01
			1,3,5-trimethylbenzene	NA	NA	0.16	0.13	0.11	0.079	0.061	0.05	0.042	0.037	0.033	0.023	0.019	0.01	0.014	0.01
			benzene	NA	NA	0.12	0.096	0.08	0.059	0.046	0.037	0.032	0.028	0.024	0.017	0.014	<0.01	0.011	<0.01
			1,2,3-trimethylbenzene	NA	NA	0.11	0.085	0.071	0.052	0.04	0.033	0.028	0.024	0.022	0.015	0.012	<0.01	<0.01	<0.01
	Garfield County:	Drilling	benzene	NA	NA	0.3	0.26	0.21	0.15	0.12	0.1	0.086	0.13	0.11	0.068	0.075	0.054	0.042	0.03
		Fracking	m+p-xylene	NA	NA	0.95	0.65	0.53	0.64	0.52	0.44	0.38	0.33	0.29	0.23	0.2	0.15	0.12	0.076

	Valley (Rifle)		n-nonane	NA	NA	0.58	0.4	0.32	0.39	0.32	0.27	0.23	0.2	0.18	0.14	0.12	0.089	0.072	0.046
			benzene	NA	NA	0.52	0.36	0.29	0.34	0.28	0.23	0.2	0.18	0.15	0.12	0.11	0.079	0.064	0.041
			1,2,4-trimethylbenzene	NA	NA	0.23	0.16	0.13	0.15	0.12	0.1	0.09	0.078	0.068	0.054	0.046	0.036	0.029	0.019
			1,3,5-trimethylbenzene	NA	NA	0.17	0.12	0.095	0.12	0.094	0.079	0.068	0.059	0.052	0.041	0.035	0.027	0.022	0.014
		Flowback	n-nonane	NA	NA	0.26	0.2	0.16	0.14	0.11	0.09	0.081	0.12	0.11	0.066	0.071	0.05	0.036	0.025
			m+p-xylene	NA	NA	0.24	0.18	0.15	0.13	0.1	0.083	0.075	0.11	0.097	0.061	0.066	0.046	0.033	0.023
			1,3,5-trimethylbenzene	NA	NA	0.19	0.15	0.12	0.077	0.081	0.066	0.059	0.089	0.078	0.048	0.052	0.037	0.026	0.019
			1,2,4-trimethylbenzene	NA	NA	0.18	0.14	0.12	0.076	0.079	0.065	0.058	0.087	0.076	0.047	0.051	0.036	0.026	0.018
			benzene	NA	NA	0.14	0.11	0.089	0.079	0.061	0.05	0.045	0.067	0.058	0.037	0.039	0.028	0.02	0.014
			1,2,3-trimethylbenzene	NA	NA	0.12	0.096	0.078	0.051	0.053	0.043	0.039	0.059	0.051	0.031	0.034	0.024	0.017	0.012
	Northern Front Range	Drilling	benzene	NA	NA	0.41	0.33	0.27	0.19	0.15	0.12	0.097	0.081	0.068	0.05	0.039	0.032	0.026	0.022
			toluene	NA	NA	0.13	0.11	0.088	0.062	0.049	0.039	0.031	0.026	0.022	0.016	0.013	0.01	<0.01	<0.01
		Flowback	benzene	NA	NA	0.9	0.75	0.62	0.44	0.34	0.27	0.22	0.18	0.16	0.12	0.092	0.074	0.062	0.052
			n-nonane	NA	NA	0.47	0.39	0.32	0.23	0.18	0.14	0.11	0.095	0.081	0.061	0.048	0.039	0.032	0.027
			m+p-xylene	NA	NA	0.28	0.23	0.19	0.14	0.11	0.085	0.069	0.058	0.049	0.037	0.029	0.023	0.019	0.016
			1,3,5-trimethylbenzene	NA	NA	0.2	0.16	0.14	0.096	0.076	0.06	0.048	0.041	0.034	0.026	0.02	0.016	0.014	0.012
			1,2,4-trimethylbenzene	NA	NA	0.18	0.15	0.12	0.086	0.067	0.053	0.043	0.036	0.031	0.023	0.018	0.015	0.012	0.01

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-18. Percentage of Subchronic Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 3-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Fracking	m+p-xylene	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years				NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years				NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity.

Table E-19. Largest Subchronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 3-acre Well Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet)															
				150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	0.49	0.4	0.34	0.24	0.21	0.16	0.13	0.06	0.053	0.079	0.062	0.051	0.043	0.017
			neurotoxicity	NA	NA	0.22	0.18	0.15	0.11	0.093	0.072	0.059	0.026	0.023	0.034	0.027	0.022	0.019	<0.01
		Fracking	neurotoxicity	NA	NA	2.5	2	1.7	1.2	1.1	0.84	0.68	0.56	0.47	0.39	0.31	0.25	0.21	0.18
			hematological	NA	NA	2.3	1.9	1.6	1.2	1	0.78	0.63	0.52	0.43	0.37	0.29	0.24	0.2	0.17
			respiratory	NA	NA	0.52	0.43	0.36	0.26	0.23	0.18	0.14	0.12	0.098	0.083	0.066	0.054	0.045	0.039
			systemic	NA	NA	0.12	0.097	0.081	0.059	0.051	0.04	0.033	0.027	0.022	0.019	0.015	0.012	0.01	<0.01
		Flowback	neurotoxicity	NA	NA	0.91	0.73	0.61	0.45	0.35	0.28	0.24	0.21	0.19	0.13	0.11	0.059	0.081	0.057
			hematological	NA	NA	0.78	0.63	0.52	0.38	0.3	0.24	0.21	0.18	0.16	0.11	0.09	0.05	0.07	0.049
			respiratory	NA	NA	0.42	0.34	0.28	0.21	0.16	0.13	0.11	0.097	0.086	0.062	0.049	0.027	0.038	0.026
			systemic	NA	NA	0.13	0.1	0.087	0.064	0.049	0.04	0.034	0.03	0.027	0.019	0.015	<0.01	0.011	<0.01
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	0.34	0.29	0.23	0.17	0.14	0.12	0.098	0.15	0.13	0.078	0.085	0.061	0.048	0.034
			neurotoxicity	NA	NA	0.15	0.13	0.1	0.075	0.062	0.051	0.043	0.064	0.056	0.034	0.038	0.027	0.021	0.015
		Fracking	neurotoxicity	NA	NA	2.1	1.5	1.2	1.4	1.2	0.99	0.86	0.75	0.65	0.52	0.44	0.33	0.27	0.17
			hematological	NA	NA	2	1.4	1.1	1.3	1.1	0.92	0.8	0.7	0.61	0.48	0.41	0.31	0.25	0.16
			respiratory	NA	NA	0.46	0.31	0.25	0.31	0.25	0.21	0.18	0.16	0.14	0.11	0.093	0.072	0.058	0.038
		Flowback	neurotoxicity	NA	NA	1.1	0.83	0.67	0.53	0.46	0.38	0.34	0.51	0.44	0.27	0.3	0.21	0.15	0.11
			hematological	NA	NA	0.91	0.71	0.58	0.44	0.4	0.32	0.29	0.43	0.38	0.24	0.25	0.18	0.13	0.091
			respiratory	NA	NA	0.5	0.39	0.31	0.2	0.21	0.17	0.16	0.23	0.2	0.13	0.14	0.097	0.069	0.049
			systemic	NA	NA	0.15	0.12	0.095	0.065	0.065	0.053	0.047	0.072	0.063	0.038	0.042	0.03	0.021	0.015
	Northern Front Range	Drilling	hematological	NA	NA	0.46	0.38	0.31	0.22	0.17	0.14	0.11	0.092	0.078	0.057	0.044	0.036	0.03	0.025
			neurotoxicity	NA	NA	0.2	0.16	0.14	0.097	0.076	0.06	0.048	0.04	0.034	0.025	0.019	0.016	0.013	0.011
		Flowback	hematological	NA	NA	1.7	1.4	1.2	0.81	0.64	0.5	0.41	0.34	0.29	0.22	0.17	0.14	0.11	0.097
			neurotoxicity	NA	NA	1.4	1.2	0.98	0.69	0.54	0.43	0.35	0.29	0.25	0.18	0.14	0.12	0.097	0.083
			respiratory	NA	NA	0.41	0.34	0.28	0.2	0.15	0.12	0.099	0.083	0.07	0.053	0.041	0.033	0.028	0.024
			systemic	NA	NA	0.13	0.11	0.088	0.062	0.049	0.038	0.031	0.026	0.022	0.017	0.013	0.01	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	0.49	0.4	0.34	0.24	0.21	0.16	0.13	0.06	0.053	0.079	0.062	0.051	0.043	0.017
			neurotoxicity	NA	NA	0.22	0.18	0.15	0.11	0.093	0.072	0.059	0.026	0.023	0.034	0.027	0.022	0.019	<0.01
		Fracking	neurotoxicity	NA	NA	2.5	2	1.7	1.2	1.1	0.84	0.68	0.55	0.46	0.39	0.31	0.25	0.21	0.18
			hematological	NA	NA	2.3	1.9	1.6	1.2	1	0.78	0.63	0.51	0.43	0.36	0.29	0.24	0.2	0.17
			respiratory	NA	NA	0.52	0.43	0.36	0.26	0.23	0.18	0.14	0.12	0.098	0.083	0.066	0.054	0.045	0.039
			systemic	NA	NA	0.12	0.097	0.081	0.059	0.051	0.04	0.032	0.027	0.022	0.019	0.015	0.012	0.01	<0.01
		Flowback	neurotoxicity	NA	NA	0.9	0.73	0.61	0.45	0.35	0.28	0.24	0.21	0.19	0.13	0.11	0.059	0.081	0.057

			hematological	NA	NA	0.77	0.62	0.52	0.38	0.3	0.24	0.21	0.18	0.16	0.11	0.09	0.05	0.07	0.049
			respiratory	NA	NA	0.42	0.34	0.28	0.21	0.16	0.13	0.11	0.097	0.086	0.062	0.049	0.027	0.038	0.026
			systemic	NA	NA	0.13	0.1	0.087	0.064	0.049	0.04	0.034	0.03	0.026	0.019	0.015	<0.01	0.011	<0.01
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	0.34	0.29	0.23	0.17	0.14	0.12	0.098	0.14	0.13	0.078	0.085	0.061	0.047	0.034
			neurotoxicity	NA	NA	0.15	0.13	0.1	0.075	0.062	0.051	0.043	0.064	0.056	0.034	0.038	0.027	0.021	0.015
		Fracking	neurotoxicity	NA	NA	2.1	1.5	1.2	1.4	1.2	0.99	0.86	0.75	0.65	0.51	0.44	0.33	0.27	0.17
			hematological	NA	NA	2	1.4	1.1	1.3	1.1	0.92	0.8	0.69	0.61	0.48	0.41	0.31	0.25	0.16
			respiratory	NA	NA	0.45	0.31	0.25	0.31	0.25	0.21	0.18	0.16	0.14	0.11	0.093	0.072	0.058	0.038
		Flowback	neurotoxicity	NA	NA	1.1	0.83	0.67	0.52	0.46	0.37	0.34	0.5	0.44	0.27	0.3	0.21	0.15	0.11
			hematological	NA	NA	0.91	0.71	0.58	0.44	0.39	0.32	0.29	0.43	0.38	0.23	0.25	0.18	0.13	0.09
			respiratory	NA	NA	0.49	0.39	0.31	0.2	0.21	0.17	0.16	0.23	0.2	0.13	0.14	0.097	0.069	0.049
			systemic	NA	NA	0.15	0.12	0.095	0.065	0.065	0.052	0.047	0.072	0.063	0.038	0.042	0.03	0.021	0.015
	Northern Front Range	Drilling	hematological	NA	NA	0.46	0.38	0.31	0.22	0.17	0.14	0.11	0.092	0.077	0.057	0.044	0.036	0.03	0.025
			neurotoxicity	NA	NA	0.2	0.16	0.14	0.097	0.076	0.06	0.048	0.04	0.034	0.025	0.019	0.016	0.013	0.011
		Flowback	hematological	NA	NA	1.7	1.4	1.2	0.81	0.64	0.5	0.41	0.34	0.29	0.22	0.17	0.14	0.11	0.097
			neurotoxicity	NA	NA	1.4	1.2	0.98	0.69	0.54	0.43	0.35	0.29	0.25	0.18	0.14	0.12	0.098	0.083
			respiratory	NA	NA	0.41	0.34	0.28	0.2	0.15	0.12	0.099	0.083	0.07	0.053	0.041	0.034	0.028	0.024
			systemic	NA	NA	0.13	0.11	0.088	0.062	0.049	0.038	0.031	0.026	0.022	0.017	0.013	0.01	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	0.49	0.4	0.34	0.24	0.21	0.16	0.13	0.06	0.053	0.079	0.062	0.051	0.043	0.017
			neurotoxicity	NA	NA	0.22	0.18	0.15	0.11	0.093	0.072	0.059	0.026	0.023	0.035	0.027	0.022	0.019	<0.01
		Fracking	neurotoxicity	NA	NA	2.5	2	1.7	1.2	1.1	0.84	0.68	0.55	0.47	0.39	0.31	0.25	0.21	0.18
			hematological	NA	NA	2.3	1.9	1.6	1.2	1	0.78	0.63	0.52	0.43	0.36	0.29	0.24	0.2	0.17
			respiratory	NA	NA	0.52	0.43	0.36	0.26	0.23	0.18	0.14	0.12	0.098	0.083	0.066	0.054	0.045	0.039
			systemic	NA	NA	0.12	0.097	0.081	0.059	0.051	0.04	0.033	0.027	0.022	0.019	0.015	0.012	0.01	<0.01
		Flowback	neurotoxicity	NA	NA	0.91	0.73	0.61	0.45	0.35	0.28	0.24	0.21	0.19	0.13	0.11	0.059	0.081	0.057
			hematological	NA	NA	0.78	0.63	0.52	0.38	0.3	0.24	0.21	0.18	0.16	0.11	0.09	0.05	0.07	0.049
			respiratory	NA	NA	0.42	0.34	0.28	0.21	0.16	0.13	0.11	0.097	0.086	0.062	0.049	0.027	0.038	0.026
			systemic	NA	NA	0.13	0.1	0.087	0.064	0.049	0.04	0.034	0.03	0.027	0.019	0.015	<0.01	0.011	<0.01
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	0.34	0.29	0.23	0.17	0.14	0.12	0.098	0.15	0.13	0.078	0.085	0.061	0.048	0.034
			neurotoxicity	NA	NA	0.15	0.13	0.1	0.075	0.062	0.051	0.043	0.064	0.056	0.034	0.038	0.027	0.021	0.015
		Fracking	neurotoxicity	NA	NA	2.1	1.5	1.2	1.4	1.2	0.99	0.86	0.75	0.66	0.52	0.45	0.33	0.27	0.17
			hematological	NA	NA	2	1.4	1.1	1.3	1.1	0.92	0.8	0.7	0.61	0.48	0.41	0.31	0.25	0.16
			respiratory	NA	NA	0.45	0.31	0.25	0.31	0.25	0.21	0.18	0.16	0.14	0.11	0.094	0.072	0.058	0.038
		Flowback	neurotoxicity	NA	NA	1.1	0.83	0.67	0.53	0.46	0.38	0.34	0.51	0.44	0.27	0.3	0.21	0.15	0.11
			hematological	NA	NA	0.92	0.71	0.58	0.44	0.4	0.32	0.29	0.43	0.38	0.24	0.25	0.18	0.13	0.091
			respiratory	NA	NA	0.5	0.39	0.31	0.2	0.21	0.17	0.16	0.23	0.2	0.13	0.14	0.097	0.069	0.049
			systemic	NA	NA	0.15	0.12	0.095	0.065	0.065	0.053	0.047	0.072	0.063	0.038	0.042	0.03	0.021	0.015

Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
	Northern Front Range	Drilling	hematological	NA	NA	0.46	0.38	0.31	0.22	0.17	0.14	0.11	0.092	0.078	0.057	0.045	0.036	0.03	0.025
			neurotoxicity	NA	NA	0.2	0.16	0.14	0.097	0.076	0.06	0.048	0.04	0.034	0.025	0.019	0.016	0.013	0.011
		Flowback	hematological	NA	NA	1.7	1.4	1.2	0.81	0.64	0.5	0.41	0.34	0.29	0.22	0.17	0.14	0.11	0.097
			neurotoxicity	NA	NA	1.4	1.2	0.98	0.69	0.54	0.43	0.35	0.29	0.25	0.18	0.14	0.12	0.097	0.083
			respiratory	NA	NA	0.41	0.34	0.28	0.2	0.15	0.12	0.099	0.083	0.07	0.053	0.041	0.033	0.028	0.024
			systemic	NA	NA	0.13	0.11	0.088	0.062	0.049	0.038	0.031	0.026	0.022	0.017	0.013	0.01	<0.01	<0.01

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D).

Table E-20. Percentage of Subchronic Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 3-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Fracking	neurotoxicity	NA	NA	68%	55%	40%	8%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	64%	49%	34%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	61%	29%	5%	24%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	56%	22%	1%	17%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	neurotoxicity	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range		hematological	NA	NA	45%	29%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	NA	NA	32%	11%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)	Fracking	neurotoxicity	NA	NA	68%	55%	40%	8%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	64%	49%	34%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	61%	29%	5%	24%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	56%	22%	1%	17%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	neurotoxicity	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Northern Front Range		hematological	NA	NA	45%	29%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	NA	NA	32%	11%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)	Fracking	neurotoxicity	NA	NA	66%	53%	39%	7%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	62%	47%	33%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	59%	28%	5%	24%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	54%	21%	1%	16%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
		Flowback	neurotoxicity	NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range		hematological	NA	NA	44%	28%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	NA	NA	31%	11%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D).

E.1.2.3 5-acre Well Pad

Table E-21. Largest Subchronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	0.44	0.36	0.31	0.24	0.19	0.15	0.12	0.052	0.046	0.067	0.054	0.044	0.037	0.032
			toluene	NA	NA	0.14	0.12	0.1	0.076	0.06	0.048	0.039	0.017	0.015	0.022	0.017	0.014	0.012	0.01
		Fracking	m+p-xylene	NA	NA	1.1	0.95	0.81	0.62	0.49	0.39	0.32	0.27	0.23	0.18	0.14	0.12	0.097	0.083
			n-nonane	NA	NA	0.69	0.58	0.49	0.38	0.3	0.24	0.19	0.16	0.14	0.11	0.086	0.07	0.059	0.051
			benzene	NA	NA	0.61	0.51	0.44	0.33	0.26	0.21	0.17	0.14	0.12	0.095	0.076	0.062	0.052	0.045
			1,2,4-trimethylbenzene	NA	NA	0.27	0.22	0.19	0.15	0.12	0.093	0.076	0.064	0.054	0.042	0.033	0.027	0.023	0.02
			1,3,5-trimethylbenzene	NA	NA	0.2	0.17	0.15	0.11	0.088	0.07	0.057	0.048	0.041	0.032	0.025	0.021	0.017	0.015
	Garfield County: Valley	Drilling	benzene	NA	NA	0.33	0.27	0.21	0.15	0.12	0.1	0.085	0.13	0.11	0.069	0.075	0.058	0.042	0.03
			toluene	NA	NA	0.11	0.086	0.068	0.048	0.04	0.032	0.027	0.041	0.036	0.022	0.024	0.019	0.013	<0.01
		Fracking	m+p-xylene	NA	NA	1	0.69	0.56	0.4	0.51	0.43	0.37	0.33	0.28	0.22	0.19	0.15	0.12	0.073

	(Rifle)		n-nonane	NA	NA	0.61	0.42	0.33	0.24	0.31	0.26	0.23	0.2	0.17	0.14	0.12	0.091	0.073	0.045
			benzene	NA	NA	0.54	0.37	0.29	0.21	0.28	0.23	0.2	0.18	0.15	0.12	0.1	0.081	0.065	0.04
			1,2,4-trimethylbenzene	NA	NA	0.24	0.16	0.13	0.092	0.12	0.1	0.088	0.077	0.067	0.053	0.045	0.035	0.028	0.018
			1,3,5-trimethylbenzene	NA	NA	0.18	0.12	0.098	0.07	0.092	0.078	0.067	0.059	0.051	0.04	0.035	0.027	0.021	0.013
	Northern Front Range	Drilling	benzene	NA	NA	0.39	0.32	0.26	0.19	0.15	0.11	0.093	0.078	0.066	0.048	0.038	0.031	0.025	0.021
			toluene	NA	NA	0.12	0.1	0.084	0.06	0.046	0.037	0.03	0.025	0.021	0.015	0.012	<0.01	<0.01	<0.01
		Flowback	benzene	NA	NA	0.88	0.72	0.6	0.42	0.33	0.26	0.21	0.18	0.15	0.11	0.087	0.071	0.058	0.049
			n-nonane	NA	NA	0.45	0.37	0.31	0.22	0.17	0.14	0.11	0.091	0.075	0.057	0.045	0.036	0.03	0.025
			m+p-xylene	NA	NA	0.27	0.23	0.19	0.13	0.1	0.082	0.066	0.055	0.045	0.035	0.027	0.022	0.018	0.015
			1,3,5-trimethylbenzene	NA	NA	0.19	0.16	0.13	0.093	0.072	0.057	0.046	0.039	0.032	0.024	0.019	0.015	0.013	0.011
			1,2,4-trimethylbenzene	NA	NA	0.17	0.14	0.12	0.084	0.064	0.051	0.041	0.034	0.028	0.022	0.017	0.014	0.011	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	0.43	0.36	0.31	0.24	0.19	0.15	0.12	0.052	0.046	0.067	0.053	0.044	0.037	0.031
			toluene	NA	NA	0.14	0.12	0.1	0.076	0.06	0.048	0.039	0.017	0.015	0.022	0.017	0.014	0.012	0.01
		Fracking	m+p-xylene	NA	NA	1.1	0.95	0.81	0.62	0.49	0.39	0.32	0.27	0.23	0.18	0.14	0.12	0.097	0.083
			n-nonane	NA	NA	0.69	0.58	0.49	0.38	0.3	0.24	0.19	0.16	0.14	0.11	0.086	0.07	0.059	0.05
			benzene	NA	NA	0.61	0.51	0.44	0.33	0.26	0.21	0.17	0.14	0.12	0.095	0.076	0.062	0.052	0.044
			1,2,4-trimethylbenzene	NA	NA	0.27	0.22	0.19	0.15	0.12	0.093	0.076	0.064	0.054	0.042	0.033	0.027	0.023	0.02
			1,3,5-trimethylbenzene	NA	NA	0.2	0.17	0.15	0.11	0.088	0.07	0.057	0.048	0.041	0.032	0.025	0.021	0.017	0.015
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	0.33	0.27	0.21	0.15	0.12	0.1	0.085	0.13	0.11	0.069	0.075	0.058	0.042	0.03
			toluene	NA	NA	0.11	0.086	0.068	0.048	0.04	0.032	0.027	0.041	0.036	0.022	0.024	0.019	0.013	<0.01
		Fracking	m+p-xylene	NA	NA	1	0.69	0.55	0.4	0.51	0.43	0.37	0.32	0.28	0.22	0.19	0.15	0.12	0.073
			n-nonane	NA	NA	0.61	0.42	0.33	0.24	0.31	0.26	0.23	0.2	0.17	0.14	0.12	0.091	0.073	0.045
			benzene	NA	NA	0.54	0.37	0.29	0.21	0.28	0.23	0.2	0.18	0.15	0.12	0.1	0.081	0.065	0.04
			1,2,4-trimethylbenzene	NA	NA	0.24	0.16	0.13	0.092	0.12	0.1	0.088	0.077	0.067	0.052	0.045	0.035	0.028	0.018
			1,3,5-trimethylbenzene	NA	NA	0.18	0.12	0.098	0.07	0.092	0.078	0.067	0.059	0.051	0.04	0.035	0.027	0.021	0.013
	Northern Front Range	Drilling	benzene	NA	NA	0.39	0.31	0.26	0.19	0.14	0.11	0.092	0.077	0.065	0.048	0.038	0.03	0.025	0.021
			toluene	NA	NA	0.12	0.1	0.084	0.059	0.046	0.037	0.03	0.025	0.021	0.015	0.012	<0.01	<0.01	<0.01
		Flowback	benzene	NA	NA	0.88	0.72	0.6	0.42	0.33	0.26	0.21	0.18	0.15	0.11	0.087	0.071	0.058	0.049
			n-nonane	NA	NA	0.45	0.37	0.31	0.22	0.17	0.13	0.11	0.091	0.075	0.057	0.045	0.036	0.03	0.025
			m+p-xylene	NA	NA	0.27	0.23	0.19	0.13	0.1	0.081	0.066	0.055	0.045	0.035	0.027	0.022	0.018	0.015
			1,3,5-trimethylbenzene	NA	NA	0.19	0.16	0.13	0.092	0.072	0.057	0.046	0.038	0.032	0.024	0.019	0.015	0.013	0.011
			1,2,4-trimethylbenzene	NA	NA	0.17	0.14	0.12	0.084	0.064	0.051	0.041	0.034	0.028	0.022	0.017	0.014	0.011	<0.01
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	benzene	NA	NA	0.44	0.36	0.31	0.24	0.19	0.15	0.12	0.052	0.046	0.067	0.054	0.044	0.037	0.032
			toluene	NA	NA	0.14	0.12	0.1	0.076	0.06	0.048	0.039	0.017	0.015	0.022	0.017	0.014	0.012	0.01
		Fracking	m+p-xylene	NA	NA	1.1	0.95	0.81	0.62	0.49	0.39	0.32	0.27	0.23	0.18	0.14	0.12	0.097	0.083
			n-nonane	NA	NA	0.69	0.58	0.49	0.38	0.3	0.24	0.19	0.16	0.14	0.11	0.086	0.07	0.059	0.051
			benzene	NA	NA	0.61	0.51	0.44	0.33	0.26	0.21	0.17	0.14	0.12	0.095	0.076	0.062	0.052	0.045

			1,2,4-trimethylbenzene	NA	NA	0.27	0.22	0.19	0.15	0.12	0.093	0.076	0.064	0.054	0.042	0.033	0.027	0.023	0.02
			1,3,5-trimethylbenzene	NA	NA	0.2	0.17	0.15	0.11	0.088	0.07	0.057	0.048	0.041	0.032	0.025	0.021	0.017	0.015
	Garfield County: Valley (Rifle)	Drilling	benzene	NA	NA	0.33	0.27	0.21	0.15	0.12	0.1	0.085	0.13	0.11	0.069	0.075	0.058	0.042	0.03
			toluene	NA	NA	0.11	0.086	0.068	0.048	0.04	0.032	0.027	0.041	0.036	0.022	0.024	0.019	0.013	<0.01
		Fracking	m+p-xylene	NA	NA	1	0.69	0.56	0.4	0.51	0.43	0.37	0.33	0.28	0.22	0.19	0.15	0.12	0.073
			n-nonane	NA	NA	0.61	0.42	0.33	0.24	0.31	0.26	0.23	0.2	0.17	0.14	0.12	0.091	0.073	0.045
			benzene	NA	NA	0.54	0.37	0.29	0.21	0.28	0.23	0.2	0.18	0.15	0.12	0.1	0.081	0.065	0.04
			1,2,4-trimethylbenzene	NA	NA	0.24	0.16	0.13	0.092	0.12	0.1	0.088	0.077	0.067	0.053	0.045	0.035	0.028	0.018
			1,3,5-trimethylbenzene	NA	NA	0.18	0.12	0.098	0.07	0.092	0.078	0.067	0.059	0.051	0.04	0.035	0.027	0.021	0.013
	Northern Front Range	Drilling	benzene	NA	NA	0.39	0.32	0.26	0.19	0.15	0.11	0.093	0.078	0.066	0.048	0.038	0.031	0.025	0.021
			toluene	NA	NA	0.12	0.1	0.084	0.06	0.046	0.037	0.03	0.025	0.021	0.015	0.012	<0.01	<0.01	<0.01
		Flowback	benzene	NA	NA	0.88	0.72	0.6	0.42	0.33	0.26	0.21	0.18	0.15	0.11	0.087	0.071	0.058	0.049
			n-nonane	NA	NA	0.45	0.37	0.31	0.22	0.17	0.14	0.11	0.091	0.075	0.057	0.045	0.036	0.03	0.025
			m+p-xylene	NA	NA	0.27	0.23	0.19	0.13	0.1	0.082	0.066	0.055	0.045	0.035	0.027	0.022	0.018	0.015
			1,3,5-trimethylbenzene	NA	NA	0.19	0.16	0.13	0.093	0.072	0.057	0.046	0.039	0.032	0.024	0.019	0.015	0.013	0.011
			1,2,4-trimethylbenzene	NA	NA	0.17	0.14	0.12	0.084	0.064	0.051	0.041	0.034	0.028	0.022	0.017	0.014	0.011	<0.01

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity. Flowback is not shown for the Garfield County sites because it lasts more than 1 year in the 5-acre scenario with many wells being developed (so we defer to a chronic assessment).

Table E-22. Percentage of Subchronic Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Fracking	m+p-xylene	NA	NA	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years				NA	NA	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years				NA	NA	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Flowback is not shown for the Garfield County sites because it lasts more than 1 year in the 5-acre scenario with many wells being developed (so we defer to a chronic assessment).

Table E-23. Largest Subchronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 5-acre Well Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet)															
				150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	0.5	0.41	0.35	0.27	0.21	0.17	0.14	0.06	0.053	0.075	0.061	0.05	0.041	0.036
			neurotoxicity	NA	NA	0.22	0.18	0.16	0.12	0.094	0.075	0.055	0.026	0.023	0.031	0.026	0.022	0.016	0.016
		Fracking	neurotoxicity	NA	NA	2.6	2.1	1.8	1.4	1.1	0.89	0.72	0.61	0.52	0.4	0.32	0.26	0.22	0.19
			hematological	NA	NA	2.4	2	1.7	1.3	1	0.83	0.67	0.57	0.48	0.37	0.3	0.24	0.2	0.17
			respiratory	NA	NA	0.54	0.45	0.39	0.3	0.23	0.19	0.15	0.13	0.11	0.084	0.067	0.055	0.046	0.04
			systemic	NA	NA	0.12	0.1	0.089	0.068	0.054	0.043	0.035	0.029	0.025	0.019	0.015	0.013	0.011	<0.01
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	0.38	0.3	0.24	0.17	0.14	0.11	0.096	0.15	0.13	0.079	0.086	0.066	0.048	0.034
			neurotoxicity	NA	NA	0.17	0.13	0.11	0.076	0.062	0.05	0.042	0.064	0.056	0.035	0.038	0.029	0.021	0.015
		Fracking	neurotoxicity	NA	NA	2.3	1.6	1.2	0.89	1.2	0.98	0.84	0.73	0.64	0.5	0.43	0.34	0.27	0.17
			hematological	NA	NA	2.1	1.4	1.2	0.83	1.1	0.91	0.79	0.69	0.6	0.47	0.4	0.31	0.25	0.16
			respiratory	NA	NA	0.48	0.32	0.26	0.19	0.24	0.21	0.18	0.15	0.14	0.11	0.092	0.071	0.057	0.036
			systemic	NA	NA	0.11	0.075	0.06	0.043	0.057	0.048	0.041	0.036	0.031	0.025	0.021	0.016	0.013	<0.01
	Northern Front Range	Drilling	hematological	NA	NA	0.44	0.36	0.3	0.21	0.17	0.13	0.11	0.088	0.075	0.055	0.043	0.035	0.029	0.024
			neurotoxicity	NA	NA	0.2	0.16	0.13	0.093	0.073	0.058	0.046	0.039	0.033	0.024	0.019	0.015	0.013	0.011
		Flowback	hematological	NA	NA	1.6	1.3	1.1	0.79	0.61	0.48	0.39	0.33	0.27	0.21	0.16	0.13	0.11	0.091
			neurotoxicity	NA	NA	1.4	1.1	0.94	0.67	0.52	0.41	0.33	0.28	0.23	0.17	0.14	0.11	0.091	0.077
			respiratory	NA	NA	0.39	0.32	0.27	0.19	0.15	0.12	0.094	0.079	0.065	0.05	0.039	0.032	0.026	0.022
			systemic	NA	NA	0.12	0.1	0.085	0.06	0.047	0.037	0.03	0.025	0.021	0.016	0.012	<0.01	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	0.5	0.41	0.35	0.27	0.21	0.17	0.14	0.059	0.053	0.074	0.061	0.05	0.04	0.036
			neurotoxicity	NA	NA	0.22	0.18	0.16	0.12	0.094	0.075	0.055	0.026	0.023	0.031	0.026	0.022	0.016	0.016
		Fracking	neurotoxicity	NA	NA	2.6	2.1	1.8	1.4	1.1	0.89	0.72	0.61	0.52	0.4	0.32	0.26	0.22	0.19
			hematological	NA	NA	2.4	2	1.7	1.3	1	0.83	0.67	0.57	0.48	0.37	0.3	0.24	0.2	0.17
			respiratory	NA	NA	0.54	0.45	0.39	0.3	0.23	0.19	0.15	0.13	0.11	0.084	0.067	0.055	0.046	0.04
			systemic	NA	NA	0.12	0.1	0.089	0.068	0.054	0.043	0.035	0.029	0.025	0.019	0.015	0.013	0.011	<0.01
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	0.38	0.3	0.24	0.17	0.14	0.11	0.096	0.15	0.13	0.079	0.086	0.066	0.048	0.034
			neurotoxicity	NA	NA	0.16	0.13	0.11	0.075	0.062	0.05	0.042	0.064	0.056	0.035	0.038	0.029	0.021	0.015
		Fracking	neurotoxicity	NA	NA	2.3	1.5	1.2	0.89	1.2	0.97	0.84	0.73	0.64	0.5	0.43	0.34	0.27	0.17
			hematological	NA	NA	2.1	1.4	1.2	0.83	1.1	0.91	0.79	0.68	0.6	0.47	0.4	0.31	0.25	0.16
			respiratory	NA	NA	0.47	0.32	0.26	0.19	0.24	0.21	0.18	0.15	0.14	0.11	0.092	0.071	0.057	0.036
			systemic	NA	NA	0.11	0.075	0.06	0.043	0.056	0.048	0.041	0.036	0.031	0.025	0.021	0.016	0.013	<0.01
	Northern	Drilling	hematological	NA	NA	0.44	0.36	0.3	0.21	0.16	0.13	0.11	0.088	0.075	0.055	0.043	0.035	0.029	0.024

	Front Range		neurotoxicity	NA	NA	0.19	0.16	0.13	0.093	0.073	0.058	0.046	0.039	0.033	0.024	0.019	0.015	0.013	0.011
		Flowback	hematological	NA	NA	1.6	1.3	1.1	0.78	0.61	0.48	0.39	0.33	0.27	0.21	0.16	0.13	0.11	0.091
			neurotoxicity	NA	NA	1.4	1.1	0.94	0.67	0.52	0.41	0.33	0.28	0.23	0.17	0.14	0.11	0.091	0.077
			respiratory	NA	NA	0.39	0.32	0.27	0.19	0.15	0.12	0.094	0.078	0.065	0.05	0.039	0.031	0.026	0.022
			systemic	NA	NA	0.12	0.1	0.085	0.06	0.047	0.037	0.03	0.025	0.021	0.016	0.012	<0.01	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)	Drilling	hematological	NA	NA	0.5	0.41	0.35	0.27	0.21	0.17	0.14	0.06	0.053	0.075	0.061	0.05	0.041	0.036
			neurotoxicity	NA	NA	0.22	0.18	0.16	0.12	0.094	0.075	0.055	0.026	0.023	0.031	0.026	0.022	0.016	0.016
		Fracking	neurotoxicity	NA	NA	2.6	2.1	1.8	1.4	1.1	0.89	0.72	0.61	0.52	0.4	0.32	0.26	0.22	0.19
			hematological	NA	NA	2.4	2	1.7	1.3	1	0.83	0.67	0.57	0.48	0.37	0.3	0.24	0.2	0.17
			respiratory	NA	NA	0.54	0.45	0.39	0.3	0.23	0.19	0.15	0.13	0.11	0.084	0.067	0.055	0.046	0.04
			systemic	NA	NA	0.12	0.1	0.089	0.068	0.054	0.043	0.035	0.029	0.025	0.019	0.015	0.013	0.011	<0.01
	Garfield County: Valley (Rifle)	Drilling	hematological	NA	NA	0.38	0.3	0.24	0.17	0.14	0.11	0.096	0.15	0.13	0.079	0.086	0.067	0.048	0.034
			neurotoxicity	NA	NA	0.17	0.13	0.11	0.076	0.062	0.05	0.042	0.064	0.056	0.035	0.038	0.029	0.021	0.015
		Fracking	neurotoxicity	NA	NA	2.3	1.6	1.2	0.89	1.2	0.98	0.84	0.73	0.64	0.5	0.43	0.34	0.27	0.17
			hematological	NA	NA	2.1	1.4	1.2	0.83	1.1	0.91	0.79	0.69	0.6	0.47	0.41	0.32	0.25	0.16
			respiratory	NA	NA	0.48	0.32	0.26	0.19	0.24	0.21	0.18	0.15	0.14	0.11	0.092	0.071	0.057	0.036
			systemic	NA	NA	0.11	0.075	0.06	0.043	0.057	0.048	0.041	0.036	0.031	0.025	0.021	0.016	0.013	<0.01
	Northern Front Range	Drilling	hematological	NA	NA	0.44	0.36	0.3	0.21	0.17	0.13	0.11	0.088	0.075	0.055	0.043	0.035	0.029	0.024
			neurotoxicity	NA	NA	0.2	0.16	0.13	0.093	0.073	0.058	0.046	0.039	0.033	0.024	0.019	0.015	0.013	0.011
		Flowback	hematological	NA	NA	1.6	1.3	1.1	0.79	0.61	0.48	0.39	0.33	0.27	0.21	0.16	0.13	0.11	0.091
			neurotoxicity	NA	NA	1.4	1.1	0.94	0.67	0.52	0.41	0.33	0.28	0.23	0.17	0.14	0.11	0.091	0.077
			respiratory	NA	NA	0.39	0.32	0.27	0.19	0.15	0.12	0.094	0.079	0.065	0.05	0.039	0.032	0.026	0.022
			systemic	NA	NA	0.12	0.1	0.085	0.06	0.047	0.037	0.03	0.025	0.021	0.016	0.012	<0.01	<0.01	<0.01

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D). Flowback is not shown for the Garfield County sites because it lasts more than 1 year in the 5-acre scenario with many wells being developed (so we defer to a chronic assessment).

Table E-24. Percentage of Subchronic Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 5-acre Well Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet)															
				150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge	Fracking	neurotoxicity	NA	NA	72%	61%	49%	25%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Top (BarD)		hematological	NA	NA	68%	57%	43%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	68%	39%	16%	0%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	64%	32%	7%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Flowback	hematological	NA	NA	44%	28%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	NA	NA	32%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)	Fracking	neurotoxicity	NA	NA	72%	61%	49%	25%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	68%	56%	43%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	67%	39%	15%	0%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	63%	32%	6%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Flowback	hematological	NA	NA	44%	28%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	NA	NA	32%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)	Fracking	neurotoxicity	NA	NA	70%	59%	47%	24%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	66%	55%	42%	17%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	66%	38%	15%	0%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	62%	31%	6%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range	Flowback	hematological	NA	NA	44%	27%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	NA	NA	31%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D). Flowback is not shown for the Garfield County sites because it lasts more than 1 year in the 5-acre scenario with many wells being developed (so we defer to a chronic assessment).

E.1.3 Chronic Non-cancer Hazards

E.1.3.1 5-acre Well Pad

Table E-25. Largest Chronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 5-acre Well Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet)															
				150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Flowback	n-nonane	NA	NA	2.1	1.7	1.4	1	0.81	0.65	0.56	0.49	0.43	0.31	0.25	0.14	0.19	0.13
			benzene	NA	NA	1	0.8	0.66	0.48	0.37	0.3	0.26	0.23	0.2	0.14	0.11	0.064	0.088	0.062
			m+p-xylene	NA	NA	0.79	0.63	0.52	0.38	0.3	0.24	0.2	0.18	0.16	0.11	0.091	0.051	0.07	0.049
			1,3,5-trimethylbenzene	NA	NA	0.54	0.43	0.36	0.26	0.2	0.16	0.14	0.12	0.11	0.076	0.062	0.035	0.048	0.034
			1,2,4-trimethylbenzene	NA	NA	0.53	0.42	0.35	0.26	0.2	0.16	0.14	0.12	0.11	0.075	0.061	0.034	0.047	0.033
			2-ethyltoluene	NA	NA	0.53	0.42	0.35	0.25	0.2	0.16	0.14	0.12	0.1	0.074	0.06	0.048	0.041	0.032
			1,2,3-trimethylbenzene	NA	NA	0.35	0.28	0.23	0.17	0.13	0.11	0.09	0.079	0.07	0.049	0.04	0.023	0.031	0.022
			o-xylene	NA	NA	0.15	0.12	0.096	0.07	0.054	0.044	0.038	0.033	0.029	0.02	0.017	<0.01	0.013	<0.01
			3-ethyltoluene	NA	NA	0.12	0.098	0.081	0.06	0.046	0.037	0.032	0.028	0.025	0.017	0.014	<0.01	0.011	<0.01
	Garfield County: Valley (Rifle)		n-nonane	NA	NA	2.7	2	1.6	1	1.1	0.89	0.81	1.2	1	0.65	0.69	0.49	0.35	0.25
			benzene	NA	NA	1.3	0.95	0.76	0.48	0.52	0.42	0.38	0.54	0.48	0.3	0.32	0.23	0.16	0.11
			m+p-xylene	NA	NA	0.98	0.75	0.59	0.38	0.41	0.33	0.3	0.43	0.37	0.24	0.25	0.18	0.13	0.09
			1,3,5-trimethylbenzene	NA	NA	0.67	0.51	0.41	0.26	0.28	0.22	0.2	0.29	0.25	0.16	0.17	0.12	0.086	0.061
			1,2,4-trimethylbenzene	NA	NA	0.65	0.5	0.39	0.25	0.27	0.22	0.2	0.28	0.25	0.16	0.17	0.12	0.084	0.06
			2-ethyltoluene	NA	NA	0.65	0.49	0.39	0.25	0.27	0.22	0.2	0.28	0.24	0.16	0.16	0.11	0.081	0.058
			1,2,3-trimethylbenzene	NA	NA	0.43	0.33	0.26	0.16	0.18	0.14	0.13	0.19	0.16	0.11	0.11	0.076	0.055	0.039
			o-xylene	NA	NA	0.18	0.14	0.11	0.069	0.074	0.06	0.054	0.078	0.068	0.044	0.046	0.032	0.023	0.016
			3-ethyltoluene	NA	NA	0.15	0.12	0.092	0.059	0.063	0.051	0.046	0.066	0.058	0.037	0.039	0.027	0.02	0.014
18 to 59 Years	Garfield County: Ridge Top (BarD)		n-nonane	NA	NA	2.1	1.7	1.4	1	0.81	0.65	0.56	0.49	0.43	0.31	0.25	0.14	0.19	0.13
			benzene	NA	NA	1	0.8	0.66	0.48	0.37	0.3	0.26	0.23	0.2	0.14	0.11	0.064	0.088	0.062
			m+p-xylene	NA	NA	0.79	0.63	0.52	0.38	0.3	0.24	0.2	0.18	0.16	0.11	0.09	0.05	0.069	0.049
			1,3,5-trimethylbenzene	NA	NA	0.54	0.43	0.36	0.26	0.2	0.16	0.14	0.12	0.11	0.076	0.062	0.035	0.048	0.034
			1,2,4-trimethylbenzene	NA	NA	0.53	0.42	0.35	0.26	0.2	0.16	0.14	0.12	0.11	0.074	0.06	0.034	0.046	0.033
			2-ethyltoluene	NA	NA	0.52	0.42	0.35	0.25	0.2	0.16	0.14	0.12	0.1	0.074	0.06	0.048	0.041	0.032
			1,2,3-trimethylbenzene	NA	NA	0.35	0.28	0.23	0.17	0.13	0.11	0.09	0.079	0.07	0.049	0.04	0.023	0.031	0.022
			o-xylene	NA	NA	0.14	0.12	0.096	0.07	0.054	0.044	0.037	0.033	0.029	0.02	0.017	<0.01	0.013	<0.01
			3-ethyltoluene	NA	NA	0.12	0.098	0.081	0.059	0.046	0.037	0.032	0.028	0.025	0.017	0.014	<0.01	0.011	<0.01

	Garfield County: Valley (Rifle)		n-nonane	NA	NA	2.7	2	1.6	1	1.1	0.89	0.81	1.2	1	0.65	0.69	0.48	0.35	0.24
			benzene	NA	NA	1.2	0.95	0.75	0.48	0.51	0.41	0.37	0.54	0.47	0.3	0.32	0.23	0.16	0.11
			m+p-xylene	NA	NA	0.98	0.75	0.59	0.38	0.4	0.33	0.29	0.43	0.37	0.24	0.25	0.18	0.13	0.089
			1,3,5-trimethylbenzene	NA	NA	0.67	0.51	0.4	0.26	0.28	0.22	0.2	0.29	0.25	0.16	0.17	0.12	0.086	0.061
			1,2,4-trimethylbenzene	NA	NA	0.65	0.5	0.39	0.25	0.27	0.22	0.2	0.28	0.25	0.16	0.17	0.12	0.084	0.059
			2-ethyltoluene	NA	NA	0.64	0.49	0.39	0.25	0.27	0.21	0.19	0.28	0.24	0.16	0.16	0.11	0.081	0.058
			1,2,3-trimethylbenzene	NA	NA	0.43	0.33	0.26	0.16	0.18	0.14	0.13	0.19	0.16	0.11	0.11	0.076	0.055	0.039
			o-xylene	NA	NA	0.18	0.14	0.11	0.068	0.074	0.059	0.054	0.077	0.068	0.044	0.046	0.032	0.023	0.016
			3-ethyltoluene	NA	NA	0.15	0.12	0.092	0.058	0.063	0.051	0.046	0.066	0.058	0.037	0.039	0.027	0.02	0.014
60+ Years	Garfield County: Ridge Top (BarD)		n-nonane	NA	NA	2.1	1.7	1.4	1	0.81	0.65	0.56	0.49	0.43	0.31	0.25	0.14	0.19	0.13
			benzene	NA	NA	1	0.8	0.66	0.48	0.37	0.3	0.26	0.23	0.2	0.14	0.11	0.064	0.088	0.062
			m+p-xylene	NA	NA	0.79	0.63	0.52	0.38	0.3	0.24	0.2	0.18	0.16	0.11	0.091	0.051	0.07	0.049
			1,3,5-trimethylbenzene	NA	NA	0.54	0.43	0.36	0.26	0.2	0.16	0.14	0.12	0.11	0.076	0.062	0.035	0.048	0.034
			1,2,4-trimethylbenzene	NA	NA	0.53	0.42	0.35	0.26	0.2	0.16	0.14	0.12	0.11	0.075	0.061	0.034	0.047	0.033
			2-ethyltoluene	NA	NA	0.53	0.42	0.35	0.25	0.2	0.16	0.14	0.12	0.1	0.074	0.06	0.048	0.041	0.032
			1,2,3-trimethylbenzene	NA	NA	0.35	0.28	0.23	0.17	0.13	0.11	0.091	0.079	0.07	0.049	0.04	0.023	0.031	0.022
			o-xylene	NA	NA	0.15	0.12	0.096	0.07	0.054	0.044	0.038	0.033	0.029	0.02	0.017	<0.01	0.013	<0.01
			3-ethyltoluene	NA	NA	0.12	0.098	0.081	0.06	0.046	0.038	0.032	0.028	0.025	0.017	0.014	<0.01	0.011	<0.01
	Garfield County: Valley (Rifle)		n-nonane	NA	NA	2.7	2	1.6	1	1.1	0.89	0.81	1.2	1	0.65	0.69	0.49	0.35	0.25
			benzene	NA	NA	1.3	0.95	0.76	0.48	0.52	0.42	0.38	0.54	0.48	0.3	0.32	0.23	0.16	0.11
			m+p-xylene	NA	NA	0.98	0.75	0.59	0.38	0.41	0.33	0.3	0.43	0.37	0.24	0.25	0.18	0.13	0.09
			1,3,5-trimethylbenzene	NA	NA	0.67	0.51	0.41	0.26	0.28	0.22	0.2	0.29	0.25	0.16	0.17	0.12	0.086	0.061
			1,2,4-trimethylbenzene	NA	NA	0.65	0.5	0.39	0.25	0.27	0.22	0.2	0.28	0.25	0.16	0.17	0.12	0.084	0.06
			2-ethyltoluene	NA	NA	0.65	0.49	0.39	0.25	0.27	0.22	0.2	0.28	0.24	0.16	0.16	0.11	0.081	0.058
			1,2,3-trimethylbenzene	NA	NA	0.43	0.33	0.26	0.16	0.18	0.14	0.13	0.19	0.16	0.11	0.11	0.076	0.055	0.039
			o-xylene	NA	NA	0.18	0.14	0.11	0.069	0.074	0.06	0.054	0.078	0.068	0.044	0.046	0.032	0.023	0.016
			3-ethyltoluene	NA	NA	0.15	0.12	0.092	0.059	0.063	0.051	0.046	0.066	0.058	0.037	0.039	0.027	0.02	0.014

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity. Drilling and fracking for the Garfield County sites, and all development activities for the Northern Front Range, are not shown because they last less than 1 year in the 5-acre scenario with many wells being developed (so we defer to a subchronic assessment).

Table E-26. Percentage of Chronic Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Flowback	n-nonane	NA	NA	67%	51%	36%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		n-nonane	NA	NA	78%	64%	45%	0%	8%	0%	0%	15%	0%	0%	0%	0%	0%	0%
			benzene	NA	NA	23%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)		n-nonane	NA	NA	66%	51%	35%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		n-nonane	NA	NA	78%	63%	45%	0%	8%	0%	0%	14%	0%	0%	0%	0%	0%	0%
			benzene	NA	NA	22%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)		n-nonane	NA	NA	65%	49%	34%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		n-nonane	NA	NA	76%	62%	44%	0%	8%	0%	0%	14%	0%	0%	0%	0%	0%	0%
			benzene	NA	NA	22%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Drilling and fracking for the Garfield County sites, and all development activities for the Northern Front Range, are not shown because they last less than 1 year in the 5-acre scenario with many wells being developed (so we defer to a subchronic assessment).

Table E-27. Largest Chronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Flowback	neurotoxicity	NA	NA	4.6	3.7	3	2.2	1.7	1.4	1.2	1	0.92	0.65	0.53	0.3	0.4	0.28
			hematological	NA	NA	2.4	1.9	1.6	1.2	0.91	0.74	0.63	0.55	0.48	0.34	0.28	0.16	0.21	0.15
			respiratory	NA	NA	1.5	1.2	0.99	0.72	0.56	0.45	0.39	0.34	0.3	0.21	0.17	0.096	0.13	0.093
			systemic	NA	NA	0.83	0.67	0.55	0.4	0.31	0.25	0.22	0.19	0.17	0.12	0.096	0.068	0.068	0.052
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	5.7	4.3	3.4	2.2	2.4	1.9	1.7	2.5	2.2	1.4	1.5	1	0.74	0.52
			hematological	NA	NA	3	2.3	1.8	1.2	1.2	1	0.91	1.3	1.1	0.74	0.77	0.54	0.39	0.27
			respiratory	NA	NA	1.8	1.4	1.1	0.71	0.76	0.62	0.56	0.8	0.7	0.45	0.47	0.33	0.24	0.17
			systemic	NA	NA	1	0.78	0.62	0.39	0.43	0.34	0.31	0.44	0.39	0.25	0.26	0.18	0.13	0.093
18 to 59 Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	4.6	3.7	3	2.2	1.7	1.4	1.2	1	0.92	0.65	0.53	0.29	0.4	0.28
			hematological	NA	NA	2.4	1.9	1.6	1.2	0.91	0.74	0.63	0.55	0.48	0.34	0.28	0.16	0.21	0.15
			respiratory	NA	NA	1.5	1.2	0.98	0.72	0.56	0.45	0.39	0.34	0.3	0.21	0.17	0.096	0.13	0.092
			systemic	NA	NA	0.83	0.66	0.55	0.4	0.31	0.25	0.21	0.19	0.17	0.12	0.095	0.068	0.068	0.051
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	5.7	4.3	3.4	2.2	2.4	1.9	1.7	2.5	2.2	1.4	1.5	1	0.73	0.52
			hematological	NA	NA	3	2.3	1.8	1.1	1.2	1	0.91	1.3	1.1	0.73	0.77	0.54	0.39	0.27
			respiratory	NA	NA	1.8	1.4	1.1	0.71	0.76	0.61	0.56	0.8	0.7	0.45	0.47	0.33	0.24	0.17
			systemic	NA	NA	1	0.78	0.62	0.39	0.42	0.34	0.31	0.44	0.38	0.25	0.26	0.18	0.13	0.093
60+ Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	4.6	3.7	3	2.2	1.7	1.4	1.2	1	0.92	0.65	0.53	0.3	0.4	0.29
			hematological	NA	NA	2.4	1.9	1.6	1.2	0.91	0.74	0.63	0.55	0.48	0.34	0.28	0.16	0.21	0.15
			respiratory	NA	NA	1.5	1.2	0.99	0.72	0.56	0.45	0.39	0.34	0.3	0.21	0.17	0.096	0.13	0.093
			systemic	NA	NA	0.83	0.67	0.55	0.4	0.31	0.25	0.22	0.19	0.17	0.12	0.096	0.068	0.068	0.052
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	5.7	4.3	3.4	2.2	2.4	1.9	1.7	2.5	2.2	1.4	1.5	1	0.74	0.52
			hematological	NA	NA	3	2.3	1.8	1.2	1.2	1	0.91	1.3	1.1	0.74	0.77	0.54	0.39	0.27
			respiratory	NA	NA	1.8	1.4	1.1	0.71	0.76	0.62	0.56	0.8	0.7	0.45	0.47	0.33	0.24	0.17
			systemic	NA	NA	1	0.78	0.62	0.39	0.43	0.34	0.31	0.44	0.39	0.25	0.26	0.18	0.13	0.093

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Drilling and fracking for the Garfield County sites, and all development activities for the Northern Front Range, are not shown because they last less than 1 year in the 5-acre scenario with many wells being developed (so we defer to a subchronic assessment).

Table E-28. Percentage of Chronic Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Development Activities, by Distance from the 5-acre Well Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet)															
				150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Flowback	neurotoxicity	NA	NA	95%	90%	83%	69%	51%	33%	18%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	73%	60%	44%	16%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	40%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	99%	94%	88%	68%	73%	60%	52%	75%	67%	34%	38%	0%	0%	0%
			hematological	NA	NA	83%	71%	56%	13%	22%	0%	0%	27%	12%	0%	0%	0%	0%	0%
			respiratory	NA	NA	57%	35%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	95%	90%	83%	69%	51%	33%	18%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	73%	60%	44%	15%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	40%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	99%	94%	88%	68%	72%	59%	51%	75%	67%	34%	38%	0%	0%	0%
			hematological	NA	NA	83%	71%	56%	13%	22%	0%	0%	27%	11%	0%	0%	0%	0%	0%
			respiratory	NA	NA	57%	34%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	93%	88%	80%	67%	49%	33%	17%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	71%	58%	44%	15%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	39%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	97%	92%	86%	66%	71%	57%	49%	72%	65%	33%	38%	0%	0%	0%
			hematological	NA	NA	81%	69%	54%	12%	21%	0%	0%	26%	12%	0%	0%	0%	0%	0%
			respiratory	NA	NA	56%	33%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Drilling and fracking for the Garfield County sites, and all development activities for the Northern Front Range, are not shown because they last less than 1 year in the 5-acre scenario with many wells being developed (so we defer to a subchronic assessment).

E.2 Oil and Gas Production

E.2.1 Acute Non-cancer Hazards

Table E-29. Largest Acute Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Production Activities, by Distance from the Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Production	benzene	2.6	2.1	1.8	1.6	1.4	1.4	0.94	0.77	0.68	0.63	0.58	0.51	0.45	0.4	0.35	0.32
			2-ethyltoluene	0.38	0.28	0.24	0.21	0.2	0.21	0.13	0.11	0.096	0.088	0.082	0.072	0.063	0.056	0.05	0.045
			toluene	0.32	0.25	0.22	0.2	0.18	0.18	0.11	0.092	0.078	0.068	0.06	0.046	0.037	0.031	0.026	0.022
			cyclohexane	0.13	0.1	0.09	0.079	0.07	0.068	0.046	0.042	0.038	0.035	0.032	0.029	0.025	0.022	0.02	0.018
			isobutane	0.13	0.094	0.082	0.072	0.064	0.085	0.058	0.052	0.048	0.044	0.041	0.036	0.031	0.028	0.025	0.022
			n-butane	0.12	0.087	0.075	0.066	0.059	0.078	0.053	0.048	0.044	0.04	0.037	0.033	0.029	0.025	0.023	0.02
	Garfield County: Valley (Rifle)		benzene	2.7	1.8	1.6	1.4	1.2	1.1	0.99	0.9	0.83	0.77	0.71	0.61	0.5	0.3	0.36	0.18
			2-ethyltoluene	0.36	0.27	0.22	0.2	0.19	0.16	0.14	0.13	0.12	0.11	0.1	0.083	0.072	0.063	0.051	0.031
			toluene	0.31	0.23	0.18	0.17	0.15	0.14	0.12	0.11	0.098	0.091	0.083	0.066	0.06	0.053	0.042	0.024
			isobutane	0.16	0.1	0.08	0.071	0.064	0.053	0.052	0.046	0.042	0.039	0.036	0.027	0.021	0.018	0.016	<0.01
			n-butane	0.15	0.095	0.074	0.065	0.059	0.049	0.048	0.042	0.039	0.036	0.033	0.025	0.019	0.017	0.015	<0.01
			cyclohexane	0.13	0.089	0.076	0.067	0.061	0.053	0.049	0.044	0.041	0.038	0.035	0.03	0.025	0.015	0.018	<0.01
	Northern Front Range		benzene	2.9	2.3	2.1	2	1.9	1.6	1.7	1.5	1.3	1.2	1.1	0.85	0.72	0.61	0.46	0.41
			2-ethyltoluene	0.42	0.33	0.29	0.26	0.24	0.21	0.21	0.19	0.17	0.16	0.15	0.12	0.1	0.088	0.072	0.064
			toluene	0.4	0.31	0.28	0.25	0.22	0.18	0.16	0.14	0.13	0.12	0.11	0.1	0.086	0.073	0.06	0.053
			isobutane	0.19	0.16	0.14	0.13	0.12	0.099	0.091	0.081	0.075	0.069	0.064	0.046	0.039	0.033	0.025	0.022
			n-butane	0.18	0.14	0.13	0.12	0.11	0.091	0.083	0.075	0.068	0.063	0.058	0.042	0.036	0.03	0.023	0.02
			cyclohexane	0.15	0.12	0.11	0.1	0.095	0.08	0.082	0.073	0.066	0.061	0.056	0.042	0.035	0.03	0.022	0.02
18 to 59 Years	Garfield County: Ridge Top (BarD)		benzene	2.6	2.1	1.8	1.6	1.4	1.4	0.94	0.77	0.68	0.63	0.58	0.51	0.45	0.4	0.35	0.32
			2-ethyltoluene	0.38	0.28	0.24	0.21	0.2	0.21	0.13	0.11	0.096	0.088	0.082	0.072	0.063	0.056	0.05	0.045
			toluene	0.32	0.25	0.22	0.2	0.18	0.18	0.11	0.092	0.078	0.068	0.06	0.046	0.037	0.031	0.026	0.022
			cyclohexane	0.13	0.1	0.09	0.079	0.07	0.068	0.046	0.042	0.038	0.035	0.032	0.029	0.025	0.022	0.02	0.018
			isobutane	0.13	0.094	0.082	0.072	0.064	0.085	0.058	0.052	0.048	0.044	0.041	0.036	0.031	0.028	0.025	0.022
			n-butane	0.12	0.087	0.075	0.066	0.059	0.078	0.053	0.048	0.044	0.04	0.037	0.033	0.029	0.025	0.023	0.02
	Garfield County: Valley (Rifle)		benzene	2.7	1.8	1.6	1.4	1.2	1.1	0.99	0.9	0.83	0.77	0.71	0.61	0.5	0.3	0.36	0.18
			2-ethyltoluene	0.36	0.27	0.22	0.2	0.19	0.16	0.14	0.13	0.12	0.11	0.1	0.083	0.072	0.063	0.051	0.031
			toluene	0.31	0.23	0.18	0.17	0.15	0.14	0.12	0.11	0.098	0.091	0.083	0.066	0.06	0.053	0.042	0.024

	(Rifle)		isobutane	0.16	0.1	0.08	0.071	0.064	0.053	0.052	0.046	0.042	0.039	0.036	0.027	0.021	0.018	0.016	<0.01
			n-butane	0.15	0.095	0.074	0.065	0.059	0.049	0.048	0.042	0.039	0.036	0.033	0.025	0.019	0.017	0.015	<0.01
			cyclohexane	0.13	0.089	0.076	0.067	0.061	0.053	0.049	0.044	0.041	0.038	0.035	0.03	0.025	0.015	0.018	<0.01
	Northern Front Range		benzene	2.9	2.3	2.1	2	1.9	1.6	1.7	1.5	1.3	1.2	1.1	0.85	0.72	0.61	0.46	0.41
			2-ethyltoluene	0.42	0.33	0.29	0.26	0.24	0.21	0.21	0.19	0.17	0.16	0.15	0.12	0.1	0.088	0.072	0.064
			toluene	0.4	0.31	0.28	0.25	0.22	0.18	0.16	0.14	0.13	0.12	0.11	0.1	0.086	0.073	0.06	0.053
			isobutane	0.19	0.16	0.14	0.13	0.12	0.099	0.091	0.081	0.075	0.069	0.064	0.046	0.039	0.033	0.025	0.022
			n-butane	0.18	0.14	0.13	0.12	0.11	0.091	0.083	0.075	0.068	0.063	0.058	0.042	0.036	0.03	0.023	0.02
			cyclohexane	0.15	0.12	0.11	0.1	0.095	0.08	0.082	0.073	0.066	0.061	0.056	0.042	0.035	0.03	0.022	0.02
60+ Years	Garfield County: Ridge Top (BarD)		benzene	2.6	2.1	1.8	1.6	1.4	1.4	0.94	0.77	0.68	0.63	0.58	0.51	0.45	0.4	0.35	0.32
			2-ethyltoluene	0.38	0.28	0.24	0.21	0.2	0.21	0.13	0.11	0.096	0.088	0.082	0.072	0.063	0.056	0.05	0.045
			toluene	0.32	0.25	0.22	0.2	0.18	0.18	0.11	0.092	0.078	0.068	0.06	0.046	0.037	0.031	0.026	0.022
			cyclohexane	0.13	0.1	0.09	0.079	0.07	0.068	0.046	0.042	0.038	0.035	0.032	0.029	0.025	0.022	0.02	0.018
			isobutane	0.13	0.094	0.082	0.072	0.064	0.085	0.058	0.052	0.048	0.044	0.041	0.036	0.031	0.028	0.025	0.022
			n-butane	0.12	0.087	0.075	0.066	0.059	0.078	0.053	0.048	0.044	0.04	0.037	0.033	0.029	0.025	0.023	0.02
	Garfield County: Valley (Rifle)		benzene	2.7	1.8	1.6	1.4	1.2	1.1	0.99	0.9	0.83	0.77	0.71	0.61	0.5	0.3	0.36	0.18
			2-ethyltoluene	0.36	0.27	0.22	0.2	0.19	0.16	0.14	0.13	0.12	0.11	0.1	0.083	0.072	0.063	0.051	0.031
			toluene	0.31	0.23	0.18	0.17	0.15	0.14	0.12	0.11	0.098	0.091	0.083	0.066	0.06	0.053	0.042	0.024
			isobutane	0.16	0.1	0.08	0.071	0.064	0.053	0.052	0.046	0.042	0.039	0.036	0.027	0.021	0.018	0.016	<0.01
			n-butane	0.15	0.095	0.074	0.065	0.059	0.049	0.048	0.042	0.039	0.036	0.033	0.025	0.019	0.017	0.015	<0.01
			cyclohexane	0.13	0.089	0.076	0.067	0.061	0.053	0.049	0.044	0.041	0.038	0.035	0.03	0.025	0.015	0.018	<0.01
	Northern Front Range		benzene	2.9	2.3	2.1	2	1.9	1.6	1.7	1.5	1.3	1.2	1.1	0.85	0.72	0.61	0.46	0.41
			2-ethyltoluene	0.42	0.33	0.29	0.26	0.24	0.21	0.21	0.19	0.17	0.16	0.15	0.12	0.1	0.088	0.072	0.064
			toluene	0.4	0.31	0.28	0.25	0.22	0.18	0.16	0.14	0.13	0.12	0.11	0.1	0.086	0.073	0.06	0.053
			isobutane	0.19	0.16	0.14	0.13	0.12	0.099	0.091	0.081	0.075	0.069	0.064	0.046	0.039	0.033	0.025	0.022
			n-butane	0.18	0.14	0.13	0.12	0.11	0.091	0.083	0.075	0.068	0.063	0.058	0.042	0.036	0.03	0.023	0.02
			cyclohexane	0.15	0.12	0.11	0.1	0.095	0.08	0.082	0.073	0.066	0.061	0.056	0.042	0.035	0.03	0.022	0.02

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-30. Percentage of Acute Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Production Activities, by Distance from the Well Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet) 150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Production	benzene	6%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)			11%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range			8%	3%	2%	2%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)			6%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)			11%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range			8%	3%	2%	2%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)			6%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Garfield County: Valley (Rifle)			10%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range			7%	3%	2%	2%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity.

Table E-31. Largest Acute Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Production Activities, by Distance from the Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Production	hematological	2.7	2.1	1.8	1.6	1.4	1.4	0.95	0.78	0.68	0.63	0.58	0.51	0.45	0.4	0.35	0.32
			neurotoxicity	0.58	0.47	0.4	0.35	0.31	0.31	0.21	0.17	0.14	0.12	0.11	0.095	0.083	0.074	0.066	0.059
			respiratory	0.15	0.11	0.096	0.084	0.075	0.099	0.067	0.061	0.056	0.051	0.047	0.042	0.036	0.032	0.029	0.026
			systemic	0.14	0.1	0.091	0.08	0.071	0.093	0.064	0.058	0.053	0.048	0.045	0.04	0.035	0.031	0.027	0.024
	Garfield County: Valley (Rifle)		hematological	2.7	1.8	1.6	1.4	1.3	1.1	1	0.91	0.84	0.77	0.71	0.62	0.51	0.3	0.36	0.18
			neurotoxicity	0.6	0.4	0.34	0.3	0.28	0.24	0.22	0.2	0.18	0.17	0.16	0.14	0.11	0.088	0.08	0.04
			respiratory	0.19	0.12	0.094	0.083	0.074	0.062	0.06	0.053	0.049	0.045	0.041	0.032	0.025	0.021	0.018	<0.01
			systemic	0.18	0.11	0.089	0.078	0.07	0.059	0.057	0.051	0.046	0.043	0.039	0.03	0.023	0.02	0.017	<0.01
	Northern Front Range		hematological	2.9	2.3	2.1	2	1.9	1.6	1.7	1.5	1.4	1.2	1.1	0.86	0.72	0.61	0.46	0.41
			neurotoxicity	0.63	0.51	0.47	0.44	0.42	0.36	0.37	0.33	0.3	0.27	0.25	0.19	0.16	0.13	0.1	0.09
			respiratory	0.22	0.18	0.17	0.15	0.14	0.12	0.11	0.095	0.087	0.08	0.074	0.054	0.045	0.038	0.029	0.025
			systemic	0.21	0.17	0.16	0.14	0.13	0.11	0.1	0.09	0.082	0.076	0.07	0.051	0.043	0.036	0.027	0.024
18 to 59 Years	Garfield County: Ridge Top (BarD)		hematological	2.7	2.1	1.8	1.6	1.4	1.4	0.95	0.78	0.68	0.63	0.58	0.51	0.45	0.4	0.35	0.32
			neurotoxicity	0.58	0.47	0.4	0.35	0.31	0.31	0.21	0.17	0.14	0.12	0.11	0.095	0.083	0.074	0.066	0.059
			respiratory	0.15	0.11	0.096	0.084	0.075	0.099	0.067	0.061	0.056	0.051	0.047	0.042	0.036	0.032	0.029	0.026
			systemic	0.14	0.1	0.091	0.08	0.071	0.093	0.064	0.058	0.053	0.048	0.045	0.04	0.035	0.031	0.027	0.024
	Garfield County: Valley (Rifle)		hematological	2.7	1.8	1.6	1.4	1.3	1.1	1	0.91	0.84	0.77	0.71	0.62	0.51	0.3	0.36	0.18
			neurotoxicity	0.6	0.4	0.34	0.3	0.28	0.24	0.22	0.2	0.18	0.17	0.16	0.14	0.11	0.088	0.08	0.04
			respiratory	0.19	0.12	0.094	0.083	0.074	0.062	0.06	0.053	0.049	0.045	0.041	0.032	0.025	0.021	0.018	<0.01
			systemic	0.18	0.11	0.089	0.078	0.07	0.059	0.057	0.051	0.046	0.043	0.039	0.03	0.023	0.02	0.017	<0.01

	Northern Front Range		hematological	2.9	2.3	2.1	2	1.9	1.6	1.7	1.5	1.4	1.2	1.1	0.86	0.72	0.61	0.46	0.41
			neurotoxicity	0.63	0.51	0.47	0.44	0.42	0.36	0.37	0.33	0.3	0.27	0.25	0.19	0.16	0.13	0.1	0.09
			respiratory	0.22	0.18	0.17	0.15	0.14	0.12	0.11	0.095	0.087	0.08	0.074	0.054	0.045	0.038	0.029	0.025
			systemic	0.21	0.17	0.16	0.14	0.13	0.11	0.1	0.09	0.082	0.076	0.07	0.051	0.043	0.036	0.027	0.024
60+ Years	Garfield County: Ridge Top (BarD)		hematological	2.7	2.1	1.8	1.6	1.4	1.4	0.95	0.78	0.68	0.63	0.58	0.51	0.45	0.4	0.35	0.32
			neurotoxicity	0.58	0.47	0.4	0.35	0.31	0.31	0.21	0.17	0.14	0.12	0.11	0.095	0.083	0.074	0.066	0.059
			respiratory	0.15	0.11	0.096	0.084	0.075	0.099	0.067	0.061	0.056	0.051	0.047	0.042	0.036	0.032	0.029	0.026
			systemic	0.14	0.1	0.091	0.08	0.071	0.093	0.064	0.058	0.053	0.048	0.045	0.04	0.035	0.031	0.027	0.024
	Garfield County: Valley (Rifle)		hematological	2.7	1.8	1.6	1.4	1.3	1.1	1	0.91	0.84	0.77	0.71	0.62	0.51	0.3	0.36	0.18
			neurotoxicity	0.6	0.4	0.34	0.3	0.28	0.24	0.22	0.2	0.18	0.17	0.16	0.14	0.11	0.088	0.08	0.04
			respiratory	0.19	0.12	0.094	0.083	0.074	0.062	0.06	0.053	0.049	0.045	0.041	0.032	0.025	0.021	0.018	<0.01
			systemic	0.18	0.11	0.089	0.078	0.07	0.059	0.057	0.051	0.046	0.043	0.039	0.03	0.023	0.02	0.017	<0.01
	Northern Front Range		hematological	2.9	2.3	2.1	2	1.9	1.6	1.7	1.5	1.4	1.2	1.1	0.86	0.72	0.61	0.46	0.41
			neurotoxicity	0.63	0.51	0.47	0.44	0.42	0.36	0.37	0.33	0.3	0.27	0.25	0.19	0.16	0.13	0.1	0.09
			respiratory	0.22	0.18	0.17	0.15	0.14	0.12	0.11	0.095	0.087	0.08	0.074	0.054	0.045	0.038	0.029	0.025
			systemic	0.21	0.17	0.16	0.14	0.13	0.11	0.1	0.09	0.082	0.076	0.07	0.051	0.043	0.036	0.027	0.024

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D).

Table E-32. Percentage of Acute Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Production Activities, by Distance from the Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Production	hematological	6%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)			11%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Northern Front Range			8%	3%	2%	2%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)			6%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)			11%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range			8%	3%	2%	2%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)			6%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)			11%	2%	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range			7%	3%	2%	2%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals, including ethyltoluenes, could not be assigned to any acute critical-effect group (see Appendix D).

E.2.2 Chronic Non-cancer Hazards

Table E-33. Largest Chronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Production Activities, by Distance from the Well Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet)															
				150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Production	benzene	1.1	0.63	0.49	0.4	0.33	0.25	0.2	0.15	0.12	0.1	0.086	0.065	0.052	0.042	0.035	0.03
			1,2,4-trimethylbenzene	0.33	0.19	0.15	0.12	0.1	0.076	0.061	0.048	0.038	0.032	0.027	0.02	0.016	0.013	0.011	<0.01
			n-nonane	0.3	0.18	0.14	0.11	0.094	0.069	0.055	0.043	0.035	0.029	0.024	0.018	0.014	0.012	<0.01	<0.01
			2-ethyltoluene	0.25	0.14	0.11	0.092	0.077	0.057	0.045	0.036	0.028	0.024	0.02	0.015	0.012	<0.01	<0.01	<0.01
			1,2,3-trimethylbenzene	0.14	0.082	0.064	0.052	0.044	0.032	0.026	0.02	0.016	0.013	0.011	<0.01	<0.01	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		benzene	1.2	0.5	0.39	0.32	0.27	0.21	0.17	0.14	0.12	0.1	0.092	0.071	0.063	0.054	0.04	0.029
			1,2,4-trimethylbenzene	0.38	0.15	0.12	0.098	0.083	0.063	0.051	0.043	0.037	0.032	0.028	0.022	0.019	0.016	0.012	<0.01
			n-nonane	0.34	0.14	0.11	0.088	0.075	0.057	0.047	0.039	0.033	0.029	0.026	0.02	0.017	0.015	0.011	<0.01
			2-ethyltoluene	0.28	0.11	0.089	0.073	0.062	0.047	0.038	0.032	0.028	0.024	0.021	0.016	0.014	0.012	<0.01	<0.01
			1,2,3-trimethylbenzene	0.16	0.065	0.051	0.042	0.035	0.027	0.022	0.018	0.016	0.014	0.012	<0.01	<0.01	<0.01	<0.01	<0.01
	Northern Front Range		benzene	0.93	0.52	0.41	0.34	0.28	0.2	0.16	0.13	0.1	0.087	0.074	0.056	0.044	0.036	0.03	0.025
			1,2,4-trimethylbenzene	0.29	0.16	0.13	0.1	0.086	0.062	0.048	0.038	0.031	0.026	0.022	0.017	0.013	0.011	<0.01	<0.01
			n-nonane	0.26	0.14	0.11	0.093	0.077	0.056	0.044	0.035	0.029	0.024	0.02	0.016	0.012	<0.01	<0.01	<0.01
			2-ethyltoluene	0.21	0.12	0.094	0.077	0.064	0.046	0.036	0.029	0.023	0.02	0.017	0.013	<0.01	<0.01	<0.01	<0.01
			1,2,3-trimethylbenzene	0.12	0.067	0.053	0.043	0.036	0.026	0.021	0.016	0.013	0.011	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)		benzene	1.1	0.63	0.49	0.4	0.33	0.25	0.2	0.15	0.12	0.1	0.086	0.065	0.052	0.042	0.035	0.03
			1,2,4-trimethylbenzene	0.33	0.19	0.15	0.12	0.1	0.076	0.061	0.048	0.038	0.032	0.027	0.02	0.016	0.013	0.011	<0.01
			n-nonane	0.3	0.18	0.14	0.11	0.094	0.069	0.055	0.043	0.035	0.029	0.024	0.018	0.014	0.012	<0.01	<0.01
			2-ethyltoluene	0.25	0.14	0.11	0.092	0.077	0.057	0.045	0.036	0.028	0.024	0.02	0.015	0.012	<0.01	<0.01	<0.01
			1,2,3-trimethylbenzene	0.14	0.082	0.064	0.052	0.044	0.032	0.026	0.02	0.016	0.013	0.011	<0.01	<0.01	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		benzene	1.2	0.5	0.39	0.32	0.27	0.21	0.17	0.14	0.12	0.1	0.091	0.071	0.062	0.054	0.04	0.028
			1,2,4-trimethylbenzene	0.37	0.15	0.12	0.098	0.083	0.063	0.051	0.043	0.037	0.032	0.028	0.022	0.019	0.016	0.012	<0.01
			n-nonane	0.34	0.14	0.11	0.088	0.075	0.057	0.047	0.039	0.033	0.029	0.026	0.02	0.017	0.015	0.011	<0.01
			2-ethyltoluene	0.28	0.11	0.089	0.073	0.062	0.047	0.038	0.032	0.028	0.024	0.021	0.016	0.014	0.012	<0.01	<0.01
			1,2,3-trimethylbenzene	0.16	0.065	0.051	0.041	0.035	0.027	0.022	0.018	0.016	0.014	0.012	<0.01	<0.01	<0.01	<0.01	<0.01
	Northern Front Range		benzene	0.93	0.52	0.41	0.34	0.28	0.2	0.16	0.13	0.1	0.087	0.074	0.056	0.044	0.036	0.03	0.025
			1,2,4-trimethylbenzene	0.29	0.16	0.13	0.1	0.085	0.062	0.048	0.038	0.031	0.026	0.022	0.017	0.013	0.011	<0.01	<0.01
			n-nonane	0.26	0.14	0.11	0.093	0.077	0.056	0.044	0.035	0.029	0.024	0.02	0.016	0.012	<0.01	<0.01	<0.01
			2-ethyltoluene	0.21	0.12	0.094	0.077	0.064	0.046	0.036	0.029	0.023	0.02	0.017	0.013	<0.01	<0.01	<0.01	<0.01
			1,2,3-trimethylbenzene	0.12	0.067	0.053	0.043	0.036	0.026	0.021	0.016	0.013	0.011	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
60+ Years	Garfield County:		benzene	1.1	0.63	0.49	0.4	0.33	0.25	0.2	0.15	0.12	0.1	0.086	0.065	0.052	0.042	0.035	0.03
			1,2,4-trimethylbenzene	0.33	0.19	0.15	0.12	0.1	0.076	0.061	0.048	0.038	0.032	0.027	0.02	0.016	0.013	0.011	<0.01

	Ridge Top (BarD)		n-nonane	0.3	0.18	0.14	0.11	0.094	0.069	0.055	0.043	0.035	0.029	0.024	0.018	0.014	0.012	<0.01	<0.01
			2-ethyltoluene	0.25	0.14	0.11	0.092	0.077	0.057	0.045	0.036	0.028	0.024	0.02	0.015	0.012	<0.01	<0.01	<0.01
			1,2,3-trimethylbenzene	0.14	0.082	0.064	0.052	0.044	0.032	0.026	0.02	0.016	0.013	0.011	<0.01	<0.01	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		benzene	1.2	0.5	0.39	0.32	0.27	0.21	0.17	0.14	0.12	0.1	0.092	0.071	0.063	0.054	0.04	0.029
			1,2,4-trimethylbenzene	0.38	0.15	0.12	0.098	0.083	0.063	0.051	0.043	0.037	0.032	0.028	0.022	0.019	0.016	0.012	<0.01
			n-nonane	0.34	0.14	0.11	0.088	0.075	0.057	0.047	0.039	0.033	0.029	0.026	0.02	0.017	0.015	0.011	<0.01
			2-ethyltoluene	0.28	0.11	0.089	0.073	0.062	0.047	0.038	0.032	0.028	0.024	0.021	0.016	0.014	0.012	<0.01	<0.01
			1,2,3-trimethylbenzene	0.16	0.065	0.051	0.042	0.035	0.027	0.022	0.018	0.016	0.014	0.012	<0.01	<0.01	<0.01	<0.01	<0.01
	Northern Front Range		benzene	0.93	0.52	0.41	0.34	0.28	0.2	0.16	0.13	0.1	0.087	0.074	0.056	0.044	0.036	0.03	0.025
			1,2,4-trimethylbenzene	0.29	0.16	0.13	0.1	0.086	0.062	0.048	0.038	0.031	0.026	0.022	0.017	0.013	0.011	<0.01	<0.01
			n-nonane	0.26	0.14	0.11	0.093	0.077	0.056	0.044	0.035	0.029	0.024	0.02	0.016	0.012	<0.01	<0.01	<0.01
			2-ethyltoluene	0.21	0.12	0.094	0.077	0.064	0.046	0.036	0.029	0.023	0.02	0.017	0.013	<0.01	<0.01	<0.01	<0.01
			1,2,3-trimethylbenzene	0.12	0.067	0.053	0.043	0.036	0.026	0.021	0.016	0.013	0.011	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients within a given combination of age group, site, and activity.

Table E-34. Percentage of Chronic Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Production Activities, by Distance from the Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Production	benzene	4%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)			19%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)			4%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Garfield County: Valley (Rifle)			20%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)			4%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)			19%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity.

Table E-35. Largest Chronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Production Activities, by Distance from the Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Production	hematological	1.6	0.94	0.74	0.6	0.5	0.37	0.29	0.23	0.18	0.15	0.13	0.098	0.077	0.063	0.052	0.045
			neurotoxicity	1.1	0.66	0.52	0.42	0.35	0.26	0.21	0.16	0.13	0.11	0.09	0.068	0.054	0.044	0.037	0.031
			respiratory	0.58	0.34	0.27	0.22	0.18	0.13	0.11	0.084	0.067	0.055	0.047	0.035	0.028	0.023	0.019	0.016
			systemic	0.34	0.2	0.16	0.13	0.11	0.078	0.063	0.049	0.039	0.032	0.027	0.021	0.016	0.013	0.011	<0.01
	Garfield County: Valley (Rifle)		hematological	1.8	0.74	0.58	0.48	0.41	0.31	0.25	0.21	0.18	0.16	0.14	0.11	0.093	0.08	0.06	0.042
			neurotoxicity	1.3	0.52	0.41	0.33	0.28	0.21	0.17	0.15	0.13	0.11	0.096	0.074	0.064	0.055	0.041	0.029
			respiratory	0.66	0.27	0.21	0.17	0.15	0.11	0.09	0.076	0.065	0.057	0.05	0.038	0.033	0.029	0.021	0.015
			systemic	0.38	0.16	0.12	0.1	0.085	0.065	0.053	0.044	0.038	0.033	0.029	0.023	0.02	0.017	0.012	<0.01
	Northern Front Range		hematological	1.4	0.77	0.61	0.5	0.42	0.3	0.24	0.19	0.15	0.13	0.11	0.083	0.066	0.053	0.044	0.037
			neurotoxicity	0.97	0.54	0.43	0.35	0.29	0.21	0.17	0.13	0.11	0.089	0.076	0.058	0.045	0.037	0.03	0.026
			respiratory	0.5	0.28	0.22	0.18	0.15	0.11	0.085	0.068	0.055	0.046	0.039	0.03	0.023	0.019	0.016	0.013
			systemic	0.3	0.16	0.13	0.11	0.089	0.064	0.05	0.04	0.032	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge		hematological	1.6	0.94	0.73	0.6	0.5	0.37	0.29	0.23	0.18	0.15	0.13	0.098	0.077	0.063	0.052	0.045
			neurotoxicity	1.1	0.66	0.52	0.42	0.35	0.26	0.21	0.16	0.13	0.11	0.09	0.068	0.054	0.044	0.037	0.031

	Top (BarD)		respiratory	0.58	0.34	0.27	0.22	0.18	0.13	0.11	0.084	0.067	0.055	0.047	0.035	0.028	0.023	0.019	0.016
			systemic	0.34	0.2	0.16	0.13	0.11	0.078	0.063	0.049	0.039	0.032	0.027	0.021	0.016	0.013	0.011	<0.01
	Garfield County: Valley (Rifle)		hematological	1.8	0.74	0.58	0.48	0.4	0.31	0.25	0.21	0.18	0.16	0.14	0.11	0.093	0.08	0.06	0.042
			neurotoxicity	1.3	0.52	0.4	0.33	0.28	0.21	0.17	0.15	0.13	0.11	0.096	0.074	0.064	0.055	0.041	0.029
			respiratory	0.66	0.27	0.21	0.17	0.15	0.11	0.09	0.076	0.065	0.057	0.05	0.038	0.033	0.028	0.021	0.015
			systemic	0.38	0.16	0.12	0.1	0.085	0.065	0.053	0.044	0.038	0.033	0.029	0.023	0.02	0.017	0.012	<0.01
	Northern Front Range		hematological	1.4	0.77	0.61	0.5	0.42	0.3	0.24	0.19	0.15	0.13	0.11	0.083	0.066	0.053	0.044	0.037
			neurotoxicity	0.97	0.53	0.43	0.35	0.29	0.21	0.17	0.13	0.11	0.089	0.076	0.058	0.045	0.037	0.03	0.026
			respiratory	0.5	0.28	0.22	0.18	0.15	0.11	0.085	0.068	0.055	0.046	0.039	0.03	0.023	0.019	0.016	0.013
			systemic	0.3	0.16	0.13	0.11	0.089	0.064	0.05	0.04	0.032	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)		hematological	1.6	0.94	0.74	0.6	0.5	0.37	0.29	0.23	0.18	0.15	0.13	0.098	0.077	0.063	0.052	0.045
			neurotoxicity	1.1	0.66	0.52	0.42	0.35	0.26	0.21	0.16	0.13	0.11	0.09	0.068	0.054	0.044	0.037	0.031
			respiratory	0.58	0.34	0.27	0.22	0.18	0.13	0.11	0.084	0.067	0.055	0.047	0.035	0.028	0.023	0.019	0.016
			systemic	0.34	0.2	0.16	0.13	0.11	0.078	0.063	0.049	0.039	0.032	0.027	0.021	0.016	0.013	0.011	<0.01
	Garfield County: Valley (Rifle)		hematological	1.8	0.75	0.58	0.48	0.41	0.31	0.25	0.21	0.18	0.16	0.14	0.11	0.093	0.08	0.06	0.042
			neurotoxicity	1.3	0.52	0.41	0.33	0.28	0.21	0.17	0.15	0.13	0.11	0.096	0.074	0.064	0.055	0.041	0.029
			respiratory	0.66	0.27	0.21	0.17	0.15	0.11	0.09	0.076	0.065	0.057	0.05	0.038	0.033	0.029	0.021	0.015
			systemic	0.38	0.16	0.12	0.1	0.086	0.065	0.053	0.044	0.038	0.033	0.029	0.023	0.02	0.017	0.012	<0.01
	Northern Front Range		hematological	1.4	0.77	0.61	0.5	0.42	0.3	0.24	0.19	0.15	0.13	0.11	0.083	0.066	0.053	0.044	0.037
			neurotoxicity	0.97	0.54	0.43	0.35	0.29	0.21	0.17	0.13	0.11	0.089	0.076	0.058	0.045	0.037	0.03	0.026
			respiratory	0.5	0.28	0.22	0.18	0.15	0.11	0.085	0.068	0.055	0.046	0.039	0.03	0.023	0.019	0.016	0.013
			systemic	0.3	0.16	0.13	0.11	0.089	0.064	0.05	0.04	0.032	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D).

Table E-36. Percentage of Chronic Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Production Activities, by Distance from the Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge	Production	hematological	42%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Top (BarD)		neurotoxicity	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		hematological	53%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	24%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range		hematological	33%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)		hematological	43%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		hematological	54%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	24%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range		hematological	32%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)		hematological	42%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		hematological	52%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			neurotoxicity	23%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range		hematological	32%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D).

E.3 Sequential Oil and Gas Development and Production

E.3.1 Development

E.3.1.1 1-acre Well Pad

We do not show a table in this section about percentage of subchronic non-cancer hazard quotients (across the hypothetical population) that are above 1 during development activities in sequence (by distance from the 1-acre well pad) because this scenario had no hazard quotients above 1. All sequences of activities shown here last less than 365 days in total, so we calculated only subchronic results here (no chronic results).

Table E-37. Largest Subchronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities in Sequence, by Distance from the 1-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Development	m+p-xylene	NA	NA	0.49	0.4	0.34	0.21	0.16	0.081	0.068	0.057	0.05	0.036	0.03	0.019	0.022	0.016
			n-nonane	NA	NA	0.49	0.4	0.34	0.2	0.15	0.072	0.061	0.052	0.046	0.033	0.027	0.016	0.02	0.015
			benzene	NA	NA	0.4	0.33	0.28	0.18	0.13	0.082	0.067	0.044	0.039	0.028	0.023	0.016	0.017	0.013
			1,3,5-trimethylbenzene	NA	NA	0.37	0.3	0.25	0.14	0.11	0.048	0.041	0.035	0.031	0.022	0.019	0.01	0.014	0.011
			1,2,4-trimethylbenzene	NA	NA	0.36	0.3	0.25	0.14	0.11	0.049	0.042	0.036	0.032	0.023	0.019	0.011	0.014	0.011
			1,2,3-trimethylbenzene	NA	NA	0.26	0.21	0.14	0.1	0.078	0.034	0.029	0.025	0.022	0.016	0.014	<0.01	0.01	<0.01
			2-ethyltoluene	NA	NA	0.18	0.14	0.097	0.069	0.053	0.023	0.019	0.016	0.014	0.01	<0.01	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		m+p-xylene	NA	NA	0.25	0.23	0.19	0.14	0.15	0.12	0.11	0.099	0.09	0.071	0.068	0.047	0.033	0.024
			n-nonane	NA	NA	0.23	0.21	0.18	0.13	0.14	0.12	0.11	0.095	0.088	0.069	0.065	0.045	0.03	0.023
			benzene	NA	NA	0.22	0.19	0.16	0.13	0.13	0.11	0.095	0.083	0.075	0.06	0.056	0.041	0.029	0.019
			1,2,4-trimethylbenzene	NA	NA	0.16	0.15	0.12	0.092	0.1	0.085	0.079	0.069	0.061	0.05	0.046	0.032	0.021	0.016
			1,3,5-trimethylbenzene	NA	NA	0.16	0.15	0.12	0.09	0.1	0.085	0.079	0.069	0.061	0.05	0.046	0.033	0.021	0.016
			1,2,3-trimethylbenzene	NA	NA	0.11	0.1	0.084	0.063	0.069	0.058	0.054	0.047	0.042	0.034	0.032	0.022	0.014	0.011
	Northern Front Range		benzene	NA	NA	0.67	0.54	0.44	0.31	0.24	0.18	0.15	0.12	0.1	0.078	0.061	0.049	0.041	0.034
			n-nonane	NA	NA	0.27	0.22	0.18	0.13	0.097	0.076	0.061	0.051	0.043	0.033	0.026	0.021	0.017	0.014
			m+p-xylene	NA	NA	0.17	0.14	0.11	0.08	0.06	0.048	0.038	0.031	0.027	0.02	0.016	0.013	0.011	<0.01
			1,3,5-trimethylbenzene	NA	NA	0.12	0.095	0.078	0.056	0.042	0.033	0.026	0.022	0.019	0.014	0.011	<0.01	<0.01	<0.01
			1,2,4-trimethylbenzene	NA	NA	0.11	0.087	0.072	0.051	0.038	0.03	0.024	0.02	0.017	0.013	0.01	<0.01	<0.01	<0.01
18 to 59	Garfield		m+p-xylene	NA	NA	0.5	0.41	0.34	0.2	0.16	0.082	0.068	0.057	0.049	0.036	0.03	0.019	0.022	0.017

Years	County: Ridge Top (BarD)		n-nonane	NA	NA	0.48	0.4	0.33	0.19	0.15	0.071	0.06	0.051	0.045	0.032	0.027	0.016	0.02	0.015
			benzene	NA	NA	0.4	0.33	0.28	0.18	0.14	0.083	0.068	0.044	0.039	0.028	0.022	0.015	0.016	0.013
			1,2,4-trimethylbenzene	NA	NA	0.37	0.3	0.25	0.15	0.11	0.05	0.042	0.036	0.032	0.023	0.02	0.011	0.015	0.011
			1,3,5-trimethylbenzene	NA	NA	0.37	0.3	0.25	0.15	0.11	0.049	0.041	0.036	0.032	0.022	0.02	0.011	0.015	0.011
			1,2,3-trimethylbenzene	NA	NA	0.26	0.21	0.14	0.1	0.079	0.034	0.029	0.025	0.022	0.016	0.014	<0.01	0.01	<0.01
			2-ethyltoluene	NA	NA	0.18	0.14	0.096	0.069	0.053	0.023	0.019	0.016	0.015	0.01	<0.01	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		m+p-xylene	NA	NA	0.24	0.22	0.18	0.14	0.15	0.12	0.11	0.098	0.089	0.07	0.067	0.049	0.033	0.024
			n-nonane	NA	NA	0.23	0.21	0.17	0.13	0.14	0.12	0.11	0.095	0.087	0.069	0.064	0.047	0.031	0.023
			benzene	NA	NA	0.22	0.18	0.15	0.13	0.12	0.1	0.093	0.082	0.074	0.06	0.055	0.041	0.028	0.019
			1,2,4-trimethylbenzene	NA	NA	0.16	0.15	0.12	0.09	0.099	0.083	0.077	0.068	0.06	0.049	0.046	0.032	0.021	0.016
			1,3,5-trimethylbenzene	NA	NA	0.15	0.15	0.12	0.089	0.1	0.083	0.078	0.069	0.061	0.05	0.046	0.032	0.021	0.016
			1,2,3-trimethylbenzene	NA	NA	0.11	0.1	0.084	0.063	0.068	0.057	0.054	0.047	0.042	0.034	0.031	0.022	0.014	0.011
	Northern Front Range		benzene	NA	NA	0.66	0.53	0.44	0.31	0.24	0.18	0.15	0.12	0.1	0.078	0.061	0.049	0.041	0.034
			n-nonane	NA	NA	0.27	0.22	0.18	0.13	0.096	0.076	0.06	0.05	0.043	0.033	0.026	0.021	0.017	0.014
			m+p-xylene	NA	NA	0.17	0.14	0.11	0.08	0.06	0.048	0.038	0.031	0.027	0.02	0.016	0.013	0.011	<0.01
			1,3,5-trimethylbenzene	NA	NA	0.12	0.095	0.078	0.056	0.042	0.033	0.026	0.022	0.019	0.014	0.011	<0.01	<0.01	<0.01
			1,2,4-trimethylbenzene	NA	NA	0.11	0.087	0.072	0.051	0.038	0.03	0.024	0.02	0.017	0.013	0.01	<0.01	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)		m+p-xylene	NA	NA	0.49	0.41	0.34	0.21	0.16	0.084	0.07	0.059	0.051	0.037	0.03	0.019	0.022	0.017
			n-nonane	NA	NA	0.49	0.4	0.34	0.2	0.15	0.074	0.062	0.053	0.047	0.033	0.027	0.016	0.02	0.015
			benzene	NA	NA	0.4	0.33	0.28	0.18	0.14	0.082	0.067	0.043	0.038	0.027	0.022	0.015	0.016	0.013
			1,2,4-trimethylbenzene	NA	NA	0.37	0.3	0.25	0.15	0.11	0.05	0.042	0.036	0.032	0.023	0.02	0.011	0.015	0.011
			1,3,5-trimethylbenzene	NA	NA	0.37	0.3	0.26	0.15	0.11	0.049	0.041	0.036	0.032	0.022	0.02	0.011	0.015	0.011
			1,2,3-trimethylbenzene	NA	NA	0.26	0.21	0.14	0.1	0.078	0.034	0.029	0.025	0.022	0.016	0.014	<0.01	0.01	<0.01
			2-ethyltoluene	NA	NA	0.18	0.14	0.096	0.069	0.053	0.023	0.019	0.016	0.015	0.01	<0.01	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		m+p-xylene	NA	NA	0.25	0.23	0.19	0.14	0.15	0.12	0.11	0.1	0.092	0.073	0.07	0.051	0.035	0.025
			n-nonane	NA	NA	0.23	0.21	0.17	0.13	0.14	0.12	0.11	0.096	0.088	0.069	0.067	0.048	0.032	0.024
			benzene	NA	NA	0.22	0.19	0.16	0.13	0.13	0.11	0.094	0.083	0.075	0.06	0.057	0.041	0.028	0.02
			1,2,4-trimethylbenzene	NA	NA	0.16	0.15	0.12	0.092	0.1	0.083	0.077	0.068	0.06	0.049	0.046	0.033	0.021	0.016
			1,3,5-trimethylbenzene	NA	NA	0.16	0.15	0.12	0.091	0.099	0.083	0.077	0.068	0.06	0.049	0.046	0.033	0.021	0.016
			1,2,3-trimethylbenzene	NA	NA	0.11	0.1	0.085	0.064	0.069	0.057	0.054	0.047	0.042	0.035	0.031	0.022	0.014	0.011
	Northern Front Range		benzene	NA	NA	0.67	0.54	0.44	0.32	0.24	0.18	0.15	0.12	0.1	0.078	0.061	0.049	0.041	0.034
			n-nonane	NA	NA	0.27	0.22	0.18	0.13	0.097	0.077	0.06	0.05	0.043	0.033	0.026	0.021	0.017	0.014
			m+p-xylene	NA	NA	0.17	0.14	0.11	0.08	0.061	0.048	0.038	0.031	0.027	0.02	0.016	0.013	0.011	<0.01
			1,3,5-trimethylbenzene	NA	NA	0.12	0.095	0.078	0.056	0.042	0.033	0.026	0.022	0.019	0.014	0.011	<0.01	<0.01	<0.01
			1,2,4-trimethylbenzene	NA	NA	0.11	0.087	0.072	0.051	0.038	0.03	0.024	0.02	0.017	0.013	0.01	<0.01	<0.01	<0.01

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-38. Largest Subchronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities in Sequence, by Distance from the 1-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Development	neurotoxicity	NA	NA	2.1	1.7	1.4	0.86	0.66	0.32	0.27	0.22	0.2	0.14	0.12	0.069	0.086	0.065
			hematological	NA	NA	1.9	1.6	1.3	0.79	0.6	0.3	0.25	0.2	0.18	0.13	0.11	0.064	0.077	0.059
			respiratory	NA	NA	0.99	0.81	0.64	0.39	0.3	0.13	0.11	0.096	0.085	0.06	0.052	0.028	0.039	0.029
			systemic	NA	NA	0.33	0.27	0.19	0.13	0.098	0.043	0.037	0.031	0.027	0.02	0.017	0.012	0.013	<0.01
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	1	0.92	0.76	0.57	0.62	0.52	0.48	0.42	0.38	0.3	0.28	0.2	0.13	0.1
			hematological	NA	NA	0.92	0.84	0.69	0.53	0.56	0.47	0.43	0.38	0.34	0.27	0.25	0.18	0.12	0.09
			respiratory	NA	NA	0.42	0.4	0.33	0.24	0.27	0.23	0.21	0.19	0.16	0.13	0.12	0.087	0.056	0.044
			systemic	NA	NA	0.13	0.13	0.1	0.078	0.088	0.077	0.068	0.06	0.053	0.043	0.04	0.028	0.018	0.014
	Northern Front Range		hematological	NA	NA	1.1	0.9	0.75	0.53	0.41	0.31	0.25	0.21	0.18	0.13	0.1	0.085	0.07	0.059
			neurotoxicity	NA	NA	0.89	0.72	0.59	0.42	0.32	0.25	0.2	0.16	0.14	0.11	0.083	0.067	0.056	0.047
			respiratory	NA	NA	0.25	0.2	0.17	0.12	0.089	0.07	0.055	0.046	0.039	0.03	0.023	0.019	0.016	0.013
18 to 59 Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	2.1	1.8	1.4	0.86	0.65	0.31	0.26	0.22	0.19	0.14	0.12	0.07	0.087	0.066
			hematological	NA	NA	1.9	1.6	1.3	0.78	0.6	0.3	0.25	0.2	0.18	0.13	0.11	0.064	0.079	0.06
			respiratory	NA	NA	1	0.82	0.65	0.39	0.3	0.13	0.11	0.097	0.086	0.061	0.053	0.029	0.039	0.029
			systemic	NA	NA	0.33	0.27	0.19	0.13	0.098	0.043	0.037	0.031	0.028	0.02	0.018	0.012	0.013	<0.01
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	0.97	0.89	0.73	0.55	0.6	0.51	0.47	0.41	0.37	0.3	0.28	0.2	0.13	0.098
			hematological	NA	NA	0.89	0.81	0.66	0.51	0.55	0.46	0.42	0.37	0.34	0.27	0.25	0.18	0.12	0.089
			respiratory	NA	NA	0.42	0.4	0.33	0.24	0.27	0.22	0.21	0.18	0.16	0.13	0.12	0.086	0.056	0.043
			systemic	NA	NA	0.13	0.13	0.1	0.077	0.086	0.076	0.067	0.059	0.053	0.043	0.04	0.028	0.018	0.014
	Northern Front Range		hematological	NA	NA	1.1	0.89	0.73	0.52	0.4	0.31	0.24	0.2	0.17	0.13	0.1	0.083	0.068	0.058
			neurotoxicity	NA	NA	0.88	0.71	0.59	0.42	0.32	0.25	0.2	0.16	0.14	0.11	0.082	0.066	0.055	0.046
			respiratory	NA	NA	0.25	0.2	0.17	0.12	0.088	0.07	0.055	0.046	0.039	0.03	0.023	0.019	0.016	0.013
60+ Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	2.2	1.8	1.5	0.87	0.66	0.32	0.27	0.23	0.2	0.14	0.12	0.07	0.088	0.066
			hematological	NA	NA	2	1.6	1.3	0.79	0.6	0.3	0.25	0.2	0.18	0.13	0.11	0.064	0.079	0.06
			respiratory	NA	NA	1	0.82	0.65	0.39	0.3	0.13	0.11	0.097	0.085	0.061	0.054	0.029	0.04	0.03
			systemic	NA	NA	0.33	0.27	0.19	0.13	0.098	0.043	0.037	0.031	0.028	0.02	0.018	0.012	0.013	<0.01
	Garfield County:		neurotoxicity	NA	NA	0.99	0.92	0.76	0.57	0.6	0.5	0.47	0.41	0.37	0.3	0.28	0.2	0.14	0.1
			hematological	NA	NA	0.91	0.84	0.69	0.53	0.55	0.46	0.42	0.37	0.33	0.27	0.26	0.18	0.12	0.091

	Valley (Rifle)		respiratory	NA	NA	0.43	0.41	0.33	0.25	0.27	0.22	0.21	0.18	0.16	0.13	0.12	0.087	0.056	0.044
			systemic	NA	NA	0.13	0.13	0.11	0.079	0.086	0.075	0.067	0.059	0.052	0.043	0.039	0.028	0.018	0.014
	Northern Front Range		hematological	NA	NA	1.1	0.9	0.74	0.53	0.41	0.31	0.25	0.21	0.18	0.13	0.1	0.084	0.069	0.059
			neurotoxicity	NA	NA	0.89	0.72	0.59	0.42	0.32	0.25	0.2	0.16	0.14	0.11	0.083	0.067	0.055	0.047
			respiratory	NA	NA	0.25	0.2	0.17	0.12	0.088	0.07	0.056	0.046	0.039	0.03	0.023	0.019	0.016	0.013

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D).

Table E-39. Percentage of Subchronic Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Development Activities in Sequence, by Distance from the 1-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Development	neurotoxicity	NA	NA	57%	41%	23%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	49%	32%	11%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range			NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	57%	41%	22%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	49%	32%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Northern Front Range			NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	56%	40%	22%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	47%	31%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

				150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
	Northern Front Range			NA	NA	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D).

E.3.1.2 3-acre Well Pad

We do not show tables in this section about percentage of subchronic non-cancer hazard quotients and hazard indices (across the hypothetical population) that are above 1 during development activities in sequence (by distance from the 3-acre well pad) because this scenario had no hazard quotients or hazard indices above 1. All sequences of activities shown here last less than 365 days in total, so we calculated only subchronic results here (no chronic results).

Table E-40. Largest Subchronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities in Sequence, by Distance from the 3-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Development	benzene	NA	NA	0.21	0.17	0.14	0.1	0.085	0.067	0.056	0.038	0.033	0.032	0.025	0.018	0.018	0.011
			m+p-xylene	NA	NA	0.21	0.17	0.14	0.1	0.083	0.067	0.056	0.047	0.041	0.031	0.025	0.016	0.019	0.014
			n-nonane	NA	NA	0.19	0.16	0.13	0.096	0.076	0.062	0.052	0.045	0.039	0.029	0.023	0.014	0.017	0.013
			1,2,4-trimethylbenzene	NA	NA	0.13	0.11	0.088	0.064	0.05	0.041	0.035	0.03	0.026	0.019	0.015	<0.01	0.012	<0.01
			1,3,5-trimethylbenzene	NA	NA	0.13	0.1	0.086	0.063	0.049	0.04	0.034	0.029	0.026	0.019	0.015	<0.01	0.011	<0.01
	Garfield County: Valley (Rifle)		m+p-xylene	NA	NA	0.23	0.17	0.14	0.13	0.1	0.085	0.076	0.1	0.088	0.057	0.059	0.042	0.031	0.021
			n-nonane	NA	NA	0.22	0.17	0.14	0.13	0.098	0.08	0.072	0.1	0.087	0.056	0.059	0.042	0.03	0.021
			benzene	NA	NA	0.19	0.15	0.12	0.11	0.085	0.069	0.061	0.084	0.074	0.047	0.05	0.035	0.026	0.019
			1,2,4-trimethylbenzene	NA	NA	0.15	0.11	0.093	0.064	0.065	0.053	0.048	0.069	0.06	0.038	0.04	0.029	0.021	0.014
			1,3,5-trimethylbenzene	NA	NA	0.15	0.11	0.092	0.063	0.064	0.052	0.047	0.069	0.06	0.038	0.04	0.029	0.02	0.014
	Northern Front Range		benzene	NA	NA	0.56	0.46	0.38	0.27	0.21	0.17	0.14	0.11	0.096	0.071	0.056	0.045	0.038	0.032
			n-nonane	NA	NA	0.22	0.18	0.15	0.11	0.083	0.066	0.053	0.045	0.038	0.028	0.022	0.018	0.015	0.013
			m+p-xylene	NA	NA	0.14	0.11	0.095	0.067	0.052	0.042	0.033	0.028	0.024	0.018	0.014	0.011	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top		benzene	NA	NA	0.21	0.17	0.14	0.1	0.085	0.067	0.056	0.038	0.033	0.032	0.025	0.018	0.018	0.011
			m+p-xylene	NA	NA	0.21	0.17	0.14	0.1	0.083	0.066	0.056	0.047	0.041	0.031	0.025	0.016	0.019	0.014
			n-nonane	NA	NA	0.19	0.16	0.13	0.096	0.076	0.061	0.052	0.044	0.039	0.029	0.023	0.014	0.017	0.013

	Top (BarD)		1,2,4-trimethylbenzene	NA	NA	0.13	0.1	0.087	0.064	0.05	0.041	0.035	0.03	0.026	0.019	0.015	<0.01	0.012	<0.01
			1,3,5-trimethylbenzene	NA	NA	0.13	0.1	0.086	0.063	0.049	0.04	0.034	0.029	0.026	0.019	0.015	<0.01	0.011	<0.01
	Garfield County: Valley (Rifle)		m+p-xylene	NA	NA	0.23	0.17	0.14	0.13	0.1	0.085	0.075	0.1	0.088	0.057	0.059	0.042	0.031	0.022
			n-nonane	NA	NA	0.22	0.17	0.14	0.13	0.097	0.08	0.071	0.099	0.087	0.056	0.058	0.041	0.03	0.021
			benzene	NA	NA	0.19	0.15	0.12	0.11	0.085	0.069	0.061	0.084	0.074	0.047	0.05	0.035	0.026	0.018
			1,2,4-trimethylbenzene	NA	NA	0.15	0.11	0.093	0.064	0.065	0.053	0.048	0.068	0.06	0.038	0.04	0.029	0.021	0.014
			1,3,5-trimethylbenzene	NA	NA	0.15	0.11	0.092	0.063	0.064	0.052	0.047	0.068	0.06	0.038	0.04	0.029	0.02	0.014
	Northern Front Range		benzene	NA	NA	0.56	0.46	0.38	0.27	0.21	0.17	0.14	0.11	0.096	0.072	0.056	0.045	0.038	0.032
			n-nonane	NA	NA	0.22	0.18	0.15	0.11	0.084	0.066	0.053	0.045	0.038	0.028	0.022	0.018	0.015	0.013
			m+p-xylene	NA	NA	0.14	0.11	0.095	0.067	0.053	0.042	0.034	0.028	0.024	0.018	0.014	0.011	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)		benzene	NA	NA	0.21	0.17	0.14	0.1	0.085	0.068	0.056	0.038	0.033	0.032	0.025	0.018	0.018	0.011
			m+p-xylene	NA	NA	0.21	0.17	0.14	0.1	0.083	0.066	0.056	0.047	0.041	0.031	0.025	0.016	0.019	0.014
			n-nonane	NA	NA	0.19	0.16	0.13	0.096	0.076	0.061	0.052	0.044	0.039	0.029	0.023	0.014	0.017	0.013
			1,2,4-trimethylbenzene	NA	NA	0.13	0.11	0.088	0.064	0.05	0.041	0.035	0.03	0.026	0.019	0.015	<0.01	0.012	<0.01
			1,3,5-trimethylbenzene	NA	NA	0.13	0.1	0.086	0.063	0.049	0.04	0.034	0.029	0.026	0.019	0.015	<0.01	0.011	<0.01
	Garfield County: Valley (Rifle)		m+p-xylene	NA	NA	0.23	0.17	0.14	0.13	0.1	0.085	0.076	0.1	0.088	0.057	0.059	0.042	0.031	0.021
			n-nonane	NA	NA	0.22	0.17	0.14	0.13	0.098	0.08	0.071	0.099	0.087	0.056	0.059	0.042	0.03	0.021
			benzene	NA	NA	0.19	0.15	0.12	0.11	0.085	0.069	0.061	0.084	0.074	0.047	0.05	0.036	0.026	0.019
			1,2,4-trimethylbenzene	NA	NA	0.15	0.11	0.093	0.064	0.065	0.053	0.048	0.068	0.06	0.038	0.04	0.029	0.021	0.014
			1,3,5-trimethylbenzene	NA	NA	0.15	0.11	0.092	0.063	0.065	0.053	0.047	0.069	0.06	0.038	0.04	0.029	0.02	0.014
	Northern Front Range		benzene	NA	NA	0.56	0.46	0.38	0.27	0.21	0.17	0.14	0.11	0.096	0.071	0.056	0.045	0.038	0.032
			n-nonane	NA	NA	0.22	0.18	0.15	0.11	0.083	0.066	0.053	0.045	0.038	0.028	0.022	0.018	0.015	0.013
			m+p-xylene	NA	NA	0.14	0.11	0.095	0.067	0.052	0.042	0.033	0.028	0.024	0.018	0.014	0.011	<0.01	<0.01

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-41. Largest Subchronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities in Sequence, by Distance from the 3-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Development	neurotoxicity	NA	NA	0.83	0.67	0.56	0.41	0.33	0.26	0.22	0.19	0.16	0.12	0.099	0.061	0.075	0.053
			hematological	NA	NA	0.79	0.64	0.53	0.39	0.31	0.25	0.21	0.17	0.15	0.12	0.094	0.06	0.07	0.048
			respiratory	NA	NA	0.34	0.28	0.23	0.17	0.13	0.11	0.091	0.078	0.069	0.051	0.04	0.023	0.031	0.022
			systemic	NA	NA	0.11	0.085	0.071	0.052	0.041	0.033	0.028	0.024	0.021	0.016	0.012	<0.01	<0.01	<0.01
	Garfield		neurotoxicity	NA	NA	0.93	0.72	0.58	0.47	0.41	0.34	0.3	0.42	0.37	0.23	0.25	0.18	0.13	0.089

	County: Valley (Rifle)		hematological	NA	NA	0.85	0.66	0.53	0.43	0.37	0.31	0.27	0.38	0.33	0.21	0.23	0.16	0.12	0.081
			respiratory	NA	NA	0.39	0.3	0.25	0.17	0.17	0.14	0.13	0.18	0.16	0.1	0.11	0.076	0.054	0.038
			systemic	NA	NA	0.12	0.093	0.075	0.052	0.052	0.042	0.038	0.056	0.049	0.03	0.033	0.023	0.016	0.012
	Northern Front Range		hematological	NA	NA	0.94	0.77	0.64	0.45	0.36	0.28	0.23	0.19	0.16	0.12	0.094	0.076	0.063	0.054
			neurotoxicity	NA	NA	0.73	0.6	0.5	0.35	0.28	0.22	0.18	0.15	0.13	0.094	0.074	0.06	0.05	0.042
			respiratory	NA	NA	0.2	0.17	0.14	0.097	0.077	0.061	0.049	0.041	0.035	0.026	0.02	0.017	0.014	0.012
18 to 59 Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	0.83	0.67	0.56	0.41	0.33	0.26	0.22	0.19	0.16	0.12	0.099	0.061	0.075	0.053
			hematological	NA	NA	0.79	0.64	0.53	0.39	0.31	0.25	0.21	0.17	0.15	0.12	0.094	0.06	0.07	0.048
			respiratory	NA	NA	0.34	0.28	0.23	0.17	0.13	0.11	0.091	0.078	0.069	0.05	0.04	0.023	0.031	0.022
			systemic	NA	NA	0.11	0.085	0.071	0.052	0.041	0.033	0.028	0.024	0.021	0.016	0.012	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	0.93	0.71	0.58	0.47	0.41	0.33	0.3	0.42	0.37	0.23	0.25	0.18	0.13	0.09
			hematological	NA	NA	0.84	0.65	0.53	0.43	0.37	0.3	0.27	0.38	0.33	0.21	0.22	0.16	0.12	0.082
			respiratory	NA	NA	0.39	0.3	0.25	0.17	0.17	0.14	0.12	0.18	0.16	0.099	0.11	0.076	0.054	0.038
			systemic	NA	NA	0.12	0.093	0.075	0.052	0.052	0.042	0.038	0.056	0.049	0.03	0.033	0.023	0.016	0.012
	Northern Front Range		hematological	NA	NA	0.94	0.78	0.64	0.45	0.36	0.28	0.23	0.19	0.16	0.12	0.095	0.076	0.063	0.054
			neurotoxicity	NA	NA	0.73	0.61	0.5	0.35	0.28	0.22	0.18	0.15	0.13	0.094	0.074	0.06	0.05	0.042
			respiratory	NA	NA	0.2	0.17	0.14	0.097	0.077	0.061	0.049	0.041	0.035	0.026	0.02	0.017	0.014	0.012
60+ Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	0.84	0.68	0.56	0.41	0.33	0.26	0.22	0.19	0.16	0.12	0.099	0.061	0.075	0.053
			hematological	NA	NA	0.79	0.64	0.53	0.39	0.31	0.25	0.21	0.17	0.15	0.12	0.094	0.06	0.07	0.048
			respiratory	NA	NA	0.34	0.28	0.23	0.17	0.13	0.11	0.091	0.078	0.069	0.051	0.04	0.023	0.031	0.022
			systemic	NA	NA	0.11	0.085	0.071	0.052	0.041	0.033	0.028	0.024	0.021	0.016	0.012	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	0.93	0.72	0.58	0.47	0.41	0.33	0.3	0.42	0.37	0.23	0.25	0.18	0.13	0.089
			hematological	NA	NA	0.85	0.66	0.53	0.43	0.37	0.31	0.27	0.38	0.33	0.21	0.22	0.16	0.12	0.081
			respiratory	NA	NA	0.39	0.3	0.25	0.17	0.17	0.14	0.13	0.18	0.16	0.099	0.11	0.076	0.054	0.038
			systemic	NA	NA	0.12	0.093	0.075	0.052	0.052	0.042	0.038	0.056	0.049	0.03	0.033	0.023	0.016	0.012
	Northern Front Range		hematological	NA	NA	0.94	0.78	0.64	0.45	0.36	0.28	0.23	0.19	0.16	0.12	0.094	0.076	0.063	0.054
			neurotoxicity	NA	NA	0.73	0.61	0.5	0.35	0.28	0.22	0.18	0.15	0.13	0.094	0.074	0.06	0.05	0.042
			respiratory	NA	NA	0.2	0.17	0.14	0.097	0.076	0.061	0.049	0.041	0.035	0.026	0.02	0.017	0.014	0.012

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D).

E.3.1.3 5-acre Well Pad

We do not show tables in this section about percentage of subchronic non-cancer hazard quotients and hazard indices (across the hypothetical population) that are above 1 during development activities in sequence (by distance from the 5-acre well pad) because this scenario had no hazard quotients or hazard indices above 1. Sequences of development activities at the Garfield County sites last more than 365 days in total, so we calculated only chronic results for those scenarios (no subchronic results). Sequences of development activities at the NFR site last less than 365 days in total, so we calculated only subchronic results for those scenarios (no chronic results).

Table E-42. Largest Subchronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Development Activities in Sequence, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
18 to 59 Years	Northern Front Range	Development	benzene	NA	NA	0.55	0.45	0.37	0.26	0.2	0.16	0.13	0.11	0.09	0.068	0.054	0.043	0.036	0.03
			m+p-xylene	NA	NA	0.13	0.11	0.091	0.064	0.05	0.04	0.032	0.027	0.022	0.017	0.013	0.011	0.0089	0.0075
			n-nonane	NA	NA	0.21	0.17	0.14	0.1	0.08	0.063	0.051	0.042	0.035	0.027	0.021	0.017	0.014	0.012
60+ Years			benzene	NA	NA	0.55	0.45	0.37	0.26	0.21	0.16	0.13	0.11	0.091	0.069	0.054	0.044	0.036	0.03
			m+p-xylene	NA	NA	0.13	0.11	0.091	0.064	0.05	0.04	0.032	0.027	0.022	0.017	0.013	0.011	0.0089	0.0075
			n-nonane	NA	NA	0.21	0.17	0.14	0.1	0.08	0.063	0.051	0.043	0.035	0.027	0.021	0.017	0.014	0.012
Up to 17 Years			benzene	NA	NA	0.55	0.45	0.37	0.26	0.2	0.16	0.13	0.11	0.09	0.069	0.054	0.043	0.036	0.03
			m+p-xylene	NA	NA	0.13	0.11	0.091	0.064	0.05	0.04	0.032	0.027	0.022	0.017	0.013	0.011	0.0089	0.0075
			n-nonane	NA	NA	0.21	0.17	0.14	0.1	0.08	0.063	0.051	0.043	0.035	0.027	0.021	0.017	0.014	0.012

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity. Entries for Garfield County sites are not shown because development activities in sequence there last a total of more than 1 year in the 5-acre development scenario with many wells being developed (so we defer to a chronic assessment).

Table E-43. Largest Subchronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Development Activities in Sequence, by Distance from the 5-acre Well Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
18 to 59 Years	Northern Front Range	Development	hematological	NA	NA	0.91	0.75	0.62	0.44	0.34	0.27	0.22	0.18	0.15	0.11	0.09	0.073	0.06	0.051
			neurotoxicity	NA	NA	0.71	0.58	0.48	0.34	0.27	0.21	0.17	0.14	0.12	0.089	0.07	0.057	0.047	0.04
			respiratory	NA	NA	0.19	0.16	0.13	0.094	0.073	0.058	0.047	0.039	0.032	0.025	0.019	0.016	0.013	0.011
60+ Years			hematological	NA	NA	0.91	0.75	0.62	0.44	0.34	0.27	0.22	0.18	0.15	0.11	0.09	0.073	0.06	0.051
			neurotoxicity	NA	NA	0.71	0.58	0.48	0.34	0.27	0.21	0.17	0.14	0.12	0.089	0.07	0.057	0.047	0.04
			respiratory	NA	NA	0.19	0.16	0.13	0.095	0.073	0.058	0.047	0.039	0.032	0.025	0.019	0.016	0.013	0.011
Up to 17			hematological	NA	NA	0.91	0.75	0.62	0.44	0.34	0.27	0.22	0.18	0.15	0.11	0.09	0.073	0.06	0.051

Years			neurotoxicity	NA	NA	0.71	0.58	0.48	0.34	0.27	0.21	0.17	0.14	0.12	0.089	0.07	0.057	0.047	0.04
			respiratory	NA	NA	0.19	0.16	0.13	0.094	0.073	0.058	0.047	0.039	0.032	0.025	0.019	0.016	0.013	0.011

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any subchronic critical-effect group (see Appendix D). Entries for Garfield County sites are not shown because development activities in sequence there last a total of more than 1 year in the 5-acre development scenario with many wells being developed (so we defer to a chronic assessment).

E.3.2 Development and Production

E.3.2.1 1-acre Development Well Pad (1-acre Production Pad)

We do not show tables in this section about percentage of subchronic non-cancer hazard quotients and hazard indices (across the hypothetical population) that are above 1 during all activities in sequence (by distance from the 1-acre development well pad/1-acre production pad) because this scenario had no hazard quotients or hazard indices above 1. All sequences of activities shown here last more than 365 days in total, so we calculated only chronic results here (no subchronic results).

Table E-44. Largest Chronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during All Activities in Sequence, by Distance from the 1-acre Development Well Pad/1-acre Production Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	All	benzene	NA	NA	0.5	0.4	0.34	0.25	0.2	0.16	0.12	0.1	0.087	0.066	0.052	0.042	0.035	0.03
			1,2,4-trimethylbenzene	NA	NA	0.15	0.13	0.1	0.076	0.061	0.048	0.038	0.032	0.027	0.02	0.016	0.013	0.011	<0.01
			n-nonane	NA	NA	0.15	0.12	0.1	0.073	0.058	0.045	0.036	0.03	0.025	0.019	0.015	0.012	0.01	<0.01
			2-ethyltoluene	NA	NA	0.12	0.094	0.078	0.058	0.046	0.036	0.029	0.024	0.02	0.015	0.012	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		benzene	NA	NA	0.39	0.32	0.27	0.21	0.17	0.14	0.12	0.11	0.092	0.072	0.063	0.054	0.041	0.029
			1,2,4-trimethylbenzene	NA	NA	0.12	0.099	0.084	0.064	0.052	0.044	0.037	0.033	0.029	0.022	0.019	0.016	0.012	<0.01
			n-nonane	NA	NA	0.11	0.092	0.078	0.059	0.049	0.041	0.035	0.031	0.027	0.021	0.018	0.015	0.011	<0.01
	Northern Front Range		benzene	NA	NA	0.42	0.34	0.28	0.2	0.16	0.13	0.1	0.088	0.075	0.057	0.045	0.036	0.03	0.025
			1,2,4-trimethylbenzene	NA	NA	0.13	0.1	0.086	0.062	0.048	0.038	0.031	0.026	0.022	0.017	0.013	0.011	<0.01	<0.01
			n-nonane	NA	NA	0.12	0.095	0.079	0.057	0.045	0.036	0.029	0.024	0.021	0.016	0.013	0.01	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge		benzene	NA	NA	0.5	0.4	0.34	0.25	0.2	0.16	0.12	0.1	0.087	0.066	0.052	0.042	0.035	0.03
			1,2,4-trimethylbenzene	NA	NA	0.15	0.13	0.1	0.076	0.061	0.048	0.038	0.032	0.027	0.02	0.016	0.013	0.011	<0.01

	Top (BarD)		n-nonane	NA	NA	0.15	0.12	0.1	0.073	0.058	0.045	0.036	0.03	0.025	0.019	0.015	0.012	0.01	<0.01
			2-ethyltoluene	NA	NA	0.12	0.094	0.078	0.058	0.046	0.036	0.029	0.024	0.02	0.015	0.012	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		benzene	NA	NA	0.39	0.32	0.27	0.21	0.17	0.14	0.12	0.11	0.092	0.072	0.063	0.054	0.04	0.029
			1,2,4-trimethylbenzene	NA	NA	0.12	0.099	0.084	0.064	0.052	0.043	0.037	0.033	0.029	0.022	0.019	0.016	0.012	<0.01
			n-nonane	NA	NA	0.11	0.092	0.078	0.059	0.049	0.041	0.035	0.031	0.027	0.021	0.018	0.015	0.011	<0.01
	Northern Front Range		benzene	NA	NA	0.42	0.34	0.28	0.2	0.16	0.13	0.1	0.088	0.075	0.057	0.045	0.036	0.03	0.025
			1,2,4-trimethylbenzene	NA	NA	0.13	0.1	0.086	0.062	0.048	0.038	0.031	0.026	0.022	0.017	0.013	0.011	<0.01	<0.01
			n-nonane	NA	NA	0.12	0.095	0.079	0.057	0.045	0.036	0.029	0.024	0.021	0.016	0.012	0.01	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)		benzene	NA	NA	0.5	0.4	0.34	0.25	0.2	0.16	0.12	0.1	0.087	0.066	0.052	0.042	0.035	0.03
			1,2,4-trimethylbenzene	NA	NA	0.15	0.13	0.1	0.076	0.061	0.048	0.038	0.032	0.027	0.02	0.016	0.013	0.011	<0.01
			n-nonane	NA	NA	0.15	0.12	0.1	0.073	0.058	0.045	0.036	0.03	0.025	0.019	0.015	0.012	0.01	<0.01
			2-ethyltoluene	NA	NA	0.12	0.094	0.078	0.058	0.046	0.036	0.029	0.024	0.02	0.015	0.012	<0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		benzene	NA	NA	0.4	0.32	0.27	0.21	0.17	0.14	0.12	0.11	0.093	0.072	0.063	0.054	0.041	0.029
			1,2,4-trimethylbenzene	NA	NA	0.12	0.099	0.084	0.064	0.052	0.044	0.037	0.033	0.029	0.022	0.019	0.016	0.012	<0.01
			n-nonane	NA	NA	0.11	0.092	0.078	0.059	0.049	0.041	0.035	0.031	0.027	0.021	0.018	0.015	0.011	<0.01
	Northern Front Range		benzene	NA	NA	0.42	0.34	0.28	0.2	0.16	0.13	0.1	0.088	0.075	0.057	0.045	0.036	0.03	0.025
			1,2,4-trimethylbenzene	NA	NA	0.13	0.1	0.086	0.062	0.048	0.038	0.031	0.026	0.022	0.017	0.013	0.011	<0.01	<0.01
			n-nonane	NA	NA	0.12	0.095	0.079	0.057	0.045	0.036	0.029	0.024	0.021	0.016	0.013	0.01	<0.01	<0.01

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-45. Largest Chronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during All Activities in Sequence, by Distance from the 1-acre Development Well Pad/1-acre Production Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	All	hematological	NA	NA	0.75	0.61	0.51	0.37	0.3	0.23	0.19	0.15	0.13	0.098	0.078	0.063	0.053	0.045
			neurotoxicity	NA	NA	0.53	0.43	0.36	0.26	0.21	0.16	0.13	0.11	0.092	0.069	0.055	0.044	0.037	0.032
			respiratory	NA	NA	0.27	0.22	0.19	0.14	0.11	0.085	0.068	0.056	0.047	0.036	0.028	0.023	0.019	0.016
			systemic	NA	NA	0.16	0.13	0.11	0.08	0.064	0.05	0.04	0.033	0.028	0.021	0.017	0.014	0.011	<0.01
	Garfield County:		hematological	NA	NA	0.59	0.48	0.41	0.31	0.25	0.21	0.18	0.16	0.14	0.11	0.094	0.081	0.06	0.043
			neurotoxicity	NA	NA	0.41	0.34	0.29	0.22	0.18	0.15	0.13	0.11	0.099	0.077	0.067	0.057	0.042	0.03

	Valley (Rifle)		respiratory	NA	NA	0.21	0.17	0.15	0.11	0.092	0.077	0.066	0.058	0.051	0.039	0.034	0.029	0.022	0.016
			systemic	NA	NA	0.12	0.1	0.087	0.066	0.054	0.045	0.039	0.034	0.03	0.023	0.02	0.017	0.013	<0.01
	Northern Front Range		hematological	NA	NA	0.62	0.5	0.42	0.3	0.24	0.19	0.15	0.13	0.11	0.084	0.066	0.054	0.044	0.038
			neurotoxicity	NA	NA	0.43	0.35	0.29	0.21	0.17	0.13	0.11	0.09	0.077	0.058	0.046	0.037	0.031	0.026
			respiratory	NA	NA	0.22	0.18	0.15	0.11	0.086	0.068	0.055	0.046	0.039	0.03	0.023	0.019	0.016	0.013
			systemic	NA	NA	0.13	0.11	0.089	0.064	0.05	0.04	0.032	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)		hematological	NA	NA	0.74	0.61	0.51	0.37	0.3	0.23	0.19	0.15	0.13	0.098	0.078	0.063	0.053	0.045
			neurotoxicity	NA	NA	0.53	0.43	0.36	0.26	0.21	0.16	0.13	0.11	0.092	0.069	0.055	0.044	0.037	0.032
			respiratory	NA	NA	0.27	0.22	0.19	0.14	0.11	0.085	0.068	0.056	0.047	0.036	0.028	0.023	0.019	0.016
			systemic	NA	NA	0.16	0.13	0.11	0.08	0.064	0.05	0.04	0.033	0.028	0.021	0.017	0.014	0.011	<0.01
	Garfield County: Valley (Rifle)		hematological	NA	NA	0.59	0.48	0.41	0.31	0.25	0.21	0.18	0.16	0.14	0.11	0.094	0.081	0.06	0.043
			neurotoxicity	NA	NA	0.41	0.34	0.29	0.22	0.18	0.15	0.13	0.11	0.099	0.076	0.066	0.057	0.042	0.03
			respiratory	NA	NA	0.21	0.17	0.15	0.11	0.092	0.077	0.066	0.058	0.051	0.039	0.034	0.029	0.022	0.015
			systemic	NA	NA	0.12	0.1	0.086	0.066	0.054	0.045	0.039	0.034	0.03	0.023	0.02	0.017	0.013	<0.01
	Northern Front Range		hematological	NA	NA	0.62	0.5	0.42	0.3	0.24	0.19	0.15	0.13	0.11	0.084	0.066	0.054	0.044	0.038
			neurotoxicity	NA	NA	0.43	0.35	0.29	0.21	0.17	0.13	0.11	0.09	0.077	0.058	0.046	0.037	0.031	0.026
			respiratory	NA	NA	0.22	0.18	0.15	0.11	0.086	0.068	0.055	0.046	0.039	0.03	0.023	0.019	0.016	0.013
			systemic	NA	NA	0.13	0.11	0.089	0.064	0.05	0.04	0.032	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)		hematological	NA	NA	0.75	0.61	0.51	0.37	0.3	0.23	0.19	0.15	0.13	0.098	0.078	0.063	0.053	0.045
			neurotoxicity	NA	NA	0.53	0.43	0.36	0.26	0.21	0.16	0.13	0.11	0.092	0.069	0.055	0.044	0.037	0.032
			respiratory	NA	NA	0.27	0.22	0.19	0.14	0.11	0.085	0.068	0.056	0.047	0.036	0.028	0.023	0.019	0.016
			systemic	NA	NA	0.16	0.13	0.11	0.08	0.064	0.05	0.04	0.033	0.028	0.021	0.017	0.014	0.011	<0.01
	Garfield County: Valley (Rifle)		hematological	NA	NA	0.59	0.48	0.41	0.31	0.25	0.21	0.18	0.16	0.14	0.11	0.094	0.081	0.06	0.043
			neurotoxicity	NA	NA	0.41	0.34	0.29	0.22	0.18	0.15	0.13	0.11	0.099	0.077	0.067	0.057	0.042	0.03
			respiratory	NA	NA	0.21	0.17	0.15	0.11	0.092	0.077	0.066	0.058	0.051	0.039	0.034	0.029	0.022	0.016
			systemic	NA	NA	0.12	0.1	0.087	0.066	0.054	0.045	0.039	0.034	0.03	0.023	0.02	0.017	0.013	<0.01
	Northern Front Range		hematological	NA	NA	0.62	0.5	0.42	0.3	0.24	0.19	0.15	0.13	0.11	0.084	0.066	0.054	0.044	0.038
			neurotoxicity	NA	NA	0.43	0.35	0.29	0.21	0.17	0.13	0.11	0.09	0.077	0.058	0.046	0.037	0.031	0.026
			respiratory	NA	NA	0.22	0.18	0.15	0.11	0.086	0.068	0.055	0.046	0.039	0.03	0.023	0.019	0.016	0.013
			systemic	NA	NA	0.13	0.11	0.089	0.064	0.05	0.04	0.032	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D).

E.3.2.2 3-acre Development Well Pad (1-acre Production Pad)

We do not show tables in this section about percentage of subchronic non-cancer hazard quotients and hazard indices (across the hypothetical population) that are above 1 during all activities in sequence (by distance from the 1-acre development well pad/1-acre production pad) because this scenario had no hazard quotients or hazard indices above 1. All sequences of activities shown here last more than 365 days in total, so we calculated only chronic results here (no subchronic results).

Table E-46. Largest Chronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during All Activities in Sequence, by Distance from the 3-acre Development Well Pad/1-acre Production Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	All	benzene	NA	NA	0.53	0.43	0.36	0.26	0.21	0.17	0.13	0.11	0.091	0.071	0.056	0.045	0.038	0.032
			n-nonane	NA	NA	0.19	0.15	0.13	0.093	0.075	0.059	0.048	0.04	0.034	0.026	0.02	0.015	0.014	0.012
			1,2,4-trimethylbenzene	NA	NA	0.16	0.13	0.11	0.08	0.064	0.05	0.04	0.033	0.028	0.021	0.017	0.013	0.012	<0.01
			2-ethyltoluene	NA	NA	0.12	0.099	0.082	0.061	0.048	0.038	0.031	0.025	0.022	0.016	0.013	0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		benzene	NA	NA	0.43	0.35	0.29	0.23	0.18	0.15	0.13	0.12	0.11	0.08	0.072	0.06	0.045	0.032
			n-nonane	NA	NA	0.16	0.13	0.11	0.089	0.072	0.06	0.052	0.055	0.048	0.034	0.032	0.025	0.019	0.013
			1,2,4-trimethylbenzene	NA	NA	0.13	0.11	0.09	0.068	0.056	0.047	0.04	0.038	0.033	0.025	0.022	0.019	0.014	<0.01
	Northern Front Range		benzene	NA	NA	0.44	0.36	0.3	0.22	0.17	0.14	0.11	0.094	0.08	0.061	0.048	0.039	0.032	0.027
			1,2,4-trimethylbenzene	NA	NA	0.13	0.1	0.086	0.062	0.049	0.039	0.031	0.026	0.022	0.017	0.013	0.011	<0.01	<0.01
			n-nonane	NA	NA	0.13	0.11	0.089	0.064	0.051	0.04	0.033	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)		benzene	NA	NA	0.52	0.43	0.36	0.26	0.21	0.17	0.13	0.11	0.091	0.071	0.056	0.045	0.038	0.032
			n-nonane	NA	NA	0.19	0.15	0.13	0.093	0.074	0.059	0.048	0.04	0.034	0.026	0.02	0.015	0.014	0.012
			1,2,4-trimethylbenzene	NA	NA	0.16	0.13	0.11	0.08	0.064	0.05	0.04	0.033	0.028	0.021	0.017	0.013	0.012	<0.01
			2-ethyltoluene	NA	NA	0.12	0.098	0.082	0.061	0.048	0.038	0.031	0.025	0.022	0.016	0.013	0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		benzene	NA	NA	0.42	0.35	0.29	0.23	0.18	0.15	0.13	0.12	0.11	0.08	0.072	0.06	0.045	0.032
			n-nonane	NA	NA	0.16	0.13	0.11	0.089	0.072	0.059	0.052	0.055	0.048	0.034	0.032	0.025	0.019	0.013
			1,2,4-trimethylbenzene	NA	NA	0.13	0.11	0.089	0.067	0.056	0.047	0.04	0.038	0.033	0.025	0.022	0.018	0.014	<0.01
	Northern Front		benzene	NA	NA	0.44	0.36	0.3	0.22	0.17	0.14	0.11	0.094	0.08	0.061	0.048	0.039	0.032	0.027
			1,2,4-trimethylbenzene	NA	NA	0.13	0.1	0.086	0.062	0.049	0.039	0.031	0.026	0.022	0.017	0.013	0.011	<0.01	<0.01

	Range		n-nonane	NA	NA	0.13	0.11	0.089	0.064	0.051	0.04	0.033	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)		benzene	NA	NA	0.53	0.43	0.36	0.26	0.21	0.17	0.13	0.11	0.091	0.071	0.056	0.045	0.038	0.032
			n-nonane	NA	NA	0.19	0.15	0.13	0.093	0.075	0.059	0.048	0.04	0.034	0.026	0.02	0.015	0.014	0.012
			1,2,4-trimethylbenzene	NA	NA	0.16	0.13	0.11	0.08	0.064	0.05	0.04	0.033	0.028	0.021	0.017	0.013	0.012	<0.01
			2-ethyltoluene	NA	NA	0.12	0.099	0.082	0.061	0.048	0.038	0.031	0.025	0.022	0.016	0.013	0.01	<0.01	<0.01
	Garfield County: Valley (Rifle)		benzene	NA	NA	0.43	0.35	0.29	0.23	0.18	0.15	0.13	0.12	0.11	0.08	0.072	0.06	0.045	0.032
			n-nonane	NA	NA	0.16	0.13	0.11	0.089	0.072	0.059	0.052	0.055	0.048	0.034	0.032	0.025	0.019	0.013
			1,2,4-trimethylbenzene	NA	NA	0.13	0.11	0.09	0.068	0.056	0.047	0.04	0.038	0.033	0.025	0.022	0.019	0.014	<0.01
	Northern Front Range		benzene	NA	NA	0.45	0.36	0.3	0.22	0.17	0.14	0.11	0.094	0.08	0.061	0.048	0.039	0.032	0.027
			1,2,4-trimethylbenzene	NA	NA	0.13	0.1	0.087	0.062	0.049	0.039	0.031	0.026	0.022	0.017	0.013	0.011	<0.01	<0.01
			n-nonane	NA	NA	0.13	0.11	0.089	0.064	0.051	0.04	0.033	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity.

Table E-47. Largest Chronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during All Activities in Sequence, by Distance from the 3-acre Development Well Pad/1-acre Production Pad

Age Group	Site	Activity	Chemical or Critical-effect Group	Distance from Well Pad (feet) 150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	All	hematological	NA	NA	0.79	0.64	0.54	0.4	0.32	0.25	0.2	0.16	0.14	0.11	0.084	0.067	0.058	0.048
			neurotoxicity	NA	NA	0.62	0.5	0.42	0.31	0.25	0.19	0.16	0.13	0.11	0.083	0.066	0.051	0.046	0.038
			respiratory	NA	NA	0.29	0.24	0.2	0.15	0.12	0.092	0.074	0.062	0.052	0.039	0.031	0.024	0.021	0.018
			systemic	NA	NA	0.17	0.14	0.12	0.085	0.068	0.054	0.043	0.036	0.03	0.023	0.018	0.014	0.012	0.01
	Garfield County: Valley (Rifle)		hematological	NA	NA	0.65	0.53	0.44	0.34	0.28	0.23	0.2	0.19	0.16	0.12	0.11	0.093	0.069	0.049
			neurotoxicity	NA	NA	0.52	0.42	0.35	0.28	0.23	0.19	0.16	0.16	0.14	0.1	0.096	0.078	0.057	0.041
			respiratory	NA	NA	0.24	0.2	0.17	0.12	0.1	0.087	0.076	0.073	0.064	0.047	0.043	0.035	0.026	0.019
			systemic	NA	NA	0.14	0.11	0.096	0.073	0.061	0.051	0.044	0.042	0.037	0.027	0.025	0.02	0.015	0.011
	Northern Front Range		hematological	NA	NA	0.65	0.53	0.44	0.32	0.25	0.2	0.16	0.14	0.12	0.088	0.069	0.056	0.046	0.039
			neurotoxicity	NA	NA	0.45	0.37	0.31	0.22	0.18	0.14	0.11	0.095	0.081	0.061	0.048	0.039	0.032	0.027
			respiratory	NA	NA	0.23	0.18	0.15	0.11	0.087	0.069	0.056	0.047	0.04	0.03	0.024	0.019	0.016	0.014
			systemic	NA	NA	0.13	0.11	0.09	0.065	0.051	0.04	0.033	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge		hematological	NA	NA	0.79	0.64	0.54	0.4	0.32	0.25	0.2	0.16	0.14	0.11	0.084	0.067	0.058	0.048
			neurotoxicity	NA	NA	0.61	0.5	0.42	0.31	0.25	0.19	0.16	0.13	0.11	0.083	0.066	0.051	0.046	0.038

Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
	Top (BarD)		respiratory	NA	NA	0.29	0.24	0.2	0.15	0.12	0.092	0.074	0.062	0.052	0.039	0.031	0.024	0.021	0.018
			systemic	NA	NA	0.17	0.14	0.12	0.085	0.068	0.054	0.043	0.036	0.03	0.023	0.018	0.014	0.012	0.01
	Garfield County: Valley (Rifle)		hematological	NA	NA	0.65	0.53	0.44	0.34	0.28	0.23	0.2	0.19	0.16	0.12	0.11	0.092	0.069	0.049
			neurotoxicity	NA	NA	0.52	0.42	0.35	0.28	0.23	0.19	0.16	0.16	0.14	0.1	0.096	0.077	0.057	0.041
			respiratory	NA	NA	0.24	0.2	0.17	0.12	0.1	0.087	0.075	0.073	0.064	0.047	0.043	0.035	0.026	0.019
			systemic	NA	NA	0.14	0.11	0.096	0.073	0.061	0.05	0.044	0.042	0.037	0.027	0.025	0.02	0.015	0.011
	Northern Front Range		hematological	NA	NA	0.65	0.53	0.44	0.32	0.25	0.2	0.16	0.14	0.12	0.088	0.069	0.056	0.046	0.039
			neurotoxicity	NA	NA	0.45	0.37	0.31	0.22	0.18	0.14	0.11	0.095	0.081	0.061	0.048	0.039	0.032	0.027
			respiratory	NA	NA	0.23	0.18	0.15	0.11	0.087	0.069	0.056	0.047	0.04	0.03	0.024	0.019	0.016	0.014
			systemic	NA	NA	0.13	0.11	0.09	0.065	0.051	0.04	0.033	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)		hematological	NA	NA	0.79	0.65	0.54	0.4	0.32	0.25	0.2	0.16	0.14	0.11	0.084	0.067	0.058	0.048
			neurotoxicity	NA	NA	0.62	0.5	0.42	0.31	0.25	0.19	0.16	0.13	0.11	0.083	0.066	0.051	0.046	0.038
			respiratory	NA	NA	0.29	0.24	0.2	0.15	0.12	0.092	0.074	0.062	0.052	0.039	0.031	0.024	0.021	0.018
			systemic	NA	NA	0.17	0.14	0.12	0.085	0.068	0.054	0.043	0.036	0.03	0.023	0.018	0.014	0.012	0.01
	Garfield County: Valley (Rifle)		hematological	NA	NA	0.65	0.53	0.44	0.34	0.28	0.23	0.2	0.19	0.16	0.12	0.11	0.093	0.069	0.049
			neurotoxicity	NA	NA	0.52	0.42	0.35	0.28	0.23	0.19	0.16	0.16	0.14	0.1	0.096	0.078	0.057	0.041
			respiratory	NA	NA	0.24	0.2	0.17	0.12	0.1	0.087	0.076	0.073	0.064	0.047	0.043	0.035	0.026	0.019
			systemic	NA	NA	0.14	0.11	0.096	0.073	0.061	0.051	0.044	0.042	0.037	0.027	0.025	0.02	0.015	0.011
	Northern Front Range		hematological	NA	NA	0.65	0.53	0.44	0.32	0.25	0.2	0.16	0.14	0.12	0.088	0.069	0.056	0.046	0.039
			neurotoxicity	NA	NA	0.45	0.37	0.31	0.22	0.18	0.14	0.11	0.095	0.081	0.061	0.048	0.039	0.032	0.027
			respiratory	NA	NA	0.23	0.18	0.15	0.11	0.087	0.069	0.056	0.047	0.04	0.03	0.024	0.019	0.016	0.014
			systemic	NA	NA	0.13	0.11	0.09	0.065	0.051	0.04	0.033	0.027	0.023	0.018	0.014	0.011	<0.01	<0.01

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D).

E.3.2.3 5-acre Development Well Pad (1-acre Production Pad)

Table E-48. Largest Chronic Non-cancer Hazard Quotients for the Highest Exposed Hypothetical Individuals during Activities in Sequence, by Distance from the 5-acre Development Well Pad/1-acre Production Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17	Garfield	Development	n-nonane	NA	NA	2	1.6	1.3	0.98	0.76	0.61	0.52	0.45	0.39	0.29	0.23	0.14	0.17	0.13

Years	County: Ridge Top (BarD)		benzene	NA	NA	1.8	1.4	1.2	0.92	0.72	0.58	0.48	0.32	0.28	0.26	0.21	0.15	0.15	0.12
			m+p-xylene	NA	NA	0.84	0.68	0.57	0.42	0.33	0.27	0.22	0.19	0.17	0.12	0.099	0.063	0.072	0.055
			1,2,4-trimethylbenzene	NA	NA	0.45	0.36	0.3	0.22	0.17	0.14	0.12	0.1	0.089	0.064	0.052	0.031	0.039	0.028
			1,3,5-trimethylbenzene	NA	NA	0.44	0.35	0.29	0.21	0.17	0.13	0.11	0.099	0.087	0.062	0.051	0.03	0.038	0.028
			2-ethyltoluene	NA	NA	0.41	0.33	0.27	0.2	0.16	0.13	0.11	0.092	0.082	0.059	0.048	0.038	0.033	0.026
			1,2,3-trimethylbenzene	NA	NA	0.28	0.23	0.19	0.14	0.11	0.086	0.073	0.062	0.055	0.04	0.032	0.019	0.025	0.018
			o-xylene	NA	NA	0.14	0.11	0.091	0.067	0.052	0.042	0.036	0.03	0.026	0.02	0.016	<0.01	0.012	<0.01
			3-ethyltoluene	NA	NA	0.11	0.085	0.071	0.052	0.041	0.033	0.028	0.024	0.021	0.015	0.012	<0.01	<0.01	<0.01
		All	benzene	NA	NA	0.56	0.45	0.38	0.28	0.22	0.18	0.14	0.11	0.096	0.076	0.06	0.048	0.041	0.035
			n-nonane	NA	NA	0.23	0.19	0.16	0.12	0.092	0.073	0.06	0.051	0.044	0.032	0.026	0.019	0.018	0.015
			1,2,4-trimethylbenzene	NA	NA	0.17	0.14	0.11	0.083	0.067	0.052	0.042	0.035	0.03	0.022	0.018	0.014	0.012	0.01
			2-ethyltoluene	NA	NA	0.13	0.1	0.087	0.064	0.051	0.04	0.033	0.027	0.023	0.017	0.014	0.011	<0.01	<0.01
	Garfield County: Valley (Rifle)	Development	n-nonane	NA	NA	2.3	1.7	1.4	0.89	0.99	0.8	0.72	0.97	0.85	0.56	0.57	0.41	0.3	0.21
			benzene	NA	NA	1.7	1.3	1.1	0.71	0.72	0.58	0.51	0.7	0.61	0.4	0.41	0.3	0.22	0.15
			m+p-xylene	NA	NA	0.95	0.71	0.56	0.37	0.41	0.34	0.3	0.39	0.34	0.23	0.23	0.16	0.12	0.083
			1,2,4-trimethylbenzene	NA	NA	0.53	0.4	0.32	0.2	0.22	0.18	0.16	0.22	0.2	0.13	0.13	0.094	0.068	0.048
			1,3,5-trimethylbenzene	NA	NA	0.53	0.4	0.32	0.2	0.22	0.18	0.16	0.23	0.2	0.13	0.13	0.094	0.068	0.048
			2-ethyltoluene	NA	NA	0.5	0.38	0.3	0.19	0.21	0.17	0.15	0.21	0.18	0.12	0.12	0.087	0.063	0.045
			1,2,3-trimethylbenzene	NA	NA	0.34	0.26	0.2	0.13	0.14	0.11	0.1	0.14	0.13	0.082	0.084	0.059	0.043	0.03
			o-xylene	NA	NA	0.16	0.12	0.094	0.061	0.066	0.054	0.048	0.065	0.057	0.038	0.039	0.028	0.02	0.014
			3-ethyltoluene	NA	NA	0.13	0.095	0.075	0.048	0.053	0.043	0.039	0.053	0.046	0.03	0.031	0.022	0.016	0.011
		All	benzene	NA	NA	0.46	0.37	0.31	0.23	0.2	0.16	0.14	0.14	0.12	0.088	0.081	0.067	0.05	0.035
			n-nonane	NA	NA	0.22	0.18	0.14	0.1	0.096	0.079	0.069	0.079	0.069	0.048	0.046	0.035	0.026	0.018
			1,2,4-trimethylbenzene	NA	NA	0.14	0.11	0.096	0.071	0.061	0.05	0.044	0.043	0.037	0.028	0.025	0.02	0.015	0.011
			2-ethyltoluene	NA	NA	0.11	0.089	0.074	0.055	0.047	0.039	0.034	0.034	0.03	0.022	0.02	0.016	0.012	<0.01
	Northern Front Range		benzene	NA	NA	0.54	0.44	0.37	0.26	0.21	0.17	0.13	0.11	0.095	0.072	0.057	0.046	0.038	0.032
			n-nonane	NA	NA	0.18	0.14	0.12	0.086	0.068	0.054	0.043	0.036	0.031	0.023	0.018	0.015	0.012	0.011
			1,2,4-trimethylbenzene	NA	NA	0.13	0.11	0.089	0.064	0.05	0.04	0.032	0.027	0.023	0.017	0.014	0.011	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)	Development	n-nonane	NA	NA	2	1.6	1.3	0.98	0.76	0.61	0.52	0.45	0.39	0.29	0.23	0.14	0.17	0.13
			benzene	NA	NA	1.8	1.4	1.2	0.91	0.71	0.57	0.48	0.32	0.28	0.26	0.21	0.15	0.15	0.12
			m+p-xylene	NA	NA	0.84	0.68	0.57	0.42	0.33	0.27	0.22	0.19	0.17	0.12	0.098	0.063	0.072	0.055
			1,2,4-trimethylbenzene	NA	NA	0.44	0.36	0.3	0.22	0.17	0.14	0.12	0.1	0.088	0.063	0.051	0.031	0.039	0.028
			1,3,5-trimethylbenzene	NA	NA	0.44	0.35	0.29	0.21	0.17	0.13	0.11	0.099	0.087	0.062	0.05	0.03	0.038	0.028
			2-ethyltoluene	NA	NA	0.41	0.33	0.27	0.2	0.16	0.13	0.11	0.092	0.081	0.059	0.048	0.038	0.033	0.026
			1,2,3-trimethylbenzene	NA	NA	0.28	0.22	0.19	0.14	0.11	0.086	0.073	0.062	0.055	0.04	0.032	0.019	0.025	0.018
			o-xylene	NA	NA	0.14	0.11	0.091	0.067	0.052	0.042	0.036	0.03	0.026	0.019	0.016	<0.01	0.011	<0.01
			3-ethyltoluene	NA	NA	0.11	0.085	0.071	0.052	0.041	0.033	0.028	0.024	0.021	0.015	0.012	<0.01	<0.01	<0.01

		All	benzene	NA	NA	0.56	0.45	0.38	0.28	0.22	0.18	0.14	0.11	0.096	0.076	0.06	0.048	0.041	0.035
			n-nonane	NA	NA	0.23	0.19	0.16	0.12	0.092	0.073	0.06	0.051	0.044	0.032	0.026	0.019	0.018	0.015
			1,2,4-trimethylbenzene	NA	NA	0.17	0.14	0.11	0.083	0.067	0.052	0.042	0.035	0.03	0.022	0.018	0.014	0.012	0.01
			2-ethyltoluene	NA	NA	0.13	0.1	0.087	0.064	0.051	0.04	0.033	0.027	0.023	0.017	0.014	0.011	<0.01	<0.01
	Garfield County: Valley (Rifle)	Development	n-nonane	NA	NA	2.3	1.7	1.4	0.89	0.98	0.8	0.72	0.97	0.84	0.56	0.57	0.41	0.3	0.2
			benzene	NA	NA	1.7	1.3	1.1	0.71	0.72	0.58	0.51	0.7	0.61	0.4	0.41	0.3	0.22	0.15
			m+p-xylene	NA	NA	0.95	0.71	0.56	0.37	0.41	0.33	0.3	0.39	0.34	0.23	0.23	0.16	0.12	0.082
			1,2,4-trimethylbenzene	NA	NA	0.53	0.4	0.32	0.2	0.22	0.18	0.16	0.22	0.2	0.13	0.13	0.093	0.068	0.048
			1,3,5-trimethylbenzene	NA	NA	0.53	0.4	0.32	0.2	0.22	0.18	0.16	0.22	0.2	0.13	0.13	0.094	0.067	0.048
			2-ethyltoluene	NA	NA	0.5	0.38	0.3	0.19	0.21	0.17	0.15	0.21	0.18	0.12	0.12	0.087	0.063	0.044
			1,2,3-trimethylbenzene	NA	NA	0.34	0.25	0.2	0.13	0.14	0.11	0.1	0.14	0.13	0.082	0.084	0.059	0.043	0.03
			o-xylene	NA	NA	0.16	0.12	0.093	0.06	0.066	0.054	0.048	0.065	0.057	0.038	0.039	0.027	0.02	0.014
			3-ethyltoluene	NA	NA	0.13	0.095	0.075	0.048	0.053	0.043	0.038	0.053	0.046	0.03	0.031	0.022	0.016	0.011
		All	benzene	NA	NA	0.46	0.37	0.31	0.23	0.2	0.16	0.14	0.14	0.12	0.088	0.081	0.067	0.05	0.035
			n-nonane	NA	NA	0.22	0.17	0.14	0.1	0.096	0.079	0.069	0.078	0.069	0.048	0.046	0.035	0.026	0.018
			1,2,4-trimethylbenzene	NA	NA	0.14	0.11	0.095	0.071	0.06	0.05	0.044	0.042	0.037	0.027	0.025	0.02	0.015	0.011
			2-ethyltoluene	NA	NA	0.11	0.089	0.074	0.055	0.047	0.039	0.034	0.034	0.03	0.022	0.02	0.016	0.012	<0.01
	Northern Front Range		benzene	NA	NA	0.54	0.44	0.37	0.26	0.21	0.17	0.13	0.11	0.095	0.072	0.057	0.046	0.038	0.032
			n-nonane	NA	NA	0.18	0.14	0.12	0.086	0.068	0.054	0.043	0.036	0.031	0.023	0.018	0.015	0.012	0.01
			1,2,4-trimethylbenzene	NA	NA	0.13	0.11	0.089	0.064	0.05	0.04	0.032	0.027	0.023	0.017	0.014	0.011	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)	Development	n-nonane	NA	NA	2	1.6	1.3	0.98	0.76	0.61	0.52	0.45	0.39	0.29	0.23	0.14	0.17	0.13
			benzene	NA	NA	1.8	1.4	1.2	0.92	0.72	0.58	0.48	0.32	0.28	0.26	0.21	0.15	0.15	0.12
			m+p-xylene	NA	NA	0.84	0.68	0.57	0.42	0.33	0.27	0.22	0.19	0.17	0.12	0.099	0.063	0.072	0.055
			1,2,4-trimethylbenzene	NA	NA	0.45	0.36	0.3	0.22	0.17	0.14	0.12	0.1	0.089	0.064	0.052	0.031	0.039	0.028
			1,3,5-trimethylbenzene	NA	NA	0.44	0.35	0.29	0.21	0.17	0.13	0.11	0.099	0.087	0.062	0.051	0.03	0.038	0.028
			2-ethyltoluene	NA	NA	0.41	0.33	0.27	0.2	0.16	0.13	0.11	0.092	0.082	0.059	0.048	0.038	0.033	0.026
			1,2,3-trimethylbenzene	NA	NA	0.28	0.23	0.19	0.14	0.11	0.086	0.073	0.062	0.055	0.04	0.032	0.019	0.025	0.018
			o-xylene	NA	NA	0.14	0.11	0.091	0.067	0.052	0.042	0.036	0.03	0.026	0.02	0.016	<0.01	0.012	<0.01
			3-ethyltoluene	NA	NA	0.11	0.085	0.071	0.052	0.041	0.033	0.028	0.024	0.021	0.015	0.012	<0.01	<0.01	<0.01
		All	benzene	NA	NA	0.56	0.45	0.38	0.28	0.22	0.18	0.14	0.11	0.096	0.076	0.06	0.048	0.041	0.035
			n-nonane	NA	NA	0.23	0.19	0.16	0.12	0.092	0.073	0.06	0.051	0.044	0.032	0.026	0.019	0.018	0.015
			1,2,4-trimethylbenzene	NA	NA	0.17	0.14	0.11	0.083	0.067	0.052	0.042	0.035	0.03	0.022	0.018	0.014	0.012	0.01
			2-ethyltoluene	NA	NA	0.13	0.1	0.087	0.064	0.051	0.04	0.033	0.027	0.023	0.017	0.014	0.011	<0.01	<0.01
	Garfield County: Valley (Rifle)	Development	n-nonane	NA	NA	2.3	1.7	1.4	0.89	0.99	0.8	0.72	0.97	0.85	0.56	0.57	0.41	0.3	0.21
			benzene	NA	NA	1.7	1.3	1.1	0.71	0.72	0.58	0.51	0.7	0.61	0.4	0.41	0.3	0.22	0.15
			m+p-xylene	NA	NA	0.95	0.71	0.56	0.37	0.41	0.34	0.3	0.39	0.34	0.23	0.23	0.16	0.12	0.083
			1,2,4-trimethylbenzene	NA	NA	0.53	0.4	0.32	0.2	0.22	0.18	0.16	0.22	0.2	0.13	0.13	0.094	0.068	0.048

			1,3,5-trimethylbenzene	NA	NA	0.53	0.4	0.32	0.2	0.22	0.18	0.16	0.23	0.2	0.13	0.13	0.094	0.068	0.048
			2-ethyltoluene	NA	NA	0.5	0.38	0.3	0.19	0.21	0.17	0.15	0.21	0.18	0.12	0.12	0.087	0.063	0.045
			1,2,3-trimethylbenzene	NA	NA	0.34	0.26	0.2	0.13	0.14	0.11	0.1	0.14	0.13	0.082	0.084	0.059	0.043	0.03
			o-xylene	NA	NA	0.16	0.12	0.094	0.061	0.066	0.054	0.048	0.066	0.057	0.038	0.039	0.028	0.02	0.014
			3-ethyltoluene	NA	NA	0.13	0.095	0.075	0.048	0.053	0.043	0.039	0.053	0.046	0.03	0.031	0.022	0.016	0.011
		All	benzene	NA	NA	0.46	0.37	0.31	0.23	0.2	0.16	0.14	0.14	0.12	0.088	0.081	0.067	0.05	0.035
			n-nonane	NA	NA	0.22	0.18	0.14	0.1	0.096	0.079	0.07	0.079	0.069	0.048	0.046	0.035	0.026	0.018
			1,2,4-trimethylbenzene	NA	NA	0.14	0.11	0.096	0.071	0.061	0.05	0.044	0.043	0.037	0.028	0.025	0.02	0.015	0.011
			2-ethyltoluene	NA	NA	0.11	0.089	0.074	0.055	0.047	0.039	0.034	0.034	0.03	0.022	0.02	0.016	0.012	<0.01
	Northern Front Range		benzene	NA	NA	0.54	0.44	0.37	0.26	0.21	0.17	0.13	0.11	0.095	0.072	0.057	0.046	0.038	0.032
			n-nonane	NA	NA	0.18	0.14	0.12	0.086	0.068	0.054	0.043	0.036	0.031	0.023	0.018	0.015	0.012	0.011
			1,2,4-trimethylbenzene	NA	NA	0.13	0.11	0.089	0.064	0.05	0.04	0.032	0.027	0.023	0.017	0.014	0.011	<0.01	<0.01

Notes: Only showing chemicals with hazard quotients above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Chemicals are shown sorted from largest to smallest hazard quotients, within a given combination of age group, site, and activity. Entries for development activities in Northern Front Range are not shown because they last a total of less than 1 year in the 5-acre development scenario with many wells being developed (so we defer to a subchronic assessment).

Table E-49. Percentage of Chronic Non-cancer Hazard Quotients, Across the Hypothetical Population, That are Above 1 during Activities in Sequence, by Distance from the 5-acre Development Well Pad/1-acre Production Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Development	n-nonane	NA	NA	60%	42%	26%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			benzene	NA	NA	52%	35%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		n-nonane	NA	NA	71%	52%	32%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			benzene	NA	NA	52%	28%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)		n-nonane	NA	NA	60%	42%	26%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			benzene	NA	NA	51%	35%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

	Garfield County: Valley (Rifle)		n-nonane	NA	NA	71%	51%	32%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			benzene	NA	NA	51%	27%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)		n-nonane	NA	NA	58%	42%	26%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			benzene	NA	NA	49%	34%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		n-nonane	NA	NA	69%	49%	31%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			benzene	NA	NA	49%	27%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing chemicals with hazard quotients above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Chemical are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Entries for development activities in Northern Front Range are not shown because they last a total of less than 1 year in the 5-acre development scenario with many wells being developed (so we defer to a subchronic assessment).

Table E-50. Largest Chronic Non-cancer Hazard Indices for the Highest Exposed Hypothetical Individuals during Activities in Sequence, by Distance from the 5-acre Development Well Pad/1-acre Production Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Development	neurotoxicity	NA	NA	4.2	3.4	2.8	2.1	1.6	1.3	1.1	0.95	0.84	0.61	0.49	0.3	0.37	0.27
			hematological	NA	NA	2.9	2.4	2	1.5	1.2	0.94	0.78	0.58	0.51	0.43	0.35	0.23	0.25	0.19
			respiratory	NA	NA	1.2	1	0.83	0.61	0.47	0.38	0.32	0.28	0.25	0.18	0.14	0.085	0.11	0.078
			systemic	NA	NA	0.68	0.54	0.45	0.33	0.26	0.21	0.18	0.15	0.13	0.097	0.078	0.057	0.056	0.043
		All	hematological	NA	NA	0.85	0.69	0.58	0.43	0.34	0.27	0.22	0.18	0.15	0.12	0.091	0.072	0.063	0.053
			neurotoxicity	NA	NA	0.71	0.58	0.48	0.35	0.28	0.22	0.18	0.15	0.13	0.097	0.077	0.058	0.054	0.044
			respiratory	NA	NA	0.32	0.26	0.22	0.16	0.13	0.1	0.081	0.067	0.057	0.043	0.034	0.026	0.024	0.019
			systemic	NA	NA	0.18	0.15	0.12	0.092	0.073	0.058	0.046	0.039	0.033	0.025	0.02	0.016	0.014	0.011
	Garfield County: Valley (Rifle)	Development	neurotoxicity	NA	NA	4.9	3.7	2.9	1.9	2.1	1.7	1.5	2.1	1.8	1.2	1.2	0.87	0.63	0.44
			hematological	NA	NA	3.1	2.4	1.9	1.2	1.3	1.1	0.94	1.3	1.1	0.74	0.76	0.55	0.4	0.28
			respiratory	NA	NA	1.5	1.1	0.89	0.57	0.62	0.5	0.45	0.63	0.55	0.36	0.37	0.26	0.19	0.13
			systemic	NA	NA	0.81	0.61	0.49	0.31	0.34	0.27	0.25	0.34	0.3	0.2	0.2	0.14	0.1	0.073
		All	hematological	NA	NA	0.72	0.58	0.48	0.36	0.3	0.25	0.22	0.22	0.19	0.14	0.13	0.1	0.078	0.055
			neurotoxicity	NA	NA	0.64	0.51	0.42	0.3	0.28	0.23	0.2	0.21	0.19	0.13	0.12	0.098	0.072	0.051

			respiratory	NA	NA	0.28	0.22	0.18	0.14	0.12	0.098	0.085	0.087	0.076	0.055	0.051	0.041	0.03	0.021
			systemic	NA	NA	0.16	0.13	0.11	0.078	0.068	0.056	0.049	0.05	0.043	0.032	0.029	0.023	0.017	0.012
	Northern Front Range		hematological	NA	NA	0.76	0.62	0.51	0.37	0.29	0.23	0.19	0.16	0.13	0.1	0.08	0.064	0.053	0.045
			neurotoxicity	NA	NA	0.53	0.43	0.36	0.26	0.2	0.16	0.13	0.11	0.093	0.071	0.056	0.045	0.037	0.032
			respiratory	NA	NA	0.24	0.2	0.16	0.12	0.093	0.073	0.059	0.05	0.042	0.032	0.025	0.02	0.017	0.014
			systemic	NA	NA	0.14	0.11	0.092	0.066	0.052	0.041	0.033	0.028	0.024	0.018	0.014	0.012	<0.01	<0.01
18 to 59 Years	Garfield County: Ridge Top (BarD)	Development	neurotoxicity	NA	NA	4.2	3.4	2.8	2.1	1.6	1.3	1.1	0.95	0.83	0.61	0.49	0.3	0.37	0.27
			hematological	NA	NA	2.9	2.4	2	1.5	1.2	0.93	0.78	0.58	0.51	0.43	0.34	0.23	0.25	0.19
			respiratory	NA	NA	1.2	0.99	0.83	0.61	0.47	0.38	0.32	0.28	0.25	0.18	0.14	0.085	0.11	0.078
			systemic	NA	NA	0.68	0.54	0.45	0.33	0.26	0.21	0.18	0.15	0.13	0.096	0.078	0.057	0.056	0.043
		All	hematological	NA	NA	0.85	0.69	0.58	0.43	0.34	0.27	0.22	0.18	0.15	0.11	0.091	0.072	0.063	0.053
			neurotoxicity	NA	NA	0.71	0.58	0.48	0.35	0.28	0.22	0.18	0.15	0.13	0.097	0.077	0.057	0.054	0.044
			respiratory	NA	NA	0.32	0.26	0.22	0.16	0.13	0.1	0.08	0.067	0.057	0.043	0.034	0.026	0.024	0.019
			systemic	NA	NA	0.18	0.15	0.12	0.092	0.073	0.057	0.046	0.039	0.033	0.025	0.02	0.016	0.014	0.011
	Garfield County: Valley (Rifle)	Development	neurotoxicity	NA	NA	4.9	3.7	2.9	1.9	2.1	1.7	1.5	2.1	1.8	1.2	1.2	0.87	0.63	0.44
			hematological	NA	NA	3.1	2.4	1.9	1.2	1.3	1.1	0.94	1.3	1.1	0.74	0.76	0.55	0.4	0.28
			respiratory	NA	NA	1.5	1.1	0.89	0.57	0.62	0.5	0.45	0.63	0.55	0.36	0.37	0.26	0.19	0.13
			systemic	NA	NA	0.81	0.61	0.49	0.31	0.34	0.27	0.25	0.34	0.3	0.2	0.2	0.14	0.1	0.073
		All	hematological	NA	NA	0.72	0.58	0.48	0.36	0.3	0.25	0.22	0.22	0.19	0.14	0.13	0.1	0.077	0.055
			neurotoxicity	NA	NA	0.64	0.51	0.42	0.3	0.27	0.23	0.2	0.21	0.19	0.13	0.12	0.098	0.072	0.051
			respiratory	NA	NA	0.28	0.22	0.18	0.14	0.12	0.098	0.085	0.087	0.076	0.055	0.051	0.041	0.03	0.021
			systemic	NA	NA	0.16	0.13	0.11	0.078	0.068	0.056	0.049	0.05	0.043	0.032	0.029	0.023	0.017	0.012
	Northern Front Range		hematological	NA	NA	0.75	0.62	0.51	0.37	0.29	0.23	0.19	0.16	0.13	0.1	0.079	0.064	0.053	0.045
			neurotoxicity	NA	NA	0.53	0.43	0.36	0.26	0.2	0.16	0.13	0.11	0.093	0.071	0.055	0.045	0.037	0.032
			respiratory	NA	NA	0.24	0.2	0.16	0.12	0.092	0.073	0.059	0.05	0.042	0.032	0.025	0.02	0.017	0.014
			systemic	NA	NA	0.13	0.11	0.092	0.066	0.052	0.041	0.033	0.028	0.024	0.018	0.014	0.012	<0.01	<0.01
60+ Years	Garfield County: Ridge Top (BarD)	Development	neurotoxicity	NA	NA	4.2	3.4	2.8	2.1	1.6	1.3	1.1	0.95	0.84	0.61	0.49	0.3	0.37	0.27
			hematological	NA	NA	2.9	2.4	2	1.5	1.2	0.94	0.78	0.58	0.51	0.43	0.35	0.23	0.25	0.19
			respiratory	NA	NA	1.2	1	0.83	0.61	0.47	0.38	0.32	0.28	0.25	0.18	0.14	0.085	0.11	0.078
			systemic	NA	NA	0.68	0.54	0.45	0.33	0.26	0.21	0.18	0.15	0.13	0.097	0.078	0.057	0.056	0.043
		All	hematological	NA	NA	0.85	0.69	0.58	0.43	0.34	0.27	0.22	0.18	0.15	0.12	0.091	0.072	0.063	0.053
			neurotoxicity	NA	NA	0.71	0.58	0.48	0.35	0.28	0.22	0.18	0.15	0.13	0.097	0.077	0.058	0.054	0.044
			respiratory	NA	NA	0.32	0.26	0.22	0.16	0.13	0.1	0.081	0.067	0.057	0.043	0.034	0.026	0.024	0.019
			systemic	NA	NA	0.18	0.15	0.12	0.092	0.073	0.058	0.046	0.039	0.033	0.025	0.02	0.016	0.014	0.011
	Garfield County: Valley (Rifle)	Development	neurotoxicity	NA	NA	4.9	3.7	2.9	1.9	2.1	1.7	1.5	2.1	1.8	1.2	1.2	0.87	0.63	0.44
			hematological	NA	NA	3.1	2.4	1.9	1.2	1.3	1.1	0.94	1.3	1.1	0.74	0.76	0.55	0.4	0.28
			respiratory	NA	NA	1.5	1.1	0.89	0.57	0.62	0.5	0.45	0.63	0.55	0.36	0.37	0.26	0.19	0.13

	(Rifle)		systemic	NA	NA	0.81	0.61	0.49	0.31	0.34	0.27	0.25	0.34	0.3	0.2	0.2	0.14	0.1	0.073
		All	hematological	NA	NA	0.72	0.58	0.48	0.36	0.31	0.25	0.22	0.22	0.19	0.14	0.13	0.1	0.078	0.055
			neurotoxicity	NA	NA	0.64	0.51	0.42	0.3	0.28	0.23	0.2	0.21	0.19	0.13	0.12	0.098	0.072	0.051
			respiratory	NA	NA	0.28	0.22	0.18	0.14	0.12	0.098	0.085	0.087	0.076	0.055	0.051	0.041	0.03	0.021
			systemic	NA	NA	0.16	0.13	0.11	0.078	0.068	0.056	0.049	0.05	0.044	0.032	0.029	0.023	0.017	0.012
	Northern Front Range		hematological	NA	NA	0.76	0.62	0.51	0.37	0.29	0.23	0.19	0.16	0.13	0.1	0.08	0.064	0.053	0.045
			neurotoxicity	NA	NA	0.53	0.43	0.36	0.26	0.2	0.16	0.13	0.11	0.093	0.071	0.056	0.045	0.037	0.032
			respiratory	NA	NA	0.24	0.2	0.16	0.12	0.093	0.073	0.059	0.05	0.042	0.032	0.025	0.02	0.017	0.014
			systemic	NA	NA	0.14	0.11	0.092	0.066	0.052	0.041	0.033	0.028	0.024	0.018	0.014	0.012	<0.01	<0.01

Notes: Only showing critical-effect groups with hazard indices above 0.1. Shading used to differentiate values above 10 (darker blue with white font), values between 1 and 10 (medium blue), values 0.1 to 1 (light blue), and values below 0.1 (gray). Critical-effect groups are shown sorted from largest to smallest hazard indices, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Entries for development activities in Northern Front Range are not shown because they last a total of less than 1 year in the 5-acre development scenario with many wells being developed (so we defer to a subchronic assessment).

Table E-51. Percentage of Chronic Non-cancer Hazard Indices, Across the Hypothetical Population, That are Above 1 during Activities in Sequence, by Distance from the 5-acre Development Well Pad/1-acre Production Pad

				Distance from Well Pad (feet)															
Age Group	Site	Activity	Chemical or Critical-effect Group	150	250	300	350	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000
Up to 17 Years	Garfield County: Ridge Top (BarD)	Development	neurotoxicity	NA	NA	93%	87%	80%	64%	44%	26%	6%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	81%	72%	61%	38%	12%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	21%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	97%	91%	83%	59%	65%	49%	40%	64%	56%	16%	19%	0%	0%	0%
			hematological	NA	NA	85%	73%	59%	21%	26%	1%	0%	25%	10%	0%	0%	0%	0%	0%
			respiratory	NA	NA	39%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
18 to 59 Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	93%	87%	79%	64%	44%	26%	6%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	81%	71%	61%	38%	12%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	21%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley		neurotoxicity	NA	NA	97%	90%	82%	58%	65%	49%	40%	64%	55%	16%	19%	0%	0%	0%
			hematological	NA	NA	84%	72%	58%	21%	25%	1%	0%	25%	10%	0%	0%	0%	0%	0%

	(Rifle)		respiratory	NA	NA	39%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
60+ Years	Garfield County: Ridge Top (BarD)		neurotoxicity	NA	NA	91%	85%	78%	62%	44%	25%	6%	0%	0%	0%	0%	0%	0%	0%
			hematological	NA	NA	79%	70%	59%	37%	11%	0%	0%	0%	0%	0%	0%	0%	0%	0%
			respiratory	NA	NA	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Garfield County: Valley (Rifle)		neurotoxicity	NA	NA	95%	88%	79%	57%	63%	47%	40%	62%	53%	16%	19%	0%	0%	0%
			hematological	NA	NA	82%	71%	57%	21%	25%	1%	0%	24%	10%	0%	0%	0%	0%	0%
			respiratory	NA	NA	39%	9%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Notes: Only showing critical-effect groups with hazard indices above 1. Shading used to differentiate higher values (darker oranges) from lower values (lighter greens) and from values of 0 (gray). Critical-effect groups are shown sorted from largest to smallest percentage, within a given combination of age group, site, and activity. Some chemicals could not be assigned to any chronic critical-effect group (see Appendix D). Entries for development activities in Northern Front Range are not shown because they last a total of less than 1 year in the 5-acre development scenario with many wells being developed (so we defer to a subchronic assessment).

COLORADO
Department of Public Health & Environment

At-A-Glance

Human Health Risk Assessment for Oil & Gas Operations in Colorado

What the study does	What the study does not do
The study uses actual emissions data from oil and gas operations in Colorado, to estimate or "model" hypothetical exposures and risks of health impacts. Modeling is used to predict how pollutants move through the air, accounting for weather conditions and emissions from a source, to estimate exposures at multiple distances from a well pad. These estimated exposures are then used to understand the potential risk to public health.	The study is not based on actual health impacts people have reported from oil and gas operations or on measured concentrations in the air surrounding the well pad.
The study says that there may be a risk of negative health impacts (e.g., headaches; dizziness; respiratory, eye, and skin irritation) from short-term exposures to chemicals such as benzene during worst-case conditions. Worst-case conditions represent the highest of what could reasonably be expected from a single well pad during various phases of oil and gas development.	The study does not examine risk of short-term health impacts from average or everyday conditions, nor does it estimate the frequency of worst-case conditions. The state has collected approximately 5,000 samples near well pads with its mobile monitoring lab in recent years, but has not measured concentrations above what we expect would cause short- or long-term health impacts.
The study found that the risk of negative short-term health impacts could occur at all distances modeled in the study (from 300 feet to 2,000 feet).	The study does not show the risk of negative short-term health impacts at distances greater than 2,000 feet, but does not rule out the possibility of health impacts at greater distances.
The study looks at potential exposure to chemicals directly attributable to oil and gas operations. It estimates exposure to 47 volatile organic compounds during the different phases of oil and gas development and production. The study found the risk of short-term health impacts were largely from exposure to benzene, toluene, and ethyltoluenes.	The study does not consider exposure to other chemicals potentially released from oil and gas operations and/or other activities. It also does not account for natural exposure or "background exposure" to these chemicals-- nor does it account for other factors that might influence public health like particulate matter (e.g., exhaust, dust, pollen, etc.), indoor air pollution, occupational exposures, or noise.
The study does not determine any elevated risk of chronic health impacts from any single substance at 500 feet or greater. The study shows slightly elevated risk of blood and nervous system effects from multiple chemicals at 500 ft but not at 2000 ft. Cancer risk under all exposures was within the Environmental Protection Agency's acceptable risk range.	The study does not rule out the possibility of chronic health impacts, because it does not comprehensively measure chronic exposures representative of what happens in areas with multiple well pads. It does not consider other potential impacts on human health.
The study largely uses data that was released to the public by CSU in 2016. It is mostly based on data collected after 2014, when stricter state methane and VOC regulations went into effect. Some of the data collected from Garfield County is from before 2014, when less strict policies were in effect.	The study does not contain new data and may not reflect the most current controls and technology used at pre-production sites today.
The study only speaks to the risk of health impacts from being near one well pad.	The study does not speak to the health impacts of being near multiple well pads.
This study adds to the body of knowledge we have on oil and gas development and its potential health impacts.	The study does not definitively dictate a setback that is protective of public health, but it can help inform policy decisions.

Concerned Health Professionals of NY

PSR Physicians for Social Responsibility

Science & Environmental Health Network

Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking and Associated Gas and Oil Infrastructure

Eighth Edition

April 2022

Photo ©Ted Auch, FracTracker Alliance, 2021

The Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking (the Compendium) is a fully referenced compilation of evidence outlining the risks and harms of fracking. It is a public, open-access document that is housed on the websites of Concerned Health Professionals of New York (www.concernedhealthny.org) and Physicians for Social Responsibility (www.psr.org).

The seven earlier editions of the Compendium have been used and referenced all over the world. The Compendium has been twice translated into Spanish: independently in 2014 by a Madrid-based environmental coalition, followed by an official translation of the third edition, funded by the Heinrich Böll Foundation and subsequently updated in December 2019 with new data from the sixth edition. The Compendium has been used in the European Union, South Africa, the United Kingdom, Australia, Mexico, and Argentina.

About Concerned Health Professionals of New York and the Science and Environmental Health Network

Concerned Health Professionals of New York (CHPNY) is an initiative by health professionals, scientists, and medical organizations for raising science-based concerns about the impacts of fracking on public health and safety. CHPNY provides educational resources and works to ensure that careful consideration of science and health impacts are at the forefront of the fracking debate. In June 2021, the Ceres Trust granted funding for CHPNY to become a program of the Science and Environmental Health Network (SEHN). Since 1998, SEHN has been the leading proponent in the United States of the Precautionary Principle as a basis for environmental and public health policy. In service to communities and future generations, the Science and Environmental Health Network is a research institution that forges law, ethics, and science into tools for action.

About Physicians for Social Responsibility

Working for more than 50 years to create a healthy, just, and peaceful world for both present and future generations, Physicians for Social Responsibility (PSR) uses medical and public health expertise to educate and advocate on urgent issues that threaten human health and survival, with the goals of reversing the trajectory towards climate change, protecting the public and the environment from toxic chemicals, and addressing the health consequences of fossil fuels. PSR was founded by physicians concerned about nuclear weapons, and the abolition of nuclear weapons remains central to its mission.

Contents

FRONT MATTER

COMPILATION OF STUDIES AND FINDINGS

About this Report

The Compendium exists within a moving stream of data. As we prepared this eighth edition, the authors of the Compendium continued to see evidence of the rapid expansion of our knowledge base, which has grown both quantitatively and qualitatively and enables some fairly solid conclusions that, even a few years ago, were emerging concerns. **The risks and harms of fracking for public health and the climate are real and growing.** Many early warnings in our previous editions have been borne out. Further, despite the continuing challenges of exposure assessments, the results of recent studies confirm and extend the validity of earlier findings. We see a growing consistency of evidence across various themes.

Organizational structure

To organize this now-vast body of research and make it accessible to public officials, researchers, journalists, and the public at large, we have created both topical categories and have identified trends within and across these topic areas. The reader who wants to delve deeper can consult the reviews, studies, and articles referenced herein. In addition, the Compendium is complemented by a fully searchable, near-exhaustive citation database of peer-reviewed journal articles pertaining to shale gas and oil extraction, the Repository for Oil and Gas Energy Research, that was developed by PSE Healthy Energy and is housed on its website (https://www.psehealthyenergy.org/our-work/shale-gas-research-library/). As of January 1, 2022, **2,239 published peer-reviewed studies** that pertain to shale and tight gas development were archived in the ROGER database.

In our cataloguing of the findings, sixteen topical categories emerged, and these serve as the chapter titles of the Compendium. Readers will notice the ongoing upsurge in reported problems, making each section top-heavy with recent data. In accordance, the Compendium is organized in reverse chronological order within sections, with the most recent information first. Introducing this compilation of studies is a section of our report called **Emerging Trends,** which identifies strong patterns within and across these topic areas. **Current Political, Cultural, and Economic Contexts** explores the profound crisis that characterizes the fracking industry in 2022.

The Compendium focuses on topics most closely related to the public health and safety impacts of drilling and fracking. These necessarily include threats to climate stability. By 2018 there was extensive documentation of harm. **A categorical review of all original research papers published from 2016-2018 on the health impacts of fracking showed that 90.3 percent of studies found a positive association with harm or potential harm.**[1]

Additional risks and harms arise from industrial activities associated with drilling and fracking operations. A detailed accounting of all these ancillary impacts is beyond the scope of this

[1] Kyle Ferrar, Erica Jackson, and Samantha Malone, "Categorical Review of Health Reports on Unconventional Oil and Gas Development; Impacts in Pennsylvania," Issue Paper (FracTracker Alliance, 2019), https://www.delawareriverkeeper.org/sites/default/files/FracTrackerAlliance_DRKHealthReview_Final_4.25.19_0.pdf.

document. Nevertheless, in this edition we include discussions of impacts from fracking infrastructure that focus on

- compressor stations and pipelines;
- silica sand mining operations;
- natural gas storage facilities;
- the manufacture and transportation of liquefied natural gas (LNG);
- natural gas power plants;
- fracking waste disposal; and
- carbon capture and storage and the creation of “blue hydrogen.”

(Note that threats from flare stacks are included in the section on air pollution.)

Many other relevant concerns—including the use of fracked gas as a feedstock in petrochemical manufacturing—are not included here. We hope to take up these issues in future editions.

Similarly, this edition of the Compendium does not examine the harms and risks posed by other forms of unconventional oil and gas extraction, such as cyclic steaming (which uses pressurized, superheated water to release oil), microwave extraction (which points microwave beams into shale formations to liquefy oil), and artificial lift (which uses gases, chemicals, or pumps to extract natural gas).

Methodology

For this eighth edition of the Compendium, as before, we collected and compiled findings from three sources: articles from peer-reviewed medical and scientific journals; investigative reports by journalists; and reports from, or commissioned by, government agencies. Peer-reviewed articles were identified through databases such as PubMed and Web of Science and from within the ROGER database. We included review articles when such reviews revealed new understanding of the evidence. We excluded papers that focused purely on methodologies or instrumentation. News articles appearing as individual entries signify reports that contain original research. In many cases, this reportage is based on data collected by industry or government agencies that were revealed by investigative journalists and not otherwise known to the scientific community. While advocacy organizations continue to compile many useful reports on the impacts of fracking and its ancillary infrastructure, these appear in our Compendium only when they provide otherwise inaccessible data.

For purposes of this Compendium, we use the word “fracking” to refer to a collective suite of unconventional oil and gas production methods that depend on hydraulic fracturing to extract dispersed oil or natural gas trapped inside rock layers that would otherwise not flow to the surface. In other words, “fracking” encompasses a range of activities and ancillary infrastructure both before and after the actual fracturing stage, including drilling, flowback, and well completion.

Our entries briefly describe studies that investigated harm, or risk of harm, associated with fracking, and summarize the principal findings. Entries do not include detailed results or a critique of the strengths and weaknesses of each study. Because much of medicine's early understanding of new diseases and previously unsuspected epidemiological correlations comes through assessment of case reports, we have included published case reports and anecdotal reports when they are data-based and verifiable.

The scientific papers referenced in the dated entries and catalogued within the Compilation of Studies & Findings are current through July 15, 2021. The footnoted citations here in the front matter represent studies and articles that are not referenced in the Compendium itself or which appeared after July 15, 2021 but before we went to press in April 2022.

Within the compiled entries, we have also provided references to articles appearing in the popular press, when available, that describe the results of the corresponding peer-reviewed study and place them in context with the results of other studies. For this purpose, we sought out articles that included comments by principal investigators on the significance of their findings. In such cases, footnotes for the peer-reviewed study and the matching popular article appear together in one entry. We hope these tandem references will make the findings more accessible and meaningful to readers.

Acronyms are spelled out the first time they appear in each section.

For some sources, cross-referenced footnotes are provided, as when wide-ranging government reports or peer-reviewed papers straddled two or more topics.

Citation style

For this eighth edition, readers will find changes to our citation style. Footnotes now appear in Chicago Manual of Style 17th edition (full note) format. Further, between the release of the previous edition and this one, a change of ownership at the news organization *E&E News*, from which we have drawn many important reports, placed some previously open-access stories behind a pay wall. In such cases, and when available, we have provided footnotes that direct readers to URLs drawn from the Internet Archive, a 501(c)(3) non-profit organization that maintains open access to many documents by "building a digital library of Internet sites and other cultural artifacts in digital form."

Please note that the date of a Compendium entry sometimes represents the first online appearance of an advance copy or a pre-publication version of the paper, whereas the date in the footnote citation always refers to the formal publication date. Thus, entry dates are not always identical to dates in corresponding footnotes.

The Compendium as a living document

Given the rapidly expanding body of evidence related to the harms and risks of unconventional oil and gas extraction, we plan to continue revising and updating the Compendium approximately every year. It is a living document, housed on the websites of Concerned Health

Professionals of New York and Physicians for Social Responsibility, which serves as an educational tool in important ongoing public and policy dialogues.

We welcome your feedback and comments.

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Summary of Findings

As of 2022, hydraulic fracturing techniques have been used on an estimated one million wells across the United States to shatter rock layers and extract the oil or gas trapped inside. With hydraulically fractured shale wells now producing at least 79 percent of U.S. natural gas and 65 percent of U.S. crude oil, fracking, no longer "unconventional," has become the standard method for oil and gas extraction. As fracking operations in the United States and abroad have increased in frequency, size, and intensity, a significant body of evidence has emerged to demonstrate that these activities are harmful in ways that cannot be mitigated through regulation. Threats include detrimental impacts on public health, climate stability, water and air quality, farming, property values, economic vitality, and quality of life.

Emerging science also shows that fracking is an environmental injustice, with injuries not borne equally by all. Throughout the United States, pregnant women, children, Indigenous people, communities of color, and low-income communities are disproportionately harmed by fracking.

A growing and substantial body of research reveals fundamental problems with the entire life cycle of operations associated with fracking and its infrastructure. Independent, peer-reviewed analyses indicate that fracking is an unpredictable process with innate engineering problems that include uncontrolled fracturing, induced earthquakes, and well casing failures that worsen with age. Intractable problems also include radiation releases; abandoned wells that serve as pathways for contamination; and venting, flaring, and blowdowns that result in methane releases.

As documented in more than 100 studies, toxic air pollution accompanies fracking. More than 200 airborne chemical contaminants have been detected near drilling and fracking operations, and air monitoring has confirmed strikingly high levels of toxic air pollutants in communities near these sites. Of these, 61 are classified as hazardous air pollutants with known health risks, including the potent carcinogens benzene and formaldehyde. Additional fracking-related air pollutants include diesel exhaust, fine particles, hydrogen sulfide gas, nitrogen oxides, and other chemical precursors of ground-level ozone (smog), which can damage respiratory, cardiovascular, and nervous systems. In many cases, concentrations of fracking-related air pollutants in communities where people live and work exceed federal safety standards, with ground-level ozone reaching levels typical of urban centers in otherwise rural communities. Research shows that air emissions from fracking and flaring can drift and pollute the air hundreds of miles downwind.

Each day in the United States, more than two billion gallons of pressurized fracking fluids are pumped underground for the purpose of extracting oil and gas or, after the fracking is finished, to inject the extracted wastewater into any of more than 187,000 disposal wells across the country. As documented by more than 180 studies, these fracking-related activities have depleted or contaminated water resources, including drinking water sources. Studies from across the United States provide irrefutable evidence that groundwater contamination has occurred as a result of fracking activities and is more likely to occur close to well pads. Spills and intentional discharges into surface water have profoundly altered the chemistry and ecology of streams throughout entire watersheds, increasing downstream levels of radioactive elements, heavy metals, endocrine disruptors, toxic disinfection byproducts, and acidity, and decreasing aquatic biodiversity. Demand for water to use in U.S. fracking operations has more than doubled since 2016. The water used for fracking that remains in the shale formation is permanently lost to the hydrological cycle. Studies also show that fracking can deplete streams and aquifers in ways that create water scarcity in drought-prone regions. Along with fracking itself, the injection of fracking waste is a proven cause of earthquakes. The disposal of fracking wastewater remains a problem with no solution.

With more than 17.6 million U.S. residents living within one mile of at least one active oil and gas well, the result is a public health and climate crisis. As documented in more than 100 studies, public health harms now linked with drilling, fracking, and associated infrastructure are well-established. They include cancers, asthma, respiratory diseases, skin rashes, heart problems, and mental health problems. Multiple corroborating studies of pregnant women residing near fracking operations across the nation show impairments to infant health, including birth defects, preterm birth, and low birth weight. Emerging evidence shows harm to maternal health—including elevated risks for eclampsia during pregnancy—and shortened lifespans among older residents living in proximity to oil and gas wells.

Fracking is accelerating the climate crisis. North American fracking operations for both oil and gas are driving the current surge in global levels of methane, a greenhouse gas 86 times more potent at trapping heat than carbon dioxide over a twenty-year period and which has contributed 40 percent of all global warming to date. Methane escapes into the atmosphere from all parts of the extraction, processing, and distribution system, at significant rates that, as demonstrated through multiple methodologies, sometimes exceed earlier estimates by a factor of two to six. Recent scientific findings indicate that slashing methane emissions is far more critical in halting global warming than previously understood. Liquefying natural gas via super-chilling to allow its overseas transport as LNG requires immense energy and evaporative cooling technology, both of which add further to the prodigious greenhouse gas emissions of natural gas obtained via fracking.

Carbon capture and storage, now being promoted as a tool to address climate change, is an unproven set of technologies that does not account for methane emissions, cannot obviate the climate damage created by fracking, and, as currently practiced, mostly serves as a tool of enhanced oil recovery that allows depleted wells to produce more oil.

In sum, the vast body of scientific studies now published on hydraulic fracturing in the peer-reviewed scientific literature confirms that the climate and public health risks from fracking are real and the range of environmental harms wide. **Our examination uncovered no evidence that fracking can be practiced in a manner that does not threaten human health directly or without imperiling climate stability upon which human health depends.**

The rapidly expanding body of evidence compiled here is massive, troubling, and cries out for decisive action. Across a wide range of parameters, the data continue to reveal a plethora of recurring problems that cannot be sufficiently averted through regulatory frameworks. The risks and harms of fracking are inherent in its operation. The only method of mitigating its grave threats to public health and the climate is a complete and comprehensive ban on fracking. Indeed, a fracking phase-out is a requirement of any meaningful plan to prevent catastrophic climate change.

The Compendium in Historical Context

2014: New York State fracking ban

The release of the first edition of the Compendium by Concerned Health Professionals of New York in July 2014 coincided with a meteoric rise in the publication of new scientific studies about the risks and harms of fracking. A second edition was released five months later, in December 2014, and included new studies that further explicated recurrent problems.

Almost concurrently, on December 17, 2014, the New York State Department of Health (NYS DOH) released its own review of the public health impacts of fracking. (See footnote 1062.) That document served as the foundation for a statewide ban on high-volume hydraulic fracturing (HVHF), announced by New York Governor Andrew Cuomo on the same day. Its conclusions—

> [I]t is clear from the existing literature and experience that HVHF activity has resulted in environmental impacts that are potentially adverse to public health. Until the science provides sufficient information to determine the level of risk to public health from HVHF and whether the risks can be adequately managed, HVHF should not proceed in New York State.

The New York State Department of Environmental Conservation's final environmental impact statement and attendant Findings Statement incorporated the earlier health review into a larger analysis of the impacts of fracking. (See footnote 796.) The Findings Statement made clear that no known regulatory framework can adequately mitigate the multiple risks of fracking:

> Even with the implementation of an extensive suite of mitigation measures…the significant adverse public health and environmental impacts from allowing high-volume hydraulic fracturing to proceed under any scenario cannot be adequately avoided or minimized to the maximum extent practicable….

2015-2016: Paris Climate Agreement

The third edition of the Compendium, released in October 2015, included the results of the first substantive government reports on the impacts of fracking.

In December 2015, the third edition became the basis of invited testimony at conferences taking place concurrently with the United Nations' climate talks in Paris. Those international negotiations resulted in an historical international accord, the Paris Agreement, which recognizes climate change as a grave threat to public health and establishes as a key goal the need to limit global temperature increases to < 2^{o} Celsius, or, ideally, 1.5^{o} C, above pre-industrial times. As such, the treaty articulates a vision for energy by compelling nations to monitor their greenhouse gas emissions and set increasingly ambitious targets and timetables to reduce them.

The Compendium's fourth edition was released in November 2016, just as the Paris Agreement went into force and as several new studies conclusively demonstrated that expansion of shale gas and oil extraction was incompatible with climate stability and the goal of rapid decarbonization that it requires. All together, these data show that because of increasing emissions of methane—a powerful heat-trapping gas—the United States was on track to miss its pledge under the Paris Agreement to reduce greenhouse gas emissions 26-28 percent by 2025. (See footnotes 1573, 1574.) The evidence showed that methane leaks from U.S. oil and gas operations were significantly higher than previously estimated, as were U.S. methane emissions overall. (See footnotes 1575-1577, 1583, 1594, 1595.)

2017-2020: Environmental retrenchment and COVID-19 pandemic

The fifth, sixth, and seventh editions (released in March 2018, June 2019, and December 2020 respectively) were all launched in a time of deep environmental retrenchment by the federal government. The Trump administration had announced an era of "energy dominance" based on surging domestic production of oil and natural gas, most of it extracted via fracking. The White House declared its intent to withdraw from the Paris Agreement—and did so—even as the American Meteorological Society released a major report that identified climate change as a contributor to several recent extreme weather events and even as the Fourth National Climate Assessment—a quadrennial report compiled by 13 federal agencies—confirmed human activities as the dominant cause for ongoing global warming.[2, 3]

Among the more than 100 federal environmental regulations rescinded during this period were many that governed drilling and fracking operations. These included rules requiring companies drilling on public and tribal lands to reduce methane leaks and cut back on flaring and venting, a system for oil and gas facilities to report methane leaks, a rule mandating disclosure of chemicals in fracking fluid on public lands, and tighter standards for wastewater disposal.[4, 5]

By September 2018, the United States had become the world's leading oil and gas producer, surpassing both Russia and Saudi Arabia.[6] Much of that growth was driven by fracking operations in the Permian Basin of West Texas and eastern New Mexico as the Permian became the leading source of U.S. crude oil exports.[7] By 2019, aggressive attacks on regulatory oversight

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[2] Stephanie C. Herring et al., eds., "Explaining Extreme Events of 2016 from a Climate Perspective," *Bulletin of the American Meteorological Society* 99, no. 1 (2018): S1–57, https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2016.1.
[3] "Climate Science Special Report: Fourth National Climate Assessment, Volume 1" (U.S. Global Change Research Program, 2017), https://www.globalchange.gov/browse/reports/climate-science-special-report-fourth-national-climate-assessment-nca4-volume-i.
[4] Harvard University Environmental Law Program, "Environmental Regulation Rollback Tracker," 2019, http://environment.law.harvard.edu/policy-initiative/regulatory-rollback-tracker/.
[5] Chris Mooney, "To Round out a Year of Rollbacks, the Trump Administration Just Repealed Key Regulations on Fracking," *The Washington Post*, December 29, 2017, sec. Climate and environment, https://www.washingtonpost.com/news/energy-environment/wp/2017/12/29/to-round-out-a-year-of-rollbacks-the-trump-administration-just-repealed-key-regulations-on-fracking/?utm_term=.f16b4db99128.
[6] mU.S. Energy Information Administration, "The United States Is Now the Largest Global Crude Oil Producer," Today in Energy, September 12, 2018, https://www.eia.gov/todayinenergy/detail.php?id=37053.
[7] Kiah Collier, Jamie Smith Hopkins, and Rachel Leven, "As Oil and Gas Exports Surge, West Texas Becomes the World's 'Extraction Colony,'" *The Texas Tribune*, October 11, 2018, https://www.texastribune.org/2018/10/11/west-texas-becomes-worlds-extraction-colony-oil-gas-exports-surge/.

of U.S. oil and gas extraction had extended to the science underlying the targeted regulations.[8, 9] Unimpeded by federal regulations and driven by fracking, U.S. oil and gas production reached record levels and spurred a massive build-out of fracking infrastructure, leading to large-scale industrialization in formerly rural areas and densely populated communities alike. The Federal Energy Regulatory Commission (FERC) eased the process to build new pipelines while executive orders impeded the ability of states to block pipeline construction.[10, 11] Throughout 2018 and 2019, in the face of flattening domestic demand for gas and falling prices in a closed market, the ongoing fracking boom was increasingly directed at export markets, which prompted the planning of 15 new LNG terminals, beyond the six then in operation.[12, 13, 14]

In 2020, the COVID-19 pandemic slashed global oil demand and sent oil prices to historical lows. The price of oil dropped by two-thirds, a plunge that even briefly sent the price of crude oil to negative $40 a barrel. Natural gas prices also declined in 2020, driven down both by warmer winters and overproduction.[15] In both the gas and oil sectors, the pandemic accelerated job lay-offs that automation had begun. In August 2020, Exxon's market value had sunk to just a third of its 2008 value, and the once-mighty fossil fuel giant dropped off the Dow Jones industrial average.[16] By October 2020, Deloitte had announced that the return on invested capital of oil and gas companies was largely on par with top renewable energy companies, and the International Energy Agency (IEA) reported that the worth of major oil and gas companies had fallen by more than $50 billion, with investment in oil and gas falling by one-third.[17, 18] (An autonomous intergovernmental organization formed in the aftermath of the 1973 oil crisis, the IEA is a clearinghouse of statistical information on the international oil market, as well as on clean energy technologies, and serves as the world's leading energy modeling agency.)

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8 Jonathan Stempel, "U.S. EPA Is Sued for Ousting Scientists from Advisory Committees," Reuters, June 3, 2019, https://www.reuters.com/article/us-epa-lawsuit/us-epa-is-sued-for-ousting-scientists-from-advisory-committees-idUSKCN1T42H8.

9 Coral Davenport, "Trump Administration Hardens Its Attack on Climate Science," *The New York Times*, May 27, 2019, sec. Climate and environment, https://www.nytimes.com/2019/05/27/us/politics/trump-climate-science.html.

10 Rachel Leven, "Drilling Overwhelms Agency Protecting America's Lands," Associated Press, November 13, 2018, https://www.apnews.com/dac08562077c41a8a08845a291cbfb6c.

11 Nicholas Kusnetz, "Trump Aims to Speed Pipeline Projects by Limiting State Environmental Reviews," Inside Climate News, April 11, 2019, https://insideclimatenews.org/news/11042019/trump-pipeline-executive-order-environmental-review-keystone-xl-clean-water-act-states-rights.

12 Darrell Proctor, "Plenty of Natural Gas Around-It Just Needs a Market," *Power Magazine*, April 1, 2019, https://powermag.com/plenty-of-natural-gas-to-go-around-it-just-needs-a-market/.

13 European Commission, "EU-U.S. Joint Statement: Liquefied Natural Gas (LNG) Imports from the U.S. Continue to Rise, up by 181%," press release, March 8, 2018, http://europa.eu/rapid/press-release_IP-19-1531_en.htm.

14 U.S. Department of Energy, "Department of Energy Authorizes Additional LNG Exports from Freeport LNG," Press Release, May 29, 2019, https://www.energy.gov/articles/department-energy-authorizes-additional-lng-exports-freeport-lng.

15 Zak Hudak, "COVID Compounds Pennsylvania's Fracking Industry Problems," CBS News, August 7, 2020, https://www.cbsnews.com/news/covid-compounds-pennsylvanias-fracking-industry-problems/.

16 Dino Grandoni, "Big Oil Just Isn't as Big as It Once Was," *The Washington Post*, September 4, 2020, sec. Business, https://www.washingtonpost.com/business/2020/09/04/exxon-dow-jones/.

17 Duane Dickson, Tom Bonny, and Noemie Tilghman, "The Future of Work in Oil, Gas and Chemicals," Deloitte Insights, October 5, 2020, https://www2.deloitte.com/global/en/insights/industry/oil-and-gas/future-of-work-oil-and-gas-chemicals.html.

18 International Energy Agency, "World Energy Outlook 2020," October 2020, https://www.iea.org/reports/world-energy-outlook-2020#.

Current Political, Cultural, and Economic Contexts

Profound disruption and crisis characterize the fracking industry in 2022, with contradictory and opposing forces pushing and pulling the industry in several directions at once.

On the surface, as we go to press with the eighth edition, the U.S. fracking industry appears ascendent. U.S. oil and gas drillers are working at "breakneck pace," with companies currently using almost all available fracking equipment and crews and expected to expand spending by more than 25 percent in 2022.[19] Much of this activity is being driven by a booming export market. As we write, Europe faces a full-on energy crisis following Russia's invasion of Ukraine, which began on February 24, 2022 and is ongoing. With the European Union presently relying on Russia for about 45 percent of its natural gas imports, the war has prompted an urgent and overdue assessment of this relationship. In early March 2022, the International Energy Agency (IEA) released "A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas,"[20] and the European Commission followed with its plan, REPowerEU, the following week.[21] The Commission's plan aims to phase out dependence on fossil fuels from Russia "well before 2030," beginning with natural gas.

In the short term, this means diversifying supplies from elsewhere and relying more heavily on gas from the United States, which would arrive as LNG via ship to existing but also new and proposed terminals. The EU's plan also accelerates the adoption of renewable energy technologies and building upgrades to reduce consumption. In these ways, REPowerEU aims to reduce two-thirds of EU demand for Russian gas before the end of 2022. On March 8, 2022 the United States banned the import of Russian fossil fuels, by executive order of the President.[22] On March 25, President Biden pledged to supply Europe with 15 billion cubic meters (bcm) of LNG in 2022, ramping up to 50 bcms annually until 2030.[23]

Even before the EU's war-prompted pivot toward increased reliance on U.S. gas, the swelling global demand had allowed the United States to surpass Australia and Qatar as the world's biggest exporter of LNG. Indeed, by January 2022, U.S. LNG exports into the European Union had grown 22 times larger since the July 2018 meeting of U.S. and EU Commission Presidents to

[19] David Wethe, "Oil Explorers Are Fracking at Breakneck Pace, Fueling Inflation," Transport Topics, January 24, 2022, https://www.ttnews.com/articles/oil-explorers-are-fracking-breakneck-pace-fueling-inflation.
[20] "A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas" (International Energy Agency, March 2022), https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-russian-natural-gas.
[21] "REPowerEU: Joint European Action for More Affordable, Secure and Sustainable Energy" (European Commission, March 8, 2022), https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511.
[22] The White House, "FACT SHEET: United States Bans Imports of Russian Oil, Liquefied Natural Gas, and Coal" (United States Government, March 8, 2022), https://www.whitehouse.gov/briefing-room/statements-releases/2022/03/08/fact-sheet-united-states-bans-imports-of-russian-oil-liquefied-natural-gas-and-coal/.
[23] The White House, "FACT SHEET: United States and European Commission Announce Task Force to Reduce Europe's Dependence on Russian Fossil Fuels," March 25, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/03/25/fact-sheet-united-states-and-european-commission-announce-task-force-to-reduce-europes-dependence-on-russian-fossil-fuels/.

diffuse a trade war.[24] The supply for these exports is largely being met by U.S. fracking operations, especially in the Permian Basin.[25] On February 12, 2022, the flow of gas to the nation's LNG export terminals had reached record highs, with more than two-thirds of the cargo ships heading to Europe, and, during the first two months of 2022, the total number of U.S. LNG cargoes bound for Europe and Turkey reached a record of 164.[26] Venture Global LNG's Calcasieu Pass facility in Louisiana was given approval by the Federal Energy Regulatory Commission (FERC) to begin exports even though it remains under construction.[27] Early construction work has begun on another.[28]

In March 2022, under industry pressure and amid a push to increase natural gas exports, FERC retreated from a sweeping new policy plan to consider climate and environmental justice impacts in its decision-making on interstate pipeline approvals. This plan, agreed upon only one month earlier in a 3 to 2 vote, would have addressed upstream greenhouse gas emissions from a project's construction and operations as well as emissions from eventual combustion.[29, 30] It has now been declared a draft and its implementation deferred indefinitely.[31]

However, behind fracking's apparent momentum, a multiplicity of contradictory forces is roiling the oil and gas industry. These make fracking's long-term prospects more uncertain than its current rebound seems to presage.

At least six interlocking factors now impede or are poised to disrupt the North American fracking boom:

The surging export market has made renewable energy more attractive

The first factor working against long-term viability of the fracking industry is the surging export market itself**.** The U.S. LNG industry exists to ship natural gas abroad and currently consists of six fully operational terminals, one partially operational plant, and one that is expected to be functional by 2025. With more than ten percent of the nation's natural gas production now

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[24] European Commission, "EU-U.S. LNG Trade: U.S. Liquefied Natural Gas Has the Potential to Help Meet EU Gas Needs," January 8, 2020, https://ec.europa.eu/energy/sites/ener/files/eu-us_lng_trade_folder.pdf.
[25] Stanley Reed, "Natural Gas Shipments, Mostly from U.S., Ease Europe's Energy Crunch," *New York Times*, February 3, 2022, https://www.nytimes.com/2022/02/03/business/natural-gas-europe-us.html.
[26] Marwa Rashad, "U.S. LNG Exporters Emerge as Big Winners of Europe Natgas Crisis," Reuters, March 9, 2022, https://www.reuters.com/business/energy/us-lng-exporters-emerge-big-winners-europe-natgas-crisis-2022-03-09/.
[27] Sergio Chapa, "U.S. Is Exporting Every Molecule of LNG Possible," Yahoo Finance, February 12, 2022, https://ca.finance.yahoo.com/news/full-house-u-exporting-every-202646852.html.
[28] Mark Passwaters, "Calcasieu Pass LNG Block 2 Gets Ferc Approval," Upstream, December 13, 2021, https://www.upstreamonline.com/lng/calcasieu-pass-lng-block-2-gets-ferc-approval/2-1-1122384.
[29] Niina H. Farah, Miranda Willson, and Carlos Anchondo, "How FERC, Courts May Change Pipeline Industry in 2022," *E&E News*, January 20, 2022, https://www.eenews.net/articles/how-ferc-courts-may-change-pipeline-industry-in-2022/.
[30] Rachel Frazin, "Gas Pipeline Regulators to Consider Climate Impacts for New Projects," *The Hill*, February 17, 2022, https://thehill.com/policy/energy-environment/594832-gas-pipeline-regulators-to-consider-climate-impacts-for-new.
[31] Matthew Daly, "US Pipeline Agency Pulls Back Plan to Assess Climate Impacts," AP, March 24, 2022, https://apnews.com/article/russia-ukraine-climate-business-mitch-mcconnell-joe-manchin-c47b9fa92f95376a597b5c87435a9a70.

headed overseas where prices are higher, domestic gas prices within the United States have spiked in turn, making renewable energy resources more attractive.[32, 33] Further growth in the export market will only exacerbate this trend. Gas consumption for electric power generation in the United States peaked in the summer of 2020 and is likely now in an irreversible decline.[34]

At the same time, further investments in fracking are at odds with trends in the economics of renewable energy. Continuing innovation, increasing economies of scale, and rapid declines in the cost of wind, solar, and battery storage prices have made renewable energy a cheaper alternative than coal and gas for most major economies. A 2022 modeling analysis shows that a 100-percent renewable energy system in the United States would reduce electricity costs, serve as a hedge on inflation, and eliminate an estimated 53,200 deaths each year—along with $700 billion in health costs—from fossil-fuel associated air pollution.[35] Meanwhile, as oil and gas companies chase reserves that are increasingly difficult to extract, the costs of producing oil and gas are rising.

Fracking contradicts climate change commitments

Secondly, U.S. fracking and its protracted deregulation are at odds with the scientific consensus on the scale and tempo of necessary climate change mitigation and with rising alarm about the climate crisis that this consensus has amplified.[36, 37, 38, 39] In a trilogy of major reports released in 2021 and 2021 and affirmed by other international teams of scientists, the United Nations Intergovernmental Panel on Climate Change (IPCC) emphasized that the world needs to reduce emissions by 45 percent by 2030 and reach net zero by 2050 to avoid the worst outcomes of the climate crisis and avoid wholesale collapse of ecosystems. In a major review of the findings of climate science released in August 2021, the IPCC's first report issued a "code red for humanity," starkly warning of irreversible changes to planetary support systems that are, in some

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32 U.S. Energy Information Administration, "U.S. Liquefied Natural Gas Exports Grew to Record Highs in the First Half of 2021," Today in Energy (U.S. Energy Information Administration, July 27, 2021), https://www.eia.gov/todayinenergy/detail.php?id=48876.

33 Justin Gerdes, "Opinion: LNG Exports Are Backfiring on the US Oil and Gas Industry," Energy Monitor, October 12, 2021, https://www.energymonitor.ai/analysis/opinion-lng-exports-are-backfiring-on-the-us-oil-and-gas-industry.

34 Seth Feaster and Dennis Wamstead, "IEEFA U.S.: Power Sector Gas Consumption Has Likely Hit Its Peak" (Institute for Energy Economics and Financial Analysis, February 16, 2022), https://ieefa.org/power-sector-gas-consumption-has-likely-hit-its-peak/.

35 Mark Z. Jacobson et al., "Zero Air Pollution and Zero Carbon from All Energy at Low Cost and without Blackouts in Variable Weather throughout the U.S. with 100% Wind-Water-Solar and Storage," *Renewable Energy* 184 (2022): 430–42, https://doi.org/10.1016/j.renene.2021.11.067.

36 V. Masson-Delmotte et al., "Global Warming of 1.5°C," An IPCC Special Report (The Intergovernmental Panel on Climate Change, 2018), https://www.ipcc.ch/sr15/.

37 Coral Davenport, "Major Climate Report Describes a Strong Risk of Crisis as Early as 2040," *The New York Times*, October 7, 2018, https://www.nytimes.com/2018/10/07/climate/ipcc-climate-report-2040.html.

38 E. Dinerstein et al., "A Global Deal for Nature: Guiding Principles, Milestones, and Targets," *Science Advances* 5, no. 4 (April 19, 2019): eaaw2869, https://doi.org/10.1126/sciadv.aaw2869.

39 United Nations Development Program, "Climate Action Summit: A Joint Appeal from the UN System to the Secretary-General's Climate Action Summit," May 10, 2019, https://www.undp.org/content/undp/en/home/news-centre/speeches/2019/climate-action-summit.html.

cases, have already begun.[40, 41] In February 2022, the IPCC released a second report that reviewed the ecological limits of the natural world together with the vulnerabilities and capacities of human societies to adapt to climate change. Noting that some irreversible ecological impacts are already underway, the report concluded that climate change has already pushed some natural and human systems beyond their ability to adapt, thereby harming public health, undermining global food security, and leaving 3.3 to 3.6 billion people living in contexts that are highly vulnerable.[42] In April 2022, the third IPCC report, focused on mitigation, made clear that the window to averting runaway, irreversible climate impact is rapidly closing. To prevent global warming from exceeding 1.5° C—after which severe harm will accelerate—rising emissions must end before 2025. In a stark warning to fossil fuel investors the IPCC made clear that that future fossil fuel assets will become stranded if governments act in accordance with the science.[43]

In 2021, the IEA released its roadmap for how net zero by 2050 could be reached. In it, the Agency made clear that the pathway to zero allows for no new fossil fuel production, and, indeed, that any further investments in fossil fuels—beyond what is already under contract—must cease. In this way, the IEA, departing from its past support of gas and oil development, has signaled its support for the conclusions of the IPCC and joined the global call to stop the expansion of fossil fuel extraction. (See footnote 2142.) To stay within a 1.5° C global warming scenario, methane emissions from fossil fuels must, according to the IEA, fall by around 75 percent between 2020 and 2030.[44]

Methane is a key driver of climate change and fracking is a key driver of methane

Third and more specifically, methane is now recognized as a chief agent of climate change as more accurate methods for calculating emissions inventories reveal that runaway methane emissions are negating recent declines in carbon dioxide emissions and undermining efforts to stabilize the climate. For example, in New York State, a study using more comprehensive inventory approaches found that, as increased consumption of natural gas has replaced coal from 1995 to 2015, total greenhouse gas emissions did not fall but remained largely unchanged.[45] In a conclusion echoed by the IEA, the United Nations Environment Programme (UNEP) made clear in its May 2021 Global Methane Assessment that any further expansion of natural gas

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[40] Intergovernmental Panel on Climate Change, "Climate Change 2021: The Physical Science Basis," Sixth Assessment Report, August 6, 2021, https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/.
[41] Matt McGrath, "Climate Change: IPCC Report Is 'Code Red for Humanity,'" *BBC News*, August 9, 2021, https://www.bbc.com/news/science-environment-58130705.
[42] Intergovernmental Panel on Climate Change, "Climate Change 2022: Impacts, Adaptation and Vulnerability," Sixth Assessment Report, February 28, 2022, https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_FinalDraft_FullReport.pdf.
[43] Intergovernmental Panel on Climate Change, "Climate Change 2022: Mitigation of Climate Change," Sixth Assessment Report, April 4, 2022, https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf.
[44] International Energy Agency, "Tackling Methane Emissions from Fossil Fuel Operations Is Essential to Combat Near-Term Global Warming," IEA.org, October 7, 2021, https://www.iea.org/news/tackling-methane-emissions-from-fossil-fuel-operations-is-essential-to-combat-near-term-global-warming.
[45] Robert W. Howarth, "Methane Emissions from Fossil Fuels: Exploring Recent Changes in Greenhouse-Gas Reporting Requirements for the State of New York," *Journal of Integrative Environmental Sciences* 17, no. 3 (2020): 69–81, https://doi.org/10.1080/1943815X.2020.1789666.

infrastructure and usage is incompatible with limiting global warming to 1.5°C. (See footnote 1473.) As part of the Global Methane Pledge, launched in November 2021 at COP26 climate summit in Glasgow, Scotland, more than 100 countries pledged to cut global methane emissions by 30 percent by 2030 from 2020 levels.[46] (China, Russia, India and Iran—all leading methane emitters—were not among the pact's signatories.) After briefing leveling off between 2000 and 2006, atmospheric methane levels have been surging upward ever since. In April 2022, the National Oceanic and Atmospheric Administration announced that methane rose more than any other year on record in 2021, including 2020, which was also a record-breaking year.[47]

The growing awareness that cutting methane from fossil fuels is a strong and necessary lever to slow climate change over the next two decades has roiled conversations within both the United States and the European Union about commitments to move forward with cross-border natural gas projects—including fracked gas imports from the United States.[48] The European Union imported more than 83 percent of its gas supply in 2020.[49] Of the gas imported as liquefied fuel, the United States became Europe's number one supplier in 2020. Prior to the Russian invasion of Ukraine, the European Union was in the process of negotiating standards to codify its commitment to reducing upstream methane emissions from imported gas used in its domestic energy sector.[50, 51, 52] In November 2020, a German trading firm, citing lack of interest from buyers, announced that it was reevaluating its plans to build a new LNG import terminal in Wilhelmshaven.[53] By January 2022, all three of Germany's proposed LNG import terminals—which would be serviced by fracked gas imported from the United States—were facing delays as both wild price swings and ongoing uncertainty about the future of fossil fuels in general had spooked potential clients.[54]

Immediately after Russia's invasion of Ukraine in February 2022, languishing efforts to boost LNG imports from the United States to the EU were revived. Discussions around proposed

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[46] Kate Abnett et al., "More than 100 Countries Join Pact to Slash Planet-Warming Methane Emissions," Reuters, November 2, 2021, https://www.reuters.com/world/middle-east/more-than-100-countries-join-pact-slash-planet-warming-methane-emissions-2021-11-02/.
[47] Raymond Zhong, "Methane Emissions Soared to a Record in 2021, Scientists Say," April 7, 2022, https://www.nytimes.com/2022/04/07/climate/methane-emissions-record.html.
[48] Stuart Elliott and Jonathan Fox, "EU Ombudsman Points to EC Climate Process Failures for PCI Gas Projects," S&P Global, November 19, 2020, https://www.spglobal.com/platts/ko/market-insights/latest-news/natural-gas/111920-eu-ombudsman-points-to-ec-climate-process-failures-for-pci-gas-projects.
[49] "Natural Gas Supply Statistics," Eurostat, October 2022, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_supply_statistics.
[50] Food & Water Europe, "Fracked Gas Imports Produced Europe's Fossil Fuel Crisis," January 31, 2022, https://www.foodandwatereurope.org/blogs/fracked-gas-imports-produced-europes-fossil-fuel-crisis/.
[51] Paul Bledsoe, "The Role of Natural Gas in Meeting Global Energy and Climate Change Goals" (Progressive Policy Institute, December 2021), https://www.progressivepolicy.org/wp-content/uploads/2021/12/The-Role-of-Natural-Gas-in-Meeting-Global-Energy-and-Climate-Change-Goals.pdf.
[52] Andy Gheorghiu, "Methane Pledges with No Cutting Edges? Is the EU Commission Ready to Walk the Talk on Tackling Crucial Overall Emissions?," Energy Transition, December 16, 2021, https://energytransition.org/2021/12/methane-pledges-with-no-cutting-edges-is-the-eu-commission-ready-to-walk-the-talk-on-tackling-crucial-overall-emissions/.
[53] "Uniper to Reconsider Plans for LNG Terminal in Germany," Hydrocarbons Technology, November 9, 2020, https://www.hydrocarbons-technology.com/news/uniper-to-reconsider-plans-for-lng-terminal-in-germany/.
[54] Vanessa Dezem and Anna Shiryaevskaya, "German Natural Gas Import Terminal Delayed by Market Volatility," BNN Bloomberg, January 13, 2022, https://www.bnnbloomberg.ca/german-natural-gas-import-terminal-delayed-by-market-volatility-1.1707015.

German LNG terminals, including the one at Wilhelmshaven, rose to the top of the agenda and include provisions of major public subsidies. In early March, for example, the German state bank KfW and a utility owned by the Dutch state entered, together with the German energy company RWE, a memorandum of understanding on one of the three proposed LNG import terminals in Germany.[55] The German state agreed to finance half of the construction costs for the terminal.

However, even with fast-track permitting procedures and even as government officials invoke the imperative to cease Russian gas imports as justification for pushing forward, none of Germany's proposed LNG terminals could be operational before 2024. Twenty-year supply contracts are necessary to finance their construction, and public concerns about the climate crisis are blunting enthusiasm for further investments in fracked gas infrastructure.[56] On March 11, the White House shelved an interagency review of ways to boost LNG imports to Europe with Reuters reporting that the expansion of the U.S. LNG trade has raised raising climate concerns among the President Biden's climate team.[57] An April 2022 analysis by the Institute for Energy Economics and Financial Analysis found that the United States can boost gas exports to Europe without building new LNG terminals beyond what is already under construction.[58]

At the same time, fracking within the European Union and the United Kingdom has largely fallen out of favor, with Northern Ireland the most recent economy preparing to ban fracking.[59] As part of two symbolic, non-binding resolutions on methane in June and October 2021, the EU Parliament urged its member states to halt existing fracking operations and stop permitting new ones. "On the basis of the precautionary principle and the principle that preventive action should be taken, and taking into account the risks and the negative climate, environmental and biodiversity impacts involved in hydraulic fracturing for the extraction of unconventional hydrocarbons – not to authorise any new hydraulic fracturing operations in the EU and to halt all existing operations."[60] And yet, more recently in the UK, orders to plug and decommission two pre-existing shale gas wells in Lancashire, which had been drilled prior to the 2019 national moratorium on fracking, were overturned in April 2022. The fracking of these two wells had triggered earthquakes, and the operator had been told to permanently seal the wells by June. The

[55] Nikolaus J. Kurmayer, "Germany Signs Initial Contract to Build First LNG Terminal," Euractiv.com, March 7, 2022, https://www.euractiv.com/section/energy/news/germany-signs-first-stage-contract-to-build-first-lng-terminal/.
[56] Jessica Bateman, "Plans for Construction of First German LNG Terminal Plagued by Delays and Uncertainty," Clean Energy Wire, February 14, 2022, https://www.cleanenergywire.org/news/plans-construction-first-german-lng-terminal-plagued-delays-and-uncertainty.
[57] Jarrett Renshaw and Timothy Gardner, "U.S. Push to Export LNG amid Ukraine Crisis Slowed by Climate Concerns, Sources Say," Reuters, March 11, 2022, https://www.reuters.com/business/energy/us-push-export-lng-amid-ukraine-conflict-slowed-by-climate-concerns-sources-2022-03-10/.
[58] Clark Williams-Derry, "The U.S. Can Increase LNG Exports to Europe" (Institute for Energy Economics and Financial Analysis, April 2022), https://ieefa.org/wp-content/uploads/2022/04/The-US-Can-Increase-LNG-Exports-to-Europe_April-2022.pdf.
[59] Shauna Corr, "Fracking Is Nearly Banned on the Island of Ireland," Buzz, February 16, 2022, https://www.buzz.ie/news/irish-news/fracking-nearly-banned-island-ireland-26204802.
[60] European Parliament, "An EU Strategy to Reduce Methane Emissions," Texts Adopted (Strasbourg, October 21, 2021), https://www.europarl.europa.eu/doceo/document/TA-9-2021-0436_EN.html.

current ruling delays plugging for another year, as lawmakers debate whether or not to lift the moratorium, in light of the imperative to break from Russian-supplied hydrocarbons.[61, 62]

These conversations are taking place against rapidly changing norms on the disclosure of climate risks within the financial sector. In August 2021, *S&P Global* reported that governments around the world have started to make climate-risk reporting mandatory instead of voluntary. Many policymakers have endorsed the framework of the Taskforce on Climate-related Financial Disclosures (TCFD) as a standardized disclosure framework. The financial sector has shown strong support for the TCFD, with the strongest support coming from Europe, Asia and North America.[63] By October 2021, the Institute for Energy Economics and Financial Analysis reported that "finance is leaving oil and gas," citing 66 globally significant financial institutions that have formally decided to restrict or terminate financial support for oil and gas drilling.[64] In March 2022, the Securities and Exchange Commission voted to issue draft rules that would require public companies to include climate-related disclosures for investors, including information about registrants' direct greenhouse gas emissions.[65]

Labor shortages persist

A fourth drag on the ability of the U.S. fracking industry to continue its expansion is a persistent labor shortage. Fracking crews and truck drivers, especially those that ferry the vast amounts of water and sand needed for fracking, are in short supply. Many employees and contractors relocated to other states and found other jobs during the industry contraction that followed the price crashes in 2020 and are wary of returning to jobs within a volatile industry that relies on mass lay-offs to control costs when commodity prices plunge and investment dollars dwindle.[66] According to North Dakota's mineral resources director, lack of skilled workers is the reason that oil production in the Bakken Shale remained flat in spring and summer 2021 in spite of higher oil prices. Similar trends were seen this year in the Texas Permian Basin and Canadian

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61 Helena Horton, Jessica Elgot, and Fiona Harvey, "PM Does Not Think It Makes Sense to Seal Shale Gas Wells, Minister Says," *The Guardian*, March 9, 2022, https://www.theguardian.com/environment/2022/mar/09/uk-fracking-position-not-changed-phase-out-russian-oil.

62 Rob Davies and Helena Horton, "Cuadrilla Allowed to Delay Closure of Lancashire Fracking Wells," *The Guardian*, March 31, 2022, https://www.theguardian.com/environment/2022/mar/31/cuadrilla-allowed-to-delay-closure-of-lancashire-fracking-wells?utm_campaign=Daily%20Briefing&utm_content=20220401&utm_medium=email&utm_source=Revue%20newsletter.

63 Gautam Naik, "Companies, Investors Face New Pressure from Compulsory Disclosure of Climate Risk," S&P Global, August 25, 2021, https://www.spglobal.com/esg/insights/companies-investors-face-new-pressure-from-compulsory-disclosure-of-climate-risk.

64 Institute for Energy Economics and Financial Analysis, "Finance Is Leaving Oil and Gas," IIEFA.org, October 1, 2021, https://ieefa.org/finance-exiting-oil-and-gas/.

65 U.S. Securities and Exchange Commission, "SEC Proposes Rules to Enhance and Standardize Climate-Related Disclosures for Investors," Press release, March 21, 2022, https://www.sec.gov/news/press-release/2022-46.

66 Collin Eaton, "U.S. Frackers Fear Vaccine Mandate Will Worsen Worker Crunch," *Wall Street Journal*, September 30, 2021, https://www.wsj.com/articles/u-s-frackers-fear-vaccine-mandate-will-worsen-worker-crunch-11632994201.

oilfields.[67, 68] A shortage of truck drivers to haul sand to well pads is hampering fracking operations throughout the Permian Basin.[69]

Corroborating these reports is a 2021 survey, commissioned by the oil and gas industry, of nearly 17,000 energy-industry recruiters, companies, and workers around the world. The survey found that applications per vacancy have remained low even as oil and gas extraction activities have ramped back up, with 43 percent of employees reporting a desire to leave the field altogether within the next five years, 56 percent of oil and gas workers reporting plans to pursue employment in the renewables sector, and 31 percent of recruiters identifying an aging, shrinking workforce as their biggest challenge.[70]

Drilling locations have become scarce

Depletion of drilling locations—what industry insiders call "limited inventory"—is a fifth impediment to further growth in the U.S. fracking industry. Companies are running out of new places to drill that do not interfere with the productivity of nearby pre-existing wells and are thus unable to respond to higher prices with higher rates of extraction. Individual shale wells, which deplete more quickly than conventional wells, are pumping less oil and gas than predicted and require drillers to constantly expand their operations, increasing their capital costs, just to keep production level. Further, the industry has largely depleted its inventory of already drilled but untapped wells, which it relied upon to lower costs and survive the pandemic-induced price crash in 2020.[71] The enormous number of new wells now required to return to pre-pandemic extraction levels, along with labor shortages and lack of available financing, has depressed production even now that prices are high.

For all these reasons, the Permian Basin, the most prolific U.S. oil and gas region, is now expected to plateau in 2025, far sooner than had been earlier predicted.[72] The Bakken Shale in North Dakota is now branded as "mature," with the U.S. Geological Survey recently revising down its estimate of the volumes of "technically recoverable" oil remaining in the Bakken by 40

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[67] David Wethe, Sheela Tobben, and Josyana Joshua, "Ex-Fracker at Walmart Reveals One Risk to U.S. Oil Supply Growth," Bloomberg, October 21, 2021, https://www.bloomberg.com/news/articles/2021-08-26/ex-fracker-at-walmart-reveals-one-risk-to-u-s-oil-supply-growth.
[68] Geoffrey Morgan, "Rigs Sit Idle and Jobs Go Unfilled in Canadian Oilfields as Workers Walk Away from Volatile Job Market," *Financial Post*, January 4, 2022, https://financialpost.com/commodities/energy/oil-gas/rigs-sit-idle-and-jobs-go-unfilled-in-canadian-oilfields-as-worker-walk-away-from-volatile-job-market.
[69] Liz Hampton, "As Oil Prices Soar, U.S. Drillers Scramble to Find Sand for Fracking," Reuters, February 15, 2022, https://www.reuters.com/business/energy/oil-prices-soar-us-drillers-scramble-find-sand-fracking-2022-02-15/.
[70] "Energy Outlook 2021/22 Report" (Oil and Gas Jobs Search, n.d.), https://hiring.oilandgasjobsearch.com/energy-outlook-report-2021-22.
[71] Collin Eaton, "Shale Companies Drilling More, but Oil Output Growing Little," *Wall Street Journal*, March 21, 2022, https://www.wsj.com/articles/shale-companies-drilling-more-but-oil-output-growing-little-11647855002.
[72] Collin Eaton, "Oil Frackers Brace for End of the U.S. Shale Boom," *Wall Street Journal*, February 3, 2022, https://www.wsj.com/articles/fracking-oil-prices-shale-boom-11643824329.

percent from an earlier assessment and raising concerns among operators and investors about the feasibility of continued extraction and the productivity of existing wells.[73, 74]

Thus, the apparent ongoing expansion of fracking activities in the United States, with oil and gas rig counts rising, is paradoxical. The current flurry of drilling is taking place within a struggling, not a flourishing, industry whose capital expenses are rising, production flattening, and investors in retreat and which is no longer able to greatly increase the total amount oil and gas flowing out of the shale in response to higher prices nor at a pace that can quickly compensate for embargoes against Russian oil.[75, 76]

With public opinion turned against fracking, many U.S. fracking-related projects have collapsed or are struggling

The sixth trend working against growth in the fracking industry: public opinion has turned decidedly against fracking.[77, 78] Public polling shows more Americans now oppose fracking than support it, including 52 percent of registered voters in Pennsylvania.[79] By spring 2021, a separate poll indicated that only 31 percent of Pennsylvania voters wanted fracking to continue in the state, while 55 percent wanted it to end as soon as possible or be phased out over time.[80]

Public pressure on state governments to prohibit or limit fracking and, more generally, to reduce their dependency on fossil fuels in order to address climate change, has intensified. Protests and legal challenges against pipelines carrying the products of fracking have spread and become more sophisticated. Some elected officials and government bodies, both in the United States and abroad, have begun to take steps in response to increasing public alarm at the accelerating climate crisis and the role that fracking plays in driving it.

Several high-profile projects have recently collapsed or are entangled in complex regulatory troubles. In all cases, they faced overwhelming, well-organized public opposition.

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[73] U.S. Geological Survey, "Assessment of Undiscovered Continuous Oil Resources in the Bakken and Three Forks Formations of the Williston Basin Province, North Dakota and Montana, 2021," National and Global Petroleum Assessment (U.S. Geological Survey, December 15, 2021), https://pubs.usgs.gov/fs/2021/3058/fs20213058.pdf.
[74] Adam Willis, "Bakken Oil Play Now Branded 'mature' as Industry Appetites Shrink in North Dakota," Inforum, February 14, 2022, https://www.inforum.com/news/bakken-oil-play-now-branded-mature-as-industry-appetites-shrink-in-north-dakota.
[75] Scott Disavino, "U.S. Drillers Add Oil and Gas Rigs for Record 16th Month -Baker Hughes," Reuters, November 24, 2021, https://www.reuters.com/business/energy/us-drillers-add-oil-gas-rigs-record-16th-month-baker-hughes-2021-11-24/.
[76] Derek Brower and Myles McCormick, "Top Shale Oil Boss Warns US Can't Replace Any Russia Shortfall," *Financial Times*, March 4, 2022, https://www.ft.com/content/1b517f6d-9056-41ba-9d1e-324e495b5041?
[77] Art Swift, "Americans Split on Support for Fracking in Oil, Natural Gas," Gallup, March 23, 2015, https://news.gallup.com/poll/182075/americans-split-support-fracking-oil-natural-gas.aspx.
[78] Seth Borenstein, Nicholas Riccardi, and Hannah Fingerhut, "AP-NORC Poll: 64% Disapprove of Trump's Climate Change Views," Associated Press, September 12, 2019, https://apnews.com/article/82e8e6fd7b43436cbf5208ee1558d6b1.
[79] Ben German, "Poll: A Majority of Pennsylvanians Oppose Fracking," Axios, August 10, 2020, https://www.axios.com/pennsylvania-fracking-poll-4e215784-4838-4120-b9f3-29147742f5fb.html.
[80] Eric de Place, "Pennsylvania Voters Support a Serious Crackdown on Fracking Operations" (Ohio River Valley Institute, July 29, 2021), https://ohiorivervalleyinstitute.org/dfp-poll/.

In May 2020, New York's then-Governor Andrew Cuomo blocked a permit for the **Williams Northeast Supply Enhancement pipeline**, which would have ferried fracked gas from Pennsylvania, through New Jersey, across the New York Harbor, and into Long Island. In so doing, he cited the state's climate legislation. (However, in May 2021, FERC approved William's request for a two-year extension of the certificate to construct this pipeline.[81]) Signed into law in July 2019, New York's Climate Leadership and Community Protection Act mandates, among other benchmarks, an economy-wide emissions reduction of 85 percent by 2050.

The state's Climate Act, which specifically requires the state to reach 70 percent carbon-free electricity by 2030 and 100 percent by 2040, was instrumental in the denial of permits to multiple proposed fracked gas infrastructure projects in the state.[82] These include a fracked-gas power plant in Queens (the **NRG project**) and the proposed expansion of the **Danskammer gas-fired power plant** in the Hudson River Valley.[83, 84] Separately, in December 2021, the **Gowanus Generating Station** on the Brooklyn waterfront withdrew its application to repower its turbines with natural gas and announced it will be pursuing renewable energy and energy storage options.[85]

The fate of **National Grid's North Brooklyn Pipeline**, which would carry fracked gas from Brownsville to Bushwick through low-income communities of color, is still in play. In October 2021, the U.S. Environmental Protection Agency (EPA) announced it would investigate the state's decision to approve the pipeline in response to a federal civil rights complaint. In November 2021, the U.S. Department of Transportation likewise launched a civil rights probe into the pipeline's approval process.[86, 87] The pipeline, now partially operational, has been the subject of widespread protest by community members.

In December 2021, New York City Council passed a local law, signed by the mayor, that bans the burning of fossil fuels, including natural gas, in all new buildings, with buildings of all sizes

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[81] Reuters Staff, "U.S. Gives Williams More Time to Build Pennsylvania-NY Natgas Line," Reuters, May 20, 2021, https://www.reuters.com/business/energy/us-gives-williams-more-time-build-pennsylvania-ny-natgas-line-2021-05-20/.

[82] New York State Governor's Office, "Governor Cuomo Executes the Nation's Largest Offshore Wind Agreement and Signs Historic Climate Leadership and Community Protection Act," press release, July 18, 2019, https://www.governor.ny.gov/news/governor-cuomo-executes-nations-largest-offshore-wind-agreement-and-signs-historic-climate.

[83] Daniel Whitehead, "Notice of Denial of Title V Air Permit, DEC ID: 2-6301-00191/00014" (New York State Department of Environmental Conservation, October 27, 2021), https://www.dec.ny.gov/docs/administration_pdf/nrgastoriadecision10272021.pdf.

[84] Daniel Whitehead, "Notice of Denial of Title V Air Permit, DEC ID: 3-3346-00011/00017" (New York State Department of Environmental Conservation, October 27, 2021), https://www.dec.ny.gov/docs/permits_ej_operations_pdf/danskammerdecision102721.pdf.

[85] Shant Shahrigian, "Power Company Scraps Plan for Natural Gas Turbines in Gowanus, Brooklyn," *New York Daily News*, December 26, 2021, https://www.nydailynews.com/news/politics/new-york-elections-government/ny-gowanus-astoria-generating-company-natural-gas-20211226-dnph2e5arjhynargdzsdjh6s54-story.html.

[86] Samantha Maldonado, "Feds Launch a Second Civil Rights Investigation Into Brooklyn Gas Pipeline," *The City*, February 9, 2022, https://www.thecity.nyc/environment/2021/11/19/22792264/brooklyn-gas-pipeline-new-federal-civil-rights-investigation.

[87] Brooklyn Eagle Staff, "EPA to Investigate State's Approval of North Brooklyn Gas Pipeline," *Brooklyn Eagle*, October 25, 2021, https://brooklyneagle.com/articles/2021/10/25/epa-to-investigate-states-approval-of-north-brooklyn-gas-pipeline/.

to be constructed fully electric by 2027.[88] In January 2022, New York Governor Hochul announced her support for a statewide natural gas ban for new buildings, as part of a policy blueprint that is part of a draft plan for how to fulfill the state's new climate law. The draft plan recommends an orderly phase-out of the state's gas distribution system and includes accelerating prohibitions on the use of oil and gas for boilers, cooking appliances, and hot water heaters.[89] Also in January 2022, National Grid abandoned its plans for the **Albany Loop**, a fracked gas pipeline across the Hudson River, a project that, citizen groups argued, was incompatible with this policy shift.[90]

In Missouri, the two-year-old, 65-mile **Spire pipeline** which carries fracked gas as an extension of the Rockies Express pipeline, lost its license to operate after a judicial panel ruled, in June 2021, that a market need for this pipeline was never established and that it should not have been approved by FERC. After this ruling was upheld on appeal, the Commission gave Spire an emergency permit extension through the winter. In February 2022, the Commission agreed to keep the temporary certificate valid, allowing Spire to remain operational for now. The long-term fate of this pipeline remains unknown.

In addition to the **Jordan Cove LNG plant** in Oregon, which folded after a 15-year campaign of public opposition (see pages 67-68), the $6.2 billion **Mountain Valley Pipeline,** which would carry fracked gas from northwestern West Virginia 300 miles south to southern Virginia and for which construction is already underway, has lost key regulatory approvals. In February 2022, the Army Corps of Engineers announced it would not be issuing a key water permit that would allow it to cross streams and wetlands until issues regarding endangered species are resolved by the U.S. Fish and Wildlife Service, which had initially greenlighted the project until a federal appeals court invalidated that opinion.[91] As of January 2022, 56 civil actions against the Mountain Valley Pipeline had been brought in state and federal courts in Virginia.[92] In 2021 the Virginia Air Pollution Control Board denied a permit for the **Lambert Compressor Station**, which would have pushed gas through a proposed extension of the Mountain Valley Pipeline. Also in Virginia, the 83-mile **Chickahominy Pipeline**, under development since 2016, was suspended in February 2022 after the gas-fired power plant that it was to serve failed to meet development deadlines, obtain regulatory approvals, and secure financing.[93]

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[88] "Mayor de Blasio Signs Landmark Bill to Ban Combustion of Fossil Fuels in New Buildings," NYC: The Official Website of the City of New York, December 22, 2021, https://www1.nyc.gov/office-of-the-mayor/news/852-21/mayor-de-blasio-signs-landmark-bill-ban-combustion-fossil-fuels-new-buildings.

[89] David Iaconangelo, "N.Y. Governor Backs Nation's First Statewide Gas Ban," *E&E News*, January 6, 2022, https://www.eenews.net/articles/n-y-governor-backs-nations-first-statewide-gas-ban/.

[90] Larry Rulison, "National Grid Scraps Plan to Build Pipeline across Hudson," *Times Union*, January 28, 2022, https://www.timesunion.com/business/article/National-Grid-scraps-plan-to-build-pipeline-16813176.php.

[91] Laurence Hammack, "Mountain Valley Hits Another Snag in Its Pipeline Plans," *Roanoake Times*, February 11, 2022, https://roanoke.com/news/local/mountain-valley-hits-another-snag-in-its-pipeline-plans/article_b4daa376-8b69-11ec-a5b3-e34446874bba.html.

[92] Laurence Hammack, "Legal Fights Continue over the Mountain Valley Pipeline," *Martinsville Bulletin*, January 8, 2022, https://martinsvillebulletin.com/news/state-and-regional/legal-fights-continue-over-the-mountain-valley-pipeline/article_ffc34322-2243-5d16-afbd-5452abd70ca8.html.

[93] Sarah Vogelsong, "Chickahominy Pipeline Will 'Press Pause' on Project Crossing Five Central Va. Counties," *Virginia Mercury*, February 14, 2022, https://www.virginiamercury.com/blog-va/chickahominy-pipeline-will-press-pause-on-project-crossing-five-central-va-counties/.

Similarly, plans for the 124-mile **Constitution pipeline,** which would have carried fracked gas from Susquehanna County, Pennsylvania to Schoharie County, New York, were abandoned in February 2020 after the developer cited regulatory difficulties obtaining permits and diminishing returns on investment.[94] Further, five acres of forested land seized by eminent domain to make way for that pipeline were returned to the family who owned them after a federal court vacated the taking.[95]

The 116-mile **PennEast pipeline project**, which would have ferried fracked gas from Luzerne County, Pennsylvania to Mercer County, New Jersey was blocked after New Jersey denied key water permits. PennEast's cancellation in September 2021 took place just months after the U.S. Supreme Court had ruled in favor of the pipeline company over eminent domain issues.[96]

The proposed **Gibbstown LNG terminal** in New Jersey is facing public opposition and regulatory uncertainties. In June 2019, the Delaware River Basin Commission greenlighted a plan to construct the terminal on the Delaware River with the aim of exporting natural gas extracted from shale gas wells in Pennsylvania.[97, 98] This decision was appealed, twice delaying the project.[99] The Commission's final approval of the project came in December 2020.[100] However, all three major permits for the project have been appealed and additional approvals are still required. According to the proposal, LNG will be delivered to the export terminal by truck and train from a new liquefaction plant planned for Pennsylvania's Bradford County.[101]

To make that route possible, the Trump administration's Pipeline and Hazardous Materials Safety Administration (PHMSA) issued a Special Permit for the transport of LNG by rail over 200 miles from Bradford County to Gibbstown.[102] Subsequent to that, PHMSA amended regulations to allow for the nationwide bulk transport of highly explosive LNG by rail tank cars

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[94] Scott Blanchard, "Constitution Pipeline Project Ends as Builder Cites 'Diminished' Return on Investment," State Impact Pennsylvania, February 25, 2020, https://stateimpact.npr.org/pennsylvania/2020/02/25/constitution-pipeline-project-ends-as-builder-cites-diminished-return-on-investment/.

[95] Susan Phillips, "Family That Lost Hundreds of Trees to Failed Pipeline Project Settles with Company, Gets Land Back," State Impact Pennsylvania, July 3, 2020, https://stateimpact.npr.org/pennsylvania/2020/07/03/family-lost-hundreds-of-trees-to-failed-pipeline-project-settles-with-company-gets-land-back/.

[96] Susan Phillips, "PennEast Cancels Natural Gas Pipeline Project; Cites Lack of Environmental Permits from N.J.," WHYY, September 27, 2021, https://whyy.org/articles/penneast-cancels-natural-gas-pipeline-project-cites-lack-of-environmental-permits-from-n-j/.

[97] Andrew Maykuth, "Contentious Plan to Remake N.J. Dynamite Plant into Shale-Gas Export Terminal Is Approved," *The Philadelphia Inquirer*, June 12, 2019, sec. Business, https://www.inquirer.com/business/lng-export-terminal-philadelphia-repauno-fortress-approved-20190612.html.

[98] Jon Hurdle, "DRBC Confirms Plan to Build LNG Export Terminal at New South Jersey Port," *NJ Spotlight News*, June 12, 2019, sec. Energy & Environment, https://www.njspotlight.com/2019/06/19-06-11-drbc-confirms-plan-to-build-lng-export-terminal-at-new-south-jersey-port/.

[99] Yale Environment 360, "Controversy Mounts over Proposed LNG Export Facility on the Delaware River," *E360 Digest*, October 22, 2020, https://e360.yale.edu/digest/controversy-mounts-over-proposed-lng-export-facility-on-the-delaware-river.

[100] Andrew Maykuth, "Contentious N.J. River Terminal to Export Fracked Pa. Natural Gas Gets Final Approval," *The Philadelphia Inquirer*, December 9, 2020, sec. Business, https://www.inquirer.com/business/lng-port-delaware-river-repauno-drbc-gibbstown-approved-20201209.html.

[101] Andrew Maykuth, "The 'hidden' Plan to Remake an Old Dynamite Factory near Philly into a Major Gas Export Terminal," *The Philadelphia Inquirer*, June 9, 2020, sec. Business, https://www.inquirer.com/business/energy/philadelphia-lng-export-terminal-delaware-river-fortress-20190609.html.

[102] Pipeline Hazardous Materials Safety Administration, "Special Permit DOT-SP 20534" (U.S. Department of Transportation, December 5, 2019), https://www.phmsa.dot.gov/safe-transportation-energy-products/dot-20534-pdf.

(the "Trump Rule"). This rule upended the longstanding federal ban on the transport of LNG by rail. Despite a legal challenge filed in federal court by fourteen states and the District of Columbia and environmental organizations,[103] the new rule took effect in August 2020.[104, 105] However, after two years of no use, the Special Permit expired in November 2021 and is currently under PHMSA review for possible renewal. The potential impacts to public safety and greenhouse gas emissions have been further documented since the issuance of the Special Permit was rushed through. The Biden Administration has proposed a federal rulemaking to suspend the "Trump Rule" and PHMSA was expected to decide on the federal rule suspension in 2022.[106]

New Fortress Energy, one of Gibbstown project's developers, also owns the Shannon LNG import terminal in Ireland. Quashed several times between 2015 and 2019, this project was revived again in 2021, continues to face fierce public resistance, and was, strikingly, not listed as a Project of Common Interest by the European Commission in November 2021.[107] New Fortress Energy also owns an import terminal in San Juan, Puerto Rico. Built without authorization from FERC, this facility must either shut down or secure FERC approval under the Natural Gas Act, which is not a given. These continuing uncertainties about two of the company's planned import terminals are raising questions about whether its LNG export terminal in Gibbstown will become a stranded asset.

And yet fracking is far from senescence

In spite of rising public opposition, less-favorable regulatory policies, and faltering long-term prospects, the fracking industry is far from senescence. In the United States and elsewhere, it has been able to attract private equity funds and retains a firm and corrupting grip on the political process.[108] As of February 2022, a total of 119 oil pipelines and 477 gas pipelines were under development around the world in spite of the fact that 90 percent of the global economy is under a net-zero pledge and despite warnings by both the IPCC and the IEA that exploiting new oil and gas fields is incompatible with a net zero goal, and "given the rapid decline of fossil fuels,

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[103] "Petition for Review in the United States Court of Appeals for the District Of Columbia Circuit Sierra Club, Center for Biological Diversity, Clean Air Council, Delaware Riverkeeper Network, Environmental Confederation of Southwest Florida, and Mountain Watershed Association Petitioners, v. United States Department of Transportation, et Al.," August 18, 2020, https://earthjustice.org/sites/default/files/files/petition_for_review_final.pdf.

[104] "Hazardous Materials: Notice of Issuance of Special Permit Regarding Liquefied Natural Gas," Notice (National Archives and Records Administration, December 11, 2019), https://www.federalregister.gov/documents/2019/12/11/2019-26614/hazardous-materials-notice-of-issuance-of-special-permit-regarding-liquefied-natural-gas.

[105] Hannah Chinn, "No 'Bomb Trains': 14 States Aim to Take New Rule on LNG Transport off the Rails," State Impact Pennsylvania, August 21, 2020, https://stateimpact.npr.org/pennsylvania/2020/08/21/no-bomb-trains-14-states-aim-to-take-new-rule-on-lng-transport-off-the-rails/.

[106] Pipeline and Hazardous Materials Safety Administration, "Hazardous Materials: Suspension of HMR Amendments Authorizing Transportation of Liquefied Natural Gas by Rail" (Federal Register, November 8, 2021), https://www.federalregister.gov/documents/2021/11/08/2021-23132/hazardous-materials-suspension-of-hmr-amendments-authorizing-transportation-of-liquefied-natural-gas.

[107] European Commission, "Annex VII: The Union List of Projects of Common Interest ('Union List')," November 19, 2021, https://ec.europa.eu/energy/sites/default/files/fifth_pci_list_19_november_2021_annex.pdf.

[108] Hiroko Tabuchi, "Private Equity Funds, Sensing Profit in Tumult, Are Propping Up Oil," *New York Times*, October 13, 2021, https://www.nytimes.com/2021/10/13/climate/private-equity-funds-oil-gas-fossil-fuels.html.

significant investments in new oil and gas pipelines are not needed."[109] Here is a sampling of some of fracking-related projects and initiatives still moving forward:

United States. By February 2022, 20 states—including Texas, Florida, and Ohio—had passed laws blocking municipalities from banning or disincentivizing natural gas by, for example, enacting building codes that would mandate electrification of new buildings or phase out gas use in new or existing buildings. This wave of state laws prohibits the very pathway that the IEA has called for and identified as the most viable route to net-zero emissions by 2050. And a peer-reviewed financial analysis of four oil and gas majors, published in February 2022, reveals business models and investment behaviors based on continuing oil and gas extraction rather than a transition to renewable energy sources, in spite of public pledges to the contrary.[110]

Europe. Opposition to fracking in Europe appears to be softening. To the surprise of many, a draft of the EU's "green energy taxonomy" released in December 2021 labeled natural gas a transitional fuel and included natural gas projects in its list of investments that it considers sustainable. A technical document that enumerates for the financial sector the investments considered green by the EU bloc, the taxonomy was endorsed by the European Commission in February 2022 over objections that it would lead to the construction of more gas-fired power plants.[111] In June 2021, the French utility Engie, of which the French government is a shareholder, signed a secretive, 11-year sale and purchase agreement with Texas-based Cheniere Energy to import LNG from its Corpus Christi terminal. This deal represents an about-face for Engie, which, in November 2020, pulled out of a 20-year, $7 billion contract with the developers of the Rio Grande LNG export terminal in Brownsville, Texas, citing concerns about greenhouse gas emissions in Permian Basin fracking operations.[112, 113] Germany has entered an agreement with the Australian oil and gas company Woodside to acquire LNG from the Corpus Christi LNG Project in Texas.[114]

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[109] Nick Ferris, "Weekly Data: One Million Kilometres of New Fossil Pipelines Poses Stranded Asset Risk," Energy Monitor, February 14, 2022, https://www.energymonitor.ai/finance/risk-management/weekly-data-one-million-kilometres-of-proposed-fossil-fuel-pipelines-poses-stranded-asset-risk.

[110] Mei Li, Gregory Trencher, and Jusen Asuka, "The Clean Energy Claims of BP, Chevron, ExxonMobil and Shell: A Mismatch between Discourse, Actions and Investments," ed. Yangyang Xu, *PLOS ONE* 17, no. 2 (2022): e0263596, https://doi.org/10.1371/journal.pone.0263596.

[111] Joe Lo, "European Commission Endorses Fossil Gas as 'Transition' Fuel for Private Investment," https://www.climatechangenews.com/2022/02/02/european-commission-endorses-fossil-gas-transition-fuel-private-investment/, February 2, 2022, https://www.climatechangenews.com/2022/02/02/european-commission-endorses-fossil-gas-transition-fuel-private-investment/.

[112] Harry Weber, "Cheniere to Supply LNG from Texas Export Facility under New Deal with France's Engie," S&P Global, November 11, 2021, https://www.spglobal.com/platts/en/market-insights/latest-news/lng/111121-cheniere-to-supply-lng-from-texas-export-facility-under-new-deal-with-frances-engie.

[113] Les Amis de la Terre France, "Engie Secretly Signs a New Contract to Import Fracked Gas in France," amisdelaterre.org, December 3, 2021, https://www.amisdelaterre.org/communique-presse/mustang-contract-engie-secretly-signs-a-new-contract-to-import-fracked-gas-in-france/.

[114] Woodside Energy Ltd., "Woodside and RWE Sign Agreement for Mid-Term LNG Supply," Press Release, December 20, 2018, https://www.woodside.com.au/docs/default-source/media-releases/woodside-and-rwe-sign-agreement-for-mid-term-lng-supply.pdf.

Australia. In April 2022, Woodside's LNG terminal near Perth in Western Australia received final approval. One of the largest oil and gas projects in the nation, the $16.5 billion LNG export facility is expected to go on line in 2026.[115]

Mexico. In November 2021, one year after Sempra Energy announced that it had received the final permit from the government of Mexico to construct an LNG export terminal on the Pacific coast of Baja California, Sempra announced plans to begin building a second LNG export plant in the Mexican port city of Topolobampo on the Gulf of California.[116, 117]

Argentina. Fracking has also rebounded in Argentina. During the peak of COVID-19 lockdown in 2020, fracking activities in the nation's vast Vaca Muerta Basin had all but ceased and its future as an economically viable operation was in doubt, with climate campaigners predicting that it could become one of the first major fossil fuel projects "where a decision is made to 'keep it in the ground.'"[118]

This has not happened. Indeed, fracking activity in Vaca Muerta, which is the world's second-largest shale gas deposit and fourth largest shale oil reserve, boomed in 2021 as pandemic lockdowns eased, demand rose, and pricing structures encouraged expanded drilling for gas and oil. This spike in fracking operations is the result of a years-long policy process to incentivize and subsidize further oil and gas exploration in a nation where half of the energy mix is natural gas, of which 45 percent is extracted through fracking, and fracking is seen by political leaders as an economic driver. In its 2020 investment plan, Argentina's state-run energy company Yacimientos Petrolíferos Fiscales (YPF) and its private partners proposed to spend $2.1 billion on fracking.[119] This company is the nation's biggest producer both of gas and oil.

In December 2020, Argentina launched a four-year program to "improve returns on gas production with higher pricing and long-term supply contracts,"[120] and Argentina's President Alberto Fernandez announced his intention to push forward with a major new pipeline to boost exports of natural gas extracted from the Vaca Muerta Basin. As reported by Reuters, the timeline and plans for the new pipeline "come as Argentina seeks to ramp up gas production and

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[115] Rebecca Turner, "Woodside's Controversial Scarborough LNG Project Gets Final Approval amid Climate Warnings," *ABC News*, April 6, 2022, https://www.abc.net.au/news/2022-04-07/woodside-scarborough-lng-approval-despite-climate-emissions/100971214.
[116] Rob Nikolewski, "Sempra to Build LNG Export Facility in Baja," *The San Diego Union-Tribune*, November 17, 2020, sec. Business, https://www.sandiegouniontribune.com/business/story/2020-11-17/sempra-to-build-lng-export-facility-in-baja.
[117] Rob Nikolewski, "Sempra Planning a Second LNG Project in Mexico," *San Diego Union-Tribune*, November 5, 2021, https://www.sandiegouniontribune.com/business/story/2021-11-05/sempra-planning-a-second-lng-project-in-mexico.
[118] Jonathan Watts, "Coronavirus Pandemic Threatens Controversial Fracking Project in Argentina," *The Guardian*, April 29, 2020, https://www.theguardian.com/environment/2020/apr/29/fate-of-vaca-muerta-oil-and-gas-fields-may-point-way-forward-on-fossil-fuels-after-coronavirus.
[119] "We've Been Bamboozled! Fracking and Big Fortunes in Argentina," Observatorio Petrolero Sur, December 1, 2020, https://opsur.org.ar/2020/12/01/weve-been-bamboozled-fracking-and-big-fortunes-in-argentina/.
[120] Charles Newbery, "Argentina's Vaca Muerta Fracking Activity Hits 17-Month High in January," S&P Global, February 3, 2021, https://www.spglobal.com/commodity-insights/en/market-insights/latest-news/oil/020321-argentinas-vaca-muerta-fracking-activity-hits-17-month-high-in-january.

exports to bring in much-needed foreign currency to refill depleted reserve levels and amid debt talks with the International Monetary Fund."[121]

In January 2022, Mexico-based Vista Oil & Gas acquired two concessions in the Vaca Muerta Basin and announced that it intended to "redouble its commitment to the shale region's development," with plans to invest $2.3 billion from 2022-2026 to increase extraction and exports. Among the most problematic issues at the local level and in terms of social and health-related impacts are continuing earthquake swarms near extraction zones; inadequate strategies for storing and treating fracking waste; water scarcity; and the ongoing breaching of human rights within indigenous Mapuche communities in the area, which are largely opposed to fracking.

Southern Africa. Local resistance to drilling and fracking is also growing in Namibia and Botswana, where the Canadian energy company ReconAfrica has licensed more than 13,000 square miles of land in the Kavango Basin. This region includes habitat and migratory routes for elephants and other endangered wildlife species. According to petroleum engineer Nick Steinsberger, a pioneer of fracking in Texas' Eagle Ford Shale and board member of ReconAfrica who originally led the exploratory effort in the Kavango Basin, "We're looking for the next American shale boom, and Africa's got the most potential."[122]

Beginning in January 2021, ReconAfrica began test drilling near a riverbed in Namibia with the goal of drilling and fracking hundreds of wells in an area that overlaps with critical habitat and migratory routes for the world's largest remaining elephant population and could affect the unique Okavango Delta.[123] The license, which includes a contracted production period of at least 25 years, also originally covered the Tsodilo Hills, a World Heritage Site with deep spiritual significance for the indigenous San people, but this area was subsequently excluded after public outcry and intervention by the United Nations Educational, Scientific, and Cultural Organization (UNESCO).[124, 125, 126] Fracking in this extremely arid region would require the industrialization of this pristine landscape as well as the destruction of billions of gallons of fresh water.

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[121] Eliana Raszewski, "Argentina President Set to Decree $1.6 Bln Vaca Muerta Gas Pipeline - Gov't Source," Reuters, December 21, 2021, https://www.reuters.com/business/energy/exclusive-argentina-president-set-decree-16-bln-vaca-muerta-gas-pipeline-govt-2021-12-21/.
[122] James Stafford, "The World's Last Great Oilfield: An Interview with Nick Steinsberger," OilPrice.com, September 16, 2020, https://oilprice.com/Interviews/The-Worlds-Last-Great-Oilfield-An-Interview-With-Nick-Steinsberger.html.
[123] Jeffrey Barbee and Laurel Neme, "Oil Drilling, Possible Fracking Planned for Okavango Region—Elephant's Last Stronghold," *National Geographic*, October 28, 2020, https://www.nationalgeographic.com/animals/article/oil-drilling-fracking-planned-okavango-wilderness.
[124] Jeffrey Barbee and Laurel Neme, "Test Drilling for Oil and Gas Begins in Namibia's Okavango Region," *National Geographic*, January 28, 2021, https://www.nationalgeographic.com/animals/article/oil-gas-test-drilling-begins-namibia-okavango-region.
[125] Reconnaissance Energy Africa, Ltd., "Republic of Botswana and ReconAfrica Amend Exploration License to Exclude Entire Tsodilo Hills Area," Cision, January 5, 2021, https://www.newswire.ca/news-releases/republic-of-botswana-and-reconafrica-amend-exploration-license-to-exclude-entire-tsodilo-hills-area-837436712.html.
[126] UNESCO, "UNESCO Vigilant on Potential Impacts of Oil Exploration in Namibia and Botswana on World Heritage Properties," UNESCO, December 21, 2020, https://whc.unesco.org/en/news/2230.

ReconAfrica has expressed confidence in its ability to set up fracking operations in the Kavango Basin because "surface rights and access are held by the government."[127]

In March 2021, *National Geographic* reported that the waste pits created for the test wells were unlined, contrary to standard industry practice in British Columbia where the company is headquartered. Aerial photography taken in September 2021 indicates that ReconAfrica has drilled in the conservancy without first securing necessary permissions. By December 2021, ReconAfrica had, without required permits, bulldozed land and drilled a second test well inside a protected wildlife conservancy area and was accused of offering jobs to local leaders in exchange for their silence.[128]

In July 2021, ReconAfrica's continued exploration activities in Namibia prompted the United Nations Educational, Scientific and Cultural Organization (UNESCO) to express its concern about the granting of oil exploration licenses in environmentally sensitive areas within the Okavango River Basin and, as part of a formal decision, to request further regulatory oversight. Specifically, UNESCO "urges the States Parties of Botswana and Namibia to ensure that potential further steps to develop the oil project, which include the use of new exploration techniques, are subject to rigorous and critical prior review, including through Environmental Impact Assessment (EIA) that corresponds to international standards, including an assessment of social impacts and a review of potential impacts on the World Heritage property,"[129] UNESCO set a deadline of February 1, 2022, for the state parties to submit to the World Heritage Center an updated report on the state of conservation of the property and the implementation of the EIA, but this deadline and the requirement of a proper EIA was ignored by both Namibia and Botswana. Local and international groups continue to fight the project.

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[127] Mark Heim, "ReconAfrica Research Report," Research (ReconAfrica, July 2020), https://reconafrica.com/wp-content/uploads/ReconAfrica-Research-Report-July-2020.pdf.
[128] Jeffrey Barbee and Laurel Neme, "Oil Company Accused of Drilling in African Wildlife Reserve, Offering Jobs for Silence," *National Geographic*, December 13, 2021, https://www.nationalgeographic.com/animals/article/oil-company-reconafrica-accused-of-drilling-in-african-wildlife-reserve.
[129] UNESCO, "Convention Concerning the Protection of the World Cultural and Natural Heritage" (United Nations, July 31, 2021), https://whc.unesco.org/archive/2021/whc-21-44com-18-en.pdf.

Introduction to Fracking

How fracking works

Since the end of the 20th century, horizontal drilling has been combined with high-volume hydraulic fracturing to extract dispersed oil and natural gas, primarily from shale bedrock, that would otherwise not flow to the surface. Typically, these extraction methods (collectively known as "fracking") take place on clustered multi-well pads where individual wellbores extend vertically down into the shale formation and then turn horizontally, tunneling through the shale in various directions. These lateral tunnels can extend as far as two miles underground.

To liberate the gas (methane) or oil trapped inside the shale, many small explosive charges followed by high volumes of pressurized fluid are sent into the shale layer to expand and extend its many naturally occurring cracks, bedding planes, and faults. Silica sand grains (or sometimes ceramic beads) are carried by the pressurized fluid into these spaces and remain there after the pressure is released, acting to prop open these now-widened fissures in the shale and allowing the methane or oil trapped within to flow up the well.

Formerly called "unconventional gas and oil extraction," the techniques of fracking are now standard practice in the United States. About 40 percent of the natural gas inventory in the United States is used to generate utility-scale electricity, and, enabled by fracking, natural gas exceeded coal as the nation's leading source of electricity in 2016.[130] Hydraulically fractured wells now produce 79 percent of U.S. natural gas and 65 percent of U.S. crude oil, with hydraulic fracturing used in 95 percent of new wells.[131, 132]

Fracking fluid

Fracking fluid consists of millions of gallons of fresh water to which is added a sequence of chemicals that include biocides, lubricants, gelling agents, anti-scaling, and anti-corrosion agents. Some of the water used to frack wells remains trapped within the fractured zone and, as such, is permanently removed from the hydrologic cycle. The remainder travels back up to the surface. This flowback fluid contains not only the original chemical additives, many of which are toxic, but also harmful substances carried up from the shale zone, which often include brine, heavy metals, and radioactive elements.

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130 Bobby Magill, "Fracking Hits Milestone as Natural Gas Use Rises in U.S.," Climate Central, May 6, 2016, http://www.climatecentral.org/news/fracking-milestone-as-natural-gas-use-rises-20330.
131 U.S. Energy Information Administration, "Natural Gas Explained: Use of Natural Gas," EIA.gov, December 7, 2021, https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php.
132 U.S. Energy Information Administration, "How Much Shale Gas Is Produced in the United States?," EIA.gov, October 4, 2021, https://www.eia.gov/tools/faqs/faq.php?id=907&t=8.

Fracking waste

Once in production, a fracked well continues to generate liquid throughout its lifetime. This produced water, which contains many of the same toxic substances as flowback fluid, is a second component of fracking waste, and it also requires containment and disposal. In addition, fracking waste includes solid drilling cuttings, which are typically laced with various chemical substances used to aid the drilling process. These cuttings, which can also contain radioactive elements, are typically disposed of in municipal waste landfills. Fracking waste is exempt from federal hazardous waste regulations that would otherwise prohibit this practice.

In the United States, more than two billion gallons of water and fracking fluids are injected daily under high pressure into the earth for the purpose of enabling oil and gas extraction via fracking or, after the fracking is finished, to flush the extracted wastewater down any of the more than 187,000 disposal wells across the country that accept oil and gas waste. All of that two billion daily gallons of fluid is toxic, and the wells that ferry it pass through the nation's groundwater aquifers on their way to the deep geological strata below, where the injection of fracking waste demonstrably raises the risk of earthquakes.

Upstream and downstream elements of fracking

Downstream elements of fracking infrastructure, which lie between the wellhead and the point of combustion, include processing plants, transport infrastructure such as pipelines and compressor stations, distribution lines, storage facilities, gas-fired power plants, and LNG liquefaction plants and export terminals. Upstream elements include silica sand mining operations and water withdrawal operations.

Legal secrecies

Industry secrecy continues to thwart scientific inquiry into the health and environmental impacts of fracking's many component parts and operations, leaving many potential problems—especially cumulative, long-term risks—unidentified, unmonitored, and largely unexplored. This problem is compounded by non-disclosure agreements, sealed court records, and legal settlements that prevent families and their doctors from discussing injuries and illnesses that result from fracking and related operations.

The long-entrenched problem of secrecy shows no sign of resolving. The identity of chemicals used in fracking fluids remains proprietary and lies beyond the reach of federal right-to-know legislation that governs other industries. The nation's largest public database on chemicals used in fracking operations, FracFocus, operates on a voluntary basis, and while 23 states have adopted it to serve as a *de facto* chemical disclosure registry, its data has, over time, become increasingly less, rather than more, comprehensive and transparent. Rates of withheld information and claims of trade secrecy have increased since FracFocus was first launched in 2011. (See footnotes 2258, 2259.)

The incomplete picture created by a lack of transparency in regard to chemicals used, produced, emitted, or created during the drilling and fracking process complicates the task of identifying potential hazards and exposure pathways. Nevertheless, the evidence to date indicates that fracking operations pose severe threats to health, both from water contamination and from air pollution.

In the air around drilling and fracking operations and their attendant infrastructure, researchers have measured strikingly high levels of toxic pollutants, including the potent carcinogen benzene and the chemical precursors of ground-level ozone (smog). In some cases, concentrations of fracking-related air pollutants in communities where people live and work exceed federal safety standards. Research shows that air emissions from fracking can drift and pollute the air hundreds of miles downwind. (See footnotes 459, 460.)

The geography of fracking

Drilling and fracking operations and their ancillary infrastructure have profoundly altered Earth's landscape. The flare stacks and artificial lights from major shale plays are visible from space,[133] as is the upward buckling of Earth's surface that is caused by the high-pressure injection of fracking wastewater into disposal wells.[134]

The dramatic increase in fracking over the last decade in the United States has pushed oil and gas extraction operations into heavily populated areas. In the Marcellus Shale alone, which underlies much of the Mid-Atlantic United States, 15,939 wells were drilled and fracked between 2008 and 2018.[135] More than 11,000 of these wells are in Pennsylvania.

At least six percent of the U.S. population—17.6 million Americans—now live within a mile of an active oil or gas well, a number that includes 1.4 million young children and 1.1 million elderly people.[136, 137] About 8.6 million people are served by a drinking water source that is located within a mile from an unconventional well. (See footnote 615.) Understanding the potential for exposure and accompanying adverse impacts is a public health necessity.

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[133] "Shale Revolution: As Clear as Night and Day," NASA Earth Observatory, February 15, 2016, http://earthobservatory.nasa.gov/IOTD/view.php?id=87725&src=eoa-iotd.
Andy Coghlan, "You Can See Fracking's Impact on Earth's Surface from Space," NewScientist, September 22, 2016, https://www.newscientist.com/article/2106886-you-can-see-frackings-impact-on-earths-surface-from-space/.
[135] Jeffrey B. Jacquet et al., "A Decade of Marcellus Shale: Impacts to People, Policy, and Culture from 2008 to 2018 in the Greater Mid-Atlantic Region of the United States," *Extractive Industries and Society* 5, no. 4 (2018): 596–609, https://doi.org/10.1016/j.exis.2018.06.006.
[136] Eliza D. Czolowski et al., "Toward Consistent Methodology to Quantify Populations in Proximity to Oil and Gas Development: A National Spatial Analysis and Review," *Environmental Health Perspectives* 125, no. 8 (2017), https://doi.org/10.1289/EHP1535.
[137] Lindsey Konkel, "In the Neighborhood of 18 Million: Estimating How Many People Live near Oil and Gas Wells," *Environmental Health Perspectives* 125, no. 12 (2017), https://doi.org/10.1289/EHP2553.

Timeline of Fracking Bans and Moratoriums

As a response to the proliferating documentation of the risks and harms of fracking—augmented by increasing evidence of its declining benefits and unrealized promises—various countries, states, and municipalities have instituted bans and moratoriums.[138]

France banned fracking in July 2011 and **Bulgaria** in January 2012.

In May 2012, the state of **Vermont** banned fracking and prohibited the storage and treatment of fracking waste.

In July 2012, a revision of environmental laws in **Austria** prompted the main Austrian oil and gas group to announce a stop to its shale gas plans in the country.

In April 2013, the **Luxembourg** parliament passed a motion against shale gas exploration.

In July 2014, the Flanders region of **Belgium** temporarily banned fracking. This ban is still valid.

The **California** counties of Santa Cruz, San Benito, and Mendocino all banned fracking in 2014.

New York State banned fracking in December 2014.

In January 2015, **Scotland** became the first country in the United Kingdom to impose a formal moratorium on fracking. In 2016, as part of the ongoing moratorium process, the government of Scotland released a series of reports that reconfirmed the evidence for potential contamination of air and water, threats to worker health from silica dust exposure, and risks to the health of nearby residents. It further noted that the pursuit of unconventional oil and gas extraction would make it more difficult for Scotland to achieve its climate targets on greenhouse gas emissions.[139, 140] In October 2017, Scotland's moratorium was extended "indefinitely" in a decision that led to an unsuccessful court challenge by the British petrochemical company Ineos. In October 2019, the government confirmed that would no longer issue licenses for fracking nor grant permission for any onshore drilling projects.[141] In May 2020, Ineos purchased tens of thousands of acres of leases near Austin, Texas and applied for fracking permits.[142]

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[138] Héctor Herrera, "The Legal Status of Fracking Worldwide: An Environmental Law and Human Rights Perspective," The Global Network for Human Rights and the Environment, January 6, 2020, https://gnhre.org/2020/01/06/the-legal-status-of-fracking-worldwide-an-environmental-law-and-human-rights-perspective/.

[139] Health Protection Scotland, "A Health Impact Assessment of Unconventional Oil and Gas in Scotland: Volume 1 - Full Report" (Public Health Scotland, November 8, 2016), http://www.hps.scot.nhs.uk/resourcedocument.aspx?resourceid=3102.

[140] Energy and Climate Change Directorate, "Unconventional Oil and Gas: Compatibility with Scottish Greenhouse Gas Emissions Targets," Research and Analysis, Scottish Government, November 8, 2016, http://www.gov.scot/Resource/0050/00509324.pdf.

[141] Severin Carrell, "Scottish Government Extends Ban on Fracking," October 19, 2019, sec. UK Politics, https://www.theguardian.com/uk-news/2019/oct/03/scottish-government-extends-ban-on-fracking.

[142] Sergio Chapa, "Drilling down: British Petrochemical Giant Ineos Plans to Begin Fracking in Texas," *Houston Chronicle*, May 7, 2020, sec. Sector News, https://www.borderless.net/news/chemical-value-chain/drilling-down-british-petrochemical-giant-ineos-plans-to-begin-fracking-in-texas/.

In February 2015 the government of **Wales** declared a moratorium on fracking "until it is proven safe." In July 2018, the Welsh government confirmed that shale gas was not compatible with decarbonization targets and said it would not support applications for fracking.

In March 2015, the Canadian province of **New Brunswick** declared a moratorium on fracking.

In July 2015, the **Netherlands** banned all shale gas fracking through 2020 on the grounds that "research shows that there is uncertainty" about impacts. In October 2018, the Dutch government announced that gas extraction of all kinds in the Groningen gas field would entirely cease by 2030 after public outcry over continuing earthquakes in the region. Gas production has already been cut by 60 percent since its peak in 2013. On May 22, 2019, Groningen was hit with a magnitude 3.4 earthquake that damaged multiple homes.[143]

In August 2015, **Denmark** declared a stop to new applications for shale gas drilling, extending its 2012 moratorium.

In December 2015, the plenary of the **European Parliament** affirmed the incompatibility of shale gas extraction via hydraulic fracturing with the European Union's commitment to decarbonization, and it acknowledged public concerns about the environmental and health impacts of fracking. While falling short of an outright EU-wide moratorium on fracking, the report states that "it is questionable whether hydraulic fracturing can be a viable technology in the European Union."[144]

In January 2016, **Broward County, Florida**, one of three counties that make up the larger Miami metropolitan region, banned both hydraulic fracking and acid fracking via a unanimous vote of the Broward County Commission.

In 2016, **New Brunswick** extended its moratorium on fracking "indefinitely," citing unresolved problems with the disposal of fracking wastewater, and in the Canadian province of **Newfoundland and Labrador**, where a moratorium had been in place since 2013, a government-appointed panel recommended that fracking remain "paused," citing data gaps and unresolved questions about the underlying geology.

In June 2016, **Germany** adopted a moratorium on unconventional fracking in shale until 2021 but will permit exploratory drilling research projects. Fracking in sandstone is still explicitly permitted.

Also in 2016, Butte and Alameda counties in **California** banned fracking, along with Monterey County, which also banned all new oil drilling.

In August 2016, the state of Victoria in **Australia** halted both fracking and conventional gas extraction on the grounds that the risks outweighed any potential benefits. In March 2020, the

[143] "Groningen Hit by Strong Earthquake as Gas Extraction Impact Continues," *Dutch News*, May 22, 2019, https://www.dutchnews.nl/news/2019/05/groningen-hit-by-strong-earthquake-as-gas-extraction-impact-continues/.
[144] Committee on Industry, Research and Energy, "Report: On towards a European Energy Union" (European Parliament, n.d.), http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+REPORT+A8-2015-0341+0+DOC+XML+V0//EN.

fracking ban became permanent while the ban on conventional drilling without fracking was lifted.[145]

In September 2016, a **California** judge, arguing that the agency had failed to consider the dangers of fracking, struck down a bid by the Bureau of Land Management (BLM) to open one million acres of public land in central California to oil drilling.

In November 2016, Winona County, **Minnesota** banned the mining of frack sand, a decision that was upheld in district court in November 2017 and upheld again by the Minnesota Supreme Court in March 2020.[146, 147] In January 2021 the U.S. Supreme Court refused to hear the case, and the Winona County ban on frack sand mining prevailed.[148]

In December 2016, the Portland City Council in **Oregon** approved zoning code changes that banned the construction of new fossil fuel projects, including terminals for storing and transporting natural gas, and also prohibited the expansion of pre-existing facilities, including an LNG plant.

In March 2017, the Castilla Leon region in **Spain** signed a political agreement to give up on shale gas exploration. This decision followed the implementation of several other regional bans in Spain or laws that otherwise made fracking unviable. These regions include Cantabria (April 2013), La Rioja (May 2013), Catalonia (February 2014), Basque Country (June 2015), and Castillo La Mancha (March 2017). The Climate Change Bill, currently under consideration by the Spanish Parliament, would ban fracking nationally as part of a strategy to promote green growth as a driver of COVID-19 recovery.[149]

In April 2017, **Maryland** became the third U.S. state to ban fracking when Governor Larry Hogan signed a ban bill that was overwhelmingly approved by the state legislature. Maryland's ban followed a two-and-a-half-year statewide moratorium.

Also in April 2017, Entre Ríos passed the first province-wide ban on fracking in **Argentina**. This ban follows 50 individual municipal bans and is intended to protect the Guarani Aquifer, which extends beneath parts of Argentina, Brazil, Paraguay, and Uruguay.

In June 2017, **France** expanded its fracking ban to include a ban on all new oil and gas exploration.

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[145] Samantha Hepburn, "Victoria Bans Fracking for Good, but Quietly Lifts Onshore Gas Exploration Ban," Phys.org, March 19, 2020, https://phys.org/news/2020-03-victoria-fracking-good-quietly-onshore.html.
[146] Chris Rogers, "Supreme Court Considers Frac Ban," *Winona Post*, April 17, 2019, http://www.winonapost.com/Article/ArticleID/63818/Supreme-Court-considers-frac-ban.
[147] Matt McKinney, "Minnesota Supreme Court Upholds Winona County Ban on Frac Sand Mining," *StarTribune*, March 11, 2020, https://www.startribune.com/minnesota-supreme-court-upholds-winona-county-ban-on-frac-sand-mining/568701922/.
[148] Matt McKinney, "U.S. Supreme Court Rejects Suit against Winona County Frac Sand Ban," *Star Tribune*, January 12, 2021, https://www.startribune.com/u-s-supreme-court-rejects-suit-against-winona-county-frac-sand-ban/600009755/.
[149] Herbert Smith Freehills, "Spain Is in the Process of Approving a Full Set of New Regulations to Achieve the Goal of Climate-Neutrality by 2050," Lexology, September 4, 2020, https://www.lexology.com/library/detail.aspx?g=6e4d5364-2413-4b58-b557-0923ac7eea9f.

In July 2017, **Ireland** banned fracking when legislation was signed into law by the president.

Also in October 2017, Canada's **Prince Edward Island** included a prohibition on fracking as part of its Water Act.

In December 2017, **Uruguay** prohibited fracking for four years.

In March 2018, the **Australian state of Tasmania** extended its moratorium on fracking until 2025.

In October 2018, the National Authority for Environmental Licenses denied applications for commercial fracking in **Colombia.** In December 2019, the Colombian Ministry of Mines approved a regulatory framework for fracking pilot studies. In April 2022, a judge suspended the license of one such project on the grounds that Afro-Colombian communities had not been consulted.

In December 2018, the newly elected president of **Mexico** announced a suspension of all further energy auctions for three years, temporarily halting permits for new fracking operations. This announcement was widely seen as a possible step by President Obrador toward fulfilling a campaign promise to ban fracking in Mexico.[150] However, he has not done so.

In May 2019, **Washington State** enacted a statewide ban on fracking.

In June 2019, the state of **Oregon** put in place a five-year fracking moratorium.

Also in June 2019, the state of **Connecticut**, where no fracking takes place, banned the disposal of oil and gas extraction waste.

In November 2019, **the United Kingdom** declared a moratorium on fracking after an Oil and Gas Authority analysis found that preventing earthquakes associated with fracking is not possible with existing technology but left open the possibility that the temporary ban could be reversed if induced seismicity became manageable. In April 2022, the government ordered a new report from the British Geological Survey to assess any recent changes to the science, a decision seen by the industry as a possible first step toward overturning the ban.[151]

Also in November 2019, Governor Gavin Newsom announced a moratorium on all new fracking and cyclic steam permits for the state of **California**. This moratorium lasted until April 2020 when 24 new permits were issued for fracking in Kern County.[152]

In April 2020, the state legislature, in a bill signed by Governor Ralph Northam, banned fracking east of I-95 in the state of **Virginia**.

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[150] Rebecca Bertram, "Will Fracking Be Banned in Mexico?," Energy Transition, April 17, 2019, https://energytransition.org/2019/04/will-fracking-be-banned-in-mexico/.
[151] "Business Secretary Kwasi Kwarteng Orders Scientific Review of Fracking Impact," BBC.com, April 5, 2022, https://www.bbc.com/news/uk-politics-60999026.
[152] Janet Wilson, "Fracking in California Gets Green Light after 9-Month Pause; Aera Energy Receives Permits," *Desert Sun*, April 3, 2020, https://www.desertsun.com/story/news/environment/2020/04/03/calgem-approves-24-fracking-permits-aera-energy-after-9-month-pause/2944712001/.

In June 2020, the new coalition government in **Ireland** extended its national fracking ban by pledging to not support construction of LNG terminals to import fracked gas from the United States, thus halting forward motion on three planned LNG projects, including the long-delayed Shannon LNG terminal that is under development by a U.S.-based private equity firm. As stated in the Programme for Government, "As Ireland moves forward on carbon neutrality, we do not believe it makes sense to develop LNG gas import terminals [and] accordingly we shall withdraw the Shannon LNG terminal from the EU Projects of Common Interest (PCI) list in 2021"[153]

On August 3, 2020, **New York State** banned the importation of out-of-state fracking waste for disposal in municipal waste landfills and wastewater treatment plants. Seven different landfills across New York State had accepted liquid and solid fracking waste from Pennsylvania.

In February 2021, **the Delaware River Basin Commission**—which consists of governors of New York, New Jersey, Pennsylvania, and Delaware together with the U.S. Army Corps of Engineers—finalized a rule to permanently ban fracking in the Delaware River watershed on the grounds that fracking exposes its waters to "significant, immediate, and long-term risks." This ban replaces a temporary moratorium on fracking that had been in place since 2010.[154] In October 2021, the Commission proposed additional rules that would prohibit the discharge of fracking wastewater to water or land within the Basin but that would not explicitly disallow the importation of wastewater from fracking operations located outside the Basin for storage, treatment, processing, or re-use within the Basin. These rules also do not expressly prohibit water withdrawals from the Delaware River and its tributaries for export and use in fracking operations.[155] The longest free-flowing river in the Northeast, the Delaware River provides drinking water to more than 15 million people (approximately five percent of the U.S. population). About one-third of the river's watershed is underlain by the Marcellus shale formations.

In 2021 and 2022 prohibitions under multiple jurisdictions advanced in **California.** In April 2021, Governor Gavin Newsom announced a plan to ban fracking of new and existing wells by 2024 and to consider phasing out oil production statewide by 2045. In practice, the state has begun denying fracking permits, citing climate concerns.[156] In September 2021, the Los Angeles County Board of Supervisors voted unanimously to end oil and gas drilling in the County's "unincorporated" areas, which includes 1,600 wells, many in the Inglewood Oil Field, one of the largest urban drilling sites in the country. Effective November 2021, Culver City, California prohibited the drilling of any new, or redrilling of any existing, gas or oil well. The City Council also required the phasing out, plugging and restoration of all existing gas and oil wells, by November 24, 2026. A portion of the Inglewood Oil Field, one of the largest U.S. urban oil

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[153] Stuart Elliott and Alisdair Bowles, "New Irish Government Policy Pledges Deal Significant Blow to Gas," S&P Global, June 30, 2020, https://www.spglobal.com/platts/zh/market-insights/latest-news/natural-gas/063020-feature-new-irish-government-policy-pledges-deal-significant-blow-to-gas.
[154] Michael Rubinkam, "Agency Permanently Bans Fracking Near Delaware River," PBS.org, February 25, 2021, https://www.pbs.org/newshour/nation/agency-permanently-bans-fracking-near-delaware-river.
[155] Delaware River Basin Commission, "Full Text of FAQ: Proposed Regulations Addressing Importation and Exportation of Water and the Discharge of Wastewater from High Volume Hydraulic Fracturing," December 7, 2021, https://www.state.nj.us/drbc/meetings/proposed/notice_import-export-rules_faq_full-text.html.
[156] Los Angeles Times Editorial Board, "Did California Issue Its Last Fracking Permit? Let's Hope So," *Los Angeles Times*, December 17, 2021, https://www.latimes.com/opinion/story/2021-12-17/fracking-permits.

fields, lies within Culver City. In late January 2022, the Los Angeles City Council voted unanimously to ban new oil and gas wells and phase out existing ones.

The government of **North Ireland** declared a moratorium on fracking in 2011. In February 2022, Northern Ireland's Minister for the Economy Gordon Lyons announced that the preferred option resulting from his Department's policy review would be a ban on all forms of petroleum licensing. This comprehensive ban would be a step further than any promised fracking ban bills that failed to materialize because it would ban licensing for all forms of petroleum (oil and gas) exploration and extraction. The preferred policy still needs support of the majority of Ministers in the Northern Ireland Executive to become policy and progress to law. At this writing, the Democratic Unionist Party has withdrawn its First Minister, and as a result Northern Ireland has no Executive. It is currently unclear if or when the proposed new policy and legislation needed to end the ten-year fight to defend Northern Ireland's fragile post-conflict community health from fracking will be agreed upon and become law.

In April 2022, in a unanimous vote by the National Assembly, **Slovenia** imposed a complete ban on fracking in the face of threatened lawsuits by a UK-based fracking investor seeking to extract gas in the northeastern part of the country.[157]

In sum, as evidence continues to mount of its environmental and public health costs, legislative and governmental bodies are increasingly apprehensive about the risks and harms of fracking.

Nevertheless, in several notable cases, hard-won bans and other restrictions on fracking have been overturned:

A fracking ban passed by the city of **Denton, Texas** in 2014 was invalidated in 2015 by a state law, pushed by oil and gas interests, that prohibits Texas municipalities from passing local bans.

In **Colorado,** the Colorado Supreme Court struck down local fracking bans in the cities of Fort Collins and Longmont in May 2016, and a subsequent attempt to reinstate the ban in Longmont was struck down by a Boulder district judge in November 2020. In January 2019, the Colorado Supreme Court ruled against a case brought by six youth that would have halted new drilling permits pending a comprehensive study of health and environmental impacts. The ruling allows Colorado to continue to weigh costs and technical feasibility against adverse public health impacts. A statewide ballot measure (Proposition 112) to increase well setback distances to 2,500 feet from occupied buildings, public spaces, and bodies of water narrowly failed in November 2018. According to the Colorado Oil and Gas Conservation Commission, the measure would have prevented drilling on approximately 85 percent of non-federal lands in the state.

In April 2019, the Colorado State legislature passed a bill (SB 181) intended to reorient state oversight of the oil and gas industry away from promoting fossil fuel extraction and toward protecting public health and the environment. As a result of the law, the state setback distance was set at 2,000 feet. This buffer zone applies only to new wells on new well pads and allows for the drilling and fracking of new wells on pre-existing well pads. Further, the rule allows requests for waivers. In March 2022, the Colorado Oil and Gas Conservation Commission (COGCC) denied a waiver request from Occidental Petroleum for a large proposed fracking site that would

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[157] Sebastijan R. Maček, "Slovenia Imposes Blanket Ban on Fracking," isds.bilaterals.org, April 7, 2022, https://www.isds.bilaterals.org/?slovenia-imposes-blanket-ban-on.

have drilled 26 wells fewer than 2,000 feet from 62 homes in a residential area of Firestone.[158] SB 181 also grants Colorado municipalities more regulatory authority over fracking activities. In February 2022, the Broomfield city council banned the use of perfluoroalkyl and polyfluoroalkyl substances (PFAS chemicals) in fracking operations.[159] Nevertheless, waivers were granted for three different projects sited closer than 2,000 feet from homes in 2021 and at least one, thus far, in 2022. A 2022 analysis of the impact of SB 181 in Colorado one year after its implementation found that the reforms wrought by this legislation have, up to now, led to many changes in process but few in outcome. "The oil and gas industry still largely gets its way with the agency and residents near oil and gas facilities are still suffering from negative effects to their health, safety, and welfare. The COGCC still operates from an outlook that presumes permitting of new facilities and the continued operation of existing facilities rather than first determining whether those activities are truly protective of people, the environment, and wildlife."[160]

In December 2017, **Australia's Northern Territory** government delayed a decision to extend or lift a fracking moratorium after a draft final report identified multiple risks to water, land, tourism, and indigenous culture. In April 2018, it lifted this moratorium. In September 2021, more than 60 climate scientists issued a dire warning over the plan to frack in the Beetaloo Basin within the Northern Territory after the federal government used grants to incentivize gas exploration there.[161, 162] In October 2021, Empire Energy won approval to begin fracking in the Beetaloo Basin. In December 2021, a territorial court voided the fracking grants but did not rule against fracking. However, consent must be secured from the region's traditional owners. Lack of consultation with landowners was the subject of a Senate inquiry in March 2022.[163]

In November 2018, the statewide moratorium in **Western Australia** was lifted over intense opposition, highlighting the limitations of aboriginal land rights. However, local bans in heavily populated areas of the state were left in place.

In October 2021 a state appeals court struck down a ballot initiative that, five years earlier, had banned new oil and gas wells and phased out wastewater disposal in **Monterey County, California.**

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[158] Judith Kohler, "Colorado Regulators Reject Drilling Plan near Homes in Growing Firestone Community," *Greeley Tribune*, March 10, 2022, https://www.greeleytribune.com/2022/03/10/colorado-rejects-kerr-mcgee-firestone-drilling-plan/.

[159] Sydney McDonald, "PFAS Chemicals Banned in Broomfield Fracking Operations," *Daily Camera*, February 9, 2022, https://www.dailycamera.com/2022/02/09/pfas-chemicals-banned-in-broomfield-fracking-operations/.

[160] Mike Foote and Casey Morris, "COGCC: One Year After Mission Change," Prepared for Colorado Sierra Club, January 17, 2022, https://www.larimeralliancеblog.org/wp-content/uploads/2022/01/COGCC-One-Year-After-Mission-Change-1.pdf.

[161] "Over 60 Scientists & Experts Call on NT Chief Minister Gunner to Honour Commitment to Net-Zero Fracking Emissions," The Australia Institute, September 23, 2021, https://australiainstitute.org.au/post/over-60-scientists-experts-call-on-chief-minister-gunner-to-honour-commitment-to-net-zero-fracking-emissions/.

[162] Christopher Knaus, "'Grave Mistake': Climate Scientists Issue Dire Warning over Beetaloo Basin Fracking Plans," *The Guardian*, September 22, 2021, https://www.theguardian.com/australia-news/2021/sep/23/grave-mistake-climate-scientists-issue-dire-warning-over-beetaloo-basin-fracking-plans.

[163] Christopher Knaus, "Beetaloo Traditional Owners yet to Be Consulted on Production of Fracking Gas, Senate Inquiry Hears," *The Guardian*, March 21, 2022, https://www.theguardian.com/australia-news/2022/mar/22/beetaloo-traditional-owners-yet-to-be-consulted-on-production-of-fracking-gas-senate-inquiry-hears.

Timeline of Medical Calls for Fracking Bans and Moratoriums

Health professionals are increasingly calling for bans or moratoriums on fracking, based on a range of health hazards and as reviews of the data confirm evidence for harm. Concerned Health Professionals of New York, which provided scientific and medical guidance for the successful effort to ban fracking in New York State, helped launch a movement by health professionals that has grown both nationally and, increasingly, around the world. It has inspired multiple affiliations of like-minded public health scientists and health care providers that have been advocating for moratoriums or bans on fracking, including Concerned Health Professionals of Maryland, Concerned Health Professionals of Pennsylvania, Concerned Health Professionals of Ireland, Concerned Health Professionals of Neuquén, Argentina, and Concerned Health Professionals UK.

In May 2015, the **Medical Society of the State of New York** passed a resolution recognizing the potential health impacts of natural gas infrastructure and pledging support for a governmental assessment of the health and environmental risks associated with natural gas pipelines. (See footnote 1826.) The American Medical Association (AMA) adopted a similar resolution that supports legislation requiring all levels of government to seek a comprehensive Health Impact Assessment regarding the health and environmental risks associated with natural gas pipelines. (See footnote 1825.)

In May 2016, **Physicians for Social Responsibility** called for a ban on fracking. (See footnote 2256.)

In July 2016, the UK health professional organization **Medact** released an updated assessment of the potential health impacts of shale fracking in England, concluding that the United Kingdom should abandon its policy to encourage shale gas extraction and urged an "indefinite moratorium" on fracking. (See footnote 2254.)

In October 2016, a group of **health care professionals in Massachusetts** called for an immediate moratorium on major new natural gas infrastructure until the impact of these projects on the health of the communities affected could be adequately determined through a comprehensive Health Impact Assessment. (See footnotes 2250, 2251.) The group noted that the operation of natural gas facilities increases the risk of human exposures to toxic, cancer-causing, and radioactive pollution due to the presence of naturally co-occurring contaminants, toxic additives to the hydraulic fracturing process, and through the operation of transmission pipelines.

Also in 2016, in a unanimous vote of the society's 300-member House of Delegates, the **Pennsylvania Medical Society** called for a moratorium on new shale gas drilling and fracking in Pennsylvania and an initiation of a health registry in communities with pre-existing operations. (See footnotes 2248, 2249.)

In March 2019, **Doctors for the Environment Australia** announced the reinforcement of its position that no new gas extraction of any kind should occur in Australia. (See footnote 2222.)

In November 2019, **over 100 leading Israeli scientists**, including Nobel laureate Robert

Aumann, called for the reversal of the government's decision to build a new network of gas-fired power plants and appealed for a transition to renewable energy. "During the production, refining and delivery of the gas, much greater quantities of methane are released than were previously recognized. These emissions contain volatile organic compounds that are recognized as carcinogenic." (See footnote 2219.)

In January 2020, the **Canadian Association of Physicians for the Environment** called for a moratorium on the development of new fracked natural gas wells in each province and territory across Canada and a plan to phase out existing fracking wells to meet Canada's commitments under the Paris Agreement. In addition, they asked for health assessments to prioritize wells for early closure and just transition for industry workers to help them prepare for a new low-carbon economy. (See footnote 2216.)

In December 2020, **the Massachusetts Medical Society** passed a resolution calling for "a legislative review of the approval process of the Enbridge natural gas compressor station in Weymouth and why the health impact assessment did not include a safety evacuation plan, an assessment of the project's climate impact, or consideration of the important health risks from emissions to the children who live in close proximity to the compressor."

In February 2022, **United Kingdom medical institutions** with a combined membership of more than 250,000, including the British Medical Association and the Royal Colleges of Physicians, Paediatricians, Obstetricians and Gynaecologists, and Psychiatrists, plus over 600 individual health professionals, called for an immediate halt to new oil and gas exploration. "As healthcare professionals, we know that any new fossil fuel projects and their contribution to climate change constitute a grave threat to our patients and the resilience of our healthcare system."[164]

[164] Adele Waters, "Medical Leaders Urge Ministers to End UK's Fossil Fuel Dependence," *BMJ*, 2022, o389, https://doi.org/10.1136/bmj.o389.

Emerging Trends

1) Regulations are incapable of preventing harm.

Studies reveal inherent problems in the natural gas and oil extraction process, such as well integrity failures caused by aging or the pressures of fracking itself, in the process of extracting fracking fluids from the well, and in the waste disposal process. These issues lead to water contamination, greenhouse gas emissions, air pollution with carcinogens and other toxic chemicals, earthquakes, and a range of health, environmental and other stressors inflicted on communities.

Some of fracking's many component parts—which include the subterranean geological landscape itself—are simply not controllable.

Compounding the innate unpredictability of the fracking process: The number of wells and their attendant infrastructure continues to proliferate, creating burgeoning cumulative impacts, and the size of individual wells keeps growing. With the horizontal portions of a single well now extending as far as two miles or more underground, fluid injections, once typically three to five million gallons per fracked well, now can easily reach 10 to 20 million gallons per well.

The injection of ever-increasing volumes of fluids into an ever-increasing number of wells creates significant deformations in the shale. These are translated upwards, a mile or more, to the surface. Along the way, these "pressure bulbs" can impact, in unpredictable ways, faults and fissures in the overlying rock strata, including strata that intersect freshwater aquifers. Such pressure bulbs may mobilize contaminants left over from previous drilling and mining activities. (See footnotes 683, 684.) No set of regulations can obviate these potential impacts to groundwater.

Regulations cannot eliminate earthquake risks. (See footnote 1202.) Fracking activities have triggered earthquakes around the world. New research in California finds that oilfield waste injection is linked to earthquakes near the San Andreas Fault.[165] In spite of emerging knowledge about the mechanics of how fracking and the underground disposal of fracking waste trigger earthquakes via activation of faults, no model can predict where or when earthquakes will occur or how powerful they will be. Induced earthquakes can occur many miles from fracking sites. (See footnote 224.) According to the UK's Oil and Gas Authority, methods for predicting a relationship between the volume of injected fracking fluids and the location, timing, and magnitude of seismic activity "lack convincing empirical evidence or proven theoretical basis." (See footnote 1139.)

Regulations cannot prevent air pollution. The state of California determined that fracking can have "significant and unavoidable" impacts on air quality, including driving pollutants to levels that violate air quality standards. (See footnote 449.) In northeastern Colorado, ambient levels of atmospheric hydrocarbons have continued to increase even with stricter emission standards. (See

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[165] Thomas H. Goebel and Manoochehr Shirzaei, "More than 40 Yr of Potentially Induced Seismicity Close to the San Andreas Fault in San Ardo, Central California," *Seismological Research Letters* 92, no. 1 (2021): 187–98, https://doi.org/10.1785/0220200276.

footnote 464.) Tighter state regulations and tougher enforcement, including unannounced visits by state health inspectors equipped with infrared cameras, have reduced leaking methane and toxic vapors at individual well sites, but total air emissions continue to rise as the total number of wells continues to increase. At this writing, there are 53,000 active oil and gas wells in Colorado.[166]

Regulations cannot stop radioactive emissions. Radioactive elements commonly found in shale formations are released during the process of drilling and fracking. They may accumulate in tubes, pipes, and equipment at fracking sites at levels known to cause health risks. Excess radioactivity has been detected in the soil near well pads, downstream of water facilities where fracking wastewater is treated, and in municipal landfills where fracking waste is dumped. (See footnotes 825, 827.) Radioactive liquids and solid drilling waste from fracking operations in the United States are essentially unregulated. Radioactive airborne particles are also released from fracking wells themselves and are detectable in residential areas downwind from drilling and fracking operations.[167]

Regulations cannot stop wells from leaking. Methane leakage of active wells is wildly variable: Four percent of wells nationwide are responsible for fully half of all methane emissions from drilling and fracking-related activities. Predicting which wells will become "super-emitters" is not possible, according to a survey of 8,000 wells using helicopters and infrared cameras. However, as is revealed in a recent study, marginal wells near the end of their lifespans—so-called stripper wells—appear to represent a disproportionately large source of methane emissions relative to their production, sometimes leaking more gas than is extracted and put into a pipeline.[168] Stripper wells are typically not profitable to operate but, because the cost of decommissioning them can be greater than the cost of keeping them running, they remain online or at the ready.

In addition to unintentional well leakage, purposeful methane releases are engineered into the routine operation of fracking extraction, processing, and transport infrastructure, as when vapors are vented through release valves in order to regulate pressure and prevent explosions. These releases are not fixable plumbing problems. (See footnotes 1590, 1591.)

2) Idle and abandoned wells are a significant source of methane leakage.

Long after they have ceased pumping oil or gas, well sites continue to leak in ways that are not always fixable. Idle and abandoned wells are a significant source of methane leakage into the atmosphere, and, based on findings from New York and Pennsylvania, may exceed cumulative

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[166] Bruce Finley, "Colorado's Unannounced Air-Pollution Inspections at Oil and Gas Sites Are Showing Results—yet Emissions Are up as Production Increases," *Denver Post*, April 21, 2019, sec. Environment, https://www.denverpost.com/2019/04/21/colorado-air-pollution-oil-gas-sites/.
[167] Carly Cassella, "Elevated Radiation Found near US Fracking Sites Has Public Health Experts Worried," Science Alert, October 23, 2020, https://www.sciencealert.com/elevated-radiation-levels-discovered-near-us-fracking-sites-study-finds.
[168] Jacob A. Deighton et al., "Measurements Show That Marginal Wells Are a Disproportionate Source of Methane Relative to Production," *Journal of the Air & Waste Management Association* 70, no. 10 (2020): 1030–42, https://doi.org/10.1080/10962247.2020.1808115.

total leakage from oil and gas wells currently in production in these states. Plugging abandoned wells can, but does not always, reduce methane emissions, and plugs themselves deteriorate over time. (A well is plugged when the wellbore is filled with cement or clay after debris and uncemented pipe is removed. See footnote 789. An unplugged well is considered idle if it has not produced oil or gas for two or more years.) Further, countless abandoned wells are unmapped and their locations unknown. Many have no apparent owner.

Inactive wells left behind by industry during energy price downturns or after bankruptcy are growing in number across North America, are poorly monitored and, as conduits for toxic air pollution and fluid leakage, are health and safety threats. Some have exploded. As well casings deteriorate, methane gas can mix with gypsum rock to create deadly hydrogen sulfide gas.[169] State and federal policies that do not require companies to post bonds covering clean-up costs prior to the start of operations incentivize companies to delay plugging wells as long as possible.

Of the nearly half million oil and gas wells in Alberta, Canada alone, 172,000 wells are inactive, decommissioned, or abandoned and in need of reclamation.[170] The amount of methane seeping from them is not known. The risk of leaks is known to increase inexorably as inactive wells age.[171, 172] As revealed in a pair of investigations, there is no systematic auditing or monitoring of sites that have been deemed reclaimed and mounting evidence to suggest that Alberta's inactive oil and gas wells are not reclaimed in the long run.[173, 174]

In its current draft Greenhouse Gas Emissions Inventory, the U.S. Environmental Protection Agency (EPA) estimates that 3.5 million inactive oil and gas wells are scattered across the United States, of which only 39 percent are plugged.[175] Pennsylvania alone is home to 200,000 to 750,000 old wells, most of which are not mapped or even visible on the surface.[176]

California has 124,000 abandoned oil and gas wells and 38,000 idle wells. That same EPA study measured methane emissions from a representative sample of abandoned oil and gas wells in

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[169] Chris Ensing, "Wheatley Explosion Could Be 'Tip of the Iceberg' in Ontario Given Number of Abandoned Wells: Expert," *CBC News*, September 2, 2021, https://www.cbc.ca/news/canada/windsor/wheatley-explosion-gas-wells-1.6161023.
[170] "Oil and Gas Liabilities Management," Alberta.ca, 2022, https://www.alberta.ca/oil-and-gas-liabilities-management.aspx.
[171] Sharon J. Riley, "Regulator Projects Alberta's Inactive Well Problem Will Double in Size by 2030, Documents Reveal," The Narwhal, April 8, 2019, http://thenarwhal.ca/regulator-projects-albertas-inactive-well-problem-will-double-in-size-by-2030-documents-reveal/.
[172] Alec Jacobson, "These Zombies Threaten the Whole Planet: Canada's Oil Patch Has Nearly 100,000 Suspended Wells, Neither Active nor Capped, and They're a Worrying Source of Planet-Warming Methane," *The New York Times*, October 30, 2020, https://www.nytimes.com/2020/10/30/climate/oil-wells-leak-canada.html?referringSource=articleShare.
[173] Sharon J. Riley, "Report 'Buried' by Alberta Government Reveals 'Mounting Evidence' That Oil and Gas Wells Aren't Reclaimed in the Long Run," *The Narwhal*, January 23, 2020, https://thenarwhal.ca/report-buried-by-alberta-government-reveals-mounting-evidence-that-oil-and-gas-wells-arent-reclaimed-in-the-long-run/.
[174] Sharon J. Riley, "Stonewalled: Alberta Ignored Warnings about Oil and Gas Cleanup, Ex-Government Scientist Says," March 20, 2022, https://thenarwhal.ca/alberta-oil-gas-wells-reclamation-scientist/.
[175] EPA, "Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020" (U.S. Environmental Protection Agency, February 15, 2022), https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020.
[176] Mike Lee, "Millions of Abandoned Wells Spark Climate, Safety Fears," E&E News, May 20, 2019, https://web.archive.org/web/20190520165746/https://www.eenews.net/stories/1060364121.

California and found a wide range of leakage rates—with unplugged idle wells leaking more than plugged abandoned wells and with the worst culprits leaking enough to substantially impact California's methane budget.[177] No state or federal agency routinely monitors methane leakage from abandoned and idle wells. (See footnotes 1344, 1349.)

Low prices for oil and gas throughout 2019 and 2020 triggered a 50 percent rise in oil and gas company bankruptcies and resulted in a further surge in abandoned and so-called orphaned wells for which no responsible party can be located. The upfront bonds required of drillers to cover future cleanup and well plugging—a condition of receiving of permit to drill—are typically inadequate, shifting the full cost of remediation to state and federal taxpayers (See footnote 1307.) In 2019, the U.S. Government Accountability Office estimated a clean-up and plugging cost of $20,000 to $145,000 per abandoned well and projected a total of cost $60 billion to $435 billion to clean up all of the abandoned oil and gas wells in the United States. (See footnote 1321.) State and federal policies have further incentivized abandoning wells, rather than paying to plug them, by allowing marginal or idle wells to remain on the books as active wells even when they may be leaking more methane into the atmosphere than they are capturing. A 2021 *Bloomberg* investigation of idle wells in Ohio found methane leaks at most of the 44 sites visited by reporters, with 59 percent of sites leaking methane at levels sufficient to trigger a safety alarm.[178]

In November 2021, the bipartisan infrastructure packaged earmarked $4.7 billion for the plugging and remediation of abandoned or orphaned gas and oil wells, an indirect subsidy to the fracking industry. As of this writing, 26 states have indicated that they intend to apply for these funds.

3) Fracking is accelerating the climate crisis.

Natural gas is 85-95 percent methane. On the grounds that natural gas emits, when combusted, only 53 percent of the carbon dioxide emitted by coal, early promoters of fracking argued that natural gas could serve as a "bridge fuel" while renewable energy sources ramp up. Scientific evidence now disproves these claims and shows that natural gas is as damaging to the climate as coal and may be worse. Now that satellites and aircraft can observe methane on a fine scale, we see a growing gap between the measurable methane emissions from fracking operations and the estimated levels reported by the oil and gas industry. Recent research shows that fracking operations and their ancillary infrastructure are emitting significantly more methane than disclosed by the industry and several times higher than current greenhouse gas inventories have estimated.[179] The liquefaction and transportation of natural gas as LNG raises its greenhouse gas

[177] Eric D. Lebel et al., "Methane Emissions from Abandoned Oil and Gas Wells in California," *Environmental Science & Technology* 54, no. 22 (2020): 14617–26, https://doi.org/10.1021/acs.est.0c05279.
[178] Zachary R. Mider and Rachel Adams-Heard, "An Empire of Dying Wells," *Bloomberg Green*, October 12, 2021, https://www.bloomberg.com/features/diversified-energy-natural-gas-wells-methane-leaks-2021/?cmpid=BBD101221_MKT&utm_medium=email&utm_source=newsletter&utm_term=211012&utm_campaign=markets&sref=kq5Tnm64.
[179] Terry Slavin, "Analysis: Benchmark of Big Oil on Methane Emissions Shows 'Significant Gap' between Reality and Reporting," Reuters, August 14, 2021, https://www.reuters.com/article/emissions-methane/analysis-benchmark-

emissions even further, by another 30 percent, both because of the need for evaporative cooling and venting but also because flaring is used to control pressure during regasification.

Research also demonstrates that methane, while less persistent in the atmosphere than carbon dioxide, is a far more powerful greenhouse gas than formerly understood. The United Nations Intergovernmental Panel on Climate Change (IPCC) estimates that over a 20-year time frame—longer than the decade remaining to limit global warming to 1.5^{o} C—methane can, pound for pound, trap 86 times more heat than carbon dioxide. (See footnote 1641.) Methane concentrations in the atmosphere have nearly tripled since pre-industrial times, with levels surging past 1,900 parts per billion by the end of 2021.[180]

Altogether, the science to date shows that methane is the biggest contributor to the ongoing failure to meet agreed-upon global emissions targets and stabilize the climate. According to the IPCC's Sixth Assessment Report, the first installment of which was released in August 2021, methane has contributed nearly 40 percent of all global warming to date. The report devoted an entire chapter to the problem of methane and potent heat-trapping gasses other than carbon dioxide. To avoid exceeding 1.5^{o} C of global warming, the IPCC urged "strong, rapid, and sustained reductions" in methane emissions. (See footnote 40.) At the November 2021 climate summit in Glasgow, 105 nations signed the Global Methane Pledge to cut methane emissions globally by 30 percent by 2030 in an attempt to limit warming to 1.5^{o} C.

The call to curtail methane in order to stabilize the climate was echoed in 2021 by the both the U.N. Environment Programme (UNEP) and the International Energy Agency (IEA), which found that oil and gas operations around the world emit a level of methane that is equivalent to all the energy-related emissions of carbon dioxide from the European Union.[181] (See footnotes 1493, 2142.) According to a 2019 study, shale gas production in North America alone contributes more than half of all of the increased emissions from fossil fuels globally and at least one-third of the total increased emissions from all sources globally over the past decade. (See footnote 1530.) A 2021 study found that reductions in human-caused methane emissions alone, of which oil and gas wells are the single largest source, could avert nearly one-third of the global warming expected in the next two decades. (See footnote 1474.)

Multiple studies, using a range of methodologies, now also show that real-world methane leakage rates from North American drilling and fracking operations greatly exceed earlier EPA estimates and are likely driving the current surge in global methane levels. IEA's Global Methane Tracker 2022 found that global methane emissions from the energy sector are about 70 percent greater than the amount national governments have officially reported, with North American methane emissions reported at 14.0 million tonnes (Mt), but estimated by the IEA to be 20.9 Mt.[182]

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of-big-oil-on-methane-emissions-shows-significant-gap-between-reality-and-reporting-idUSMTZSPDEH8EU9J79K.

[180] Jeff Tollefson, "Scientists Raise Alarm over 'Dangerously Fast' Growth in Atmospheric Methane," *Nature*, February 8, 2022, d41586-022-00312–2, https://doi.org/10.1038/d41586-022-00312-2.

[181] International Energy Agency, "Methane Tracker 2021" (IEA, January 2021), https://www.iea.org/reports/methane-tracker-2021.

[182] International Energy Agency, "Methane Tracker 2022" (IEA, February 2022), https://www.iea.org/reports/global-methane-tracker-2022/overview.

Methane escapes into the atmosphere from all parts of the extraction, processing, and distribution system—for both oil and gas—all the way to the burner tip. In the heavily drilled Barnett Shale of northeastern Texas, methane emissions were shown to be 50 percent higher than the EPA had estimated. Fracking operations and associated infrastructure contributed 71-85 percent of the methane emissions in the region. A 2018 analysis of methane leaks from the entire U.S. oil and gas supply chain found leakage rates were 60 percent higher than reported by the EPA, and a 2019 study in southwestern Pennsylvania found shale gas emissions that were underreported by a factor of five when compared to EPA estimates. (See footnotes 1523, 1558.) A November 2021 study of the intensely drilled and fracked Uintah Basin in northern Utah found that 6 to 8 percent of the total gas extracted escaped as atmospheric emissions, a shockingly high leakage rate that remained constant between 2015 and 2020, even as gas production in the region declined over the same period.[183]

The Permian Basin in West Texas and eastern New Mexico—the world's largest shale deposit for oil and gas—accounts for more than 30 percent of total U.S. oil extraction. According to a 2020 study using satellite observations, methane leakage from drilling and fracking activities in the Permian is two times higher than previously estimated and is now thought to contribute half of the methane emissions from all U.S. oil- and gas-producing regions, with newer wells and associated flaring operations a major culprit. (See footnote 1492.) As we went to press, a Stanford University study that combined aerial data with surface-level measurements calculated methane emissions at 9.4 percent of gas production in New Mexico's portion of the Permian Basin, a leakage rate that is 6.7 times higher than the EPA's 1.4 percent estimate.[184, 185] Halting methane emissions from the Permian could do more to slow climate change than almost any other single measure.[186]

Much of the methane emitted from drilling and fracking activities and associated infrastructure originates not from accidental leaks but from purposeful losses that are inherent in the design of the industry's machinery or to normal operating use and are, therefore, not possible to mitigate. (See footnotes 1818-1820.) Methane is vented into the atmosphere during routine maintenance on compressor stations and pipelines; to create evaporative cooling for LNG storage and transport; during the flowback period after a well is fracked; and as an emergency procedure to control pressures.

Malfunctioning flare stacks are a major culprit. Research from Texas comparing satellite measurements with data on flaring volumes collected in state databases reveal that mass venting of raw gas into the atmosphere is much higher than reported, with methane emissions exceeding 3 percent of production rather than the widely presumed 1-2 percent. (See footnotes 397, 398.)

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[183] John C. Lin et al., "Declining Methane Emissions and Steady, High Leakage Rates Observed over Multiple Years in a Western US Oil/Gas Production Basin," *Nature Scientific Reports* 11, no. 1 (2021): 22291, https://doi.org/10.1038/s41598-021-01721-5.
[184] Yuanlei Chen et al., "Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey," *Environmental Science & Technology*, March 23, 2022, acs.est.1c06458, https://doi.org/10.1021/acs.est.1c06458.
[185] Maggie Astor, "Methane Leaks in New Mexico Far Exceed Current Estimates, Study Suggests," *New York Times*, March 24, 2022, https://www.nytimes.com/2022/03/24/climate/methane-leaks-new-mexico.html.
[186] Zachary R. Mider, "The Methane Hunters," *Bloomberg Businessweek + Green*, August 20, 2021, https://www.bloomberg.com/features/2021-methane-hunters-climate-change/.

Liquid storage tanks are significant emitters of methane, according to a 2021 study.[187] Inactive, abandoned wells are also significant methane emitters. Methane leakage at the levels now being documented, using multiple approaches in measurement and modeling, negates previously hypothesized benefits from burning methane instead of coal in most existing power plants. A 2020 study demonstrated that trading coal plants for gas plants does not reduce cumulative lifetime carbon emissions when upstream methane leaks are factored in. (See footnote 1977.)

Rising methane levels in the atmosphere make increasingly difficult the urgent task of limiting global warming to below levels called for in the Paris Agreement, which was based on older presumptions that global methane levels had plateaued. Instead, methane levels began to rise in 2007 and then shot up sharply in 2014, a time period that corresponds to a massive increase in the use of fracking in North America.

Indeed, increasing evidence points to fossil fuels in general, and fracking in particular, as the main driver of this surge. Isotopic analysis identifies shale gas production as the source of at least one-third of the total increased emissions from all sources globally and the source of more than half of the increased emissions from fossil fuels globally. These results suggest that the North American fracking boom is a major culprit of the ongoing rise in atmospheric methane levels. (See footnotes 1530, 1537, 1559.)

4) Fracking contaminates and depletes drinking water sources.

Many instances of drinking water sources contamination by drilling and fracking activities, or by associated waste disposal, exist. As identified by the EPA in 2016, water contamination occurs through three confirmed pathways: spills; discharge of fracking waste into rivers and streams; and underground migration of chemicals, including gas, into drinking water wells.

Methane and fracking-related contaminants can reach drinking water sources through cracks in well casings, through spaces between the casing and the wellbore, through naturally occurring fractures and fissures connecting shale layers with aquifers, and through abandoned wells. Methane migration into drinking water aquifers can change water chemistry in ways that mobilize metals or release hydrogen sulfide. (See footnote 561.)

In June 2020, the attorney general of Pennsylvania announced 15 criminal counts related to fracking activities in northeastern Pennsylvania, including nine felony charges, filed against Cabot Oil and Gas stemming from violations of the state's Clean Streams Law. According to the grand jury's report, "We find that, over a period of many years, and despite mounting evidence, Cabot Oil and Gas failed to acknowledge and correct conduct that polluted Pennsylvania water through stray gas migration."[188] The charges were part of a two-year grand jury investigation into environmental crimes committed by fracking companies that focused on contamination of

[187] Jeffrey S. Rutherford et al., "Closing the Methane Gap in US Oil and Natural Gas Production Emissions Inventories," *Nature Communications* 12, no. 1 (2021): 4715, https://doi.org/10.1038/s41467-021-25017-4.
[188] Susan Phillips, "Pa. Attorney General Charges Cabot Oil and Gas with Environmental Crimes," State Impact Pennsylvania, June 15, 2020, https://stateimpact.npr.org/pennsylvania/2020/06/15/pa-attorney-general-charges-cabot-oil-and-gas-with-environmental-crimes/.

drinking water and damage to public health.[189, 190] As of February 2022, the case had not yet gone to trial and had entered a difficult phase as the state's criminal environmental laws offer limited penalties and with at least one resident insisting that any settlement must compel Cabot to connected the homes of affected residents to public water.[191]

A second company, Range Resources, pleaded no contest to environmental crimes at two sites in southwestern Pennsylvania involving leaks and spills that contaminated surface water and groundwater.[192] In its report, the grand jury also criticized Pennsylvania's Department of Health for failure to collect data and act on health complaints and denounced the state's Department of Environmental Protection for its "culture of inadequate oversight" that resulted in harm to public health and the environment.

Researchers working in Texas found 19 different fracking-related contaminants—including cancer-causing benzene—in hundreds of drinking water samples collected from the aquifer overlying the heavily drilled Barnett Shale, thereby documenting widespread water contamination.

Similarly, researchers working in Susquehanna County, Pennsylvania found chemical additives known to be ingredients in fracking fluid as well as chemicals associated with fracking wastewater in private drinking water wells near fracking operations and in nearby lakes, springs, and ponds. (See footnote 541.) Also in Pennsylvania, a solvent used in fracking fluid was found in drinking water wells near drilling and fracking operations known to have well-casing problems. Fracking waste discharged to rivers and streams has led to elevated levels of brominated and iodinated disinfection byproducts that are particularly toxic and "raise concerns regarding human health." (See footnote 599.)

In New Mexico a shift from conventional drilling to fracking triggered dramatic increases in groundwater contamination with dissolved solids, sodium, and calcium, with levels of contaminants correlated with density of oil wells.

In California, state regulators admitted that they had mistakenly allowed oil companies to inject drilling wastewater into aquifers containing clean, potable water. (See footnotes 662, 663.)

A 2021 Physicians for Social Responsibility (PSR) investigation revealed that the EPA had, ten years earlier and over the objections of its own staff scientists, approved the use of chemicals for oil and gas drilling and/or fracking that the scientists feared could degrade into highly toxic per- and polyfluoroalkyl substances (PFAS, or so-called "forever chemicals"). PSR also found that oil

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[189] Office of the Attorney General, Commonwealth of Pennsylvania, "AG Shapiro and 43rd Statewide Grand Jury," press release, June 15, 2020, https://www.attorneygeneral.gov/taking-action/press-releases/ag-shapiro-and-43rd-statewide-grand-jury-file-criminal-charges-against-nepa-fracking-company/.

[190] Office of the Attorney General, Commonwealth of Pennsylvania, "Report 1 of the Forty-Third Statewide Investigating Grand Jury," June 15, 2020, https://www.attorneygeneral.gov/wp-content/uploads/2020/06/FINAL-fracking-report-w.responses-with-page-number-V2.pdf.

[191] Michael Rubinkam, "'Irreversible': No Easy Fix for Pa. Water Fouled by Gas Driller," *The Philadelphia Inquirer*, February 18, 2022, https://www.inquirer.com/news/pennsylvania/pennsylvania-fracking-gas-drilling-tainted-water-dimock-criminal-case-20220218.html.

[192] Reid Frazier and Susan Phillips, "Pa. Grand Jury Report on Fracking: DEP Failed to Protect Public Health," State Impact Pennsylvania, June 25, 2020, https://stateimpact.npr.org/pennsylvania/2020/06/25/pa-grand-jury-report-on-fracking-dep-failed-to-protect-peoples-health/.

and gas companies had used PFAS—or chemicals that could break down into PFAS in at least 1,200 wells in six U.S. states (Louisiana, Arkansas, New Mexico, Texas, Oklahoma, and Wyoming). Extensive use of chemical trade secret claims and other lax chemical disclosure rules prevented PSR researchers from determining whether any of the 1,200 wells were injected with the same chemicals approved by the EPA. PFAS chemicals are linked to cancer and birth defects at vanishingly low concentrations, are known to contaminate drinking water sources, and do not break down in the environment. (See footnotes 514, 515). A follow-up analysis of public data by the *Philadelphia Inquirer* identified the use of PFAS in at least eight Pennsylvania fracking wells between 2012 and 2014.[193] Building on the multi-state report, data unearthed by PSR reveals that PFAS have, since 2008, also been used in fracking operations in at least ten counties in Colorado, mostly in Weld and Garfield counties.[194]

Fracking also threatens drinking water supplies through water depletion, especially in arid regions. According to a 2019 report, the volume of water used for fracking U.S. oil wells has more than doubled since 2016. (See footnote 558.) Oil and gas operations in the arid Permian Basin used eight times more water for fracking in 2018 than they did in 2011, threatening groundwater supplies. (See footnote 7.) In Arkansas, researchers found that water withdrawals for fracking operations deplete streams used for drinking water and recreation. (See footnote 588.)

With increasing volumes of wastewater now exceeding the storage capacity for underground injection wells—and with underground injection linked to earthquake risk—Texas and Colorado are now petitioning the EPA to allow release of fracking wastewater into rivers and streams and to allow its use for irrigation and watering livestock. These practices further imperil drinking water sources.[195]

The trend toward mega-fracking, with longer and more extensive horizontal wellbores per well pad, coupled with the ongoing proliferation in the number of wells, has pushed the demand for water use in fracking operations ever higher, exacerbating both the problem of drinking water depletion and the problem of how to dispose of ever-increasing amounts of toxic fracking wastewater. A 2018 study found that water used for U.S. fracking operations increased by 770 percent per well between 2011 and 2016, while the amount of wastewater generated increased by 1,440 percent. (See footnote 572.)

[193] Editorial Board, “Fracking in Pennsylvania Used Toxic ‘Forever Chemicals’ as Pa. Officials Maintain Willful Ignorance,” *The Philadelphia Inquirer*, October 5, 2021, https://www.inquirer.com/opinion/editorials/fracking-pennsylvania-pfas-toxic-chemicals-water-20210805.html.
[194] Dusty Horwitt, Barbara Gottlieb, and Gary Allison, “Fracking with ‘Forever Chemicals’ in Colorado” (Physicians for Social Responsibility, January 2022), https://www.psr.org/wp-content/uploads/2022/01/fracking-with-forever-chemicals-in-colorado.pdf.
[195] Paul Stinson, “Texas, Oklahoma Want More Say in Handling Fracking Wastewater,” Bloomberg Law, August 15, 2019, https://news.bloomberglaw.com/environment-and-energy/texas-oklahoma-want-more-say-in-handling-fracking-wastewater.

5) Fracking creates air pollution at levels known to harm health.

More than 200 airborne chemical contaminants have been detected near drilling and fracking sites. Of these, 61 are classified as hazardous air pollutants, including carcinogens; 26 are endocrine-disrupting compounds that have been linked to reproductive, developmental, and neurological damage. In addition to the wells themselves, the sources of these air pollutants include a wide range of equipment, including condensate tanks, wastewater pits, and flare stacks. (See footnotes 412, 424.) A 2021 systematic review of the literature found that sources of methane emissions, which are located throughout the oil and gas supply chain, are nearly always also sources of other health-damaging air pollutants.[196]

Drilling and fracking operations emit fine particles, including soot from diesel exhaust; volatile organic air pollutants, including benzene and formaldehyde; and nitrogen oxides that combine to create ground-level ozone (smog) even in otherwise rural regions. Elevated levels of fine particle emissions from fracking well pads have been measured at distances of more than four miles. (See footnote 399.) Exposure to these pollutants is known to cause premature death, exacerbate asthma, and contribute to poor birth outcomes and increased rates of hospitalization and emergency room visits.

The production phase of drilling and fracking operations—when the raw gas or oil is flowing from the well—typically emits the highest levels and most complex mixtures of hazardous air pollutants over the longest period of time. A 2021 study that quantified ozone precursor emissions from oil and gas extracting regions across the United States found that volatile organic pollutants and nitrogen oxides from oil and gas basins are three times higher than current estimates. (See footnote 376.) In the Permian Basin, levels of hydrogen sulfide gas from drilling and fracking operations can exceed legal limits in the ambient air of communities near drilling and fracking operations. (See footnote 393, 394.) In California's San Joaquin Valley, evaporation from liquid waste pits is a significant source of benzene, toluene, ethylbenzene, and xylene. (See footnote 398.)

Of the lower 48 states, six states (Texas, Oklahoma, Colorado, North Dakota, West Virginia, and Pennsylvania) produce nearly 70 percent of the nation's natural gas and over 74 percent of its onshore crude oil. These six states experience the highest levels of ground-level ozone and fine particle pollution attributable to oil and gas extraction activities.

Volatile organic compounds (VOCs) from drilling and fracking operations, together with nitrogen oxides, are responsible for 17 percent of locally produced ozone in Colorado's heavily drilled Front Range. (See footnote 438.) Colorado has exceeded federal ozone limits for the past decade, a period that corresponds to a boom in oil and gas drilling (See footnote 436.) Air pollution near drilling and fracking operations is high enough in some Colorado communities to raise cancer risks, according to a 2018 study. (See footnote 423.) A 2021 study found that the fracking boom in northeastern Colorado was a significant source of toxic and smog-making air pollutants, including benzene and toluene. (See footnote 388.)

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[196] Drew Michanowicz et al., "Methane and Health-Damaging Air Pollutants from the Oil and Gas Sector: Bridging 10 Years of Scientific Understanding," Technical Report (PSE Healthy Energy, October 2021), https://www.psehealthyenergy.org/our-work/publications/archive/methane-and-health-damaging-air-pollutants-from-the-oil-and-gas-sector-bridging-10-years-of-scientific-understanding/.

Living near drilling and fracking operations significantly increases asthma attacks for residents of Pennsylvania. Those living near active gas wells are 1.5 to 4 times more likely to suffer from asthma attacks than those living farther away, with the closest group having the highest risk. (See footnotes 1043, 1044.)

In California, fracking occurs disproportionately in areas already suffering from serious air quality problems and can drive ozone and other federally regulated air pollutants to levels that violate air quality standards. (See footnotes 448, 449.) This increased air pollution and smog formation pose a serious risk to all those already suffering from respiratory issues, such as children with asthma. With an average of 203 high-ozone days a year, intensely fracked Kern County, California is the fifth-most ozone-polluted county in the nation, according to the American Lung Association. In September 2021, an analysis of drilling sites across California based on 14 years of air monitoring data found that living near oil and gas wells increases the exposure of nearby residents to levels of air pollutants sufficient to harm health. The study documented elevated ozone levels up to 2.5 miles from the wells, with Black and Latino communities disproportionately affected.[197]

Several studies have documented a sharp uptick in atmospheric ethane, a gas that co-occurs with methane and whose presence is attributable to emissions from oil and gas wells. This trend reverses a previous, decades-long decline. Ethane is a potent precursor to ground-level ozone. (See footnotes 408, 440-442.)

The United States leads the world in the number of drill site **flaring operations**. Flares are used to control pressure but, more frequently, to burn off natural gas as waste during oil drilling in places that lack infrastructure for gas capture and transport. The ongoing boom in domestic oil production enabled by fracking has caused natural gas flaring to proliferate. Emissions from flare stacks contribute to ozone creation and include several carcinogens, notably benzene and formaldehyde. Flaring also releases carbon monoxide, carbon black, and toxic heavy metals. In 2016, the EPA acknowledged that it had dramatically underestimated health-damaging air pollutants from flaring operations. (See footnotes 434, 435.) A 2017 study of plume samples from gas flares in North Dakota found that incomplete combustion from flaring is responsible for 20 percent of the total emissions of methane and ethane from the Bakken shale fields—more than double the expected value. (See footnote 430.)

Studies of flaring in the Eagle Ford Shale region of Texas show that flaring was the dominant source of exposure to nitrogen oxide air pollutants in rural areas. (See footnote 414.) An August 2021 study that used aircraft equipped with gas-imaging cameras to identify flares and compared the results with the state flaring database found that, in the Texas Permian oil basin, more than two-thirds of flares (69-84 percent) are operating without state permits.[198, 199] As we go to press, a new study of the environmental health costs of flaring in the Bakken Shale region of North

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[197] David J.X. Gonzalez et al., "Upstream Oil and Gas Production and Ambient Air Pollution in California," *Science of The Total Environment* 806 (2022), https://doi.org/10.1016/j.scitotenv.2021.150298.
[198] Jack McDonald and Sharon Wilson, "Flaring in Texas: A Comprehensive Government Failure" (Earthworks, August 2021), https://41p14t2a856b1gs8ii2wv4k4-wpengine.netdna-ssl.com/assets/uploads/2021/08/Flaring-in-Texas-FINALsm.pdf.
[199] Valerie Volcovici and Nichola Groom, "Most Flares from Texas Permian Oil Drilling Lack Permits -Study," Reuters, August 19, 2021, https://www.reuters.com/business/energy/most-flares-texas-permian-oil-drilling-lack-permits-study-2021-08-19/.

Dakota finds a link between increased hospitalizations for respiratory distress and increases in flaring activity, with effects seen in people living up to 60 miles away.[200] A second study calculated that U.S. flaring was responsible for 26 to 53 premature deaths in 2019 from exposure to the soot-like air pollutant carbon black alone.[201]

6) Public health problems associated with fracking include prenatal harm, respiratory impacts, cancer, heart disease, mental health problems, and premature death.

As we go to press, a major new national study from Harvard University has linked air pollution from fracking sites to early death of nearby residents. Using data gathered from more than 15 million Medicare recipients and records from more than 2.5 million gas and oil wells, the research team found that older citizens (65 years old and up) living near wells were at higher risk for dying earlier than those who lived in areas without fracking and, further, that those living downwind from fracking wells were more likely to suffer premature death than those upwind.[202]

Poor birth outcomes have been linked to fracking activities in multiple studies in multiple locations using a variety of methods. Studies of mothers living near oil and gas extraction operations consistently find impaired infant health, especially elevated risks for low birth weight and preterm birth. As we go to press, a new study in Pennsylvania finds "consistent and robust evidence that drilling shale gas wells negatively impacts both drinking water and quality of infant health." Using exact geographic locations of mothers' residences, gas wells, and public drinking water sources—as well as dates of infant births, timing of drilling and fracking activities, and water measurements—the research team showed that shale gas operations near mothers' homes raises levels of contaminants in drinking water and raises the risk for preterm birth and low birthweight.[203] A new Canadian study found that babies born to individuals living within 6.2 miles (10 kilometers) of one or more fracking wells in rural Alberta had increased incidence of low birth weight, premature birth, and major congenital abnormalities. This study, published in *JAMA Pediatrics*, included nearly 35,000 pregnancies over a six-year period, 2013-2018.[204]

A 2020 study of pregnant women living in the Eagle Ford Shale area of Texas found that exposure to oil and gas flaring was associated with a 50 percent increase in the risk of preterm birth.[205] (See footnotes 978, 979.) A 2020 study of pregnant women in California's San Joaquin Valley found that mothers with the highest exposure to oil and gas wells were 8 to 14 percent

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[200] Wesley Blundell and Anatolii Kokoza, "Natural Gas Flaring, Respiratory Health, and Distributional Effects," *Journal of Public Economics* 208 (April 2022): 104601, https://doi.org/10.1016/j.jpubeco.2022.104601.
[201] Chen Chen et al., "Black Carbon Emissions and Associated Health Impacts of Gas Flaring in the United States," *Atmosphere* 13, no. 3 (February 25, 2022): 385, https://doi.org/10.3390/atmos13030385.
[202] Longxiang Li et al., "Exposure to Unconventional Oil and Gas Development and All-Cause Mortality in Medicare Beneficiaries," *Nature Energy*, 2022, https://doi.org/10.1038/s41560-021-00970-y.
[203] Elaine L. Hill and Lala Ma, "Drinking Water, Fracking, and Infant Health," *Journal of Health Economics*, 2022, 102595, https://doi.org/10.1016/j.jhealeco.2022.102595.
[204] Zoe F. Cairncross et al., "Association Between Residential Proximity to Hydraulic Fracturing Sites and Adverse Birth Outcomes," *JAMA Pediatrics*, April 4, 2022, https://doi.org/10.1001/jamapediatrics.2022.0306.
[205] Wendee Nicole, "On Wells and Wellness: Oil and Gas Flaring as a Potential Risk Factor for Preterm Birth," *Environmental Health Perspectives* 128, no. 11 (November 23, 2020), https://doi.org/10.1289/EHP7952.

more likely to experience a preterm birth. These risks were especially pronounced for Black and Hispanic women. (See footnote 980.) Another 2020 study, the largest of its kind, found that living near active oil and gas wells during pregnancy increased the risk of low-birthweight babies born to mothers throughout California. (See footnote 982.)

Similarly, a 2017 study that examined birth certificates for all 1.1 million infants born in Pennsylvania between 2004-2013 found indicators of poorer infant health and significantly lower birth weights among babies born to mothers living near fracking sites. (See footnote 1032.) Another Pennsylvania study found a 40 percent increase in the risk of preterm birth among infants born to mothers who lived near active drilling and fracking sites, while an Oklahoma study and two Colorado studies variously found an elevated incidence of neural tube defects and congenital heart defects. The newer studies add to existing evidence on poor birth outcomes related to fracking. (See footnotes 1000, 1013, 1019, 1071.)

A 2017 pilot study in British Columbia found elevated levels of muconic acid—a marker of benzene exposure—in the urine of pregnant women living near fracking sites. (See footnote 1034.) A 2019 study of pregnant Indigenous women living near fracking sites in British Columbia found elevated levels of the developmental toxicants barium and strontium in their hair and urine. (See footnote 1004.) A 2021 study found that the air inside the homes of 85 pregnant women living close to fracking operations in British Columbia had higher levels of volatile organic compounds, including chloroform and acetone, compared with the general population. Further, greater well density was linked to increased exposure. Proximity to fracking operations was inconsistently linked to preterm birth and smaller birthweights.[206, 207] (See also footnote 980.)

Prenatal health risks from fracking operations extend to mothers as well as their infants. A 2021study of more than 3 million pregnant women in Texas showed that living near an active oil or gas well increased the risks for high blood pressure (gestational hypertension) and eclampsia (onset of seizures or coma during pregnancy or childbirth).[208]

An emerging body of evidence from both human and animal studies shows harm to fertility and reproductive success from exposure to oil and gas operations, at least some of which may be linked to the dozens of known endocrine-disrupting chemicals used in hydraulic fracturing. (See footnotes 424, 533, 541, 566, 584, 723, 733, 984, 985, 1047, 2252, 2257.)

A 2017 Colorado study found higher rates of leukemia among children and young adults living in areas dense with oil and gas wells, while a Yale University research team reported that carcinogens involved in fracking operations had the potential to contaminate both air and water in nearby communities in ways that may increase the risk of childhood leukemia. The Yale team

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[206] Élyse Caron-Beaudoin et al., "Volatile Organic Compounds (VOCs) in Indoor Air and Tap Water Samples in Residences of Pregnant Women Living in an Area of Unconventional Natural Gas Operations: Findings from the EXPERIVA Study," *Science of The Total Environment* 805 (2022), https://doi.org/10.1016/j.scitotenv.2021.150242.
[207] Hina Alam, "Homes near Fracking Sites in B.C. Have Higher Levels of Some Pollutants, Study Finds," *CBC News*, September 23, 2021, https://www.cbc.ca/news/canada/british-columbia/homes-near-fracking-sites-in-b-c-have-higher-levels-of-some-pollutants-study-finds-1.6187801.
[208] Mary D Willis et al., "Associations between Residential Proximity to Oil and Gas Extraction and Hypertensive Conditions during Pregnancy: A Difference-in-Differences Analysis in Texas, 1996–2009," *International Journal of Epidemiology*, 2021, dyab246, https://doi.org/10.1093/ije/dyab246.

identified 55 known or possible carcinogens that are known to be used in fracking operations and that may be released into the air and water. Of these, 20 are linked to leukemia or lymphoma. (See footnotes 1039, 2238.)

In 2019, the *Pittsburgh Post-Gazette* documented 27 cases of Ewing's sarcoma, a rare bone cancer that tends to strike young people, in four counties in southwestern Pennsylvania that are at the center of the Marcellus Shale fracking boom.[209] Six cases occurred in the same school district. (The typical rate is 250 cases of Ewing's sarcoma per year in the United States as a whole. The cancer has no known cause.) There are also high numbers of other childhood cancers in the region, which is home to several polluting legacy industries. The Pennsylvania Department of Health reported "no conclusive findings" of a cancer cluster in the Canon-McMillan School District and Washington County, but as additional cases came to light, calls for more comprehensive investigations grew louder.[210, 211, 212, 213, 214] In November 2019, Governor Tom Wolf announced funding for two additional three-year studies, but the planning for this research is still in preliminary stages.[215]

Other documented adverse health indicators among residents living near drilling and fracking operations variously include exacerbation of asthma as well as increased rates of hospitalization, ambulance runs, emergency room visits, self-reported respiratory problems and rashes, motor vehicle fatalities, trauma, drug abuse, and gonorrhea. According to a 2017 study, Pennsylvania residents with the highest exposure to active fracked gas wells were nearly twice as likely to experience a combination of migraine headaches, chronic nasal and sinus symptoms, and severe fatigue. (See footnote 1041.)

Similarly, a 2020 study that used a novel method of quantifying exposures found that respiratory, neurological, and muscular symptoms tracked with cumulative well density around residential

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[209] Eliza Griswold, "When the Kids Started Getting Sick," *The New Yorker*, March 2, 2021, https://www.newyorker.com/news/dispatch/when-the-kids-started-getting-sick.
[210] David Templeton and Don Hopey, "CDC, State Officials Investigating Multiple Cases of Rare Cancer in Southwestern Pa.," *Pittsburgh Post-Gazette*, March 28, 2019, https://www.post-gazette.com/news/health/2019/03/28/Ewing-sarcoma-Washington-Westmoreland-cancer-Canon-McMillan-school-cecil-pennsylvania/stories/201903280010.
[211] David Templeton, "No Ewing Sarcoma Cluster in the Canon–McMillan School District, State Says," *Pittsburgh Post-Gazette*, April 23, 2019, https://www.post-gazette.com/news/health/2019/04/23/Ewing-sarcoma-cluster-Canon-McMillan-Pennsylvania-Health-Department/stories/201904230128.
[212] Meghan Schiller, "Families Affected by Rare Cancer Demand Answers after Pa. Health Dept. Investigation Results in 'No Conclusive Findings,'" KDKA2 CBS Pittsburgh, April 24, 2019, https://pittsburgh.cbslocal.com/2019/04/24/families-demand-answers-pa-health-dept-cancer-cluster-findings/.
[213] David Templeton and Don Hopey, "The Human Toll—Risk and Exposure in the Gas Lands," *Pittsburgh Post-Gazette*, May 14, 2019, https://newsinteractive.post-gazette.com/blog/childhood-cancer-pittsburgh-pennsylvania-canon-mcmillan-pollution/.
[214] The Editorial Board, "Young Lives at Stake: Rural Areas Deserve Answers on Child Cancers," *Pittsburgh Post-Gazette*, May 22, 2019, https://www.post-gazette.com/opinion/editorials/2019/05/22/childhood-cancer-pittsburgh-pennsylvania-canon-mcmillan-pollution-rural-areas-greene-fayette-washington-westmoreland/stories/201905220064.
[215] Eric T. Chaffin, "Pennsylvania Governor Funds Research Examining Potential Fracking Health Impacts," Pittsburgh Injury Law News, January 27, 2020, https://pittsburgh.legalexaminer.com/environment/pennsylvania-governor-funds-research-examining-potential-fracking-health-impacts/.

areas in southwestern Pennsylvania.[216] A 2020 study in Texas documented a link between intensity of drilling and fracking activities and frequency of hospitalization for childhood asthma.[217]

As demonstrated in multiple studies, mental health problems linked to living near drilling and fracking operations include depression, anxiety, and trauma. (See "Noise pollution, light pollution, and stress.")

Accumulating evidence shows connections between proximity to fracking sites and cardiovascular disease. In 2020, a major study of more than 12,000 heart failure patients in Pennsylvania showed that those living near fracking sites were significantly more likely to become hospitalized. The results also showed strong associations between fracking activity and two types of heart failure. "These associations can be attributed to the environmental impacts of fracking, including air pollution, water contamination, and noise, traffic, and community impacts." (See footnotes 972, 973.)

In 2022, a retrospective cohort study in north central West Virginia documented a rise in cases of a rare autoimmune disease (ANCA-associated vasculitis) in areas of increased fracking activity.[218]

7) Health and safety risks for workers are severe and employment promises unrealized.

Drilling and fracking operations are exempt from federal Occupational Safety and Health Administration (OSHA) standards designed to prevent catastrophic releases of toxic, flammable, or explosive chemicals in workplaces. They are also exempt from OSHA rules written for the construction industry designed to prevent falls and other accidents on the job. Although announced by the agency in 1983 as forthcoming, federal safety regulations for the oil and gas industry have never materialized.[219, 220] Instead, inspectors can only apply the "general duty clause" which is widely recognized as grossly inadequate for an industry with unique hazards and a fatality rate far above the national average.

From 2008–2017, 1,038 oil and gas extraction workers were killed on the job, resulting in an annual fatality rate more than six times higher than the rate among all U.S. workers during that period.[221] From 2018 through 2020, 242 more oil and gas workers were killed. This includes

[216] Hannah N. Blinn et al., "Exposure Assessment of Adults Living near Unconventional Oil and Natural Gas Development and Reported Health Symptoms in Southwest Pennsylvania, USA," *PLoS One* 15, no. 8 (2020): e0237325, https://doi.org/10.1371/journal.pone.0237325.
[217] Mary Willis et al., "Natural Gas Development, Flaring Practices and Paediatric Asthma Hospitalizations in Texas," *International Journal of Epidemiology* 49, no. 6 (2021): 1883–96, https://doi.org/10.1093/ije/dyaa115.
[218] Devan Makati et al., "Prevalence of ANCA-Associated Vasculitis amid Natural Gas Drilling Sites in West Virginia," *Journal of Nephrology*, 2022, https://doi.org/10.1007/s40620-021-01243-3.
[219] Corey Jones, "OSHA Standards Moot in Quinton Rig Explosion Because of Exemption for Oil-and-Gas Industry," *Tulsa World*, February 3, 2018, http://www.tulsaworld.com/news/state/osha-standards-moot-in-quinton-rig-explosion-because-of-exemption/article_162d0efa-7860-5f4b-b982-ebdeb142c075.html.
[220] Mike Lee, "Feds: Deadliest Drilling Accident in a Decade 'Preventable,'" E&E News, June 13, 2019, https://web.archive.org/web/20190613185313/https://www.eenews.net/stories/1060564501.
[221] Oil and Gas Extraction Program, "Oil and Gas Extraction: Burden, Need & Impact," National Institute for Occupational Safety and Health, November 30, 2018, https://www.cdc.gov/niosh/programs/oilgas/burden.html.

late-breaking 2020 fatality numbers showing 44 oil and gas extraction worker deaths.[222] In 2019, the most recent year of the AFL-CIO's "Death on the Job: The Toll of Neglect" report, 104 oil and gas extraction workers died on the job, accounting for 82 percent of the fatal work injuries in the mining sector, which overall continues to have fatality rate at least four times the national average. (See footnote 867.)

Studies in specific states, as well as some national studies, have provided additional details on regional rates and circumstances of injuries and deaths. Fatality rates among workers in the oil and gas extraction sector in North Dakota were seven times the national fatality rates in this industry, which itself has more deaths from fires and explosions than any other private industry. An increase in workplace deaths likewise accompanied the initial fracking boom period in West Virginia. Between 2011 and 2016, at least 60 workers at oil and gas drilling sites in Oklahoma were killed on the job. On January 22, 2018, a natural gas rig exploded in southeastern Oklahoma, killing five workers trapped inside the driller's cabin. (See footnotes 890, 891, 895.) The U.S. Chemical Safety Board determined that two preventive barriers designed to prevent uncontrolled gas blowouts had failed as a consequence of significant lapses in safety protocols and further discovered that "there is no guidance to ensure that an emergency evacuation option is present onboard these rigs or can protect workers in the driller's cabin from fire hazards." (See footnotes 881, 882, 887.)

In 2014, the National Institute for Occupational Safety and Health (NIOSH) began to collect detailed information about the locations and circumstances related to deaths of workers in oil and gas extraction. In two consecutive reports, covering 2015-2016 and then 2017, Texas had the most such fatalities and "well servicing" was by far the most common industry sub-group represented for the deaths. Consistently, the majority of deaths were transportation and contact injury related. This project is unique in counting cardiac events that begin at work, recognizing toxic exposures at oil and gas sites that can induce cardiac events, as well as work conditions that can influence their outcomes.

Pipeline construction workers also suffer elevated rates of injuries and fatalities, dying on the job 3.6 times more than workers in other industries. (See footnote 893.)

A University of Tennessee study assessed the occupational inhalation risks from the hazardous and carcinogenic air pollutants emitted from various sources around fracking wells and found that chemical storage tanks presented the highest cancer risk. Benzene has been detected in the urine of well pad workers in Colorado and Wyoming. The National Institute for Occupational Safety and Health named oil and gas extraction industry workers among those at risk for silicosis, an incurable lung disease caused by exposure to silica dust, from the silica sand that is used extensively in fracking operations. (See footnotes 905, 906, 948, 953.)

In 2020, the National Violent Death Reporting System reported that among the 20 major industry groups analyzed, men in the labor sector "Mining, Quarrying, and Oil and Gas Extraction" had the highest suicide rate in 2016, at 54.2 per 100,000 workers. (See footnote 877.)

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[222] U.S. Bureau of Labor Statistics, "Fatal Occupational Injuries in Private Sector Mining, Quarrying, and Oil and Gas Extraction Activities," U.S. Bureau of Labor Statistics, December 16, 2021, https://www.bls.gov/charts/census-of-fatal-occupational-injuries/fatal-occupational-injuries-private-sector-mining.htm.

A 2020 study showed that retired oil and gas workers had the highest prevalence of self-reported poor health of all industry categories of retirees. (See footnote 869.)

Independent economic analyses show that the promise of job creation, especially in the Marcellus Shale region of Appalachia, was greatly exaggerated, with many fracking-related jobs going to out-of-area workers. (See footnote 2008). During the height of the fracking boom, from 2008-2019, the most intensely drilled counties in Appalachia typically experienced both net job loss and population loss. (See footnote 2019.) Throughout all shale plays, oil and gas jobs are being increasingly lost to automation, and job losses accelerated with the contraction of the industry in 2019 and 2020. In the steepest rate of job loss in the industry's history, oil and gas eliminated 107,000 U.S. jobs between March and August 2020 alone. The result has been mass lay-offs and high unemployment among fracking crews and associated workers who often suffer occupational exposures to harmful substances and lack health insurance.

8) Fracking and the injection of fracking waste cause earthquakes.

Injection of fracking wastewater into underground disposal wells is a known trigger of earthquake swarms in multiple locations, as demonstrated by several major studies, using different methods. Newer research in Canada, Oklahoma, Ohio, Texas, the United Kingdom, and China links the practice of fracking itself to earthquakes, including some that take place many miles from well sites and many years later, suggesting that seismic risks have been previously underestimated with much larger areas at risk and for longer periods of time.[223, 224] In November 2019, the UK government halted fracking operations indefinitely after a report found that fracking-related earthquakes in Lancashire were neither predictable nor manageable with existing technology. (See footnote 1134.)

In Oklahoma, Texas, Louisiana, and New Mexico, the number of earthquakes linked to fracking wastewater injection more than tripled between 2017 and 2020. Current trends in this region show increasing frequency of fracking-related earthquakes as well as increasing strength. In 2021, according to state data analyzed by the *Texas Tribune*, Texas experienced more than 200 earthquakes of 3.0-magnitude or higher—more than double the number in 2020—with most of these quakes taking place in the West Texas Permian Basin as a consequence of fracking wastewater injection.[225] A 2021 study led by the U.S. Geological Survey determined that the proliferation of seismic activity near the Permian Basin city of Pecos since 2000 is likely caused by fracking wastewater disposal practices.[226]

[223] Pathikrit Bhattacharya and Robert C. Viesca, "Fluid-Induced Aseismic Fault Slip Outpaces Pore-Fluid Migration," *Science* 364, no. 6439 (2019): 464–68, https://doi.org/10.1126/science.aaw7354.
[224] Gillian Foulger, "Fracking Can Cause Earthquakes," Cosmos, May 13, 2019, https://cosmosmagazine.com/geoscience/fracking-can-cause-earthquakes-a-long-way-from-its-site.
[225] Erin Douglas, "Earthquakes in Texas Doubled in 2021. Scientists Cite Years of Oil Companies Injecting Sludgy Water Underground.," *Texas Tribune*, February 8, 2022, https://www.texastribune.org/2022/02/08/west-texas-earthquakes-fracking/.
[226] Robert J. Skoumal and Daniel T. Trugman, "The Proliferation of Induced Seismicity in the Permian Basin, Texas," *Journal of Geophysical Research: Solid Earth* 126, no. 6 (2021), https://doi.org/10.1029/2021JB021921.

A 2017 study of the Fort Worth Basin showed that a swarm of small earthquakes in northern Texas was originating in long-inactive fault lines in deep formations where fracking wastewater was being injected. Human activity is the only plausible explanation. (See footnote 1172, 1173.) Another study using satellite-based radar imagery provided proof that the migration of fracking wastewater into faults increased pressures in ways that triggered a 4.8-magnitude earthquake in east Texas in 2012, while a third study documented the rupture of a fault plane that set off a 4.9-magnitude earthquake in Kansas in 2014 immediately following a rapid increase in fracking wastewater injection nearby. (See footnotes 1196, 1197.)

The number of earthquakes of magnitude 3.0 or higher skyrocketed in Oklahoma starting with the advent of the fracking boom—with fewer than two per year before 2009 and more than 900 in 2015. The 5.8 earthquake that struck near Pawnee on September 3, 2016 was the strongest in Oklahoma's history and prompted an order from state regulators to shut down 67 wastewater disposal wells in the area. (See footnotes 1194, 1195.) In October 2016, the EPA recommended a moratorium on the underground injection of fracking wastewater in certain earthquake-prone parts of Oklahoma because regulations had not solved the problem. (See footnote 1192.) Earthquake frequency began to decline in the state in 2017. In February 2018, after a new cluster of earthquakes, the state further restricted fracking activities.[227]

There is no evidence that fracking-induced earthquakes can be prevented solely by limiting the rate or volume of injected fluid. A 2018 analysis of shale basins across the United States found that shallower disposal wells can help lower the risk of earthquakes. However, injection of fracking waste into shallow formations increases the risk of groundwater contamination. (See footnote 1156.)

In China's Sichuan Province, a series of earthquakes have been linked to fracking, including one in December 2018 with a magnitude of 5.7, the largest fracking-induced earthquake to date. The likely cause was reactivation of unmapped faults by underground fluid pressure.[228] In February 2019, three additional earthquakes, all with a magnitude of over four, struck Sichuan Basin, killing two people, injuring 13, and damaging 20,000 homes. The government temporarily suspended fracking operations in the area.[229]

9) Fracking waste disposal is a problem without a solution.

Fracking generates prodigious amounts of waste that comes in two basic forms: solid waste left over from drilling—so-called drill cuttings—and liquid wastewater generated after a well is fracked. As fracking operations with horizontal drilling have evolved toward ever-longer lateral

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[227] David Wethe, "Oklahoma Toughens Oil Fracking Rules after Shale Earthquakes," Bloomberg, February 28, 2018, https://www.bloomberg.com/news/articles/2018-02-27/oklahoma-toughens-oil-fracking-rules-as-shale-earthquakes-climb.
[228] Xinglin Lei, Zhiwei Wang, and Jinrong Su, "The December 2018 ML 5.7 and January 2019 ML 5.3 Earthquakes in South Sichuan Basin Induced by Shale Gas Hydraulic Fracturing," *Seismological Research Letters* 90, no. 3 (2019): 1099–1110, https://doi.org/10.1785/0220190029.
[229] Steven Lee Myers, "China Experiences a Fracking Boom, and All the Problems That Go with It," *The New York Times*, March 8, 2019, sec. Asia Pacific, https://www.nytimes.com/2019/03/08/world/asia/china-shale-gas-fracking.html.

wellbores, the volumes of both solid drill cuttings and fracking wastewater have increased markedly, although no national inventories are kept and not all states collect and maintain data on volumes of waste generated within their borders. In 1980, oil and gas waste received a Congressional exemption from the Resource Conservation and Recovery Act, the flagship federal law that regulates the disposal of hazardous waste. Hence, fracking waste is not required to be handled as hazardous although much of it highly toxic and radioactive.[230]

Drill cuttings, which largely consist of gooey, pulverized rock fragments removed from the wellbore by augurs during drilling operations, often contain highly toxic metals and naturally occurring radioactive materials such as radium, lead, uranium, thorium, and polonium isotopes. Depending on state laws, drill cuttings may be buried on site, spread on soil, or dumped in municipal landfills where their contaminants can enter the leachate created when rainwater percolates through the waste piles. The EPA has estimated that 7.5 million tons of drilling cuttings are generated each year from oil and gas operations.[231]

In Pennsylvania alone, drilling and fracking operations sent 244,000 tons of drill cuttings to landfills in 2020. A 2019 study found levels of radium in Pennsylvania drill cuttings that would exceed regulatory limits for disposal in landfills if drilling cuttings were not exempt from federal regulations governing hazardous waste. In the same year, a Fayette County water treatment plant sued after finding high levels of oil and gas contaminants in the leachate sent to it from a nearby landfill. In July 2021, the Pennsylvania Department of Environmental Protection announced it will require all landfills that take solid fracking waste to test their leachate for radioactive materials.[232] Drill cuttings from Pennsylvania fracking operations are also sent out of state for disposal, including to Ohio. (See footnote 815.)

The liquid waste that flows out a well immediately after it is fracked is called *flowback fluid*; the wastewater that continues to rise to the surface after the well is attached to a pipeline is called *produced water*. This shift in nomenclature indicates when in the extraction process the wastewater is generated and does not represent a substantive chemical difference, although flowback waste does tend to contain a higher concentration of the chemical additives used in fracking fluid, and produced water contains proportionately more brine and naturally occurring toxicants, such arsenic or barium and volatile compounds such as hydrogen sulfide and benzene. The chemicals used as ingredients in fracking fluid generally decrease over time in produced

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230 United States Code, "Title 42 - The Public Health and Welfare, Chapter 82 - Solid Waste Disposal, Subchapter III - Hazard Waste Management, Sec. 6921 - Identification and Listing of Hazardous Waste" (U.S. Government Publishing Office, 2010), 42, https://www.govinfo.gov/content/pkg/USCODE-2010-title42/html/USCODE-2010-title42-chap82-subchapIII-sec6921.htm.
231 U. S. Environmental Protection Agency, Office of Land and Emergency Management, and Office of Resource Conservation and Recovery, "Management of Exploration, Development and Production Wastes: Factors Informing a Decision on the Need for Regulatory Action," April 2019, https://www.epa.gov/sites/default/files/2019-04/documents/management_of_exploration_development_and_production_wastes_4-23-19.pdf.
232 Reid Frazier, "DEP to Require Landfills to Test for Radioactivity from Fracking Waste," State Impact Pennsylvania, July 26, 2021, https://stateimpact.npr.org/pennsylvania/2021/07/26/dep-to-require-landfills-to-test-for-radioactivity-from-fracking-waste/.

water but can persist for more than eight months after a well is put into production.[233, 234] A 2021 study of fracking wastewater from the Utica and Marcellus shale basins found that flowback fluid from newly fractured wells was the most highly toxic. (See footnote 521.) An estimated 21.2 billion barrels of briny wastewater are generated each year from one million active oil and gas wells in the United States. (See footnotes 546-548.)

In 2022, a team of chemists led by the University of Toledo used specialized extraction methods to document the presence of many toxic and cancer-causing contaminants in fracking wastewater—including volatile organic compounds, hazardous heavy metals, and radioactive substances—at levels capable of causing harm to humans and wildlife. Some of these hazardous contaminants represent chemical additives used in the fracking fluid itself, while others represent contaminants mobilized from the geological fracture zone. In all, the team detected 266 different dissolved organic compounds and 29 elements in the wastewater they assessed, which was collected from the Permian Basin and Eagle Ford formation in Texas.[235]

Like drill cuttings, fracking wastewater is often radioactive and can contain a variety of radioactive substances—including radium, thorium, and uranium—particularly in the Marcellus Shale region where some water samples show Radium-226 levels at 3,600 times the EPA's safe drinking water standard. A 2018 study in the Marcellus Shale region showed that extreme salinity, as well as the chemical composition of fracking fluid, interacts with the shale during the fracking process in ways that mobilize radium and make fracking wastewater radioactive. (See footnote 834.) In fall 2021, three bills introduced into the Pennsylvania legislature that would have reclassify oil and gas waste as hazardous did not progress to a vote.[236]

There is no known solution for the problem of fracking wastewater. It cannot be filtered or otherwise remediated to create clean, drinkable water, nor is there any safe method of disposal. Treating and discharging to rivers and streams is associated with elevated bromide and chloride levels downstream, as well as with the formation of cancer-causing disinfection byproducts. High levels of radium have been found in sediments downstream of sewage treatment plants used years earlier for fracking waste disposal. (See footnotes 604, 605.) Recycling fracking wastewater for use in new fracking operations is an expensive, limited option that increases radionuclide levels of subsequent wastewater, raises health risks for workers, incentivizes further fracking activity, and raises questions about the ultimate disposal of production wastewater from existing wells after the demand for fracking new wells ends. (See "Radioactive releases.") Disposal of liquid fracking waste into porous underground rock formations via injection wells is considered a best practice but is also a proven cause of earthquakes. (See "Earthquakes and

[233] Maryam A. Cluff et al., "Temporal Changes in Microbial Ecology and Geochemistry in Produced Water from Hydraulically Fractured Marcellus Shale Gas Wells," *Environmental Science & Technology* 48, no. 11 (2014): 6508–17, https://doi.org/10.1021/es501173p.
[234] Tanya J. Gallegos et al., "Insights on Geochemical, Isotopic, and Volumetric Compositions of Produced Water from Hydraulically Fractured Williston Basin Oil Wells," *Environmental Science & Technology* 55, no. 14 (2021): 10025–34, https://doi.org/10.1021/acs.est.0c06789.
[235] Ronald V. Emmons et al., "Unraveling the Complex Composition of Produced Water by Specialized Extraction Methodologies," *Environmental Science & Technology* 56, no. 4 (2022): 2334–44, https://doi.org/10.1021/acs.est.1c05826.
[236] Kristina Marusic, "Should Oil and Gas Companies Be Exempt from Pennsylvania's Hazardous Waste Laws?," October 6, 2021, https://www.ehn.org/radioactive-waste-oil-and-gas-2655217995.html.

seismic activity.") Further, many injection wells are now reaching capacity and cannot continue accepting more waste.

Transporting fracking waste to injection wells creates additional dangers. An increasing fraction of the wastewater created from fracking operations in western Pennsylvania is hauled to Ohio for disposal, both because the geology is more favorable for injection wells and because the rules governing the handling of oil and gas waste have not been finalized, leaving the disposal of radioactive waste from fracking operations, in effect, entirely unregulated by state law.[237, 238] A proposal to allow the transport of fracking wastewater by barge down the Ohio River to injection wells in Ohio is currently under consideration with three companies having submitted applications to the U.S. Army Corps of Engineers to obtain construction permits for barge terminals to receive liquid drilling wastes.[239]

Pressure is mounting to expand opportunities for the conversion of fracking waste, both solid and liquid, into ingredients for commercial products, a practice called beneficial re-use. Driving this discussion is the intractable problem of earthquakes when produced water is injected as liquid waste into deep geological formations and the declining storage capacities in shallower formations where groundwater contamination is a bigger risk. At last count, 11 states had approved various beneficial uses for drill cuttings (concrete, road base, grading). Thirteen U.S. states allow oil and gas wastewater to be used as a dust suppressant on unpaved roads. However, the presence of toxic heavy metals and radioactive radium accumulate with repetitive treatments and have the potential to become airborne. Further, a 2021 study found that the high levels of sodium render oil and gas wastewater ineffective in actually suppressing dust compared with other commercially available products.[240] However, there is almost no data collected on the frequency of different uses or the volumes involved. (See footnote 815.)

In western states suffering from water shortages and prolonged drought, the fracking industry seeks to expand the reuse of fracking wastewater for irrigation and livestock watering. At least ten known or suspected chemical carcinogens have been identified in wastewater reused for irrigation and livestock watering in California, and a 2020 study found elevated levels of sodium and boron in California soils irrigated with wastewater. Agricultural uses of wastewater raise questions about food crop contamination. Soil degradation, lower crop yields, and impaired microbial diversity were seen in land irrigated with oil and gas wastewater. Studies and case reports from across the country have highlighted instances of deaths, neurological disorders, aborted pregnancies, and stillbirths in farm animals that have come into contact with fracking wastewater. (See "Threats to agriculture, soil quality, and forests").

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[237] Talia Wiener, "Under 'Chief's Orders' Ohio Operates a Radioactive Industry Off the Record" (Public Herald, July 2021), https://publicherald.org/under-chiefs-orders-ohio-operates-a-radioactive-industry-off-the-record/.
[238] Lee Ann L. Hill et al., "Temporal and Spatial Trends of Conventional and Unconventional Oil and Gas Waste Management in Pennsylvania, 1991–2017," *Science of The Total Environment* 674 (2019): 623–36, https://doi.org/10.1016/j.scitotenv.2019.03.475.
[239] Don Hopey, "Network of Companies Looking to Move Fracking Wastewater in Barges Up and Down Pittsburgh's Rivers," *Pittsburgh Post-Gazette*, May 31, 2021, https://www.post-gazette.com/news/environment/2021/05/31/pennsylvania-ohio-monongahela-allegheny-rivers-fracking-wastewater-transport-barges-environment-health/stories/202105250142.
[240] Audrey M. Stallworth et al., "Efficacy of Oil and Gas Produced Water as a Dust Suppressant," *Science of the Total Environment*, https://doi.org/10.1016/j.scitotenv.2021.149347, 799 (2021).

10) Fracking infrastructure poses exposure risks to those living nearby.

Drilling and fracking activities are relatively short-term operations, but **compressor stations** are semi-permanent facilities that pollute the air 24 hours a day as long as gas is flowing through pipelines. Day-to-day emissions from compressor stations are subject to highly episodic variations due to pressure changes and maintenance-related deliberate releases and can create periods of potentially extreme exposures. Compressor stations generally have shorter emissions stacks than other polluting facilities such as power plants, which means their harmful emissions are more concentrated at ground level than if released from a greater height. A 2019 study of air emissions from 74 compressor stations in New York State found 39 chemicals known to be human carcinogens and documented large releases of greenhouse gases. (See footnote 1756.)

Because of their high pressures, compressor station explosions can have catastrophic consequences. In January 2019, a compressor station in rural Michigan malfunctioned during a period of extreme cold and released a large amount of methane gas that ignited and exploded.

An independent, two-part report detailing safety-related risks at a natural gas compressor station in **Weymouth, Massachusetts** shows that, in a worst-case scenario explosion, injuries could extend for thousands of feet into densely populated residential neighborhoods, ignite a nearby industrial diesel fuel storage tank, and kill motorists driving on an adjacent highway.[241] Further, an assessment of noise, water, and air pollution from the compressor station project revealed flaws in the regulatory process that allowed the compressor station to be permitted, concluded that "no regulatory framework can make this facility safe for the surrounding community or for the residents of the Commonwealth," and called for a halt to its construction.[242] Nevertheless, in fall 2020, the Weymouth compressor station received permission to operate and went on line in January 2021. Two accidents during the commissioning process released large plumes of methane and necessitated emergency shutdowns. Since then, the compressor station has suffered multiple subsequent accidents, venting gas and volatile organic compounds and going offline for the fourth time in May 2021.[243] In January 2022, the Federal Energy Regulatory Commission (FERC) re-examined its decision to grant the permit and issued a statement saying that it "likely erred" in siting the compressor station in a "heavily populated area with two environmental justice communities and a higher-than-normal level of cancer and asthma due to heavy industrial activity." However, because "there was no legal basis to prevent [it] from entering into service,"

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[241] Anna Baker et al., "Flammable, High-Pressure Industry in a Populated Coastal Flood Zone? Public Safety and Emergency Response Aspects of a Proposed Methane Gas Compressor in Weymouth" (Greater Boston Physicians for Social Responsibility, May 13, 2019), https://www.psr.org/wp-content/uploads/2019/05/compressor-public-safety-report.pdf.

[242] Regina LaRocque, Brita Lundberg, and Zoe Petropoulos, "A Comprehensive Assessment of the Potential Human Health Impacts of a Proposed 'natural' Gas Compressor Station in Weymouth, Massachusetts" (Greater Boston Physicians for Social Responsibility, September 24, 2019), https://gbpsr.org/wp-content/uploads/sites/11/2019/09/gbpsr-report-09-24-19.pdf.

[243] Joseph Winters, "The Weymouth Compressor Station," *Harvard Political Review*, May 24, 2021, https://harvardpolitics.com/weymouth-compressor-station/.

the Commission announced it would not be revoking its approval.[244] Area residents are now pressing forward with their opposition in the courts.

The Weymouth compressor station is a key component of the Enbridge Atlantic Bridge pipeline project intended to ferry fracked gas beneath the Boston Harbor and north into Canada. A 2016 investigation by journalist Itai Vardi and a December 2020 *Boston Globe* Spotlight report by journalist Mike Stanton explicated a tangle of industry conflicts of interest during the state and federal permitting process for the compressor station, as well as sleight-of-hand revisions in early drafts of the health impact assessment that deleted from the final report evidence documenting serious risks to nearby residents.[245, 246]

Pipelines themselves can freeze, corrode, break, and leak. Low-pressure flow lines alone have been responsible for more than 7,000 spills and leaks since 2009. (See footnote 1791.) Distribution lines that deliver gas into homes and offices are a significant source of leaking methane and contribute to the death of urban trees according to a 2020 study. (See footnote 1746.)

Significant pipeline accidents happen roughly 300 times each year in the United States and, between 1998 and 2017, killed 299 people and injured 1,190 others, according to the PHMSA. Extreme weather patterns caused by climate change are making pipeline accidents more likely. Landslides, sinking and caving of land, and other types of land movement have been linked to at least six ruptures and explosions of gas pipelines built in the steeply sloped Appalachian Mountains. In May 2019, PHMSA sent a warning to pipeline operators about increased risks of leaks and explosions caused by more frequent flooding, sinkholes, and severe rainfall patterns in the eastern United States.[247] In September 2018, heavy rains and landslides triggered the explosion of the **Revolution Pipeline** in Beaver County, Pennsylvania, destroying a house.[248] In February 2022, Energy Transfer was charged with nine environmental crimes related to that explosion after a grand jury investigation found it had failed to oversee construction and prevent erosion.[249] In August 2020, a sinkhole formed during the construction of the **Mariner East Pipeline** in Chester County, Pennsylvania, and 8,000 gallons of drilling fluid bubbled to the

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244 Jessica Trufant, "Feds: Regulators 'Should Never Have Approved' Weymouth Compressor, Too Late to Shut It Down," *The Patriot Ledger*, January 20, 2022, https://www.patriotledger.com/story/news/2022/01/20/federal-regulators-say-they-cant-shut-down-compressor-station/6593139001/.
245 Itai Vardi, "Revealed: Contractors Hired by FERC to Review a New Spectra Energy Pipeline Work for Spectra on a Related Project," DeSmog, May 26, 2016, https://www.desmogblog.com/2016/05/26/revealed-contractors-hired-ferc-review-new-spectra-energy-pipeline-work-spectra-related-project.
246 Mike Stanton, "In Weymouth, a Brute Lesson in Power Politics," *Boston Globe*, December 12, 2020, https://www.bostonglobe.com/2020/12/12/metro/was-it-ever-fair-fight/.
247 Pipeline Hazardous Materials Safety Administration, "Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards" (National Archives and Records Administration, May 2, 2019), https://www.federalregister.gov/documents/2019/05/02/2019-08984/pipeline-safety-potential-for-damage-to-pipeline-facilities-caused-by-earth-movement-and-other.
248 Susan Phillips, "Federal Pipeline Safety Regulators Issue Warning on Floods and Subsidence," State Impact Pennsylvania, May 21, 2019, https://stateimpact.npr.org/pennsylvania/2019/05/21/federal-pipeline-safety-regulators-issue-warning-on-floods-and-subsidence/.
249 Reid Frazier, "Energy Transfer Facing Nine Counts of Environmental Crimes for 2018 Pipeline Blast," State Impact Pennsylvania, February 3, 2022, https://stateimpact.npr.org/pennsylvania/2022/02/03/energy-transfer-facing-nine-counts-of-environmental-crimes-for-2018-pipeline-blast/.

surface, contaminating a lake in a state park.[250] Subsidence and the development of sinkholes have plagued the Mariner East Pipeline since construction began and continues to delay its completion. The Mariner East would transport natural gas liquids from the Marcellus Shale fields in western Pennsylvania to an export terminal on the Delaware River near Philadelphia.

Gas-fired power plants are major emitters of carbon monoxide and nitrogen oxides, which contribute to smog. In Virginia, greenhouse gas emissions increased after the state largely retired its fleet of coal-burning power plants and replaced them with gas-fired facilities. (See footnote 1983.)

In the Upper Midwest, Wisconsin residents living near **silica sand mining operations** that service the fracking industry reported dust exposure and respiratory problems. Silica dust is a known cause of silicosis and lung cancer. West Texas is also experiencing a fracking sand boom where roughly 20 new sand mines have opened since July 2017. (See footnote 7.)

Fracking infrastructure in the United States also includes 400 **underground gas storage facilities** in 31 states, with aging equipment and scant federal oversight. A four-month leak at the nation's fifth-largest facility, **Aliso Canyon** in southern California, resulted in exposures of a large suburban population to an uncontrollable array of chemicals. With a release of nearly 100,000 metric tons of methane between October 2015 and February 2016, it became the worst methane leak in U.S. history. (See footnote 1881.) It exposed residents in the region to benzene spikes, high ongoing odorant releases, hydrogen sulfide at levels far above average urban levels, and many other contaminants of concern. More than 8,300 households were evacuated and relocated, with residents reporting multiple symptoms, including headaches, nosebleeds, eye irritation, and nausea. As part of a 2019 agreement with city, county and state authorities, SoCalGas must pay for the $25 million health research study now being initiated by the Los Angeles County Health Department.[251] Many have criticized the long wait for the study, its reliance on flawed monitoring, and possible exclusion of clinical evaluation. (See footnote 1840.)

In May 2019, state investigators announced that the cause of the massive leak at Aliso Canyon was the rupture of a well casing triggered by microbial corrosion within a well that had been originally drilled in 1954 and, over the years, had come in contact with groundwater.[252] The report also faulted the operator, SoCalGas, for failure to monitor and investigate more than 60 previous leaks at the gas storage complex.[253] In November 2020, over intense public opposition, the California Public Utilities Commission voted unanimously to allow the Aliso Canyon facility to maintain its current storage capacity until a study could determine the feasibility of shutting it

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[250] Andrew Maykuth, "Sunoco Wants to Block Order to Reroute Mariner East Pipeline Away from Chester's Marsh Creek Lake," *The Philadelphia Inquirer*, October 26, 2020, sec. Business, https://www.inquirer.com/business/mariner-east-pipeline-sunoco-energy-transfer-pennsylvania-marsh-creek-leak-chester-county-20201026.html.

[251] Hayley Smith, "L.A. County Calls for Independent Health Study of Massive Natural Gas Leak in Aliso Canyon," *Los Angeles Times*, January 20, 2022, https://www.latimes.com/california/story/2022-01-20/l-a-county-calls-for-independent-health-study-of-massive-natural-gas-leak-in-aliso-canyon.

[252] Blade Energy Partners, "Root Cause Analysis of the Uncontrolled Hydrocarbon Release from Aliso Canyon" (California Public Utilities Commission, May 16, 2019), https://www.californiageo.org/wp-content/uploads/Exec-Sum-on-Aliso-by-Blade-5-16-19.pdf.

[253] Mihir Zaveri, "Corroded Well Lining Caused Aliso Canyon Gas Leak That Displaced Thousands, Report Says," *The New York Times*, May 17, 2019, https://www.nytimes.com/2019/05/17/business/porter-ranch-gas-leak.html.

down.[254] In November 2021, The California Public Utilities Commission voted to increase storage at the facility, although the Commissioner said the increase would not be permanent and "in no way diminishes the ability to decommission Aliso."[255] (See also footnote 1886.) The shutdown feasibility study has not been released. A state senator has introduced a bill that would, no later than an unspecified date in 2027, [close] all natural gas operations at the Aliso Canyon natural gas storage facility."[256]

In a 2018 analysis of the safety risks of all 14 facilities in California that store gas in depleted oil fields, the California Council of Science and Technology found that gas companies do not disclose the chemicals they are pumping underground nor do state regulators possess the necessary information to assess risks. Further, many wells servicing the storage fields are 60 to 90 years old with no regulatory limit to the age of a well. (See footnote 1874.) After the price and demand collapse in mid-2020, producers sought and received special permission to store growing inventories of oil and gas in underground salt caverns in Texas for up to five years over concerns about possible threats to the nine aquifers underlying the state. (See footnote 1847.)

LNG facilities create acute security, public safety, and climate threats, as well as massive coastal habitat destruction. LNG is purified methane in the form of a bubbling, super-cold liquid. It is created through the capital-intensive, energy-intensive process of cryogenics and relies on evaporative cooling, via methane venting, to keep the liquid fuel chilled during transport. LNG is explosive and possesses the ability to flash-freeze human flesh. Its greenhouse gas emissions are 30 percent higher than conventional natural gas due not only to its need for venting and refrigeration but also because flaring is used to control pressure when converting the liquid back into a gas. The need to strip volatile impurities such as benzene from the gas prior to chilling it also makes LNG liquefaction plants a source of toxic air pollutants. (See footnotes 1917-1969.)

Cheniere Energy's **Sabine Pass terminal** in Louisiana became the subject of a federal investigation in January 2019 after a steel storage tank cracked and escaping LNG quickly vaporized into a flammable cloud. Another tank was found to be leaking gas from multiple places. PHMSA ordered both tanks shut down.[257]

In Coos Bay, Oregon, the proposed **Jordan Cove LNG export terminal** and its associated pipeline from Canada would have imperiled 20 different threatened and endangered species and crossed 300 bodies of water. Originally rejected by FERC in 2016 for its dependency on seizing private land through eminent domain while lacking buyers for its gas in Asia, a Republican-controlled Commission, as part of a March 2020 reversal and over the objection of landowners,

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[254] Linh Tat, "Pleas Spurned to Limit Storage at Aliso Canyon, Site of Massive Gas Leak 5 Years Ago," *Los Angeles Daily News*, November 19, 2020, sec. News, from https://www.dailynews.com/2020/11/19/socalgas-aliso-canyon-gas-storage-facility-eludes-limits-on-capacity/.
[255] Gregory Yee, "Utilities Commission Approves Gas Storage Plan at Aliso Canyon over Residents' Objections," *Los Angeles Times*, November 5, 2021, https://www.latimes.com/california/story/2021-11-05/utilities-commission-approves-gas-storage-plan-at-aliso-canyon-site-over-residents-objections.
[256] Henry Stern, "SB 1486 Natural Gas: Aliso Canyon Natural Gas Storage Facility: Reliability.," Openstates, February 18, 2022, https://openstates.org/ca/bills/20212022/SB1486/.
[257] Jenny Mandel and Jie Jenny Zou, "Leaks Threaten Safety—and Success—of America's Top Natural Gas Exporter," The Center for Public Integrity, May 30, 2019, https://publicintegrity.org/environment/leaks-threaten-safety-and-success-of-americas-top-natural-gas-exporter/.

approved both the terminal and the fracked gas pipeline that would have served it.[258, 259] In April 2021, the developer, unable to secure state permits to operate, put the project on indefinite hold and, in December 2021, asked FERC to cancel authorizations for both the export terminal and the Pacific Connector pipeline.[260]

11) Drilling and fracking activities release radioactivity.

Naturally occurring radioactive substances often co-occur with oil and gas inside the deep shale layers that are targeted for fracking. These substances are brought to the surface in the rocky material removed during drilling (drill cuttings) and in fracking wastewater. Fracking itself can open pathways for the migration of radioactive materials, which can be released as airborne particles from the wellhead itself during operations. Radionuclides can build up in pipes, equipment, and trucks. Exposure to increased radiation levels from fracking materials is a risk for both workers and residents.

Levels of radon—a radioactive, carcinogenic gas—inside Pennsylvania homes have risen since the advent of the fracking boom, and buildings in heavily drilled areas have significantly higher radon readings than areas without well pads—a difference that did not exist before 2004. Similar patterns have been documented in Ohio. (See footnotes 830, 847.)

A 2018 simulation study of radium-226 in fracking wastewater from North Dakota's Bakken Shale found potential risk to human health from fracking wastewater spills into surface water. (See footnote 836.)

Potential radioactive exposures are particularly concerning for drivers of brine trucks, as was documented in a 2020 investigative report on radium in liquid fracking waste. In at least 13 states where it is legal, oil and gas waste that may be radioactive is purposely spread on roadways as a de-icer in the winter and/or as a dust-control agent in the summer. (See footnote 825.)

In 2020, a Harvard team documented the presence of airborne radioactivity downwind from fracking sites at levels sufficient to raise health risks for nearby residents. Using data collected from 157 radiation-monitoring stations built across the nation during the Cold War, the researchers showed a seven percent increase in radioactive pollution in communities located 12 to 31 miles downwind from operational fracking sites as compared to background levels. The closer communities were located to the wells, the higher the radioactivity in airborne particles. In the Fort Worth, Texas area, where more than 600 fracking wells are located upwind from the city, the team estimated a 40 percent increase in radiation levels. The radioactive elements carried by the ultrafine particles, including polonium, represent the radioactive decay products of

[258] Oregon Department of Environmental Quality, "DEQ Issues a Decision on Jordan Cove's Application for 401 Water Quality Certification," Letter, May 6, 2019, https://www.oregon.gov/deq/FilterDocs/jcdecletter.pdf.
[259] Nick Cunningham, "When Can Pipelines Take Private Land? Jordan Cove LNG Project a Test for Eminent Domain," DeSmog, November 24, 2020, https://www.desmogblog.com/2020/11/24/pacific-connector-pipeline-jordan-cove-lng-eminent-domain.
[260] Niina H. Farah, Miranda Willson, and Carlos Anchondo, "Jordan Cove Project Dies. What It Means for FERC, Gas," *E&E News*, December 2, 2021, https://www.eenews.net/articles/jordan-cove-project-dies-what-it-means-for-ferc-gas/.

uranium isotopes that are liberated from the shale during fracking operations. (See footnote 816.)

12) Drilling and fracking activities harm wildlife.

Animals serve as sentinels for chemical exposures that may also affect human residents who share their environment. In addition, animals perform ecosystem services essential to human existence, as confirmed by a landmark United Nations report in May 2019.[261] For both reasons, harm to wildlife by fracking operations has consequences for public health.

Fracking impacts on wildlife are profound, diverse and widespread. A 2022 analysis found that only restrictions on fracking or a reduction in the number of wells—by, for example, a transition to renewable energy sources—led to protection of both wildlife populations and public health. Other types of mitigations, such as siting fracking wells away from residential areas, can simply shift the burden of harm from human to wildlife populations.[262]

Wildlife can be killed outright by gas flares and chemical pollution. Birds and other wildlife have been poisoned by fracking wastewater held in open pits, while spills and discharges of fracking waste have precipitated mass die-offs of fish, as documented in Ohio, Kentucky, and Pennsylvania. (See footnotes 719, 744.) Freshwater mussels, which are endangered throughout North America, accumulate contaminants, including strontium, when fracking wastewater is discharged through sewage treatment plants. (See footnote 567) Chemicals in fracking waste are toxic to, or otherwise disrupt development in, many species of fish and amphibians. (See footnotes 559, 639.) In remote locations in Pennsylvania, streams once classified as high-quality brook trout habitat had no fish at all after the arrival of drilling and fracking operations. (See footnote 624.) Overall, aquatic habitats impacted by fracking activities show decreased biodiversity.

Wildlife is harmed by fracking through loss of food resources. Water fleas (*Daphnia spp.*), the basis of freshwater aquatic food chains, become unable to vertically navigate through water columns upon exposure to trace amounts of fracking fluid. (See footnote 554.) In West Virginia, populations of Louisiana waterthrush, a warbler that relies on aquatic food sources, have declined in areas of drilling and fracking. (See footnote 560, 1423.)

Light and noise pollution from oil and gas production disrupt wildlife behavior, including in protected areas and critical habitats of endangered species, and have been linked to mass die-offs of waterfowl and declines in songbird populations in Alberta, Canada, Pennsylvania, West Virginia, eastern Ohio, and New Mexico. (See footnotes 1093, 1108.) Chronic noise from drilling and fracking operations interferes with the ability of birds to respond to acoustic cues. (See footnotes 1779, 1780.) A 2021 study found that natural gas compressor stations emit loud,

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[261] S. Diaz et al., "Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services" (IPBES Secretariat, 2019), https://ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf.

[262] Nicole C Deziel, Bhavna Shamasunder, and Liba Pejchar, "Synergies and Trade-Offs in Reducing Impacts of Unconventional Oil and Gas Development on Wildlife and Human Health," *BioScience*, March 30, 2022, biac014, https://doi.org/10.1093/biosci/biac014.

low-frequency noise that travels hundreds of meters, is audible to birds, and lowers the hatching success of eastern bluebirds and tree swallows. (See footnote 1724.) Wildlife biologists in West Virginia found genetic changes in the Louisiana waterthrush that were linked to fracking activities and possible exposure to the heavy metals barium and strontium. (See footnote 1423.)

Fracking harms wildlife through climate change and habitat destruction. Oil and gas infrastructure, including compressor stations, has caused declines in grassland songbirds in Canada. Populations of forest songbirds declined markedly in response to even low levels of fracking activities in dense forested Appalachian regions. Sand mining operations in Texas are imperiling the dunes sagebrush lizard. The proposed route of the now-canceled Atlantic Coast Pipeline would have cut through critical habitat for four endangered species.

The proposed route of the Mountain Valley Pipeline, bisecting steep, highly erodible terrain in Virginia and West Virginia, would cross 1,108 bodies of water and 235 miles of forest, including 24 core forest areas, 892 acres of which would suffer permanent damage.[263] (In August 2020, its expansion into North Carolina was denied state approval.[264]) A 2019 study found that forest disturbances driven by drilling and fracking activities are altering the abundance of songbird populations in central Appalachia, particularly harming species whose habitats are forest interiors.[265] Well pad construction hastens the spread of invasive non-native plant species which harms wildlife habitat. (See footnotes 1432, 1436.)

According to economists, the cost of wildlife habitat fragmentation due to fracking is $3.5 to 4.45 billion per year. (See footnote 2059.)

13) The economic instabilities of fracking exacerbate public health risks.

Fracking is not a stable business. In contrast with conventional drilling, fracking operators are unable to forecast how much oil or gas can be extracted from a given shale basin based on the production of existing wells. Shale wells deplete more rapidly than conventional wells and often yield significantly less oil and gas than their operators predict to their investors. Because the production of individual shale wells falls precipitously over the course of a few years, operators must continue drilling new wells at an ever-swifter pace to maintain growth targets—even as owners are under pressure to cut costs in the face of price declines.

The result is lack of profits, dependency on Wall Street financing and low-interest loans, and asset sell-offs throughout the fracking industry as a whole. (See footnote 2165.) These unstable

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[263] Federal Energy Regulatory Commission, "Mountain Valley Project and Equitrans Expansion Project: Final Environmental Impact Statement," June 2017, https://bloximages.newyork1.vip.townnews.com/roanoke.com/content/tncms/assets/v3/editorial/b/04/b0452cda-e2b8-5925-a221-9ca818399c60/594de39d9433e.pdf.pdf.

[264] Harry Weber and Valarie Jackson, "Mountain Valley Pipeline Gas Expansion into North Carolina Denied State Approvals," S&P Global, August 11, 2020, https://www.spglobal.com/platts/en/market-insights/latest-news/oil/081120-mountain-valley-pipeline-gas-expansion-into-north-carolina-denied-state-approvals.

[265] Laura Farwell et al., "Proximity to Unconventional Shale Gas Infrastructure Alters Breeding Bird Abundance and Distribution," *The Condor* 121, no. 3 (2019): 1–20.

economic fundamentals have multiple consequences for public health and safety as cumulative impacts mount from wells both old and new.

Pressures to cut costs incentivize cutbacks in safety measures and leave landscapes pock-marked by increasing numbers of hastily abandoned wells in need of remediation and long-term monitoring. The ongoing financial crisis in the oil and gas industry, and the resulting bankruptcy waves, have allowed companies, which are typically insufficiently bonded, to walk away from inactive wells and shift decommissioning and clean-up costs to the public. (See Emerging Trend 2 above.)

In both North Dakota's Bakken Shale and western Texas' Permian Basin, cost-cutting pressures, coupled with a desperate rush to drill new oil wells to compensate for declining rates of production from older wells, have meant that waste natural gas generated as a byproduct of oil drilling is simply wasted—vented or flared rather than captured—in order to speed up the rate of oil drilling.[266, 267] By April 2019, the amount of natural gas burned off via flaring in the Permian oil fields had reached a record high and exceeded the amount of gas needed to power every residence in Texas.[268, 269] According to state data compiled by the U.S. Energy Information Administration, the amount of natural gas lost to venting and flaring operations across the nation nearly doubled between 2015 (when 289,545 million cubic feet were lost) to 2019 (when 538,479 million cubic feet were lost).[270]

14) The social costs of fracking are severe.

With the arrival of drilling and fracking operations, communities have experienced steep increases in rates of crime including sex trafficking, rape, assault, drunk driving, drug abuse, and violent victimization—all of which carry public health consequences, especially for women.

Social costs include road damage, failed local businesses, loss of affordable rental housing, higher divorce rates, and strains on law enforcement and municipal services. School districts report increased stress, increased absenteeism, and lower student test scores. Economic analyses have found that drilling and fracking activities threaten property values and can diminish tax revenues for local governments. Additionally, drilling and fracking on private land pose an inherent conflict with mortgages and property insurance due to the hazardous materials used and

[266] Catherine Ngai, "Mind the Drop: Decline Rates from Maturing Oil Wells on the Rise," Bloomberg, October 9, 2018, https://www.bloombergquint.com/business/mind-the-drop-decline-rates-from-maturing-oil-wells-on-the-rise.
[267] Mike Lee, "Gas Glut Spurs Near-Record Flaring across Shale States," E&E News, May 8, 2019, https://web.archive.org/web/20190508141234/https://www.eenews.net/energywire/stories/1060292021021.
[268] Jennifer Hiller, "Natural Gas Flaring Hits Record High in First Quarter in U.S. Permian Basin," Reuters, June 4, 2019, https://www.reuters.com/article/us-usa-shale-flaring/natural-gas-flaring-hits-record-high-in-first-quarter-in-us-permian-basin-idUSKCN1T5235.
[269] Kevin Crowley and Ryan Collins, "Oil Producers Are Burning Enough 'waste' Gas to Power Every Home in Texas," Bloomberg, April 10, 2019, https://www.bloomberg.com/news/articles/2019-04-10/permian-basin-is-flaring-more-gas-than-texas-residents-use-daily.
[270] U.S. Energy Information Administration, "Natural Gas Annual" (U.S. Department of Energy, September 30, 2020), https://web.archive.org/web/20201018020729/https://www.eia.gov/naturalgas/annual/pdf/nga19.pdf. Table 1, Summary Statistics for natural gas in the United States, 2015-2019, September 30, 2020, https://www.eia.gov/naturalgas/annual/pdf/nga19.pdf

the associated risks. (See "Inaccurate jobs claims, increased crime rates, threats to property values and mortgages, and local government burden.")

A 2019 study that monetized the external and cumulative costs of health and climate impacts of fracking in Appalachia found that, from 2004 to 2016, premature deaths caused by the industry's pollution had a cumulative economic cost of $23 billion, while climate impacts cost an additional $34 billion. Their findings showed that one year of life is lost for every three job years created by the industry. (See footnote 2030.)

15) Fracking violates principles of environmental justice and human rights.

Inequalities in opportunities to participate in environmental decision-making, as well as uneven impacts of environmental hazards along racial and socioeconomic lines, are signature issues of environmental justice. Studies consistently show that Black, Indigenous, Hispanic, rural, and low-income white communities bear the brunt of exposures to toxic waste and fossil fuel-derived air pollution.[271, 272, 273] These patterns extend to fracking and its infrastructure.[274]

In acknowledgement, the U.S. Federal Energy Regulatory Commission announced for the first time in February 2022 that it will consider a proposed project's impact on environmental justice communities as part of its determinations.[275]

In multiple regions where fracking is practiced, well pads, pipelines, and associated infrastructure are disproportionately sited in non-white, Indigenous, or low-income communities.[276, 277] A 2019 analysis of socio-demographic characteristics of people living close to drilling and fracking operations in the states of Colorado, Oklahoma, Pennsylvania, and Texas found strong evidence that minorities, especially African Americans, disproportionately live near fracking wells.[278] A nationwide study in 2021 found that Black, Indigenous, and people of color

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[271] Christopher W. Tessum et al., "Inequity in Consumption of Goods and Services Adds to Racial–Ethnic Disparities in Air Pollution Exposure," *PNAS* 116, no. 3 (2019): 6001–6, https://doi.org/10.1073/pnas.1818859116.
[272] Nikayla Jefferson and Leah C. Stokes, "Our Racist Fossil Fuel Energy System," *Boston Globe*, July 17, 2020, https://www.bostonglobe.com/2020/07/13/opinion/our-racist-fossil-fuel-energy-system/.
[273] Jill Johnston, "Chemical Exposures, Health, and Environmental Justice in Communities Living on the Fenceline of Industry," *Current Environmental Health Reports* 7 (2020): 48–57, https://doi.org/10.1007/s40572-020-00263-8.
[274] Adrianne C. Kroepsch et al., "Environmental Justice in Unconventional Oil and Natural Gas Drilling and Production: A Critical Review and Research Agenda," *Environmental Science & Technology* 53, no. 12 (2019): 6601–15, https://doi.org/10.1021/acs.est.9b00209.
[275] Federal Energy Regulatory Commission, "Certification of New Interstate Natural Gas Facilities: [Docket No. PL18-1-000]" (United States, February 18, 2022), https://www.ferc.gov/media/pl18-1-000.
[276] Noel Healy, Jennie C. Stephens, and Stephanie Malin, "Embodied Energy Injustices: Unveiling and Politicizing the Transboundary Harms of Fossil Fuel Extractivism and Fossil Fuel Supply Chains," *Energy Research & Social Science* 48 (n.d.): 219–34, https://doi.org/10.1016/j.erss.2018.09.016.
[277] Emily Clough, "Environmental Justice and Fracking: A Review," *Current Opinion in Environmental Science & Health* 3 (2018): 14–18, https://doi.org/10.1016/coesh.2018.02.005.
[278] Klara Zwickl, "The Demographics of Fracking: A Spatial Analysis for Four U.S. States.," *Ecological Economics* 161 (2019): 202–15, https://doi.org/10.1016/j.ecolecon.2019.02.001.

in the United States are disproportionately exposed to flaring from drill and fracking operations.[279]

In southern Texas, patterns of racially biased permitting have been documented in the heavily drilled Eagle Ford where non-white communities are targeted for both fracking waste disposal and fracking-associated flare stacks. In 2016, a public health research team showed that disposal wells for fracking wastewater were more than twice as common in areas where residents are more than 80 percent people of color than in majority-white communities.[280] Since 2007, more than 1,000 waste disposal wells have been permitted in the Eagle Ford Shale region where groundwater is the primary source of drinking water.[281] A 2020 study found that Hispanic residents living in the Eagle Ford area were exposed to significantly more fracking-associated flaring than white residents. Flares to burn off unwanted methane can operate continuously for months, releasing hazardous air pollutants as well as serving as sources of noise and light pollution.[282] Living near gas flaring operations raises the risk of preterm birth among pregnant women.[283]

Racial patterns of gas and oil development also exist in the eighteen counties in North Texas that sit atop the intensely drilled Barnett Shale. In Denton, Texas, a study found that those economically benefiting most from shale gas fracking mostly lived elsewhere, while the environmental burdens remained local and fell hardest on those who did not have a voice in mineral-leasing decisions. "Non-mineral owners are essentially excluded from the private decisions, as the mineral owners not only receive the direct monetary benefits, but also hold a great deal of state-sanctioned power to decide if and how [shale gas development] proceeds."[284] In August 2020, residents in nearby Arlington, Texas, appealed to the city's racial justice resolution to block the expansion of fracking activity near African-American and Hispanic neighborhoods.[285]

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[279] Lara J. Cushing et al., "Up in Smoke: Characterizing the Population Exposed to Flaring from Unconventional Oil and Gas Development in the Contiguous US," *Environmental Research Letters* 16 (2021), https://doi.org/10.1088/1748-9326/abd3d4.
[280] Jill E. Johnston, Emily Werder, and Daniel Sebastian, "Wastewater Disposal Wells, Fracking, and Environmental Injustice in Southern Texas," *American Journal of Public Health* 106, no. 3 (n.d.): 550–56, https://doi.org/10.2105/AJPH.2015.303000.
[281] Brian Bienkowski, "Fracking's Costs Fall Disproportionately on the Poor and Minorities in South Texas," Inside Climate News, February 17, 2016, https://insideclimatenews.org/news/17022016/poor-minorities-carry-burden-fracking-waste-south-texas-eagle-ford-shale/#:~:text=Fracking%E2%80%99s%20Costs%20Fall%20Disproportionately%20on%20the%20Poor%20and,Brian%20Bienkowski%2C%20Environmental%20Health%20News%20February%2017%2C%202016.
[282] Jill E. Johnston et al., "Environmental Justice Dimensions of Oil and Gas Flaring in South Texas: Disproportionate Exposure among Hispanic Communities," *Environmental Science & Technology* 54, no. 10 (n.d.): 6289–98, https://doi.org/10.1021/acs.est.0c00410.
[283] Jill E. Johnston and Lara Cushing, "The Risk of Preterm Birth Rises near Gas Flaring, Reflecting Deep-Rooted Environmental Injustices in Rural America," The Conversation, August 20, 2020, https://theconversation.com/the-risk-of-preterm-birth-rises-near-gas-flaring-reflecting-deep-rooted-environmental-injustices-in-rural-america-143413.
[284] Matthew Fry, Adam Briggle, and Jordan Kincaid, "Fracking and Environmental (in)Justice in a Texas City," *Ecological Economics* 117 (2015): 97–107, https://doi.org/10.1016/j.ecolecon.2015.06.012.
[285] Kara Harris, "A Texas Oil Town Takes on Fracking as a Racial Justice Issue," Bloomberg Law, August 28, 2020, https://news.bloomberglaw.com/environment-and-energy/a-texas-oil-town-takes-on-fracking-as-a-racial-justice-issue.

Poor communities of color are disproportionately affected by drilling activities in California. More than three-quarters of the 21,397 new oil wells drilled in California between 2011 and 2018 are located in low-income minority communities, according to state data.[286] Of Los Angeles residents living within a quarter-mile of a well, more than 90 percent are people of color. In November 2015, civic groups led by youth sued the city of Los Angeles for racial discrimination based on allegations of a preferential permitting process and unequal regulatory enforcement for oil wells located in neighborhoods of color. Together, these differential practices have resulted in a higher concentration of wells with fewer environmental protections in Black and Latino communities.[287] South Coast Air Quality Management District records show that oil drilling operations in Los Angeles neighborhoods released into the air 21 million pounds of toxic chemicals between June 2013 and February 2017. These emissions included crystalline silica, hydrofluoric acid, and formaldehyde.[288] In February 2021, two historically disenfranchised rural Kern Counties communities, Arvin and Lamont, won inclusion in a community air protection law that compels power-sharing between California's regional air pollution districts and affected communities. The residents of Arvin and Lamont, surrounded by oil wells and refineries, suffer from some of the worst air pollution in the state. (See footnote 386.)

In Greeley, Colorado, a massive well pad housing 24 wells was sited near Bella Romera Academy, an elementary school in a low-income community where 82 percent of students are Latino, after earlier plans were scrapped for a site near a charter school where students are majority white and middle-class.[289] An analysis of state data in 2020 showed that benzene levels in the air near the school exceeded health-based limits 113 times, including spikes during four full school days in 2019.[290] Benzene is a known cause of leukemia.

In West Virginia and Pennsylvania, a geographic study found a higher concentration of drilling and fracking operations in impoverished communities but did not find differences with respect to race. "The results demonstrate that environmental injustice occurs in areas with unconventional wells in Pennsylvania with respect to the poor population."[291] These findings are supported by census tract data in western Pennsylvania showing that among nearly 800 gas wells, only two were drilled in communities where home values exceeded $200,000.[292] In Ohio, geographic evidence reveals that disposal wells for fracking wastewater are disproportionately located in

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[286] Center for Biological Diversity, "Analysis: Most Oil Wells Approved by Gov. Brown Are in Low-Income Areas, Communities of Color," press release, August 16, 2018, https://www.biologicaldiversity.org/news/press_releases/2018/california-oil-drilling-08-16-2018.php.
[287] Emily Alpert Reyes, "Environmental Advocates Sue L.A., Accusing It of 'rubber Stamping' Oil Drilling Plans," *Los Angeles Times*, November 6, 2015, sec. California, http://www.latimes.com/local/lanow/la-me-ln-lawsuit-oil-drilling-20151106-story.html.
[288] John C. Fleming and Candice Kim, "Danger next Door: The Top 12 Air Toxics Used for Neighborhood Oil Drilling in Los Angeles" (Center for Biological Diversity, December 2017), http://www.biologicaldiversity.org/publications/papers/DangerNextDoor.pdf.
[289] Julie Turkewitz, "In Colorado, a Fracking Boom and a Population Explosion Collide," *The New York Times*, May 31, 2018, https://www.nytimes.com/2018/05/31/us/colorado-fracking-debates.html.
[290] John Herrick, "Report: Cancer-Causing Benzene Spiked More than Once at Bella Romero," *The Colorado Independent*, March 11, 2020, https://www.coloradoindependent.com/2020/03/11/report-benzene-bella-romero/.
[291] Yelena Ogneva-Himmelberger and Liyao Huang, "Spatial Distribution of Unconventional Gas Wells and Human Populations in the Marcellus Shale in the United States: Vulnerability Analysis," *Applied Geography* 60 (2015): 165–74, https://doi.org/10.1016/j.apgeog.2015.03.011.
[292] Reid Frazier, "Is Fracking an Environmental Justice Issue?," The Allegheny Front, June 30, 2017, https://www.alleghenyfront.org/is-fracking-an-environmental-justice-issue/.

lower-income, rural communities.[293]

Environmental justice issues extend to downstream fracking infrastructure. In May 2018, community groups in North Carolina filed an environmental justice complaint against Dominion's Energy's $8 billion Atlantic Coast Pipeline, alleging the project poses disproportionate risk of harm to people of color. Thirteen percent of those living along the pipeline route are Native Americans in a state where Native Americans make up only 1.2 percent of the population.[294, 295] A compressor station in Virginia that would service this pipeline was proposed to be sited in the historically African-American community of Union Hill.[296] In January 2020, the 4th U.S. Circuit Court quashed the approval of this compressor station, noting that state regulators had failed to fully consider disproportionate harms to an environmental justice community. In July 2020, Dominion Energy canceled the Atlantic Coast pipeline project entirely and sold off assets.[297]

Meanwhile, Mountain Valley Pipeline's 75-mile Southgate Extension, which would ferry fracked gas from West Virginia between southern Virginia and North Carolina, calls for two compressor stations that would disproportionately affect Black and Indigenous communities.[298, 299] In May 2021, the North Carolina Department of Environmental Quality denied certification to the pipeline itself, the object of Indigenous-led opposition to the project.[300] In December 2021, the Virginia Air Pollution Control Board denied a permit to the Lambert compressor station on environmental justice grounds.[301]

In April 2020, FERC approved the Sabal Trail compressor station in the majority Black community in Albany, Georgia—one of the worst COVID-19 hotspots in the nation at the time—in a decision that provoked pointed criticism from the National Black Environmental Justice Network. The Commission also approved three LNG projects in Brownsville, Texas—even after finding that most of the people potentially harmed by one of these three projects and

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[293] Genevieve S. Silva, Joshua L. Warren, and Nicole Deziel, "Spatial Modeling to Identify Sociodemographic Predictors of Hydraulic Fracturing Wastewater Injection Wells in Ohio Census Block Groups," *Environmental Health Perspectives* 126, no. 6 (n.d.): 067008, https://doi.org/10.1289/EHP2663.
[294] Phil McKenna, "Atlantic Coast Pipeline Faces Civil Rights Complaint after Key Permit Is Blocked," Inside Climate News, May 18, 2018, https://insideclimatenews.org/news/18052018/atlantic-coast-pipeline-natural-gas-civil-rights-environmental-justice-epa.
[295] Ryan E. Emanuel, "Flawed Environmental Justice Analyses," *Science* 375, no. 6348 (2017): 260, https://doi.org/10.1126/science/aao2684.
[296] Mary Finley-Brook et al., "Critical Energy Justice in US Natural Gas Infrastructuring," *Energy Research & Social Science* 41 (2018), https://doi.org/10.1016/j.erss.2018.04.019.
[297] Carlos Anchondo, Kristi E. Swartz, and Hannah Northey, "Decision to Kill Atlantic Coast Project Upends Natural Gas," Energy Wire, July 6, 2020, https://www.eenews.net/energywire/stories/1063513089.
[298] Karenna Gore, "The Common Wealth of Water," *Virginia Mercury*, October 18, 2021, https://www.virginiamercury.com/2021/10/18/the-common-wealth-of-water/.
[299] Alexa Sutton Lawrence, "Updated Community Impact Assessment of Lambert Compressor Station" (Land and Heritage Consulting, February 25, 2021), https://www.deq.virginia.gov/home/showpublisheddocument/5326/637499574094200000.
[300] Nick de la Canal, "NC Regulators Reject Natural Gas Pipeline Extension For Second Time," WFAE.org, May 1, 2021, https://www.wfae.org/energy-environment/2021-05-01/nc-regulators-reject-natural-gas-pipeline-extension-for-second-time.
[301] Sarah Vogelsong, "Virginia Regulatory Board Denies Mountain Valley Pipeline Compressor Station Permit," *Virginia Mercury*, December 3, 2021, https://www.virginiamercury.com/2021/12/03/virginia-regulatory-board-denies-mountain-valley-pipeline-compressor-station-permit/.

the associated pipeline were Latino and one-third lived below the poverty line. This decision is currently being challenged in court for failure to consider the disproportionate health impacts on environmental justice communities.[302] (The future of this project, the proposed Rio Grande LNG export plant, was subsequently called into question in November 2020 when its French financial backer, Engie, pulled out of its $7 billion, 20-year import contract based on climate change concerns from the project's methane emissions.[303])

The siting of gas-fired power plants often reveals racial and economic bias. In Pennsylvania, gas-fired power plants are disproportionately located in low-income and minority communities.[304] Across California, gas-fired power plants are disproportionately located in disadvantaged communities, as classified by an environmental justice screening tool developed by the state Office of Environmental Health Hazard Assessment.[305] Fully half of California's fleet of gas-fired peaker plants are located in disadvantaged communities. Designed to ramp up quickly to meet peak electrical demand, peaker plants have higher emission rates of both greenhouse gases and smog-creating air pollutants when running than do continuously operating gas-fired plants.[306] In Arizona, Massachusetts, New Jersey, and New York, peaker plants tend to be located in minority and low-income communities or in areas the state has otherwise designated as environmental justice communities.[307] In southern Virginia, two different gas-fired power plants have been proposed for an impoverished majority Black community in Charles City County. In July 2020, plans for one of them were deferred due to environmental justice concerns.[308] In December 2020, the Virginia State Corporation Commission denied a request to Virginia Natural Gas to file a revised application for the Header Improvement Project, which encompassed the two proposed power plants.[309, 310]

In New Orleans, the city council approved the construction of Entergy's gas-fired power plant to be built amid largely African American and Vietnamese-American neighborhoods over the opposition of community groups who had both questioned the necessity of the plant and denied that meaningful input from local residents—or an investigation into clean energy alternatives—had ever taken place. The gas plant would annually release more than one million pounds of

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302 Arianna Skibell and Niina H. Farah, "FERC Faces Environmental Justice Reckoning," E&E News, July 31, 2020, https://web.archive.org/web/20200801222929/https://www.eenews.net/stories/1063659305.
303 Irina Slav, "Europe's Green Deal Is Bad News for U.S. LNG," OilPrice, November 14, 2020, https://oilprice.com/Energy/Natural-Gas/Europes-Green-Deal-Is-Bad-News-For-US-LNG.html.
304 Nextgen Climate America, & PSE Healthy Energy, "Our Air: Health and Equity Impacts of Pennsylvania's Power Plants," n.d., https://www.psehealthyenergy.org/wp-content/uploads/2017/11/NGCA-PSE-Our-Air-Health-and-Equity-Impacts-PA-2016-0710.pdf.
305 PSE Healthy Energy, "Natural Gas Power Plants in California's Disadvantaged Communities," research brief, April 2017, https://www.psehealthyenergy.org/wp-content/uploads/2017/04/CA.EJ_.Gas_.Plants.pdf.
306 PSE Healthy Energy, "California Peaker Power Plants," May 2020, https://www.psehealthyenergy.org/wp-content/uploads/2020/05/California.pdf.
307 PSE Healthy Energy, "Energy Storage Peaker Plant Replacement Project," PSE: Bringing Science to Energy Policy, n.d., https://www.psehealthyenergy.org/our-work/energy-storage-peaker-plant-replacement-project/.
308 Mike Soraghan, "Environmental Justice Concerns Stall Va. Power Project," E&E News, July 23, 2020, https://web.archive.org/web/20200723181021/https://www.eenews.net/stories/1063611741.
309 Sandy Hausman, "Another Pipeline Hits Regulator Roadblock," Radio WVTF, December 1, 2020, https://www.wvtf.org/post/another-pipeline-hits-regulator-roadblock#stream/0.
310 Sarah Vogelsong, "Virginia Natural Gas Infrastructure Expansion to Be Scaled Back amid Plant Financing Troubles," *Virginia Mercury*, November 17, 2020, sec. Energy & Environment, https://www.virginiamercury.com/2020/11/17/virginia-natural-gas-infrastructure-expansion-to-be-scaled-back-amid-plant-financing-troubles/.

toxic air pollution and more than 700 million pounds of greenhouse gases. In November 2019, a judge voided the council's approval, ruling that crucial public meetings had, in fact, been illegally packed with paid pro-gas actors indirectly hired by Entergy.[311] In February 2020, a state appellate court overturned that decision and let stand the city council's approval of construction.[312]

In New York City, six gas-fired peaker plants located in low-income communities have been targeted for replacement with renewable energy and battery storage technologies after the New York Power Authority signed an agreement with a coalition of environmental justice groups.[313] Peaker plants operate intermittently at times of peak energy demand.

Apart from disparities circumscribed by race and income, fracking raises fundamental questions of human rights. A comprehensive analysis that charts the international legal development of water rights as they apply to oil and gas extraction concluded that the right to water for residents living near fracking sites is "likely to be severely curtailed." This analysis emphasizes that access to clean and safe drinking water is codified by the United Nations General Assembly as a human right essential to the full development of life and all other human rights. And yet, the fracking industry does not bear the true societal cost of water in their production decisions.

Accordingly, the authors argue, ownership of this essential-to-life resource is effectively transferred from society to industry, with no protection for this essential human right. In the United States alone, "there is considerable evidence that the human right to water will be seriously undermined by the growth of the unconventional oil and gas industry, and given its spread around the globe, this could soon become a global human rights issue."[314]

Three international human rights bodies have called for prohibitions on fracking. In February 2019, the Committee on Elimination of Discrimination Against Women, which monitors the implementation of the 1979 United Nations treaty that serves as an international bill of rights for women, called on the United Kingdom to ban fracking on the ground that fracking damages communities and imperils the climate in ways that disproportionately harm women and girls

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[311] Ivan Penn, "Natural Gas or Renewables? New Orleans Choice Is Shadowed by Katrina," *The New York Times*, November 8, 2019, sec. Energy & Environment, https://www.nytimes.com/2019/11/08/business/energy-environment/gas-power-plants.html.
[312] Jessica Williams, "New Orleans Council Violated Law, but Vote on Entergy Power Plant Still OK, Judges Rule," *The Times-Picayune*, February 13, 2020, https://www.nola.com/news/politics/article_13af7070-4e81-11ea-bf49-db5ebb91c620.html.
[313] New York Power Authority, "NYPA and Environmental Justice Groups Agree to Explore Options for Transitioning NYPA's Natural Gas 'peaker' Plants to Cleaner Energy Technologies," press release, October 13, 2020, https://www.nypa.gov/news/press-releases/2020/20201013-ej.
[314] Robert C. Palmer, Damien Short, and Walter E. Ted Auch, "The Human Right to Water and Unconventional Energy," *International Journal of Environmental Research and Public Health* 15, no. 9 (n.d.): 1858, https://doi.org/10.3390/ijerph15091858.

living in rural areas.[315, 316] In October 2018, the United Nations Committee on Economic, Social and Cultural Rights warned Argentina that its plans for large-scale fracking in the Vaca Muerta Shale region would create adverse economic and cultural rights impacts on the indigenous Mapuche people.[317] In May 2018, the Permanent People's Tribunal, a Rome-based forum focused on human rights violations, issued an advisory opinion based on a two-year investigation that collected testimonies and reports from scientists and fracking-impacted communities.

In the words of the Tribunal,

> The evidence clearly demonstrates that the processes of fracking contribute substantially to anthropogenic harm, including climate change and global warming, and involve massive violations of a range of substantive and procedural human rights and the rights of nature. Thus the industry has failed to fulfill its legal and moral obligations…. The dangers of fracking to the rights of people, communities, and nature are inherent in the industry….We will go beyond the call for a moratorium and recommend that fracking should be banned.[318]

In October 2021, the United Nations Human Rights Council, an intergovernmental body within the United Nations system charged with addressing situations of human rights violations, passed a resolution recognizing the right to a healthy and sustainable environment as a basic human right, and in a second resolution, established a Special Rapporteur dedicated specifically to the human rights impacts of climate change.[319]

16) Carbon capture and storage fails to mitigate the dangers of fracking.

In the United States, gas and oil companies have turned to carbon capture and storage (CCS) as a method of offsetting, on paper, their greenhouse gas emissions without ending fossil fuel

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[315] United Nations Committee on the Elimination of Discrimination Against Women, "List of Issues in Relation to the Eighth Periodic Report of the United Kingdom of Great Britain and Northern Ireland," UN Treaty Body Database, United Nations Human Rights Treaty Bodies, July 27, 2018, https://tbinternet.ohchr.org/_layouts/15/treatybodyexternal/Download.aspx?symbolno=CEDAW%2fC%2fGBR%2fCO%2f8&Lang=en.
[316] Center for International Environmental Law, "UN Body Recommends UK Consider Complete Fracking Ban to Protect Human Rights," press release, March 13, 2018, https://www.ciel.org/news/un-body-recommends-uk-consider-complete-fracking-ban-to-protect-human-rights/.
[317] Center for International Environmental Law, "CIEL Statement on the Committee on Economic, Social, and Cultural Rights (CESCR)'s Recommendations for the State of Argentina Regarding Its Vaca Muerta Shale Gas Development," press release, October 19, 2018, https://www.ciel.org/news/ciel-statement-on-the-committee-on-economic-social-and-cultural-rights-cescrs-recommendations-for-the-state-of-argentina-regarding-its-vaca-muerta-shale-gas-development/.
[318] Permanent Peoples' Tribunal, "Session on Human Rights, Fracking and Climate Change—Advisory Opinion," May 14, 2018, http://permanentpeoplestribunal.org/wp-content/uploads/2019/04/AO-final-12-APRIL-2019.pdf.
[319] Office of the High Commissioner, "Bachelet Hails Landmark Recognition That Having a Healthy Environment Is a Human Right," United Nations Human Rights, October 8, 2021, https://www.ohchr.org/EN/NewsEvents/Pages/DisplayNews.aspx?NewsID=27635&LangID=E).

extraction or combustion. This technology is linked to fracking in several ways and has recently received major support by the Biden administration.[320]

In contrast to direct air capture of ambient carbon dioxide, CCS is a process by which complex machinery, typically powered by a gas-fired turbine, is added to an existing point source of carbon dioxide, such as the smoke stack of a power plant. Its purpose is to catch some of the carbon dioxide that would otherwise be released into the atmosphere from fossil-fuel combustion, separate it from other emissions, pressurize it into a liquid, and then transport the liquefied carbon dioxide through pipelines to an underground repository or to oil fields for use in oil extraction operations. CCS relies on multiple technologies. Carbon dioxide emissions may be captured by membranes, for example, or, more typically, absorbed into a solvent.[321]

All CCS methods are hugely expensive, with carbon capture from a gas-fired power plant costing $49-$150 per ton of carbon captured.[322] Because there is no market for carbon dioxide waste, CCS must be supported by massive public subsidies, as, for example, by offering tax credits. Under current law, Section 45Q of the Internal Revenue Code supports CCS efforts by offering a tax credit for each ton of carbon dioxide captured and stored but does not yet provide sufficient incentive to make CCS economical. (With the current—and, at this date, stalled—version of the Build Back Better Act, the 45Q tax credit would significantly increase.)

As a highly experimental set of unproven technologies, CCS has largely failed to reach its promised rates of capture. Claims that CCS can reduce carbon dioxide emissions by 90 percent or more have never been realized, with pilot projects capturing as little as 30 percent. Currently only 27 commercial CCS facilities are operational worldwide, of which twelve are in the United States. Of these U.S. facilities, four are used for natural gas processing, three for ethanol production, three for fertilizer production, one for synthesis gas production, and one in hydrogen production. Only one, the Illinois Industrial Carbon Capture and Storage Project, actually stores the carbon it captures, and it has consistently failed to reach its promised goal each year.[323]

Capturing carbon dioxide from gas-fired power plants or other types of fracking infrastructure, including LNG terminals, has not proceeded past demonstration projects. No commercial-scale projects are currently operating for utilities. Indeed, CCS has largely failed for coal-fired power plants and, for gas-fired plants, would require massive investment, complex infrastructure, and further federal subsidies.[324] The flagship demonstration project for CCS, at Chevron's $54 billion

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[320] Council on Environmental Quality, "Council on Environmental Quality Report to Congress on Carbon Capture, Utilization, and Sequestration" (The White House, June 20, 2021), https://www.whitehouse.gov/wp-content/uploads/2021/06/CEQ-CCUS-Permitting-Report.pdf.
[321] Stefano E. Zanco et al., "Postcombustion CO_2 Capture: A Comparative Techno-Economic Assessment of Three Technologies Using a Solvent, an Adsorbent, and a Membrane," *ACS Engineering Au* 1, no. 1 (October 20, 2021): 50–72, https://doi.org/10.1021/acsengineeringau.1c00002.
[322] Jonathan M. Moch, William Xue, and John P. Holdren, "Carbon Capture, Utilization, and Storage: Technologies and Costs in the U.S. Context," Policy Brief (Harvard Kennedy School Belfer Center for Science and International Affairs, January 2022), https://www.belfercenter.org/publication/carbon-capture-utilization-and-storage-technologies-and-costs-us-context.
[323] Angela C. Jones and Ashley J. Lawson, "Carbon Capture and Sequestration (CCS) in the United States" (Congressional Research Service, October 18, 2021), https://sgp.fas.org/crs/misc/R44902.pdf.
[324] U.S. Government Accountability Office, "Carbon Capture and Storage: Actions Needed to Improve DOE Management of Demonstration Projects" (U.S. Government Accountability Office, December 2021), https://www.gao.gov/assets/gao-22-105111.pdf.

Gorgon LNG plant in Western Australia, has been plagued with technical problems and was operating at only half-capacity in 2021, having buried only 30 percent of the carbon dioxide it generated since 2016. Failing to meet its five-year target for carbon dioxide injection rates, Chevron was ultimately forced to purchase carbon offset credits as a penalty.[325, 326] Here in the United States, the sole utility-scale CCS project, the Petra Nova coal-fired plant in Texas, shut down in 2020 after oil prices crashed. Petra Nova pumped its captured carbon dioxide to the Permian Basin to assist in oil extraction operations, which were largely suspended during the pandemic.[327]

A 2020 review of more than 200 papers on carbon-capturing technology published in scientific journals concluded that the failures of CCS are systemic and irremediable. Because it can never store more than it captures, point-source CCS is not a negative emissions technology and cannot significantly reduce atmospheric carbon dioxide. Indeed, as currently practiced, CCS is net additive, releasing into the atmosphere more carbon dioxide than it removes.[328]

A 2021 study found that equipping a coal plant with carbon-capture technology would, over a 20-year period, result in only a 10 percent reduction in carbon dioxide entering the atmosphere compared to a coal plant operating without CCS.[329] Further, the CCS equipment is itself a source of greenhouse gas emissions, which are unaccounted for in most assessments of CCS climate impacts. Because powering this equipment is energy intensive, CCS also makes local air pollution worse. The emissions from the gas turbine that powers the capture equipment is itself not captured, nor are the methane leaks from the turbine itself, nor are the upstream methane emissions from extracting and collecting the natural gas to run the turbine. Further, extra energy is needed to run the carbon-capturing machinery. CCS requires 10 to 20 percent of a power plant's energy output, for example.[330] Hence, a CCS-equipped facility, such as a gas-fired power plant, will consume more power and hence generate more air pollution, including soot and smog-producing vapors. Unlike carbon dioxide, these additional co-pollutants are not collected and captured, and they pose additional health threats to local residents. The total social cost (equipment plus health plus climate cost) of a coal plant outfitted with gas-powered CCS equipment is over twice that of wind replacing coal directly (See footnote 328).

Because power plants and other heavy industries targeted for CCS are disproportionately located in low-income neighborhoods and communities of color, CCS is an environmental justice

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[325] Josh Lewis, "Chevron's Flagship Gorgon CCS Project Still Failing to Live up to Expectations," *Upstream*, February 10, 2022, https://www.upstreamonline.com/energy-transition/chevrons-flagship-gorgon-ccs-project-still-failing-to-live-up-to-expectations/2-1-1166185.
[326] Sonali Paul, "Chevron, Partners to Fork out for Carbon Offsets for Gorgon LNG Carbon Capture Shortfall," Reuters, November 10, 2021, https://www.reuters.com/business/sustainable-business/chevron-invest-29-mln-address-co2-injection-shortfall-australia-lng-site-2021-11-11/.
[327] Kevin Robinson-Avila, "Debating the Promise and Perils of Carbon Capture in New Mexico," *Albuquerque Journal*, February 5, 2022, https://www.abqjournal.com/2467622/the-promise-and-perils-of-carbon-capture.html.
[328] June Sekera and Andreas Lichtenberger, "Assessing Carbon Capture: Public Policy, Science, and Societal Need: A Review of the Literature on Industrial Carbon Removal," *Biophysical Economics and Sustainability* 5, no. 3 (September 2020): 14, https://doi.org/10.1007/s41247-020-00080-5.
[329] Mark Z. Jacobson, "The Health and Climate Impacts of Carbon Capture and Direct Air Capture," *Energy & Environmental Science* 12, no. 12 (2019): 3567–74, https://doi.org/10.1039/C9EE02709B.
[330] Suraj Vasudevan et al., "Energy Penalty Estimates for CO2 Capture: Comparison between Fuel Types and Capture-Combustion Modes," *Energy* 103 (May 2016): 709–14, https://doi.org/10.1016/j.energy.2016.02.154.

issue.[331] In essence, CCS prolongs the life of major sources of pollution, reduces carbon dioxide emissions only modestly, and increases the levels other deadly co-pollutants linked to asthma, stroke, heart attack risk, and preterm birth.

The dangers of CCS to public health and the climate continue during the transportation and storage phases. Once collected, the captured carbon is pressurized to 1,000 pounds per square inch and thereby turned into liquid for transport through pipelines. These pressurized pipelines may leak or rupture in ways that cause asphyxiation hazards for nearby residents due to the ability of carbon dioxide to displace oxygen. In February 2020, a carbon dioxide pipeline ruptured in Satartia, Mississippi, hospitalizing 49 people. Many victims continue to suffer long-lasting health problems.[332] (The carbon dioxide within this particular pipeline was also contaminated with hydrogen sulfide gas.) Widespread development of CCS at commercial scale would require massive pipeline construction. An oil and gas industry-funded study from Princeton University proposed a pathway to net zero carbon by 2050 that would necessitate 66,000 miles of carbon dioxide pipelines, including more than 13,000 miles of interstate lines, heading to thousands of deep-earth burial sites.[333, 334]

Once the carbon dioxide waste is buried in geological formations, its long-term behavior is unknown.[335] Under Section 45Q of the Internal Revenue Code, companies claiming tax credits for its capture do not need to ensure that carbon dioxide stays in the ground.[336] And there are reasons to believe it may not. Some fraction of the injected carbon dioxide will begin to mineralize. However, when in the presence of moisture, carbon dioxide converts to carbonic acid and can react chemically, leaching heavy metals and dissolving rock and cement.[337, 338] If fissures in caprocks or abandoned wells offer pathways for leakage, liquid carbon dioxide waste could potentially acidify and permanently contaminate underground aquifers, poisoning drinking water for millions of people. In the event of a technological failure or earthquake, carbon dioxide would gasify and immediately be released back to the atmosphere.[339] Storage of liquified carbon

331 Heather Payne, "Chasing Squirrels in the Energy Transition," *Environmental Law* 52 (2022), https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3998197.
332 Dan Zegart, "The Gassing of Satartia," *Huffington Post*, October 26, 2021, https://www.huffpost.com/entry/gassing-satartia-mississippi-co2-pipeline_n_60ddea9fe4b0ddef8b0ddc8f.
333 Eric Larson et al., "Net-Zero America: Potential Pathways, Infrastructure, and Impacts (Interim Report)" (Princeton University, December 15, 2020), https://netzeroamerica.princeton.edu/img/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.
334 Elizabeth Abramson, Dane McFarlane, and Jeff Brown, "Transport Infrastructure for Carbon Capture and Storage" (Great Plains Institute, June 2020), https://www.betterenergy.org/wp-content/uploads/2020/06/GPI_RegionalCO2Whitepaper.pdf.
335 Juan Alcalde et al., "Estimating Geological CO2 Storage Security to Deliver on Climate Mitigation," *Nature Communications* 9, no. 1 (2018): 2201, https://doi.org/10.1038/s41467-018-04423-1.
336 Nicholas Kusnetz, "Fossil Fuel Companies Are Quietly Scoring Big Money for Their Preferred Climate Solution: Carbon Capture and Storage," *Inside Climate News*, August 17, 2021, https://insideclimatenews.org/news/17082021/carbon-capture-storage-fossil-fuel-companies-climate/.
337 John Fogarty, "Health and Safety Risks of Carbon Capture and Storage," *JAMA* 303, no. 1 (2010): 67, https://doi.org/10.1001/jama.2009.1951.
338 Peilin Cao, Zuleima T. Karpyn, and Li Li, "The Role of Host Rock Properties in Determining Potential CO2 Migration Pathways," *International Journal of Greenhouse Gas Control* 45 (2016): 18–26, https://doi.org/10.1016/j.ijggc.2015.12.002.
339 Physicians for Social Responsibility Los Angeles, "Danger Ahead: The Public Health Disaster That Awaits From Carbon Capture and Sequestration (CCS)," PSR-LA.org, February 10, 2022, https://www.psr-la.org/danger-ahead-the-public-health-disaster-that-awaits-from-carbon-capture-and-sequestration-ccs/.

dioxide in deep geological formations is, like the injection of fracking wastewater, linked to increased risks for earthquakes that could compromise the seal integrity of these repositories. Even absent significant seismic activity, carbon sequestration itself can create pressure build-up large enough to break the reservoirs' seals, releasing the stored carbon dioxide. Old wells, boreholes, and faults are the most common pathways for free-form carbon dioxide to escape to the surface.[340, 341] To be effective, carbon dioxide repositories need to be monitored for carbon dioxide leakage over long periods and require a leak rate of less than one percent per thousand years.[342] The U.S. Department of Energy is currently examining 19 sites in the midwestern United States to serve as possible storage depots for carbon dioxide waste.[343]

In addition to providing the gas for carbon dioxide-capturing turbines, fracking is linked to CCS in two other ways. First, the primary current use of CCS is to enhance oil extraction from aging wells. Indeed, all but one of the 12 CCS projects in the United States use the captured carbon dioxide for enhanced oil recovery in which captured carbon dioxide is pumped into partially depleted oil wells to extract more oil.[344] Indeed, enhanced oil recovery is the only existing commercially available market for millions of tons of captured carbon dioxide, and the downstream emissions from burning this oil, which would otherwise remain underground, is not accounted for in CCS "net-zero" models.

Second, CCS is used in the production of "blue hydrogen." There are several methods for producing hydrogen fuel. One uses electrolysis of water powered by renewable energy to produce hydrogen and oxygen. This is so-called "green hydrogen." The other two methods use natural gas as a starting point. In the first, hydrogen fuel is manufactured by using heat and pressure to convert the methane in natural gas to hydrogen and prodigious amounts of carbon dioxide, which is released into the atmosphere. The hydrogen produced in this way is called "gray hydrogen." "Blue hydrogen" is produced in the same way as gray hydrogen, but with some of its carbon dioxide emissions captured and stored. As of 2021, just four facilities globally—two in Alberta, one in Texas, and one in Oklahoma—used natural gas with CCS to manufacture blue hydrogen. In all cases the estimated proportion of carbon dioxide captured is below 50 percent.[345]

Although blue hydrogen has been touted as a climate solution, recent research indicates that its carbon footprint is 20 percent greater than burning natural gas directly. Furthermore, combustion

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340 Peter Kelemen et al., "An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations," *Frontiers in Climate* 1 (November 15, 2019): 9, https://doi.org/10.3389/fclim.2019.00009.
341 Curtis M. Oldenburg, Preston D. Jordan, and Elizabeth Burton, "Recommendations for Geologic Carbon Sequestration in California: I. Siting Criteria and Monitoring Approaches, II. Example Application Case Study," June 15, 2017, https://ww2.arb.ca.gov/sites/default/files/2018-12/LBNL_CARB_QM_Final_Report_6-15-17.pdf?msclkid=0b14779dabb511ec9b6ebda6eea66910.
342 Mark D. Zoback and Steven M. Gorelick, "Earthquake Triggering and Large-Scale Geologic Storage of Carbon Dioxide," *Proceedings of the National Academy of Sciences* 109, no. 26 (June 26, 2012): 10164–68, https://doi.org/10.1073/pnas.1202473109.
343 "Carbonsafe," National Energy Technology Laboratory, n.d., https://www.netl.doe.gov/coal/carbon-storage/storage-infrastructure/carbonsafe.
344 Leah Douglas, "Factbox: Biden Administration Sees Carbon Capture as Key Tool in Climate Fight," Reuters, February 7, 2022, https://www.reuters.com/business/environment/biden-administration-sees-carbon-capture-key-tool-climate-fight-2022-02-07/.
345 Jan Gorski, Tahra Jutt, and Karen Tam Wu, "Carbon Intensity of Blue Hydrogen Production" (Pembina Institute, August 2021), https://www.pembina.org/reports/carbon-intensity-of-blue-hydrogen-revised.pdf.

emissions from the machinery needed to run the carbon and capture equipment, plus fugitive methane emissions, make blue hydrogen a dirtier fuel than burning methane alone.[346] Greenhouse gas emissions from the manufacture of hydrogen using methane as a starting point are substantial, even with carbon capture and storage.[347]

In sum, CCS functions as a fossil fuel subsidy, entrenches fossil fuel demand, impedes the phase-out of fracking, requires massive public investment, captures far less carbon dioxide than claimed, and suffers from incomplete emissions accounting. Namely, CCS strategies fail to account for upstream fugitive methane emissions as well as for carbon dioxide emissions created from the combustion of oil retrieved by injecting captured carbon dioxide into otherwise depleted wells.[348] CCS is aimed at prolonging drilling and fracking for oil and natural gas and does not address the many public health, climate, and environmental justice problems created by fracking, as detailed in this Compendium. In these ways, CCS enables fracking and is an expensive, dangerous diversion away from renewable energy investments.[349]

[346] Robert W. Howarth and Mark Z. Jacobson, "How Green Is Blue Hydrogen?," *Energy Science & Engineering* 9, no. 10 (October 2021): 1676–87, https://doi.org/10.1002/ese3.956.
[347] Thomas Longden et al., "'Clean' Hydrogen? – Comparing the Emissions and Costs of Fossil Fuel versus Renewable Electricity Based Hydrogen," *Applied Energy* 306 (2022): 118145, https://doi.org/10.1016/j.apenergy.2021.118145.
[348] "Letter from Scientists, Academics, and Energy System Modellers: Prevent Proposed CCUS Investment Tax Credit from Becoming a Fossil Fuel Subsidy," January 19, 2022, https://cehoicka.lab.yorku.ca/files/2022/01/Letter-from-Academics-re-CCUS-tax-investment-credit_January-2022-4.pdf?x98920.
[349] Howard J. Herzog, "Scaling up Carbon Dioxide Capture and Storage: From Megatons to Gigatons," *Energy Economics* 33, no. 4 (July 2011): 597–604, https://doi.org/10.1016/j.eneco.2010.11.004.

Case study: Drilling and Fracking in California

California is the nation's seventh-most prolific oil-producing state. As of 2021, about 17 percent of California's oil and gas was extracted via fracking.[350]

Fracking is practiced in ten California counties, most notably in Kern County where half of all new oil wells are fracked. In April 2021, a bill (SB 467) that would have banned fracking in the state by 2023 and instituted mandatory setback distances between drilling sites and residences failed to pass the state legislature. Also in April 2021, California Governor Gavin Newsom announced a plan to stop issuing new fracking permits in the state by 2024 as part of a larger proposal to phase out all oil extraction in the state by 2045.[351] By November 2021, ahead of the 2024 ban, California had already denied 109 fracking permits.[352]

Hydraulic fracturing in California is practiced differently than in other states, making its risks different. Wells are more likely to be vertical rather than horizontal, and the oil-containing rock layer is shallower. Hence, much less water is used per well for fracking as compared to other states. However, the fracking fluid used is much more chemically concentrated, the fracking zones are located closer to overlying aquifers, and the risk of a fracture reaching groundwater is higher. Furthermore, although fracking in California requires considerably less water per well, it takes place disproportionately in areas of prolonged, severe water shortages and can compete with municipal and agricultural needs for freshwater.

California is the only state that allows wastewater from oil fields to be held in unlined open pits, which creates risks for both air and groundwater contamination. Evaporation from wastewater pits is a significant source of toxic air pollution in California's San Joaquin Valley. These emissions include the volatile organic compounds benzene, toluene, ethylbenzene, and xylene, all of which are neurological toxicants. Benzene is a known cause of leukemia. The results of a 2020 investigation showed that evaporation of these four toxic chemicals from oil and gas waste pits alone represented up to two percent of the air basin's inventory of these substances. (See footnote 398.) As of July 2018, 1,086 such pits were operational in the Central Valley, with the vast majority in Kern County. An investigation by reporters for NBC Bay Area found additional pits not on the state's official list. In at least two instances, toxic wastewater from the pits had migrated underground for more than a mile.[353]

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[350] Rachel Becker and Laurel Rosenhall, "Newsom Orders Ban on New Oil Fracking by 2024," *Cal Matters*, April 23, 2021, https://calmatters.org/environment/2021/04/newsom-ban-new-oil-fracking/.
[351] Emma Bowman, "California Governor Moves To Ban Fracking By 2024," NPR.org, April 23, 2021, https://www.npr.org/2021/04/23/990368418/california-governor-moves-to-ban-fracking-by-2024.
[352] Dustin Gardiner and J.D. Morris, "Citing Climate Risks, California Is Denying Fracking Permits in Droves," *San Francisco Chronicle*, November 23, 2021, https://www.sfchronicle.com/politics/article/Citing-climate-risks-California-is-denying-16643010.php.
[353] Stephen Stock et al., "Toxic Wastewater from Oil Fields Endangers California's Water Supply, Scientists Tell NBC Bay Area," NBC Bay Area, November 27, 2018, https://www.nbcbayarea.com/investigations/Toxic-WasteWater-From-Oil-Fields-Endangers-Californias-Water-Supply-Scientists-Tell-NBC-Bay-Area-483089841.html.

In 2019, a U.S. Geological Survey team working within the San Joaquin Valley in Kern County documented aquifer contamination from the downward migration of fluids stored in unlined wastewater pits as well as from the outward migration of fluids from underground disposal wells. Contamination of groundwater from disposal wells was detectable as far away as one-third of a mile (1800 feet) away. (See footnote 543.)

Similarly, a 2021 study documented contamination of groundwater resources from unlined wastewater pits throughout the southern Tulare Basin region of the San Joaquin Valley, which is also the nation's most productive agricultural region with groundwater widely used for irrigation. In one case, the carcinogen benzene was found in groundwater underlying waste pits at levels 45 times higher than the safety limit for drinking water. However, regulators concluded that remediation costs would be prohibitive.[354, 355]

In 2014, the discovery that companies had, for years, been wrongly allowed to inject oil and gas waste directly into California's freshwater aquifers led to the closing of 175 disposal wells. Impacts on drinking water are unknown. (See footnotes 602, 603.) Nevertheless, throughout 2020 and into 2021, the state issued more than 300 permits to oil and gas companies for new underground injection wells.[356]

Most fracking operations in California have taken place in areas with a long history of oil extraction. A high density of old and abandoned wells provides potential leakage pathways, should fractures intersect with them.

The combination of ongoing drought and lack of disposal options has resulted in the diversion of fracking wastewater to farmers for irrigation of crops, raising concerns about contaminated water potentially affecting food crops and draining into groundwater. Investigative reports in 2015 revealed that Chevron Corporation piped 21 million gallons of recycled oil and gas wastewater per day to farmers for crop irrigation. Tests showed the presence of several volatile organic compounds, including acetone, which is linked in lab studies to kidney, liver, and nerve damage. (See footnotes 1445-1447.)

These activities project fracking's impacts onto geographically distant populations, especially in cases where wastewater is used in crop irrigation and livestock watering. Kern County, for example, the epicenter of fracking in California, is also the world's leading producer of almonds and pistachios. Food is a troubling possible exposure route to fracking chemicals, in part because so little is known about these chemicals. According to a hazard assessment of chemicals used in California oil drilling operations that reuse wastewater for livestock watering and other agricultural purposes, more than one-third of the 173 chemicals used are classified as trade secrets: Their identities are entirely unknown. Of the remainder, ten are likely carcinogens, 22

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[354] Dominic C. DiGiulio et al., "Vulnerability of Groundwater Resources Underlying Unlined Produced Water Ponds in the Tulare Basin of the San Joaquin Valley, California," *Environmental Science & Technology* 55, no. 21 (November 2, 2021): 14782–94, https://doi.org/10.1021/acs.est.1c02056.
[355] Liza Gross, "Unchecked Oil and Gas Wastewater Threatens California Groundwater," *Inside Climate News*, October 24, 2021, https://insideclimatenews.org/news/24102021/california-oil-wastewater-produced-water-drought-groundwater-contamination/.
[356] Aaron Cantu, "California Is Greenlighting Oil Wells Linked to Groundwater Pollution," *Capital & Main*, April 8, 2021, https://capitalandmain.com/california-is-greenlighting-oil-wells-linked-to-groundwater-pollution-0408.

are toxic air contaminants, and 14 had no toxicity data available. Estimating risks to consumers of the food produced with wastewater irrigation is thus not possible. (See footnote 1440.)

In fall 2021, the Central Valley Regional Water Quality Control Board assured the public that eating California crops grown with oil field wastewater "creates no identifiable increased health risks" based on the results of a study conducted by oil industry consultants.[357] The Board's own expert panel, however, conceded that the data gaps in the analysis left "potentially significant unknowns" about the chemicals in question and concluded that the investigation did not answer fundamental safety questions about irrigating crops with wastewater from drilling operations. More than 60 percent of chemicals identified in the study as most likely to pose risks to human health lacked both toxicity information and approved testing methods.[358]

The other area in California where fracking is concentrated, the Los Angeles Basin, is located directly under the most populous county in the United States. As of this writing, there are a total of 7,174 operational oil and gas wells in Los Angeles County; 3,577 are active and 3,597 idle. "Unincorporated" areas of the county include 1,683 wells; 997 of those are active and 686 are idle. Of the 2,062 wells located in the City of Los Angeles, 725 are active and 1,337 are idle. Another city within the county, Culver City, includes a portion of the Inglewood Oil field, one of the largest urban drilling areas in the country, though the majority of the field's wells are located in unincorporated areas.[359]

At least 1.7 million people in Los Angeles live or work within one mile of an active oil or gas well, and 600,000 live within a half mile. A 2017 study shows that many of the same chemicals used to stimulate wells during fracking operations are also used in urban oil wells located in densely populated areas of southern California. (See footnote 608.) A 2021 study that deployed air quality monitors in Los Angeles neighborhoods where oil and gas drilling take place found methane spikes near wells and an associated pipeline. A second study found that ambient air levels of methane—along with benzene, toluene, styrene, ethane, propane and other volatile compounds—were highly elevated during operations and fell when wells were subsequently idled. (See footnote 377.) Air pollutants from urban oil and gas operations disproportionately affect the city's Black and Latino residents. (See footnote 286.)

In December 2020, after a lengthy legal analysis, the Los Angeles City Council environment committee voted unanimously to support a proposal to outlaw all oil drilling within the city limits via updates to zoning codes that would make oil and gas extraction "nonconforming land use" across Los Angeles.[360] In January 2022, the motion was unanimously passed by the full Council, which voted to ban all new oil and gas wells and phase out the more than 2,000 existing

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[357] Carolyn M. Cooper et al., "Oil and Gas Produced Water Reuse: Opportunities, Treatment Needs, and Challenges," *ACS ES&T Engineering*, 2021, acsestengg.1c00248, https://doi.org/10.1021/acsestengg.1c00248.
[358] Liza Gross, "A California Water Board Assures the Public That Oil Wastewater Is Safe for Irrigation, But Experts Say the Evidence Is Scant," *Inside Climate News*, February 6, 2022, https://insideclimatenews.org/news/06022022/a-california-water-board-assures-the-public-that-oil-wastewater-is-safe-for-irrigation-but-experts-say-the-evidence-is-scant/.
[359] Kyle Ferrar, "Personal Correspondence" (Western Program Coordinator, FracTracker Alliance, February 25, 2022).
[360] Nathan Solis, "Los Angeles Moves Closer to Forcing Oil & Gas Drillers out of City," Courthouse News Service, December 1, 2020, https://www.courthousenews.com/los-angeles-moves-closer-to-forcing-oil-gas-drillers-out-of-city/.

ones. In the interim, the Los Angeles County Board of Supervisors unanimously voted to phase out oil and gas drilling and to ban new drilling within the county's unincorporated areas, on a schedule to be determined, and Culver City unanimously voted to prohibit the drilling of any new, or redrilling of any existing, wells, and to require the phasing out, plugging, and restoration of all existing wells by November 24, 2026.

There are currently no statewide set-back requirements in California, which remains the only oil- or gas-producing state that does not limit how close to residences or schools drilling and fracking activities may be conducted. (Pennsylvania requires a 500-foot setback distance, for example, while Colorado requires 2,000 feet.) In October 2021, Governor Newsom issued draft regulations that would halt new drilling within 3,200 feet (one kilometer) of homes, schools, hospitals, and nursing homes. In February 2022, the state announced it had received 83,500 public comments during the comment period and is currently reviewing them. The setback rule, as proposed and not yet finalized, would not apply to existing wells and would not prohibit the drilling of new wells on existing well pads or the redrilling of inactive wells, raising the possibility that idled wells and well pads close to homes may yet be revived across the state in spite of the rule.[361, 362]

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[361] Office of Governor Gavin Newsom, "California Moves to Prevent New Oil Drilling Near Communities, Expand Health Protections," CA.gov, October 21, 2021, https://www.gov.ca.gov/2021/10/21/california-moves-to-prevent-new-oil-drilling-near-communities-expand-health-protections-2/.
[362] Aaron Cantu, "California Oil Safety Rule Contains 'Zombie Well' Loophole, Advocates Say," *Capital & Main*, February 17, 2022, https://capitalandmain.com/california-oil-safety-rule-contains-zombie-well-loophole-advocates-say.

Case Study: Drilling and Fracking in Florida

Gas and oil drilling in Florida, now only a minor industry, is currently concentrated in two areas: the western Panhandle near Pensacola and the Everglades area of southwest Florida. So far, fracking has been used at least once—in 2013 at a test well located in the Corkscrew Swamp Sanctuary near Naples in Collier County. The Texas company that fracked this well, using high-pressure acid fracturing techniques to dissolve the bedrock, received a cease-and-desist order from the Florida Department of Environmental Protection.[363]

Florida is heavily dependent on natural gas, which provides 70 percent of the electricity generated in its power plants. Renewed interest in oil and gas exploration in Florida has prompted public debate about fracking and whether to promulgate state regulations or prohibit it outright, possibly including a ban on the use of the rock-dissolving technology called matrix acidizing in addition to hydraulic fracturing *per se.* Bills that sought to ban fracking but not acidizing failed to pass in the Florida legislature in the 2019 legislative session.[364] In November 2019, a bill to ban both hydraulic fracturing and matrix acidization (SB 200) passed a Florida Senate committee but failed to pass in the 2020 legislative session.[365] A fracking ban proposal (SB 546) that included matrix acidization also failed in the spring 2021 legislative session, as did a bill (SB722) that would have banned oil and gas drilling within the Everglades Protection Area.[366]

In spite of the failure of fracking ban bills to pass the Florida state legislature, drilling and fracking in the state has been thwarted by other efforts. In May 2020, the state of Florida purchased a 20,000-acre tract of land in the Everglades to prevent the family who owned it from drilling for oil. The owners had won a legal battle that allowed them to secure permits for an exploratory well.[367, 368] In November 2021, the Florida Department of Environmental Protection

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363 "Could Leftover Wastewater from Balky Oil Well End up a Health Hazard?," *Naples Daily News*, January 1, 2015, http://archive.naplesnews.com/news/local/could-leftover-wastewater-from-balky-oil-well-end-up-a-health-hazard-ep-853723380-335781721.html/.
364 Samantha J. Gross, "Environmentalists Cite Report on Florida Oil Spills as Bid to Ban Fracking Stalls," *Miami Herald*, April 17, 2019, sec. Environment, https://www.miamiherald.com/news/local/environment/article229355974.html.
365 Jim Turner, "Florida Fracking Ban Could Run into Roadblocks," *Pensacola News Journal*, November 5, 2019, sec. News, https://www.pnj.com/story/news/2019/11/05/florida-fracking-ban-could-run-into-roadblocks/4163695002/.
366 "SB 546: Well Stimulation," The Florida Senate, April 30, 2021, https://www.flsenate.gov/Session/Bill/2021/546.
367 Alex Harris, "Florida Plans to Buy and Protect Everglades Land in Broward Targeted for Oil Drilling," *Miami Herald*, January 15, 2020, sec. Environment, https://www.miamiherald.com/news/local/environment/article239311568.html#:~:text=Ron%20DeSantis%20announced%20Wednesday.,land%20acquisition%20in%20a%20decade.
368 David Fleshler, "Land Purchase Finalized to Prevent Everglades Oil Drilling," *Sun Sentinel*, May 5, 2020, sec. Local News, https://www.sun-sentinel.com/local/broward/fl-ne-everglades-oil-drilling-deal-20200505-a2aq232m35h4ngx2gt2vlphv5m-story.html.

denied an exploratory drilling permit in Immokalee, one of the nation's leading tomato-growing regions and part of the Big Cypress watershed.[369]

In June 2021, Florida governor Ron DeSantis signed into law a bill (SB 1128/HB119) that invalidates local comprehensive plans that restrict natural gas use or otherwise pursue 100 percent renewable energy initiatives. An earlier version of the bill would have also preempted municipalities from enacting local fracking bans. As amended, it does not.[370]

Florida has more available groundwater than any other state; it is the drinking water source for 93 percent of Florida's population. Groundwater is also pumped to irrigate crops and provide frost protection to winter crops. Most of this water is held in the Floridan Aquifer, which extends across the entire peninsula and into parts of Georgia, Alabama, and South Carolina. This aquifer provides drinking water to ten million people in both rural and urban communities, including residents of several major cities: Gainesville, Jacksonville, Orlando, Tallahassee, and Tampa. Overlain by smaller, shallower aquifers in southern Florida, it is a highly permeable, highly interconnected subterranean system, with water moving rapidly in multiple directions through massive shelves of limestone, which represent the dissolved shells and fossilized skeletons of prehistoric marine organisms. Honeycombed with pores, fissures, joints, and caves, the underground terrain of the Floridan Aquifer resembles a vast, brittle, sponge partly covered with sand and clay. Springs and sinkholes are common.[371, 372]

It is not known whether fracking in Florida could induce sinkholes to open up or whether alterations in underground pressures could cause springs to go dry. Certainly, Florida's porous geology makes it vulnerable to groundwater contamination. Crumbly, soluble limestone offers pathways for contaminants spilled on the surface to travel deep into the aquifer, where they can be dispersed over great distances by the aquifer's river-like currents. A 2003 experiment with a dye tracer showed the special susceptibility of Florida's groundwater to potential contamination; within a few hours, the red dye traveled through the aquifer a distance (330 feet) that researchers had presumed would take days.[373]

Compounding these risks, Florida's exposure to hurricanes makes it vulnerable to spills of fracking-related chemicals. In August 2017, flooding from Hurricane Harvey shut down fracking sites in Texas and triggered 31 separate spills at wells, storage tanks, and pipelines. (See footnotes 1385-1387.)

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369 Karl Schneider, "State Denies Oil Drilling Permit in Immokalee, Fried Calls for End to State Permits," *Naples Daily News*, November 8, 2021, https://www.naplesnews.com/story/news/environment/2021/11/08/fdep-denies-oil-drilling-permit-immokalee-nikki-fried-calls-end-state-permits/6337066001/.
370 Florida House of Representatives, "366.032 Preemption over Utility Service Restrictions.," n.d., https://www.flsenate.gov/Session/Bill/2021/919/BillText/er/PDF.
371 Richard H. Johnston and Peter W. Bush, "Summary of the Hydrology of the Floridan Aquifer System in Florida and in Parts of Georgia, South Carolina, and Alabama," September 4, 2013, https://pubs.er.usgs.gov/publication/pp1403A.
372 Ann B. Tihansky and Lari A. Knochenmus, "Karst Features and Hydrogeology in West-Central Florida—a Field Perspective" (U.S. Geological Survey, February 13, 2001), http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.565.2989&rep=rep1&type=pdf.
373 Wellfield Technical Work Group, "Report of the Miami-Dade County Wellfield Technical Workgroup" (Miami-Dade County Department of Regulatory and Economic Resources, July 2017), https://ecmrer.miamidade.gov/reports/WellfieldTechnicalWorkgroupReportJuly2017.pdf.

It is unclear where Florida would send any potential fracking wastewater for treatment and/or for underground injection. Florida currently injects other types of liquid waste into disposal wells that are located above, rather than below, oil- and gas-producing zones. The injection of fracking waste in these same shallower layers may make earthquakes less likely than, for example, in Oklahoma (where it is injected into deep formations), but it would also locate that waste closer to the aquifers, which are poorly mapped. To undertake the necessary study to determine how securely Florida's geological formations could contain wastewater from drilling and fracking operations and protect drinking water would be, in the words of two geophysicists, "a monumental task requiring full-time work…for decades."[374] There are reasons to be concerned. In South Florida in the 1990s, 20 stringently regulated disposal wells failed and leaked sewage waste into the Upper Floridan Aquifer, a potential future source of drinking water for Miami.[375]

[374] Ray Russo and Elizabeth Screaton, "Should Florida 'frack' Its Limestone for Oil and Gas? Two Geophysicists Weigh In," University of Florida News, May 5, 2016, http://news.ufl.edu/articles/2016/05/should-florida-frack-its-limestone-for-oil-and-gas-two-geophysicists-weigh-in.php.
[375] Abrahm Lustgarten, "Injection Wells: The Poison Beneath Us," ProPublica, June 21, 2012, https://www.propublica.org/article/injection-wells-the-poison-beneath-us.

Compilation of Studies & Findings

Air pollution

Air pollution associated with fracking and flaring is a grave concern with a range of impacts. Researchers have documented more than 200 different air pollutants near drilling and fracking operations. Of these, 61 are classified as hazardous air pollutants with known health risks, and 26 are classified as endocrine disruptors.

Areas with substantial drilling and fracking build-out show high levels of ground-level ozone (smog), striking declines in air quality, and, in several cases, increased rates of health problems with known links to air pollution. Air sampling surveys find high concentrations of fine particulate air pollutants and volatile organic compounds (VOCs), especially carcinogenic benzene and formaldehyde, both at the wellhead and at distances that exceed legal setback distances from wellhead to residence. In some cases, VOC concentrations exceeded federal safety standards by several orders of magnitude.

Researchers in Colorado have documented that air pollution increased with proximity to drilling and fracking operations and was sufficiently high to raise cancer risks in some cases. Exposure to emissions from natural gas flares and diesel exhaust from the 4,000-6,000 truck trips per well pad also pose respiratory health risks for those living near drilling operations. The United States leads the world in the number of flare stacks. Air pollutants from flaring operations include VOCs, polycyclic aromatic hydrocarbons, carbon monoxide, toxic heavy metals, formaldehyde, and soot.

Evidence implicates U.S. shale gas extraction in the global spike in atmospheric ethane and propane. Drilling and fracking operations in North Dakota's Bakken oil and gas field alone contribute two percent of global ethane emissions and directly impact air quality across North America. Like methane, ethane is both a greenhouse gas and a precursor for ozone formation.

A 2021 Harvard study found that, in at least 19 states, burning gas to generate electricity now kills more people from air pollution than coal due to exposure to the fine particulate matter air pollution (PM2.5) that is generated when gas is burned.

- June 23, 2021 – A National Oceanic and Atmospheric Administration (NOAA) team quantified methane emissions and emissions of other volatile organic air pollutants known to create ozone (smog) from oil- and gas-producing regions across the United States. The findings showed that volatile organic compounds (VOCs) from oil and natural gas extraction have likely been underestimated by a factor of two and that oil and gas emissions represent a significant source of volatile organic compounds to the atmosphere over the United States.[376]

[376] Colby B. Francoeur et al., "Quantifying Methane and Ozone Precursor Emissions from Oil and Gas Production Regions across the Contiguous US," *Environmental Science & Technology* 55 (2021): 9129–39, https://doi.org/10.1021/acs.est.0c07352.

- May 19, 2021 – Air concentrations of methane, non-methane hydrocarbons (NMHC), benzene, toluene, ethylbenzene, xylenes, styrene, n-hexane, n-pentane, ethane, and propane decreased following the suspension of urban drilling activities in a Los Angeles, California neighborhood. A USC-led team used ambient air monitoring adjacent to the AllenCo oil and gas production site during active operations and during the following idle period, the first study of its kind. The team determined that the drilling activities contributed 23.7 percent to the total VOCs measured during the active phase, versus 0.6 percent in the idle phase. Average methane concentrations were 2.53 ppm in the active phase and 1.68 ppm in the idle phase (consistent with background averages in California), and the highest one-minute averaged real-time methane concentration was 37.54 ppm. Average NMHC concentrations also dropped from the active phase to the idle phase. Authors wrote, "the results suggests that a broad range of hazardous air pollutants are co-emitted during active operations, and these compounds may be biologically additive or act synergistically in the human body, near a vulnerable population." They note that the community near the AllenCo site "is home to over 90% people of color… and approximately three-quarters of households live below 200% of the federal poverty line," and is "among the top 10% most disproportionately-environmentally burdened in the state."[377]

- May 5, 2021 – Ethane co-occurs with methane as a volatile air pollutant released by drilling and fracking operations. While methane also has many natural sources, such as wetlands, ethane has almost none. Therefore, ethane can be used as a surrogate for estimating methane emissions from oil and gas extraction activities. Using measurements of ethane collected by aircraft in the southcentral and eastern United States, a Pennsylvania State University research team showed that methane emissions from oil and gas extraction are significantly higher than previously presumed and, indeed, consistently exceed values calculated by leak rate estimates used by the U.S. Environmental Protection Agency (EPA). The team estimated that methane emissions arising from drilling and fracking are larger than EPA inventory values by 48 to 76 percent. This study corroborates several other earlier studies, all of which raise concerns of a broad, historic underestimation of methane leakage from U.S. oil and gas operations.[378]

- May 5, 2021 – Over the last decade, the U.S. fracking boom has prompted an energy transition away from coal and toward natural gas and biomass, as gas has replaced coal in both electricity generation and industry. However, this switch has not eliminated harm to public health from air pollution. A Harvard-led team used modeling and emissions inventory data to reconstruct the changes in health impacts from particulate matter air pollution in the United States from 2008 to 2017. The results showed substantial changes in the contribution to mortality impacts from stationary sources of fine-particle ($PM_{2.5}$) air pollution. In 19 states, burning gas for electricity now kills more people from

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[377] Jill E. Johnston et al., "Changes in Neighborhood Air Quality after Idling of an Urban Oil Production Site," *Environmental Science: Processes & Impacts* 23, no. 7 (2021): 967–80, https://doi.org/10.1039/D1EM00048A.
[378] Zachary R. Barkley et al., "Analysis of Oil and Gas Ethane and Methane Emissions in the Southcentral and Eastern United States Using Four Seasons of Continuous Aircraft Ethane Measurements," *JGR: Atmospheres* 126, no. 10 (2021), https://doi.org/10.1029/2020JD034194.

exposure to fine particles than does coal. In 2008, when coal produced nearly half the nation's electricity, power plant emissions caused between 59,000 and 66,000 premature deaths. By 2017, 10,000 to 12,000 deaths were caused by power plants. Sharp reductions in sulfur dioxide emissions, the source of which is largely electricity generation from coal, have led to a much more complex picture of contributors to particulate air pollution and to public health impacts, with many sources now contributing, all within the same order of magnitude and with transportation emissions now having a larger proportion of total air pollution health impacts. This study found that air pollution from gas, wood, and biomass were, by 2017, collectively responsible for between 29,000 and 46,000 premature deaths. The authors emphasized that their study does not include any health impacts from exposure to ozone or nitrogen oxides or localized health impacts from hazardous air pollution emissions from fuel extraction processes or combustion. It also does not include methane leaks across the gas supply and distribution chain or health impacts of indoor exposures to gas combustion.[379] What the study does show, said lead author Jonathan Buonocore, is that "if you swap out one combustion fuel for another, that's not a pathway to a healthy energy system." As gas represents an increasing fraction of fuel burned for U.S. electricity production, it has also become increasingly responsible for a larger proportion of health harms from air pollution generated from stationary sources.[380]

- April 29, 2021 – An investigation by *Bloomberg News* revealed that two Permian basin facilities that process and purify raw natural gas were the two biggest polluters during the February 2021 cold snap in Texas, accounting for nearly one-fifth of the state's total air pollution. Gas processing plants are designed for continuous flow of gas, and power outages therefore require flaring of all incoming gas. During the prolonged winter blackouts in Texas, loss of gas supply to power plants contributed to the power outages, which, in turn, compounded operations problems at the gas processors, leading to "a complete collapse of general infrastructure." Further, as revealed in an analysis of state records, these two plants are persistent super-emitters, releasing hazardous gases above permitted levels more than 400 times since the beginning of 2019.[381]

- March 26, 2021 – Using an ambient air monitoring laboratory, a research team identified and quantified air contaminants from a fracking well pad in West Virginia from September 2015 through February 2016. The results showed a shifting profile of air pollution that was a function of the phase of well pad development. The peak concentration was observed during the drill-out stage. There was a dramatic increase in ethane and methane emissions during the flowback phase. The emission rates of benzene and other volatile organic compounds also peaked during flowback. Benzene was also

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[379] Jonathan J. Buonocore et al., "A Decade of the U.S. Energy Mix Transitioning Away from Coal: Historical Reconstruction of the Reductions in the Public Health Burden of Energy," *Environmental Research Letters* 16, no. 5 (2021), https://doi.org/10.1088/1748-9326/abe74c.

[380] Alexander C. Kaufman, "Cleaner 'Bridge' Fuels Are Killing Up to 46,000 Americans Per Year, Study Shows," *Huffington Post*, May 5, 2021, https://www.huffpost.com/entry/air-pollution-bridge-fuels_n_608c4fbde4b0ccb91c31d21a.

[381] Kevin Crowley, "Hidden Super Polluters Revealed in Wake of Texas Energy Crisis," *Bloomberg Green*, April 29, 2021, https://www.bloomberg.com/news/articles/2021-04-29/hidden-super-polluters-revealed-in-wake-of-texas-energy-crisis.

high during hydraulic fracturing as was toluene, which was mainly released from motor vehicle emissions. Overall, a multivariate analysis showed that there were three potential factor profiles: natural gas, regional transport/photochemistry, and engine emissions. "This is the first study, to our knowledge, to collect high-time-resolution ambient concentrations of compounds emitted from well pad activity on Marcellus Shale during various phases of operation such that the relative air quality effect of each phase of development can be investigated."[382]

- March 11, 2021 – Satellite data shows that gas flaring at U.S. oil and gas facilities reached an all-time high in February 2021 when frigid weather conditions in Texas forced refineries, gas processing plants, and LNG terminals to release massive amounts of gas on an emergency basis in response to a collapse in the state's energy infrastructure.[383]

- March 9, 2021 – An independent analysis by three environmental organizations revealed that industrial facilities in Texas illegally released more than three million excess pounds of pollution in advance of, and during, the winter storm in February 2021. In addition, emissions increased in every major oil field in the state—the West Texas Permian Basin, South Texas' Eagle Ford Shale, and the Barnett Shale in North Texas—as drillers flared off natural gas that they could not store or transport as pipelines started to freeze.[384]

- March 3, 2021 – A research team used air quality monitors to evaluate air pollutants over a four-year period in three Los Angeles neighborhoods where oil and gas drilling takes place. They found elevated methane levels near drilling sites, including at an oil and gas facility classified as inactive. Other VOCs were also elevated in close proximity to wells and appeared related to oil and gas activity.[385]

- February 25, 2021 – Two rural communities in California's Central Valley that suffer some of the worst air pollution in the state gained negotiating power under a law that compels regional air pollution districts to share decision-making with communities. Located in the heart of the state's oil-producing region, Arvin and Lamont intend to demand stricter regulations over oil and gas extraction activities in Kern County, where 70 to 80 percent of California's oil production takes place.[386]

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[382] Nur H. Orak, Matthew Reeder, and Natalie J. Pekney, "Identifying and Quantifying Source Contributions of Air Quality Contaminants During Unconventional Shale Gas Extraction," *Atmospheric Chemistry and Physics* 21 (2021): 4729–39, https://doi.org/10.5194/acp-21-4729-2021.
[383] Pippa Luck, "Rystad Energy: Gas Flaring at US Oil Refineries Reached Highest on Record," *Hydrocarbon Engineering*, March 11, 2021, https://www.hydrocarbonengineering.com/refining/11032021/rystad-energy-gas-flaring-at-us-oil-refineries-reached-highest-on-record/.
[384] Amal Ahmed, "Industrial Facilities Released Millions of Pounds of Illegal Pollution During the Winter Storm," *Texas Observer*, April 9, 2021, https://www.texasobserver.org/industrial-facilities-released-millions-of-pounds-of-illegal-pollution-during-the-winter-storm/.
[385] Kristen Okorn et al., "Characterizing Methane and Total Non-Methane Hydrocarbon Levels in Los Angeles Communities with Oil and Gas Facilities Using Air Quality Monitor," *Science of the Total Environment* 777 (2021), https://doi.org/10.1016/j.scitotenv.2021.146194.
[386] Ingrid Lobet, "Small Towns Get Ready to Fight Big Oil over Air Quality in Central Valley," *Capital & Main*, February 25, 2021, https://capitalandmain.com/small-towns-get-ready-for-big-fights-over-air-quality-in-california-heartland-0225.

- February 23, 2021 – A research team from University of California, Los Angeles used satellite observations and census data to estimate the number of nightly flaring events across all fracking sites (oil shale plays) in the United States between March 2012 and February 2020. They found that 83 percent of the flaring took place in three basins—the Williston Basin in North Dakota, Permian Basin in west Texas, and the Western Gulf Basin in southern Texas and Louisiana—and estimated that over half a million people in these basins reside within three miles of a flare, with 39 percent of them living near more than 100 nightly flares. In these regions, Black, Indigenous, and people of color were disproportionately exposed to flaring. The research team recommended stricter regulations.[387]

- February 1, 2021 – The fracking boom in the Denver-Julesburg Basin is a significant source of air pollution, including benzene and toluene, in northeastern Colorado. Oil production in the region increased by eight-fold between 2006 and 2016, while natural gas production tripled over the same time period. An international team of researchers estimated the contribution of these pollutants to ozone creation (smog) in Plattville, a small municipality within an area of intense drilling and fracking, and compared it to the urban core of Denver. They found that vapors from condensate tanks and other fracking infrastructure dominated the source contributions in Plattville, whereas vehicular emissions have a higher contribution in Denver. The largest contributor to benzene in the ambient air of Plattville was drilling and fracking operations, whereas vehicular emissions were the largest source of benzene in Denver.[388]

- December 22, 2020 – Utah's Uinta Basin contains about 10,000 active oil and gas wells and suffers during winter months from high levels of ozone. The oil and gas industry is the major source of chemical emissions that combine to create ozone. A team from Utah State University measured the composition and distribution of ozone-forming pollutants in the basin. They found higher levels of these pollutants in areas of dense oil production than in dense gas production. Twenty-eight percent of the potential for air pollutants to create ozone was due to alkenes in areas with dense oil production. The most likely source of these air pollutants was natural gas-fueled engines in the oil-producing regions, especially artificial lift engines, which are commonly used at oil wells but not at natural gas wells.[389]

- November 9, 2020 – Using a U.S. Department of Energy mobile air-monitoring laboratory, researchers collected ambient air monitoring data from two fracking sites in Pennsylvania and six in West Virginia throughout the production lifecycle—from well-pad construction through drilling, fracturing, flowback, and completion. The objective of

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[387] Lara J. Cushing et al., "Up in Smoke: Characterizing the Population Exposed to Flaring from Unconventional Oil and Gas Development in the Contiguous US," *Environmental Research Letters* 16 (2021), https://doi.org/10.1088/1748-9326/abd3d4.
[388] Congmeng Lyu et al., "Evaluating Oil and Gas Contributions to Ambient Nonmethane Hydrocarbon Mixing Ratios and Ozone-Related Metrics in the Colorado Front Range," *Atmospheric Environment* 246 (2021), https://doi.org/10.1016/j.atmosenv.2020.118113.
[389] Seth N. Lyman et al., "High Ethylene and Propylene in an Area Dominated by Oil Production," *Atmosphere* 12, no. 1 (2021), https://doi.org/10.3390/atmos1201000.

this study was to analyze the air pollutants from the various upstream stages of shale gas production and develop a predictive model. The results showed that ethane was the most consistently detected air pollutant and can be used as a tracer for natural gas operations; there are few sources of ethane other than those related to natural gas extraction. At two of the sites, elevated levels of methane levels, emissions of which were sporadic, corresponded to a change in isotopic signature that showed that its source was the well pad. The authors found that air pollution risk from fracking can indeed be predicted by developing a Bayesian network model.[390]

- October 20, 2020 – Between 2005 and 2017, more than 18,000 shale gas wells were permitted in the Marcellus shale region of Pennsylvania, and drilling and fracking operations moved closer to residential areas. Pennsylvania's current setback policy is that no well can be located closer than 500 feet from a home. A study investigated the sufficiency of this setback distance to protect residents from exposure to fracking-derived air pollution. Using census block data to estimate the number of people who experience levels of particulate matter that exceed air quality standards, the researchers demonstrated that these emissions could increase the number of exceedances by more than 36,000 persons in a single year, which is almost one percent of the population in Pennsylvania's Marcellus shale region. Further, most of the elevated exposures were caused by a small number of wells near populated areas. These results, according to the authors, support the idea that Pennsylvania's 500-foot setback distance is not adequate. Instead, policies should consider the number of wells per well pad and local conditions in addition to pushing wells back from residential areas.[391]

- September 9, 2020 – Ground-level ozone (smog) is created by chemical reactions between two other air pollutants: VOCs and nitrogen oxides, both of which are released from fracking operations. Using a simulation model and data from global monitoring programs, an international research team assessed the air quality impacts of increased emissions of VOCs and nitrogen oxides from U.S. oil and gas extraction operations during the 2010-2015 fracking boom. They found effects on surface ozone concentrations across a large geographical area—but especially in midwestern and central United States regions—including increased number of days during the year with elevated average ozone levels. These findings demonstrated that U.S. fracking boom significantly degraded air quality across most of the United States, can regionally negate ozone reductions from other sectors, and can impede a region's ability to meet National Ambient Air Quality Standard obligations for ozone.[392]

- June 29, 2020 – In response to public complaints about noxious odors and increased air pollution in the heavily drilled Permian Basin, the Texas Commission on Environmental

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[390] Nur H. Orak and Natalie J. Pekney, "Air Pollution Risk Associated with Unconventional Shale Gas Development," *Carbon Management* 11, no. 6 (2021): 645–51, https://doi.org/10.1080/17583004.2020.1840873.
[391] Zoya Banan and Jeremy M. Gernand, "Emissions of Particulate Matter Due to Marcellus Shale Gas Development in Pennsylvania: Mapping the Implications," *Energy Policy* 148, Part B (2021), https://doi.org/10.1016/j.enpol.2020.111979.
[392] Andrea Pozzer, Martin G. Schultz, and Detlev Helmig, "Impact of U.S. Oil and Natural Gas Emission Increases on Surface Ozone Is Most Pronounced in the Central United States," *Environmental Science & Technology* 54 (2020): 12423–33.

Quality conducted two air monitoring surveys in December 2019 and February 2020. Results showed levels of hydrogen sulfide gas that exceeded legal limits—as high as 500 percent—in several places on multiple days. These levels are sufficient to create long-term health impacts. Hydrogen sulfide is poisonous to the central nervous system and can impair oxygen utilization.[393, 394, 395]

- May 8, 2020 – Along with Russia, Iran, and Iraq, the United States is one of the world's top nations for flaring. A team of atmospheric scientists measured air quality in the heavily drilled Eagle Ford Shale in southern Texas. They identified flaring as a significant source of smog-forming nitrogen oxides and carcinogenic benzene in this otherwise rural region. These results confirm those of previous studies.[396, 397]

- May 2020 – Evaporation from liquid waste pits connected to oil and gas extraction operations are a significant source of toxic air pollutants in the San Joaquin Valley air basin, according to research conducted by the California Environmental Protection Agency. These emissions include benzene, toluene, ethylbenzene, and xylene. The total emissions of this family of volatile organic compounds (total BTEX emissions) estimated in this study were then compared to the California Toxics Inventory for the San Joaquin Valley air basin, which currently does not include emissions from wastewater pits. The results showed that evaporation of toxic BTEX chemicals from the waste pits alone represented up to two percent of the air basin inventory, indicating that their inclusion in the inventory should be considered. Although these facilities are not thought to be a major source of methane emissions, the researchers note that future work could involve more regular monitoring of facilities in order to better characterize how emissions change over time.[398]

- March 12, 2020 – Fine particulate air pollution has been documented in communities near drilling and fracking operations. An interdisciplinary research team analyzed fine particulate samples collected from filters at an active well pad in Morgantown, West

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[393] Strategic Sampling Work Group, "Permian Basin Survey Region 7 Midland December 9-13, 2019" (Texas Commission on Environmental Quality Monitoring Division, April 2020), https://https://web.archive.org/web/20210528085509/https://www.tceq.texas.gov/assets/public/assistance/sblga/oil-gas/PB1912_Report.pdf.

[394] Strategic Sampling Work Group, "Permian Basin Survey Region 2 Lubbock and Region 7 Midland February 9-13, 2020" (Texas Commission on Environmental Quality Monitoring Division, June 2020), https://web.archive.org/web/20210528085519/https://www.tceq.texas.gov/assets/public/assistance/sblga/oil-gas/PB2002_Report.pdf.

[395] Dominic A. Walsh, "Some Populated Texas Areas Are at Risk of Hydrogen Sulfide Pollution According to New Report," Texas Public Radio, June 29, 2020, https://www.tpr.org/post/some-populated-texas-areas-are-risk-hydrogen-sulfide-pollution-according-new-report.

[396] Geoffrey S. Roest and Gunnar W. Schade, "Air Quality Measurements in the Western Eagle Ford Shale," *Elementa Science of the Anthropocene* 8, no. 18 (2020), https://doi.org/10.1525/elementa.414.

[397] Gunnar W. Schade, "Routine Gas Flaring Is Wasteful, Polluting and Undermeasured," The Conversation, July 29, 2020, https://theconversation.com/routine-gas-flaring-is-wasteful-polluting-and-undermeasured-139956?utm_source=twitter&utm_medium=bylinetwitterbutton.

[398] California Air Resources Board, "Measurement of Produced Water Air Emissions from Crude Oil and Natural Gas Operations," final, May 2020, https://ww2.arb.ca.gov/sites/default/files/2020-07/CARB%20Oil%20Wastewater%20Emissions%20Final%20Report_05.11.2020_ADA.pdf.

Virginia to determine which elements were traceable downwind and if they corresponded to measurements of particulate matter. If so, tracer elements could be used in future health studies as surrogates to estimate community exposure to air pollution from drilling and fracking operations. Results suggests that magnesium might serve as a useful tracer. The team also found that well pad emissions can be measured at distances of more than four miles (7 kilometers).[399]

- January 13, 2020 – A public health team from Harvard, Columbia, and University of Colorado critiqued a study led by Judy Hess of the Shell Health Risk Science Team, and funded by Shell Oil, that had called into question epidemiological methods for ascertaining air pollution exposures and the health harms to residents living near drilling and fracking operations in the Marcellus Shale. The public health team said, "Because of the unrepresentative air monitoring locations and inappropriate statistical methods, the Hess et. al. study does not improve our understanding of the residential exposures associated with [oil and gas wells.] For these same reasons, the Hess et al. study also does not provide information useful for decisions relevant to the health of communities nearby."[400, 401] A response to this critique, also funded by Shell, argued against the validity of modeling well activity when estimating human exposures to air pollution from those wells and asserted bias in a suite of earlier studies that had identified health risks from fracking-related air pollution.[402]

- January 6, 2020 – Between 2005 and 2016, one-fifth of electric power infrastructure across the United States was redistributed as coal-fired power plants were retired and new gas-fired power plants took their place. An analysis of local air quality during this time period traced changing patterns of polluting emissions. New natural gas-fired plants created higher local pollution levels when they came on-line, but the spatial pattern and chemical composition of these pollutant were different from coal.[403]

- December 16, 2019 – An assessment of air quality changes in British Columbia from 2005 to 2018 revealed increasing nitrogen dioxide and sulfur dioxide levels in the immediate vicinity of drilling and fracking operations. Within the overall increasing trend of nitrogen dioxide levels during this time period, there was a decreasing trend between

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[399] Maya Nye et al., "Use of Tracer Elements for Estimating Community Exposure to Marcellus Shale Development Operations," *International Journal of Environmental Research and Public Health* 12, no. 17 (2020): 1837, https://doi.org/10.3390/ijerph17061837.
[400] Jonathan J. Buonocore et al., "Air Monitoring Stations Far Removed from Drilling Activities Do Not Represent Residential Exposures to Marcelus Shale Air Pollutants. Response to the Paper by Hess et al. on Proximity-Based Unconventional Natural Gas Exposure Metrics," *International Journal of Environmental Research and Public Health* 17, no. 2 (2020): 504, https://doi.org/10.3390/ijerph17020504.
[401] Judy W. Hess et al., "Assessing Agreement in Exposure Classification Between Proximity-Based Metrics and Air Monitoring Data in Epidemiology Studies of Unconventional Resource Development," *International Journal of Environmental Research and Public Health* 23, no. 16 (2019): 3055, https://doi.org/10.3390/ijerph16173055.
[402] Judy W. Hess, Gerald Bachler, and Fayaz Momin, "Response to Buonocore et al. Comments on Wendt Hess et al. 'Assessing Agreement in Exposure Classification between Proximity-Based Metrics and Air Monitoring Data in Epidemiology Studies of Unconventional Resource Development,'" *International Journal of Environmental Research and Public Health* 17, no. 2 (2020): 512, https://doi.org/10.3390/ijerph17020512.
[403] Jennifer A. Burney, "The Downstream Air Pollution Impacts of the Transition From Coal to Natural Gas in the United States," *Nature Sustainability* 3 (2020): 152–60, https://doi.org/10.1038/s41893-019-0453-5.

2011-2013, a two-year period of time that corresponds to stricter compliance and enforcement of regulations for flaring.[404]

- December 6, 2019 – Although the United Kingdom and Germany have shale formations that contain methane, shale gas extraction via fracking is currently prohibited in both nations. Using modeling, a German team explored how fracking would affect ozone formation locally and, via long-distance transport, regionally. Overall, the findings demonstrate that "shale gas production in Europe can worsen ozone air quality on both the local and regional scales."[405]

- December 2, 2019 – Fracking activities are known to increase airborne nitrogen oxides, an important precursor for smog formation. Less known is how these air pollutants may be transported through atmosphere and deposited back to earth in rain and snow (wet deposition or as particles and gases (dry deposition). When nitrogen deposition exceeds a limit known as critical load, it can acidify rivers and streams and disrupt nutrient cycling in soils. A research team measured total dry deposition attributable to two fracking wells on a single well pad in the Marcellus Shale. They found that the magnitude of total nitrogen deposition per well was high enough that it would exceed critical loads in intensely fracked areas with high densities of wells.[406]

- November 12, 2019 – Wyoming is the nation's seventh largest gas-producing state with the Upper Green River Basin serving as the center of extraction. A research team studied how volatile fracking-related pollutants are transported in the air of this region. Previous estimates varied widely by methodology. Using technology that allowed for direct measurements from oil and gas facilities, the team found that 20 percent of facilities were responsible for 67 percent of the total emissions of benzene, toluene, methylbenzene, and xylenes that traveled off site. (This study was partially funded by the oil and gas industry, members of which also assisted in the collection of canister samples.)[407]

- November 11, 2019 – A long-term trend study found increases in airborne ethane, propane, butane and other organic carbon compounds in the Barnett Shale in northern Texas from 2000 to 2017. These trends mirror drilling and fracking activities in the area, specifically the changes in production volume from nearby natural gas wells and liquid condensate facilities. Benzene and xylene concentrations followed these same trends,

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[404] S. M. Nazrul Islam et al., "Impact of Natural Gas Production on Nitrogen Dioxide and Sulphur Dioxide over Northeast British Columbia, Canada," *Atmospheric Environment* 223 (2020): 117231, https://doi.org/10.1016/j.atmosenv.2019.117231.
[405] Lindsey B. Weger et al., "Modeling the Impact of a Potential Shale Gas Industry in Germany and the United Kingdom on Ozone with WRF-Chem," *Elementa Science of the Anthropocene* 7 (2019): 49, https://doi.org/10.1525/elementa.387.
[406] Justin G. Coughlin et al., "Quantifying Atmospheric Reactive Nitrogen Concentrations, Dry Deposition, and Isotope Dynamics Surrounding a Marcellus Shale Well Pad," *Atmospheric Environment* 223 (2020): 117196, https://doi.org/10.1016/j.atmosenv.2019.117196.
[407] Rachel Edie et al., "Off-Site Flux Estimates of Volatile Organic Compounds from Oil and Gas Production Facilities Using Fast-Response Instrumentation," *Environmental Science & Technology* 54, no. 3 (2020): 1385–94, https://doi.org/10.1021/acs.est.9b05621.

suggesting that fracking, rather than vehicular emissions and other urban sources, are influencing the levels of these hazardous air pollutants.[408]

- October 30, 2019 – A Colorado State University team measured emissions of volatile organic air pollutants from oil and gas wells in Colorado's Denver-Julesberg basin and Piceance basin during the periods of drilling, fracking, and flowback. Emission rates of benzene and other volatile organic compounds were highest in both basins during the flowback period—when injected fracking fluids return to the surface after a well is fracked. (This study was partially funded by the oil and gas industry.)[409]

- April 8, 2019 – Before fracking was suspended in England, a rural area near Kirby Misperton in North Yorkshire was one of the first sites in the country to seek permits for shale gas exploration and became the focus of intensive long-term environmental monitoring. As part of these efforts, air quality monitoring began in 2016, in advance of preparatory work on the site, which began in late 2017. The most significant effect noted during air monitoring was an increase in nitrogen oxide levels during the pre-operational period when equipment was brought to the site and vehicular activity increased. These effects were transitory. Hydraulic fracturing of the well did not take place, and the on-site equipment was eventually decommissioned and removed. Thereafter, air quality parameters returned to baseline.[410]

- April 1, 2019 – A University of California, Berkeley team undertook a comprehensive review of current peer-reviewed literature on hazardous air pollutants found near oil and gas extraction operations. Hazardous air pollutants are those known or suspected to cause cancer, reproductive harm, birth defects, or other serious health effects. Reviewing 37 studies, the team identified a total of 61 different hazardous air pollutants that have been detected and measured near oil and gas drilling and fracking operations. The sources of these dangerous pollutants include a wide range of equipment, activities, and facilities—from dehydrators and condensate tanks to well drilling, flowback treatment, and oil storage facilities. The team found that the production phase of oil and gas extraction has the potential to emit the highest concentrations and the most complex mixtures of hazardous air pollutants over the longest time. (During the production phase, raw oil or natural gas is flowing from the well and is processed within various ancillary equipment, all of which can emit hazardous pollutants, such as benzene.) The highest and most sustained concentrations of hazardous air pollutants were found in "regions rich in oil, wet gas, and condensate." Their results further suggest that "exposure risks can be much higher if production equipment is collocated with condensate storage and wastewater impoundments." The research team also uncovered an important disconnect between air

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[408] Guo Quan Lim and Kuruvilla John, "Impact of Energy Production in the Barnett Shale Gas Region on the Measured Ambient Hydrocarbon Concentrations in Denton, Texas," *Atmospheric Pollution Research* 11, no. 2 (2020): 409–108, https://doi.org/10.1016/j.apr.2019.11.013.
[409] Arsineh Hecobian et al., "Air Toxics and Other Volatile Organic Compound Emissions from Unconventional Oil and Gas Development," *Environmental Science & Technology Letters* 6, no. 12 (2019): 720–26, https://doi.org/10.1021/acs.estlett.9b00591.
[410] Ruth M. Purvis et al., "Effects of 'Pre-Fracking' Operations on Ambient Air Quality at a Shale Gas Exploration Site in Rural North Yorkshire, England," *Science of the Total Environment* 673 (2019): 445–54, https://doi.org/10.1016/j.scitotenv.2019.04.077.

pollution monitoring studies and those reporting on health impacts. In general, the levels of air pollution detected in the monitoring studies fell short of those known to cause health impacts and yet multiple health-based studies continue to find evidence of a spatial relationship between concentrations of hazardous air pollutants and incidence of health problems among people living near oil and gas operations. These findings suggest that existing air sampling methodologies may be under-reporting emissions or that prevailing health benchmarks are inadequate to identify health problems, especially when exposures include multiple chemicals.[411]

- March 14, 2019 – Approximately 1.7 million people live within one mile of an active oil or gas well in the Los Angeles metropolitan area. A University of California pilot study investigated air pollution around active wells in this densely populated urban area and showed that, even in neighborhoods where residents are exposed to complex mixtures of air pollution from multiple sources, levels of several volatile organic pollutants are higher in communities closer to wellheads and decrease in concentration with distance away from the wellheads. These include the carcinogen benzene and n-hexane. "We were able to identify gradient behavior along the transect downwind of the target oil/natural gas facility that was likely due, in part, to emissions from the facility."[412]

- February 15, 2019 – In the first modeling study of drilling and fracking-related air pollution to include criteria air pollutants, a University of Texas, Arlington team found that concentrations of pollutants in the Barnett Shale region in north Texas were varied by terrain, with strongly sloping terrain giving the highest maximum concentrations for criteria air pollutants compared to level and moderate terrain. (Regulated by the U.S. Environmental Protection Agency [EPA] via applicable standards, the criteria air pollutants are ozone, particulate matter, lead, carbon monoxide, sulfur oxides, and nitrogen oxides.) The highest benzene and methane concentrations occurred in flat terrain and exceeded health-based standards.[413]

- January 18, 2019 – Flaring is a widely used practice for disposal of waste natural gas during oil drilling, in places that lack infrastructure for its capture and transport. Enabled by fracking, domestic oil production is at an all-time high, and this upswing has outpaced the build-out of pipelines to contain the natural gas that accompanies the oil as it flows to the surface. Using satellite technology, researchers identified 43,887 distinct oil and gas flares in the Eagle Ford Shale region of south Texas from 2012 to 2016, with a peak in activity in 2014 and an estimated 4.5 billion cubic meters of total gas volume flared over the study period. Comparing these results with well permit data showed the majority of flares (82 percent) were linked to oil wells, with more than 90 percent associated with

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[411] Diane A. Garcia-Gonzales et al., "Hazardous Air Pollutants Associated with Upstream Oil and Natural Gas Development: A Critical Synthesis of Current Peer-Reviewed Literature," *Annual Review of Public Health* 40 (2019): 283–304, https://doi.org/10.1146/annurev-publhealth-040218-043715.
[412] Diane A. Garcia-Gonzales, Bhavna Shamasunder, and Michael Jerrett, "Distance Decay Gradients in Hazardous Air Pollution Concentrations Around Oil and Natural Gas Facilities in the City of Los Angeles: A Pilot Study," *Environmental Research* 173 (2019): 232–36, https://doi.org/10.1016/j.envres.2019.03.027.
[413] Farzaneh Khalaj and Melanie Sattler, "Modeling of VOCs and Criteria Pollutants from Multiple Natural Gas Well Pads in Close Proximity, for Different Terrain Conditions: A Barnett Shale Case Study," *Atmospheric Pollution Research* 10, no. 4 (2019): 1239–49, https://doi.org/10.1016/j.apr.2019.02.007.

horizontally drilled wells. These flares were not equally distributed across the region. Just five of 49 counties in the Eagle Ford Shale area accounted for 71 percent of flaring. "Our results suggest flaring may be a significant environmental exposure in parts of this region." Air pollutants from flaring operations include VOCs, polycyclic aromatic hydrocarbons, carbon monoxide, toxic heavy metals, formaldehyde, and soot.[414]

- July 27, 2018 – A report written by the United Kingdom's Air Quality Expert Group found that shale gas operations would increase air pollution (nitrogen dioxides and VOCs) both nationally and locally within the United Kingdom. However, the report languished for three years and was finally released four days after shale gas extraction was officially approved for the Lancashire region of northwest England.[415, 416]

- July 16, 2018 – A team from the Colorado Department of Public Health and Environment used existing air monitoring data sets from disparate locations to determine if air pollution levels near drilling and fracking operations are sufficient to create health problems in Colorado residents who live more than 500 feet away from a well head. Overall, they found individual VOC levels below those that are known to pose cancer and non-cancer health risks. However, the authors could not evaluate the risk of possible intermittent spikes in emissions during different phases of operation and evaluated only a subset of all VOCs emitted from drilling and fracking operations at these different phases. "Future studies are greatly needed that focus on quantifying these acute, peak exposures to people living near oil and gas operations, with particular emphasis on characterization of the volatile organic compounds identified as posing the greatest potential public health concerns, such as benzene."[417]

- July 13, 2018 – Drilling and fracking operations emit pollutants that form ozone and fine particles. Because air pollution from oil and gas operations originate from a large number of small, diffuse sources, estimating the level and location of emissions is difficult. An EPA team used a national emissions inventory for the year 2011 to characterize oil and gas emissions over space and time and to estimate the future human health burden attributable to the oil and gas sector. For the year 2025, the authors projected that oil and gas extraction activities will cause 1000 deaths across the United States from exposure to

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[414] Meredith Franklin et al., "Characterizing Flaring from Unconventional Oil and Gas Operations in South Texas Using Satellite Observations," *Environmental Science & Technology* 53, no. 4 (2019): 2220–28, https://doi.org/10.1021/acs.est.8b05355.
[415] Air Quality Expert Group, "Potential Air Quality Impacts of Shale Gas Extraction in the UK" (Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland, July 27, 2018), https://cedrec.com/cedrec_images/1807251315_AQEG_Shale_Gas_Extraction_Advice_Note_vfinal_for_publishing.pdf.
[416] Damian Carrington, "Buried UK Government Report Finds Fracking Increases Air Pollution," *The Guardian*, August 2, 2018, sec. Environment, https://www.theguardian.com/environment/2018/aug/02/buried-uk-government-report-finds-fracking-increases-air-pollution.
[417] Tami S. McMullin et al., "Exposures and Health Risks from Volatile Organic Compounds in Communities Located near Oil and Gas Exploration and Production Activities in Colorado (U.S.A.)," *International Journal of Environmental Research and Public Health* 15, no. 7 (2018): 1500, https://doi.org/10.3390/ijerph15071500.

fine particles and 970 deaths from ozone exposure, with the highest impacts in Colorado, Pennsylvania, Texas, and West Virginia.[418]

- June 13, 2018 – A British team used a new air quality forecasting model to simulate the health impacts of potential emissions from fracking operations in the United Kingdom, should large-scale fracking go forward. The results showed large projected increases in nitrogen oxides and volatile organic compounds across the UK airshed. These increases would contribute to approximately 110 extra premature deaths (with a range of 50-530 deaths) each year across the U.K.[419]

- May 31, 2018 – Using an air pollution model that can describe the movement of pollutants in the atmosphere, a Pennsylvania study evaluated the minimum necessary distance from a fracked gas well pad to remain within air quality standards for particulate matter. The findings show that well pads that host only one active well are unlikely to expose residents living 500 feet away to unlawful levels of particulate matter. However, a typical well pad comprised of six wells with high emissions could require a minimum setback of up to 2400 feet.[420]

- May 29, 2018 – An Oregon State University team measured polycyclic aromatic hydrocarbon air pollutants near drilling and fracking operations in rural eastern Ohio. A known component of fracking-related air pollution, polycyclic aromatic hydrocarbons are linked to cancer risk, respiratory distress, and poor birth outcomes. Using both air samplers and wristbands to assess personal exposures of residents living near active or proposed well sites, the researchers found elevated air pollution levels near active well sites. Further, the wristbands from participants who lived in homes with well pads on their property registered higher levels of air pollutants than participants without wells. "These findings suggest that living or working near an active natural gas extraction well may increase personal polycyclic aromatic hydrocarbon exposure."[421]

- May 18, 2018 – A Canadian and U.S. research team monitored methane levels in urban Morgantown, West Virginia during various stages of hydraulic fracturing at a single well pad. They found that emissions at the site were greatest during the flow-back stage, a result that supports previous studies.[422]

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[418] N. Fann et al., "Assessing Human Health PM2.5 and Ozone Impacts from U.S. Oil and Natural Gas Sector Emissions in 2025," *Environmental Science & Technology* 52, no. 15 (2018): 8095–8103, https://doi.org/10.1021/acs.est.8b02050.
[419] A. T. Archibald et al., "Potential Impacts of Emissions Associated with Unconventional Hydrocarbon Extraction on UK Air Quality and Human Health," *Air Quality, Atmosphere & Health* 11 (2018): 627–37, https://doi.org/10.1007/s11869-018-0570-8.
[420] Zoya Banan and Jeremy M. Gernand, "Evaluation of Gas Well Setback Policy in the Marcellus Shale Region of Pennsylvania in Relation to Emissions of Fine Particulate Matter," *Journal of the Air & Waste Management Association* 68, no. 9 (2018): 988–1000, https://doi.org/10.1080/10962247.2018.1462866.
[421] L. Blair Paulik et al., "Environmental and Individual PAH Exposures Near Rural Natural Gas Extraction," *Environmental Pollution* 241 (2018): 397–405, https://doi.org/10.1016.j.envpol.2018.05.010.
[422] Philip J. Williams et al., "Atmospheric Impacts of a Natural Gas Development Within the Urban Context of Morgantown, West Virginia," *Science of the Total Environment* 639 (2018): 406–16, https://doi.org/10.1016/j.scitotenv.2018.04.422.

- March 27, 2018 – A team led by University of Colorado School of Public Health scientists found that air pollution levels along Colorado's heavily drilled Front Range increased with proximity to drilling and fracking operations and were sufficiently high to raise cancer risks. For people living within 500 feet of a well, lifetime cancer risks were eight times higher than the EPA's upper threshold. Elevated levels of benzene and alkanes were of particular concern. "These findings indicate that state and federal regulatory policies may not be protective of health for populations residing near oil and gas facilities."[423]

- March 21, 2018 – Evaluating 48 peer-reviewed studies that sampled air near drilling and fracking operations, researchers identified more than 200 different airborne chemicals associated with oil and gas extraction. Ethane, benzene, and n-pentane were the three most frequently detected. Twenty-six of these 200 chemicals are classified as endocrine disruptors—chemicals that can interfere with hormone systems and may affect reproduction, development, and neurological functioning.[424]

- March 18, 2018 – There are now more than 22,000 active fracking wells in the rural Eagle Ford Shale region of Texas, which has undergone a 10-fold increase in oil and gas extraction since 2010. A research team from San Francisco State University and University of Southern California used remote sensing data that incorporated infrared observations of combustion sources to estimate exposure of local residents to hazardous air pollutants from associated flaring operations. Their method confirmed extensive flaring in close proximity to homes.[425]

- February 26, 2018 – The presence of ethane and propane in the atmosphere is an indication of leaks during fossil fuel extraction and distribution, including fracking and its attendant activities, especially venting and flaring. (Fossil fuel combustion is not a source of ethane or propane.) According to a study led by a University of York team that used data collected from 20 observatories around the world, global atmospheric levels of ethane and propane have been underestimated by more than 50 percent. These results mean that hydrocarbon emissions from fossil fuel extraction activities in general—including methane—may be two to three times higher than previously presumed. Both ethane and methane are ozone precursors and contribute to the creation of smog. The authors noted that enhanced ethane and propane emission results mean higher levels of health-damaging ozone in both rural and urban areas.[426] In related press materials about this research, Ally Lewis, a co-author of the study, said, "Levels of ethane and propane

[423] Lisa M. McKenzie et al., "Ambient Nonmethane Hydrocarbon Levels Along Colorado's Northern Front Range: Acute and Chronic Health Risks," *Environmental Science & Technology* 52, no. 8 (2018): 4514–25, https://doi.org/10.1021/acs.est.7b05983.
[424] Ashley L. Bolden et al., "Exploring the Endocrine Activity of Air Pollutants Associated With Unconventional Oil and Gas Extraction," *Environmental Health* 17 (2018): 26, https://doi.org/10.1186/s12940-018-0368-z.
[425] Lara Cushing et al., "Using Satellite Observations to Estimate Exposure to Flaring: Implications for Future Studies of the Health Impacts of Unconventional Oil and Gas Operations," *Occupational & Environmental Medicine* 75, no. Suppl 1 (2018): A5–6, https://doi.org/10.1136/oemed-2018-ISEEabstracts.13.
[426] Stig G. Dalsøren et al., "Discrepancy Between Simulated and Observed Ethane and Propane Levels Explained by Underestimated Fossil Emissions," *Nature Geoscience* 11, no. 3 (2018): 178–84, https://doi.org/10.1038.s41561-018-0073-0.

declined in many places in the 1980s and 1990s, but global growth in the demand for natural gas means these trends may be reversing. The effects of higher ozone would be felt in the rural environment where it damages crops and plants, and in cities on human health." Co-author Lucy Carpenter, said, "We know that a major source of ethane and propane in the atmosphere is from 'fugitive' or unintentional escaping emissions during fossil fuel extraction and distribution. If ethane and propane are being released at greater rates than we thought, then we also need to carefully re-evaluate how much of the recent growth of methane in the atmosphere may also have come from oil and natural gas development."[427]

- February 5, 2018 – The Tropospheric Ozone Assessment Report analyzes data from all available ozone monitors around the world. Its 2018 report found that, in the United States, levels of ground-level ozone (smog) dropped steadily between 2000 and 2014 except in rural areas of the Rocky Mountain west where levels remained steady or rose. Oil and gas drilling is likely responsible. Rural areas in the western United States have fewer emission sources and yet they have been experiencing high ozone levels, especially in the winter.[428]

- November 2, 2017 – In a review paper that explores how the U.S. fracking boom has contributed to air pollution in impacted communities, Texas A&M atmospheric scientist Gunnar W. Schade identified ozone and benzene as two important chemicals of concern. Documenting trends is challenging because fracking-related air pollutants typically originate in rural places without routine air pollution monitoring. A new air monitor in the Eagle Ford Shale region allowed researchers to use fingerprinting analysis to show that 60 percent of ambient benzene in the air now comes from drilling and fracking operations, including gas flares. Before the shale boom, the majority of benzene in the region came from tailpipe emissions. "In some areas, decades-long progress on ozone air quality has stalled; in others, particularly the Uintah basin in Utah, a new ozone problem has emerged due to the fracking industry's emissions." Downwind of the Eagle Ford Shale, San Antonio's ozone levels are now trending close to 75 ppb, which exceeds the new recommended limit of 70 ppb. "The shale boom has create a new source of large-scale, diffuse hydrocarbon emissions that adversely affect air toxics levels. . . . The continued growth of the fracking industry as well as plans to remove regulations on methane emissions will not alleviate high hydrocarbon emissions and associated regional ozone problems."[429]

- April 12, 2017 – Using aircraft, a University of Michigan-led team collected plume samples from 37 flare stacks in the Bakken Shale region of North Dakota to calculate

[427] University of York, "Global Fossil Fuel Emissions of Hydrocarbons Underestimated," University of York, February 26, 2018, https://www.york.ac.uk/news-and-events/news/2018/research/global-fossil-fuel-emissions-underestimated/.
[428] Zoë L. Fleming et al., "Topospheric Ozone Assessment Report: Present-Day Ozone Distribution and Trends Relevant to Human Health," *Elementa Science of the Anthropocene* 6 (2018): 12, https://doi.org/10.1525/elementa.273.
[429] Gunnar W. Schade, "How Has the US Fracking Boom Affected Air Pollution in Shale Areas?," The Conversation, November 2, 2017, https://theconversation.com/how-has-the-us-fracking-boom-affected-air-pollution-in-shale-areas-66190.

emissions of black carbon (soot), methane, and ethane from natural gas flares. They determined that flares contribute almost 20 percent of the total emissions of methane and ethane from the Bakken region, as measured by field studies.[430]

- December 29, 2016 – Exposure to air pollutants from well pads decreases quickly with distance. However, according to recent studies, people living kilometers away from actual drilling and fracking operations also show elevated risk of disease known to be linked to air pollution. This review paper investigated the possible role that exposure to diesel exhaust from fracking-related road traffic is playing in creating public health impacts in surrounding communities. "Road traffic generated by hydraulic fracturing operations is one possible source of environmental impact whose significance has, until now, been largely neglected . . . with 4,000-6,000 vehicles visiting the well pad during the operations." As a starting point for exposure assessment, the author recommended GIS modeling studies with a focus on traffic patterns and exacerbation of pediatric asthma.[431, 432]

- October 16, 2016 – A review of recent studies documenting harm to both public health and agricultural yields from rising ozone levels identified oil and gas fields as "a major and growing source of ozone in the United States."[433]

- October 16, 2016 – In response to a lawsuit, the EPA acknowledged that its 33-year-old formula for estimating emissions from flaring operations requires revision as it may dramatically underestimate levels of health-damaging air pollutants. Emissions from flare stacks typically include carbon monoxide, nitrogen oxides, benzene, formaldehyde, and xylene, but levels of these smog-forming compounds are seldom measured directly.[434, 435]

- October 5, 2016 – A review of recent studies documented connections between oil and gas development and worsening ozone levels in western states. Drilling and fracking operations have pushed Pinedale, Wyoming out of compliance with federal ozone

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[430] Alexander Gvakharia et al., "Methane, Black Carbon, and Ethane Emissions from Natural Gas Flares in the Bakken Shale, North Dakota," *Environmental Science & Technology* 51, no. 9 (2017): 5317–25, https://doi.org/10.1021/acs.est.6b05183.
[431] Michael A. McCawley, "Does Increased Traffic Flow Around Unconventional Resource Development Activities Represent the Major Respiratory Hazard to Neighboring Communities?," *Current Opinion in Pulmonary Medicine* 23, no. 2 (2017): 161–66, https://doi.org/10.1097/MCP.0000000000000361.
[432] Reid Frazier, "On Health Effects, Blame the Trucks, Not the Fracking?," The Allegheny Front, June 16, 2017, https://www.alleghenyfront.org/on-health-effects-blame-the-trucks-not-the-fracking/.
[433] Jim Robbins, "In New Ozone Alert, a Warning of Harm to Plants and People," Yale Environment 360, October 17, 2016, http://e360.yale.edu/feature/ground_level_ozone_harming_plants_humans/3044/.
[434] United States District Court for the District of Columbia, "Air Alliance Houston, et al., v. Gina McCarthy, Administrator, Environmental Protection Agency," Consent Decree, October 7, 2016, https://www.documentcloud.org/documents/3127584-Consent-Decree-on-Flares.html.
[435] David Hasemyer, "EPA Agrees Its Emissions Estimates From Flaring May Be Flawed," Inside Climate News, October 13, 2016, Agency says it will re-examine the formulas it uses, based on data provided by industry, and people near oil and gas sites hope that means cleaner air.

standards. Colorado has exceeded federal ozone limits for the past decade, a period that corresponds to a statewide boom in oil and gas drilling.[436]

- September 1, 2016 – A NASA-led research team collected whole air samples throughout the Barnett Shale basin in Texas. Chemical analysis showed that they contained benzene, hexane, and toluene at levels 2-50 times greater than the local background and similar to those seen in other intensely drilled shale basins in Colorado and Utah. There is "some evidence to suggest that public concerns for potential chronic health risks are not unwarranted."[437]

- July 23, 2016 – A study conducted at the Boulder Atmospheric Observatory examined sources of summertime ozone formation (smog) in Colorado's Front Range and found that 17 percent of locally created ozone was created by VOCs from drilling and fracking operations.[438] Colorado has exceeded the federal ozone standard for the past nine years, a period of time that corresponds to a boom in oil and gas drilling in the Wattenberg Gas Field where the number of active wells has nearly doubled.[439]

- June 13, 2016 – Between 2009 and 2014, ethane emissions in the Northern Hemisphere increased by about 400,000 tons annually, the bulk of it from North American oil and gas activity, according to research by an international team led by the University of Colorado Boulder.[440] After peaking in the 1970s, global ethane emissions began declining, primarily due to stricter air quality emission controls. In 2009, however, that downward trend reversed itself. "About 60 percent of the drop we saw in ethane levels over the past 40 years has already been made up in the past five years…. If this rate continues, we are on track to return to the maximum ethane levels we saw in the 1970s in only about three more years. We rarely see changes in atmospheric gases that quickly or dramatically," said lead researcher Detlev Helmig.[441] Samples were collected from locations around the world, but the largest increases in ethane were documented over areas of heavy oil and gas activity in the central and eastern United States. Ethane contributes to the creation of ground-level ozone pollution (smog), a known human health hazard. The authors noted that "… ozone production from these emissions has led to air quality standard exceedances in the Uintah Basin, Utah, and Upper Green River Basin, Wyoming, [oil and

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436 Anna Boiko-Weyrauch, "Ozone, Asthma And The Oil And Gas Connection," Inside Energy, October 5, 2016, http://insideenergy.org/2016/10/05/ozone-asthma-and-the-oil-and-gas-connection/.
437 Josette E. Marrero et al., "Estimating Emissions of Toxic Hydrocarbons from Natural Gas Production Sites in the Barnett Shale Region of Northern Texas," *Environmental Science & Technology* 50, no. 19 (September 1, 2016): 10756–64, https://doi.org/10.1021/acs.est.6b02827.
438 Erin E. McDuffie et al., "Influence of Oil and Gas Emissions on Summertime Ozone in the Coloraddo Northern Front Range," *Journal of Geophysical Research: Atmospheres* 121, no. 14 (2016): 8712–29, https://doi.org/10.1002/2016JD025265.
439 University of Colorado at Boulder, "Accounting for Ozone: Study First to Quantify Impact of Oil and Gas Emissions on Denver's Ozone Problem," Science Daily, August 8, 2016, https://www.sciencedaily.com/releases/2016/08/160808123832.htm.
440 Detlev Helmig et al., "Reversal of Global Atmospheric Ethane and Propane Trends Largely Due to US Oil and Natural Gas Production," *Nature Geoscience* 9 (June 13, 2016): 490–95, https://doi.org/10.1038/ngeo2721.
441 Detlev Helmig and J. Scott, "Global Ethane Concentrations Rising Again, Says Study," News Center University of Colorado Boulder, June 13, 2016, http://www.colorado.edu/news/releases/2016/06/13/global-ethane-concentrations-rising-again-says-study.

natural gas] regions." Two scientists not involved in the study published an accompanying commentary, concluding, "There is a danger that these non-methane hydrocarbon emission changes can offset emission policies and controls aimed at reducing ozone concentrations," and "[t]hese oil and gas operations are threatening to reverse what had been an important success story: decades of declining air pollution in North America."[442] (See also the entry dated April 2, 2016 in Threats to the Climate System.)

- June 1, 2016 – Existing data on air pollutants emitted from drilling and fracking operations "support precautionary measures to protect the health of infants and children," according to a review by a team of researchers (members of which include co-authors of this Compendium). Researchers focused on exposures to ozone, particulate matter, silica dust, benzene, and formaldehyde—all of which are associated with drilling and fracking operations—noting that all are linked to adverse respiratory health effects, particularly in infants and children. Benzene, for example, emitted from gas wells, production tanks, compressors, and pipelines, is a carcinogen also linked to serious respiratory outcomes in infants and children, including pulmonary infections in newborns. As the authors emphasized, this review did not consider other air pollutants commonly associated with drilling and fracking activities, namely hydrogen sulfide, polycyclic aromatic hydrocarbons, and oxides of nitrogen. Although improved exposure assessment, air monitoring, and long-term studies are still lacking, existing evidence was sufficient for the authors to "strongly recommend precautionary measures at this time."[443]

- April 26, 2016 – About two percent of global ethane emissions originate from the Bakken shale oil and gas field, which, according to research led by University of Michigan researchers, emits 250,000 tons of ethane per year.[444] "Two percent might not sound like a lot, but the emissions we observed in this single region are 10 to 100 times larger than reported in inventories. They directly impact air quality across North America. And they're sufficient to explain much of the global shift in ethane concentrations," according to Eric Kort, first author of the study.[445] Ethane is a gas that affects climate and decreases air quality. As a greenhouse gas, ethane is the third-largest contributor to human-caused climate change. Ethane contributes to ground-based ozone pollution as it breaks down and reacts with sunlight to create smog. This surface-level ozone is linked to respiratory problems, eye irritation, and crop damage. Global ethane levels were decreasing until 2009, leading the researchers to suspect that the U.S. shale gas boom may be responsible for the global increase in levels since 2010.

[442] Hannele Hakola and Heidi Hellén, "The Return of Ethane," *Nature Geoscience* 9 (June 13, 2016): 475–76, https://doi.org/10.1038/ngeo2736.
[443] Ellen Webb et al., "Potential Hazards of Air Pollutant Emissions From Unconventional Oil and Natural Gas Operations on the Respiratory Health of Children and Infants," *Reviews on Environmental Health* 31, no. 2 (2016): 225–43, https://doi.org/10.1515/reveh-2014-0070.
[444] E. A. Kort et al., "Fugitive Emissions From the Bakken Shale Illustrate Role of Shale Production in Global Ethane Shift," *Geophysical Research Letters* 43 (2016): 4617–23, https://doi.org/10.1002/2016GL068703.
[445] Nicole C. Moore and K. Human, "One Oil Field a Key Culprit in Global Ethane Gas Increase," Michigan News, April 26, 2016, http://ns.umich.edu/new/multimedia/videos/23735-one-oil-field-a-key-culprit-in-global-ethane-gas-increase.

- February 19, 2016 – Legally enforced minimal distances between well sites and residences are based on political compromises rather than peer-reviewed science and "may not be sufficient to reduce potential threats to human health in areas where hydraulic fracturing occurs," according to the findings of an interdisciplinary team including medical professionals and other researchers. The team incorporated geography, current regulations, historical records of blowout incidents and evacuations, thermal modeling, direct air pollution measurement, and vapor cloud modeling within the Marcellus (PA), Barnett (TX), and Niobrara (Northeastern and Northwestern Colorado and parts of Wyoming, Kansas, and Nebraska) Shale regions. The authors focused solely on well sites and excluded pipelines and compressor stations, which limited the data on explosions and evacuations and restricted air pollution results. Even so, the results showed that current natural gas well setbacks in the three areas "cannot be considered sufficient in all cases to protect public health and safety." People living within setback distances are potentially vulnerable to thermal injury during a well blowout, and they are also susceptible to exposures of benzene and hydrogen sulfide at levels above those known to cause health risks.[446]

- August 1, 2015 – "[C]linicians should be aware of the potential impact of fracking when evaluating their patients," concluded a team writing on behalf of the Occupational and Environmental Health Network of the American College of Chest Physicians. Their article stated that the over 200,000 U.S. workers employed by well-servicing companies "… are exposed to silica, diesel exhaust, and VOCs, and, at some sites, hydrogen sulfide and radon, raising concerns about occupational lung diseases, including silicosis, asthma, and lung cancer." The authors went on to say, "[i]n addition to occupational exposures, workers and nearby residents are also exposed to air pollutants emitted from various stages of fracking, including nitrogen oxides (NOx), VOCs, ozone, hazardous air pollutants, methane, and fine particulate matter." Authors pointed to several recent reversals in progress on air quality owed to fracking-related activity, including significant emissions of nitrogen oxides, a precursor of ozone, and spikes in fine particulate matter in fracking-intensive areas of Pennsylvania.[447]

- July 9, 2015 – The California Council on Science and Technology, in collaboration with the Lawrence Berkeley National Laboratory, released the second and third volumes of an extensive, peer-reviewed assessment of fracking in California. Air quality impacts are the focus of volume 2, chapter 3. The assessment found that current inventory methods underestimate methane and volatile organic chemical emissions from oil and gas operations and that fracking occurs in areas of California—most notably in the San Joaquin Valley and South Coast Air Basins—that already suffer from serious air quality problems. Further, no experimental studies of air emissions from drilling and fracking operations have ever been conducted in California. Although California has well-developed air quality inventory methods, they are "not designed to estimate well

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[446] Marsha Haley et al., "Adequacy of Current State Setbacks for Directional High-Volume Hydraulic Fracturing in the Marcellus, Barnett, and Niobrara Shale Plays," *Environmental Health Perspectives* 124, no. 9 (2016): 1323–33, https://doi.org/10.1289/ehp.1510547.
[447] Richard B. Evans, David Prezant, and Yuh Chin T. Huang, "Hydraulic Fracturing (Fracking) and the Clean Air Act," *Chest* 148, no. 2 (2015): 298–300, https://doi.org/10.1378/chest.14-2582.

stimulation emissions directly, and it is not possible to determine well stimulation emissions from current inventory methods."[448]

- July 1, 2015 – In accordance with California Senate Bill No. 4, the California Division of Oil, Gas, and Geothermal Resources released a three-volume environmental impact report on oil and gas well stimulation treatments in the state (which, in California, include fracking along with acidizing and other unconventional extraction technologies that break up oil- or gas-containing rock). The Division determined that fracking and related operations can have "significant and unavoidable" impacts on air quality, including increasing ozone and other federally regulated pollutants to levels that violate air quality standards or that would make those violations worse.[449, 450]

- May 29, 2015 – Each of stage of the drilling and fracking process "… has distinct operations that occur and particular sets of air emissions that may affect the respiratory tract," wrote West Virginia University researcher Michael McCawley. Some states do have setback requirements, which "… may provide a margin of safety for fire and explosions but [do] not necessarily assure complete dilution or negligible exposure from air emissions." His paper described the specific air contaminants associated with respiratory effects for each stage of operations. For example, the actual fracking stage potentially emits diesel exhaust, VOCs, particulate matter, ozone precursors, silica, and acid mists. McCawley reviewed the health effects linked to each of the contaminant types. Though many long-term effects may not yet be apparent in shale gas regions, "[a]t a minimum, one would expect to see similar rates of respiratory disease to that found near highways with heavy traffic flow."[451]

- April 21, 2015 – In a study funded by the electric power industry, a research team found that fracking had diminished air quality in rural areas downwind of gas sites in two heavily drilled Pennsylvania counties but that concentrations of VOCs were not as high as expected based on results in other states. Methane levels were higher than previous research had found.[452] The extent to which the results can be generalized to the Marcellus basin as a whole, the authors emphasized, remains uncertain.[453]

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[448] Adam Brandt et al., "Air Quality Impacts From Well Stimulation," in *An Independent Scientific Assessment of Well Stimulation in California*, vol. II, III vols. (California Council on Science & Technology, 2015), 182–266, https://ccst.us/wp-content/uploads/160708-sb4-vol-II-3-1.pdf.
[449] California Department of Conservation, Division of Oil, Gas, and Geothermal Resources, "Analysis of Oil and Gas Well Stimulation Treatments in California, Volume II," July 1, 2015, https://web.archive.org/web/20150121160541/http://www.conservation.ca.gov/dog/SB4DEIR/Pages/SB4_DEIR_TOC.aspx.
[450] Julie Cart, "State Issues Toughest-In-the-Nation Fracking Rules," *Los Angeles Times*, July 1, 2015, http://www.latimes.com/local/lanow/la-me-ln-state-issues-fracking-rules-20150701-story.html.
[451] Michael A. McCawley, "Air Contaminants Associated With Potential Respiratory Effects From Unconventional Resource Development Activities," *Seminars in Respiratory and Critical Care Medicine* 36, no. 3 (2015): 379–87, https://doi.org/10.1055/s-0035-1549453.
[452] Susan Phillips, "Study: Lower Than Expected Air Pollutants Detected at Marcellus Drilling Sites," State Impact Pennsylvania, May 19, 2015, https://stateimpact.npr.org/pennsylvania/2015/05/19/study-lower-than-expected-air-pollutants-from-gas-drilling-sites/.
[453] J. Douglas Goetz et al., "Atmospheric Emission Characterization of Marcellus Shale Natural Gas Development Sites," *Environmental Science & Technology* 49, no. 11 (2015): 7012–20, https://doi.org/10.1021/acs.est.5b00452.

- April 15, 2015 – In a review of the literature, Colorado researchers demonstrated that four common chemical air pollutants from drilling and fracking operations—benzene, toluene, ethylbenzene, and xylene (BTEX)—are endocrine disruptors commonly found in ambient air that have the ability to interfere with human hormones at low exposure levels, including at concentrations well below EPA recommended exposure limits. Among the health conditions linked to ambient level exposures to the BTEX family of air pollutants: sperm abnormalities, reduced fetal growth, cardiovascular disease, respiratory dysfunction, and asthma.[454] "This review suggests that BTEX may…have endocrine disrupting properties at low concentrations, presenting an important line of inquiry for future research. BTEX are used globally in consumer products, and are released from motor vehicles and oil and natural gas operations that are increasingly in close proximity to homes, schools, and other places of human activity."[455]

- March 31, 2015 – University of Wyoming researchers identified a wastewater treatment and recycling facility as an important contributor to high winter ozone levels in Wyoming's Green River Basin. The facility released a signature mixture of volatile hydrocarbons, including toluene and xylene, which are ozone precursors.[456] This study documented that recycling activities can transfer volatile pollutants from water into air when fracking wastewater is cleaned up for reuse and that water treatment emissions can serve as an important point source of air pollutants.[457]

- March 26, 2015 – Fracking can pollute air hundreds of miles downwind from the well pad, according to the results of a study from University of Maryland. Researchers took hourly measurements of ethane in the air over Maryland and the greater Washington, DC area, where fracking does not occur, and compared them to ethane data from areas of West Virginia, Pennsylvania, and Ohio where it does. They found month-to-month correlations, indicating that the ethane pollution in the air over Maryland appears to be coming from drilling and fracking operations in these other states. Ethane, a minor component of natural gas, rose 30 percent in the air over the Baltimore and Washington DC area since 2010, even as other air pollutants declined in concentration. By contrast, no increase in ethane levels were found in Atlanta, Georgia, which is not downwind of

[454] Brian Bienkowski, "Scientists Warn of Hormone Impacts From Benzene, Xylene, Other Common Solvents," Environmental Health News, April 15, 2015, http://www.environmentalhealthnews.org/ehs/news/2015/apr/endocrine-disruption-hormones-benzene-solvents.
[455] Ashley L. Bolden, Carol F. Kwiatkowski, and Theo Colborn, "New Look at BTEX: Are Ambient Levels a Problem?," *Environmental Science & Technology* 49, no. 9 (2015): 5261–76, https://doi.org/10.1021/es505316f.
[456] R. A. Field et al., "Influence of Oil and Gas Field Operations on Spatial and Temporal Distributions of Atmospheric Non-Methane Hydrocarbons and Their Effect on Ozone Formation in Winter," *Atmospheric Chemistry and Physics* 15 (2015): 3527–42, https://doi.org/10.5194/acp-15-3527-2015.
[457] Amanda Peterka, "Study Links Wyoming Winter Ozone to Drillers' Wastewater Plant," *WyoFile*, April 2, 2015, https://web.archive.org/web/20150403112532/https://www.wyofile.com/study-links-wyoming-winter-ozone-drillers-wastewater-plant/.

fracking operations.[458, 459] Given this evidence for widespread ethane leakage, the paper's lead author asked how much methane and other, more reactive emissions might be escaping from wells, noting that "a substantial amount of hydrocarbons" are emitted as a result of flowback procedures following the fracturing process.[460]

- February 27, 2015 – A team of researchers from University of Texas, funded in part by the gas industry, examined ozone (smog) production resulting from natural gas extraction and use in Texas. Previous research by this team had found that the increased use of natural gas for generating electricity, as a replacement for coal, contributed to overall reductions in daily maximum ozone concentrations in northeastern Texas. By contrast, the results of this study found an increase in ozone in the Eagle Ford Shale area of south Texas. The Eagle Ford Shale is upwind from both Austin and San Antonio.[461] A potent greenhouse gas, methane is also a precursor for ground-level ozone and hence a contributor to smog formation.

- January 16, 2015 – Researchers from a number of universities, including the University of New Hampshire and Appalachian State University, used a source apportionment model to estimate the contribution of natural gas extraction activities to overall air pollution, including ozone, in heavily drilled southwest Pennsylvania. This regional air sampling effort demonstrated significant changes in atmospheric chemistry from drilling and fracking operations there. The researchers found that drilling and fracking operations may affect compliance with ozone standards.[462]

- November 20, 2014 – The Texas Commission on Environmental Quality confirmed high levels of benzene emissions and other VOCs around an oil and gas facility in the Eagle Ford Shale. Symptoms reported by local residents were consistent with those known to be associated with exposure to such chemicals.[463]

- November 14, 2014 – A University of Colorado at Boulder research team found that residential areas in intensely drilled northeastern Colorado have high levels of fracking-related air pollutants, including benzene. In some cases, concentrations exceed those

[458] Timothy Vinciguerra et al., "Regional Air Quality Impacts of Hydraulic Fracturing and Shale Natural Gas Activity: Evidence From Ambient VOC Observations," *Atmospheric Environment* 110 (2015): 144–50, https://doi.org/10.1016/j.atmosenv.2015.03.056.
[459] Katie Valentine, "Fracking Wells Could Pollute The Air Hundreds Of Miles Away," *Climate Progress*, April 30, 2015, https://archive.thinkprogress.org/fracking-wells-could-pollute-the-air-hundreds-of-miles-away-e65ff4f3b24c/.
[460] F. Levine and L. Tune, "Emissions from Natural Gas Wells May Travel Far Downwind," Department of Chemical & Biomolecular Engineering, University of Maryland, April 30, 2015, https://chbe.umd.edu/news/story/emissions-from-natural-gas-wells-may-travel-far-downwind.
[461] Adam P. Pacsi et al., "Regional Ozone Impacts of Increased Natural Gas Use in the Texas Power Sector and Development in the Eagle Ford Shale," *Environmental Science & Technology* 49, no. 6 (2015): 3966–73, https://doi.org/10.1021/es5055012.
[462] Robert F. Swarthout et al., "Impact of Marcellus Shale Natural Gas Development in Southwest Pennsylvania on Volatile Organic Compound Emissions and Regional Air Quality," *Environmental Science & Technology* 49, no. 5 (2015): 3175–84, https://doi.org/10.1021/es504315f.
[463] Barry Davis, "TCEQ Memo Proves Toxic Chemicals Are Being Released in the Eagle Ford Shale," *USA Today*, November 20, 2014, https://www.usatoday.com/story/news/investigations/i-team/2014/11/20/benzene-oil-toxic-fumes/70020596/.

found in large urban centers and are within the range of exposures known to be linked to chronic health effects. According to the study, “High ozone levels are a significant health concern, as are potential health impacts from chronic exposure to primary emissions of non-methane hydrocarbons (NMHC) for residents living near wells.” The study also noted that tighter regulations have not resulted in lower air pollution levels, “Even though the volume of emissions per well may be decreasing, the rapid and continuing increase in the number of wells may potentially negate any real improvements to the air quality situation.”[464]

- October 30, 2014 – A research team assembled by University at Albany Institute for Health and the Environment identified eight highly toxic chemicals in air samples collected near fracking and associated infrastructure sites across five states: Arkansas, Colorado, Pennsylvania, Ohio, and Wyoming. The most common airborne chemicals detected included two proven human carcinogens (benzene and formaldehyde) and two potent neurotoxicants (hexane and hydrogen sulfide). In 29 out of 76 samples, concentrations far exceeded federal health and safety standards, sometimes by several orders of magnitude. Further, high levels of pollutants were detected at distances exceeding legal setback distances from wellheads to homes. Highly elevated levels of formaldehyde, for example, were found up to a half-mile from a wellhead. In Arkansas, seven air samples contained formaldehyde at levels up to 60 times the level known to raise the risk for cancer.[465] “This is a significant public health risk,” said lead author David O. Carpenter, MD, in an accompanying interview: “Cancer has a long latency, so you’re not seeing an elevation in cancer in these communities. But five, 10, 15 years from now, elevation in cancer is almost certain to happen.”[466]

- October 21, 2014 – Responding to health concerns by local residents, a research team from University of Cincinnati and Oregon State University found high levels of air pollution in heavily drilled areas of rural Carroll County, Ohio. Air monitors showed 32 different hydrocarbon-based air pollutants, including the carcinogens naphthalene and benzo[a]pyrene.[467] The researchers plan additional monitoring and analysis.

- October 21, 2014 – Using a mobile laboratory designed by NOAA, a research team from the University of Colorado at Boulder, the NOAA Earth System Research Laboratory, and the Karlsruhe Institute of Technology looked at air pollution from drilling and fracking operations in Utah’s Uintah Basin. The researchers found that drilling and fracking emit prodigious amounts of volatile organic air pollutants, including benzene, toluene, and methane, all of which are precursors for ground-level ozone (smog).

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[464] Chelsea R. Thompson, Jacques Hueber, and Detlev Helmig, “Influence of Oil and Gas Emissions on Ambient Atmospheric Non-Methane Hydrocarbons in Residential Areas of Northeastern Colorado,” *Elementa: Science of the Anthropocene* 3 (2014), https://doi.org/10.12952/journal.elementa.000035.
[465] Gregg P. Macey et al., “Air Concentrations of Volatile Compounds Near Oil and Gas Production: A Community-Based Exploratory Study,” *Environmental Health* 13, no. 82 (2014), https://doi.org/10.1186/1476-069X-13-82.
[466] Alan Neuhauser, “Toxic Chemicals, Carcinogens Skyrocket Near Fracking Sites,” *U.S. News*, October 30, 2014, http://www.usnews.com/news/articles/2014/10/30/toxic-chemicals-and-carcinogens-skyrocket-near-fracking-sites-study-says.
[467] Environmental Health Sciences Center, “List of 62 PAH Analyzed in Carroll County, OH,” Oregon State University, 2014, http://ehsc.oregonstate.edu/air/62PAHList of 62 PAH Analyzed in Carroll County, OH.

Multiple pieces of equipment on and off the well pad, including condensate tanks, compressors, dehydrators, and pumps, served as the sources of these emissions. This research shows that drilling and fracking activities are the cause of the extraordinarily high levels of winter smog in the remote Uintah basin—which regularly exceed air quality standards and rival that of downtown Los Angeles.[468]

- October 2, 2014 – A joint investigation by *Inside Climate News* and the Center for Public Integrity found that toxic air emissions wafting from fracking waste pits in Texas are unmonitored and unregulated due to federal exemptions that classify oil and gas field waste as non-hazardous.[469]

- October 1, 2014 – In a major paper published in *Nature*, an international team led by the National Oceanic and Atmospheric Administration demonstrated that exceptionally high emissions of VOCs explain how drilling and fracking operations in Utah's Uintah Basin create extreme wintertime ozone events even in the absence of abundant ultraviolet light and water vapor, which are typically required to produce ground-level ozone (smog). Current air pollution trends in the United States are toward lower nitrogen oxides from urban sources and power generation, but increasing methane and VOCs from oil and gas extraction activities threaten to reverse decades of progress in attaining cleaner air. According to the study, the consequences for public health are "as yet unrecognized."[470]

- September 6, 2014 – As part of a comparative lifecycle analysis, a British team from the University of Manchester found that shale gas extracted via fracking in the United Kingdom would generate more smog than any other energy source evaluated (coal, conventional and liquefied gas, nuclear, wind, and solar). Leakage of vaporous organic compounds during the necessary removal of hydrogen sulfide gas, along with the venting of gas both during drilling and during the process of making the well ready for production, were major contributors. "In comparison to other technologies, shale gas has high [photochemical smog]. In the central case, it is worse than solar PV, offshore wind and nuclear power by factors of 3, 26 and 45, respectively. Even in the best case, wind and nuclear power are still preferable (by factors of 3.3 and 5.6 respectively)."[471]

- September 2014 – ShaleTest Environmental Testing conducted ambient air quality tests and gas-finder infrared video for several children's play areas in North Texas that are located in close proximity to shale gas development. The results showed a large number of compounds detected above the Method Reporting Limit (the minimum quantity of the compound that can be confidently determined by the laboratory). Air sampling found

[468] C. Warneke et al., "Volatile Organic Compound Emissions From the Oil and Natural Gas Industry in the Uintah Basin, Utah: Oil and Gas Well Pad Emissions Compared to Ambient Air Composition," *Atmospheric Chemistry and Physics* 14 (2014): 10977–88, https://doi.org/10.5194/acp-14-10977-2014.
[469] David Hasemyer, "Open Pits Offer Cheap Disposal for Fracking Sludge, But Health Worries Mount," *Inside Climate News*, October 2, 2014, http://www.publicintegrity.org/2014/10/02/15826/open-pits-offer-cheap-disposal-fracking-sludge-health-worries-mount.
[470] Peter M. Edwards et al., "High Winter Ozone Pollution from Carbonyl Photolysis in an Oil and Gas Basin," *Nature* 514 (2014): 351–54, https://doi.org/10.1038/nature13767.
[471] Laurence Stamford and Adisa Azapagic, "Life Cycle Environmental Impacts of UK Shale Gas," *Applied Energy* 134 (2014): 506–18, https://doi.org/10.1016/j.apenergy.2014.08.063.

three known/suspected carcinogens, and a number of other compounds associated with significant health effects. Benzene results from Denton, Dish, and Fort Worth are particularly alarming since they exceeded the long-term ambient air limits set by the Texas Commission on Environmental Quality, and benzene is a known carcinogen. "Benzene was found at all but one sampling location …. This is particularly noteworthy as benzene is a known carcinogen (based on evidence from studies in both people and lab animals), AND because it exceeds [levels above which effects have the potential to occur.]"[472]

- August 24, 2014 – A *Salt Lake City Tribune* investigation found that evaporation from 14 fracking waste pits in western Colorado has added tons of toxic chemicals to Utah's air in the last six years. Further, the company responsible operated with no permit, underreported its emissions and provided faulty data to regulators.[473]

- August 2014 – A four-part investigation by the *San Antonio Express-News* found that natural gas flaring in the Eagle Ford Shale in 2012 contributed more than 15,000 tons of VOCs and other contaminants to the air of southern Texas—which is roughly equivalent to the pollution that would be released annually by six oil refineries. No state or federal agency is tracking the emissions from individual flares.[474]

- June 26, 2014 – Public health professionals at the Southwest Pennsylvania Environmental Health Project reported significant recurrent spikes in the amount of particulate matter in the air inside of residential homes located near drilling and fracking operations. Captured by indoor air monitors, the spikes tend to occur at night when stable atmospheric conditions hold particulate matter low to the ground. Director Raina Ripple emphasized that spikes in airborne particulate matter are likely to cause acute health impacts in community members. She added, "What the long-term effects are going to be, we're not certain."[475]

- May 8, 2014 – Researchers at NOAA found high levels of methane leaks as well as benzene and smog-forming VOCs in the air over oil and gas drilling areas in Colorado. Researchers found methane emissions three times higher than previously estimated and benzene and VOC levels seven times higher than estimated by government agencies. The

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[472] ShaleTest Environmental Testing, "Project Playground: Cleaner Air for Active Kids," September 2014, https://web.archive.org/web/20150913195017/http://www.shaletest.org/wp-content/uploads/2014/09/ProjectPlaygoundPatagoniaReport-5-1.pdf.
[473] Brian Maffly, "Utah Grapples With Toxic Water From Oil and Gas Industry," *The Salt Lake Tribune*, August 28, 2014, http://www.sltrib.com/sltrib/news/58298470-78/danish-flats-ponds-company.html.
[474] John Tedesco and Jennifer Hiller, "Up in Flames: Flare in Eagle Ford Shale Wasting Natural Gas," *San Antonio Express-News*, August 2014, http://www.expressnews.com/business/eagleford/item/Up-in-Flames-Day-1-Flares-in-Eagle-Ford-Shale-32626.php.
[475] Jeff McMahon, "Air Pollution Spikes In Homes Near Fracking Wells," *Forbes*, June 26, 2014, Air Pollution Spikes In Homes Near Fracking Wells.

Denver Post noted that Colorado's Front Range has failed to meet federal ozone air quality standards for years.[476]

- April 26, 2014 – A Texas jury awarded a family $2.8 million because, according to the lawsuit, a fracking company operating on property nearby had "created a 'private nuisance' by producing harmful air pollution and exposing [members of the affected family] to harmful emissions of volatile organic compounds, toxic air pollutants and diesel exhaust." The family's 11-year-old daughter became ill, and family members suffered a range of symptoms, including "nosebleeds, vision problems, nausea, rashes, blood pressure issues."[477] Because drilling did not occur on their property, the family had initially been unaware that their symptoms were caused by activities around them.

- April 16, 2014 – Reviewing the peer-review literature to date of "direct pertinence to the environmental public health and environmental exposure pathways," a U.S. team of researchers concluded: "[a] number of studies suggest that shale gas development contributes to levels of ambient air concentrations known to be associated with increased risk of morbidity and mortality."[478]

- April 11, 2014 – A modeling study commissioned by the state of Texas made striking projections about worsening air quality in the Eagle Ford Shale. Findings included the possibility of a 281 percent increase in emissions of VOCs. Some VOCs cause respiratory and neurological problems; others, like benzene, are also carcinogens. Another finding was that nitrogen oxides—which react with VOCs in sunlight to create ground-level ozone, the main component of smog—increased 69 percent during the peak ozone season.[479]

- March 29, 2014 – Scientists warn that current methods of collecting and analyzing emissions data do not accurately assess health risks. Researchers with the Southwest Pennsylvania Environmental Health Project showed that methods do not adequately measure the intensity, frequency, or durations of community exposure to the toxic chemicals routinely released from drilling and fracking activities. They found that exposures may be underestimated by an order of magnitude, mixtures of chemicals are not taken into account, and local weather conditions and vulnerable populations are ignored.[480]

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[476] Bruce Finley, "Scientists Flying Over Colorado Oil Boom Find Worse Air Pollution," *The Denver Post*, May 7, 2014, sec. Environment, http://www.denverpost.com/environment/ci_25719742/scientists-flying-over-colorado-oil-boom-find-worse.
[477] Jason Morris, "Texas Family Plagued With Ailments Gets $3M in 1st-of-Its-Kind Fracking Judgment," *CNN*, April 26, 2014, http://www.cnn.com/2014/04/25/justice/texas-family-wins-fracking-lawsuit/.
[478] Seth B. C. Shonkoff, Jake Hays, and Madelon Finkel, "Environmental Public Health Dimensions of Shale and Tight Gas Development," *Environmental Health Perspectives* 122, no. 8 (2014), https://doi.org/10.1289/ehp.1307866.
[479] Jim Morris, Lisa Song, and David Hasemayer, "Report: Air Quality to Worsen in Eagle Ford Shale," *The Texas Tribune*, April 11, 2014, http://www.texastribune.org/2014/04/11/report-air-quality-worsen-eagle-ford-shale/.
[480] David Brown et al., "Understanding Exposure From Natural Gas Drilling Puts Current Air Standards to the Test," *Reviews on Environmental Health* 29, no. 4 (n.d.): 277–92, https://doi.org/10.1515/reveh-2014-0002.

- March 27, 2014 – University of Texas research pointed to "potentially false assurances" in response to community health concerns in shale gas development areas. Dramatic shortcomings in air pollution monitoring to date include no accounting for cumulative toxic emissions or children's exposures during critical developmental stages, and the potential interactive effects of mixtures of chemicals. Chemical mixtures of concern include benzene, toluene, ethylbenzene, and xylenes.[481, 482]

- March 13, 2014 – VOCs emitted in Utah's heavily drilled Uintah Basin led to 39 winter days exceeding the EPA's eight-hour National Ambient Air Quality Standards level for ozone pollutants the previous winter. "Levels above this threshold are considered to be harmful to human health, and high levels of ozone are known to cause respiratory distress and be responsible for an estimated 5,000 premature deaths in the U.S. per year," according to researchers at the University of Colorado. Their observations "reveal a strong causal link between oil and gas emissions, accumulation of air toxics, and significant production of ozone in the atmospheric surface layer."[483] Researchers estimated that total annual VOC emissions at the fracking sites are equivalent to those of about 100 million cars.[484]

- March 3, 2014 – In a report summarizing "the current understanding of local and regional air quality impacts of natural gas extraction, production, and use," a group of researchers from NOAA, Stanford, Duke, and other institutions described what is known and unknown with regard to air emissions including greenhouse gases, ozone precursors (VOCs and nitrogen oxides), air toxics, and particulates. Crystalline silica was also discussed, including as a concern for people living near well pads and production staging areas.[485]

- February 18, 2014 – An eight-month investigation by the *Weather Channel*, the *Center for Public Integrity,* and *Inside Climate News* into fracking in the Eagle Ford Shale in Texas revealed that fracking is "releasing a toxic soup of chemicals into the air." They noted very poor monitoring by the state of Texas and reported on hundreds of air complaints filed relating to air pollution associated with fracking.[486]

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[481] Rachael Rawlins, "Planning for Fracking on the Barnett Shale: Urban Air Pollution, Improving Health Based Regulation, and the Role of Local Governments," *Virginia Environmental Law Journal* 31, no. 2 (2013): 223–306.
[482] University of Texas at Austin, "Air Pollution and Hydraulic Fracturing: Better Monitoring, Planning and Tracking of Health Effects Needed in Texas," *UT News*, March 27, 2014, https://news.utexas.edu/2014/03/27/air-pollution-and-hydraulic-fracturing-better-monitoring-planning-and-tracking-of-health-effects-needed-in-texas/.
[483] D. Helmig et al., "Highly Elevated Atmospheric Levels of Volatile Organic Compounds in the Uintah Basin, Utah," *Environmental Science & Technology* 48, no. 9 (2014): 4707–15, https://doi.org/10.1021/es405046r.
[484] Deirdre Lockwood, "Harmful Air Pollutants Build Up Near Oil And Gas Fields," *Chemical & Engineering News*, March 25, 2014, http://cen.acs.org/articles/92/web/2014/03/Harmful-Air-Pollutants-Build-Near.html.
[485] Christopher W. Moore et al., "Air Impacts of Increased Natural Gas Acquisition, Processing, and Use: A Critical Review," *Environmental Science & Technology* 48, no. 15 (2014): 8349–5359, https://doi.org/10.1021/es4053472.
[486] David Hasemyer, Jim Morris, and Lisa Song, *Fracking the Eagle Ford Shale: Big Oil and Bad Air on the Texas Prairie* (The Weather Channel, 2014), https://insideclimatenews.org/project/fracking-the-eagle-ford-shale/#:~:text=Fracking%20the%20Eagle%20Ford%20Shale%20Big%20Oil%20%26,overtook%20the%20oil%20and%20gas%20fields%20of%20Texas.

- December 18, 2013 – An interdisciplinary group of researchers in Texas collected air samples in residential areas near shale gas extraction and production, going beyond previous Barnett Shale studies by including emissions from the whole range of production equipment. They found that most areas had "atmospheric methane concentrations considerably higher than reported urban background concentrations," and many toxic chemicals were "strongly associated" with compressor stations.[487]

- December 10, 2013 – Health department testing at fracking sites in West Virginia revealed dangerous levels of benzene in the air. Wheeling-Ohio County Health Department Administrator Howard Gamble stated, "The levels of benzene really pop out. The amounts they were seeing were at levels of concern. The concerns of the public are validated."[488]

- October 11, 2013 – Air sampling before, during, and after drilling and fracking of a new natural gas well pad in rural western Colorado documented the presence of the toxic solvent methylene chloride, along with several polycyclic aromatic hydrocarbons at "concentrations greater than those at which prenatally exposed children in urban studies had lower developmental and IQ scores." The study linked this single well pad to more than 50 airborne chemicals, 44 of which have known health effects. [489]

- September 19, 2013 – In Texas, air monitoring data in the Eagle Ford Shale area revealed potentially dangerous exposures of nearby residents to hazardous air pollutants, including cancer-causing benzene and the neurological toxicant, hydrogen sulfide.[490]

- September 13, 2013 – A study by researchers at the University of California at Irvine found dangerous levels of VOCs in Canada's "Industrial Heartland" where there are more than 40 oil, gas, and chemical facilities. The researchers noted high levels of hematopoietic cancers (leukemia and non-Hodgkin's lymphoma) in men who live closer to the facilities.[491]

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[487] Alisa Rich, James P. Gover, and Melanie L. Sattler, "An Exploratory Study of Air Emissions Associated With Shale Gas Development and Production in the Barnett Shale," *Journal of the Air & Waste Management Association* 64, no. 1 (2014): 61–72, https://doi.org/10.1080/10962247.2013.832713.
[488] C. Junkins, "Health Dept. Concerned About Benzene Emissions Near Local Gas Drilling Sites," *The Intelligencer, Wheeling News-Register*, December 10, 2013, sec. Community, https://www.theintelligencer.net/news/community/2013/12/health-dept-concerned-about-benzene-emissions-near-local-gas-drilling-sites/.
[489] Theo Colborn et al., "An Exploratory Study of Air Quality Near Natural Gas Operations," *Human and Ecological Risk Assessment: An International Journal* 20, no. 1 (2014): 86–105, https://doi.org/10.1080/10807039.2012.749447.
[490] Sharon Wilson, Lisa Sumi, and Wilma Subra, "Reckless Endangerment While Fracking the Eagle Ford Shale" (Earthworks, September 19, 2013), http://www.earthworksaction.org/library/detail/reckless_endangerment_in_the_eagle_ford_shale#.UkGi-4Y3uSo.
[491] Isobel J. Simpson et al., "Air Quality in the Industrial Heartland of Alberta, Canada and Potential Impacts on Human Health," *Atmospheric Environment* 81 (2013): 702–9, https://doi.org/10.1016/j.atmosenv.2013.09.017.

- April 29, 2013 – Using American Lung Association data, researchers with the Environmental Defense Fund determined that air quality in rural areas with fracking was worse than air quality in urban areas.[492]

- March 2013 – A review of regional air quality damages in parts of Pennsylvania in 2012 from Marcellus Shale development found that air pollution was a significant concern, with regional damages ranging from $7.2-$32 million in 2011.[493]

- February 27, 2013 – In a letter from Concerned Health Professionals of New York to Governor Andrew Cuomo, a coalition of hundreds of health organizations, scientists, medical experts, elected officials, and environmental organizations noted serious health concerns about the prospects of fracking in New York State, making specific note of air pollution.[494] Signatory organizations included the American Academy of Pediatrics of New York, the American Lung Association of New York, and Physicians for Social Responsibility. The New York State Medical Society, representing 30,000 medical professionals, has issued similar statements.[495]

- January 2, 2013 – A NOAA study identified emissions from oil and gas fields in Utah as a significant source of pollutants that contribute to ozone problems.[496] Exposure to elevated levels of ground-level ozone is known to worsen asthma and has been linked to respiratory illnesses and increased risk of stroke and heart attack.[497]

- July 18, 2012 – A study by the Houston Advanced Research Center modeled ozone formation from a natural gas processing facility using accepted emissions estimates and showed that regular operations could significantly raise levels of ground-level ozone (smog) in the Barnett Shale in Texas and that gas flaring further contributed to ozone levels.[498]

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[492] Dan Grossman, "Clean Air Report Card: CO, WY Counties Get F's Due To Oil And Gas Pollution," *Environmental Defense Fund* (blog), April 29, 2013, http://blogs.edf.org/energyexchange/2013/04/29/clean-air-report-card-co-wy-counties-get-fs-due-to-oil-and-gas-pollution/#sthash.FXRV6Nxi.dpuf.
[493] Aviva Litovitz et al., "Estimation of Regional Air-Quality Damages From Marcellus Shale Natural Gas Extraction in Pennsylvania," *Environmental Research Letters* 8, no. 1 (2013), https://doi.org/10.1088/1748-9326/8/1/014017.
[494] Concerned Health Professionals of NY, "Letter to Governor Cuomo," February 27, 2013, http://concernedhealthny.org/letters-to-governor-cuomo/.
[495] J. Campbell, "Fracking Roundup: Gas Prices Up; Medical Society Wants Moratorium," *Politics on the Hudson* (blog), April 17, 2013, http://polhudson.lohudblogs.com/2013/04/17/fracking-roundup-gas-prices-up-medical-society-wants-moratorium/.
[496] Jeff Tollefson, "Methane Leaks Erode Green Credentials of Natural Gas," *Nature* 493 (2013): 12, https://doi.org/10.1038/493012a.pdf.
[497] American Lung Association, "State of the Air 2013: American Lung Association Report Reveals America's Most Polluted Cities," April 24, 2013.
[498] Eduardo P. Olaguer, "The Potential Near-Source Ozone Impacts of Upstream Oil and Gas Industry Emissions," *Journal of the Air & Waste Management Association* 62, no. 8 (2012): 966–77, https://doi.org/10.1080/10962247.2012.688923.

- March 19, 2012 – A Colorado School of Public Health study found air pollutants near fracking sites linked to neurological and respiratory problems and cancer.[499, 500] The study, based on three years of monitoring at Colorado sites, found a number of "potentially toxic petroleum hydrocarbons in the air near gas wells including benzene, ethylbenzene, toluene, and xylene." Lisa McKenzie, PhD, MPH, lead author of the study and research associate at the Colorado School of Public Health, said, "Our data show that it is important to include air pollution in the national dialogue on natural gas development that has focused largely on water exposures to hydraulic fracturing."[501]

- December 12, 2011 – Cancer specialists, cancer advocacy organizations, and health organizations summarized the cancer risks posed by all stages of the shale gas extraction process in a letter to New York Governor Andrew Cuomo.[502]

- October 5, 2011 – More than 250 medical experts and health organizations reviewed the multiple health risks from fracking in a letter sent to New York Governor Andrew Cuomo.[503]

- April 21, 2011 – *Environment & Energy (E&E)* reported that ozone levels exceeding federal health standards in Utah's Uintah Basin, as well as wintertime ozone problems in other parts of the Intermountain West, stem from oil and gas extraction. Levels reached nearly twice the federal standard, potentially dangerous even for healthy adults to breathe. Keith Guille, spokesman for the Wyoming Department of Environmental Quality, said, "We recognize that definitely the main contributor to the emissions that are out there is the oil and gas industry…."[504]

- March 8, 2011 – The Associated Press reported that gas drilling in some remote areas of Wyoming caused a decline of air quality from pristine mountain air to levels of smog and pollution worse than Los Angeles on its worst days, resulting in residents complaining of watery eyes, shortness of breath, and bloody noses.[505]

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[499] David Kelly, "Study Shows Air Emissions Near Fracking Sites May Have Serious Health Impacts," *University of Colorado Denver*, March 19, 2012, https://news.cuanschutz.edu/news-stories/health-impacts-of-fracking-emissions.
[500] Lisa M. McKenzie et al., "Human Health Risk Assessment Of Air Emissions From Development Of Unconventional Natural Gas Resources," *Science of the Total Environment* 424 (2012): 79–87, https://doi.org/10.1016/j.scitotenv.2012.02.018.
[501] Neela Banerjee, "Study: 'Fracking' May Increase Air Pollution Health Risks," *Los Angeles Times*, March 20, 2012, https://www.latimes.com/science/la-xpm-2012-mar-20-la-me-gs-fracking-increases-air-pollution-health-risks-to-residents-20120320-story.html.
[502] Physicians, Scientists & Engineers for Health Energy, "Appeal to Gov. Cuomo to Consider Cancer Risks Re: High Volume Hydraulic Fracturing for Natural Gas," Letter to A. Cuomo, December 12, 2011, http://steingraber.com/wp-content/uploads/CancerFrackingDec12.pdf.
[503] Concerned Health Professionals of NY, "Letter to Governor Cuomo," October 5, 2011, https://concernedhealthny.org/letters-to-governor-cuomo/.
[504] Scott Streater, "Air Pollution: Winter Ozone Problem Continues to Mystify Regulators, Industry.," *E&E News*, April 21, 2011, https://web.archive.org/web/20131024193123/http://www.eenews.net/stories/1059948108.
[505] Mead Gruver, "Wyoming Is Beset by a Big-City Problem: Smog," *USA Today*, March 8, 2011, http://usatoday30.usatoday.com/money/industries/energy/2011-03-08-natural-gas-ozone-wyoming_N.htm.

- November 18, 2010 – A study of air quality in the Haynesville Shale region of east Texas, northern Louisiana, and southwestern Arkansas found that shale oil and gas extraction activities contributed significantly to ground-level ozone (smog) via high emissions of ozone precursors, including VOCs and nitrogen oxides.[506] Ozone is a key risk factor for asthma and other respiratory and cardiovascular illnesses.[507, 508, 509, 510]

- September 2010 – A health assessment by the Colorado School of Public Health for gas development in Garfield County, Colorado determined that air pollution will likely "be high enough to cause short-term and long-term disease, especially for residents living near gas wells. Health effects may include respiratory disease, neurological problems, birth defects and cancer."[511, 512]

- January 27, 2010 – Of 94 drilling sites tested for benzene in air over the Barnett Shale, the Texas Commission on Environmental Quality discovered two well sites emitting what they determined to be "extremely high levels" and another 19 emitting elevated levels.[513]

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506 Susan Kemball-Cook et al., "Ozone Impacts of Natural Gas Development in the Haynesville Shale," *Environmental Science & Technology* 15, no. 44 (2010): 9357-9363, https://doi.org/10.1021/es1021137.
507 United States Environmental Protection Agency, "Integrated Science Assessment (ISA) for Ozone and Related Photochemical Oxidants," EPA, 2013, https://www.epa.gov/isa/integrated-science-assessment-isa-ozone-and-related-photochemical-oxidants.
508 Anoop S. B. Shah et al., "Short Term Exposure to Air Pollution and Stroke: Systematic Review and Meta-Analysis," *British Medical Journal* 350, no. h1295 (2015), https://doi.org/10.1136/bmj.h1295.
509 Anoop S. B. Shah et al., "Global Association of Air Pollution and Heart Failure: A Systematic Review and Meta-Analysis," *Lancet* 382, no. 9897 (2013): 1039–48, https://doi.org/10.1016/S0140-6736(13)60898-3.
510 Orrin Myers et al., "The Association Between Ambient Air Quality Ozone Levels and Medical Visits for Asthma in San Juan County" (New Mexico Department of Health, Environmental Health Epidemiology Bureau Epidemiology and Response Division, August 2007), https://fossil.energy.gov/ng_regulation/sites/default/files/programs/gasregulation/authorizations/2012/applications/sierra_exhibits_12_100_LNG/Ex._51_-_Myers_Association_Btwn_Ambient.pdf.
511 R. Witter et al., "Health Impact Assessment for Battlement Mesa, Garfield County Colorado" (Garfield County, Colorado, 2010), https://www.garfield-county.com/environmental-health/battlement-mesa-health-impact-assessment-draft1/.
512 "Battlement Mesa HIA/EHMS" (Garfield County, Colorado, November 30, 2013), https://www.garfield-county.com/environmental-health/battlement-mesa-health-impact-assessment-ehms/.
513 John McFarland, "Agency Finds High Benzene Levels on Barnett Shale," *Boston Globe*, January 27, 2010, http://archive.boston.com/business/articles/2010/01/27/agency_finds_high_benzene_levels_on_barnett_shale/.

Water contamination

Drilling and fracking activities, and associated wastewater disposal practices, inherently threaten groundwater and have polluted drinking water sources. Studies from across the United States present irrefutable evidence that groundwater contamination occurs as a result of fracking activities and is more likely to occur close to well pads. In Pennsylvania alone, the state has determined that 343 private drinking water wells have been contaminated or otherwise impacted as the result of drilling and fracking operations over an eight-year period.

Evidence of instances and pathways of water contamination exist even though scientific inquiry is impeded by industry secrecy and regulatory exemptions. The 2005 Energy Policy Act exempts hydraulic fracturing from key provisions of the Safe Drinking Water Act. As a result, fracking chemicals have been protected from public scrutiny as "trade secrets." The oil and gas sector is the only U.S. industry permitted to inject known hazardous materials near, or directly into, underground drinking water aquifers. At the same time, in most states where fracking occurs, routine monitoring of groundwater aquifers near drilling and fracking operations is not required, nor are companies compelled to fully disclose the identity of chemicals used in fracking fluid, their quantities, or their fate once injected underground.

Nevertheless, of the more than 1,000 chemicals that are confirmed ingredients in fracking fluid, an estimated 100 are known endocrine disruptors, acting as reproductive and developmental toxicants, and at least 48 are potentially carcinogenic. Adding to this mix are heavy metals, radioactive elements, brine, and volatile organic compounds (VOCs), which occur naturally in deep geological formations and which can be carried up from the fracking zone with the flowback fluid. A 2020 study identified 1,198 chemicals in oil and gas wastewater, of which 86 percent lack toxicity data sufficient to complete a risk assessment. A 2021 investigation revealed that highly toxic polyfluoralkyl substances (PFAS or so-called "forever chemicals") were used as ingredients in fracking fluid in at least 1,200 oil and gas wells in six states between 2012 and 2020.

Toxic substances in the fracking waste stream pose threats to surface water and groundwater. A 2017 study found that spills of fracking fluids and fracking wastewater are common, documenting 6,678 significant spills occurring over a period of nine years in four states alone. In these states, between 2 and 16 percent of wells report spills each year. About five percent of all fracking waste is lost to spills, often during transport. A 2020 survey of groundwater wells in Kern County, California found widespread contamination with wastewater chemicals, including salts, that had leached from both surface pits and underground injection wells. A 2021 study in southeastern New Mexico found that the shift from conventional drilling to fracking was accompanied by dramatic increases in total dissolved solids, sodium, and calcium levels in groundwater aquifers with density of oil wells correlating with concentration of contaminants.

Wastewater spills are not becoming uniformly less frequent with time. Data from the Colorado Oil and Gas Conservation Commission show that the number of gas and oil spills across the state peaked in 2014 and rose again between 2018 and 2019.

Spills and intentional discharges of fracking waste into surface water have profoundly altered the chemistry and ecology of streams throughout entire watersheds, increasing downstream levels of radioactive elements, heavy metals, endocrine disruptors, toxic disinfection byproducts, and acidity, and decreasing aquatic biodiversity and populations of zooplankton and sensitive fish species, such as brook trout. Recent studies documenting changes in the bacterial flora in groundwater following drilling and fracking operations represent an emerging area of concern. Offshore fracking operations in the Gulf of Mexico dump fracking waste directly into ocean waters in amounts sufficient to poison fish and other marine life living nearby.

Demand for water to use in U.S. fracking operations continues to rise and has more than doubled since 2016. Unlike water used for agriculture or other industrial uses, the water used for fracking that remains in the shale bedrock is permanently lost to the hydrologic cycle. A suite of new studies now show that fracking can deplete streams and aquifers in ways that contribute to water stress and water scarcity. A 2018 study found that water use for fracking operations increased by 770 percent per well between 2011 and 2016 across all U.S. shale basins. At the same time, the volume of fracking wastewater generated during the first year of extraction increased by up to 1440 percent.

There is no known solution for the problem of fracking wastewater. It cannot be filtered to create clean, drinkable water, nor is there any safe method of disposal. Recycling is an expensive, limited option that increases radionuclide levels of subsequent wastewater. Underground rock formations that receive fracking wastewater via injection into disposal wells, a practice that is linked to earthquakes, are reaching capacity in many regions of the United States.

- July 12, 2021 – Using records obtained under the Freedom of Information Act and the FracFocus database of fracking chemical use, an investigation by Physicians for Social Responsibility (PSR) found that more than 1,200 oil and gas wells in six states were fracked using highly toxic per- and polyfluoralkyl substances (PFAS) between 2012 and 2020. These states are Arkansas, Louisiana, Oklahoma, New Mexico, Texas, and Wyoming. Nicknamed "forever chemicals" because of their inability to break down in the environment or in the bodies of living organisms, PFAS chemicals are linked to cancer, birth defects, high blood pressure during pregnancy, and other health harms. Drinking water is a major route of exposure to PFAS, which were widely used for decades in stain-resistant furniture and carpeting, non-stick cookware, and firefighting foam. In recent years, a growing number of states have set limits on PFAS contaminants in drinking water as evidence showed groundwater contamination from a variety of sources. The PSR investigation revealed that the U.S. Environmental Protection Agency (EPA) scientists reviewed a proposal to use PFAS chemicals as an ingredient in fracking fluid and expressed concerns about human exposures. Despite these concerns, the agency approved the use of these chemicals for fracking in 2011.[514] Researcher and author of the report, Dusty Horwitt, J.D., said in an interview with the *New York Times*, "The EPA identified serious health risks associated with chemicals proposed for use in oil and gas

[514] Dusty Horwitt, "Fracking with 'Forever Chemicals'" (Physicians for Social Responsibility, July 12, 2021), https://www.psr.org/wp-content/uploads/2021/07/fracking-with-forever-chemicals.pdf.

extraction, and yet allowed these chemicals to be used commercially with very lax regulations."[515]

- July 7, 2021 – An investigation by the Center for Biological Diversity found that fracking is widespread in offshore oil and gas extraction operations, 98 percent of which take place in federal waters in the Gulf of Mexico. Fracking companies are permitted to discharge unlimited volumes of fracking waste into the waters of the Gulf. Using data provided to the EPA by the oil industry, researchers determined that an estimated 66.3 million gallons of liquid fracking waste were dumped into the Gulf of Mexico from 2010 through 2020. Toxicity data shows that these discharges can poison fish and other marine life and are likely to do so near offshore wells.[516] [See also entry for October 14, 2020.]

- July 1, 2021 – A U.S. Geological Survey (USGS) study of fracking wastewater in North Dakota aimed to determine whether the geochemical and isotopic fingerprint of fracking wastewater can be used to pinpoint its specific source, should it contaminate drinking water or surface water. The researchers found that the chemical composition of wastewater varies locally across the shale basin. Further, the assumption that wastewater from newly fracked wells would have a different fingerprint than that of wastewater emanating from older wells was not consistently validated by the data. On the other hand, the presence of glycol ethers—which are used as an ingredient in fracking fluid—can help to distinguish fracking wastewater from naturally occurring brine. Also, assessing a specific measure of radioactivity in the form of radium activity ratios would be potentially useful for distinguishing whether the source of the contamination arose from the Bakken or the Three Forks shale formations.[517]

- June 18, 2021 – Investigating the toxicity of fracking wastewater, a laboratory study exposed larval zebrafish to varying concentrations of sediment mixtures filtered from flowback and produced water from fracking operations. The results showed that, even when removed from the fluid itself, these dissolved solids were toxic to the developing fish. Exposed larva showed alterations in genetic activity, hormone receptor signaling, and antioxidant response. Because toxic sediments settle at the bottom of natural wetlands and can act as a continuous source of contamination, these findings suggest that spills of fracking waste into aquatic ecosystems can create long-term risks for aquatic life.[518] [See also the entry for January 27, 2018.]

- June 1, 2021 – The Oxnard oil field in Ventura County, California—located north of Los Angeles along the state's southern coast—is a large reservoir of oil and tar sands that has

[515] Hiroko Tabuchi, "E.P.A. Approved Toxic Chemicals for Fracking a Decade Ago, New Files Show," *The New York Times*, July 12, 2021, https://www.nytimes.com/2021/07/12/climate/epa-pfas-fracking-forever-chemicals.html.
[516] Center for Biological Diversity, "Toxic Waters: How Offshore Fracking Pollutes the Gulf of Mexico," July 2021, https://www.biologicaldiversity.org/campaigns/fracking/pdfs/Toxic-Waters-offshore-fracking-report-Center-for-Biological-Diversity.pdf.
[517] Gallegos et al., "Insights on Geochemical, Isotopic, and Volumetric Compositions of Produced Water from Hydraulically Fractured Williston Basin Oil Wells."
[518] Yichun Lu et al., "Suspended Solids-Associated Toxicity of Hydraulic Fracturing Flowback and Produced Water on Early Life Stages of Zebrafish (Danio Rerio)," *Environmental Pollution* 287 (2021), https://doi.org/10.1016/j.envpol.2021.117614.

been intensely drilled for many decades and is now approaching depletion but remains actively in production. It is also situated within a predominantly agricultural region where crops such as strawberries, onions, and broccoli are grown. The groundwater underlying both the oil fields and the agricultural fields is heavily used and shows signs of contamination by agricultural drainage and seawater intrusion, as well as by upward movement of deeper water into shallower aquifers. A study designed to determine whether water and gases from oil-bearing geological strata had found its way into the groundwater found no evidence of water from oil-bearing strata mixing with overlying groundwater. However, methane and other hydrocarbon gases (ethane, propane, butane, pentane) were detected in five of 14 groundwater samples, and their isotopic fingerprint showed they were not from microbial sources. Further, water samples with the highest concentrations of these gases were near oil wells. Results of this study are consistent with findings of previous studies that revealed the presence of petroleum-related gases in the vicinity of injection wells. The authors conclude that deep formation water is likely to have moved upward due to large groundwater withdrawals in this area.[519]

- April 30, 2021 – A study of deep groundwater aquifers in the Permian Basin of southeastern New Mexico found that the shift from conventional drilling to fracking during the recent shale boom has led to dramatic increases in total dissolved solids, sodium, and calcium levels in groundwater. Also, the density of oil wells correlated with the levels of these substances in the water samples collected.[520]

- April 8, 2021 – Shale formations containing natural gas will, when drilled and fractured, generate large volumes of wastewater that must be disposed of. Some fraction of this wastewater represents fluids and additives used for fracking, and some represents briny water liberated, along with the gas, from the shale formation itself. Using two different screening assays, a laboratory study assessed the toxicity of fracking wastewater over time from four wells in the Utica and Marcellus shale regions. The results showed that early-stage flowback fluid was the most toxic and gradually become less toxic as the wells matured. Nevertheless, the acute toxicity specific to certain chemical additives in fracking fluid was still detectable in wastewater up to nine months after hydraulic fracturing. These results support the idea that specific chemical additives, the reactions generated by the additives, or the constituents liberated from the formation by the additives can contribute to the toxicity of hydraulic fracturing wastewater long after the fracking process is finished. The results also affirm the higher toxicity of fracking wastewater from newly fractured wells.[521]

- April 4, 2021 – A methodological study that investigated the effect of fracking on surrounding watersheds developed a protocol to assess the composition of microbial

[519] Celia Z. Rosecrans et al., "Groundwater Quality of Aquifers Overlying the Oxnard Oil Field, Ventura County, California," *Science of the Total Environment* 771 (2021), https://doi.org/10.1016/j.scitotenv.2020.144822.
[520] Haoying Wang, "Shale Oil Production and Groundwater: What Can We Learn from Produced Water Data?," *PLoS One* 16, no. 4 (2021), https://doi.org/10.1371/journal.pone.0250791.
[521] Mina Aghababaei et al., "Toxicity of Hydraulic Fracturing Wastewater from Black Shale Natural-Gas Wells Influenced by Well Maturity and Chemical Additives," *Environmental Science: Processes & Impacts* 23 (2021): 621–32, https://doi.org/10.1039/D1EM00023C.

communities in streams as a predictive biomarker for ecological harm from fracking. The researchers suggest gene sequencing of ribosomal RNA as an affordable method for determining bacterial community composition and detail collection methods that allow for an examination of changes in microbial molecular signatures, including genetic expression.[522]

- March 18, 2021 – A study of groundwater geochemistry within Texas' Fort Worth Basin did not find evidence that shallow groundwater was being influenced by the deeper and highly salty water from the intensely fractured Barnett Shale. However, the research team did find geochemical evidence for contamination with methane and other gases that suggest migration from deeper sources to the shallow drinking water aquifers. The researchers reported drinking water wells that were affected by fugitive gas contamination and documented an expansion of impacted drinking water wells over time. The presence of fugitive gases resulted in identifiable geochemical changes in the water, including sulfate reduction paired with microbial oxidation of the fugitive gas. "Together, these data suggest that fugitive gas leads to enhanced microbial activity and decreases in water quality in addition to the explosion hazards associated with a plume of fugitive natural gas in drinking-water wells."[523]

- February 4, 2021 – The city of Akron, Ohio pulled legislation before the city council to lease city-owned land just upstream from the public drinking water reservoir to a private company for drilling and fracking. The company was registered to a local attorney and former city councilmember. Widespread public opposition focused on the need to protect drinking water.[524] The public outcry followed initial approval of the deal on January 12.[525]

- January 15, 2021 – Previous studies have revealed the presence of highly toxic, highly persistent halogenated organic compounds in fracking wastewater, including trihalomethanes, which are known bladder carcinogens. A threat to drinking water, these contaminants are a result of a chemical transformation that takes place when chemical additives in fracking fluids, especially corrosion-inhibitors and substances needed to break apart gels, react with chemicals in the shale itself. A study investigated how halogen radicals so created during these reactions alter the composition of organic chemicals in fracking fluid. The results showed that halogen radicals, such as bromine and chlorine, contribute to the halogenation of additives in fracking fluid. These results

[522] Jeremy R. Chen See et al., "Evaluating the Impact of Hydraulic Fracturing on Streams Using Microbial Molecular Signatures," *Journal of Visualized Experiments* 170 (2021), https://doi.org/10.3791/61904.
[523] Colin J. Whyte et al., "Geochemical Evidence for Fugitive Gas Contamination and Associated Water Quality Changes in Drinking-Water Wells from Parker County, Texas," *Science of the Total Environment* 780 (2021), https://doi.org/10.1016/j.scitotenv.2021.146555.
[524] Robin Goist, "Akron Pulls Fracking Proposal Following Public Outcry Over Drilling at LaDue Reservoir in Geauga County," Cleveland.com, February 2, 2021, https://www.cleveland.com/akron/2021/02/akron-pulls-fracking-proposal-following-public-outcry-over-drilling-at-ladue-reservoir-in-geauga-county.html.
[525] Doug Livingston, "Akron Wants to Sell Mineral Rights for the Fracking of 475 Acres of Water Shed Land," *Akron Beacon Journal*, January 12, 2021, https://www.beaconjournal.com/story/news/2021/01/12/akron-deal-sells-mineral-rights-drill-and-frack-near-la-due-reservoir/6625435002/.

provide the first experimental evidence that halogen radicals are the key intermediates in the halogenation of the chemical additives in hydraulic fracturing fluids.[526, 527]

- December 1, 2020 – The Beetaloo Basin in Australia's Northern Territory is targeted for fracking. As part of a pre-drilling environmental assessment of the region and in collaboration with the gas industry, researchers carried out a pilot survey of groundwater wells in the basin and, in the process, discovered 11 new species of shrimp-like and snail-like organisms living in the subterranean aquifers. These stygofauna feed on fungus and microbes in the aquifer and help maintain a complex food web.[528] The researchers who made these discoveries called for the protection of these aquatic habitats. "Groundwater is vital to inland Australia. Underground ecosystems must be protected – and not considered 'out of sight, out of mind.' Our study provides the direction to reduce risks to stygofauna, ensuring their ecosystems and groundwater quality is maintained."[529]

- October 14, 2020 – In January 2015, a pipeline carrying fracking wastewater leaked and spilled into Blacktail Creek near Williston, North Dakota. A study to investigate the longer-term movement of this plume of contaminants was conducted 2.5 years later and found oil and gas wastewater markers consistent with spilled pipeline fluid in bank sediments, streambed sediments, and in groundwater seeps. These discoveries imply the existence of potential long-term reservoirs for future contamination, including with radioactivity. Further, the researchers found that the downstream movement of these sediments had also contaminated the alluvial floodplain. They also identified 41 other watersheds across the North Dakota landscape that may be subject to similar episodic inputs from fracking wastewater spills.[530]

- October 14, 2020 – Drilling and fracking operations take place offshore in the Gulf of Mexico where fracking wastewater is also dumped. The mahi-mahi (*Coryphaena hippurus*) is a fast-swimming, predatory fish species that inhabits marine ecosystems where such fracking occurs. An international team of researchers used mahi-mahi fish to study the cardio-respiratory effects of exposure to fracking wastewater. In aquaria studies, they found that exposed organisms displayed reduced swimming speed (40 percent slower) and decreased metabolic rates (61 percent slower). Laboratory studies of individual fish heart muscle cells exposed to diluted concentrations of fracking fluid

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[526] Moshan Chen et al., "Halogen Radicals Contribute to the Halogenation and Degradation of Chemical Additives Used in Hydraulic Fracturing," *Environmental Science & Technology* 55, no. 3 (2021): 1545–54, https://doi.org/10.1021/acs.est.0c03685.
[527] Moshan Chen et al., "Correction to 'Halogen Radicals Contribute to the Halogenation and Degradation of Chemical Additives Used in Hydraulic Fracturing,'" *Environmental Science & Technology* 55 (2021): 9395–9395, https://doi.org/10.1021/acs.est.1c03216.
[528] Gavin Rees et al., "Characterisation of the Stygofauna and Microbial Assemblages of the Beetaloo Sub-Basin, Northern Territory" (Australia: Commonwealth Scientific and Industrial Research Organisation, 2020), https://gisera.csiro.au/wp-content/uploads/2021/03/GISERA-Project18-Stygofauna_final-report-20201208.pdf.
[529] Jenny Davis et al., "Blind Shrimps, Translucent Snails: The 11 Mysterious New Species We Found in Potential Fracking Sites," *The Conversation*, February 15, 2021, https://theconversation.com/blind-shrimps-translucent-snails-the-11-mysterious-new-species-we-found-in-potential-fracking-sites-155137.
[530] Isabelle M. Cozzarelli et al., "Geochemical and Geophysical Indicators of Oil and Gas Wastewater Can Trace Potential Exposure Pathways Following Releases to Surface Waters," *Science of the Total Environment* 755 (2021), https://doi.org/10.1016/j.scitotenv.2020.142909.

showed diminished contractile properties. Tissue samples showed an eight-fold change in expression of a gene that regulates contraction of heart muscle was also observed in exposed fish. The team hypothesized that strontium or barium in the wastewater may be the mechanism of action. These results collectively identify cardiac function as a target for fracking wastewater toxicity and provide some of the first published data on the toxicity of fracking for marine fish.[531] These findings tell a cohesive story, according to a companion commentary in *Conservation Physiology*: "Exposure to flowback water caused cardiac abnormalities that resulted in slower-swimming mahi-mahi with less energy available for essential activities."[532]

- September 8, 2020 – A study of the endocrine-disrupting potential of fracking fluid and fracking wastewater examined surface water and groundwater samples across Garfield County, Colorado where fracking operations are densely sited. Using collected surface water and nuclear receptor reporter gene assays, the researcher team observed elevated antagonist activities for estrogen, androgen, progesterone, and glucocorticoid receptors that were associated with nearby shale gas well counts and density. These bioactivities, in some cases were well above the levels known to impact the health of aquatic organisms. They were not, however, associated with reported nearby spills. A geochemical analysis showed that some of these samples exhibited a distinct geochemical pattern that mimicked fracking wastewater from the region. However, the absence of geochemical evidence for fracking wastewater contamination in other sites suggests potential spills of fracking chemicals associated with the freshwater injection fluids, work-over chemicals, or other chemicals used throughout the development and production activities. These findings support earlier research by the same team that documented increased endocrine activities in surface and groundwater collected near fracking sites in Colorado, downstream from an injection site in West Virginia, and downstream from a fracking wastewater spill in North Dakota.[533]

- March 12, 2020 – An international research team investigated the impact of hydraulic fracturing on groundwater in three counties in the intensely drilled Permian Basin in West Texas. The team documented a relationship between intensity of oil and gas activities and levels of groundwater contamination and, in particular, a link between fracking activity and levels of arsenic. The authors noted that "fractures generated by hydraulic fracturing can transport arsenic-rich sediments to upper groundwater aquifers."[534]

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[531] Erik J. Folkerts et al., "Exposure to Hydraulic Fracturing Flowback Water Impairs Mahi- Mahi (Coryphaena Hippurus) Cardiomyocyte Contractile Function and Swimming Performance," *Environmental Science & Technology* 54 (2020), https://doi.org/10.1021/acs.est.0c02719.
[532] Lela S. Schlenker, "A Big Fracking Problem Slows Down a Fast-Swimming Fish," *Conservation Physiology* 9 (2021), https://doi.org/10.1093/conphys/coab004.
[533] Christopher D. Kassotis et al., "Endocrine Disrupting Activities and Geochemistry of Water Resources Associated with Unconventional Oil and Gas Activity," *Science of the Total Environment* 748 (2020), https://doi.org/10.1016/j.scitotenv.2020.142236.
[534] J. Rodriguez, J. Heo, and K. Kim, "The Impact of Hydraulic Fracturing on Groundwater Quality in the Permian Basin, West Texas, USA," *Water* 12, no. 3 (2020), https://doi.org/10.3390/w12030796.

- March 2, 2020 – Starting in July 2019, contaminated briny fluid, at the rate of 3 to 5 gallons per minute and then accelerating up to 15 gallons per minute, began bubbling up to the surface on a farm 30 miles northwest of Oklahoma City near eight disposal wells for fracking wastewater. Eight months later, the problem was still ongoing and the cause remained unsolved. The affected farmland has turned brown and barren. In response, three nearby fracking wells were plugged and nearby waste injection wells ceased operations. However, these efforts did not fix the problem nor is there evidence of leaking pipes. State officials are treating the problem as a "purge" of fracking waste linked to too much pressure in the shallow geological formation where companies are injecting it. The president of the Oklahoma Energy Producers Alliance blamed state regulations, put in place as an earthquake prevention measure, that deter drillers from injecting wastes into deeper bedrock. The fracking industry injects 900 billion gallons of wastewater each year into geological formations. As companies run out of room underground to store liquid waste, political pressure is building to allow them to dump the waste into rivers and streams.[535, 536]

- February 28, 2020 – Using data from the Colorado Oil and Gas Conservation Commission, an investigation by the Center for Western Priorities documented a seven percent rise in the frequency of oil and gas industry spills across Colorado in 2019 as compared to the previous year. Half of these spills took place in Weld County, which leads Colorado in drilling. One of these spills, from a ruptured natural gas pipeline, contaminated a creek with benzene. Another 2019 pipeline accident contaminated a gravel pit near the Colorado River with fracking wastewater.[537] Reported oil and gas industry spills in Colorado peaked in 2014, according to state data.

- February 26, 2020 – A team of chemists at University of Toledo working with counterparts at University of Texas created a method for identifying 201 different chemical compounds in fracking wastewater that can be used to screen for the presence of toxic substances before it is used for agricultural purpose or dumped into waterways. Among the chemicals identified by the team as present in fracking waste were carcinogens and solvents known to contaminate drinking water. These included toluene, polycyclic aromatic hydrocarbons, 1,4-dioxane, and the weed killer atrazine.[538, 539]

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[535] Karl Torp, "Saltwater Purge Turns Farmland Brown & Barren," *CBS News 9*, March 2, 2020, http://www.news9.com/story/5e627c37cd4aa89d1b92f778/saltwater-purge-turns-farmland-brown--barren.
[536] Mike Soraghan, "Toxic, Briny Water Surfaces in Okla. Is Oil to Blame?," *E&E News*, December 3, 2019, https://web.archive.org/web/20191204112839/https://www.eenews.net/stories/1061708829.
[537] Dennis Webb, "Oil, Gas Spills Up Statewide. What's the Next Step for the Industry?," *The Daily Sentinel*, April 3, 2020, https://www.gjsentinel.com/news/western_colorado/oil-gas-spills-up-statewide-and-generally-in-piceance/article_d22e128c-5984-11ea-9be1-5336425aef8f.html?fbclid=IwAR3Ts30CLqf3nZrgZWA8-430Kist6-rgP6Gzy8Y6zMxFyuJVeRMMmq57F2U.
[538] Ronald V. Emmons et al., "Optimization of Thin Film Solid Phase Microextraction and Data Deconvolution Methods for Accurate Characterization of Organic Compounds in Produced Water," *Journal of Separation Science* 43, no. 9–10 (2020): 1915–24, https://doi.org/10.1002/jssc.201901330.
[539] Science Codex, "Academic Chemists Note Presence of Chemicals in Fracking Wastewater, Declare Them Toxic at Any Level," University of Toledo, May 26, 2020, https://sciencecodex.com/utoledo-chemists-identify-toxic-chemicals-fracking-wastewater-647887.

- January 11, 2020 – The 98th meridian, a line of longitude running North to South from eastern North Dakota through the center of Texas, corresponds to a sharp drop-off in rainfall and, ecologically, marks the beginning of the Great Plains. Irrigation is typically required to support agriculture west of the 98th meridian, and livestock grazing is more prevalent. This demarcation also corresponds to an exemption in the National Pollutant Discharge Elimination System: west of the 98th meridian it is permissible to release wastewater from oil and gas extraction activities into rivers and streams for agricultural purposes (irrigation or livestock watering) if it is "of good enough quality." A research team from Colorado State and Pennsylvania State Universities undertook a chemical analysis of a stream in a remote region of Wyoming containing fracking wastewater from multiple wells. They found that most carbon-based contaminants were not detectable beyond 9.3 miles (15 kilometers) of the point of discharge because they had evaporated, biodegraded or became attached to sediments. Some non-carbon-based compounds (strontium, barium, and radium) also gradually decreased in concentration further downstream. Others, however, including sodium, sulfate, and boron, increased further downstream because of water evaporation. These results indicate that "while discharge may be safe, changes downstream could result in water that is unsuitable for beneficial reuse." Multiple organic contaminants, for example, were detected in a shallow downstream lake used by livestock, birds, and wildlife. The health implications of these findings are not clear. First, many of these chemicals have not been assessed for toxicity and lack regulatory limits. Second, mixture effects have not been considered. "Regulatory health thresholds for humans, livestock, and aquatic species for most chemical species present at the discharge are still lacking. As a result, toxicity tests are necessary to determine the potential health impacts to downstream users."[540]

- December 23, 2019 – Using biological assays and liquid chromatography-high resolution mass spectrometry, an interdisciplinary team led by Cornell University researchers analyzed surface and groundwater throughout Susquehanna County, Pennsylvania, specifically focusing on samples collected near Dimock, where fracked gas wells are known to be impaired. The team collected water from private drinking water wells, streams, ponds, springs and a lake. They found that water collected near impaired gas wells showed increased biological activity as measured by alterations of aryl hydrocarbon (Ah) receptor activity in yeast cells, a sign that gene expression has been disrupted. They also found chemicals, including chemical additives known to be present in fracking fluid, associated with samples that were either collected close to impaired wells or that showed either Ah or estrogen receptor activity. In total, the team detected in their water samples 17 potential fracking fluid additives and chemicals associated with fracking wastewater. "Although most of these compounds have other uses in addition to natural gas extraction, the association with biological activity and impaired wells suggests that anthropogenic activities, including hydraulic fracturing operations, have resulted in water contamination."[541]

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[540] Molly C. McLaughlin et al., "Water Quality Assessment Downstream of Oil and Gas Produced Water Discharges Intended for Beneficial Reuse in Arid Regions," *Science of the Total Environment* 713 (2020): 136607, https://doi.org/10.1016/j.scitotenv.2020.136607.
[541] Michelle Bamberger et al., "Surface Water and Groundwater Analysis Using Aryl Hydrocarbon and Endocrine Receptor Biological Assays and Liquid Chromatography-High Resolution Mass Spectrometry in Susquehanna

- November 6, 2019 – Oil and gas extraction operations bring to the surface 900 billion gallons of liquid waste every year. In a comprehensive literature review, researchers identified 1,198 chemicals as detected in oil and gas wastewater, of which 86 percent lack toxicity data sufficient to complete a risk assessment.[542]

- September 15, 2019 – A U.S. Geological Survey team working in Kern County, California investigated the migration of wastewater from oil drilling operations into the Tulare aquifer, using geophysical logs archived in state agencies to determine changes in aquifer salinity over time. The study identified two different routes of contaminant migration. The first is downward migration of fluids from unlined wastewater pits through the soil and into the groundwater aquifers below. The second is outward migration of fluids from underground disposal wells into the surrounding aquifers. Contamination from the waste pits was confined to the shallower alluvial aquifer. A clay layer prevents brine from reaching the Tulare aquifer below. Contamination of groundwater from disposal wells in the Tulare formation was detectable as far away as one-third of a mile (1800 feet) from the disposal well.[543]

- July 26, 2019 – Using state-based records, a Mississippi State University geoscientist modeled fracking spills from 2005-2014 in New Mexico and Colorado. In New Mexico, the average volume of fracking-related spill ranged from 3996-5626 gallons and showed no temporal-spatial clustering. In Colorado, average volume of a spill was 1895-3481 gallons, and spills were clustered. The author noted inconsistencies in recordkeeping for fracking-related spills because federal laws require minimal reporting for certain kinds of spills and because, in general, fracking fluid and flowback waste are exempt from federal regulations altogether. Because each state has its own monitoring and reporting system, comparisons are difficult. The requirement for a submitting a spill report often depends on the volume of the spill exceeding a certain threshold value, and that threshold may vary from state to state.[544]

- June 27, 2019 – A U.S. Geological Survey team working in the Marcellus Shale region analyzed water samples from private drinking water wells located near shale-gas wells (<1 kilometer) and compared them to wells located further away (>1 kilometer). Using multiple tracers, the team also estimated what fraction of the water in the various wells had been there since 1950. This information, which measures the rate of groundwater recharge, can reveal the vulnerability of well water to contamination from land-surface

County, PA," *Environmental Science: Processes & Impacts* 21, no. 6 (2019): 988–98, https://doi.org/10.1039/c9em00112c.

[542] Cloelle Danforth et al., "An Integrative Method for Identification and Prioritization of Constituents of Concern in Produced Water From Onshore Oil and Gas Extraction," *Envonmental International* 134 (2020): 105280, https://doi.org/10.1016/j.envint.2019.105280.

[543] Janice M. Gillespie et al., "Groundwater Salinity and the Effects of Produced Water Disposal in the Lost Hills-Belridge Oil Fields, Kern County, California," *Environmental Geosciences* 26, no. 3 (2019): 73–96, https://doi.org/10.1306/eg.02271918009.

[544] Qingmin Meng, "Characterizing and Modeling Environmental Emergency of Unconventional Oil and Gas Spills in the USA: Life-Year versus Spill Factors," *Journal of Cleaner Production* 237 (2019): 117794, https://doi.org/10.1016/j.jclepro.2019.117794.

sources. The results showed the presence of thermogenic methane in one nearby well that appeared to have been mobilized by shale gas drilling. Another nearby well contained five volatile hydrocarbons, including benzene, that are known to be associated with drilling and fracking activities. However, the age of the groundwater predated shale gas development in that area, suggesting that surface spills from drilling and fracking operations were not the source of the contamination. Subsurface leakage from the nearby gas well, however, remains a possibility. "Although vulnerability to land-surface sources of contamination in the Marcellus region is relatively high, the groundwater-age distributions indicate that most of the water in samples from the proximal wells could largely predate [fracking] activity. This suggests that more time is needed to fully assess the effect of past [fracking-related] spills at the land surface on groundwater quality."[545]

- June 24, 2019 – Produced water is the name for wastewater that comes up to the surface from deep geological formations when oil or gas is extracted. Typically salty, produced water includes groundwater naturally found deep in the earth as well as hydrocarbons, radioactive materials, fracking fluids, and other chemicals that were used in the process of extraction. Most produced water is injected into geological layers of porous rock as a form of waste disposal. Some is mixed with fluids used for fracking additional wells. The Groundwater Protection Council, a consortium of state ground water regulatory agencies, released a report on the possibilities of using produced water for beneficial purposes rather than treating it as waste. Driving this discussion is the growing scarcity of fresh water supplies in many drought-prone regions of the United States; the intractable problem of earthquakes when produced water is injected as liquid waste into deep geological formations; and declining storage capacity in shallower formations that are receiving ever-growing quantities of produced water. The Groundwater Protection Council concluded that new regulatory frameworks would need to oversee the recategorization of produced water from waste product to resource for use outside of the oil and gas industry. These frameworks would need to include concerns about ownership and legal liability. "As water becomes scarcer, the increasing benefits of reusing produced water in some regions may outweigh the costs of managing, treating, storing, and transporting it if health and environmental risks can be understood and appropriately managed." One million oil and gas wells in the United States generate about 21.2 billion barrels of produced water each year.[546, 547, 548]

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[545] Peter B. McMahon et al., "Hydrocarbons in Upland Groundwater, Marcellus Shale Region, Northeastern Pennsylvania and Southern New York, U.S.A.," *Environmental Science & Technology* 53, no. 14 (n.d.): 8027–35, https://doi.org/10.1021/acs.est.9b01440.
[546] Ground Water Protection Council, "Produced Water Report: Regulations, Current Practices, and Research Needs" (Ground Water Protection Council, June 2019), https://www.gwpc.org/sites/gwpc/uploads/documents/Research/Produced_Water_Full_Report___Digital_Use.pdf.
[547] Ground Water Protection Council, "Produced Water May Provide Relief for Declining Water Supplies in Areas of the US," Cound Water Protection Council, June 24, 2019, https://www.gwpc.org/news/m.blog/540/produced-water-may-provide-relief-for-declining-water-supplies-in-areas-of-the-us.
[548] Robert Nott, "What to Do With Oil Boom's Wastewater?," *Santa Fe New Mexican*, July 13, 2019, https://www.santafenewmexican.com/news/local_news/what-to-do-with-oil-boom-s-wastewater/article_ebea88d6-ba9d-5e3d-a3eb-0734377fa161.html.

- June 10, 2019 – A research team from University of Arizona and University of Saskatchewan investigated damage to groundwater from techniques of conventional oil and gas extraction as practiced in both the United States and Canada. These techniques, used since the 19th century, involve injecting water underground to flush out oil and gas--albeit not under pressures high enough to fracture the surrounding rock. The leftover wastewater is eventually disposed of by injecting it into depleted oil fields. The research team found that ten times more water was used in conventional oil and gas extraction than in hydraulic fracturing. While the injection of fluids associated with fracking are of higher pressure, conventional injections are of longer duration and "could allow for greater solute transport distances and potential for contamination." The reinjection of this wastewater has changed underground pressures and the movement of water in ways that can contaminate aquifers. Additionally, conventional wells, when abandoned, can leak and provide further pathways for contamination.[549, 550]

- April 6, 2019 – In a first study of its kind, an international team evaluated the carcinogenicity of chemicals known to be present in both fracking fluids and fracking wastewater. Among 1,173 such chemicals, 1,039 were found only in fracking fluid, 97 only in wastewater, and 37 in both. However, 84.3 percent of the chemicals known to be present in fracking fluid and/or fracking waste have never been assessed for their ability to cause cancer. The researchers found information for only 104 chemicals, of which 48 to 66 are recognized as potential human carcinogens. "Our evaluation suggests that exposure to some chemicals in hydraulic-fracturing fluids and wastewater may increase cancer risk…. Because the amount of each chemical and potential interaction between chemicals in proprietary fracking fluids are unknown, the exact level of cancer-causing potential for exposure to carcinogen-contained fracking fluids is not clear. However, the likelihood of many if not most of the chemical being carcinogenic in large doses or even small doses in fracking fluids is probably high."[551]

- March 28, 2019 – Chemical surfactants are added to fracking fluid to emulsify, reduce surface tension, and inhibit corrosion. An engineering team looked at the chemical fate of these additives when they come back to the surface as shale gas wastewater. They found that high dissolved solids (salts) in the wastewater inhibit microbes that assist in biodegradation. "The presence of higher total dissolved solids appeared to exert an appreciable, long-standing effect on microbial community composition within one week of exposure to increased salinity, suggesting that an accidental release of recycled produced water may upset naturally occurring microbial communities." These results imply that accidental spills of shale gas wastewater—or deliberate releases (as when fracking wastewater is used for de-icing roads or irrigation)—are likely to result in the environmental persistence of these surfactant chemicals. These findings have implications for treating and recycling fracking wastewater. Its high salt levels mean that

[549] Jennifer C. McIntosh and Grant Ferguson, "Conventional Oil—The Forgotten Part of the Water-Energy Nexus," *Groundwater* 57, no. 5 (2019): 669–77, https://doi.org/10.1111/gwat.12917.
[550] University of Arizona, "Fracking Has Less Impact on Groundwater than Traditional Oil and Gas Production," Phys.org, August 16, 2019, https://phys.org/news/2019-08-fracking-impact-groundwater-traditional-oil.html.
[551] Xiaohui Xu et al., "A Systematic Assessment of Carcinogenicity of Chemicals in Hydraulic-Fracturing Fluids and Flowback Water," *Environmental Pollution* 251 (2019): 128–36, https://doi.org/10.1016/j.envpol.2019.04.016.

it must be filtered through special desalinating membranes, but the persistent presence of surfactant chemicals can clog and damage these membranes.[552]

- March 14, 2019 – Rainbow trout exposed to levels of fracking wastewater that mimic those that would result from a low-level spill, as from a pipeline leak into a small river, did not show significant signs of salinity stress. However, their blood plasma did accumulate strontium and bromide. This study did not examine possible endocrine disrupting effects.[553]

- March 5, 2019 – Water fleas (*Daphnia spp.)* are freshwater zooplankton that feed on phytoplankton and play a crucial role in aquatic food webs. In a Canadian study, water fleas exposed to various concentrations of fracking wastewater displayed altered behaviors that impaired their ability to orient toward light, a response that allows them to avoid predation and find food. This study helps explain the results of earlier research that links fracking fluid exposure to decreased water flea survival. Water fleas are unable to detect and avoid fracking fluid spills.[554] (See also entry for April 28, 2018.)

- February 28, 2019 – An American University team compared water quality parameters in 19 small streams in an intensely fracked area of southwestern Pennsylvania with those of 10 equivalent streams in western Maryland where fracking is banned and has never taken place. Streams in both study areas overlie the Marcellus Shale. Even after accounting for variations in forest cover, urban development, and historical impacts from coal mining, the researchers found significant differences in concentrations of certain salts and heavy metals, including arsenic. The results "imply that water quality has been affected by [shale gas] development in the Marcellus Shale region" and "support the idea that the Pennsylvania streams have received greater pollution inputs than have the Maryland streams."[555]

- February 11, 2019 – The U.S. Justice Department reached a settlement with Antero Resources Corporation over claims that it violated the Clean Water Act at 32 different drilling and fracking-related sites in West Virginia. The violations involved unauthorized dumping of fracking waste into local waterways.[556]

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[552] Andrea J. Hanson et al., "High Total Dissolved Solids in Shale Gas Wastewater Inhibit Biodegradation of Alkyl and Nonylphenol Ethoxylate Surfactants," *Science of the Total Environment* 668 (2019): 1094–1103, https://doi.org/10.1016/j.scitotenv.2019.03.041.
[553] P. L. M. Delompré et al., "The Osmotic Effect of Hyper-Saline Hydraulic Fracturing Fluid on Rainbow Trout, Oncorhynchus Mykiss," *Aquatic Toxicology* 211 (2019): 1–10, https://doi.org/10.1016/j.aquatox.2019.03.009.
[554] P. L. M. Delompré et al., "Shedding Light on the Effects of Hydraulic Fracturing Flowback and Produced Water on Phototactic Behavior in Daphnia Magna," *Ecotoxicology and Environmental Safety* 174 (2019): 315–23, https://doi.org/10.1016./j.ecoenv.2019.03.006.
[555] Karen L. Knee and Alexandra E. Masker, "Association Between Unconventional Oil and Gas (UOG) Development and Water Quality in Small Streams Overlying the Marcellus Shale," *Freshwater Science* 38, no. 1 (2019), https://doi.org/10.1086/701675.
[556] Reuters Staff, "U.S. Settles With Antero Over Water Pollution From Fracking," *Reuters*, February 11, 2019, https://www.reuters.com/article/us-usa-antero/us-settles-with-antero-over-water-pollution-from-fracking-idUSKCN1Q021K.

- February 7, 2019 – The Karoo Basin in South Africa is a semi-arid region underlain by gas-containing shale. Its bedrock is also rich in uranium, and, consequently, the basin has a range of different naturally occurring radioactive materials, including radium and radon gas. As part of a baseline study prior to fracking, a South African team monitored the presence of radon in groundwater in 53 aquifers throughout the Karoo Basin. They found that water in seven sites had levels of radon above levels considered safe by the World Health Organization. They also observed lower levels in cool, deep aquifers and higher levels of radon in warm, shallow aquifers, where seasonal and annual fluctuations were common.[557]

- January 22, 2019 – Demand for water to use in fracking operations for oil extraction has more than doubled since 2016, according to data from Rystad Energy, an energy research intelligence company. In the Permian Basin alone, located in west Texas and southeastern New Mexico, water demand for fracking now exceeds the total U.S. demand in 2016.[558]

- January 7, 2019 – From samples of fracking wastewater in Alberta, a Canadian team isolated a previously unidentified class of contaminants, aryl phosphates, which degrade into diphenyl phosphate. Experiments showed that diphenyl phosphate does not bind to clay-rich soils. Therefore, its transportation into groundwater following fracking waste spills would be swift. Further research showed toxic effects of low-level exposure of diphenyl phosphate on fish embryos and embryonic chick tissue. Noting that hundreds of fracking waste spills are reported in Alberta each year, the researchers expressed concern that diphenyl phosphate "may pose an environmental risk to aquatic ecosystems if released into the environment."[559]

- November 28, 2018 – Drilling and fracking operations in the Marcellus Shale region are known to harm biodiversity and reduce the populations of aquatic invertebrate animals that are the basis of the food chain in streams. A research team working in West Virginia investigated whether an observed population decline in a species of bird, the Louisiana waterthrush, might be related to loss of these aquatic invertebrates, which are its prey. While the results varied from year to year and loss of food resources did not wholly explain the declines in waterthrush populations in areas of active drilling and fracking, "collective evidence suggests there may be a shale gas disturbance threshold at which waterthrush respond negatively to aquatic prey community changes."[560]

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[557] R. Botha et al., "Radon in Groundwater Baseline Study Prior to Unconventional Shale Gas Development and Hydraulic Fracturing in the Karoo Basin (South Africa)," *Applied Radiation and Isotopes* 147 (2019): 7–13, https://doi.org/10.1016/j.apradiso.2019.02.006.
[558] Rystad Energy, "Frac Water Demand Is Sky-Rocketing," press release (Rystad Energy, January 22, 2019), https://www.rystadenergy.com/newsevents/news/press-releases/Frac-water-demand-is-sky-rocketing/.
[559] Sean P. Funk et al., "Assessment of Impacts of Diphenyl Phosphate on Groundwater and Near-Surface Environments: Sorption and Toxicity," *Journal of Contaminant Hydrology* 221 (2019): 50–57, https://doi.org/10.1016/j.jconhyd.2019.01.002.
[560] Mack W. Frantz, Petra B. Wood, and George T. Merovich Jr., "Demographic Characteristics of an Avian Predator, Louisiana Waterthrush (Parkesia Motacilla), in Response to Its Aquatic Prey in a Central Appalachian USA Watershed Impacted by Shale Gas Development," *PLoS One* 13, no. 11 (2018): e0206077, https://doi.org/10.1371/journal.pone.0206077.

- November 19, 2018 – Methane can find its way into groundwater through naturally occurring fractures and fissures in shale deposits or through openings created by nearby drilling and fracking operations. A team led by Pennsylvania State University geochemist Susan Brantley sampled methane in drinking water wells in Pennsylvania with and without fracking, focusing on an area where fracking wells had been cited for contaminating nearby drinking water wells—in some cases with levels of methane high enough to be at risk for explosion. Researchers found that elevated methane levels in water wells near these fracking operations were accompanied by attendant spikes in iron and sulfates. These findings "document a way to distinguish newly migrated methane from pre-existing sources of gas." They also showed that methane and ethane concentrations in local water wells increased after gas drilling compared with predrilling concentrations and that these levels remained elevated seven years after leaks were initially reported.[561, 562] "We've documented that recent methane migration can change water chemistry in a way that can mobilize metals, such as iron, and release other unwanted chemical compounds, such as hydrogen sulfide," said Joshua Woda, a co-author of the study, in a press statement.[563]

- November 6, 2018 – As reported by the news outlet, *WyoFile*, contaminated drinking water in Pavillion, Wyoming was likely caused by gas leaking from faulty gas wells as well as by leaks from 40 unlined pits that, for many years, served as dumps for drilling wastewater. This was the conclusion of three researchers, including two former U.S. Environmental Protection Agency (EPA) scientists, who had been investigating the pollution of Pavillion's groundwater, including drinking water wells for at least 30 homes. The scientists presented their findings to the community in advance of publishing a peer-reviewed scientific journal article. Statistical analyses show a correlation between what was disposed in the pits and contaminants appearing in nearby drinking water wells. One of the former EPA scientists told community members that the Wind River Formation drinking water aquifer will likely never be cleaned up. A preliminary report from the EPA in 2011 about groundwater contamination in Pavillion was never finalized.[564]

- October 21, 2018 – Fracking brine, among other factors, is contributing to "freshwater salinization syndrome," according to a study that examined the increasing saltiness of North American inland waters. Freshwater salinization, in turn, alters the behavior of

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[561] Josh Woda et al., "Detecting and Explaining Why Aquifers Occasionally Become Degraded Near Hydraulically Fractured Shale Gas Wells," *Proceedings of the National Academy of Sciences* 115, no. 49 (2018): 12349–58, https://doi.org/10.1073/pnas.1809013115.
[562] Katherine Bourzac, "Chemical Clues Found for Methane Leaks Caused by Fracking," *Chemical & Engineering News*, November 21, 2018, https://cen.acs.org/environment/water/Chemical-clues-found-methane-leaks/96/i47.
[563] Matthew Carroll, "Ground and Stream Water Clues Reveal Shale Drilling Impacts," press release (Penn State News, November 19, 2018), https://news.psu.edu/story/548378/2018/11/19/research/ground-and-stream-water-clues-reveal-shale-drilling-impacts.
[564] Angus M. Thuermer Jr., "Pavillion Water Experts Fault Leaky Gas Wells, Unlined Pits," *WyoFile*, November 6, 2018, https://www.wyofile.com/pavillion-water-experts-fault-leaky-gas-wells-unlined-pits/.

other chemicals in water, mobilizing diverse chemical mixtures that alter drinking water quality.[565]

- October 17, 2018 – An international team of researchers tested fracking wastewater from two different wells in the Fox River area of Alberta, Canada for presence of endocrine-disrupting compounds. Using laboratory assays, they found that organic extracts of the wastewater samples did indeed disrupt hormone signaling pathways in environmentally relevant concentrations, as might occur in an accidental spill, however the wastewater from the two different wells did so in two different ways. "The results suggest that the properties and origins of endocrine-disrupting compounds in [fracking wastewater] from Wells A and B are different, complicating our understanding of potential environmental effects of releases."[566]

- September 4, 2018 – Chemicals from fracking wastewater dumped into the Allegheny River Watershed a decade ago are still accumulating in mussels that live there. Researchers working in Pennsylvania found elevated levels of strontium in the shells of freshwater mussels living downstream of a disposal facility that treated fracking wastewater and released it into streams between 2008 and 2011. (The practice was halted thereafter when heavy metals and radioactivity began rising in drinking water). Mussels living upstream of the treatment plant showed no such elevated levels. Strontium is an elemental metal and a contaminant of fracking waste. It is absorbed by living organisms in a similar manner to calcium. Because mussels excrete their shells in discreet layers that can be aged (like tree rings), researchers were able to show that shell layers created after 2011, when dumping of fracking waste into streams had ceased, did not show a sharp reduction in strontium, suggesting that downstream sediments may act as a reservoir for persistent contaminants years after dumping stops.[567] This is one of the first studies to show bioaccumulation of fracking contaminants in the bodies of living animals, which means that fracking contaminants are entering the food chain. The most endangered of all North American fauna, freshwater mussels are currently suffering a mass extinction event, as a likely result of degraded water quality.[568] Commenting on these findings in a press statement, lead author Nathaniel Warner said, "We know that Marcellus development has impacted sediments downstream for tens of kilometers. And it appears

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[565] Sujay S. Kaushal et al., "Novel 'Chemical Cocktails' in Inland Waters Are a Consequence of the Freshwater Salinization Syndrome," *Philosophical Transactions of the Royal Society B* 374, no. 1764 (2018): 20188017, https://doi.org/10.1098/rstb.2018.0017.
[566] Yuhe He et al., "In Vitro Assessment of Endocrine Disrupting Potential of Organic Fractions Extracted From Hydraulic Fracturing Flowback and Produced Water (HF-FPW)," *Environment International* 121 (2018): 824–31, https://doi.org/10.1016/j.envint.2018.10.014.
[567] Thomas J. Geeza et al., "Accumulation of Marcellus Formation Oil and Gas Wastewater Metals in Freshwater Mussel Shells," *Environmental Science & Technology* 52, no. 18 (2018): 10883–92, https://doi.org/10.1021/acs.est.8b02727.
[568] Kristina Marusic, "Fracking Chemicals Dumped in the Allegheny River a Decade Ago Are Still Showing up in Mussels: Study," *Environmental Health News*, September 5, 2018, https://www.ehn.org/chemicals-from-fracking-in-pennsylvania-polluting-freshwater-mussels-2602333500.html.

it still could be impacted for a long period of time. The short timeframe that we permitted the discharge of these wastes might leave a long legacy."[569]

- August 29, 2018 – Using reports created by the oil and gas industry, a Colorado State University team evaluated fracking waste spills in Weld County, Colorado and found that while large-scale operations generated less fracking wastewater per unit of energy generated, the total volume of spilled waste increased as the size of the operation increased. "The results suggest that employing fewer, large-scale operators would help reduce the overall volume of [wastewater] generated but not the overall volume spilled." This study also found that the probability of groundwater contamination from those spills was not correlated with either the spill area or with the volume spilled. Instead, the depth to groundwater was a more accurate predictor of the probability of contamination, with shallow water tables at highest risk.[570]

- August 17, 2018 – With 548 permitted wells as of 2017, Belmont County is the most intensely fracked county in the state of Ohio. A Yale University team collected drinking water samples from 66 households in Belmont County that were located at varying distances away from well pads and analyzed them for the presence of fracking-related chemical contaminants. They also interviewed residents about their health symptoms. The primary goal of this exploratory study was to determine whether residential proximity to fracked wells was related to detection and concentrations of health-relevant drinking water contaminants. A second objective was to evaluate possible relationships between proximity to wells and health complaints in the community. The team found that all homes had at least one volatile organic compound or other organic compound above detectable levels and that prevalence of contaminants in drinking water, including toluene, bromoform, and dichlorobromomethane, was higher in homes closer to the wells. Further, people who lived closer to multiple wells were more likely to report health problems including wheezing, stress, fatigue, and headache. This is the first study to concurrently collect drinking water samples, health information, and data on proximity to drilling and fracking operations.[571]

- August 15, 2018 – Using well information from the U.S. Energy Information Agency as well as state-based agencies, a Duke University team examined changes in water use intensity in U.S. drilling and fracking operations as horizontal drilling has evolved toward ever-longer lateral wellbores. They found that water use for fracking operations increased by 770 percent per well between 2011 and 2016 across all U.S. shale basins. At the same time, the volume of fracking wastewater generated during the first year of extraction increased by up to 1,440 percent. "The steady increase of the water footprint of hydraulic

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[569] Jennifer Matthews, "Fracking Wastewater Accumulation Found in Freshwater Mussels' Shells," *Penn State News*, October 22, 2018, https://news.psu.edu/story/543054/2018/10/22/research/fracking-wastewater-accumulation-found-freshwater-mussels-shells.
[570] Amanda Shores and Melinda Laituri, "The State of Produced Water Generation and Risk for Groundwater Contamination in Weld County, Colorado," *Environmental Science and Pollution Research* 25 (2018): 30390–400, https://doi.org/10.1007/s11356-018-2810-8.
[571] Elise G. Elliott et al., "A Community-Based Evaluation of Proximity to Unconventional Oil and Gas Wells, Drinking Water Contaminants, and Health Symptoms in Ohio," *Environmental Research* 167 (2018): 550–57, https://doi.org/10.1016/j.envres.2018.08.022.

fracturing with time implies that future unconventional oil and gas operations will require larger volumes of water for hydraulic fracturing, which will result in larger produced oil and gas wastewater volumes." Noting that the freshwater used for hydraulic fracturing is either retained within the shale formation or returns as highly saline flowback waste that is often subsequently disposed of via deep well injection, the authors concluded that "the permanent loss of water use for hydraulic fracturing from the hydrosphere could outweigh its relatively lower water intensity" compared to other industrial uses of water, such as agriculture, where water is not lost to the hydrological cycle.[572]

- August 5, 2018 – Using water collected from streams and a reservoir near Middletown, Pennsylvania, a research team investigated how contamination with fracking chemicals, as during a spill event, alters the formation of disinfection byproducts when surface water is chlorinated for use as drinking water. They found a shift toward the creation of more brominated compounds. This finding has significant concerns for public health because brominated chemicals are not easily removed during the water treatment process and because discharge of bromide to surface waters remains largely unregulated.[573]

- July 19, 2018 – By simulating spills and discharge of fracking wastewater into rivers and streams, a Pennsylvania research team investigated the effects of fracking wastewater salinity on the creation of disinfection byproducts during drinking water treatment. They found evidence that the ions in salty fracking waste enhance the creation of these deleterious chemicals in ways that conventional water treatment processes cannot easily remove. "Further studies should focus on salinity removal technologies such as reverse osmosis, nanofiltration, electrodialysis, ion exchange, and lime/soda ash softening."[574]

- July 13, 2018 – Chemicals associated with fracking operations have been known to contaminate surface and ground water, and many of them have been identified as endocrine disruptors in mammals, raising questions about possible perturbations of other biological processes, such as immunity. Using tadpoles, an international team investigated how chemicals found in fracking wastewater might affect the developing immune system in amphibians. They found evidence for concern. Even at doses below those found in groundwater near spill sites, many exposed tadpoles died. "A first finding of this study is the startling toxicity of the [fracking chemical] mixture to tadpoles…it seems likely that the lethal effect results from the combined activity of some or all of these chemicals." Lower doses significantly altered genes associated with immune functioning and made the developing frogs less able to fight off viral infections. "These findings suggest that [fracking-associated] water pollutants at low but environmentally

[572] Andrew J. Kondash, Nancy E. Lauer, and Avner Vengosh, "The Intensification of the Water Footprint of Hydraulic Fracturing," *Science Advances* 4, no. 8 (2018): eaar5982, https://doi.org/10.1126/sciadv.aar5982.
[573] Kuan Z. Huang, Yuefeng F. Xie, and Hao L. Tang, "Formation of Disinfection By-Products Under Influence of Shale Gas Produced Water," *Science of the Total Environment* 647 (2019): 744–51, https://doi.org/10.1016/j.scitotenv.2018.08.055.
[574] Kuan Z. Huang, Hao L. Tang, and Yuefeng F. Xie, "Impacts of Shale Gas Production Wastewater on Disinfection Byproduct Formation: An Investigation From a Non-Bromide Perspective," *Water Research* 144 (2018): 656–64, https://doi.org/10.1016/j.watres.2018.07.048.

relevant doses have the potential to induce acute alterations of immune function and antiviral immunity."[575]

- July 4, 2018 – Wastewater samples from a newly fracked oil well in Colorado were examined over 220 days using assays to assess changing toxicity levels. The results revealed significant toxicity throughout well production and during the first 55 days of flowback, with peak toxicity occurring on the first day of flowback. Researchers also looked at the community of microbes (bacteria and archaea) living in the wastewater. Some of these organisms originated from deep in the shale formation and others from the source water used for fracking. These species rapidly changed in relative abundance to one another as the toxicity of the wastewater evolved over time. "Late stage produced water communities gradually became similar to those in the earliest sample of flowback water, indicating that early conditions have a great impact on the resident microbiota over the life of the well."[576]

- June 21, 2018 – A Duke University-led lab study used mouse tissue cultures to investigate possible impacts of fracking wastewater exposure on the development of fat cells. They found that exposure to mixtures of 23 fracking chemicals, as well as raw stream water believed to be contaminated with fracking waste, promoted the growth of fat cells—even at very low concentrations. Collectively, these results show that fracking wastewater has the potential to impair metabolic health at levels found in the environment.[577] In a statement to the media, co-author Chris Kassotis said, "We saw significant fat cell proliferation and lipid accumulation, even when wastewater samples were diluted 1,000-fold from their raw state and when wastewater-affected surface water samples were diluted 25-fold."[578]

- April 28, 2018 – A Canadian study found that the water flea (*Daphnia magna*) becomes immobilized when the surface of test waters are contaminated with fracking waste. This effect was persistent and occurred at concentrations significantly lower than is required to kill this common zooplankton outright. Immobilized *Daphnia* did not recover after 48 hours, could not feed, and became unable to shed their carapace, thus impeding reproduction. The evidence suggests that surfactants in fracking fluid together with floating hydrocarbons work together to reduce surface tension in ways that disallow *Daphnia* from re-entering the water column. "The current study shows that an important

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[575] Jacques Robert et al., "Water Contaminants Associated With Unconventional Oil and Gas Extraction Cause Immunotoxicity to Amphibian Tadpoles," *Toxicological Sciences* 166, no. 1 (2018): 39–50, https://doi.org/10.1093/toxsci/kfy179.
[576] Natalie M. Hull et al., "Succession of Toxicity and Microbiota in Hydraulic Fracturing Flowback and Produced Water in the Denver-Julesburg Basin," *Science of the Total Environment* 10, no. 644 (2018): 183–92, https://doi.org/10.1016/j.scitotenv.2018.06.067.
[577] Christopher D. Kassotis, Susan C. Nagel, and Heather M. Stapleton, "Unconventional Oil and Gas Chemicals and Wastewater-Impacted Water Samples Promote Adipogenesis via PPARγ-Dependent and Independent Mechanisms in 3T3-L1 Cells," *Science of the Total Environment* 640–641 (2018): 1601–10, https://doi.org/10.1016/j.scitotenv.2018.05.030.
[578] Tim Lucas, "Exposure to Fracking Chemicals and Wastewater Spurs Fat Cells," Duke.edu, June 21, 2018, https://web.archive.org/web/20180621182703/https://nicholas.duke.edu/about/news/exposure-fracking-chemicals-and-wastewater-spurs-fat-cells.

component of the toxicity of [fracking wastewater] to *Daphnia magna* is physical impairment. Depending on how the endpoint of a toxicity test is defined, this mode of action may not be accounted for in laboratory assessments used to determine risk. However, physical toxicity effects are likely to be important in environmental settings where [fracking wastewater] spills may occur."[579] (See also entry for March 5, 2019.)

- April 11, 2018 – A Drexel University team undertook a risk assessment of residential exposures to drinking water contaminated by fracking wastewater (flowback water). This simulation study found that within just eight hours—a realistic timeline for continual exposure due to a spill event—radioactive substances in the wastewater could produce demonstrable risks to human health, especially through the inhalation route. These radioactive compounds posed a greater threat to human health than other contaminants examined in this assessment, including arsenic, benzene, and vinyl chloride. "Radionuclides, which are known to exist in [fracking wastewater] as a result of occurring naturally within shale formations, pose a significant risk to human health and increase the likelihood of developing cancer in exposed individuals…median values for inhalation risk are at unacceptable levels. These exposures are due to the radionuclides aerosolizing from water primarily during showering.… Exposure to certain compounds of flowback water for only a few hours or days…can still present adverse effects."[580]

- April 9, 2018 – An analysis of the bacterial community in 31 northwestern Pennsylvania trout streams showed that fracking activity altered the composition of species found in the sediment. Confirming the findings of previous studies, streams near drilling and fracking activity had significantly higher numbers of methane-metabolizing and methane-producing microorganisms, which are tolerant to acidic conditions. "Altogether, this study highlighted stable bacterial taxa responding to Marcellus shale activity and further supplements a longitudinal correlation of increased acidity of stream water and fracking activity adjacent to headwater streams over five years."[581]

- April 8, 2018 – Working in the South Fork Little Red River watershed in northern Arkansas, a research team found that populations of invertebrate animals were reduced downstream of drilling and fracking operations relative to upstream.[582]

- April 6, 2018 – Chemical characterization and toxicological testing of wastewater from fracked and conventionally drilled oil and gas wells in Pennsylvania were compared.

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[579] Tamzin A. Blewett et al., "Physical Immobility as a Sensitive Indicator of Hydraulic Fracturing Fluid Toxicity Towards Daphnia Magna," *Science of the Total Environment* 635 (2018): 639–43, https://doi.org/10.1016/j.scitotenv.2018.04.165.
[580] Noura Abualfaraj, Patrick L. Gurian, and Mira S. Olson, "Assessing Residential Exposure Risk from Spills of Flowback Water from Marcellus Shale Hydraulic Fracturing Activity," *International Journal of Environmental Research and Public Health* 15, no. 4 (2018): 727, https://doi.org/10.3390/ijerph15040727.
[581] Nikea Ulrich et al., "Response of Aquatic Bacterial Communities to Hydraulic Fracturing in Northwestern Pennsylvania: A Five-Year Study," *Scientific Reports* 8, no. 1 (2018): 5683, https://doi.org/10.1038/s41598-018-23679-7.
[582] Bradley J. Austin et al., "Can High Volume Hydraulic Fracturing Effects Be Detected In Large Watersheds? A Case Study of the South Fork Little Red River," *Current Opinion in Environmental Science & Health* 3 (2018): 40–46, https://doi.org/10.1016/j.coesh.2018.04.003.

Wastewater from both types of wells was equally toxic to animal and human cells growing in culture and was corrosive at high concentrations. This toxicity was not attributable to the presence of salts alone. Hydrocarbon chemicals were found in both well types and are known to be toxic to multiple human organs. "In vitro assays showed that normal cell survival, behavior, and morphology were severely impaired by short-term exposure to either type of sample at up to 1000-fold dilutions. … Taken together, these results suggest that exposure to leaks or spills associated with either conventional or unconventional oil and gas extraction could potentially impact human health."[583]

- April 5, 2018 – Led by researchers from the University of Missouri, a study conducted in Pavillion, Wyoming compared the effects of water pollution linked to fracking to effects from conventional drilling. Endocrine-disrupting chemicals were found in 22 groundwater samples taken near both kinds of wells. However, the results showed that contaminated groundwater collected near fracking sites was more disruptive to hormonal signaling in human cells than contaminated groundwater collected from conventional well pads. These results corroborate those of past studies.[584] In an associated news story in *WyoFile*, Christopher Kassotis, one of the co-authors of the new study, said, "We have now reported similar endocrine bioactivities across numerous unconventional oil/gas sampling regions, and other researchers are beginning to demonstrate similar effects in cell and animal models. These, above all else, lend strong support for our findings."[585]

- March 5, 2018 – An exemption in the Safe Drinking Water Act allows hydraulic fracturing operations to escape federal regulation, leaving it up to individual states to determine how groundwater resources used for drinking are protected during fracking operations that take place on lands without federal or tribal mineral rights. A research team from Stanford University, University of California, Berkeley, and Lawrence Berkeley National Laboratory assessed these state-based oil and gas regulations in 17 different states. They found that the definitions of "protected groundwater" are vague, inconsistent and, very often, offer less protection than federal regulations. For example, in Alabama and New Mexico, protection of drinking water appears discretionary. In Colorado and Texas, protection of drinking water depends on the location of the oil and gas fields. In Illinois, protection during fracking only applies to horizontal wells. In California, drinking water must be monitored but not explicitly protected. Concluding from these findings that the nation's drinking water resources are vulnerable to contamination from oil and gas extraction and wastewater disposal, the research team recommended that criteria defined by the EPA for an underground drinking water source

[583] L. M. Crosby et al., "Toxicological and Chemical Studies of Wastewater From Hydraulic Fracture and Conventional Shale Gas Wells," *Environmental Toxicology* 37, no. 8 (2018): 2098–2111, https://doi.org/10.1002/etc.4146.
[584] Christopher D. Kassotis et al., "Endocrine-Disrupting Activities and Organic Contaminants Associated with Oil and Gas Operations in Wyoming Groundwater," *Archives of Environmental Contamination and Toxicology* 75 (2018): 247–58, https://doi.org/10.1007/s00244-018-0521-2.
[585] Angus M. Thuermer Jr., "Study: Water Near Fracked Wyo Gas Field Disrupts Hormones," *WyoFile*, April 27, 2018, https://www.wyofile.com/study-water-near-fracked-wyo-gas-field-disrupts-hormones/.

be consistently used to define protected groundwater in state-based oil and gas regulations.[586]

- February 15, 2018 – A UK team used reports from the Texas Railroad Commission (1999-2015) and the Colorado Oil and Gas Conservation Commission (2009-2015) to examine spill rates from oil and gas well pads. They found that the spill rate in both Colorado and Texas significantly increased over the recorded time period, with equipment failure cited as the most common cause. In Colorado, 33 percent of the spills were discovered during site remediation and random site inspections. Using these data, the team predicted that a UK fracking industry would likely experience a spill for every 19 well pads developed.[587]

- January 31, 2018 – Researchers in Arkansas found that water withdrawals for fracking operations can dangerously deplete water levels in up to 51 percent of streams in ways that potentially threaten drinking water supplies, damage aquatic life, and disrupt recreation. "There is potential for these withdrawals to cause water stress," the paper concluded.[588] Water stress represents risk of water scarcity for people caused by increases in economic costs or altered stream flow that results in loss of aquatic biodiversity and ecosystem functioning.

- January 27, 2018 – Fracking wastewater is a developmental toxicant to zebra fish embryos, according to results of a laboratory study conducted by a Canadian team of researchers. Exposure to various concentrations of fracking flowback and produced water, collected from well sites in Alberta, was linked to spinal and heart abnormalities and patterns of altered gene expression consistent with endocrine disruption.[589]

- January 23, 2018 – An Ohio State University team developed and used numerical models to simulate how methane from a leaking well could migrate into different types of drinking water aquifers. Their results showed that rapid, long-distance gas flow was most likely to occur when a pulse of gas under high pressure from a faulty gas well entered into a fractured rock aquifer. In these cases, methane can easily migrate a distance of 1 kilometer within a week and in many different directions, including laterally away from the natural gas well. Current efforts to evaluate natural gas leakage from faulty wells

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[586] Dominic C. DiGiulio, Seth B. C. Shonkoff, and Robert B. Jackson, "The Need to Protect Fresh and Brackish Groundwater Resources During Unconventional Oil and Gas Development," *Current Opinion in Environmental Science & Health* 3 (2018): 1–7, https://doi.org/10.1016/j.coesh.2018.01.002.
[587] S. A. Clancy et al., "The Potential for Spills and Leaks of Contaminated Liquids From Shale Gas Developments," *Science of the Total Environment* 626 (2018): 1463–73, https://doi.org/10.1016/j.scitotenv.2018.01.177.
[588] Sally Entrekin et al., "Water Stress from High-Volume Hydraulic Fracturing Potentially Threatens Aquatic Biodiversity and Ecosystem Services in Arkansas, United States," *Environmental Science & Technology* 52, no. 4 (2018): 2349–58, https://doi.org/10.1021/acs.est.7b03304.
[589] Yuhe He et al., "Developmental Toxicity of the Organic Fraction from Hydraulic Fracturing Flowback and Produced Waters to Early Life Stages of Zebrafish (Danio Rerio)," *Environmental Science & Technology* 52, no. 6 (2018): 3820–30, https://doi.org/10.1021/acs.est.7b06557.

"likely underestimate contributions from small-volume, low-pressure leakage events," which require extended periods of environmental monitoring.[590]

- January 16, 2018 – An editorial in the journal *Groundwater* warned researchers against being too quick to dismiss the presence of methane in groundwater near fracking sites as "always naturally occurring," especially in places where no pre-drill baseline data are available or in studies where average methane levels are being compared. Noting that the geological conditions that facilitate the natural migration of hydrocarbons are often "muddled, obfuscating the presence of hydrocarbon pollution due to gas leaking from production wells," the editorial encouraged study designs that make use of odds-ratio tests and geochemical tracers. Fractured rocks within shallow aquifers, in particular, are concerning "both in terms of their potential for facilitating rapid … gas flow, and their inherent geometric complexity, which impact hydrocarbon gas transport mechanisms."[591]

- January 16, 2018 – The Pennsylvania Department of Environmental Protection determined that fracking wastewater that had leaked from a storage pit contaminated groundwater and rendered a natural spring used for drinking water in Greene County undrinkable.[592]

- January 9, 2018 – A University of Texas team collected groundwater samples from across shale basins in Texas and reported on the discovery of opportunistic, pathogenic bacteria in fracking-impacted water wells in Texas. These results raise questions about fracking's effects on the microbial ecology of aquifers. Commenting on their findings, the researchers noted, "The results were quite surprising. Not only did we find that various opportunistic pathogens could survive in the presence of hydrocarbon gases and chemical additives, they appeared to thrive and exhibited robust resistance profiles to multiple antibiotics. We even observed that certain pathogens were resilient to high levels of chlorination."[593]

- December 11, 2017 – A report by the *Texas Observer* investigated groundwater depletion by fracking operations in west Texas at the southern edge of the Ogallala Aquifer. Groundwater conservation districts lack legal financial resources to restrict groundwater pumping or even compel metering on water wells that would monitor exactly how much

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[590] Joachim Moortgat, Franklin W. Schwartz, and Thomas H. Darrah, "Numerical Modeling of Methane Leakage from a Faulty Natural Gas Well into Fractured Tight Formations," *Groundwater* 56, no. 2 (2018): 163–75, https://doi.org/10.1111/gwat.12630.
[591] Thomas H. Darrah, "Time to Settle the Fracking Controversy," *Groundwater* 56, no. 2 (2018): 161–62, https://doi.org/10.1111/gwat.12636.
[592] Bob Niedbala, "W.Va. Company Fined $1.7 Million for Violations at 14 Well Sites in Greene County," *Observer-Reporter*, January 17, 2020, https://observer-reporter.com/news/localnews/w-va-company-fined-million-for-violations-at-well-sites/article_cc1ce344-faec-11e7-84ca-076df3832f29.html.
[593] Zacariah Hildenbrand, Ines Santos, and Kevin Schug, "Detecting Harmful Pathogens In Water: Characterizing The Link Between Fracking And Water Safety," *Science Trends*, January 9, 2018, https://sciencetrends.com/detecting-harmful-pathogens-water-characterizing-link-fracking-water-safety/.

water is pumped. In Howard County alone, water used for fracking is now believed to constitute about 20 percent of average annual water use.[594]

- November 16, 2017 – The 2005 Energy Policy Act prohibited the EPA from regulating fracking under the Safe Drinking Water Act and from requiring that operators disclose their chemicals. According to an investigation by *Inside Climate News,* the scientific study that justified this provision (which is widely known as the Halliburton loophole) was the subject of a whistleblower complaint. The study was also disavowed by its authors, who said the conclusion of the report—that fracking posed no risk to groundwater—was not supported by the evidence. These authors removed their names from the final document. Interviewed for the story, one of these authors said that the belief that fracking was safe for water was a foregone conclusion at the EPA under George W. Bush. "What we would have said in the conclusion is that there is some form of risk from hydraulic fracturing to groundwater. How you quantify it would require further analyses, but, in general, there is some risk."[595]

- November 9, 2017 – As part of a preliminary study, a Texas team assessed the groundwater microbiome in a rural area of southern Texas where farming and fracking co-exist. Each of the sampled water wells had a unique community of microorganisms living in the water. The dominant bacteria were denitrifying species that transform nitrates into gaseous nitrogen or those that break apart hydrocarbon molecules. Earlier studies have postulated that fracking can alter the chemical composition of groundwater and change the species composition of the microbial communities living within it. The results of this study "do not provide a definitive link between [fracking] or agricultural activities and the groundwater microbiome; however, they do provide a baseline measurement of bacterial diversity and quantity in groundwater located near these anthropogenic activities."[596]

- November 1, 2017 – In Oklahoma, horizontal wells can be fracked within 600 feet of older, vertical wells that do not use fracking. Oil companies in Oklahoma that extract oil using conventional, vertical wells alleged that hundreds of their wells have been inundated by fluids from nearby horizontal wells that use high-volume hydraulic fracturing, as documented by *E&E News*. Vertical well operators have raised questions about whether these "frack hits" from nearby horizontal wells that have flooded their own wells have also reached the groundwater. "Logic said it will impact [groundwater]," said one driller. "There was water coming up out of the ground. There was enough pressure to bring it to the surface." Small operators of vertical wells, organized as the Oklahoma Energy Producers Alliance (OEPA), released a study estimating that, in just one county

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[594] Christopher Collins, "Big Spring vs. Big Oil," *The Texas Observer*, December 11, 2017, https://www.texasobserver.org/big-spring-vs-big-oil/.
[595] Neela Banerjee, "Industrial Strength: How the U.S. Government Hid Fracking's Risks to Drinking Water," *Inside Climate News*, November 16, 2017, https://insideclimatenews.org/news/16112017/fracking-chemicals-safety-epa-health-risks-water-bush-cheney.
[596] Ines C. Santos et al., "Exploring the Links Between Groundwater Quality and Bacterial Communities Near Oil and Gas Extraction Activities," *Science of the Total Environment* 618 (2018): 165–73, https://doi.org/10.1016/j.scitotenv.2017.10.264.

alone, there were 400 cases of frack fluid from horizontal wells flooding nearby vertical wells.[597, 598]

- October 31, 2017 – A study of fracking wastewater disposed of in rivers and streams found that chemical contaminants in the waste were transformed into more toxic substances when they chemically reacted with chlorinated compounds discharged from downstream drinking water treatment plants. The result was dozens of different, brominated and iodinated disinfection byproducts (DBPs). A lab analysis found that all were highly toxic to mammalian cells. Conventional water treatment practices do not remove these chemicals. "It is likely that in oil- and gas-impacted drinking water sources, iodo-phenolic DBPs could form at significant levels, particularly in cases in which chloramination is used."[599]

- October 18, 2017 – Researchers concerned about reports of skin rashes, gastrointestinal distress, and breathing problems among people who live near drilling and fracking operations found increased levels of certain harmful bacteria in private water wells impacted by fracking in the Barnett and Eagle Ford Shale areas in Texas. These results raise questions about whether drilling and fracking activities could alter the communities of microorganisms in groundwater in ways that pose health risks. According to one of the lead authors of the study, interviewed in the *Dallas News*, "the potential contribution of these microbes to these health effects is probably understudied, underappreciated, unknown."[600, 601]

- August 3, 2017 – Due to permitting errors and a mix-up in records 30 years ago, wastewater from drilling operations in California was mistakenly injected directly into drinking water aquifers. Six years after the discovery of the problem, 175 wastewater wells that were illegally injecting into protected aquifers have been shut down, but hundreds more are still operating. An investigation by KQED Science revealed that California state water regulators know very little about the actual impact of those injections on the state's drinking water reserves. "State water regulators say they hope to figure out what the larger impacts have been in years ahead, but have no set timeline. The risk is that they've allowed oil companies to contaminate drinking water aquifers to such

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597 Mike Soraghan, "Now It's Oilmen Who Say Fracking Could Harm Groundwater," *E&E News*, November 1, 2017, https://web.archive.org/web/20171101181846/https://www.eenews.net/stories/1060065209.
598 OEPA, "Are Vertical Wells Impacted by Horizontal Drilling? A Study of Kingfisher County" (OEPA, September 14, 2017), https://www.eenews.net/assets/2017/10/27/document_pm_07.pdf.
599 Hannah K. Liberatore et al., "Identification and Comparative Mammalian Cell Cytotoxicity of New Iodo-Phenolic Disinfection Byproducts in Chloraminated Oil and Gas Wastewaters," *Environmental Science & Technology Letters* 4, no. 11 (2017): 475–80, https://doi.org/10.1021/acs.estlett.7b00468.
600 Misty S. Martin et al., "Characterization of Bacterial Diversity in Contaminated Groundwater Using Matrix-Assisted Laser Desorption/Ionization Time-of-Flight Mass Spectrometry," *Science of the Total Environment* 622–623 (2018): 1562–71, https://doi.org/10.1016/j.scitotenv.2017.10.027.
601 J. Mosier, "UTA Research Finds Dangerous Bacteria in Groundwater Near Texas Gas Drilling Sites.," *Dallas News*, December 1, 2017, https://www.dallasnews.com/business/energy/2017/12/01/uta-study-finds-dangerous-bacteria-groundwater-near-texas-gas-drilling-sites.

an extent that Californians may have permanently lost those sources of fresh water."[602] An earlier investigation by KQED Science revealed that illegal wastewater wells would still be allowed to operate while the necessary paperwork was filed.[603]

- July 12, 2017 – In western Pennsylvania, a team of researchers looked at sediments in the Conemaugh River watershed downstream of a treatment plant that was specially designed to treat fracking wastewater. The researchers found contamination for many miles downstream with fracking-related chemicals that included radium, barium, strontium, and chloride, as well as endocrine-disrupting and carcinogenic compounds. The peak concentrations were found in sediment layers that had been deposited during the years of peak fracking wastewater discharge. Elevated concentrations of radium were detected as far as 12 miles downstream of the treatment plant and were up to 200 times greater than background. Some stream sediment samples were so radioactive that they approached levels that would, in some U.S. states, classify them as radioactive waste and necessitate special disposal.[604, 605]

- May 31, 2017 – A U.S. Geological Survey (USGS) team sampled drinking water wells near drilling and fracking sites in the Eagle Ford, Fayetteville, and Haynesville Shale basins and found detectable levels of methane and benzene. However, the sources of these contaminants were unclear, and, given the slow travel time of groundwater, "decades or longer may be needed to fully assess the effects of potential subsurface and surface releases of hydrocarbons on the wells."[606]

- May 1, 2017 – A study examining the impacts of drilling and fracking operations on public drinking water in Pennsylvania found evidence of contamination when drinking water source intakes were located within one kilometer (.62 miles) of a well pad. Noting that many Pennsylvanians living near well pads drink bottled water, the authors concluded, "our results suggest that these perceived risks may in fact be justified."[607] (See also entry below for October 13, 2016.)

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[602] Lauren Sommer, "How Much Drinking Water Has California Lost to Oil Industry Waste? No One Knows," *KQED Science*, August 3, 2017, https://www.kqed.org/science/1914130/how-much-drinking-water-has-california-lost-to-oil-industry-waste-no-one-knows.
[603] Lauren Sommer, "California Says Oil Companies Can Keep Dumping Wastewater During State Review," *KQED Science*, January 17, 2017, https://www.kqed.org/science/1330777/california-says-oil-companies-can-keep-dumping-wastewater-during-state-review.
[604] William D. Burgos et al., "Watershed-Scale Impacts from Surface Water Disposal of Oil and Gas Wastewater in Western Pennsylvania," *Environmental Science & Technology* 51, no. 15 (2017): 8851–60, https://doi.org/10.1021/acs.est.7b01696.
[605] Ian Johnston, "Fracking Can Contaminate Rivers and Lakes With Radioactive Material, Study Finds," *The Independent*, July 12, 2017, http://www.independent.co.uk/news/science/fracking-dangers-environment-water-damage-radiation-contamination-study-risks-a7837991.html.
[606] Peter B. McMahon et al., "Methane and Benzene in Drinking-Water Wells Overlying the Eagle Ford, Fayetteville, and Haynesville Shale Hydrocarbon Production Areas," *Environmental Science & Technology* 51, no. 12 (2017): 6727–34, https://doi.org/10.1021/acs.est.7b00746.
[607] Elaine Hill and Lala Ma, "Shale Gas Development and Drinking Water Quality," *American Economic Review: Papers & Proceedings* 107, no. 5 (2017): 522–25, https://doi.org/10.1257/aer.p20171133.

- April 19, 2017 – Using data from the South Coast Air Quality Monitoring District, a team of researchers in California compared chemicals used in fracking operations with those used in the routine maintenance of conventional oil and gas wells where chemicals are used to aid in drilling, for corrosion control, to clean the wellbore, and to enhance oil recovery. They found significant overlap in both the types and amounts of chemicals used. "The results of this study indicate regulations and risk assessments focused exclusively on chemicals used in well-stimulation activities may underestimate potential hazard or risk from overall field chemical-use. . . . Our analysis shows that hydraulic fracturing is just one of many applications of hazardous chemicals on oil and gas fields."[608]

- April 5, 2017 – A three-year study in West Virginia led by scientists at Duke University assessed surface water and groundwater drawn from drinking water wells both before and after drilling and fracking began in the region. Using geochemical techniques, including a suite of tracers that help distinguish naturally occurring methane and salts from those contained in fracking fluid, the researchers found no evidence of groundwater contamination. They did, however, document threats to surface water from fracking wastewater spills.[609] In an accompanying statement, the researchers noted, "What we found in the study area in West Virginia after three years may be different from what we see after 10 years because the impact on groundwater isn't necessarily immediate."[610]

- Feb 21, 2017 – Between 2005 and 2014, researchers surveyed spill record data from drilling and fracking operations in four states (Colorado, New Mexico, North Dakota, and Pennsylvania). During these nine years, they documented 6,678 total spills, or about five spills each year for every 100 wells. Between 2 and 16 percent of wells reported a spill each year. Half of all spills were related to storage and transport of fluids through flow lines. The authors also found that the chances of spills are highest during the first three years of a well's life and that spill reporting requirements differ markedly from state to state, making impossible the task of comparing states or creating a national picture.[611, 612]

- January 31, 2017 – California is the only state that allows fracking waste to be held in unlined, open pits, creating risks for groundwater contamination. A California Water

[608] William T. Stringfellow et al., "Comparison of Chemical-Use Between Hydraulic Fracturing, Acidizing, and Routine Oil and Gas Development," *PLoS ONE* 12, no. 4 (2017): e0175344, https://doi.org/10.1371/journal.pone.0175344.
[609] Harkness, J. S. et al., "The Geochemistry of Naturally Occurring Methane and Saline Groundwater in an Area of Unconventional Shale Gas Development," *Geochimica et Cosmochimica Acta* 208 (2017): 302–34, https://doi.org/10.1016/j.gca.2017.03.039.
[610] Tim Lucas, "West Virginia Groundwater Not Affected by Fracking, but Surface Water Is," Duke.edu, April 24, 2017, https://nicholas.duke.edu/news/west-virginia-groundwater-not-affected-fracking-surface-water.
[611] Lauren A. Patterson et al., "Unconventional Oil and Gas Spills: Risks, Mitigation Priorities, and State Reporting Requirements," *Environmental Science & Technology* 51, no. 5 (2017): 2563–73, https://doi.org/10.1021/acs.est.05749.
[612] Nicholas Kusnetz, "Fracking Well Spills Poorly Reported in Most Top-Producing States, Study Finds," *Inside Climate News*, February 21, 2017, https://insideclimatenews.org/news/21022017/fracking-spills-north-dakota-colorado.

Boards investigation found that, as of January 2017, 1,000 such pits were operational, with 400 lacking required state permits. The vast majority is located in Kern County.[613]

- December 14, 2016 – To better understand the impact of fracking fluid spills on aquatic animals, scientists at the University of Alberta exposed rainbow trout in laboratory tanks to various dilutions of fracking fluids. Even at very low exposures, the fish experienced adverse effects, including alterations in liver functioning and disruption of hormonal pathways. [This study was partially funded by industry.][614]

- December 13, 2016 – The final version of the EPA's six-year, $29 million study on the impacts of hydraulic fracturing on the nation's drinking water confirmed that fracking activities have caused contamination of water resources in the United States, and it traced the various routes by which drinking water can be impacted by fracking. Documented cases of drinking water contamination have resulted from spills of fracking fluid and fracking wastewater; discharge of fracking waste into rivers and streams; and underground migration of fracking chemicals, including gas, into drinking water wells. Depletion of aquifers caused by water withdrawals has created other impacts.[615, 616, 617, 618] The final EPA report detailed the problem of fracking-related drinking water contamination in three communities—Pavillion, Wyoming; Dimock, Pennsylvania; and Parker County, Texas.[619] Summing up the report, then-EPA Deputy Administrator Tom Burke said in a statement to *American Public Media*, "We found scientific evidence of impacts to drinking water resources at each stage of the hydraulic fracturing cycle."[620] (See also the entry for June 5, 2015, which describes the contents of the 2015 draft report.)

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[613] California Water Boards, "Produced Water Pond Status Report" (California Water Boards, January 31, 2017), https://www.waterboards.ca.gov/water_issues/programs/groundwater/sb4/docs/pond_rpt_0117_fnl.pdf.
[614] Yuhe He et al., "Effects on Biotransformation, Oxidative Stress and Endocrine Disruption in Rainbow Trout (Oncorhynchus Mykiss) Exposed to Hydraulic Fracturing Flowback and Produced Water," *Environmental Science & Technology* 51, no. 2 (2017): 940–47, https://doi.org/10.1021/acs.est.6b04695.
[615] U. S. Environmental Protection Agency, "EPA's Study of Hydraulic Fracturing for Oil and Gas and Its Potential Impact on Drinking Water Resources," 2016, https://www.epa.gov/hfstudy.
[616] U. S. Environmental Protection Agency, "EPA's Study of Hydraulic Fracturing for Oil and Gas: Impacts From the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States," Appendices (U. S. Environmental Protection Agency, 2016), https://www.epa.gov/hfstudy/hydraulic-fracturing-study-fact-sheets.
[617] U. S. Environmental Protection Agency, "EPA's Study of Hydraulic Fracturing and Its Potential Impact on Drinking Water Resources," Executive Summary (U. S. Environmental Protection Agency, 2016), https://www.epa.gov/hfstudy/executive-summary-hydraulic-fracturing-study-final-assessment-2016.
[618] Scott Tong and T. Scheck, "EPA's Late Changes to Fracking Study Downplay Risk of Drinking Water Pollution," *Marketplace*, November 30, 2016, https://www.marketplace.org/2016/11/29/world/epa-s-late-changes-fracking-study-portray-lower-pollution-risk.
[619] U. S. Environmental Protection Agency Science Advisory Board, "SAB Review of the EPA's Draft Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources" (EPA-SAB, August 11, 2016), https://yosemite.epa.gov/sab/sabproduct.nsf/LookupWebReportsLastMonthBOARD/BB6910FEC10C01A18525800C00647104/$File/EPA-SAB-16-005+Unsigned.pdf.
[620] Tom Scheck and Scott Tong, "EPA Reverses Course, Highlights Fracking Contamination of Drinking Water," *APM Reports*, December 13, 2016, https://www.apmreports.org/story/2016/12/13/epa-fracking-contamination-drinking-water.

- December 1, 2016 – According to a review paper that examines the potential environmental impacts of oil and gas wastewater, about 5 percent of fracking waste is accidentally or illegally spilled. Almost all of the rest is transported off site and injected into disposal wells that are drilled into porous geological formations. In North Dakota's Bakken Shale, disposal wells are located within miles of the well pad, and the wastewater can travel there via pipeline. In Pennsylvania's Marcellus Shale, drilling activity exceeds the capacity for disposal of waste in local wells and must be trucked out of state.[621]

- November 4, 2016 – A critical review of potential routes of water contamination from drilling and fracking operations in the Bakken Shale noted that the high salinity of fracking wastewater minimizes its recycling options and thus contributes to the need for disposal wells. Transportation of large volumes of waste to these wells, via truck or pipeline, presents opportunities for large spills that can threaten groundwater.[622]

- October 16, 2016 – A team of scientists led by researchers at the Lawrence Berkeley National Laboratory evaluated chemicals used for fracking in California oil fields. Chemical additives included a wide variety of solvents in large amounts, as well as other toxic substances, including biocides and corrosion inhibitors.[623]

- October 14, 2016 – One of the first studies to investigate the impacts of fracking on the ecology of streams found that fracking "has the potential to alter aquatic biodiversity and methyl mercury concentrations at the base of food webs." The researchers sampled 27 remote streams in the Marcellus Shale basin of Pennsylvania where drilling and fracking is taking place. They showed that methyl mercury levels in stream sites where fracking occurs were driven upwards by higher acidity and lower numbers of macroinvertebrates. In streams with the highest numbers of fracking fluid spills, "fish diversity was nil," and in some cases, there were no fish at all, including in streams previously classified as high-quality brook trout habitat. "Fracking and flowback fluids can contain various highly acidic agents, organic and inorganic compounds, and even Hg [mercury]. The flowback fluids can reach nearby streams through leaking wastewater hoses, impoundments, and lateral seepage and blowouts, as well as by backflow into the wellhead. Flowback water reaching streams can . . . decrease aquatic biodiversity. . . . Lowered stream pH increases Hg solubility, leading to increased bioaccumulation in food webs."[624]

- October 13, 2016 – Researchers at Pennsylvania State University and Ohio State University combined GIS data on drilling and fracking activities in Pennsylvania and Ohio with household data on bottled water purchases. They found that yearly household purchases of bottled water increased as local drilling and fracking intensity increased.

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[621] Lindsey Konkel, "Salting the Earth: The Environmental Impact of Oil and Gas Wastewater Spills," *Environmental Health Perspectives* 124, no. 12 (2016): A230–35, https://doi.org/10.1289/ehp.124-A230.
[622] Namita Shrestha et al., "Potential Water Resource Impacts of Hydraulic Fracturing From Unconventional Oil Production in the Bakken Shale," *Water Research* 108 (2017): 1–24, https://doi.org/10.1016/j.watres.2016.11.006.
[623] William T. Stringfellow et al., "Identifying Chemicals of Concern in Hydraulic Fracturing Fluids Used for Oil Production," *Environmental Pollution* 220, Pt A (2017): 413–20, https://doi.org/10.1016/j.envpol.2016.09.082.
[624] Christopher James Grant et al., "Fracked Ecology: Response of Aquatic Trophic Structure and Mercury Biomagnification Dynamics in the Marcellus Shale Formation," *Ecotoxicology* 25 (2016): 1739–50, https://doi.org/10.1007/s10646-016-1717-8.

This "averting behavior" is a measure of perceived risk. In 2010, averting-behavior expenditures in the form of bottle water purchases by people living in Pennsylvania's shale counties totaled $19 million.[625] (A subsequent study suggests that those engaged in tapwater averting behaviors in Pennsylvania have evidence-based reasons to be concerned. See entry above, for May 1, 2017.)

- September 22, 2016 – Using the agency's list of 1076 chemicals that have reported use as ingredients in hydraulic fracturing fluid, EPA scientists developed a framework to analyze and rank subsets of chemicals in order to better understand which fracking-related chemicals pose the greatest risk to drinking water. Their model collates multiple lines of evidence. For example, data on inherent toxicity are combined with data on occurrence and propensity for environmental transport. In the absence of local data on actual human exposures, this model can serve as a qualitative metric to "identify chemicals that may be more likely than others to impact drinking water resources."[626]

- September 16, 2016 – A reconnaissance analysis of groundwater in the Eagle Ford Shale region in southern Texas found sporadic detections of multiple VOCs and dissolved gas, providing evidence that "groundwater quality is potentially being affected by neighboring [drilling and fracking] activity, or other anthropogenic activities, in an episodic fashion." The authors called for a more extensive investigation of possible groundwater contamination in the Eagle Ford basin.[627, 628]

- July 11, 2016 – An interdisciplinary team led by University of Colorado researchers found methane in 42 water wells in the intensely drilled Denver-Julesburg Basin where high volume, horizontal fracking operations began in 2010. By examining isotopes and gas molecular ratios, the researchers determined that the gas contaminating these wells was thermogenic in origin, rather than microbial, and therefore had migrated up into the groundwater from underlying oil- and gas-containing shale. The steady rate of well contamination over time—two cases per year from 2001 to 2014—suggests that well failures, rather than the process of hydraulic fracturing itself, was the mechanism that created migration pathways for the stray gas to reach drinking water sources. Of the 42 affected wells, 11 had already been identified by state regulators as suffering from "barrier failures."[629] Duke University geochemist Avner Vengosh, who was not an author

[625] Douglas H. Wrenn, H. Allen Klaiber, and Edward C. Jaenicke, "Unconventional Shale Gas Development, Risk Perceptions, and Averting Behavior: Evidence from Bottled Water Purchases," *Journal of the Association of Environmental and Resource Economists* 3, no. 4 (2016).
[626] Erin E. Yost, John Stanek, and Lyle D. Burgoon, "A Decision Analysis Framework for Estimating the Potential Hazards for Drinking Water Resources of Chemicals Used in Hydraulic Fracturing Fluids," *Science of the Total Environment* 574 (2016): 1544–58, https://doi.org/10.1016/j.scitotenv.2016.08.167.
[627] Zacariah L. Hildenbrand et al., "A Reconnaissance Analysis of Groundwater Quality in the Eagle Ford Shale Region Reveals Two Distinct Bromide/Chloride Populations," *Science of the Total Environment* 575 (2017): 672–80, https://doi.org/10.1016/j.scitotenv.2016.09.070.
[628] Zacariah L. Hildenbrand et al., "Corrigendum to 'A Reconnaissance Analysis of Groundwater Quality in the Eagle Ford Shale Region Reveals Two Distinct Bromide/Chloride Populations,'" *Science of the Total Environment* 603 (2017): 834–35, https://doi.org/10.1016/j.scitotenv.2017.05.200.
[629] Owen A. Sherwood et al., "Groundwater Methane in Relation to Oil and Gas Development and Shallow Coal Seams in the Denver-Julesburg Basin of Colorado," *Proceedings of the National Academy of Sciences* 113, no. 30 (2016): 8391–96, https://doi.org/10.1073/pnas.1523267113.

of the paper, commented on the study in an accompanying article in *Inside Climate News*: "The bottom line here is that industry has denied any stray gas contamination: that whenever we have methane in a well, it is always preexisting. The merit of this is that it's a different oil and gas basin, a different approach, and it's saying that stray gas could happen." In this same article, *Inside Climate News* reported that national standards for well construction do not exist, nor are there laws governing the type of cement that is used to seal the wellbore and prevent leaks.[630]

- May 24, 2016 – ATSDR conducted a public health evaluation using groundwater data gathered in 2012 by the EPA from 64 private drinking water wells in Dimock, Pennsylvania where natural gas drilling and fracking activities began in 2008 and where residents began reporting problems with their water shortly thereafter. The agency found that water samples collected from 27 Dimock wells contained contaminants "at levels high enough to affect human health." These included methane, salts, organic chemicals, and arsenic. In 17 wells, levels of methane were high enough to create risk of fire or explosion.[631] Methane levels were not assessed in wells prior to the start of fracking activities in the area. Hence, the study is limited by lack of pre-drilling baseline data, and investigators did not attempt to determine the source of the contaminants. However, in its focus on identifying health impacts, ATSDR's evaluation is a more comprehensive study than that conducted four years earlier by the EPA and calls into question its earlier, more reassuring conclusions.[632, 633]

- May 9, 2016 – Sampling downstream of a fracking wastewater disposal facility in West Virginia, a USGS team documented changes in microbial communities and found evidence indicating the presence of fracking waste in water and sediment samples collected from Wolf Creek in West Virginia. Specifically, the researchers documented increased concentrations of barium, bromide, calcium, sodium, lithium, strontium, iron, and radium downstream of the disposal well.[634] In a *Washington Post* story about this study, lead author Denise Akob said that the key take-away message "is really that we're demonstrating that facilities like this can have an environmental impact."[635] (This study

[630] Neela Banerjee, "Colorado Fracking Study Blames Faulty Wells for Water Contamination," *Inside Climate News*, July 11, 2016, https://insideclimatenews.org/news/11072016/water-contamination-near-colorado-fracking-tied-well-failures.
[631] U.S. Agency for Toxic Substances and Disease Registry, "Health Consultation: Dimock Groundwater Site" (U.S. Department of Health and Human Services, May 24, 2016), https://www.atsdr.cdc.gov/hac/pha/DimockGroundwaterSite/Dimock_Groundwater_Site_HC_05-24-2016_508.pdf.
[632] Abraham Lustgarten, "Federal Report Appears to Undercut EPA Assurances on Water Safety In Pennsylvania," *ProPublica*, June 9, 2016, https://www.propublica.org/article/federal-report-appears-to-undercut-epa-assurances-water-safety-pennsylvania.
[633] U.S. Environmental Protection Agency, "EPA Completes Drinking Water Sampling in Dimock, Pa.," press release (EPA, July 25, 2012), https://archive.epa.gov/epapages/newsroom_archive/newsreleases/1a6e49d193e1007585257a46005b61ad.html.
[634] Denise M. Akob et al., "Wastewater Disposal from Unconventional Oil and Gas Development Degrades Stream Quality at a West Virginia Injection Facility," *Environmental Science & Technology* 50, no. 11 (June 7, 2016): 5517–25, https://doi.org/10.1021/acs.est.6b00428.
[635] Darryl Fears, "This Mystery Was Solved: Scientists Say Chemicals From Fracking Wastewater Can Taint Fresh Water Nearby," *The Washington Post*, May 11, 2016, sec. Climate and Environment, https://www.washingtonpost.com/news/energy-environment/wp/2016/05/11/this-mystery-was-solved-scientists-say-chemicals-from-fracking-wastewater-can-taint-fresh-water-nearby/?utm_term=.c27045b60338.

was done in collaboration with Susan Nagel's team, which studied endocrine-disrupting activity in this same stream. See entry below for April 6, 2016.)

- April 30, 2016 – As part of an investigation based on aerial photographs taken by emergency responders during spring 2016 flooding, the *El Paso Times* documented plumes and sheens of chemicals from tipped-over storage tanks and inundated oil wells and fracking sites entering rivers and streams. "Many of the photos shot during Texas' recent floods show swamped wastewater ponds at fracking sites, presumably allowing wastewater to escape into the environment—and potentially into drinking-water supplies."[636]

- April 27, 2016 – Using geochemical and isotopic tracers to identify the unique chemical fingerprint of Bakken region brines, a Duke University study found that accidental spills of fracking wastewater have contaminated surface water and soils throughout North Dakota where more than 9,700 wells have been drilled in the past decade. Contaminants included salts as well as lead, selenium, and vanadium. In the polluted streams, levels of contaminants often exceeded federal drinking water guidelines. Soils at spill sites showed elevated levels of radium.[637] The study concluded that "inorganic contamination associated with brine spills in North Dakota is remarkably persistent, with elevated levels of contaminants observed in spill sites up to 4 years following the spill events." In a comment about this study, lead author and Duke University geochemist Avner Vengosh said, "Until now, research in many regions of the nation has shown that contamination from fracking has been fairly sporadic and inconsistent. In North Dakota, however, we find it is widespread and persistent, with clear evidence of direct water contamination from fracking."[638]

- April 6, 2016 – A research team led by Susan Nagel at the University of Missouri traced a spike in endocrine-disrupting activity in a West Virginia stream, Wolf Creek, to an upstream facility that stores fracking wastewater. Levels detected downstream of the waste facility were above levels known to create adverse health effects and alter the development of fish, amphibians, and other aquatic organisms. Endocrine-disrupting compounds were not elevated in upstream sections of the creek.[639, 640] (See also entry for May 9, 2016 above.)

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[636] Marty Schladen, "Flooding Sweeps Oil, Chemicals Into Rivers," *El Paso Times*, April 30, 2016, sec. News, http://www.elpasotimes.com/story/news/2016/04/30/flooding-sweeps-oil-chemicals-into-rivers/83671348/.
[637] Nancy E. Lauer, Jennifer S. Harkness, and Avner Vengosh, "Brine Spills Associated with Unconventional Oil Development in North Dakota," *Environmental Science & Technology* 50, no. 10 (2016): 5389–97, https://doi.org/10.1021/acs.est.5b06349.
[638] Nicholas School of the Environment, "Contamination in North Dakota Linked to Fracking Spills," press release (Duke University, April 27, 2016).
[639] Christopher D. Kassotis et al., "Endocrine Disrupting Activities of Surface Water Associated With a West Virginia Oil and Gas Industry Wastewater Disposal Site," *Science of the Total Environment* 557–558 (2016): 901–10, https://doi.org/10.1016/j.sci.tenv.2016.03.113.
[640] Brian Bienkowski, "In West Virginia, Frack Wastewater May Be Messing with Hormones," *Environmental Health News*, April 5, 2016, https://www.organicconsumers.org/news/west-virginia-frack-wastewater-may-be-messing-hormones.

- March 29, 2016 – A study by Stanford University scientists determined that fracking and related oil and gas operations have indeed contaminated drinking water in the town of Pavillion, Wyoming where residents have long complained about foul-tasting water. The researchers found substances in the water that match those used in local fracking operations or found in nearby pits used for the disposal of drilling waste. Chemical contaminants included benzene, a known carcinogen, and toluene, a neurotoxicant. Possible mechanisms for contamination include defective cement well casings; spills and leaks from disposal pits; and underground migration of chemicals into aquifers from the fracked zone, which, in this area, is quite shallow. Also, in the Pavillion area, operators sometimes fracked directly into underground sources of water.[641] One of the authors of this study, Dominic DiGuilio, was also a lead scientist on the EPA's earlier aborted investigation of Pavillion's drinking water. (See entry for December 6, 2015 below.) In an interview about his new research, DiGiulio said that his findings raise concerns about similar water pollution in other heavily fracked regions. "Pavillion isn't geologically unique in the West, and I'm concerned about the Rocky Mountain region of the U.S. The impact on [underground drinking water sources] could be fairly extensive. Pavillion is like a canary in a coal mine and we need to look at other fields."[642] Co-author Rob Jackson noted, "There are no rules that would stop a company from doing this anywhere else."[643]

- February 22, 2016 – Relying on voluntary disclosures reported to the FracFocus registry and a list compiled by the U.S. Congress, a German team surveyed the physiochemical properties of chemicals used in hydraulic fracturing fluid to evaluate their environmental fate and potential toxicity. Common ingredients included those known to contaminant groundwater, such as solvents, as well as those known to react strongly with other chemicals, such as biocides and strong oxidants, indicating that almost certainly, new chemical products are formed during the process of fracking and its aftermath. Hence, non-toxic additives could potentially react with other substances to create harmful byproducts. The authors conclude that a comprehensive assessment of risks would require an unabridged list of the chemical additives used for fracking, and they call for full disclosure.[644, 645]

- February 9, 2016 – An investigation of water contamination in the Barnett Shale by ABC-affiliate station WFAA in Dallas found numerous violations by operators who

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641 Dominic C. DiGiulio and Robert B. Jackson, "Impact to Underground Sources of Drinking Water and Domestic Wells from Production Well Stimulation and Completion Practices in the Pavillion, Wyoming, Field," *Environmental Science & Technology* 50 (2016): 4524–36, https://doi.org/10.1021/acs.est.5b04970.
642 Neela Banerjee, "Fracking Study Finds Toxins in Wyoming Town's Groundwater and Raises Broader Concerns," *Inside Climate News*, March 29, 2016, sec. Fossil Fuels, https://insideclimatenews.org/news/29032016/fracking-study-pavillion-wyoming-drinking-water-contamination-epa.
643 Rob Jordan, "Stanford Researchers Show Fracking's Impact to Drinking Water Sources," *Stanford News*, March 29, 2016, http://news.stanford.edu/2016/03/29/pavillion-fracking-water-032916/.
644 Martin Elsner and Kathrin Hoelzer, "Quantitative Survey and Structural Classification of Hydraulic Fracturing Chemicals Reported in Unconventional Gas Production," *Environmental Science & Technology* 50, no. 7 (2016): 3290–3314, https://doi.org/10.1021/acs.est.5b02818.
645 American Chemical Society, "How to Get a Handle on Potential Risks Posed by Fracking Fluids," Phys.org, March 9, 2016, https://web.archive.org/web/20160310104849/http://phys.org/news/2016-03-potential-posed-fracking-fluids.html.

ignored regulations that require sealing vertical well pipes with a cement sheath to protect groundwater from stray gas and other vapors that might escape and migrate upwards into overlying aquifers. The WFAA report said that the Texas Railroad Commission, which oversees drilling and fracking operations in Texas, has failed to respond to alleged violations of a rule that requires cement seals around steel well casings in geological zones where drilling has penetrated layers of rock containing oil and gas deposits.[646]

- February 8, 2016 – An investigation by the *Columbus Dispatch* revealed that the amount of water that operators use for hydraulic fracturing in Ohio gas wells increased steadily from 2011 to 2015. The total amount of water increased, as did the volume of water used per well—from an average of 5.6 million gallons per well in 2011 to 7.6 million in 2014. The reason is that the horizontally drilled holes beneath each well have become longer, and these require more water during the fracking process.[647]

- February 2016 – In a lengthy account to Congress on the status of the underground waste injection well program that is overseen by the EPA, the U.S. Government Accountability Office (GAO) reported that the agency "has not consistently conducted oversight activities necessary to assess whether state and EPA-managed programs are protecting underground sources of drinking water" from contamination by fracking waste. Specifically, the GAO took the EPA to task for failure to require well-specific inspections, collect data on enforcement actions, review permitting requirements by state regulatory agencies, or analyze the resources the agency would need to do all the above to adequately oversee the Underground Injection Control program. The GAO noted that it had once before, in 2014, previously found the EPA negligent in its responsibilities to monitor drinking water sources for possible contamination with fracking waste.[648] (See entry below for September 23, 2014.)

- January 6, 2016 – Yale School of Public Health researchers analyzed more than 1,021 chemicals either used in fracking fluid or created during the process of hydraulic fracturing. They found that 781 of these chemicals lacked basic toxicity data. Of the 240 that remained, 157 were reproductive or developmental toxicants. These included arsenic, benzene, cadmium, formaldehyde, lead, and mercury.[649] Commenting on this study, lead author Nicole Deziel said, "This evaluation is a first step to prioritize the vast array of potential environmental contaminants from hydraulic fracturing for future exposure and health studies. Quantification of the potential exposure to these chemicals, such as by

[646] Brett Shipp, "Drilling Records Suggest Lax State Enforcement," *WFAA*, February 9, 2016, https://web.archive.org/web/20160914000244/http://www.wfaa.com/mb/news/local/investigates/rules-ignored-water-fouled-in-barnett-shale/38337835.
[647] Laura Arenschield, "Drillers Using More Water to Frack Ohio Shale," *The Columbus Dispatch*, February 8, 2016, http://www.dispatch.com/content/stories/local/2016/02/07/drillers-using-more-water-to-frack-ohio-shale.html.
[648] U.S. Government Accountability Office, "Drinking Water: EPA Needs to Collect Information and Consistently Conduct Activities to Protect Underground Sources of Drinking Water," February 2016, http://gao.gov/assets/680/675439.pdf.
[649] Elise G. Elliott et al., "A Systematic Evaluation of Chemicals in Hydraulic-Fracturing Fluids and Wastewater for Reproductive and Developmental Toxicity," *Journal of Exposure Science & Environmental Epidemiology* 27, no. 1 (2016): 90–99, https://doi.org/10.1038/jes.2015.81.

monitoring drinking water in people's homes, is vital for understanding the public health impact of hydraulic fracturing."[650]

- December 15, 2015 – A research team led by geologist Mukul Sharma from Dartmouth College discovered that chemical reactions between fracking fluid and rock can contribute to the toxicity of fracking wastewater. Specifically, the researchers found that fracking fluid can chemically react with the fractured shale in ways that cause barium, a toxic metal, to leach from clay minerals in the Marcellus Shale.[651, 652]

- December 6, 2015 – The *Caspar Star Tribune* investigated the EPA's decision to transfer its study of possible fracking-related drinking water contamination in Pavillion, Wyoming to a state agency in 2013. Preliminary data from the EPA suggested that drilling and fracking operations had contaminated drinking water supplies. To date, the state study has found no definitive link between drilling and water contamination. Interviews with officials and documents obtained under the Freedom of Information Act revealed that the EPA had bowed to political pressure from state officials and industry representatives and that Wyoming regulators narrowed the scope of the study considerably and conducted little fieldwork.[653] (See also entry above for March 29, 2016.)

- November 19, 2015 – The Science Advisory Board (SAB) for the EPA reviewed the EPA's June 2015 draft assessment of fracking's impacts on drinking water, and challenged some of the summary statements that accompanied it, saying that they were over-generalized and not always aligned with the data in the report itself. Specifically, the SAB said, in a draft review, that the data cited by the report were too limited to support the headlined claim in the executive summary that drinking water impacts were neither "widespread" nor "systemic." The SAB also critiqued the study for downplaying local impacts in its conclusions, noting that these impacts can sometimes be severe.[654]

- October 19, 2015 – A six-month investigation by *Penn Live* found long-standing "systemic failures" on the part of the Pennsylvania Department of Environmental Protection (PA DEP) to enforce regulations governing drilling and fracking operations. Lack of oversight and reliance on industry self-policing have been the hallmarks of Marcellus Shale development for the past ten years, in violation of Pennsylvanians'

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650 Michael Greenwood, "Chemicals in Fracking Fluid and Wastewater Are Toxic, Study Shows," *Yale News*, January 6, 2016, http://news.yale.edu/2016/01/06/toxins-found-fracking-fluids-and-wastewater-study-shows.s
651 Devon Renock, Joshua D. Landis, and Mukul Sharma, "Reductive Weathering of Black Shale and Release of Barium During Hydraulic Fracturing," *Applied Geochemistry* 65 (2016): 73–86, https://doi.org/10.1016/j.apgeochem.2015.11.001.
652 Dartmouth College, "Fracking Plays Active Role in Generating Toxic Metal Wastewater, Study Finds," *Science Daily*, December 15, 2015, https://www.sciencedaily.com/releases/2015/12/151215134653.htm.
653 Benjamin Storrow, "Pavillion Today: An EPA in Retreat, a Narrow State Inquiry and No Answers," *Casper Star Tribune*, December 6, 2015, http://trib.com/business/energy/pavillion-today-an-epa-in-retreat-a-narrow-state-inquiry/article_403f84de-830c-5558-9f3f-ea48fd48d7ca.html?utm_medium=social&utm_source=facebook&utm_campaign=user-share.
654 Neela Banerjee, "EPA Finding on Fracking's Water Pollution Disputed by Its Own Scientists," *Inside Climate News*, November 19, 2015, https://insideclimatenews.org/news/19112015/fracking-water-pollution-epa-study-natural-gas-drilling.

constitutional right to clean air and water. Among the findings of this investigation: chronically leaking wastewater impoundments for which no fines or notices were issued to the operator; laboratory coding systems designed to obscure possible detections of certain chemical contaminants in residents' drinking water; and lack of inspections at well sites.[655]

- October 13, 2015 – An international team of researchers found detectable levels of multiple organic chemical contaminants in private drinking water wells in northeastern Pennsylvania where fracking is practiced. One of the compounds was a known additive of fracking fluid. Chemical fingerprinting and noble gas isotopes were used to determine if the contaminants most likely originated from surface spills at the well site or via upward transport from the shale itself. The organic pollutants found in the water did not contain chemical markers—certain elements and salts—that would indicate migration from deep geological strata. The authors concluded that "the data support a transport mechanism…to groundwater via accidental release of fracturing fluid chemicals derived from the surface rather than subsurface flow of these fluids from the underlying shale formation."[656, 657]

- September 23, 2015 – A team of researchers, examining how natural gas drilling and fracking operations across the nation affect creeks, streams and rivers, developed a predictive model and vulnerability index for surface water. They found that "all shale plays, regardless of location, had a suite of catchments that spanned highly degraded to those that are less altered and naturally sensitive to alteration." Surface water in Pennsylvania's Marcellus Shale region is classified by this model as vulnerable to fracking-related impacts because of steep slopes and loose, erodible soils within the watersheds.[658]

- July 30, 2015 – As reported by the *Los Angeles Times*, unlined waste pits and hillside spraying of oil-field wastewater have contaminated groundwater in Kern County, California. Five of six monitoring wells in the 94-acre waste site showed high levels of salt, boron, and chloride, but it is not known how far and fast the contaminated plume has traveled.[659]

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[655] Candy Woodall, "Pa. Regulators Fail to Protect Environment During Marcellus Shale Boom," *Penn Live*, October 19, 2015, http://www.pennlive.com/midstate/index.ssf/2015/10/state_regulators_fail_to_prote.html.
[656] Brian D. Drollette et al., "Elevated Levels of Diesel Range Organic Compounds in Groundwater Near Marcellus Gas Operations ARe Derived From Surface Activities," *Proceedings of the National Academy of Sciences* 112, no. 43 (2015): 13184–89, https://doi.org/10.1073/pnas.1511474112.
[657] Brian D. Drollette and Desiree L. Plata, "Hydraulic Fracturing Components in Marcellus Groundwater Likely From Surface Operations, Not Wells," *Phys.Org*, October 13, 2015, http://phys.org/news/2015-10-hydraulic-fracturing-components-marcellus-groundwater.html.
[658] Sally A. Entrekin et al., "Stream Vulnerability to Widespread and Emergent Stressors: A Focus on Unconventional Oil and Gas," *PLoS ONE* 10, no. 9 (2015): e0137416, https://doi.org/10.1371/journal.pone.0137416.
Julie Cart, "Central Valley Board Allows Wastewater Disposal to Continue Despite Contamination," *Los Angeles Times*, July 30, 2015, http://www.latimes.com/local/california/la-me-oil-waste-pits-20150731-story.html.

- July 21, 2015 – By surveying records for 44,000 wells fracked between 2010 and 2013, researchers from Stanford University, Duke University, and Ohio State University attempted a first-ever assessment of the range of depths at which fracking occurs across the United States. They found that many wells are shallower than widely presumed.[660] As the authors noted, vertical fractures are able to propagate 2,000 feet upward, and hence, "shallow hydraulic fracturing often has greater potential risks of contamination than deeper hydraulic fracturing does." This study showed that drinking water sources may be more vulnerable from upward migration of fracking contaminants than previously presumed. Surprisingly, the researchers found no strong relationship between depth and the volume of water and chemicals used for fracking. Many wells were both shallow and water-intensive, with significant variation in water use from state to state.[661]

- July 9, 2015 – A multi-volume report from the California Council of Science and Technology (CCST) found threats to groundwater in California from several parts of the fracking lifecycle, most notably from toxic wastewater. First, wastewater from California fracking operations is sometimes used for crop irrigation, in which case contaminants may seep from the surface of agricultural areas into groundwater. Second, nearly 60 percent of fracking wastewater in California is disposed of in unlined, open-air pits, a practice that is banned in almost all other states. There are 900 such waste disposal pits in the state, most of which are located in Kern County. Third, for many years, fracking wastewater in California has been mistakenly sent, via injection wells, directly into protected aquifers containing clean freshwater.[662] California's Division of Oil, Gas and Geothermal Resources allowed fracking wastes to be injected into aquifers that it believed were exempt from the U.S. Safe Drinking Water Act. Conceding this mistake, the agency has shut down 23 injection wells for fracking waste disposal and established a two-year timetable for phasing out other wells injecting waste into aquifers that should have been protected.[663] Fracking also threatens California's groundwater resources through water consumption, according to the CCST study. While this volume of water represents a small percentage of overall annual water consumption in California, fracking-related water use is, the study noted, disproportionately concentrated in areas of the state already suffering from water shortages. Further drawdowns of these aquifers may interfere with agricultural and municipal water needs.[664] In addition, because the oil-containing rock layers in California are located closer to the surface than in other states, the state's groundwater is potentially vulnerable to chemical contamination through vertical faults and fissures and via old and abandoned wells. The absence of evidence for

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[660] Rob Jordan, "Shallow Fracking Raises Questions for Water, New Stanford Research Shows," *Stanford News*, July 21, 2015, http://news.stanford.edu/news/2015/july/fracking_water-jackson-072115.html.
[661] Robert A. Jackson et al., "The Depths of Hydraulic Fracturing and Accompanying Water Use Across the United States," *Environmental Science & Technology* 49, no. 5 (2015): 8969–76, https://doi.org/10.1021/acs.est.5b01228.
[662] Seth B. C. Shonkoff et al., "Chapter 6: Potential Impacts of Well Stimulation on Human Health in California," in *An Independent Scientific Assessment of Well Stimulation in California* (California Council on Science and Technology, 2015), 372–445, https://ccst.us/wp-content/uploads/160708-sb4-vol-II-6-1.pdf.
[663] David R. Baker, "U.S. Likely to Bar Oil-Waste Dumping Into 10 California Aquifers," *San Francisco Chronicle*, July 16, 2015, sec. Biz & Tech, http://www.sfchronicle.com/business/article/U-S-likely-to-bar-oil-waste-dumping-into-10-6389677.php.
[664] William T. Stringfellow et al., "Chapter 2: Impacts of Well Stimulation on Water Resources," in *An Independent Scientific Assessment of Well Stimulation in California* (California Council on Science & Technology, 2015), 49–181, http://ccst.us/publications/2015/vol-II-chapter-2.pdf.

direct contamination of groundwater by fracking, the study concluded, reflects absence of investigation rather than evidence of safety.[665]

- June 30, 2015 – The USGS released the first nationwide map of water usage for hydraulic fracturing. It shows wide geographic and temporal variation in the amount of water used to frack a single well. In general, gas wells consume more water per well (5.1 million gallons on average) than oil wells (4 million gallons). Median annual water volumes needed to frack a single horizontal oil or gas well increased dramatically—by a factor of 25 or more—between 2000 and 2014. A typical gas or oil well that is horizontally fracked now requires between six and eight Olympic-sized swimming pools of water. In 2014, the majority (58 percent) of new hydraulically fracked oil and gas wells were horizontally drilled. The watersheds where the most water was consumed for hydraulic fracturing are mostly located in southern or southwestern states and correspond to the following shale formations: the Eagle Ford and Barnett Shales in Texas; the Haynesville-Bossier Shale in Texas and Louisiana; the Fayetteville Shale in Arkansas; the Tuscaloosa Shale in Louisiana and Mississippi; and the Woodford Shale in Oklahoma. The Marcellus and Utica Shales—which underlie watersheds in parts of Ohio, Pennsylvania, West Virginia, and New York—were also in the top seven water-consuming shale plays in the United States.[666]

- June 26, 2015 – A decade-long USGS study of 11,000 public drinking water wells in California—nearly all the groundwater used for public supply—found high levels of potentially toxic contaminants in about 20 percent of the wells, affecting about 18 percent of the state's population.[667] Although the study did not specifically investigate contaminants from oil and gas extraction, it does provide evidence for farm irrigation draining into groundwater, raising questions about the possible contamination of drinking water aquifers from the reuse of fracking wastewater for crop irrigation.[668]

- June 16, 2015 – A University of Texas research team documented widespread drinking water contamination throughout the heavily drilled Barnett Shale region in northern Texas. The study, which analyzed 550 water samples from public and private water wells, found elevated levels of 19 different hydrocarbon compounds associated with fracking (including the carcinogen benzene and the reproductive toxicant, toluene), detections of methanol and ethanol, and strikingly high levels of 10 different metals.[669]

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[665] Jane C. S. Long, Jens T. Birkholzer, and Laura C. Feinstein, "An Independent Scientific Assessment of Well Stimulation in California: An Examination of Hydraulic Fracturing and Acid Stimulations in the Oil and Gas Industry," Summary Report (California Council on Science & Technology, July 9, 2015), http://ccst.us/publications/2015/2015SB4summary.pdf.
[666] Tanya J. Gallegos et al., "Hydraulic Fracturing Water Use Variability in the United States and Potential Environmental Implications," *Water Resources Research* 51, no. 7 (2015): 5839–45, https://doi.org/10.1002/2015WR017278.
[667] Kenneth Belitz, Miranda S. Fram, and Tyler D. Johnson, "Metrics for Assessing the Quality of Groundwater Used for Public Supply, CA, USA: Equivalent-Population and Area," *Environmental Science & Technology* 49, no. 14 (2015): 8330–38, https://doi.org/10.1021/acs.est.5b00265.
[668] Ellen Knickmeyer and Scott Smith, "Study Finds Contaminants in California Public-Water Supplies," *Phys.Org*, July 15, 2015, https://phys.org/news/2015-07-contaminants-california-public-water.html.
[669] Zacariah L. Hildenbrand et al., "A Comprehensive Analysis of Groundwater Quality in The Barnett Shale Region," *Environmental Science & Technology* 49, no. 13 (2015): 8254–62, https://doi.org/10.1021/acs.est.5b01526.

"In the abstract, we can't state that unconventional oil and gas techniques are responsible," the lead author, Zachariah Hildenbrand, said in a media interview. "But when you get into areas where drilling is happening, you find more instances of contamination. It's not coincidental. There are causes for concern."[670]

- June 5, 2015 – The EPA's long-awaited 600-page draft report on the potential impacts of fracking for drinking water resources confirmed specific instances of drinking water contamination linked to drilling and fracking activities. The report also identified potential mechanisms, both above and below ground, by which drinking water resources can be contaminated by fracking. In some cases, drinking water was contaminated by spills of fracking fluid and wastewater. In other cases, "[b]elow ground movement of fluids, including gas . . . have contaminated drinking water resources." The EPA investigators documented 457 fracking-related spills over six years but acknowledged that they do not know how many more may have occurred. Of the total known spills, 300 reached an environmental receptor such as surface water or groundwater. The EPA also conceded that insufficient baseline drinking water data and a lack of long-term systematic studies limited the power of its findings. The EPA investigation confirmed a number of specific instances where these potential mechanisms did indeed lead to drinking water contamination. An assertion in the EPA's accompanying press release that it had not found "widespread, systemic impacts to drinking water resources" was quoted out of context by many media sources as proof that fracking poses little threat to drinking water. To the contrary, this report confirmed that drilling and fracking activities have contaminated drinking water in some cases and acknowledged that it cannot ascertain how widespread the problem was due to insufficient data.[671] EPA Science Advisor Thomas A. Burke later clarified that the report does not show that fracking is safe. Burke said, "That is not the message of this report. The message of this report is that we have identified vulnerabilities in the water system that are really important to know about and address to keep risks as low as possible."[672]

- May 19, 2015 – A Pennsylvania State University research team documented the presence of a fracking-related solvent, 2-n-Butoxyethanol, in the drinking water from three homes in Bradford County, Pennsylvania, as part of an investigation of private drinking water wells near drilling and fracking operations that contained methane and foam. This finding represents the first fully documented case of a commonly used fracking chemical entering a drinking water source. "The most likely explanation of the incident is that stray natural gas and drilling or [hydrofracking] compounds were driven ~1-3 km along shallow to intermediate depth fractures to the aquifer used as a potable water source."[673] In an accompanying *New York Times* story, lead author Susan Brantley described the geology

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[670] C. McPhate, "New Study Reveals Potential Contamination," *Denton Record-Chronicle*, June 18, 2015.
[671] U.S. EPA, "Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources," External review draft (U. S. Environmental Protection Agency, 2015), http://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=244651.
[672] Ken Ward Jr., "EPA Says New Study Doesn't Show Fracking Is Safe," *Charleston Gazette-Mail*, June 7, 2015, http://www.wvgazettemail.com/article/20150607/GZ01/150609432.
[673] Garth T. Llewellyn et al., "Evaluating a Groundwater Supply Contamination Incident Attributed to Marcellus Shale Gas Development," *Proceedings of the National Academy of Sciences* 112, no. 20 (2015): 6325–30, https://doi.org/10.1073/pnas.1420279112/-/DCSupplemental.

in northern Pennsylvania "as being similar to a layer cake with numerous layers that extend down thousands of feet to the Marcellus Shale. The vertical fractures are like knife cuts through the layers. They can extend deep underground, and can act like superhighways for escaped gas and liquids from drill wells to travel along, for distances greater than a mile away."[674]

- May 15, 2015 – A research team from the University of Colorado Boulder and California State Polytechnic Institute developed a model for identifying which fracking fluid chemicals are most likely to contaminate drinking water. Of 996 fracking fluid compounds known to be in use, researchers screened 659 of them for their ability to persist, migrate, and reach groundwater aquifers over a short time scale. Of the fifteen compounds so identified, two were commonly used in fracking operations: naphthalene and 2-butoxyethanol. Both are ingredients in surfactants and corrosion inhibitors. The authors noted that 2-butoxyethanol has been detected in drinking water in a heavily fracked area of Pennsylvania. Exposure to 2-butoxyethanol has been linked to birth defects in animals. Naphthalene is a possible human carcinogen that is toxic to red blood cells and contributes to kidney and liver damage. Researchers did not consider the impact of mixtures, interactions between contaminants, or chemical transformations during the fracking or flowback process and noted, "the need for data on the degradation of many compounds used in fracturing fluids under conditions relevant for groundwater transport."[675]

- May 7, 2015 – A survey of streams in Arkansas, led by the University of Central Arkansas, found alterations in macroinvertebrate communities to be related to drilling and fracking operations in the Fayetteville Shale. Fracking activity near streams was associated with greater sediment and more chlorophyll. "This study suggests that land disturbance from gas development affected stream communities."[676]

- April 20, 2015 – A USGS team analyzed water brought to the surface during natural gas extraction at 13 fracked wells in northern Pennsylvania. They found large variability in the VOCs and microorganisms in the water samples from different wells. Organic chemical contaminants included benzene, toluene, and perchloroethylene, chloroform, and methylene chloride. The presence of microbes was associated with concentrations of benzene and acetate. Despite the addition of biocides during the fracking process, hydrogen sulfide-producing bacteria were present at culturable levels, along with methogenic and fermenting bacteria. The source of these microorganisms was not determined. "Therefore, we cannot exclude the possibility that these microorganisms are native to the shale formation and reactivated by [hydrofracking] activities, as their

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[674] Nicholas St. Fleur, "Fracking Chemicals Detected in Pennsylvania Drinking Water," *The New York Times*, May 4, 2015, sec. Climate and Environment, http://www.nytimes.com/2015/05/05/science/earth/fracking-chemicals-detected-in-pennsylvania-drinking-water.html?_r=0#addendums.
[675] Jessica D. Rogers et al., "A Framework for Identifying Organic Compounds of Concern in Hydraulic Fracturing Fluids Based on Their Mobility and Persistence in Groundwater," *Environmental Science & Technology Letters* 2, no. 6 (2015): 158–64, https://doi.org/10.1021/acs.estlett.5b00090.
[676] Erica Johnson et al., "Stream Macroinvertebrate Communities Across a Gradient of Natural Gas Development in the Fayetteville Shale," *Science of the Total Environment* 530–531 (2015): 323–32, https://doi.org/10.1016/j.scitotenv.2015.05.027.

physiology does not indicate a terrestrial surficial source."[677]

- April 8, 2015 – A University of Colorado Boulder research team's analysis of the organic chemicals found in liquid waste that flowed out of gas wells in Colorado after they had been fracked revealed the presence of many fracking fluid additives, including biocides, which are potentially harmful if they leak into groundwater. According to the authors, treatment of fracking wastewater must include aeration, precipitation, disinfection, a biological treatment to remove dissolved organic matter, and reverse osmosis desalination in order for it to be appropriate for non-fracking uses, such as crop irrigation.[678]

- March 18, 2015 – Using a new stream-based monitoring method, a team of scientists with USGS, Pennsylvania State University, and University of Utah found elevated levels of methane in groundwater discharging into a stream near drilling and fracking operations in Pennsylvania. In this same area, several private water wells contained high levels of methane as a result of gas migration near a gas well with a defective casing. The monitoring technique used by the scientists allowed them to demonstrate that the source of the methane was shale gas from the Middle Devonian period, which is the kind of gas found in the Marcellus Shale.[679] Researcher Susan Brantley said, "I found it compelling that using this new method for a reconnaissance of just 15 streams in Pennsylvania, we discovered one instance of natural gas entering the stream, perhaps from a nearby leaking shale gas well."[680]

- March 12, 2015 – A team led by geologist Donald Siegel of Syracuse University found no relationship between methane levels in drinking water wells and proximity to oil or gas wells in a heavily fracked area of northeastern Pennsylvania.[681] However, Siegel failed to reveal in his paper — as is required by the journal — that he had received industry funding from the Chesapeake Energy Corporation. Subsequently, the journal published a lengthy correction that revealed that Chesapeake had not only privately funded the lead author but had provided the baseline groundwater data set. A second author was revealed to be a former employee of Chesapeake, and another had worked as

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[677] Denise M. Akob et al., "Organic and Inorganic Composition and Microbiology of Produced Waters From Pennsylvania Shale Gas Wells," *Applied Geochemistry* 60 (2015): 116–25, https://doi.org/10.1016/j.apgeochem.2015.04.011.
[678] Yaal Lester et al., "Characterization of Hydraulic Fracturing Flowback Water in Colorado: Implications for Water Treatment," *Science of the Total Environment* 512–513 (2015): 637–44, https://doi.org/10.1016/j.scitotenv.2015.01.043.
[679] Victor M. Heilweil et al., "Stream Measurements Locate Thermogenic Methane Fluxes in Groundwater Discharge in an Area of Shale-Gas Development," *Environmental Science & Technology* 49, no. 7 (2015): 4057–65, https://doi.org/10.1021/es503882b.
[680] U.S. Geological Survey, "Exploring: New Stream Monitoring Method Locates Elevated Groundwater Methane In Shale-Gas Development Area," *Science Explorer*, April 1, 2015, https://www.usgs.gov/science-explorer-results?es=New+stream+monitoring+method+locates+elevated+groundwater+methane+in+shale-gas+development+area.
[681] Donald L. Siegel et al., "Methane Concentrations in Water Wells Unrelated to Proximity to Existing Oil and Gas Wells in Northeastern Pennsylvania," *Environmental Science & Technology* 49, no. 7 (2015): 4106–12, https://doi.org/10.1021/es505775c.

a consultant in the energy sector.[682]

- March 3, 2015 – A Duquesne University study of private drinking water wells in an intensely drilled southwestern Pennsylvania community compared pre-drill and post-drill data on water quality and found changes in water chemistry that coincided with the advent of drilling and fracking activities. Levels of chloride, iron, barium, strontium, and manganese were elevated. In some cases, concentrations exceeded health-based maximum contaminant levels. Methane was detected in most houses tested. Surveys of residents revealed widespread complaints about changes in water quality that began after drilling and fracking operations commenced. Violation records from the PA DEP uncovered possible pathways for water contamination. The researchers concluded that alterations of local hydrology caused by the injection of large volumes of hydraulic fracturing fluids may have mobilized contaminants left over from legacy oil, gas, and mining operations as well as opened pathways for the migration of fracking fluids themselves.[683]

- March 3, 2015 – A research team from Duquesne University reviewed the evidence for environmental impacts to air and water from activities related to shale gas extraction in Pennsylvania and explored potential mechanisms for contamination of air and water related to the drilling and fracking process itself. Among them: deformations of the shale bedrock caused by the injection of large volumes of fluid result in "pressure bulbs" that are translated through rock layers and can impact faults and fissures, so affecting groundwater.[684]

- February 23, 2015 – The arrival of drilling and fracking activities coincided with an increase in salinity in a creek that drains public land in a semi-arid region of Wyoming, determined a USGS study. The dissolved minerals associated with the rise in salinity matched those found in native soil salts, suggesting that disturbance of naturally salt-rich soils by ongoing oil and gas activities, including pipeline, road, and well pad construction, was the culprit. "As [shale gas and oil] development continues to expand in semiarid lands worldwide, the potential for soil disturbance to increase stream salinity should be considered, particularly where soils host substantial quantities of native salts."[685]

- February 14, 2015 – A review by a *Dickinson Press* news reporter of disposal well files

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[682] Donald L. Siegel et al., "Correction to Methane Concentrations in Water Wells Unrelated to Proximity to Existing Oil and Gas Wells in Northeastern Pennsylvania," *Environmental Science & Technology* 49, no. 9 (2015): 5840, https://doi.org/10.1021/acs.est.5b01800.
[683] Shyama K. Alawattegama et al., "Well Water Contamination in a Rural Communityt in Southwestern Pennsylvania Near Unconventional Shale Gas Extraction," *Journal of Environmental Science and Health, Part A* 50, no. 5 (2015): 516–28, https://doi.org/10.1080/10934529.2015.992684.
[684] David J. Lampe and John F. Stolz, "Current Perspectives on Unconventional Shale Gas Extraction in the Appalachian Basin," *Journal of Environmental Science and Health, Part A* 50, no. 5 (2015): 464–446, https://doi.org/10.1080/10934529.2015.992653.
[685] Carleton R. Bern et al., "Soil Disturbance as a Driver of Increased Stream Salinity in a Semiarid Watershed Undergoing Energy Development," *Journal of Hydrology: Regional Studies* 524 (2015): 123–36, https://doi.org/10.1016/j.jhydrol.2015.02.020.

and more than 2,090 mechanical integrity tests revealed that North Dakota frack waste injection wells were often leaky and that state regulators continued to allow fluid injection into wells with documented structural problems even though the wells did not meet EPA guidelines for wellbore integrity. Officials with the North Dakota Division of Oil and Gas said they had primary enforcement responsibilities and that EPA guidance did not apply to these wells. The investigation noted, "… a review of state and federal documents, as well as interviews with geologists, engineers, environmental policy experts and lawyers who have litigated under the Safe Drinking Water Act, suggests the agency is loosely interpreting guidance and protocols that are meant to maintain the multiple layers of protection that separate aquifers from the toxic saltwater." *The Dickinson Press* is the daily newspaper for Stark County in southwest North Dakota.[686]

- February 11, 2015 – The *Los Angeles Times* analyzed self-reported testing results on fracking wastewater that California drillers were required to submit to the state. Samples of wastewater collected from 329 fracked oil wells found that virtually all—98 percent—contained benzene at levels that exceeded standards for permissible concentrations in drinking water. This finding likely underrepresents the extent of the problem, according to the newspaper investigation, because many operators failed to comply with reporting requirements. The discovery that fracking wastewater is high in benzene is particularly alarming in light of the admission by the state of California that it had inadvertently allowed frack waste disposal directly into aquifers containing clean water that could potentially be used for drinking. Those wells are now the subject of federal and state review.[687]

- February 1, 2015 – An investigation of the chemical make-up of fracking fluid found that the compositions of these mixtures vary widely according to region and company, making the process of identifying individual compounds difficult. Classes of hydrocarbon-based chemicals include solvents, gels, biocides, scale inhibitors, friction reducers, and surfactants. Chemical analysis identified around 25 percent of the organic compounds that are believed to be present in fracking fluid and that are necessary to test for in identifying groundwater and drinking water contamination.[688] Dr. Imma Ferrer, lead author, explained in a *Science Daily* article about her research that "[b]efore we can assess the environmental impact of the fluid, we have to know what to look for."[689]

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[686] A. Brown, "Lacking Integrity? State Regulatory Officials Don't Follow EPA Guidance on Saltwater Disposal Wells.," *The Dickinson Press*, February 14, 2015, https://www.thedickinsonpress.com/business/3679507-lacking-integrity-state-regulatory-officials-dont-follow-epa.
[687] J. Cart, "High Levels of Benzene Found in Fracking Waste Water," *Los Angeles Times*, February 11, 2015, http://www.latimes.com/local/california/la-me-fracking-20150211-story.html#page=1.
[688] Imma Ferrer and E. Michael Thurman, "Chemical Constituents and Analytical Approaches for Hydraulic Fracturing Waters," *Trends in Environmental Analytical Chemistry* 5 (2015): 18–25, https://doi.org/10.1016/j.teac.2015.01.003.
[689] Elsevier, "Fracking Fluids Contain Potentially Harmful Compounds If Leaked Into Groundwater," *Science Daily*, April 8, 2015, https://www.sciencedaily.com/releases/2015/04/150408090323.htm.

- January 30, 2015 – A USGS review of national water quality databases found that insufficient data exist to understand the impact of fracking on drinking water.[690] In a media interview, lead author Zack Bowen said, "There are not enough data available to be able to assess the potential effects of oil and gas development over larger geographic areas."[691]

- January 21, 2015 – A team of researchers from the USGS and Virginia Tech University established that petroleum-based hydocarbons can break down underground in ways that promote the leaching of naturally occurring arsenic into groundwater. Arsenic is a known human carcinogen that causes bladder, lung, and skin cancer. Elevated levels of arsenic in drinking water represent a public health threat.[692] Researchers found that arsenic concentrations in a hydrocarbon plume can reach 23 times the current drinking water standard of 10 micrograms per liter. The authors of the study said that the metabolism of carbon-rich petroleum products by subterranean microbes is involved in a complex geochemical process that leads to mobilization of arsenic into aquifers.[693]

- January 14, 2015 – Researchers from Duke University, Dartmouth College, and Stanford University found high levels of iodide, bromide, and ammonium in samples of wastewater from fracking operations in both the Marcellus and Fayetteville Shales. These same chemicals were present when fracking wastewater was discharged into rivers and streams at three treatment sites in Pennsylvania and during an accidental spill in West Virginia. Iodide and bromide are known to create toxic disinfection byproducts when downstream water is subsequently chlorinated for drinking water. In water, ammonium can convert to ammonia, which is toxic to aquatic life. The authors noted that this is the first study to identify ammonium and iodide as widespread in fracking waste discharges.[694] In an interview with the *Pittsburgh Post-Gazette*, lead author Avner Vengosh said that the findings raise new concerns about the environmental and health impacts of wastewater from drilling and fracking operations.[695]

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[690] Zachary H. Bowen et al., "Assessment of Surface Water Chloride and Conductivity Trends in Areas of Unconventional Oil and Gas Development—Why Existing National Data Sets Cannot Tell Us What We Would Like to Know," *Water Resources Research* 51 (2015): 704–15, https://doi.org/10.1002/2014WR016382.
[691] Susan Phillips, "USGS: Fracking Water Quality Data 'Scarce,'" *State Impact Pennsylvania*, March 3, 2015, https://stateimpact.npr.org/pennsylvania/2015/03/03/usgs-fracking-water-quality-data-scarce/.
[692] U.S. Geological Survey, "Exploring: Natural Breakdown Of Petroleum Underground Can Lace Arsenic Into Groundwater," *Science Explorer*, January 26, 2015, https://www.usgs.gov/science-explorer-results?es=Natural+breakdown+of+petroleum+underground+can+lace+arsenic+into+groundwater.
[693] Isabelle M. Cozzarelli et al., "Arsenic Cycling in Hydrocarbon Plumes: Secondary Effects of Natural Attenuation," *Groundwater* 54, no. 1 (2016): 35–45, https://doi.org/10.1111/gwat.12316.
[694] Harkness, J. S., Dwyer, G. S., Warner, N. R., Parker, K. M., Mitch, W. A., & Vengosh, A. (2015). Iodide, bromide, and ammonium in hydraulic fracturing and oil and gas wastewaters: environmental implications. *Environmental Science & Technology*, *49,* 1955-63. doi: Jennifer S. Harkness et al., "Iodide, Bromide, and Ammonium in Hydraulic Fracturing and Oil and Gas Wastewaters: Environmental Implications," *Environmental Science & Technology* 49, no. 3 (2015): 1955–63, https://doi.org/10.1021/es504654n.
[695] Don Hopey, "Study: High Levels of Pollutants From Drilling Waste Found in Pa. Rivers," *Pittsburgh Post-Gazette*, January 14, 2015, http://powersource.post-gazette.com/powersource/latest-oil-and-gas/2015/01/14/Study-High-levels-of-pollutants-from-drilling-waste-found-in-Pennsylvania-rivers-shale/stories/201501140143.

- November 27, 2014 – An interdisciplinary team of researchers found methane contamination in drinking water wells located in eight areas above the Marcellus Shale in Pennsylvania and the Barnett Shale in Texas, with evidence of declining water quality in the Barnett Shale area. By analyzing noble gases and their isotopes (helium, neon, argon), the investigators were able to isolate the origin of the fugitive methane in drinking water. The results implicate leaks through cement well casings as well as via naturally occurring cracks and fissures in the surrounding rock.[696] In a related editorial, one of the study's authors, Robert Jackson, called on the EPA to reopen its aborted investigation into drinking water contamination in heavily fracked areas of Texas. Jackson also emphasized that methane migration through unseen cracks in the rock surrounding the wellbore "raises the interesting possibility that a drilling company could follow procedures — cementing and casing below the local aquifer — and still create a potential pathway for gas to migrate into drinking water."[697]

- November 26, 2014 – A critical review of biocides in fracking fluid by a Colorado State team found that the fate of these chemicals underground is not known and their toxicity not well understood. While many biocides are short-lived, some may transform into more toxic or persistent compounds. Among the most common chemical components of fracking fluid, biocides are used to inhibit the growth of deep-life microorganisms, including sulfate-reducing bacteria that contribute to corrosion of well casings and can form biofilms that prevent the upward flow of natural gas. Oxidizing biocides that are chlorine- or bromine-based can react with other fracking chemicals and may produce toxic halogenated byproducts. The authors noted biocides pose a unique risk for drinking water when fracking liquid waste is treated for discharge to surface water via sewage treatment plants. Sub-lethal concentrations may contribute to adaptation of surviving microorganisms and, hence, antibiotic resistance of pathogens. They cited particular concern over surface spills and well integrity issues associated with casing or cement failure.[698]

- November 3, 2014 – The West Virginia Department of Environmental Protection confirmed that three private drinking water wells were contaminated when Antero Resources mistakenly drilled into one of its own gas wells. Benzene, a human carcinogen, and toluene, a reproductive toxicant, were detected in the drinking water at concentrations four times the legal maximum limit. Additionally, a nearby abandoned gas well, a drinking water well, and an actively producing gas well were all pressurized as a result of the mishap and began exhibiting "artesian flow."[699]

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[696] Thomas H. Darrah et al., "Noble Gases Identifying the Mechanisms of Fugitive Gas Contamination in Drinking-Water Wells Overlying the Marcellus and Barnett Shales," *Proceedings of the National Academy of Sciences* 111, no. 39 (2014): 14076–81, https://doi.org/10.1073/pnas.1322107111.
[697] Rob Jackson, "Reopen Barnett Shale Water Probe," *The Texas Tribune*, December 1, 2014, http://tribtalk.org/2014/12/01/reopen-barnett-shale-water-probe/.
[698] Genevieve A. Kahrilas et al., "Biocides in Hydraulic Fracturing Fluids: A Critical Review of Their Usage, Mobility, Degradation, and Toxicity," *Environmental Science & Technology* 49, no. 1 (2015): 16–32, https://doi.org/10.1021/es503724k.
[699] Glynis Board, "DEP: September Drilling Accident Contaminated Water in Doddridge County," *West Virginia Public Broadcasting*, November 3, 2014, http://wvpublic.org/post/dep-september-drilling-accident-contaminated-water-doddridge-county.

- October 22, 2014 – A follow-up to the August 2014 Environmental Integrity Project report describes an even greater potential public health threat from a loophole in the Safe Drinking Water Act, wherein companies are allowed to inject other petroleum products (beyond diesel) without a permit, and many of these non-diesel drilling fluids contain even higher concentrations of the same toxins found in diesel. The authors recommend that "EPA should revisit its guidance and broaden the categories of diesel products that require Safe Drinking Water Act permits before they can be injected into oil and gas wells."[700]

- October 20, 2014 – While developing a technique to fingerprint and trace accidental releases of hydraulic fracturing fluids, researchers showed that liquid waste from shale gas fracking operations is chemically different than waste flowing out of conventional wells. The researchers hypothesized that the hydraulic fracturing process itself liberates elements from clay minerals in the shale formations, including boron and lithium, which then enter the liquid waste.[701]

- October 15, 2014 – Four thousand gallons of liquid fracking waste dumped into Waynesburg sewer system was discovered by sewage treatment plant workers in Greene County, Pennsylvania. The Department of Environmental Protection surmised that "someone removed a manhole cover in a remote location and dumped the fluid." The treatment plant discharges into a creek that feeds the Monongahela River, which provides drinking water to more than 800,000 people.[702]

- October 6, 2014 – A state investigation that found no fracking-related water contamination in a drinking water well in Pennsylvania's Washington County was invalidated by testimony presented to the state Environmental Hearing Board. Not all contaminants that were present in the water were reported, and the investigation relied on obsolete testing methods. More sophisticated testing revealed the presence of several chemical contaminants in the well water. The well is located 2,800 feet down gradient from a drilling site and fracking waste pit where multiple spills and leaks more than four years earlier had contaminated two springs.[703]

- September 23, 2014 – In a two-part audit of records, the GAO found that the EPA is failing to protect U.S. drinking water sources from fracking-related activities such as waste disposal via injection wells. Nationwide, 172,000 injection wells accept fracking

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[700] Eric Schaeffer and Courtney Bernhardt, "Fracking's Toxic Loophole" (The Environmental Integrity Project, October 22, 2014).
[701] N. R. Warner et al., "New Tracers Identify Hydraulic Fracturing Fluids and Accidental Releases from Oil and Gas Operations," *Environmental Science & Technology* 48, no. 21 (2014): 12552–60, https://doi.org/10.1021/es5032135.
[702] Don Hopey, "Waynesburg Officials Investigate Dumping of Fracking Wastewater," *Pittsburgh Post-Gazette*, October 14, 2014, https://www.post-gazette.com/news/environment/2014/10/15/Waynesburg-investigates-dumping-of-fracking-wastewater/stories/201410150056.
[703] Don Hopey, "Testimony: Obsolete Tests Tainted Shale Analysis," *Pittsburgh Post-Gazette*, October 5, 2014, http://powersource.post-gazette.com/powersource/companies-powersource/2014/10/06/Testimony-Obsolete-tests-tainted-shale-analysis/stories/201410060075.

waste; some are known to have contaminated drinking water. And yet, both short-term and long-term monitoring is lax, and record-keeping varies widely from state to state. The EPA neither mandates nor recommends a fixed list of chemicals for monitoring on the grounds that "injection fluids can vary widely in composition and contain different naturally occurring chemicals and fluids used in oil and gas production depending on the source of the injection fluid."[704] Disposal of oil and gas waste via injection wells is, in fact, subject to regulation under the Safe Drinking Water Act, but, in practice, no one knows exactly what the waste contains, and regulations are deficient. In the United States, at least two billion gallons of fluids are injected into the ground *each day* to enable oil and gas extraction via fracking or to dispose of liquid waste from fracking operations.[705, 706]

- September 18, 2014 – Range Resources was fined a record $4.5 million by the Pennsylvania Department of Environmental Protection for contaminating groundwater. The culprits were six leaking pits in Washington County that each held millions of gallons of fracking wastewater.[707]

- September 12, 2014 – A Pennsylvania State ecosystems scientist, together with USGS scientists, reviewed the current knowledge of the effects of fracking and its associated operations on terrestrial and aquatic ecosystems in 20 shale plays in the U.S. Findings of species and habitats at highest risk include (in addition to land-based examples) vernal pond inhabitants and stream biota. The research builds on previous reviews identifying "three main potential stressors to surface waters: changes in water quantity (hydrology), sedimentation, and water quality." Researchers determined that there are no published data specifically on the effects of fracking on forest-dwelling amphibians, but "many species breed in vernal ponds which are negatively affected by changes in water quantity and quality and direct disturbance. Many amphibians are also highly sensitive to road salts." Given that the U.S. EPA recently found 55 percent of all rivers and streams to be in poor condition, these researchers warned, "Large-scale development of shale resources might increase these percentages." They expressed concern for the native range of brook trout by the cumulative effects of shale development, especially in Pennsylvania.[708]

- September 9, 2014 – A research team from Stanford and Duke Universities discovered that fracking wastewater processed by sewage treatment plants contributes to the

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[704] U.S. Government Accountability Office, "Drinking Water: Characterization of Injected Fluids Associated with Oil and Gas Production" (U.S. GAO, September 23, 2014), http://www.gao.gov/products/GAO-14-857R.
[705] Naveena Sadasivam, "Report Criticizes EPA Oversight of Injection Wells," *ProPublica*, July 29, 2014, https://www.propublica.org/article/report-criticizes-epa-oversight-of-injection-wells.
[706] U.S. Government Accountability Office, "Drinking Water: EPA Program to Protect Underground Sources from Injection of Fluids Associated with Oil and Gas Production Needs Improvement" (U.S. GAO, June 27, 2014), http://www.gao.gov/products/GAO-14-555.
[707] Don Hopey, "Range Resources to Pay $4.15M Penalty," *Pittsburgh Post-Gazette*, September 18, 2014, http://www.post-gazette.com/local/2014/09/18/DEP-orders-Range-Resources-to-pay-4-million-fine/stories/201409180293.
[708] Margaret C. Brittingham et al., "Ecological Risks of Shale Oil and Gas Development to Wildlife, Aquatic Resources and Their Habitats," *Environmental Science & Technology* 48, no. 19 (2014): 11034–47, https://doi.org/10.1021/es5020482.

formation of carcinogenic chemical byproducts. These raise public health risks when downstream surface water is used for drinking. Even when fracking wastewater was diluted by a factor of 10,000, the bromides and iodides in the waste reacted with organic matter to create highly toxic halogenated compounds—at troublingly high concentrations. These toxic compounds are not filterable by municipal wastewater treatment plants. Halogenated disinfection byproducts in drinking water are linked to both colon and bladder cancers.[709]

- August 29, 2014 – A review of Pennsylvania Department of Environmental Protection files on fracking-related damage to drinking water—which are kept on paper and stored in regional offices—revealed that 243 private water supplies in 22 counties had been contaminated or had lost flow and dried up as a result of nearby drilling and fracking operations in the past seven years. Pollutants included methane, metals, and salts as well as carbon-based compounds (ethylene glycol and 2-butoxyethanol) that are known to be constituents of fracking fluid. As reported by the *Pittsburgh Post-Gazette*, this tally—which came as a response to multiple lawsuits and open-records requests by media sources—was the first time the agency "explicitly linked a drilling operation to the presence of industrial chemicals in drinking water."[710, 711]

- August 13, 2014 – Over the last decade, drilling companies have repeatedly claimed they are no longer using diesel fuel in fracking, although a 2011 investigation by U.S. House Democrats concluded otherwise. The Environmental Integrity Project examined disclosure data submitted to FracFocus and identified at least 351 wells in 12 states that have been fracked over the last four years with one or more of the five prohibited products identified as diesel. EIP researchers also discovered numerous fracking fluids with high diesel content for sale online, including over a dozen products sold by Halliburton and advertised as additives, friction reducers, emulsifiers, etc.[712]

- August 13, 2014 – An international team of researchers found high levels of carbon-based compounds in liquid fracking waste. These impurities can react with chlorine and bromine to create toxic byproducts. This study suggests that chemical treatment of liquid

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[709] Kimberly M. Parker et al., "Enhanced Formation of Disinfection Byproducts in Shale Gas Wastewater-Impacted Drinking Water Supplies," *Environmental Science & Technology* 48, no. 19 (2014): 11161–69, https://doi.org/10.1021/es5028184.
[710] Pennsylvania Department of Environmental Protection, "Water Supply Determination Letters," August 29, 2014, http://files.dep.state.pa.us/OilGas/BOGM/BOGMPortalFiles/OilGasReports/Determination_Letters/Regional_Determination_Letters.pdf.
[711] Laura Legere, "DEP Releases Updated Details on Water Contamination Near Drilling Sites," *Pittsburgh Post-Gazette*, September 9, 2014, http://powersource.post-gazette.com/powersource/policy-powersource/2014/09/09/DEP-releases-details-on-water-contamination/stories/201409090010.
[712] Mary Greene, "Fracking Beyond the Law: Despite Industry Denials, Investigation Reveals Continued Use of Diesel Fuels in Hydraulic Fracturing" (The Environmental Integrity Project, August 13, 2014), https://www.environmentalintegrity.org/wp-content/uploads/2016/11/2014-08_Fracking-Beyond-the-Law.pdf.

fracking waste will magnify its toxic potency, as will reusing and recycling it.[713] The European Commission subsequently published a summary of these findings.[714]

- August 13, 2014 – A team from Lawrence Berkeley National Laboratory reported that scientific efforts to understand the hazards of fracking continue to be hampered by industry secrecy. A comprehensive examination of the chemical formulations of fracking fluid—whose precise ingredients are protected as proprietary business information—revealed that no publicly available toxicity or physical chemical information was available for one-third of all the fracking chemicals surveyed. Another ten percent of chemicals, including biocides and corrosion inhibitors, were known to be toxic to mammals.[715, 716]

- August 12, 2014 – A Stanford University research team working in the Pavillion gas basin in Wyoming documented that fracking in shallow layers of bedrock, including those that serve as drinking water aquifers, is not uncommon. This finding overturns the industry claim that oil and gas deposits targeted by fracking operations are located at much greater depths than underground drinking water sources and are isolated from them by hundreds of feet of impermeable rock. Because it is exempt from provisions of the Safe Drinking Water Act, fracking in drinking water aquifers is not prohibited by law.[717]

- August 3, 2014 – An investigation by the *Pittsburgh Post-Gazette* found that half of all fracking-related spills that resulted in violations and fines were not discovered by the gas companies themselves, even though Pennsylvania state law requires them to pro-actively seek and report such incidents. The newspaper's analysis of hundreds of thousands of state and company documents showed that self-regulation in the gas fields is a failure. One-third of all spills were discovered by state inspectors, while one-sixth were found by residents. Likely, much contamination is entirely undetected and unreported.[718]

- July 21, 2014 – An investigation by the *Columbus Dispatch* showed that Halliburton delayed disclosure to federal and state EPA agencies of the full list of chemicals that spilled into a creek following a fire on one of its well pad in Monroe County, Ohio. Although the creek is an important supply of drinking water for downstream communities

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[713] Samuel J. Maguire-Boyle and Andrew R. Barron, "Organic Compounds in Produced Waters From Shale Gas Wells," *Environmental Science: Processes & Impacts* 16, no. 10 (2014), https://doi.org/10.1039/C4EM00376D.
[714] European Commission, "Chemical Composition of Fracking Wastewater," *Science for Environment Policy*, no. 404 (February 19, 2015), http://ec.europa.eu/environment/integration/research/newsalert/pdf/chemical_composition_of_fracking_wastewater_404na4_en.pdf.
[715] W. T. Stringfellow, et al., "Characterizing Compounds Used in Hydraulic Fracturing: A Necessary Step for Understanding Environmental Impacts" (American Chemical Society, San Francisco, CA, August 13, 2014).
[716] Philip Robinson, "Fracking Fluid Survey Shows Missing Information," *Scientific American*, August 19, 2014, http://www.scientificamerican.com/article/fracking-fluid-survey-shows-missing-information/.
[717] Neela Banerjee, "Oil Companies Fracking Into Drinking Water Sources, New Research Finds.," *Los Angeles Times*, August 12, 2014, http://www.latimes.com/nation/la-na-fracking-groundwater-pavillion-20140811-story.html#page=1.
[718] Sean D. Hamill, "Drillers Did Not Report Half of Spills That Led to Fines," *Pittsburgh Post-Gazette*, August 2, 2014, http://www.post-gazette.com/news/state/2014/08/03/Drillers-did-not-report-half-of-spills-that-led-to-fines/stories/201408020142.

and the spill precipitated a mass die-off of fish and other aquatic wildlife, five full days passed before EPA officials were provided a full inventory of chemicals used at Halliburton's operation. As a result, the public was denied knowledge of potential chemical exposures.[719]

- July 17, 2014 – A team of environmental scientists, biologists, and engineers, from institutions including the University of Michigan and McGill University, assessed the current state of understanding of the impact fracking and its associated activities have on the ecological health of surface waters. Though various approaches such as geographic information systems and site monitoring provide insights into potential risks to aquatic ecosystems, the authors concluded that inadequate data currently exist. They identified possible outcomes such as, "erosion and sedimentation, increased risk to aquatic ecosystems from chemical spills or runoff, habitat fragmentation, loss of stream riparian zones, altered biogeochemical cycling, and reduction of available surface and hyporheic water volumes because of withdrawal-induced lowering of local groundwater levels."[720]

- July 7, 2014 – California Department of Gas, Oil, and Geothermal Resources ordered seven energy companies to stop injecting liquid fracking waste into aquifers. The ongoing drought that has compelled farmers to supplement irrigation with water drawn from groundwater sources prompted state officials to look at the status of aquifers previously considered too deep for use or too poor in quality. They discovered that at least seven injection wells were very likely pumping liquid fracking waste into protected groundwater supplies rather than aquifers that had been sacrificed for the purpose of waste disposal. Across the United States, more than 1000 aquifers are exempt from any type of pollution protection at all, and many of these are in California, according to a related *ProPublica* investigation.[721]

- June 25, 2014 – A study by Cornell University researchers found that fracking fluid and fracking wastewater mobilized previously deposited chemical contaminants in soil particles in ways that could potentially exacerbate the impacts of fracking fluid spills or leaks. The research team concluded that, by interfering with the ability of soil to bond to and sequester pollutants such as heavy metals, fracking fluids may release from soils an additional repository of contaminants that could migrate into groundwater.[722]

- June 23, 2014 – Building on earlier findings that water samples collected from sites with confirmed fracking spills in Garfield County, Colorado exhibited moderate to high levels of estrogen and androgen-disrupting activity, a University of Missouri team extended

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[719] Laura Arenschield, "Halliburton Delayed Releasing Details on Fracking Chemicals After Monroe County Spill," *The Columbus Dispatch*, July 21, 2014, http://www.dispatch.com/content/stories/local/2014/07/21/details-on-chemicals-trickle-in-after-spill.html.
[720] G. Allen Burton Jr. et al., "Hydraulic 'Fracking': Are Surface Water Impacts an Ecological Concern?," *Environmental Toxicology and Chemistry* 33, no. 8 (2014): 1679–89, https://doi.org/10.1002/etc.2619.
[721] Abrahm Lustgarten, "California Halts Injection of Fracking Waste, Warning It May Be Contaminating Aquifers," *ProPublica*, July 18, 2014, http://www.propublica.org/article/ca-halts-injection-fracking-waste-warning-may-be-contaminating-aquifers.
[722] W. Sang et al., "Effect of Hydrofracking Fluid on Colloid Transport in the Unsaturated Zone," *Environmental Science & Technology* 48, no. 14 (2014): 8266–74, https://doi.org/10.1021/es501441e.

their investigation to other types of hormonal effects. As reported at a joint meeting of the International Society of Endocrinology and the Endocrine Society, their research documented that commonly used fracking chemicals can also block the receptors for thyroid hormone, progesterone, and glucocorticoids (a family of hormones involved in both fertility and immune functioning). Of 24 fracking chemicals tested, all 24 interfered with the activity of one or more important hormone receptors. There is no known safe level of exposure to hormone-disrupting chemicals.[723]

- May 11, 2014 – According to the GAO, the federal government is failing to inspect thousands of oil and gas wells located on public land, including those that pose special risks of water contamination or other environmental damage. An investigation by the Associated Press found that the Bureau of Land Management "had failed to conduct inspections on more than 2,100 of the 3,702 wells that it had specified as 'high priority' and drilled from 2009 through 2012. The agency considers a well 'high priority' based on a greater need to protect against possible water contamination and other environmental safety issues."[724]

- March 25, 2014 – An industry-funded study of oil and gas well integrity found that more than six percent of wells in a major shale exploration region in Pennsylvania showed evidence of leaking and conceded that this number is likely an underestimate. Researchers concluded that the percentage of wells with some form of well barrier or integrity failure is highly variable and could be as high as 75 percent. A separate analysis in the same study found 85 examples of cement or casing failures in Pennsylvania wells monitored between 2008 and 2011.[725]

- March 7, 2014 – In a comprehensive evaluation, Duke University scientists and colleagues reviewed the state of knowledge on possible effects of shale gas and hydraulic fracturing on water resources in the United States and concluded, "Analysis of published data (through January 2014) reveals evidence for stray gas contamination, surface water impacts in areas of intensive shale gas development, and the accumulation of radium isotopes in some disposal and spill sites."[726]

- February 19, 2014 – A Pennsylvania court found a gas corporation guilty of contaminating a woman's drinking water well in Bradford County. Methane levels after

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[723] Endocrine Society, "Hormone-Disrupting Activity of Fracking Chemicals Worse than Initially Found," *Science Daily*, June 23, 2014, http://www.sciencedaily.com/releases/2014/06/140623103939.htm?utm_source=feedburner&utm_medium=email&utm_campaign=Feed%3A+sciencedaily%2Ftop_news%2Ftop_health+%28ScienceDaily%3A+Top+Health+News%29.
[724] Hope Yen, "Fed Govt Failed to Inspect Higher Risk Oil Wells," *Pittsburgh Post-Gazette*, May 11, 2014, https://www.post-gazette.com/business/powersource/2014/05/11/Fed-govt-failed-to-inspect-higher-risk-oil-wells-2/stories/201405110198.
[725] R. J. Davies et al., "Oil and Gas Wells and Their Integrity: Implications for Shale and Unconventional Resource Exploitation," *Marine and Petroleum Geology* 56 (2014): 239–54, https://doi.org/10.1016/j.marpetgeo.2014.03.001.
[726] Avner Vengosh et al., "A Critical Review of the Risks to Water Resources From Unconventional Shale Gas Development and Hydraulic Fracturing in the United States," *Environmental Science & Technology* 48, no. 15 (2014): 8334–48, https://doi.org/10.1021/es405118y.

fracking were 1,300-2,000 times higher than baseline, according to the court brief. Iron levels and turbidity had also increased. The brief stated, “In short, Jacqueline Place lived for ten months deprived totally of the use of her well, and even after its ‘restoration,’ has been burdened with a water supply with chronic contamination, requiring constant vigilance and ongoing monitoring.”[727]

- January 16, 2014 – Data from the Colorado Oil and Gas Conservation Commission showed that fracking-related chemical spills in Colorado exceed an average rate of one spill per day. Of the 495 chemical spills that occurred in that state over a one-year period of time, nearly a quarter impacted ground or surface water. Sixty-three of the spills spread within 1,500 feet of pigs, sheep, and cows; 225 spread within 1,500 feet of buildings.[728]

- January 10, 2014 – Duke University water tests revealed ongoing water contamination in Parker County, Texas, providing evidence that the EPA had prematurely ended its prior investigation into the water contamination.[729]

- January 5, 2014 – An Associated Press investigation into drinking water contamination from fracking in four states—Pennsylvania, Ohio, West Virginia, and Texas—found many cases of confirmed water contamination and hundreds more complaints. The Associated Press noted that their analysis “casts doubt on industry view that it rarely happens.”[730]

- December 24, 2013 – A report from the EPA Inspector General concluded that evidence of fracking-related water contamination in Parker County, Texas was sound and faulted the EPA for prematurely ending its investigation there, relying on faulty water testing data from the gas industry in doing so, and failure to intervene when affected residents’ drinking water remained unsafe.[731] As reported by *Business Insider*, “The EPA Screwed Up When It Dropped This Fracking Investigation.”[732]

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[727] Brendan Gibbons, “Another ‘Documented’ Case! American Arbitration Association, Commercial Arbitration Tribunal, Orders Chesapeake to Pay Jacqueline Place of Terry Township, Bradford County PA, $60,000 for Temporary Methane Contamination in Water Well After Hydraulic Fracturing,” *The Daily Review*, February 19, 2014, https://www.ernstversusencana.ca/american-arbitration-association-commercial-arbitration-tribunal-orders-chesapeake-to-pay-jaqueline-place-of-terry-township-bradford-county-pa-60000-for-methane-contamination-of-water-after-fracing/.
[728] John Tomasic, “Colorado Drilling Data: More than a Spill a Day,” *The Colorado Independent*, January 16, 2014, http://www.coloradoindependent.com/145629/colorado-drilling-data-more-than-a-spill-a-day.
[729] Mark Drajem, “Duke Fracking Tests Reveal Dangers Driller’s Data Missed,” *Bloomberg*, January 9, 2014, http://www.bloomberg.com/news/2014-01-10/epa-s-reliance-on-driller-data-for-water-irks-homeowners.html.
[730] Kevin Begos, “4 States Confirm Water Pollution From Drilling,” *USA Today*, January 5, 2014, http://www.usatoday.com/story/money/business/2014/01/05/some-states-confirm-water-pollution-from-drilling/4328859/.
[731] Neela Banerjee, “EPA Report on Fracking in Texas Raises New Concerns,” *Los Angeles Times*, December 24, 2013, http://www.latimes.com/nation/la-na-epa-fracking-20131225,0,6042944.story#ixzz2oVB9FXVY.
[732] Douwe Miedema, “The EPA Screwed Up When It Dropped This Fracking Investigation,” *Insider*, December 25, 2013, http://www.businessinsider.com/epa-criticized-for-dropping-fracking-investigation-2013-12.

- December 16, 2013 – Lead by Susan Nagel of the University of Missouri School of Medicine, researchers documented endocrine-disrupting properties in chemicals commonly used as ingredients of fracking fluid and found similar endocrine-disrupting activity in groundwater and surface water samples collected near drilling and fracking sites in Garfield County, Colorado. Endocrine disruptors are chemicals that interfere with the activity of hormones in the body and, at very low concentrations, can raise the risk of reproductive, metabolic, and neurological disorders, especially when exposures occur in early life. [733, 734, 735]

- December 7, 2013 – Reporting on the second gas leak at a single gas well in one month, the Fort Worth *Star-Telegram* uncovered another inherent risk of fracking for groundwater contamination: Silica sand, which is used as an ingredient in fracking fluid for its ability to prop open the shale fractures, can damage steel pipes as it flows back up the well along with the gas. According to Dan Hill, head of the petroleum engineering department at Texas A&M University, new wells are the most susceptible to sand erosion because "the amount of sand and gas rushing through valves and flow lines is at its greatest when a well first goes into production."[736]

- November 26, 2013 – A USGS report found serious impacts of fracking on watersheds and water quality throughout the Appalachian Basin, as well as issues with radiation and seismic events. As noted in the report, the knowledge of how extraction affects water resources has not kept pace with the technology.[737] Meanwhile, clean fresh water is becoming an increasingly scant resource. A report prepared for the U.S. State Department forecasts a serious freshwater shortage by 2030, with global demand exceeding supply by 40 percent.[738]

- November 22, 2013 – A USGS study of pollution from oil production in North Dakota, where horizontal drilling and hydraulic fracturing are heavily used, identified two potential plumes of groundwater contamination covering 12 square miles. The cause was traced to a casing failure in a wastewater disposal well. Drilling companies had incorrectly assumed that, once injected underground, the wastewater would remain contained. According to *EnergyWire*, the development of the Bakken oil formation is

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[733] Christopher C. Kassotis et al., "Estrogen and Androgen Receptor Activities of Hydraulic Fracturing Chemicals and Surface and Ground Water in a Drilling-Dense Region," *Endocrinology*, 2013, https://doi.org/10.1210/en.2013-1697.

[734] Banerjee, N. (2013, December 16). Hormone-disrupting chemicals found in water at fracking sites. *Los Angeles Times*. Retrieved from http://articles.latimes.com/2013/dec/16/science/la-sci-fracking-health-20131217

[735] Endocrine Society, "Fracking Chemicals Disrupt Hormone Function," *Science Daily*, December 16, 2013, www.sciencedaily.com/releases/2013/12/131216140428.htm.

[736] Caty Hirst and Jim Fuquay, "Second Leak Reported at East Fort Worth Gas Well Site," *Fort Worth Star-Telegram*, December 7, 2013, https://www.star-telegram.com/news/local/fort-worth/article3839099.html.

[737] William M. Kappel, John H. Williams, and Zoltan Szabo, "Water Resources and Shale Gas/Oil Production in the Appalachian Basin—Critical Issues and Evolving Developments" (U.S. Geological Survey, August 2013), http://pubs.usgs.gov/of/2013/1137/pdf/ofr2013-1137.pdf.

[738] National Intelligence Council, "Global Water Security," Intelligence Community Assessment, February 2, 2012, http://www.dni.gov/files/documents/Special%20Report_ICA%20Global%20Water%20Security.pdf.

"leaving behind an imprint on the land as distinct as the ones left by the receding ice sheets of the ice age."[739]

- October 25, 2013 – An Associated Press investigation uncovered nearly 300 oil pipeline spills in North Dakota in the previous ten months, all with no public notification. These were among some 750 "oil field incidents" that had occurred in the state over the same time period, also without public notification. Until the AP inquiry, industry and state officials had kept quiet about one particular "massive spill" that had been accidentally discovered by a wheat farmer. Even small spills can contaminate water sources permanently and take cropland out of production.[740]

- September 10, 2013 – Pennsylvania Attorney General Kathleen Kane filed criminal charges against Exxon Mobil Corporation's subsidiary, XTO Energy Corporation, for a spill of 50,000 gallons of toxic drilling wastewater in 2010 that contaminated a spring and a tributary of the Susquehanna River. In July, XTO settled civil charges for the incident without admitting liability by agreeing to pay a $100,000 fine and improve its wastewater management.[741]

- September 10, 2013 – Out of concern for risks posed to drinking water in the nation's capital, George Hawkins, General Manager of DC Water, Washington, DC's local water provider, called for a prohibition on horizontal drilling and hydraulic fracturing in the George Washington National Forest until the process can be proven safe.[742] The Potomac River is the source of the District's water supply and has its headwaters in the George Washington National Forest, which sits atop the Marcellus Shale. The general managers of Fairfax Water, provider of drinking water for Fairfax County, Virginia, and the U.S. Army Corps of Engineers have called for a similar prohibition.[743]

- August 28, 2013 – A joint USGS and U.S. Fish and Wildlife Service study documented a causal link between a fracking wastewater spill and the widespread death of fish in the Acorn Fork, a creek in Kentucky.[744]

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[739] Gayathri Vaidyanathan, "Bakken Shale: As Oil Production Sets in, Pollution Starts to Migrate -- Scientists," *E&E News*, November 22, 2013, https://web.archive.org/web/20131212051756/http://www.eenews.net/stories/1059990892.
[740] James MacPherson, "AP News Break: Nearly 300 Oil Pipeline Spills Went Unreported to US State Since 2012," *Canadian Business*, October 25, 2013, https://www.canadianbusiness.com/business-news/ap-newsbreak-nearly-300-oil-pipeline-spills-went-unreported-to-north-dakota-public-since-2012/.
[741] Andrew Maykuth, "Shale Criminal Charges Stun Drilling Industry," *The Philadelphia Inquirer*, September 12, 2013, https://www.inquirer.com/philly/business/20130912_AG_s_criminal_charges_stun_drilling_industry.html.
[742] George Hawkins, "Letter from George Hawkins, General Manager, DC Water, to U.S. Secretary of Agriculture, Thomas Vilsack," September 10, 2013, https://www.documentcloud.org/documents/798238-gwforestdcwaterletter.html.
[743] Aaron Wiener, "DC Water Chief Urges Agriculture Secretary Not to Allow Fracking Near D.C.," *Washington City Paper*, September 20, 2013, http://www.washingtoncitypaper.com/blogs/housingcomplex/2013/09/20/dc-water-chief-urges-agriculture-secretary-not-to-allow-fracking-near-d-c/.
[744] D. Papoulias and T. MacKenzie, "Hydraulic Fracturing Fluids Likely Harmed Threatened Kentucky Fish Species," *USGS Newsroom*, August 28, 2013, https://www.usgs.gov/news/hydraulic-fracturing-fluids-likely-harmed-threatened-kentucky-fish-species.

- July 25, 2013 – A University of Texas at Arlington study of drinking water found elevated levels of arsenic and other heavy metals in some samples from private drinking water wells located within five kilometers of active natural gas wells in the Barnett Shale.[745]

- July 3, 2013 – *ProPublica* reported that the EPA was wrong to have halted its investigation of water contamination in Wyoming, Texas and Pennsylvania—where high levels of benzene, methane, arsenic, oil, methane, copper, vanadium, and other chemicals associated with fracking operations have been documented.[746] Although numerous organizations and health professionals around the country have since called on the agency to resume its investigation, no action was taken.

- June 6, 2013 – Reviewing hundreds of regulatory and legal filings, *Bloomberg News* reported that drillers have offered out-of-court cash settlements and property buyouts to homeowners who claim that fracking ruined their water. These agreements typically come with gag orders and sealed records. This strategy, the investigation noted, allows the industry to continue claiming that no cases of water contamination due to fracking have ever been confirmed, impedes public health research, and shields data from regulators, policy makers, and the new media.[747] The EPA also long ago noted how non-disclosure agreements between oil and gas operators and landowners challenge scientific progress and keep examples of drilling harm secret from the public. In a 1987 report, the EPA wrote, "In some cases, even the records of well-publicized damage incidents are almost entirely unavailable for review. In addition to concealing the nature and size of any settlement entered into between the parties, impoundment curtails access to scientific and administrative documentation of the incident."[748]

- June 3, 2013 – A study by Duke University researchers linked fracking with elevated levels of methane, ethane, and propane in nearby groundwater.[749] Published in *Proceedings of the National Academy of Sciences*, the study included results from 141 northeastern Pennsylvania water wells. Methane levels were, on average, six times higher

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745 Brian E. Fontenot et al., "An Evaluation of Water Quality in Private Drinking Water Wells Near Natural Gas Extraction Sites in the Barnett Shale Formation," *Environmental Science & Technology* 47, no. 17 (2013): 10032–40, https://doi.org/10.1021/es4011724.

746 Abrahm Lustgarten, "EPA's Abandoned Wyoming Fracking Study One Retreat of Many," *ProPublica*, July 3, 2013, http://www.propublica.org/article/epas-abandoned-wyoming-fracking-study-one-retreat-of-many.

747 J. Efstathiou Jr. and Mark Drajem, "Drillers Silence Fracking Claims with Sealed Settlements," *Bloomberg*, June 5, 2013, http://www.bloomberg.com/news/2013-06-06/drillers-silence-fracking-claims-with-sealed-settlements.html.

748 Environmental Protection Agency, "Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy (Vol. 2 of 3: Geothermal Energy)," Report to Congress (U. S. Environmental Protection Agency, December 1987), Report to Congress: Management of wastes from the exploration, development, and production of crude oil, natural gas, and geothermal energy.

749 Robert B. Jackson et al., "Increased Stray Gas Abundance in a Subset of Drinking Water Wells Near Marcellus Shale Gas Extraction," *Proceedings of the National Academy of Sciences* 110, no. 28 (2013): 11250–55, https://doi.org/10.1073/pnas.1221635110.

in drinking water wells closer to drilling sites when compared with those farther away, while ethane was 23 times higher.[750]

- May 19, 2013 – In Pennsylvania, the *Scranton Times-Tribune* released details of an investigation that revealed at least 161 cases of water contamination from fracking between 2008 and the fall of 2012, according to state Department of Environmental Protection records.[751]

- April 2013 – Researchers analyzing publicly available Colorado data found 77 surface spills impacting groundwater in Weld County alone. Samples of these spills often exceeded drinking water maximum contaminant levels (MCLs) for benzene, toluene, ethylbenzene and xylene; for benzene, a known carcinogen, 90 percent of the samples exceeded the legal limit.[752]

- March 4, 2013 – Researchers at the University of Pittsburgh Graduate School of Public Health analyzed samples of gas drilling wastewater discharged to surface water through wastewater treatment plants. Barium, strontium, bromides, chlorides, and benzene all exceeded levels known to cause human health impacts.[753]

- December 8, 2012 – State data in Colorado showed more than 350 instances of groundwater contamination resulting from more than 2,000 spills from oil and gas operations over the past five years. Further, as the *Denver Post* reported, "Contamination of groundwater—along with air emissions, truck traffic and changed landscapes—has spurred public concerns about drilling along Colorado's Front Range."[754]

- May 4, 2012 – A report for the Canadian Government, released under the Access to Information Act, reviewed the process, the regulatory framework globally, and the potential health hazards related to shale gas extraction. Additionally, the report evaluated mechanisms for potential impacts and summarized the data knowledge and data gaps. Regarding water contamination, the report determined, "Although quantitative data are lacking, the qualitative data available indicate that potential contamination of water related to the shale gas industry may present hazard to the public health, especially for local population." Regarding air contamination: "air emissions related to the shale gas

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[750] CBS/AP, "Methane Found in Pa. Drinking Water Near Fracked Wells," *CBS News*, June 25, 2013, http://www.cbsnews.com/news/methane-found-in-pa-drinking-water-near-fracked-wells/.
[751] Laura Legere, "Sunday Times Review of DEP Drilling Records Reveals Water Damate, Murky Testing Methods," *The Times-Tribune*, May 18, 2013, http://thetimes-tribune.com/news/sunday-times-review-of-dep-drilling-records-reveals-water-damage-murky-testing-methods-1.1491547.
[752] Sherilyn A. Gross et al., "Analysis of BTEX Groundwater Concentrations from Surface Spills Associated With Hydraulic Fracturing Operations," *Journal of the Air & Waste Management Association* 63, no. 4 (2013): 424–32, https://doi.org/10.1080/10962247.2012.759166.
[753] Kyle J. Ferrar et al., "Assessment of Effluent Contaminants from Three Facilities Discharging Marcellus Shale Wastewater to Surface Waters in Pennsylvania," *Environmental Science & Technology* 47, no. 7 (2013): 3472–81, https://doi.org/10.1021/es301411q.
[754] Bruce Finley, "Drilling Spills Reaching Colorado Groundwater; State Mulls Test Rules," *The Denver Post*, December 8, 2012, sec. Environment, http://www.denverpost.com/environment/ci_22154751/drilling-spills-reaching-colorado-groundwater-state-mulls-test#ixzz2EihHU2fg.

industry present health hazards since the air pollutants originating from the vehicles and engines fuelled by diesel are toxic to the respiratory and cardiovascular systems and can cause premature mortality, volatile organic compounds have been associated to neurotoxicity and some of these compounds (e.g. benzene) as well as NORMs are known or possible human carcinogens." The report concluded, "Any step of shale gas exploration/exploitation may represent a potential source of drinking water and air contamination; Hydraulic fracturing and wastewater disposal were identified as the main potential sources of risk."[755]

- May 2012 – A report by researchers at Natural Resources Defense Council and Carnegie Mellon University found that the options available for dealing with fracking wastewater are inadequate to protect public health and the environment, resulting in increasing quantities of toxic wastewater as an ongoing problem without a good solution.[756]

- January 11, 2012 – The USGS reported that the Marcellus Shale is already highly fractured and that numerous fissures naturally occurring within the formation could potentially provide pathways for contaminants to migrate vertically into water supplies.[757]

- October 25, 2011 – After receiving new information from two companies, members of Congress updated their findings to show that between 2005 and 2009, oil and gas service companies injected 32.7 million gallons of diesel fuel or hydraulic fracturing fluids containing diesel fuel in wells in 20 states.[758]

- October 17, 2011 – Thomas P. Jacobus, General Manager of the U.S. Army Corps of Engineers' Washington Aqueduct, called for a prohibition on horizontal hydraulic fracturing in the George Washington National Forest because of concern that fracking poses risks to drinking water. The Washington Aqueduct—which provides drinking water to Washington, DC, Arlington County, Virginia, and Falls Church, Virginia—is supplied by the Potomac River, which has its headwaters in the George Washington National Forest that sits atop the Marcellus Shale. Jacobus said, "Enough study on the

[755] Séverine Louis, "Potential Health Hazards from Shale Gas Exploration and Exploitation" (Presented to Health Canada by SANEXEN Environmental Services; Document released under the (Canadian) Access to Information Act, May 4, 2012), https://www.ernstversusencana.ca/wp-content/uploads/2012-Health-Canada-Potential-Health-Hazards-from-Shale-Gas-Drinking-water-Ambient-Air-released-under-FOIP.pdf.
[756] Rebecca Hammer and Jeanne VanBriesen, "In Fracking's Wake: New Rules Are Needed to Protect Our Health and Environment from Contaminated Wastewater" (Natural Resources Defense Council, May 2012), http://www.nrdc.org/energy/files/fracking-wastewater-fullreport.pdf.
[757] U.S. Geological Survey, New York Water Science Center, "Comments on the Revised Draft Supplemental Generic Environmental Impact Statement," January 11, 2012, http://www.ewg.org/sites/default/files/report/ReviseddraftSGEIS_USGScomments_Version3_0.pdf.
[758] Henry A. Waxman, Edward J. Markey, and Diana DeGette, "The Honorable Lisa Jackson, Administrator, U.S. Environmental Protection Agency," Letter, October 25, 2011, https://www7.nau.edu/itep/main/iteps/ORCA/3934_ORCA.pdf.

technique [hydraulic fracturing] has been published to give us great cause for concern about the potential for degradation of the quality of our raw water supply….”[759]

- October 11, 2011 – Charles M. Murray, General Manager of Fairfax Water, called for a prohibition on horizontal hydraulic fracturing in the George Washington National Forest. “Natural gas development activities have the potential to impact the quantity and quality of Fairfax Water’s source water,” Murray wrote. “Downstream water users and consumers will bear the economic burden if drinking water sources are contaminated or the quality of our source water supply is degraded.”[760] Fairfax Water provides drinking water for Fairfax County in Virginia.

- September 7, 2011 – In its draft Supplemental Generic Environmental Impact Statement (SGEIS), the New York State Department of Environmental Conservation (NYS DEC) acknowledged that “there is questionable available capacity”[761] for New York’s public sewage treatment plants to accept drilling wastewater, yet the agency said that it would allow those facilities to accept such waste if the plants meet permitting conditions.[762] The NYS DEC proposed underground injection as one alternative to sewage treatment procession of fracking waste. Although it is a common method of disposal for fracking wastewater,[763] the last significant government study of pollution risks from oil and gas wastewater injection wells occurred in 1989 and found multiple cases of costly groundwater contamination.[764] In subsequent years, studies have continued to link underground injection of drilling wastewater to pollution as well as earthquakes.[765]

- September 2011 – A team led by Theo Colburn of the Endocrine Disruptor Exchange found that 25 percent of chemicals known to be used in fracking fluids are implicated in cancer, 37 percent could disrupt the endocrine system, and 40-50 percent could cause

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759 Thomas P. Jacobus, “Draft Environmental Impact Statement for the George Washington National Forest,” Letter to K. Landgraf, October 17, 2011, https://web.archive.org/web/20160305022532/http://www.svnva.org/wp-content/uploads/fairfax-wash-aquaduct-gwnf-comments.pdf.
760 Charles M. Murray, “Draft Environmental Impact Statement for the George Washington National Forest,” Letter to K. Landgraf, October 11, 2011, https://web.archive.org/web/20160305022532/http://www.svnva.org/wp-content/uploads/fairfax-wash-aquaduct-gwnf-comments.pdf.
761 New York State Department of Environmental Conservation, “Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program, Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs,” Report 6-62, 2011.
762 New York State Department of Environmental Conservation, “Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program, Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs,” Rep 6-57 through 6-63, 2011.
763 New York State Department of Environmental Conservation, “Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program, Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs,” Report 6-64, 2011.
764 U.S. Government Accountability Office, “Drinking Water: Safeguards Are Not Preventing Contamination From Injected Oil and Gas Wastes,” July 5, 1989, http://www.gao.gov/products/RCED-89-97.
765 Henry Fountain, “Disposal Halted at Well After New Quake in Ohio,” *The New York Times*, January 1, 2012, sec. Environment, http://www.nytimes.com/2012/01/02/science/earth/youngstown-injection-well-stays-shut-after-earthquake.html.

nervous, immune and cardiovascular system problems. The research team also found that more than 75 percent could affect the skin, eyes, and respiratory system, resulting in various problems such as skin and eye irritation or flu-like symptoms.[766]

- August 3, 2011 – As reported by the *New York Times,* the EPA had alerted Congress in 1987 about a case of water contamination caused by fracking. Its report documented that a shale gas well hydraulically fractured at a depth of more than 4,200 feet contaminated a water supply only 400 feet from the surface.[767, 768, 769]

- May 18, 2011 – The state of Pennsylvania fined Chesapeake Energy Corporation $900,000 for an incident in which improper cementing and casing in one of the company's gas wells allowed methane to migrate underground and contaminate 16 private drinking water wells in Bradford County.[770]

- May 17, 2011 – A Duke University study documented "systematic evidence for methane contamination of drinking water associated with shale gas extraction."[771] The study showed that methane levels were 17 times higher in water wells near drilling sites than in water wells in areas without active drilling.[772]

- April 22, 2011 – Describing one of many blowouts, the Associated Press reported on a shale gas well in Canton, Pennsylvania that spewed thousands of gallons of chemical-laced water on farmland and into a stream for two consecutive days before being brought under control.[773]

- April 18, 2011 – As part of a year-long investigation into hydraulic fracturing and its potential impact on water quality, U.S. Representatives Henry Waxman (D-Calif.), Edward Markey (D-Mass.) and Diana DeGette (D-Colo.) released the second of two reports issued in 2011. Their analysis of hydraulic fracturing fluids used by the 14

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[766] Theo Colborn et al., "Natural Gas Operations from a Public Health Perspective," *Human and Ecological Risk Assessment: An International Journal* 17, no. 5 (2011): 1039–56, https://doi.org/10.1080/10807039.2011.605662.
[767] Ian Urbina, "A Tainted Water Well, and Concern There May Be More," *The New York Times*, August 3, 2011, http://www.nytimes.com/2011/08/04/us/04natgas.html.
[768] U.S. Environmental Protection Agency, "Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy," Report to Congress, Sec. 4-22, 4-23, December 1987, http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=20012D4P.PDF.
[769] Dusty Horwitt, "Cracks in the Façade" (Environmental Working Group, August 3, 2011), https://static.ewg.org/reports/2011/Cracks-in-the-Facade.pdf.
[770] Andrew Maykuth, "Pa. Fines Chesapeake Energy Corp. $1.1 Million for Drilling Violation," *The Philadelphia Inquirer*, May 18, 2011, https://www.inquirer.com/philly/news/local/20110518_Pa__fines_Chesapeake_Energy_Corp___1_1_million_for_drilling_violation_1.html.
[771] Stephen G. Osborn et al., "Methane Contamination of Drinking Water Accompanying Gas-Well Drilling and Hydraulic Fracturing," *Proceedings of the National Academy of Sciences* 108, no. 20 (2011): 8172–76, https://doi.org/10.1073/pnas.1100682108.
[772] Duke University, "Methane Levels 17 Times Higher in Water Wells Near Hydrofracking Sites, Study Finds," Press Release (Science Daily, May 10, 2011), http://www.sciencedaily.com/releases/2011/05/110509151234.htm.
[773] The Associated Press, "Crews Stop Flow of Drilling Fluid From Pennsylvania Well," *Syracuse.Com*, April 22, 2011, http://www.syracuse.com/news/index.ssf/2011/04/crews_stop_flow_of_drilling_fl.html.

leading oil and natural gas service companies between 2005 and 2009 found, among other things, that the companies used more than 650 different products that contained chemicals that are known or possible human carcinogens, regulated under the Safe Drinking Water Act, or listed as hazardous air pollutants under the Clean Air Act. The report also showed that "between 2005 and 2009, the companies used 94 million gallons of 279 products that contained at least one chemical or component that the manufacturers deemed proprietary or a trade secret … in most cases the companies stated that they did not have access to proprietary information about products they purchased 'off the shelf' from chemical suppliers. In these cases, the companies are injecting fluids containing chemicals that they themselves cannot identify."[774] These findings were reported in the *New York Times*.[775]

- January 2011 – A team of scientists led by a University of Central Arkansas researcher called attention to the threat posed to surface waters by rapidly expanding shale gas development, noting a lack of data collection accompanying the rush to drill. "Gas wells are often close to surface waters that could be impacted by elevated sediment runoff from pipelines and roads, alteration of stream flow as a result of water extraction, and contamination from introduced chemicals or the resulting wastewater."[776]

- January 31, 2011 – As part of a year-long investigation into hydraulic fracturing and its potential impact on water quality, U.S. Representatives Henry Waxman (D-Calif.), Edward Markey (D-Mass.) and Diana DeGette (D-Colo.) reported that "between 2005 and 2009, oil and gas service companies injected 32.2 million gallons of diesel fuel or hydraulic fracturing fluids containing diesel fuel in wells in 19 states." Furthermore, revealing apparent widespread violation of the Safe Drinking Water Act, the investigation found that no oil and gas service companies had sought—and no state or federal regulators had issued—permits for the use of diesel fuel in hydraulic fracturing.[777]

- April 29, 2010 – In 2010, the Colorado Oil and Gas Conservation Commission fined Occidental Petroleum Corporation (OXY) USA a record $390,000 for an incident of pollution, discovered in 2008, when its drilling wastes leaked through an unlined pit, contaminated two springs with benzene, and polluted other nearby water sources. In addition, the regulators separately fined OXY USA $257,400 for a nearby case of

[774] Henry A. Waxman, Edward J. Markey, and Diana DeGette, "Chemicals Used in Hydraulic Fracturing" (United States House of Representatives Committee on Energy and Commerce Minority Staff, April 18, 2011), http://democrats.energycommerce.house.gov/sites/default/files/documents/Hydraulic-Fracturing-Chemicals-2011-4-18.pdf.

[775] Ian Urbina, "Chemicals Were Injected Into Wells, Report Says," *The New York Times*, April 17, 2011, http://www.nytimes.com/2011/04/17/science/earth/17gas.html.

[776] Sally Entrekin et al., "Rapid Expansion of Natural Gas Development Poses a Threat to Surface Waters," *Frontiers in Ecology and the Environment* 9, no. 9 (2011): 503–11, https://doi.org/10.1890/110053.

[777] Amy Mall, "Hydraulic Fracturing Has Used Diesel Fuel in 19 States; 'Appears to Be a Violation of the Safe Drinking Water Act,'" NRDC, *Expert Blog* (blog), January 31, 2011, https://www.nrdc.org/experts/amy-mall/hydraulic-fracturing-has-used-diesel-fuel-19-states-appears-be-violation-safe.

pollution, also discovered in 2008, in which a torn liner in a pit caused drilling waste fluids to leak out and contaminate two springs with benzene.[778]

- June 4, 2009 – A leaking pipe carrying fracking waste in Washington County, Pennsylvania, polluted a tributary of Cross Creek Lake, killing fish, salamanders, crayfish, and aquatic insect life in approximately three-quarters of a mile of the stream.[779]

- April 26, 2009 – Officials in three states linked water contamination and methane leaks to gas drilling. Incidents included a case in Ohio where a house exploded after gas seeped into its water well and multiple cases of exploding drinking water wells in Dimock, Pennsylvania.[780]

- November 13, 2008 – *ProPublica* reported more than 1,000 cases of drilling-related contamination documented by courts and state and local governments in Colorado, New Mexico, Alabama, Ohio, and Pennsylvania.[781]

- September 1, 2008 – In Bainbridge, Ohio, a gas well that was improperly cemented and subsequently fractured by Ohio Valley Energy Systems Corporation allowed natural gas to migrate outside of the well, causing a home to explode. In addition, 23 nearby water wells were contaminated, two of which were located more than 2,300 feet from the drilling site.[782, 783, 784]

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778 Dennis Webb, "Record Fine, Second One Against Oxy Approved," *The Daily Sentinel*, April 29, 2011, https://www.gjsentinel.com/breaking/breaking_news/record-fine-second-one-against-oxy-approved/article_ef661e6a-60db-52be-a4f1-0ad99363af72.html.
779 Pittsburg Post-Gazette, "Waste from Marcellus Shale Drilling in Cross Creek Park Kills Fish," *Pittsburgh Post-Gazette*, June 4, 2009, http://www.post-gazette.com/washington/2009/06/05/Waste-from-Marcellus-shale-drilling-in-Cross-Creek-Park-kills-fish/stories/200906050136.
780 Abrahm Lustgarten, "Officials in Three States Pin Water Woes on Gas Drilling," *ProPublica*, April 26, 2009, http://www.propublica.org/article/officials-in-three-states-pin-water-woes-on-gas-drilling-426.
781 Abrahm Lustgarten, "Buried Secrets: Is Natural Gas Drilling Endangering U.S. Water Supplies?," *ProPublica*, 2008, http://www.propublica.org/article/buried-secrets-is-natural-gas-drilling-endangering-us-water-supplies-1113.
782 Ohio Department of Natural Resources, "Report on the Investigation of the Natural Gas Invasion of Aquifers in Bainbridge Township of Geauga County, Ohio," Report on the Bainbridge Investigation (Oil Department of Natural Resources, Division of Mineral Resources Management, September 1, 2008), https://marcellus-wv.com/online-courses/well_construction/report.pdf.
783 E. S. Bair, D. C. Freeman, and J. M. Senko, "Expert Panel Technical Report, Subsurface Gas Invasion Bainbridge Township, Geauga County, Ohio," June 2010, https://web.archive.org/web/20150703190148/http://oilandgas.ohiodnr.gov/portals/oilgas/pdf/bainbridge/DMRM%200%20Title%20Page,%20Preface,%20Acknowledgements.pdf.
784 Ohio Department of Natural Resources, "Order Number 2009-17," April 14, 2009.

Inherent engineering problems that worsen with time

Studies show that many oil and gas wells leak, allowing for the migration of natural gas and potentially other substances into groundwater and/or the atmosphere. About five percent of wells leak immediately, 50 percent leak after 15 years, and 60 percent leak after 30 years. The act of fracking itself can redistribute stress and open underground pathways for fluid migration, which, in turn, can communicate with other pathways created during the fracking of neighboring wells, by the deterioration of cement in aging well casings, or by earthquakes, leading in all cases to the risk of groundwater contamination and atmospheric emissions. The injection of fracking waste into subterranean rock formations can also intersect with active and abandoned wells in ways that allow vertical migration of toxic fluids and vapors.

The problem of leaking wells, first identified by industry, has no known solution. Data from Pennsylvania's Department of Environmental Protection (DEP) agree, showing over nine percent of shale gas wells drilled in the state's northeastern counties leaking within the first five years. Leaks pose serious risks, including potential loss of life or property from explosions and migration of gas and other harmful chemicals into drinking water supplies. Methane leaking into aquifers can, under some conditions, be transformed by bacteria into hydrogen sulfide and other poisonous byproducts. Microbes from deep shale formations can likewise generate sulfides contributing, over time, to corrosion of pipes and casings.

There is no evidence to suggest that the problem of cement and well casing impairment is abating. Industry has no solution for rectifying the chronic problem of well casing/cement failures and resulting leakage. Plugging old, inactive wells is an imperfect solution because, as research shows, the cement plugs themselves degrade over time and because many wells leak from outside the well casing.

- February 5, 2021 – Fracking wastewater gushed for four days from an unplugged oil and gas well in southeastern Ohio (Noble County) that had been idle since 2012. The fluid is thought to have migrated from nearby fracking waste injection wells, of which there are at least nine in the county. Six were active at the time of the gusher.[785]

- September 5, 2020 – Fracking wastewater from an underground injection well in southeastern Ohio (Washington County) migrated to gas-producing wells five miles away, according to the Ohio Department of Natural Resources. The fracking waste was detected in 28 gas wells.[786]

- February 1, 2020 – Researchers studied possible interconnections between wells on adjacent and nearby pads to assess the potential for such wells to communicate through

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[785] Beth Burger, "Thousands of Gallons of Fracking Waste Spilled from Noble County Well for Four Days," *The Columbus Dispatch*, February 5, 2021, https://www.dispatch.com/story/news/2021/02/04/thousands-gallons-flthousands-of-gallouid-spilled-oil-and-gas-well-noble-co-damage-and-cause-unclear/4397912001/.

[786] Beth Burger, "State Investigating Whether Injection Well Waste Affecting Drinking Water," *The Columbus Dispatch*, September 5, 2020, https://www.dispatch.com/story/news/local/2020/09/05/state-investigating-whether-injection-well-waste-affecting-drinking-water/113667974/.

fracture-like pathways. Results from microseismic data, chemical and radioactive tracers, and production interference (volume and pressure measurements) confirm communication among wells at distances up to 1200 meters (0.75 miles) horizontally and 164 meters (0.10 miles) vertically (crossing shale boundary layers) and lasting for up to 1.7 years. The intensive well communication over long distances appeared to be due to reactivation of natural faults or fractures, in addition to fractures propagating into pre-existing hydraulic fractures. Since fracture height is "generally assumed as formation thickness, neglecting the possibility of fracture growth beyond the target shale formations," these results challenge existing understandings of the fracturing process, provide support for claims of contamination by fracking fluids of aquifers outside target formations, and suggest the need for set-backs of at least 1200 meters to protect subsurface water resources near fracking sites.[787]

- November 27, 2019 – To gauge the extent of possible contamination of air and water resources by subsurface leakage from oil and gas wells, Canadian researchers used ArcGIS to perform cluster analysis and identify "hot spots" where high densities of oil and gas wells (both active and abandoned) overlap with high densities of earthquake activity in California, Oklahoma, and British Columbia. The well-documented catastrophic leakage of gases from the Aliso Canyon Natural Gas Storage Field corresponds to one of the identified hot spots. Of note, a comparison of known major fault locations with earthquake clusters shows that "there are regions in each province/state where a major fault is not mapped but an earthquake cluster exists."[788]

- April 19, 2018 – As part of a major review, a University of Aberdeen team of researchers assessed the various underground pathways by which fracking creates methane leaks and concluded that aging well casings are a leading cause of methane leaks from drilling and fracking operations. While the intersection of fracture propagation with naturally present geological faults in the subsurface is another potential route for methane leakage, the more important route is the intersection of fracture propagation with other wells with old cement. "The major sources of methane leakage related to shale gas activities are the intersections of hydraulic fractures with abandoned oil and gas wells which have a reduced mechanical well integrity due to cement degradation. As a result, the stress redistributions caused by hydraulic fracturing and the deterioration of cement in abandoned wells with age allow migration pathways to be created easily, leading to both groundwater contamination and atmospheric emissions." Plugging wells is an imperfect solution because the cement commonly used for this process itself degrades with time, especially in the presence of carbon dioxide. "No concrete method [has been] established for the methane leakage mitigation from shale gas wells."[789]

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787 Yingkun Fu and Hassan Dehghanpour, "How Far Can Hydraulic Fractures Go? A Comparative Analysis of Water Flowback, Tracer, and Microseismic Data From the Horn River Basin," *Marine and Petroleum Geology* 115 (2020): 104259, https://doi.org/10.1016/j.marpetgeo.2020.104259.
788 Mary Kang et al., "Potential Increase in Oil and Gas Well Leakage Due to Earthquakes," *Environmental Research Communications* 1, no. 12 (2019): 121004, https://doi.org/10.1088/2515-7620/ab576e.
789 Azis Yudhowijoyo et al., "Subsurface Methane Leakage in Unconventional Shale Gas Reservoirs: A Review of Leakage Pathways and Current Sealing Techniques," *Journal of Natural Gas Science & Engineering* 54 (2018): 309–19, https://doi.org/10.1016/j.jngse.2018.04.013.

- November 23, 2017 – An investigative journalist from *The Tyee* in Vancouver obtained a copy of a 2013 report from British Columbia's Oil and Gas Commission warning about hundreds of uncontrolled methane leaks from shale gas wells located in the northern Rocky Mountain range near Fort Nelson. The commission's report, never shared with the public or with elected officials, remained an internal document until it was uncovered by the newspaper. Cornell University engineer Anthony Ingraffea, quoted in the story, said the report's findings served as another confirmation that wells leak badly and inevitably over time. "What do they expect from underground operations such as these, total obedience to design intent? Why are operators and regulators around the world seemingly surprised when things go wrong underground, and in so many ways, and so often?" Ingraffea said.[790, 791]

- July 5, 2017 – A team of researchers led by microbiologists from Ohio State University investigated bacteria from hydraulically fractured shale by sampling fracking wastewater from a well drilled in the Utica shale. The dominant microrganism was a bacterium that generates sulfides, which can contribute to corrosion of well casings. "The impact of microbial metabolism within these environments is poorly understood. . . . These findings emphasize the potential detrimental effects that could arise from thiosulfate-reducing microorganisms in hydraulically fractured shales, which are undetected by current industry-wide corrosion diagnostics."[792]

- April 1, 2017 – The rapid depletion of fracked wells requires drilling ever more wells to keep up with production. As time goes by, wells become more densely packed into a drilling section. Decreasing distances between wells increases the risk of inter-well communication, which occurs when the pumping of fracking fluid into one well affects a nearby well. According to an analysis in the *Journal of Petroleum Technology*, these so called "frack hits" are unpredictable, uncontrolled, and can be violent, damaging tubing, casings, and well integrity. In some cases, frack hits involve blowouts of fracking fluid. The industry has no solution for this increasingly common problem.[793] Indeed, as a sequel report describes, operators use frack hits as a tool for revealing how tightly wells can be spaced in a drilling section to maximize extraction—even while acknowledging inherent safety risks. A drilling section with no frack hits at all is presumed to lack sufficient well density for optimal "economic recovery."[794]

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790 Andrew Nikiforuk, "Despite What Politicians Say, Hundreds of BC Gas Wells Leak Methane," *The Tyee*, November 23, 2017, https://thetyee.ca/News/2017/11/23/Hundreds-of-BC-Gas-Wells-Leak-Meth/.
791 BC Oil and Gas Commission, "Gas Mitration Preliminary Investigation Report," December 2013, https://www.bcogc.ca/node/14620/download.
792 Anne E. Booker et al., "Sulfide Generation by Dominant Halanaerobium Microorganisms in Hydraulically Fractured Shales," *MSphere* 2, no. 4 (2017): e00257-17, https://doi.org/10.1128/mSphereDirect.00257-17.
793 Trent Jacobs, "Oil and Gas Producers Find Frac Hits in Shale Wells a Major Challenge," *Journal of Petroleum Technology*, March 31, 2017, https://jpt.spe.org/oil-and-gas-producers-find-frac-hits-shale-wells-major-challenge#:~:text=Risk%20management%20Oil%20and%20Gas%20Producers%20Find%20Frac,in%20oil%20and%20gas%20production.%20March%2031%2C%202017.
794 Trent Jacobs, "Frac Hits Reveal Well Spacing May Be Too Tight, Completion Volumes Too Large," *Journal of Petroleum Technology*, October 31, 2017, https://jpt.spe.org/frac-hits-reveal-well-spacing-may-be-too-tight-completion-volumes-too-large.

- July 9, 2015 – As part of a larger examination of the potential health and environmental impacts of fracking in California, the California Council on Science and Technology (CCST) documented cases of well failures triggered by underground movements that caused well casings to shear. Sheared well casings can allow gas and fluids from the fracking zone to migrate to overlying aquifers. The CCST team identified several mechanisms by which casing shears can occur in California as oil wells age: surface subsidence, heaving, reservoir compaction, and earthquakes. Prolonged drought can also damage the integrity of well casings: as groundwater levels fall, landforms can sink and contribute to casing shear.[795]

- June 30, 2015 – According to the New York State Department of Environmental Conservation (NYS DEC) Findings Statement, "there is a risk that well integrity can fail, especially over time, and questions have arisen about whether high-volume hydraulic fracturing can cause seismic changes which could potentially result in fracturing fluid migration through abandoned wells or existing fissures and faults. Thus, high-volume hydraulic fracturing could result in significant adverse impacts to water resources from well construction and fracturing fluid migration."[796]

- June 4, 2015 – As part of a draft assessment of fracking's impact on drinking water, the U.S. Environmental Protection Agency (EPA) examined cases of water contamination across the United States and concluded that "construction issues, sustained casing pressure, and the presence of natural faults and fractures can work together to create pathways for fluids to migrate toward drinking water resources." Fracking older wells poses additional risks, the draft study notes, because aging itself "can contribute to casing degradation, which can be accelerated by exposure to corrosive chemicals, such as hydrogen sulfide, carbonic acid, and brines" and because many older wells were never designed to withstand the high pressures and stress of fracking operations. The EPA estimates that 6 percent of the 23,000 U.S. oil and gas wells (= 1,380 wells) first fracked in 2009 or 2010 were drilled more than ten years earlier.[797]

- December 2, 2014 – Problems with structural integrity have been documented in a well at the only hydraulically fractured site in the United Kingdom. Email messages obtained under freedom of information laws reveal that problems with wellbore integrity emerged in April of 2014 and attempts were made to remediate the problem, although nothing was reported at that time to regulators. The drilling company, Cuadrilla Resources, continues to deny that any problems exist with the well, emphasizing that "no leak of fluids"

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[795] William T. Stringfellow et al., "Chapter Two: Impacts of Well Stimulation on Water Resources," in *An Independent Scientific Assessment of Well Stimulation in California* (California Council on Science and Technology, 2015), https://ccst.us/wp-content/uploads/160708-sb4-vol-II-2-1.pdf.

[796] New York State Department of Environmental Conservation, "Final Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program: Regulatory Program for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs," Findings Statement (NYSDEC, June 2015), http://www.dec.ny.gov/docs/materials_minerals_pdf/findingstatehvhf62015.pdf.

[797] U.S. Environmental Protection Agency, "Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources," Executive Summary (Office of Research and Development, June 2015), http://www2.epa.gov/sites/production/files/2015-06/documents/hf_es_erd_jun2015.pdf.

occurred and that "the issue" was resolved during the abandonment process. Cuadrilla had previously been reprimanded for failing to disclose a more minor deformation in the well casing. The well was abandoned at the end of last year, following two earthquakes in 2011, which scientists determined to have been caused by fracking at the site.[798]

- August 11, 2014 – Researchers affiliated with multiple universities and with the Los Alamos National Laboratory summarized recent field observations of wellbore-integrity failure, concluding that, because at least some well failures are not identified, reported barrier failure rates of 1-10 percent of wells and reported rates of groundwater contamination of 0.01-0.1 percent of wells constitute a "lower bound" for possible environmental problems. Citing hydraulic fracturing, as well as temperature and pressure changes, as operations that can induce pathways for leaks, the authors point out that few studies have considered the very-long-term fate (">50 years") of wellbore systems. They include "whether unconventional resource development alters the frequency of well integrity failures" as a critical topic for future research.[799]

- July 30, 2014 – Based on records obtained from Pennsylvania's DEP, Scranton's *Times-Tribune* reported that five natural gas wells in Bradford County have leaked methane for years because of persistent casing and cement problems. In the most recent violation, a PA-DEP inspector found combustible gas flowing through vents connected to the cement between layers of pipe. The agency issued a notice of violation for each well, saying combustible gas outside the well's surface casing violates state regulations. Each of the wells has four layers of steel casing, but nothing prevents leaking (stray) methane from flowing into the atmosphere. No evidence of water contamination has yet been seen. None of the wells have produced any gas for sale.[800]

- June 30, 2014 – A study published in *Proceedings of the National Academy of Sciences* by a Cornell University research team projected that over 40 percent of shale gas wells in Northeastern Pennsylvania will leak methane into groundwater or the atmosphere over time. Analyzing more than 75,000 state inspections of more than 41,000 oil and gas wells in Pennsylvania since 2000, the researchers identified high occurrences of casing and cement impairments inside and outside the wells. A comparative analysis showed that newer, unconventional (horizontally fracked) shale gas wells were leaking at six times the rate of conventional (vertical) wells drilled over the same time period. The leak rate for unconventional wells drilled after 2009 was at least six percent, and rising with time. In the state's northeastern counties between 2000 and 2012, over nine percent of shale gas wells drilled leaked within the first five years.[801] The study also discovered that over 8,000 oil and gas wells drilled since 2000 had not received a facility-level inspection.

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[798] Ben Bryant, "The Only Fracked Site in the United Kingdom Suffered Structural Failure," *Vice News*, December 2, 2014, https://news.vice.com/article/the-only-fracking-site-in-the-united-kingdom-suffered-structural-failure.
[799] Robert B. Jackson et al., "The Environmental Costs and Benefits of Fracking," *Annual Review of Environment and Resources* 39 (2014): 327–62, https://doi.org/10.1146/annurev-environ-031113-144051.
[800] Brendan Gibbons, "Five Gas Wells Leaked Methane for Years," *The Times-Tribune*, April 15, 2020, http://thetimes-tribune.com/news/five-gas-wells-leaked-methane-for-years-1.1727537.
[801] Anthony R. Ingraffea et al., "Assessment and Risk Analysis of Casing and Cement Impairment in Oil and Gas Wells in Pennsylvania, 2000-2012," *Proceedings of the National Academy of Sciences U.S.A.*, June 30, 2014, http://www.pnas.org/content/early/2014/06/25/1323422111.abstract.

This study helps explain the results of earlier studies that documented elevated levels of methane in drinking water aquifers located near drilling and fracking operations in Pennsylvania and points to compromised structural integrity of well casings and cement as a possible mechanism.

- May 22, 2014 – In a 69-page report, University of Waterloo researchers warned that natural gas seeping from 500,000 wellbores in Canada represents "a threat to environment and public safety" due to groundwater contamination, greenhouse gas emissions, and explosion risks wherever methane collects in unvented buildings and spaces. The report found that 10 percent of all active and suspended gas wells in British Columbia now leak methane. Additionally, the report found that some hydraulically fractured shale gas wells in that province have become "super methane emitters" that spew as much as 2,000 kilograms of methane a year.[802, 803]

- May 1, 2014 – Following a comprehensive review of evidence, the Council of Canadian Academies identified inherent problems with well integrity as one of its top concerns about unconventional drilling and fracking. According to one expert panel, "the greatest threat to groundwater is gas leakage from wells from which even existing best practices cannot assure long-term prevention."[804] Regarding their concerns related to well integrity and cement issues, the panel wrote:

> Two issues of particular concern to panel members are water resources, especially groundwater, and GHG emissions. Both related to well integrity…. Natural gas leakage from improperly formed, damaged, or deteriorated cement seals is a long-recognized yet unresolved problem …. Leaky wells due to improperly placed cement seals, damage from repeated fracturing treatments, or cement deterioration over time, have the potential to create pathways for contamination of groundwater resources and to increase GHG emissions.

They further explain:

> Cement may crack, shrink, or become deformed over time, thereby reducing the tightness of the seal around the well and allowing the fluids and gases … to escape into the annulus between casing and rock and thus to the surface…. The challenge of ensuring a tight cement seal [will] be greater for shale gas wells that are subjected to repeated pulses of high pressure during the hydraulic fracturing process than for conventional gas wells. This pressure stresses the casing and therefore the cement that isolates the well from surrounding formations

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[802] Maurice B. Dusseault, Richard E. Jackson, and Daniel MacDonald, "Towards a Road Map for Mitigating the Rates and Occurrences of Long-Term Wellbore Leakage" (Geofirma Engineering Ltd., May 22, 2014), http://geofirma.com/wp-content/uploads/2015/05/lwp-final-report_compressed.pdf.

[803] Andrew Nikiforuk, "Canada's 500,000 Leaky Energy Wells: 'Threat to Public,'" *The Tyee*, June 5, 2014, 000, http://www.thetyee.ca/News/2014/06/05/Canada-Leaky-Energy-Wells/.

[804] Council of Canadian Academies, "Environmental Impacts of Shale Gas Extraction in Canada: The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction," Scientific Publication, May 1, 2014, https://www.ccacoalition.org/en/resources/environmental-impacts-shale-gas-extraction-canada-expert-panel-harnessing-science-and.

repeatedly.

- January 8, 2013 – According to state inspections of all 6,000 wells drilled in Pennsylvania's Marcellus Shale before 2013, six to ten percent of them leaked natural gas, with the rate of leakage increasing over time. The rate was six percent in 2010 (97 well failures out of 1,609 wells drilled); 7.1 percent in 2011 (140 well failures out of 1,972 wells drilled); and 8.9 percent in 2012 (120 well failures out of 1,346 wells drilled).[805] These data include wells that were cited for leakage violations, and wells that were noted to be leaking by inspectors but which had not been given violations. The NYS DEC forecasts that 50,000 wells could be drilled over the life of the Marcellus Shale play. If they fail at the same rate as wells in Pennsylvania, 4,000 wells would fail and leak in New York almost immediately.[806]

- March 2009 – A study published by the Society of Petroleum Engineers of more than 315,000 oil, gas, and injection wells in Alberta, Canada, found that 4.5 percent of the wells had unintended gas flow to the surface. In one designated area, officials required testing for gas migration outside the well casings in addition to routine testing for gas leaks within the rings of steel casings (annuli). Within this special testing zone, 15.5 percent of wells (3,205 of 20,725) leaked gas, and the incidence of gas leaks was four times percent higher in horizontal or deviated wells than in vertical wells.[807]

- Autumn 2003 – Schlumberger, one of the world's largest companies specializing in hydraulic fracturing and other oilfield services, reported in its in-house publication, *Oilfield Review*, that more than 40 percent of approximately 15,500 wells in the outer continental shelf area in the Gulf of Mexico were leaking gas. These included actively producing wells, in addition to shut-in and temporarily abandoned wells. In many cases, the gas leaked through the spaces (annuli) between layers of steel casing that drilling companies had injected with cement precisely to prevent such gas leaks. Leakage rates increased dramatically with age: about five percent of the wells leaked immediately; 50 percent were leaking after 15 years; and 60 percent were leaking after about 30 years.[808] Gas leaks pose serious risks including loss of life from explosions and migration of gas and associated contaminants into drinking water supplies. Leaks also allow the venting of raw methane into the atmosphere where it acts as a powerful greenhouse gas.

- November 2000 – Maurice Dusseault, a specialist in rock mechanics at the University of Waterloo in Ontario, and two co-authors presented a paper published by the Society of Petroleum Engineers, in which they reported that oil and natural gas wells routinely leak

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805 Anthony R. Ingraffea, "Some Scientific Failings Within High Volume Hydraulic Fracturing Proposed Regulations 6 NYCRR Parts 550-556, 560, Comments and Recommendations Submitted to the NYS Dept. of Environmental Conservation" (PSE Healthy Energy, 2013).
806 New York State Department of Environmental Conservation, "Supplemental Generic Environmental Impact Statement (SGEIS) on the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs" (NYSDEC, 2011), https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/1777818.
807 Theresa Watson and Stefan Bachu, "Evaluation Of The Potential For Gas And CO2 Leakage Along Wellbores," *Society of Petroleum Engineers Drilling & Completion* 24 (2009): 115–26, https://doi.org/10.21.18/106817-PA.
808 Claudio Brufatto et al., "From Mud to Cement—Building Gas Wells," *Oilfield Review* 15, no. 3 (2003): 62–76.

gas through cracks in their cement casings, likely caused by cement shrinkage over time and exacerbated by upward pressure from natural gas. According to their paper, in Alberta, it is common for wells to leak natural gas into aquifers. "Because of the nature of the mechanism, the problem is unlikely to attenuate," they wrote, "and the concentration of the gases in the shallow aquifers will increase with time."[809]

[809] Maurice B. Dusseault, Malcolm N. Gray, and Pawel A. Nawrocki, "Why Oilwells Leak: Cement Behavior and Long-Term Consequences," *Society of Petroleum Engineers*, 2000, https://www.parliament.vic.gov.au/images/stories/committees/EPC/Submission_903_-_Attachment_A_-_The_Portland_Field_Naturalists_Club.pdf.

Radioactive releases

Radioactive materials, including uranium, polonium, and radon, are commonly found in shale formations. These can be released as airborne contaminants during drilling and fracking operations, as revealed by a 2020 study that documented the presence of airborne radioactive particles downwind from fracking sites at levels sufficient to raise health risks for nearby residents. Radioactive materials are also often components of solid and liquid fracking waste, raising exposure risks for workers and the general public. Exemptions from federal hazardous waste laws mean that no national regulatory framework exists for handling these radioactive materials. Instead, regulation is the responsibility of individual states, which vary widely in their approaches.

High levels of radiation documented in fracking wastewater from many shale formations raise special concerns in terms of impacts to groundwater and surface water. Measurements of radium in fracking wastewater in New York and Pennsylvania, from the particularly radioactive Marcellus Shale, have been as high as 3,600 times the regulatory limit for drinking water, as established by the U.S. Environmental Protection Agency (EPA). Studies have found toxic levels of radiation in Pennsylvania waterways even after fracking wastewater was disposed of through an industrial wastewater treatment plant. In 2020, New York State banned the practice of dumping out-of-state fracking waste in municipal landfills. A 2021 investigation found that a fracking waste disposal site in Texas has been importing radioactive oilfield waste from abroad.

Increasing evidence documents illegal, haphazard dumping of radioactive fracking waste, along with its disposal in municipal landfills not engineered to contain radioactivity. Drill cuttings—the pulverized rock pulled up during the drilling process—are a special concern as this form of solid waste, generated in prodigious amounts, is typically disposed of in municipal landfills lacking special protections for hazardous waste. Radioactivity in drill cuttings has been shown to exceed, in some cases, the regulatory limits for landfills that accept fracking waste. In some states, drill cuttings are repurposed as road-building materials.

New research suggests that the chemical composition of fracking fluid itself helps to mobilize radioactive materials in the shale.

Studies have found high levels of radon in buildings located in heavily drilled areas of both Pennsylvania and Ohio, with levels of radon rising since the start of the fracking boom. Unsafe levels of radon and its decay products in natural gas produced from the Marcellus Shale may also contaminate pipelines and compressor stations, as well as pose risks to end-users when allowed to travel into homes.

- June 1, 2021 – A longstanding target of public opposition, the Keystone Sanitary Landfill, near Scranton, Pennsylvania accepts radioactive fracking waste and is seeking approval for a major expansion across 435 acres. An investigative report found that this facility has contaminated groundwater, dumped illegally, and is under federal investigation and litigation. Of particular concern are the open piles of radioactive materials that continue to accumulate in this facility. In response, the Pennsylvania Attorney General opened an investigation into Keystone regarding an alleged leachate dumping incident in September 2016 with a specific focus on the "harmful effects on the air quality, safety, and health of the citizens of Scranton, as well as the water quality of Meadow Brook Creek and the Lackawanna River."[810]

- April 26, 2021 – Solid waste from oil-based drilling operations contains carcinogenic contaminants, including heavy metals and polycyclic aromatic hydrocarbons, as well as radionuclides. A research team assessed the chemical composition and radioactive strength in samples of this waste, in order to estimate the public health risks from exposure to these wastes when incorporated into roadbed materials. This risk assessment evaluated several pathways of exposure—ingestion, respiration, and via groundwater—and found that repurposing drill cuttings for roadbed materials poses unacceptable levels of risk.[811]

- April 22, 2021 – A year-long independent investigation documented that a large West Texas oil and disposal facility, Lotus LLC, already cited for not following its disposal protocol, has been importing radioactive oilfield waste from abroad. Classified as non-hazardous under the Bevill and Bentsen Amendments, oil and gas waste is often highly radioactive. Indeed, Lotus LLC received a drum of waste from Australia, transported on a cargo jet, containing levels of radium that exceeded EPA limits for Superfund sites and uranium mills by a factor of 400. The investigation found, through aerial photos and interviews, multiple instances of radioactive material stockpiled in "damaged, rusted, and degraded tanks or barrels stored directly on an unlined surface without proper containment to prevent leaching, runoff, and other direct risks to groundwater and surface contamination." Open tanks had large quantities of "filter socks" and pipe scale from drilling sites. Both are known to be typically highly radioactive. The state's Railroad Commission found no violations in its most recent inspection and had no comment on the photos or independent investigation. No specific permits are required to import radioactive oil and gas waste.[812]

- March 1, 2021 – In September 2020, Roulette Oil & Gas applied for an EPA permit to convert one of their conventional wells in Potter County, Pennsylvania into a Class II-D injection well to dispose of liquid waste from 110 conventional oil and gas wells in the area and possibly three fracked wells. Only 10 Class II-D permits have ever been issued for all of Pennsylvania. Local officials were not notified of the application, arousing suspicion that the secrecy was intentional. An investigative news report revealed that the permit application did not state that oil and gas waste would contain radioactive material and that the federal permit itself, if received, would only require chemical testing every

[810] Emma Lichtwardt and Joshua Boaz Pribanic, "America Is Building Mountains of Radioactive Fracking Waste & the One in Joe Biden's Hometown Is Under Criminal Investigation" (Public Herald, June 2021), https://publicherald.org/america-is-building-mountains-of-radioactive-fracking-waste-the-one-in-joe-bidens-hometown-is-under-criminal-investigation/.
[811] Deming Xiong and Chaoqiang Wang, "Risk Assessment of Human Exposure to Heavy Metals, Polycyclic Aromatic Hydrocarbons, and Radionuclides in Oil-Based Drilling Cutting Residues Used for Roadbed Materials in Chongqing, China," *Environmental Science and Pollution Research*, 2021, https://doi.org/10.1007/s11356-021-13871-0.
[812] Justin Nobel, "Where Does All The Radioactive Fracking Waste Go?," DeSmog International, April 22, 2021, https://www.desmog.com/2021/04/22/lotus-llc-radioactive-fracking-waste-disposal-texas/.

two years and would not require testing for radioactive materials. Radiation testing would be left to the state of Pennsylvania, which has not created such regulations for oil and gas wastewater injection wells."[813]

- February 18, 2021 – Two workers suffered burns in an eruption and blaze fueled by oil and gas waste materials at a truck stop cleaning station in West Virginia, prompting community and workers to raise concern about such facilities accepting and processing oil and gas waste, including radioactive waste, within Marcellus and Utica shale regions. As determined by the West Virginia Department of Environmental Protection, this particular blaze was likely ignited by a torpedo space heater when it came into contact with oil and gas vapors wafting from the fracking flowback waste and brine waste in a truck. Both materials were being processed by the facility at the time.[814]

- December 14, 2020 – Two oil and gas industry professionals described shocking experiences of radiation exposure to themselves and others, in an investigative report that referred to fracking workers in Appalachia's Marcellus Shale region as "the industry's black box." The investigation, which interviewed gas and oil industry whistleblowers, reported that workers in Ohio and Pennsylvania are exposed to radioactive materials through various tasks which bring them into direct contact with drill cuttings from fracking bores that have cut through radioactive shale, and with scales and sludges formed on piping and in tank bottoms. According to a radiation control consultant interviewed in the investigation, these materials can be, "much hotter than most stuff in nuclear plants." Radiation monitors are not typically found on site. One of the industry professionals, a hazardous materials technician for several of the largest companies regionally, described the challenge of workers trying to control their own risk when they did not have information on the hazard, as when he and co-workers decided to take their own gamma scanners onto cleanup project sites. With no training from the clients who hired them, he described a, "deliberate failure to disclose." A second professional, who trained as a nuclear health physicist in the U.S. Navy and started his own company to help the industry with radiation safety, described his encounters with "incredibly unsafe" situations for workers and their families. After finding one pipeyard with "particularly egregious" concentrations of radium-226, his company visited the employees' homes, and found "incredibly hot" laundry, as well as highly contaminated, bedding, clothing, and carpets, with two small children interacting with these materials as he took measurements. He described industry resistance to even simple interventions that companies could use to reduce risks to workers and their families.[815]

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813 Sam Sanson, "Stopping Radioactive Water: Officials Want to Ban Oil & Gas Injection Wells at Pennsylvania Headwaters," March 2021, https://publicherald.org/stopping-radioactive-water-officials-want-to-ban-oil-gas-injection-wells-at-pennsylvania-headwaters-to-block-epa-permit/.

814 Justin Nobel, "Fire at Oil and Gas Waste Site Raises Safety Concerns Around Possible Radioactive Accidents," DeSmog International, February 18, 2021, https://www.desmog.com/2021/02/18/fire-oil-gas-waste-petta-dallas-pike-safety-radioactivity/.

815 Kristen Locy and Justin Nobel, "Oil & Gas Whistleblowers Speak Out About Exposure to Radioactivity on Fracking Jobs" (Public Herald, December 2020), https://publicherald.org/if-only-i-wouldve-known-oil-gas-whistleblowers-speak-out-about-exposure-to-radioactivity-on-fracking-jobs/.

- October 13, 2020 – A Harvard team documented the presence of airborne radioactivity downwind from fracking sites at levels sufficient to raise health risks for nearby residents. Using data collected from 157 radiation-monitoring stations built across the nation during the Cold War, the researchers showed a seven percent increase in radioactive pollution in communities located 12 to 31 miles downwind from operational fracking sites as compared to background levels. The closer communities were located to the wells, the higher the radioactivity in airborne particles. In the Fort Worth, Texas area, where more than 600 fracking wells are located upwind from the city, the team estimated a 40 percent increase in radiation levels. The radioactive elements carried by the ultrafine particles, including polonium, represent the radioactive decay products of uranium isotopes that are liberated from the shale during fracking operations.[816]

- September 7, 2020 – With growing public concern about more than two dozen cases of rare Ewing's sarcoma among teens and young adults in intensely fracked areas of southwestern Pennsylvania, investigative reporters at *Public Herald* pressed the Pennsylvania Department of Health (DOH) for more information about the scope and progress of the public health studies that were promised to local residents. DOH has relinquished the study format to the University of Pittsburgh, and there is no indication that the research team is planning to investigate the issue of fracking-related radioactivity despite the concern of many residents that such exposures may be playing a role in the unusually high incidence of an otherwise rare cancer.[817]

- August 5, 2020 – Using state records and right-to-know-law requests, an investigative team at the *Public Herald* found that final destination of 66 percent of the leachate from 30 different landfills in Pennsylvania that accept oil and gas waste from fracking operations is unknown. Further, the leachate is not being tested for radioactivity before being discharged into rivers and streams. Leachate is a landfill's liquid waste formed by rainwater percolating through the landfill. It is typically sent to wastewater treatment plants before being discharged into surface water. Oil and gas waste from Marcellus Shale fracking operations that are dumped in landfills can contain high levels of Technically Enhanced Naturally Occurring Radioactive Materials (TENORMS), meaning that naturally occurring radioactivity within the earth's geological layers is mobilized and concentrated by the activities of fracking when it is brought to the surface as a constituent of liquid and solid waste. TENORMS are not removeable by the filtration systems of most treatment plants. Pennsylvania state records show radium-226 levels in fracking wastewater can be as high as 26,000 picocuries per liter, which is more than 5,000 times the limit for radium in drinking water. The team found that the Pennsylvania Department of Environmental Protection (DEP) is limiting the amount of TENORM coming into its landfills by limiting the amount of waste the landfill can receive. However, the agency is not tracking the amount of TENORM leaving the landfill and heading to water treatment facilities in the form of leachate. "The DEP says that the transaction is private between

[816] Longxiang Li et al., "Unconventional Oil and Gas Development and Ambient Particle Radioactivity," *Nature Communications* 11 (2020), https://doi.org/10.1038/s41467-020-18226-w.
[817] Kristen Locy and Joshua Pribanic, "DOH Continues to Dodge Health Impacts from Oil & Gas Radiation, Passes Study to the University of Pittsburgh" (Public Herald, September 2021), https://publicherald.org/doh-continues-to-dodge-health-impacts-from-oil-gas-radiation-passes-their-health-study-to-the-university-of-pittsburgh/.

the two entities: the landfill and the treatment plant."[818] New state legislation was drafted in 2019 that would prevent TENORM disposal in Pennsylvania public waters.[819]

- August 3, 2020 – Oil and natural gas waste became subject to state law regulating the transportation, treatment, storage and disposal of hazardous waste, as New York State Governor Andrew Cuomo signed into law S3392/A2655.[820] Though the state had banned extraction of natural gas by fracking in 2015, fracking waste arrives into the state from Pennsylvania and was previously treated as non-hazardous, in spite of the carcinogenic compounds and naturally occurring radioactive materials it contains.[821]

- July 18, 2020 – Exposure to radionuclides from oil and gas waste was greater when waste was in bulk rather than containerized, and greater exposure occurred with smaller vehicles for transport, according to researchers from the Department of Civil Engineering-University of Indonesia and the Indonesian Nuclear Energy Regulatory Agency.[822] The team evaluated exposure to radionuclides from oil and gas waste by landfill worker job description: drivers, workers receiving the waste, and workers disposing of the waste. The method used was that of the US Department of Energy to evaluate radiation exposure at Transport, Storage and Disposal (TSD) facilities.

- April 22, 2020 – The National Council of Radiation Protection and Measurements (NCRP), which is chartered under, but not overseen by, the U.S. Congress, called for the development of a full report to provide science-based national guidelines for the disposal radioactive waste from fracking operations. In its commentary, the NCRP described the geological origins of radioactivity in oil and gas drilling; the historical and current regulatory framework; options for the disposal of radioactive waste; legal considerations; and radiation protection measures for workers. The NCRP further notes that the EPA does have the authority to regulate individual radionuclides under a suite of federal environmental laws. However, because EPA has not thus far provided any regulations or even guidance, regulatory action has, heretofore, fallen to the states with little input from

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[818] Joshua Pribanic and Talia Wiener, "Pennsylvania Regulators Won't Say Where 66% of Landfill Leachate w/ Radioactive Material From Fracking Is Going…'It's Private'," *Public Herald*, August 5, 2020, https://publicherald.org/pennsylvania-regulators-wont-say-where-66-of-landfill-leachate-w-radioactive-material-from-fracking-is-going-its-private/.

[819] Joshua B. Pribanic, "'Government Failed You' - Pittsburgh State Rep. Drafts Bill to Stop Radioactive Fracking Waste (TENORM) From Entering Public Waters," *Public Herald*, December 10, 2019, https://publicherald.org/government-failed-you-pittsburgh-state-rep-drafts-bill-to-stop-radioactive-fracking-waste-tenorm-from-entering-public-waters/.

[820] "Cuomo Signs Legislation Regulating Oil- and Gas-Related Waste," *Niagara Frontier Publication*, August 3, 2020, https://www.wnypapers.com/news/article/current/2020/08/03/142660/cuomo-signs-legislation-regulating-oil-and-gas-related-waste.

[821] Rachel May, "Legislature Closes Decade Long Loophole on Treatment of Hazardous Fracking Waste," Press Release (New York State Senate, July 22, 2020), https://www.nysenate.gov/newsroom/press-releases/rachel-may/legislature-closes-decade-long-loophole-treatment-hazardous.

[822] C. A. W. Dwipayana, S. S. Moersidik, and M. A. Pratama, "Estimation Radiation Dose From Operation of Petroleum NORM Waste Disposal in Landfill Using TSD-DOSE," *Journal of Physics: Conference Series, 1572* 1572 (2020), https://doi.org/10.1088/1742-6596/1572/1/012031.

federal advisory bodies. In the absence of consistent, standard regulations across the states—and in some states there are none at all—compliance difficulties arise.[823]

- February 13, 2020 – In violation of Oregon state regulations, two million pounds of radioactive fracking waste from North Dakota Bakken's oil field was received by a chemical waste landfill near Oregon's Columbia Gorge, delivered by rail in 2016, 2017 and 2019. Some of the waste "registered radium at 300 times the state's limits," and on average, "registered radium at 140 picocuries per gram," while the state maximum for the facility is five picocuries, according to a state nuclear waste remediation specialist quoted in *Oregon Live*.[824] Citing lack of malicious intent, authorities will not fine the landfill, but require the company to create a risk assessment and action plan to address the violation.

- January 21, 2020 – *Rolling Stone* reporter Justin Nobel investigated radioactive materials in fracking waste, including fracking waste dumped in landfills and through sewage treatment plants, liquid fracking waste spread on roadways, and wastewater hauled to underground injection wells for disposal. Truckers are not required to wear protective gear or wear dosimeters to measure exposure, and they frequently become soaked in the wastewater they are disposing. Involving hundreds of interviews, *Rolling Stone's* investigation uncovered "a sweeping arc of contamination—oil-and-gas waste spilled, spread, and dumped across America, posing under-studied risks…. There is little public awareness of this enormous waste stream, the disposal of which could present dangers at every step—from being transported along America's highways in unmarked trucks; handled by workers who are often misinformed and underprotected; leaked into waterways; and stored in dumps that are not equipped to contain the toxicity. Brine has even been used in commercial products sold at hardware stores and is spread on local roads as a de-icer." A set of recently settled lawsuits among Louisiana oil and gas workers revealed chronic exposures that led to fatal cancers. Historical industry documents expose long-standing inhouse concerns about liability for oil and gas workers' health from radiation exposures.[825]

- December 23, 2019 – In a study of radioactivity within the Polish gas pipeline network, excess radon, or ^{222}Rn, concentrations were found in gas from national mines compared to gas from international sources, due to transit time and radon's short half-life. Very high radiolead, or ^{210}Pb, was found in "black powder" samples. Black powder is a product of corrosion of steel pipes and is found in filters at compressor stations and from pigging operations. Faculty researchers from the University of Science and Technology

[823] NCRP Scientific Committee 5-2, "Naturally Occurring Radioactive Material (NORM) and Technologically Enhanced NORM (TENORM) from the Oil and Gas Industry," NCRP Commentary (National Council on Radiation Protection and Measurements, 2020), https://ncrponline.org/shop/commentaries/commentary-no-29/.
[824] Laura Gunderson, "Oregon Landfill Accepted 1 Million Pounds of Radioactive Fracking Waste From North Dakota," *The Oregonian*, February 13, 2020, sec. Environment, https://www.oregonlive.com/environment/2020/02/oregon-landfill-accepted-2-million-pounds-of-radioactive-fracking-waste-from-north-dakota.html.
[825] Justin Nobel, "America's Radioactive Secret," *Rolling Stone*, January 21, 2020, sec. Politics, https://www.rollingstone.com/politics/politics-features/oil-gas-fracking-radioactive-investigation-937389/.

in Krakow, Poland concluded that handling black powder presents radiological risk to employees.[826]

- November 29, 2019 – Exposure to TENORM waste from the oil and gas industry "may lead to multiple environmental and health risks," according to a review analyzing and comparing available international data from extraction, production and transport.[827] The American Petroleum Institute reported that scales in the oil and gas industry, often found inside pipes and tubes at fracking sites, had concentrations as high as tens of thousands of Bq g^{-1}; it can also contain radon offspring, such as ^{210}Pb and ^{210}Po. In addition, some studies found excess radioactivity in soil in the vicinity of oil and gas industry fields and facilities. Based on their review of many studies, the authors concluded that oil and gas activities exceed the 10,000 Bq kg^{-1} exemption level recommended in the safety standards of the International Atomic Energy Agency (IAEA). In particular, they wrote that TENORM waste produces high levels of radiation exposure because radioactivity often accumulates on machinery and equipment, due to mismanagement, physical conditions, and other factors.

- September 25, 2019 – Radioactive materials in oil and gas industry waste represent an unknown risk for workers and community members. An Egyptian research team investigated the potential health effects of low-levels exposure to these substances in laboratory rats. Waste exposure for one and two months resulted in a significantly increased production of cellular free radicals, elevations in lipid peroxides, and damage to red blood cells.[828] Exposure also triggered a radio-adaptive response in rats subsequently exposed to a higher dose of gamma radiation, particularly in the longer-exposed animals.

- September 11, 2019 – A Pennsylvania municipal worker observed irregularities in sewage releases that led to the discovery that 40 percent of waste in a local landfill was, in fact, solid oil and gas waste, including drill cuttings. The superintendent of the Belle Vernon Municipal Authority, which runs the town's small sewage treatment plant on the banks of the Monongahela River, found barium, chlorides, and, of particular concern, radium, in the leacheate from the landfill at levels higher than allowed by EPA's drinking water standards. A *StateImpact Pennsylvania* investigation found that this sewage treatment plant, along with 12 others, were "too small to automatically qualify for stricter regulations on leachate, and have to police the landfills themselves." Duke University geochemist Avner Vengosh cautioned, "I predict that the radium will start to accumulate on the sediments at the bottom of this discharge site…The radioactivity level could be really high. And of course the risk is that once there is high radium in the sediments, there is incorporation into the ecological chain."[829]

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[826] Jakub Nowak, Pawel Jodlowski, and Jan Macuda, "Radioactivity of the Gas Pipeline Network in Poland," *Journal of Environmental Radioactivity* 213 (2020): 106143, https://doi.org/10.1016/j.jenvrad.2019.106143.
[827] Mohsen M. M. Ali et al., "Concentrations of TENORMs in the Petroleum Industry and Their Environmental and Health Effects," *RSC Advances* 9, no. 67 (2019): 39201–29, https://doi.org/10.1039/c9ra06086c.
[828] Seham M. El-Marakby et al., "Assessment of Chronic Exposure Effects and Radioadaptive Response of Natural Occurring Radioactive Materials (NORM)," *Radiation Physics and Chemistry* 166 (2020): 108502, https://doi.org/10.1016/j.radphyschem.2019.108502.
[829] Reid Frazier, "How Did Fracking Contaminants End up in the Monongahela River? A Loophole in the Law Might Be to Blame," *State Impact Pennsylvania*, September 11, 2019,

- April 10, 2019 – In a study of 118,421 homes in all 88 Ohio counties, a University of Toledo team used multilevel modeling to investigate the relationship of indoor radon concentrations and fracked well locations for the years 2007-2014. The found that proximity of Ohio homes to fracking wells was linked to higher indoor concentrations of radon gas.[830] "The shorter the distance a home is from a fracking well, the higher the radon concentration. The larger the distance, the lower the radon concentration," according to lead researcher, Ashok Kumar.[831] Most of the gas wells were located in eastern Ohio which overlies the shale deposits. The mean radon concentrations among the tested homes was 5.76 pCi/l, which is higher than the EPA's "safe" levels of 4.0 pCi/l. (The World Health Organization recommends mitigation at 2.7 pCi/l.) The highest radon concentration, 141.85 pCi/l, was found in central Ohio. The data in the study were collected from self-reported devices. Researchers concluded, "there is a strong correlation between indoor radon concentrations and hydraulic fracturing in Ohio."

- March 15, 2019 – Due to a 1980 hazardous waste exemption from the Resource Conservation and Recovery Act (RCRA), drill cuttings from oil and gas fields became exempt from federal oversight, leaving it to states to regulate the disposal of this solid waste stream. A team of researchers measured radioactivity in drill cuttings extracted from Pennsylvania wells and found levels of radium-226 and radium-228 that exceeded the regulatory limits for landfills in Ohio and New York, two states where there are regulatory limits and that accept fracking waste from other states, including from Pennsylvania. The authors recommended rescinding the RCRA exemption for hazardous fracking waste to better protect public health.[832]

- August 3, 2018 – A two-part study by Dartmouth College researchers investigated the source of radium in fracking wastewater from Marcellus Shale wells. By comparing the isotopic ratios, they showed that the high salinity of the wastewater is responsible for extracting radium from the shale. "Experimental results and wastewater data together provide a coherent picture, that the distinctive Ra isotopic signature of Marcellus wastewaters results from contemporaneous water-rock interactions that promote desorption of ^{226}Ra from organics during hydraulic fracturing."[833] In the second part of the study, the researchers used mass balance and isotope mixing models to attribute both the extreme salinity and the presence of radium in liquid fracking waste to the

https://stateimpact.npr.org/pennsylvania/2019/09/11/how-did-fracking-contaminants-end-up-in-the-monongahela-river-a-loophole-in-the-law-might-be-to-blame/.

830 Yanqing Xu, Mounika Sajja, and Ashok Kumar, "Impact of the Hydraulic Fracturing on Indoor Radon Concentrations in Ohio: A Multilevel Modeling Approach," *Frontiers in Public Health* 7, no. 76 (2019), https://doi.org/10.3389/fpubh.2019.00076.

831 University of Toledo, "Fracking Linked to Higher Radon Levels in Ohio Homes," *Science Daily*, June 18, 2019, https://www.sciencedaily.com/releases/2019/06/190618083347.htm.

832 Elaine W. Swiedler et al., "Should Solid Waste From Shale Gas Development Be Regulated as Hazardous Waste?," *Energy Policy* 129 (2019): 1020–33, https://doi.org/10.1016/j.enpol.2019.02.016.

833 Joshua D. Landis et al., "Rapid Desorption of Radium Isotopes From Black Shale During Hydraulic Fracturing. 1. Source Phases That Control the Release of Ra from Marcellus Shale," *Chemical Geology* 496 (2018): 1–13, https://doi.org/10.1016/j.chemgeo.2018.06.013.

progressive, hydrologic enrichment of injected fluids during hydraulic fracturing.[834] In sum, the chemical composition of fracking fluid itself and its interactions with black shale during the fracking process combine to make fracking waste radioactive. Explaining these findings in a news article, co-author Makul Sharam said, "Radium is sitting on mineral and organic surfaces within the fracking site waiting to be dislodged. When water with the right salinity comes by, it takes it on the radioactivity and transports it."[835]

- February 19, 2018 – A study conducted in the Bakken Shale region of North Dakota used a multivariate regression model to predict radium-226 levels in fracking wastewater based on levels of other elements (barium, strontium, calcium). Their simulation model gave results that align with the extremely limited actual data based on direct measurements of radionuclides in Bakken Shale wastewater. The research team then used their model to predict potential harm to human health based on spills into surface water that is issued as a source of drinking water, irrigation, and recreational fishing. Even in the best-case scenario, using simulated concentrations on the low end, the results indicated that "there is potential risk to human health" in North Dakota due to radium-226 in fracking wastewater spills. This model can be used for any area where oil and gas waste is produced. "Overall, the results presented in this study can be treated as a warning and a reference to conduct further investigations."[836]

- February 6, 2018 – A research team from City University of New York School of Public Health and Health Policy surveyed the various state-based regulations and state licensing requirements governing the disposal of radioactive waste from oil and gas waste streams. They found that 17 states had drafted express regulations to reduce exposure to radiation from oil and gas waste. States with active oil and gas drilling that lack such regulations "may leave the public and workers susceptible to adverse health effects from radiation." Among the authors' policy recommendations: due to accumulation of radioactivity on equipment, future studies should explore impacts on workers; exposed workers should wear badges to monitor exposures; worker exposures should be limited by shift changes; regulations across states should be harmonized to prevent cross-state dumping of large amounts of radioactive solid waste and assure protection of the public from the risk of radiation from exposure to oil and gas drilling wastes.[837]

- January 4, 2018 – A research team from Duke and Pennsylvania State universities collected stream sediments upstream and downstream from three disposal sites in

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[834] Joshua D. Landis, Mukum Sharma, and Devon Renock, "Rapid Desorption of Radium Isotopes From Black Shale During Hydraulic Fracturing. 2. A Model Reconciling Radium Extraction With Marcellus Wastewater Production," *Chemical Geology* 500 (2018): 194–206, https://doi.org/10.1016/j.chemgeo.2018.08.001.
[835] Dartmouth College, "How Slick Water and Black Shale in Fracking Combine to Produce Radioactive Waste," *Science Daily*, September 18, 2018, https://www.sciencedaily.com/releases/2018/09/180918154831.htm.
[836] L. Torres, O. P. Yadav, and E. Khan, "Risk Assessment of Human Exposure to Ra-226 in Oil Produced Water From the Bakken Shale," *Science of the Total Environment* 626 (2018): 867–74, https://doi.org/10.1016/j.scitotenv.2018.01.171.
[837] Elizabeth Ann Glass Geltman and Nichole LeClair, "Variance in State Protection from Exposure to NORM and TENORM Wastes Generated During Unconventional Oil and Gas Operations: Where We Are and Where We Need to Go," *New Solutions* 28, no. 2 (2018): 240–61, https://doi.org/10.1177/1048291118755387.

Pennsylvania that receive oil and gas wastewater, treat it, and release it into surface water. While the practice of treating and dumping liquid waste from fracking operations into Pennsylvania streams largely ended in 2011, these three facilities continue to treat and release waste from conventional drilling operations. The researchers consistently detected elevated radioactivity in stream sediments in the vicinity of the outfall compared to upstream areas. The ratios of radium isotopes to their decay products showed that some of the radium had accumulated in the sediments in recent years—after discharges of fracking waste had been halted. Hence, radioactivity from conventionally drilled wells is the likely source of the high levels of radium in sediments downstream from these three treatment plants. Consequently, policies that prohibit disposal only of fracking waste fluids "are not adequate in preventing radioactive contamination in sediments at disposal sites." Permission to treat and release any type of oil and gas wastewater via centralized waste treatment facilities "should be reconsidered."[838]

- September 22, 2017 – State health regulators confirmed that unknown quantities of radioactive waste from drilling and fracking operations have been illegally buried in Colorado landfills not permitted to accept it.[839]

- November 23, 2016 – University of Iowa researchers evaluated radioactive materials—uranium, thorium, radium, lead, and polonium isotopes—from drill cutting samples extracted from a single well drilled in northern Pennsylvania. They found complex patterns of vertical stratification. For example, the deep drill cuttings had significantly more uranium (U) than the cuttings removed from shallow portions of the well. Noting that virtually all drill cutting waste from the Marcellus Shale is deposited in landfills, the authors examined the stability of the various radioactive materials by simulating different conditions of landfill leaching. The results suggested some environmental mobility of radionuclides in drill cuttings. In particular, as acidity increased, radionuclide leaching increased, with ^{238}U and ^{234}U being the most leachable radionuclides. The authors concluded, "Although previous studies have suggested that [radioactive materials] in drill cuttings pose a minimal health risk to the general public when deposited in landfills, our results indicate that Marcellus Shale drill cuttings warrant further radiochemical investigation."[840]

- April 27, 2016 – Duke University researchers who studied oil and gas wastewater ("brine") spills reported that "the water contamination from brine spills is remarkably persistent in the environment, resulting in elevated levels of salts and trace elements that can be preserved in spill sites for at least months to years …." In addition, radioactivity was elevated in soil and sediment sampled at spill sites, indicating that radium had

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[838] Nancy E. Lauer, Nathaniel R. Warner, and Avner Vengosh, "Sources of Radium Accumulation in Stream Sediments near Disposal Sites in Pennsylvania: Implications for Disposal of Conventional Oil and Gas Wastewater," *Environmental Science & Technology* 52, no. 3 (2018): 955–62, https://doi.org/10.1021/acs.est.7b04952.
[839] Bruce Finley, "Colorado Landfills Are Illegally Burying Low-Level Radioactive Waste From Oil and Gas Industry, Denver Post Learns," *The Denver Post*, September 22, 2017, sec. Environment, https://www.denverpost.com/2017/09/22/colorado-landfills-illegally-burying-radioactive-waste-oil-gas/.
[840] Eric S. Eitrheim et al., "Disequilibrium of Naturally Occurring Radioactive Materials (NORM) in Drill Cuttings from a Horizontal Drilling Operation," *Environmental Science & Technology Letters* 3, no. 12 (2016): 425–29, https://doi.org/10.1021/acs.estlett.6b00439.

accumulated in the soils of spill-affected areas.[841] The bigger the spill, the higher the soil radioactivity level. Study author Avner Vengosh told *Inside Climate News*, "We found even if you take away the spill water… you still left behind the legacy of radioactivity in the soils," where it can linger for thousands of years.[842]

- March 10, 2016 – Louisville's *Courier-Journal* reported on illegal dumping of radioactive oil and gas drilling wastes in two Kentucky landfills. Landfill operators in Greenup and Estill counties were issued violation notices for failing to "accurately characterize the waste for what it was, allowing what's considered an illegal release of a hazardous material into the environment." The illegal dumping at the Greenup County landfill alone consisted of 369 tons of radioactive drilling waste.[843]

- February 26, 2016 – Radioactive oil and gas waste from fracking operations in Ohio, Pennsylvania, and West Virginia was illegally sent to Estill County, Kentucky's Blue Ridge Landfill. The radioactive level of the material that was buried "was at least 340 times more than the amount that is allowed to be buried at a solid waste landfill," according to WKYT in Lexington. WKYT reported that Estill County leaders would "fight 'tooth and toenail' to get the bottom of how low-level radioactive waste ended up in a county landfill," and do its own testing at the landfill and nearby schools.[844]

- November 23, 2015 – Absence of federal oversight and, in some cases, a total lack of state regulations for handling radioactive oil and gas waste was the topic of a report in *High Country News*, which detailed the regulatory situation in six Western states: Colorado, Idaho, Montana, North Dakota, South Dakota, and Wyoming. North Dakota alone generates an estimated 70 tons a day of radioactive oil and gas waste. "Because the waste is often too radioactive to be disposed of in landfills, it sometimes gets dumped illegally." Proposed new rules in North Dakota would raise the radioactivity limit for the waste.[845]

- July 8, 2015 – Radium-226 is the dominant radioactive material in flowback water from hydraulically fractured wells in the Marcellus Shale. A Pittsburgh team of researchers studied its fate in three wastewater storage pits in southwestern Pennsylvania over a 2.5-year period of time. They found that radium-226 concentrations increased when flowback water was being reused for additional fracking operations. Also, radium-226 tended to

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[841] Lauer, Harkness, and Vengosh, "Brine Spills Associated with Unconventional Oil Development in North Dakota."
[842] Z. Hirji, "Persistent Water and Soil Contamination Found at N.D. Wastewater Spills," *Inside Climate News*, April 29, 2016, http://insideclimatenews.org/news/29042016/north-dakota-wastewater-spill-water-soil-contaminiation-radium-selenium-bakken-oil.
[843] James Bruggers, "State Begins Crackdown on Radioactive Waste," *Courier Journal*, March 10, 2016, sec. Tech, http://www.courier-journal.com/story/tech/science/environment/2016/03/08/state-orders-end-hauling-radioactive-waste/81496490/.
[844] WKYT, "Estill County Leaders to Fight 'Tooth and Toenail' Over Radioactive Waste in Landfill," *WKYT*, February 26, 2016, https://www.wkyt.com/content/news/Estill-Co-leaders-to-fight-tooth-and-toenail-over-radioactive-waste-in-landfill-370308981.html.
[845] Jodi Peterson, "States Lack Rules for Radioactive Drilling Waste Disposal," *High Country News*, 2015, sec. Pollution, http://www.hcn.org/articles/states-lack-rules-for-handling-radioactive-drilling-waste.

accumulate in the bottom sludge. This sludge could be classified as radioactive solid waste because it exceeded the radium-226 limit for landfill disposal. A risk assessment showed that potential radiation dose equivalent levels around the three fracking waste pits were within the regulatory limit for the general public.[846]

- April 9, 2015 – A Johns Hopkins Bloomberg School of Public Health study found that levels of radon in Pennsylvania homes—a region with some of the highest indoor radon concentrations in the US—have been rising since 2004, around the time the fracking industry arrived in the state.[847] Radon exposure is the second leading cause of lung cancer worldwide, after cigarette smoking.[848] Researchers found that buildings in counties where the most fracking has taken place in the past decade have had significantly higher radon readings compared with those in low-fracking areas, a difference that did not exist before 2004. Use of well water was associated with 21 percent higher indoor radon concentrations than in buildings using public water sources. This study, the first to define and evaluate the predictors of indoor radon concentrations in Pennsylvania, concluded that radon's presence was related to geology, water sources, weather, and natural gas drilling.[849]

- April 2, 2015 – A team of toxicologists, geochemists, and radiation scientists led by the University of Iowa analyzed the contribution of various naturally occurring radioactive materials (NORM) to the total radioactivity of fracking waste fluids, finding evidence of long-lived, environmentally persistent radioactive decay products.[850] "NORM is emerging as a contaminant of concern in hydraulic fracturing/unconventional drilling wastes, yet the extent of the hazard is currently unknown." The study determined that previous testing and study methods likely underestimate radioactivity by focusing only on radium. The researchers developed a new method to accurately predict the concentrations of uranium, thorium, and radium and their alpha-emitting progeny, polonium and lead, in fracking wastewater. They found that, under certain conditions, radioactivity increased over time, due to ingrowth of alpha-emitting radioactive progeny of long-lived parent radionuclides such as radium. The authors warned that these decay products may potentially contaminate recreational, agricultural, and residential areas, and that a more detailed understanding is needed of how radionuclides accumulate in higher organisms. In an accompanying article in *Environmental Health Perspectives*, James Burch, a University of South Carolina epidemiologist who was not involved in the study, said that fracking activities and wastewater disposal, which often take place in close

[846] Tieyuan Zhang, Richard W. Hammack, and Radisav D. Vidic, "Fate of Radium in Marcellus Shale Flowback Water Impoundments and Assessment of Associated Health Risks," *Environmental Science & Technology* 49, no. 15 (2015): 9347–54, https://doi.org/10.1021/acs.est.5b01393.
[847] Joan A. Casey et al., "Predictors of Indoor Radon Concentrations in Pennsylvania, 1989–2013," *Environmental Health Perspectives* 123, no. 11 (2015): 1130–37, https://doi.org/10.1289/ehp.1409014.
[848] National Cancer Institute, "Radon and Cancer Fact Sheet," December 6, 2011, http://www.cancer.gov/about-cancer/causes-prevention/risk/substances/radon/radon-fact-sheet.
[849] Susan Phillips and Jon Hurdle, "New Study Raises Possible Link Between Gas Drilling and Radon Levels," *State Impact Pennsylvania*, April 9, 2015, http://stateimpact.npr.org/pennsylvania/2015/04/09/new-study-raises-possible-link-between-gas-drilling-and-radon-levels/.
[850] Andrew W. Nelson et al., "Understanding the Radioactive Ingrowth and Decay of Naturally Occurring Radioactive Materials in the Environment: An Analysis of Produced Fluids from the Marcellus Shale," *Environmental Health Perspectives* 123, no. 7 (2015), https://doi.org/10.1289/ehp.1408855.

proximity to where people live and work, raise risks for human exposure. "The technology is vastly outpacing what we know about the health effects."[851]

- May 8, 2014 – A group of leading medical experts and the American Lung Association of the Northeast detailed research and growing concerns about potential health impacts of radon and radium associated with natural gas production and the Marcellus Shale, in particular. High levels of radiation in the Marcellus Shale could pose health threats if high concentrations of radon and its decay products travel with natural gas, a problem compounded by the short distance Marcellus gas could travel in pipelines to people's homes.[852]

- March 23, 2014 – A team led by toxicology researchers at the University of Iowa identified high levels of radioactivity in fracking wastewater as a significant concern and noted that the testing methods used and recommended by state regulators in the Marcellus Shale region can dramatically underestimate the amount of radioactivity—specifically radium—in fracking wastewater.[853] Results obtained using EPA-recommended protocols can be obscured by the presence of other contaminant mixtures. Regarding the use of EPA protocols with fracking wastewater or other highly saline solutions, Duke University geochemist Avner Vengosh noted, "People have to know that this EPA method is not updated."[854]

- February 2014 – The Marcellus Shale is known to have high uranium and radium content. According to Mark Engle, USGS geochemist, the concentration of radium-226 can exceed 10,000 picoCuries/Liter (pCi/L) in the shale. Radium-226 has a half-life of 1,600 years. Radium and other naturally occurring radioactive materials (NORM) can be released from shale rock during drilling and fracking and can emerge with flowback and produced waters. It can thus enter the ambient environment and become concentrated in the sludge that results from treatment of flowback water, and in river sediment around water treatment facilities. It can also be found in landfills in which sludge and sediment have been disposed. Some radium can be found in drinking water. Geochemist Avner Vengosh warned, "Once you have a release of fracking fluid into the environment, you end up with a radioactive legacy."[855]

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[851] Lindsey Konkel, "What's NORMal for Fracking? Estimating Total Radioactivity of Produced Fluids," *Environmental Health Perspectives* 123, no. 7 (2015), http://ehp.niehs.nih.gov/123-a186/.
[852] J. Campbell, "Fracking Critics Keep Pushing for State-Backed Health Study," *Politics on the Hudson* (blog), May 8, 2014, http://polhudson.lohudblogs.com/2014/05/08/fracking-critics-keep-pushing-state-backed-health-study/.
[853] Andrew W. Nelson et al., "Matrix Complications in the Determination of Radium Levels in Hydraulic Fracturing Flowback Water from Marcellus Shale," *Environmental Science & Technology Letters* 1, no. 3 (2014): 204–8, https://doi.org/10.1021/ez5000379.
[854] Sharon Kelly, "Research Shows Some Test Methods Miss 99 Percent of Radium in Fracking Waste," *DeSmog*, March 23, 2014, http://www.desmogblog.com/2014/03/23/some-testing-methods-can-miss-99-percent-radium-fracking-waste-new-research-reports.
[855] Valeria J. Brown, "Radionuclides in Fracking Wastewater: Managing a Toxic Blend," *Environmental Health Perspectives* 122, no. 2 (2014): A50–55, https://doi.org/10.1289/ehp.122-A50.

- October 2, 2013 – A peer-reviewed study of the impacts of drilling wastewater treated and discharged into a creek by a wastewater facility in western Pennsylvania documented radium levels approximately 200 times greater in sediment samples near the discharge location than in sediment samples collected upstream of the plant or elsewhere in western Pennsylvania. "The absolute levels that we found are much higher than what you allow in the U.S. for any place to dump radioactive material," one of the authors told *Bloomberg News.* The pollution occurred despite the fact that the treatment plant removed a substantial amount of the radium from the drilling wastewater before discharging it. The researchers wrote that the accumulation of radium in sludge removed from the wastewater "could pose significant exposure risks if not properly managed."[856, 857]

- February 2013 – In an analysis of fracking sludge samples from Pennsylvania, researchers "… confirmed the presence of alpha, beta, and gamma radiation in the soil and water in reserve pits located on agricultural land." Total beta radiation exceeded regulatory guideline values by more than 800 percent, and elevated levels of some of the radioactive constituents remained in a vacated pit that had been drained and leveled. It is imperative, the research team concluded, "that we obtain better knowledge of the quantity of radioactive material and the specific radioisotopes being brought to the earth's surface from these mining processes."[858]

- July 26, 2012 – Responding to concern about radon in natural gas produced from the Marcellus Shale, the USGS analyzed ten samples of gas collected near the wellheads of three Pennsylvania gas wells. The agency found radon levels ranging from 1-79 picocuries per liter, with an average of 36 and a median of 32. (The highest radon activity reported here would decay to 19.8 pCi/L in approximately a week; by comparison, the EPA's threshold for indoor air remediation is 4 pCi/L.) Asserting they knew of no previous published measurements of radon in natural gas from the Appalachian Basin, which contains the Marcellus Shale, agency scientists concluded that the number of samples "is too small to … yield statistically valid results" and urged "collection and interpretation of additional data."[859]

- January 11, 2012 – In its review of the New York State Department of Environmental Conservation's (NYS DEC) Supplemental Generic Environmental Impact Statement (SGEIS) on high volume fracturing, the EPA expressed concerns about the diffusion of responsibility for the ultimate disposal of radioactive wastes generated by treatment or pretreatment of drilling wastewater. The EPA also raised concerns about the lack of

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[856] Nathaniel R. Warner et al., "Impacts of Shale Gas Wastewater Disposal on Water Quality in Western Pennsylvania," *Environmental Science & Technology* 47, no. 20 (2013): 11849–57, https://doi.org/10.1021/es402165b.
[857] Jim Jr. Efstathiou, "Radiation in Pennsylvania Creek Seen as Legacy of Fracking," *Bloomberg*, October 2, 2013, http://www.bloomberg.com/news/2013-10-02/radiation-in-pennsylvania-creek-seen-as-legacy-of-frackin.html.
[858] Alisa L. Rich and Ernest C. Crosby, "Analysis of Reserve Pit Sludge From Unconventional Natural Gas Hydraulic Fracturing and Drilling Operations for the Presence of Technologically Enhanced Naturally Occurring Radioactive Material (TENORM)," *New Solutions* 23, no. 1 (2013): 117–35, https://doi.org/10.2190/NS.23.1.h.
[859] Elisabeth L. Rowan and T. F. Kraemer, "Radon-222 Content of Natural Gas Samples from Upper and Middle Devonian Sandstone and Shale Reservoirs in Pennsylvania: Preliminary Data," Open-File Report Series (U.S. Geological Survey, 2012), http://pubs.usgs.gov/of/2012/1159/ofr2012-1159.pdf.

analysis of radon and other radiation exposure. "Who is responsible for addressing the potential health and safety issues and associated monitoring related to external radiation and the inhalation of radon and its decay products?" the EPA asked. "Such potential concerns need to be addressed."[860]

- September 7, 2011 – The USGS reported that radium levels in wastewater from oil and gas wells in New York and Pennsylvania, including those in the Marcellus Shale, "have a distinctly higher median … than reported for other formations in the Appalachian Basin, and range to higher values than reported in other basins." The median level of radium found in Marcellus Shale wastewater in New York, 5,490 pCi/L, is almost 1,100 times the maximum contaminant level for drinking water, which is five pCi/L. In other words, if a million gallons of Marcellus Shale wastewater contaminated with the median level of radium found in New York were to spill into a waterway, 1.1 billion gallons of water would be required to dilute the radium to the maximum legal level.[861] (The EPA's health-based goal for radium in drinking water is zero.) Over time, radium naturally decays into radioactive radon gas. Thus, higher radium levels also suggest that higher levels of radon may also be present in natural gas produced from the Marcellus Shale.

- February 27, 2011 – The *New York Times* reported on the threat to New York's drinking water from Pennsylvania drilling waste due to the presence of chemical contaminants, including high levels of radioactivity. The investigation found that sewage treatment plants were neither testing for nor capable of removing that radioactivity, which was subsequently discharged into waterways that supply drinking water, and that, in some cases, wastewater contained radium levels that were hundreds of times higher than the drinking water standard. Drillers sent some of this waste to New York State for disposal even though, as the article noted, EPA scientists had warned the state about this very problem in a December 2009 letter that advised against sewage treatment plants accepting drilling waste with radium levels 12 or more times as high as the drinking water standard.[862]

- 2008-2009 – The New York State DEC found that wastewater from 11 of 13 vertical wells drilled in New York's Marcellus Shale in 2008 and 2009 contained radium levels ranging from 400 times to nearly 3,400 times EPA's safe levellimit for radium in drinking water. These figures later informed the 2011 study of radium in drilling wastewater conducted by the USGS.[863]

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[860] Environmental Protection Agency, "EPA Comments on Revised Draft NYSDEC Revised DSGEIS for Horizontal Drilling and High-Volme Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs," Press Release, January 11, 2012, https://web.archive.org/web/20120624232731/http://www.epa.gov/region2/newsevents/pdf/EPA%20R2%20Comments%20Revised%20dSGEIS%20Enclosure.pdf.
[861] Elisabeth L. Rowan et al., "Radium Content of Oil- and Gas-Field Produced Waters in the Northern Appalachian Basin (USA): Summary and Discussion of Data," Scientific Investigations Report, September 7, 2011, https://pubs.usgs.gov/sir/2011/5135/pdf/sir2011-5135.pdf.
[862] Ian Urbina, "Regulation Lax as Gas Wells' Tainted Water Hits Rivers 347," *The New York Times*, February 26, 2011, sec. Drilling Down, http://www.nytimes.com/2011/02/27/us/27gas.html?pagewanted=all&_r=0.
[863] New York State Department of Environmental Conservation, "Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program, Well Permit Issuance for Horizontal Drilling

- January 1993 – NORM contamination in the oil and gas industry is widespread and can occur as radioactive scale, films, and sludges. "Some contamination may be sufficiently severe that maintenance and other personnel may be exposed to hazardous concentrations," according to this 1993 article in the *Journal of Petroleum Technology*.[864] Uranium, thorium, radium, and associated decay products from the production of oil is typically found in radioactive scale and produced water. Radon and its long-lived decay products more typically contaminate natural gas facilities. Federal agencies in the United States do not regulate oil and gas waste, so it is up to individual states to regulate the serious problem of disposal of radioactive materials and equipment.

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and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs (5-133, 5-141, 7-60, Appendix 12, Appendis 13, Rep.)," Technical Report, 2011.

[864] P. R. Gray, "NORM Contamination in the Petroleum Industry," *Journal of Petroleum Technology* 45, no. 1 (1993): 12–16, https://doi.org/10.2118/22880-PA.

Occupational health and safety hazards

Drilling and fracking jobs are among the most dangerous jobs in the nation with a fatality rate at least four times the national average. Irregularities in reporting practices mean that counts of on-the-job fatalities among oil and gas workers are likely underestimated. Contract workers are especially at risk. In 2019, the most recent year for which data are available, 104 oil and gas extraction workers died on the job, up from 94 in 2018. These deaths represent over 82 percent of the fatal work injuries in the mining sector. In a 2020 study of suicide deaths by industry, workers employed in mining, quarrying, and oil and gas extraction had the highest suicide rate. A 2020 study showed that retired oil and gas workers had the highest prevalence of self-reported poor health of all industry categories of retirees.

Occupational hazards in the fracking industry include head injuries, traffic accidents, blunt trauma, burns, inhalation of hydrocarbon vapors, toxic chemical exposures, radiation exposure, heat exhaustion, dehydration, and sleep deprivation. An investigation of occupational exposures found high levels of benzene in the urine of well pad workers, especially those in close proximity to flowback fluid coming up from wells following fracturing activities. Exposure to silica dust, which is definitively linked to silicosis and lung cancer, was singled out by the National Institute for Occupational Safety and Health (NIOSH) as a particular threat to workers in fracking operations where silica sand is used. [See also Sand Mining and Processing and Radioactive Releases.] At the same time, research shows that many gas field workers, despite these serious occupational hazards, are uninsured or underinsured and lack access to basic medical care.

In 2018, the first independent investigation of its kind showed that pipeline construction workers die on the job 3.6 times more often than the average U.S. worker. Pipeline worker deaths occur from crushings, fires, and heat exhaustion. The number of miles of U.S. pipelines tripled from 2006 to 2016, and newer pipelines are less safe than older ones. Pipelines built after 2010 suffer higher failure rates than pipelines built at any other time.

- June 23, 2021 – Minnesota state regulators fined Precision Pipeline $25,000, the minimum required by law, in an incident involving the death of an employee who was run over by a forklift while checking a list of materials at the Enbridge Energy Line 3 site in northern Minnesota. Precision Pipeline contested the citation.[865]

- May 21, 2021 – In its final report on the October 2019 deadly hydrogen sulfide (H_2S) release at the Aghorn Operating Inc. oil and gas site in Odessa, Texas, the U.S. Chemical Safety and Hazard Investigation Board (CSB) identified "six serious safety issues." These were nonuse of personal H_2S detector, nonperformance of "lockout/tagout," confinement of H_2S inside pump house, lack of a safety management program, nonfunctioning H_2S detection and alarm system, and deficient site security. The CSB made nine recommendations, seven to the company and one each to regulators OSHA and the Texas

[865] Associated Press, "State Cites Oil Pipeline Contractor after Worker's Death in Northern Minnesota," *Twin Cities Pioneer Press*, June 23, 2021, https://www.twincities.com/2021/06/23/state-cites-oil-pipeline-contractor-after-workers-death-in-northern-minnesota/.

Railroad Commission. The release killed an Aghorn employee and his spouse. (See July 21, 2020 entry.)[866]

- May 4, 2021 – In 2019, the U.S. Bureau of Labor Statistics category that includes oil and gas extraction workers ("mining, quarrying, and oil and gas extraction") had the second highest fatality rate, 14.6 per 100,000 workers, of any industry category. Oil and gas extraction workers specifically comprised 82 percent of the on-the-job fatalities (104 of the 127 deaths) in this category. Oil and gas extraction workers suffered ten more deaths in 2019 than in 2018, which was greater than each year before that, since 2014. Oil and gas extraction workers, according to this federal categorization system, include oil and gas extraction, drilling oil and gas wells, and support activities for oil and gas operations.[867]

- April 26, 2021 – Reporting on OSHA's "Top 10" violations for various industries in 2020, *Safety and Health Magazine* reported that out of a total of 258 OSHA violations for the oil and gas extraction, 102 were cited as serious. In addition, the article noted that 2020 was a year of one of the lowest total OSHA inspections on record.[868]

- October 26, 2020 – Retired oil and gas extraction workers had the highest prevalence of self-reported poor health and were over twice as likely as retirees in other industries to report poor health status. They also suffered a significantly higher prevalence of hearing loss than all other retirees, according to a study conducted by National Institute for Occupational Safety and Health (NIOSH) researchers. This study, the first to examine the health of retired manual labor miners and oil and gas extraction workers compared with other U.S. retirees, used a 2002-2017 National Health Interview Survey (NHIS) dataset. The NHIS is "a nationally representative survey of civilian, noninstitutionalized adults that collects information on this population's longest-held job, health status, and chronic diseases." The survey also showed that retired oil and gas extraction workers—similar to retired miners—suffer a higher prevalence of lung dysfunction or breathing problems than retirees from other industries. The researchers note that the boom and bust of extraction industries can lead to involuntary retirement and also that lack of a mandatory retirement age can compel oil and gas workers to work until they are physically unable. Researchers also noted that these workers have a higher morbidity during their working years, and this continues into retirement. This study did not have the statistical power to analyze and compare incidence of specific cancers within retirees from different industries. Researchers urged the development of illness prevention strategies and

[866] Katherine A. Lemos, "Hydrogen Sulfide Release at Aghorn Operating Waterflood Station" (U.S. Chemical Safety and Hazard Investigation Board, May 2021), https://www.csb.gov/aghorn-operating-waterflood-station-hydrogen-sulfide-release-/.
[867] AFL-CIO, "Death on the Job: The Toll of Neglect, 30th Edition," A National and State-by-State Profile of Worker Safety and Health in the United States (AFL-CIO, May 2021), https://aflcio.org/reports/death-job-toll-neglect-2021.
[868] Richard Fairfax, "On Safety: A Closer Look at OSHA's 'Top 10' Violations – Part III," *Safety and Health Magazine*, April 16, 2021, https://www.safetyandhealthmagazine.com/articles/21080-on-safety-a-closer-look-at-osha-top-10-violations-part-iii.

reductions in workplace exposures to prevalent hazards such as noise, silica, and diesel exhaust.[869]

- October 6, 2020 – In 2018, 94 oil and gas extraction workers were killed on the job, accounting for 72 percent of the fatal work injuries in the "Mining, quarrying, and oil and gas extraction" sector, and 13 deaths more than the previous year. This edition of the AFL-CIO's yearly *Death on the Job: The Toll of Neglect* stated that the reporting year saw "no forward action on critical safety and health problems, including… silica in mining."[870]

- July 21, 2020 – *E&E News* investigated the increase in oil and gas sites handling hydrogen sulfide across Texas, particularly in the Permian Basin, with a focus on the circumstances of the death of an oil worker and his wife in October 2019.[871] A "lethal fog" of hydrogen sulfide at levels 137 times the fatal dose killed Jacob Dean, 44, while at work on a repair, and Natalee Dean, 37, who went looking for him when he had not returned home. In the Deans' county alone there were 2,552 oil and gas sites with hydrogen sulfide permits. Between 2015 and 2019, 96 percent of the inspections of these sites statewide only involved verification of whether warning signs and fences were in place, according to the investigation. Though both "OSHA and Texas have regulations meant to protect people against hydrogen sulfide…. the agencies each police different aspects of the industry, and they often don't communicate with each other."

- May 14, 2020 – In a study of liquid storage tanks for organic chemical additives on 72,023 U.S. fracking well pads, over 95 percent of the total non-methane volatile organic compound (VOC) emissions were Agency for Toxic Substances & Disease Registry (ATSDR) priority-list hazardous substances. Nearly 17 percent of the emissions identified in the study were caused by 15 carcinogenic compounds. Moreover, the researchers found that median well emissions rose dramatically between 2008 and 2014, due to the increase in the amount of chemicals used to fracture each well. Researchers cautioned that limitations they faced in their ability to collect data resulted in an underestimate of emissions. They were not able to access information on proprietary chemicals, which may be toxic and/or carcinogenic, and, of the 2,000 chemicals that were reported, the researchers could only locate complete information for 475. "Therefore, the emissions of the approximately 1500 remaining compounds (including a large number of organic compounds) were not estimated."[872]

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[869] Tashina Robinson et al., "Health Conditions in Retired Manual Labor Miners and Oil and Gas Extraction Workers: National Health Interview Survey, 2007–2017," *American Journal of Industrial Medicine* 64, no. 2 (2021): 118–26, https://doi.org/10.1002/ajim.23195.
[870] AFL-CIO, "Death on the Job: The Toll of Neglect, 29th Edition," A National and State-by-State Profile of Worker Safety and Health in the United States, 2020, https://aflcio.org/sites/default/files/2020-10/DOTJ2020_Final_100620_nb.pdf.
[871] Mike Lee, "Lethal Fog Smothers Texas Oil Sites as Inspections Lag," *E&E News*, July 21, 2020, https://web.archive.org/web/20200722220615/https://www.eenews.net/stories/1063594445.
[872] Huan Chen and Kimberly E. Carter, "Hazardous Substances as the Dominant Non-Methane Volatile Organic Compounds With Potential Emissions From Liquid Storage Tanks During Well Fracturing: A Modeling Approach," *Journal of Environmental Management* 268 (2020): 110715, https://doi.org/10.1016/j.jenvman.2020.110715.

- April 30, 2020 – The National Institute for Occupational Safety and Health (NIOSH) released its 2017 data set from the Fatalities from the Oil and Gas Extraction Industry (FOG) database.[873] The FOG database was established to collect detailed information about the circumstances related to deaths of workers in oil and gas extraction. For the year 2017, "FOG captured 69 fatalities as a result of 65 incidents, including 3 multiple fatality incidents." As before, Texas was the state with the most fatalities and "well servicing" was by far the most common industry group represented. "Vehicle incidents" and "contact injuries" describe again the majority of the "event type" leading to the fatalities. 2017 data contain further detail about the material being transported during transportation-involved fatalities: the majority involved transportation of "fluids." It is important to note the FOG database is not designed to be comparable with other statistics, e.g. those of the Bureau of Labor Statistics (BLS), but rather to collect detailed information on the fatalities. "The case definitions (i.e. inclusion criteria) differ. Therefore, each system will have a different number of fatalities each year." Importantly, in contrast to BLS, FOG includes all cardiac events where symptoms begin at work.

  > *Cardiac events that begin at work are included in FOG because acute exposure to some chemicals or toxic substances can mimic or induce cardiac events. Also, they are included to support the identification and characterization of factors that may influence the occurrence or outcome of these incidents, such as physically demanding work, and working alone and in remote locations*.

  The release of 2018 data and a forthcoming summary spanning 2014-2018 have been delayed due to the current COVID-19 response.[874] The 2014 data set was the first of the program and a 2015-2016 data set was released last year. (See entries below for May 13, 2019 and August 24, 2017.)

- April 28, 2020 – A worker's foot and lower leg were crushed and permanently injured as a result of a hydraulic line blowout on a Wyoming fracking site, and he filed suit against the fracking company as well as the company that provided the equipment. The worker alleged these entities owed him a "'duty of reasonable care' to ensure the fracking equipment on the job sites was safe and properly maintained," which was violated when they "failed to have regular equipment inspections and repairs done – knowing that not doing so could result in serious injury or death."[875]

- March 3, 2020 – Using data from a Canadian population-based case-control study, researchers evaluated the associations between workplace exposures of inhaled silica particles and bladder cancer. For this study, fracking workers would presumably be included in the category "Mining and quarrying including oil and gas field occupations,"

[873] National Institute for Occupational Safety and Health (NIOSH), Western States Division, "Fatalities in the Oil and Gas Extraction Industry (FOG) FOG Data - 2017" (U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, 2020), https://www.cdc.gov/niosh/topics/fog/data2017.html.

[874] A. Ramirez-Cardenas, Personal Communication re: Data Set Release Dates and Report Delay Information, July 24, 2020.

[875] Wyoming News Exchange, "Former Worker Sues Fracking Company," *Gillette News Record*, April 28, 2020, https://www.gillettenewsrecord.com/news/wyoming/article_d906cbb9-8499-5004-a22d-24dcfb91c0e6.html.

where researchers found over 76 percent were exposed to silica.[876] Researchers noted that petrochemical workers are documented to have an increased risk of bladder cancer. For this study, they used detailed lifetime occupational histories, and considered latency, concentration, frequency and duration of silica exposure. Results indicated "workers exposed at high frequencies and/or for long durations are at increased risk of bladder cancer." This finding for silica was consistent with an exposure-response relationship.

- January 24, 2020 – The Centers for Disease Control and Prevention (CDC), using data from the 2016 National Violent Death Reporting System, reported on suicide deaths by industry and occupation in 32 states. Researchers identified a total of 15,779 such deaths, including 12,505 (79 percent) men and 3,274 (21 percent) women.[877] They found that, among the 20 major industry groups analyzed, men in the group "Mining, Quarrying, and Oil and Gas Extraction" had the highest suicide rate, at 54.2 per 100,000 workers. The next highest was Construction at 45.3 per 100,000 workers. The average for men in the entire study population was 27.4 per 100,000 workers. The data was not broken down in order to see the specific rate of oil and gas workers within the larger group.

- December 19, 2019 – In this economic analysis considering the health-related economic impact of using silica sand as the proppant in fracking, researchers found that "the use of each ton of silica proppant results in $123 of external costs from fatalities and nonfatal illness arising due to exposure to silica for a crew handing 60,000 tons of proppants."[878] They find that replacement with a less harmful, more expensive alternative would be economical if these health-related "externalities" were taken into account.

- December 17, 2019 – In 2018, the most recent year for which data are available, 94 oil and gas extraction workers died on the job, up from 81 in 2017. These deaths represent over 72 percent of the fatal work injuries in the mining sector.[879]

- September 11, 2019 – NIOSH's Western States Division staff published a paper outlining the proceedings of a day-long conference for health and safety professionals working in oil and gas exploration and production that addressed controls related to frack sand exposure. Respirable crystalline silica (RCS) is linked to silicosis, lung cancer, kidney and skin diseases. The controls described fell into the categories: elimination through use of alternative proppants; substitution (use of treated quartz sand to minimize aerosol emissions); and engineering controls. The NIOSH group was following up on their 2013 determination that "RCS exposures during these operations exceeded the relevant

[876] Lidija Latifovic et al., "Silica and Asbestos Exposure at Work and the Risk of Bladder Cancer in Canadian Men: A Population-Based Case-Control Study," *BMC Cancer* 20 (2020): 171, https://doi.org/10.1186/s12885-020-6644-7.
[877] Cora Peterson et al., "Suicide Rates by Industry and Occupation — National Violent Death Reporting System, 32 States, 2016," *Morbidity and Mortality Weekly Report* 69, no. 3 (n.d.): 57–62, https://doi.org/10.15585/mmwr.mm6903a1.
[878] Sidharth Agrawal and Jeremy M. Gernand, "Quantifying the Economic Impact of Hydraulic Fracturing Proppant Selection in Light of Occupational Exposure Risk and Functional Requirements," *Risk Analysis* 40, no. 2 (2020): 319–35, https://doi.org/10.1111/risa.13419.
[879] U.S. Bureau of Labor Statistics, "Fatal Occupational Injuries in Private Sector Mining, Quarrying, and Oil and Gas Extraction Industries," 2019, https://www.bls.gov/charts/census-of-fatal-occupational-injuries/fatal-occupational-injuries-private-sector-mining.htm.

occupational exposure limits, in some cases by a factor of 10 or more." Though they cited progress on controls implemented to help limit worker exposures in the interim years, authors pointed out limitations to the information presented at the conference. "These include lack of more exhaustive detail related to industrial hygiene sampling data and results as well as the lack of third-party confirmation and public reporting of the control assessments." The authors wrote that few scientific publications on new controls and evaluation of their effectiveness were available. They said the imperative is "that we focus as intently on controls to mitigate the risks for 'long and latent' adverse health outcomes, in this case preventable but extremely serious lung disease, including lung cancer."[880]

- June 12, 2019 – According to the U.S. Chemical Safety Investigation Board (CSB), the January 2018 explosion of a natural gas rig in southwestern Oklahoma, which killed five workers during the drilling process, was caused by the failure of two protective barriers designed to prevent uncontrolled gas blowouts. As a consequence, a mixture of mud and gas blew upwards out of the well, and the gas ignited and exploded. These mechanical failures, determined the CSB investigators, were, in turn, the result of significant lapses in safety protocols, including warning alarms that did not sound. All five workers who died were trapped inside the driller's cabin when fire blocked both exit doors. This problem, inherent to the design of the cabin, is not exceptional. The CSB investigation found that "there is no guidance to ensure that an emergency evacuation option is present onboard these rigs or can protect workers in the driller's cabin from fire hazards."[881, 882] This accident remains one of the worst oil field incidents in U.S. history.

- May 13, 2019 – NIOSH released a data set covering 2015-2016 from the FOG database, capturing "92 fatalities as a result of 79 incidents, including eight multiple fatality incidents."[883] Sixty-three of these fatalities occurred in 2015 and 29 in 2016. Forty-five of the 92 occurred in Texas, 13 in North Dakota, 8 in Oklahoma, and 5 in New Mexico. Fifty-four of the workers who were killed worked in "well servicing," and 18 in "drilling operations." Twenty-six of the fatalities involved a "vehicle incident," 22 involved a "contact injury" (crushed or struck), and 13 involved explosions. Other variables within the database describing the fatalities include ages of victims and their years of experience, whether they were working unobserved and/or alone, and the circumstances surrounding the multiple fatality incidents. Also noted is whether the information in any given category is unknown.

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[880] Eric J. Esswein et al., "Respirable Crystalline Silica Is a Confirmed Occupational Exposure Risk During Hydraulic Fracturing: What Do We Know About Controls? Proceedings From the Silica in the Oilfield Conference," *Journal of Occupational and Environmental Hygiene* 16, no. 10 (2019): 669–74, https://doi.org/10.1080/15459624.2019.1652757.

[881] U.S. Chemical Safety and Hazard Investigation Board, "Gas Well Blowout and Fire at Pryor Trust Well 1H-9," Investigative Report, June 12, 2019, http://www.nteps.com/images/documents/Pryor_Trust_Report_FINAL_FOR_PUBLICATION_opt.pdf.

[882] U.S. Chemical Safety and Hazard Investigation Board.

[883] National Institute for Occupational Safety and Health (NIOSH), Western States Division, "Fatalities in the Oil and Gas Extraction Industry (FOG) FOG Data 2015-2016" (U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, 2020), https://www.cdc.gov/niosh/topics/fog/data2015-2016.html.

- April 25, 2019 – In 2017, 81 oil and gas extraction workers died on the job, accounting for 72 percent of the fatal work injuries in the mining sector, which, overall, has a fatality rate nearly four times the national average.[884] There were 18 more fatal occupational injuries in oil and gas extraction industries than the previous year.[885] (The 29th edition of this AFL-CIO report, covering 2018, appeared on October 6, 2020; see *Emerging Trends*.)

- February 19, 2019 – An investigation into the death of oil worker Dennis Mason by *E&E News* shows how inhalation of toxic vapors is systematically overlooked as a possible cause of workplace mortality and "indicates that more than four years after worker safety officials started warning of the lethal dangers of inhaling petroleum gases, the danger is still ignored in some corners of the oil patch."[886] NIOSH has linked at least 13 oil worker deaths to inhalation of petroleum gases, such as butane and propane. However, because medical examiners do not always test for the substances, and attribute the deaths to "natural causes," there are likely more. In this case, The Occupational Safety and Health Administration (OSHA) investigators immediately suspected that Dennis Mason was killed by toxic vapors and sent information and materials to the responsible Oklahoma state medical examiner, but state officials said they did not receive them. These materials included a paper by an occupational medicine specialist describing how exposure to high concentrations of hydrocarbon gases and vapors in an oxygen-deficient atmosphere can result in sudden cardiac death among oil and gas extraction workers. Instead, the medical examiner tested only for illegal drugs and alcohol before attributing his death to natural causes.

- February 13, 2019 – A series of catastrophic explosions and fires at a gas-processing facility in Pascagoula, Mississippi shut the plant down for six months in June 2016. This facility receives raw gas from drilling operations and separates it into natural gas and hydrocarbon liquids, which are used to make petrochemicals. The U.S. Chemical Safety Board's final report identified "thermal fatigue" as the probable cause of the series of conditions leading to the explosions. A "major loss of containment" in a heat exchanger resulted in the release of methane, ethane, propane, and several other hydrocarbons, which subsequently ignited. The report's interactive 3D model showed that the heat exchanger used at the Enterprise Plant, as well as at over 500 other U.S. gas processing facilities, is innately vulnerable to thermal fatigue. The timing of the explosions at the Pascagoula Gas Plant, which occurred shortly before midnight, likely prevented injuries. According to the final report, had the event happened during the day, with many more workers present, the consequences could have been much worse. The report noted that many nearby residents chose to evacuate, and afterwards, a local community organization informed the Board that residents did not know how to respond to the explosions. "They

[884] AFL-CIO, "Death on the Job: The Toll of Neglect, 28th Edition," State-by-State Profile of Worker Safety and Health in the United States, 2019, https://aflcio.org/reports/death-job-toll-neglect-2019.
[885] U.S. Bureau of Labor Statistics, "Injuries, Illnesses, and Fatalities," 2018, https://www.bls.gov/iif/oshwc/cfoi/cfoi-chart-data-2017.htm.
[886] Mike Soraghan, "Missed Connections Leave Questions in Oil Worker's Death," *E&E News*, February 19, 2019, https://web.archive.org/web/20190219190653/https://www.eenews.net/stories/1060121345.

felt uninformed and ill equipped to know if they were in harm's way." The final report's recommendations included the development of a "robust and engaged community alert network."[887]

- December 21, 2018 – In the decade between 2008 and 2017, 1,566 U.S. workers died from on-the-job injuries in the oil and gas drilling industry and related fields. These figures were derived from data collected by the U.S. Department of Labor's Bureau of Labor Statistics as part of a special investigative report that included participation by the *Texas Tribune*. In a slightly longer overlapping period, OSHA cited companies in the oil and gas extraction industry for 10,873 violations and investigated 552 accidents that had resulted in at least one worker death. Upstream drilling and fracking operations are exempt from safety rules that govern all downstream sectors of the oil and gas industry. Among these are rules that require refineries, petrochemical plants, and other high-hazard operations to adopt procedures to prevent fires, explosions, and chemical leaks. The investigation detailed a number of specific oil and gas industry deaths in Texas, highlighting the various preventative and regulatory failures associated with traumatic injury; exposure to toxic gases, including hydrogen sulfide; and blowout risk and fires.[888]

- October 11, 2018 – In addition to social isolation and the wide-ranging effects of job-related stress, the physical costs to well pad workers are high, according to a qualitative study on oil workers' social, emotional, and psychological well-being. The study consisted of in-depth interviews with 14 oil industry workers in Alberta, Canada. Twelve were men and two were women. Thirteen of the fourteen workers were employed by third-party contractors. They included heavy-equipment operators, surveyors, health and safety specialists, environmentalists, biologists, wireline engineers, derrick hands, consultants, and drillers. All were rotational workers. Rotational work involves travel to various oil fields and working extended shift schedules, which typically involves 21 consecutive days of work followed by three days off. Most of the respondents said they experienced physical pain on a somewhat regular basis. These findings corroborate the results of other studies reviewed by the authors. "Rotational oil field workers are vulnerable to personal, social, and economic stressors that may result in degraded wellbeing…. As we explored here, 'good jobs' in the patch come at a steep psychosocial and physical health cost to the labourers."[889]

- October 10, 2018 – The most "cohesive explanation yet" for one of the worst oil field accidents in U.S. history, the January 2018 Oklahoma well fire which killed five workers, came from a lawsuit based on dozens of depositions. OSHA had sought penalties but did not offer an explanation, and the U.S. Chemical Safety Board stated plans to issue a

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[887] U.S. Chemical Safety and Hazard Investigation Board, "Loss of Containment, Fires, and Explosions at Enterprise Products Midstream Gas Plant," Case Study (CSB, February 13, 2019), https://www.csb.gov/assets/1/6/final_case_study_-_enterprise.pdf.
[888] Jim Morris, "Death in the Oilfields: Fossil Fuel Boom Brings Mounting Risk of Death, Injuries," *The Texas Tribune*, December 21, 2018, https://www.texastribune.org/2018/12/21/death-oilfields-fossil-fuel-boom-brings-mounting-risks/.
[889] Alysia C. Wright and Yannick Griep, "Burning the Midnight Oil: Examining Wellbeing and Vulnerability in Alberta's Oil Patch," *The Extractive Industries and Society* 6, no. 1 (2019): 77–84, https://doi.org/10.1016/j.exis.2018.10.001.

report over a year later. (See Emerging Trend 6 in the front matter of this report, regarding the findings of the final report.) The factors explained in the lawsuit included ignoring warnings about using a cheaper and lighter drilling mud, and a broken and locked door out of which the five workers may have been able to escape.[890] The operating company blamed contractors.[891] (See also entry below for August 16, 2018.)

- September 12, 2018 – In 2016, oil and gas pipeline construction workers died on the job 3.6 times more often than the average U.S. worker, as determined by the first independent investigation to compile and present fatality rates for those who build oil and gas pipelines in the United States. That same year oil and gas pipeline construction workers had the highest death rate and number of deaths for those employed in these jobs since 2012. "If we add the deaths of workers whose job it is to maintain and monitor the pipelines as they carry the fuels (pipeline transport), 2016 was the deadliest year for oil and gas pipeline workers since 2009."[892] Pipeline worker deaths occurred from crushings, fires, and heat exhaustion. The number of miles of U.S. pipelines carrying oil and other hazardous liquids tripled from 2006 to 2016, and newer pipelines are less safe than old ones. Pipelines built after 2010 suffer failures at a higher rate than pipelines built "at any time in the last century," with pipelines carrying natural gas over five times more disaster-prone. The author made available her complete methodology and references for the project, with a discussion of her methodology and other data sources, including strengths, weaknesses, and comparability. Her stated intention in building a first-of-its kind oil and gas pipeline fatality report was to be "as straightforward and replicable as possible."[893]

- August 20, 2018 – Nearly 1,000 workers have been killed in the ten years since hydraulic fracturing and horizontal drilling technologies rapidly expanded, although the current oil and gas worker fatality rate is down from its earlier high at seven times higher than across all industries. Persistent fatality risk factors include the practice of manual tank gauging, vehicle crashes, and inexperienced workers.[894]

- August 16, 2018 – On January 22, 2018, five workers were killed during the drilling of a gas well in Pittsburg County, Oklahoma. While the drill pipe was being lifted, a mixture of mud and gas blew upwards out of the well, and the gas subsequently ignited and exploded. A "factual update" as part of the ongoing investigation by the U.S. Chemical Safety Board found that a piece of safety equipment designed to control the release of

[890] Mike Soraghan, "Okla. Company Scrimped Before Deadly Well Fire," *E&E News*, October 10, 2018, https://web.archive.org/web/20181010202924/https://www.eenews.net/stories/1060102139.
[891] Mike Soraghan, "Well Operator in Fatal Fire Blames Contractors," *E&E News*, October 23, 2018, https://web.archive.org/web/20181023190205/https://www.eenews.net/stories/1060104019.
[892] Antonia Juhasz, "Death on the Dakota Access," *Pacific Standard*, September 12, 2018, https://psmag.com/magazine/death-on-the-dakota-access.
[893] Antonia Juhasz, "Methodology for Calculating Fatality Rates," *Pacific Standard*, September 12, 2018, https://psmag.com/magazine/methodology-for-calculating-fatality-rates.
[894] Pamela King, "Even 1 Death Is Too Many. What Does It Take to Get to 0?," *E&E News*, August 20, 2018, https://web.archive.org/web/20180820182924/https://www.eenews.net/stories/1060094701.

fluids from the well was unable to fully close on the day of the accident and that other safety corners had been cut.[895]

- April 29, 2018 – Improper or inadequate use of personal protective equipment was of highest concern in a survey of industry workers and regulators that was designed to find the frequency of "failure incidents" and near misses at wellhead sites. Workers and regulators also cited spills of flowback water due to equipment failure as a major concern, with regard to the welfare of both workers and the general public, as these spills "occur more frequently than any other scenario examined in this study."[896]

- April 26, 2018 – There were 63 deaths in oil and gas extraction in 2016, as reported in the 2018 edition of the AFL-CIO report, *Death on the Job, The Toll of Neglect.* The fatality rate for the overall mining sector, which includes oil and gas extraction, was 10.1 per 100,000 workers, nearly three times the national average. These 63 deaths in oil and gas accounted for 71 percent of the total number of fatal work injuries in the mining sector.[897]

- March 21, 2018 – The trade publication, *Industrial Safety & Hygiene News*, published a summary of January 2015 to February 2017 oil and gas extraction worker "incidents," which included 481 hospitalizations and 166 amputations. The article outlined the data gaps and limitations that make accurate tallies of severe injuries in upstream oil and gas operations hard to calculate:

    - State-run OSHA programs are not included in the count.
    - Reporting errors and underreporting are common. Based on workers compensation data, underreporting is estimated at 50 percent; self-reported incidents may lack crucial detail or information.
    - OSHA jurisdiction does not cover incidents that occur on public streets, highways, or during commuting.
    - Trucking/hauling related incidents may be listed under other [National Association of Insurance Commissioners] codes.[898]

- December 6, 2017 – Two occupational fatalities and numerous injuries resulted from explosions and fires along oil and gas pipelines in Colorado in the time since two men were killed at home from such a blast in April 2016, according to a *Denver Post* investigation. One contract worker was killed and two others were injured in May while they "were changing 'dump lines' and 'one or more tanks exploded,' according to a

[895] U.S. Chemical Safety Board, "CSB Releases Factual Update on Blowout and Fire at Pryor Trust Gas Well in Pittsburg County, Oklahoma," Press Release (CSB, August 16, 2018), https://www.csb.gov/csb-releases-factual-update-on-blowout-and-fire-at-pryor-trust-gas-well-in-pittsburg-county-oklahoma-/.
[896] Noura Abualfaraj, Patrick Gurian, and Mira Olson, "Frequency Analysis of Failure Scenarios from Shale Gas Development," *International Journal of Environmental Research and Public Health* 15, no. 5 (April 29, 2018): 885, https://doi.org/10.3390/ijerph15050885.
[897] AFL-CIO, "Death on the Job: The Toll of Neglect, 27th Edition," Workplace Health and Safety, 2018, https://aflcio.org/reports/death-job-toll-neglect-2018.
[898] Industrial Safety & Hygiene News, "Gaps in Oil & Gas Extraction Work Fatalities and Severe Injury Statistics," March 21, 2018, https://www.ishn.com/articles/108304-gaps-in-oil-gas-extraction-work-fatalities-and-severe-injury-statistics.

report filed in [Colorado Oil and Gas Conservation Commission's] database." Another worker died of his burn injuries from a flash fire in November that broke out during work on a pipeline. "The COGCC did not receive a report on this incident… because the pipeline was a 'gathering line' outside the agency's regulatory purview." The investigation documented additional gaps in regulatory oversight and responses to deaths and injuries.[899]

- October 1, 2017 – An investigation by the *Toronto Star*, the *National Observer*, *Global News,* and four Canadian journalism schools reported on hydrogen sulphide (H_2S)-related health threats and incidents (including one occupational death) in Saskatchewan, and government and industry failure to prevent, warn, and respond to this threat. The more than 50 reporters involved "examined thousands of industry and government documents, analyzed terabytes of data and delved into dozens of freedom-of-information requests," documenting, for example, the existence of government data describing H_2S "hotspots" across the province, that were never released to the public despite agency deliberations. In addition, reporters wrote,

  > Ministry and industry met four times between 2012 and 2014 to plot strategy, including emergency planning zones, a public communications document, a code of practice and a licensing regime for high-risk, single-well batteries. Those plans were never adopted, a ministry statement confirms.

  An industry salesman was killed in 2014 while taking samples. A valve broke and the concentration of H_2S in the spewed fluids, according to the company, "was estimated at 40,000 parts per million, more than enough to bring near-instant death." The investigation found that four months after the death, "a secret ministry report listed 161 facilities 'that may be in violation of (the ministry's) sour gas emission control.'"[900]

- August 24, 2017 – NIOSH's Fatalities in Oil and Gas Extraction (FOG) database identified 88 fatal incidents accounting for 101 fatalities, for the year 2014. In ten of the 88 incidents, more than one worker was fatally injured. The FOG database was established to collect detailed information about deaths related to U.S. oil and gas extraction. The report, which represents only a portion of the deaths that occurred in the industry due to the focus and limitations of the database, aims to provide a deeper understanding of the circumstances of the fatalities, such as the industry group the worker was employed by, and operations and types of activities occurring at the time of the fatal incident. The majority of fatalities in FOG, 45 percent, involved workers employed by servicing companies. These servicing company worker fatalities occurred throughout oil and gas extraction operations: completions (14 fatalities), production (11 fatalities), and well servicing, workover, or intervention (5 fatalities). The industry group

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[899] Bruce Finley, "A Dozen Fires and Explosions at Colorado Oil and Gas Facilities in 8 Months Since Fatal Blast in Firestone," *The Denver Post*, December 6, 2017, sec. Business, http://www.denverpost.com/2017/12/06/colorado-oil-gas-explosions-since-firestone-explosion/.

[900] Robert Cribb et al., "That Rotten Stench in the Air? It's the Smell of Deadly Gas and Secrecy," *Toronto Star*, October 1, 2017, https://www.thestar.com/news/canada/2017/10/01/that-rotten-stench-in-the-air-its-the-smell-of-deadly-gas-and-secrecy.html.

responsible for the second highest number of fatalities was drilling companies, at 27 percent, with most of those deaths occurring during drilling operations (20 fatalities).[901]

- May 30, 2017 – In a "rare, but not unprecedented" case, the U.S. Environmental Protection Agency (EPA) opened an investigation of air emissions from two North Dakota oil well sites where worker deaths occurred in 2012 and 2014. EPA requested information from both companies to determine Clean Air Act compliance on the day of the deaths. According to the *E&E News* report, it was not clear whether the agency was "looking at civil or criminal sanctions." Both workers, who were "flow testers," "assigned to regularly measure tank levels by hand," were found dead near tank hatches.[902] (No further information could be located on this investigation.)

- April 28, 2017 – Fatality rates for oil and gas extraction workers associated with falls increased two percent per year during 2003–2013, according to the Centers for Disease Control and Prevention's *Morbidity and Mortality Weekly Report.* These 63 fatal falls represented 15 percent of the fatal events among this group in the time period. The majority of those who were killed by falls worked for drilling contractors. In the vast majority of cases, "fall protection was required by regulation, but it was not used, was used improperly, or the equipment failed." Authors noted several limitations of their report, such as the lack of information on self-employed workers and lack of detail in some fatality reports.[903]

- April 26, 2017 – The 2017 edition of the AFL-CIO report, *Death on the Job: The Toll of Neglect,* which reported on the year 2015, showed that, although the number of deaths in the oil and gas extraction industries decreased compared to 2014 (89 compared to 144), employment in oil and gas extraction also decreased from 613,783 in 2014 to 533,184 in 2015. The deaths in the oil and gas extraction industries "accounted for 74% of the fatal work injuries in the mining sector." Referring to the challenges of getting a firm handle on statistics in this industry, the report stated that, "[f]atality rate data for the oil and gas industry are limited, but available data during the past seven years show fatality rates in oil and gas extraction that are four to seven times the national fatality rate." Further, "[n]ot surprisingly, states with large amounts of oil and gas activity also have high job fatality rates." Citing the continuing problem of assigning cause of death in the case of possible inhalation of toxic fumes, the report stated, "[w]hile some deaths are appropriately classified as inhalation deaths, others can be labeled as cardiac arrhythmia or respiratory failure, without further investigation as to whether the health event was induced by acute chemical exposure." As in previous years, the report expressed concerns

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[901] Sophia Ridl, Kyla Retzer, and Ryan Hill, "Oil and Gas Extraction Worker Fatalities 2014; NIOSH Fatalities in Oil and Gas Extraction (FOG) Database" (Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH), 2017), Oil and gas extraction worker fatalities 2014; NIOSH fatalities in oil and gas extraction (FOG) database.
[902] Mike Soraghan, "EPA Investigating Emissions in Tank Deaths," *E&E News*, May 30, 2017, https://web.archive.org/web/20170530150506/https://www.eenews.net/stories/1060055258.
[903] Krystal L. Mason et al., "Occupational Fatalities Resulting from Falls in the Oil and Gas Extraction Industry, United States, 2005–2014," *MMWR. Morbidity and Mortality Weekly Report* 66, no. 16 (April 28, 2017): 417–21, https://doi.org/10.15585/mmwr.mm6616a2.

about the regulatory gaps in controlling a range of potentially fatal hazards in the industry.[904]

- February 1, 2017 – Caused by exposure to silica particles or dust, silicosis is a progressive, autoimmune disease that scars lung tissue and restricts the ability to breathe. Any level of exposure to respirable crystalline silica can trigger silicosis. A special report on the history of silicosis in the *Journal of Environmental Health* provided background on silicosis as a workplace threat in various industries and identified drilling and fracking operations as a source of contemporary exposure. The report predicts a future cluster of silicosis among well pad workers, noting that research has already identified "unacceptable levels" of silica dust in air samples collected at fracking operations and that workers are seldom offered appropriate respiratory equipment to prevent exposure. Fracking "has the potential for future clusters of silicosis cases to emerge."[905]

- February 1, 2017 – University of Tennessee Civil and Environmental Engineering faculty investigated the occupational inhalation risks from the emissions of chemical storage tanks in 60,644 fracking wells. They also analyzed the combined occupational inhalation risks caused by open flowback pits and the storage tanks. They used AERMOD, the air pollution dispersion modeling system developed by the American Meteorological Society and EPA, and inhalation risk assessment to determine potential acute non-cancer, chronic non-cancer, acute cancer, and chronic cancer risks. Their results showed the percentage of wells presenting these risks were 12.41, 0.11, 7.53, and 5.80, respectively. They also found that the storage tanks presented the majority of the cancer risks, and the non-cancer risks were associated primarily to the open pits. The known human carcinogen formaldehyde was "the dominant contributor" to both acute (4,267 wells) and chronic (3,470 wells) cancer risk. Authors also reported that volatile organic compound (VOC) emissions from nearby wells and other on-site sources means that the data used in their study "were lower than reported concentrations from field measurements where higher occupational inhalation risks for exposure may be expected." [906]

- January 19, 2017 – A group of Canadian physicians published a report documenting ten intentional intoxications from the ingestion of fracking fluid. Each individual survived, which the authors attribute to "[r]apid case finding and diligent contact tracing." Their report, published in the *American Journal of Kidney Diseases,* focused on this appropriate response and treatment, but also described the "outbreak" challenge from a public health perspective and emphasized the need for prevention education and "requiring secure storage of these products." Though the professions or workplaces of the

[904] AFL-CIO, "Death on the Job: The Toll of Neglect, 26th Edition," 2017, https://aflcio.org/reports/death-job-toll-neglect-2017.
[905] M. Thomas Quail, "Overview of Silica-Related Clusters in the United States: Will Fracking Operations Become the Next Cluster?," *Journal of Environmental Health* 79, no. 6 (February 2017): 20–27.
[906] Huan Chen and Kimberly E. Carter, "Modeling Potential Occupational Inhalation Exposures and Associated Risks of Toxic Organics from Chemical Storage Tanks Used in Hydraulic Fracturing Using AERMOD," *Environmental Pollution* 224 (May 2017): 300–309, https://doi.org/10.1016/j.envpol.2017.02.008.

patients are not described, presumably they were oil and gas industry workers with easy access to fracking fluid.[907]

- September 25, 2016 – A four-chapter investigative series by the *Denver Post* explored in detail Colorado's 12-year record of an oil and gas worker dying, on average, every three months. The piece documented the obstacles present in even clarifying the occupational mortalities owing to the differing reporting practices of the Bureau of Labor Statistics, OSHA, and state officials. "Regulation is so disjointed that no one can even agree on the number of workers killed on the job." Investigating the details of the deaths through any available records, the *Post* described a "regulatory vacuum," as well as "little consequence" to the industry when deaths (or worksite violations) occur. Worker death circumstances examined in the piece included electrocutions, falls and collapsed structures, crushings by equipment, explosions, and a drowning in frack sand. The *Post* also identified five lawsuits over 15 years "in which workers alleged that they were punished for reporting injuries or safety hazards."[908]

- April 27, 2016 – According to the 2016 edition of the AFL-CIO report, *Death on the Job: The Toll of Neglect,* the fatality rate for workers in the oil and gas extraction industries is nearly five times the national average, and the states with prominent oil and gas industries are among the most dangerous states to work. In addition, the report emphasized, the industry has been exempted from some critical OSHA standards, including that for carcinogenic benzene. The report also emphasized the danger of silica dust exposure in hydraulic fracturing-related work and the significant delays in controlling workers' exposures in these operations. "Oil and gas extraction is subject to OSHA general industry and construction regulations, none of which are designed to address the particular safety and hazards in the oil and gas industry…. The escalating fatalities and injuries in the oil and gas extraction industry demand intensive and comprehensive intervention," the report stated.[909]

- April 21, 2016 – According to an updated report from the Bureau of Labor Statistics, fatal work injuries in oil and gas extraction industries in 2014 reached a new high of 144.[910]

- February 29, 2016 – *Inside Energy's* report on high rates of hydrocarbon vapor poisoning among oilfield workers noted that an outdated reliance on manual measurements rather than automated monitoring contributes to ongoing toxic exposures of workers. Under federal oil and gas regulations, oil companies are effectively required to send workers "up on oil and gas tanks to manually measure crude oil, putting them at risk." The report explained that the Bureau of Land Management (BLM) allows just one kind of automated

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907 David Collister et al., "A Methanol Intoxication Outbreak From Recreational Ingestion of Fracking Fluid," *American Journal of Kidney Diseases* 69, no. 5 (May 2017): 696–700, https://doi.org/10.1053/j.ajkd.2016.10.029.
908 R. J. Sangosti and John Ingold, "Drilling Through Danger," *The Denver Post*, September 25, 2016, http://extras.denverpost.com/oil-gas-deaths/index.html.
909 AFL-CIO, "Death on the Job: The Toll of Neglect, 2016," 2016, http://www.aflcio.org/Issues/Job-Safety/Death-on-the-Job-Report.
910 U.S. Bureau of Labor Statistics, "Revisions to the 2014 Census of Fatal Occupational Injuries (CFOI)," April 21, 2016, http://www.bls.gov/iif/cfoi_revised14.htm.

measurement. The method is expensive and uncommonly used: "there are only 1,500 in use, compared to more than 83,000 oil tanks on federal land. By being so inflexible, BLM's outdated rules make it very hard to use safer oil measuring devices while making manual oil tank measurement—which endangers workers—the most viable option for companies."[911]

- February 19, 2016 – The fatal injuries of a backhoe operator who struck and hit an unmarked, high-pressure gas line in July 2015 prompted an investigation by *StateImpact* in Pennsylvania. The news group noted that "there are no local, state or federal rules on how deep the lines should be buried underground, or even if they're buried at all. There are no standards for building and maintaining the lines. They don't have to be marked. And the operator of the line doesn't have to participate in PA One Call [a statewide communications system for preventing damage to underground facilities], which led to the fatality in Armstrong County."[912]

- January 15, 2016 – In a publication in Centers for Disease Control's *Mortality & Morbidity Weekly Report*, researchers urged local and state epidemiologists and medical examiners to not overlook hydrocarbon exposure as an underlying cause of death in gas and oil field workers. "Health and safety professionals need to recognize and act on nonfatal warning signs and symptoms, such as dizziness, confusion, immobility and collapse in oil and gas workers who might have been exposed to high concentrations of [hydrocarbon gas vapors] and to [oxygen]-deficient atmospheres." Only three of nine deaths that occurred between 2010 and 2015 in the oil and gas fields west of Appalachia were ruled by coroners to have resulted from exposure to gas vapors, although all nine had opened hatches of storage tanks and were exposed to hydrocarbon vapors and oxygen-deficient air.[913] The *Pittsburgh Post-Gazette* quoted emeritus professor at the University of Pittsburgh Bernard Goldstein saying, "Occupational health experts also suspect that some deaths involving fires, falls, crashes and mishandling of equipment have resulted from faulty judgement or 'wooziness' associated with hydrocarbon vapor exposure … [b]ut that underlying factor rarely shows up in fatality reports."[914]

- December 14, 2015 – As reported in the *Guardian,* the suicide rate in the Canadian province of Alberta spiked by 30 percent spike in the first half of 2015, possibly linked to the boom-and-bust cycle of the fracking industry. At the time of reporting, 40,000 jobs

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911 Emily Guerin, "'Senseless Exposures': How Money and Federal Rules Endanger Oilfield Workers," *Inside Energy*, February 29, 2016, http://insideenergy.org/2016/02/29/senseless-exposures-how-money-and-federal-rules-endanger-oilfield-workers/.
912 Susan Phillips, "Worker Dies in Pipeline Accident, PUC Steps up Calls for Reform," *State Impact Pennsylvania*, February 19, 2016, https://stateimpact.npr.org/pennsylvania/2016/02/19/worker-dies-in-pipeline-accident-puc-steps-up-calls-for-reform/.
913 Robert J. Harrison et al., "Sudden Deaths Among Oil and Gas Extraction Workers Resulting from Oxygen Deficiency and Inhalation of Hydrocarbon Gases and Vapors — United States, January 2010–March 2015," *Morbidity and Mortality Weekly Report* 65, no. 1 (2016): 6–9.
914 Anya Litvak, "Vapors Linked to Oxygen Depletion Present Hazard for Oil, Gas Workers," *Pittsburgh Post-Gazette*, January 24, 2016, http://powersource.post-gazette.com/powersource/policy-powersource/2016/01/25/Vapors-linked-to-oxygen-depletion-present-hazard-for-oil-gas-workers/stories/201601220095.

had been lost in Alberta since the drop in oil prices in late 2014. Mental health professionals interviewed for the report included Edmonton social worker Leonard McEwan, who specializes in clinical crises intervention and whose patients include those directly or indirectly employed in the oil fields, noticed a sharp increase in suicides after the recent plunge in oil prices. As revealed in the investigative report, three in every four Alberta suicides are male and the vast majority are under 55. Gladys Blackmore, executive director of a mental health program that targets those employed in the industry, believes that young, male workers "living high-risk lifestyles, often in work camps, where they 'fly-in/fly-out' for up to 24 days at a time" are particularly vulnerable.[915]

- November 7, 2015 – The *Denver Post* reported on a "new federal database that was developed to more precisely capture the deadly nature of oil and gas extraction." For Colorado, the national Fatalities in Oil and Gas Extraction (FOG) database contained two additional oil and gas worker deaths for 2014 than did the Bureau of Labor Statistics. "'We knew from the Bureau of Labor Statistics data about the basics of what's killing workers,' said Kyla Retzer, an epidemiologist who led the effort to compile the FOG report. 'We just wanted to be more in-depth in finding out what were the types of operations and equipment were involved in these deaths.'"[916] (See entry for August 24, 2017 above for official report.)

- November 4, 2015 – San Antonio's *Express-News* Editorial Board called for specific actions to address Texas's status "a national leader in oil field deaths." The Board wrote that federal fines are too low and unchanged since 1991 and that there is no Level 1 trauma center south of San Antonio near the region's oil- and gas-producing counties.[917]

- September 17, 2015 – The Bureau of Labor Statistic reported that the number of fatal work injuries in oil and gas extraction industries rose 27 percent between 2013 and 2014.[918]

- September 15, 2015 – E&E Publishing's *EnergyWire* reported on the potentially deadly risk of exposure to vapors from oil and gas field storage tanks, including deaths that were officially attributed to cardiac arrest, though inhalation of toxic gases and lack of oxygen played a role, as demonstrated in subsequent litigation. The reporter gave detail on the circumstances of several of the deaths, including that of a long-haul trucker who had heart disease and was diabetic, and whose death was classified as natural. "But he didn't suffer a heart attack that day, or a diabetic episode. Medical experts said he likely

[915] Omar Mouallem, "The Boom, the Bust, the Darkness: Suicide Rate Soars in Wake of Canada's Oil Crisis," *The Guardian*, December 14, 2015, https://www.theguardian.com/world/2015/dec/14/canada-oil-production-crisis-suicide-alberta?CMP=share_btn_fb.
[916] Monte Whaley, "Colorado Oil Deaths Greater in 2014 than Previously Calculated," *The Denver Post*, November 7, 2015, http://www.denverpost.com/2015/11/07/colorado-oil-deaths-greater-in-2014-than-previously-calculated/.
[917] Express-News Editorial Board, "Take Care of the State's Oil, Gas Workers," *MySanAntonio.Com*, November 4, 2015, http://www.mysanantonio.com/opinion/editorials/article/Take-care-of-the-state-s-oil-gas-workers-6611077.php.
[918] U.S. Department of Labor, Bureau of Labor Statistics, "National Census of Fatal Occupational Injuries in 2014 (Preliminary Results)," News Release, September 17, 2015, https://web.archive.org/web/20161218034553/https://www.bls.gov/news.release/archives/cfoi_09172015.pdf.

wouldn't have died outside the toxic atmosphere on the catwalk." A Denver cardiologist testified that "there was no other reason for him to have died that day."[919] (NIOSH has subsequently targeted outreach to medical examiners to improve their recognition of this hazard and potential cause of death; see above.)

- September 5, 2015 – In partnership with Rocky Mountain PBS I-News, *The Durango Herald* reported on the oil and gas industry's varied practices in their handling of silica sand with regard to worker protection. In 2012 the National Institute for Occupational Safety and Health issued an alert concerning workers at fracking sites being exposed to silica dust at levels that exceeded occupational exposure limits. Industry has resisted updates to the standards. The *Herald* report addressed technological and work practice controls to reduce exposure on the part of some companies. Still, authors wrote, silicosis "can hide for a decade before causing symptoms. No one knows how many oil and gas workers may have already been exposed."[920]

- June 29, 2015 – An investigation by the Center for Public Integrity (CPI) found that lung-damaging silica is not sufficiently regulated to prevent silicosis (which is incurable and has no effective treatment) or lung cancer in the workplace. Rules governing occupational exposure to silica dust are far outdated, and advocacy efforts to tighten them are four decades old. At particular risk, say the authors, are workers in oil and gas fields where silica sand is used in fracking operations. Citing research by NIOSH, the CPI team noted that nearly 80 percent of the air samples on the well pads were above the recommended exposure limit for silica dust.[921]

- June 15, 2015 – *EnergyWire* examined issues surrounding exposure to crystalline silica from frack sand mining, which is a health concern to those living near mines and to those working in the industry. Families living near industrial sand mining reported that their health has been compromised by sand mine development and are concerned that companies are not properly monitoring their extraction sites. The article noted that OSHA is working on a new exposure rule for workers that the agency estimates would save nearly 700 lives and prevent 1,600 new cases of silicosis annually. The oil and gas industry is fighting the rule because of the cost associated with complying with a more stringent permissible exposure limit. Crispin Pierce, public health researcher at the University of Wisconsin in Eau Claire, is in the midst of a three-pronged research project to look at the industry's air effects. Among other findings, his project's air monitors around sand plants have found consistently finding higher readings than the Wisconsin Department of Natural Resources' reported regional values.[922]

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919 Mike Soraghan, "SAFETY: How Shale Oil Can Kill," *E&E News*, September 14, 2015, https://web.archive.org/web/20150918032438/http://www.eenews.net/stories/1060024589.

920 Anna Boiko-Weyrauch, "Oil, Gas Industry Responding to Threat of Worker Lung Disease," *Durango Herald*, September 5, 2015, https://www.durangoherald.com/articles/oil-gas-industry-responding-to-threat-of-worker-lung-disease/.

921 Jim Morris, Jamie Smith Hopkins, and Maryam Jameel, "Slow-Motion Tragedy for American Workers," Center for Public Integrity, June 30, 2015, https://publicintegrity.org/inequality-poverty-opportunity/workers-rights/slow-motion-tragedy-for-american-workers/.

922 Pamela King, "Frac Sand Towns Question Whether Rules Protect Them against Silica Pollution," *Energy Wire*, June 15, 2015, https://web.archive.org/web/20150621073016/https://www.eenews.net/stories/1060020192.

- June 15, 2015 – In an update, NIOSH noted that silicosis death rates are rising again, reversing an earlier, decade-long decline. In the list of job tasks with known high silica exposures, the update named hydraulic fracturing of gas and oil wells. These results are particularly concerning in light of earlier research showing significant under-detection of silicosis among deceased workers with known exposure to silica dust.[923]

- June 13, 2015 – Reporting on North Dakota's fracking boom, the Center for Investigative Reporting found that the major oil companies have largely written the rules governing their own accountability for accidents. Deeply entrenched corporate practices and weak federal oversight, according to the report, have led to high injury and death rates and a shift of assigned responsibility to others. Using data from U.S. and Canadian regulators, the journalists verified 74 on-the-job deaths among workers in Bakken Shale drilling and fracking operations since 2006. The actual number of deaths is likely higher than currently reported because federal regulators do not have a systematic way to record oil- and gas-related deaths, and OSHA does not include certain fatalities, including those of independent contractors. The report concluded that there was too little oversight from OSHA, that laws to protect workers were outdated, and that there was a culture of self-regulation by the industry.[924]

- May 29, 2015 – The Centers for Disease Control and Prevention published statistics on work-related fatalities during the fracking boom. The occupational fatality rate among U.S. oil and gas industry extraction workers between 2003 and 2013 remained an average of seven times higher than among U.S. workers in general (25.1 versus 3.7 deaths per 100,000 workers per year). Within this 11-year period, the industry doubled the size of its workforce and increased drilling rigs by 71 percent. The number of occupational deaths increased 27.6 percent, with a total of 1,189 deaths, but it did not increase as much as the number of workers, resulting in an overall decrease in the fatality rate of 36.3 percent. Transportation accidents and contact with objects and equipment were the most frequent fatal events. Evidence suggests that the increased use of automated technologies on drilling rigs may be contributing to the decline in death rates.[925]

- April 22, 2015 – The AFL-CIO published data for job injuries, illnesses and deaths in a national and state-by-state profile of worker safety and health in the United States, presenting comparisons by state and industry. For the third year in a row, North Dakota had the highest on-the-job fatality rate in the nation: 14.9 deaths per 100,000 workers, a rate that is more than four times the national average, and which has more than doubled since 2007. The fatality rate in the mining and oil and gas extraction sector in North Dakota was 84.7 per 100,000, which is nearly seven times the national fatality rate of

[923] Jacek Mazurek and David Weissman, "Silicosis Update," *NIOSH Science Blog* (blog), June 15, 2015, https://blogs.cdc.gov/niosh-science-blog/2015/06/15/silicosis-update/.
[924] Jennifer Gollan, "In North Dakota's Bakken Oil Boom, There Will Be Blood," *Reveal*, June 13, 2015, http://revealnews.org/article/in-north-dakotas-bakken-oil-boom-there-will-be-blood/.
[925] Krystal L. Mason, "Occupational Fatalities During the Oil and Gas Boom — United States, 2003–2013," *Morbidity and Mortality Weekly Report* 64, no. 20 (May 29, 2015): 551–54.

12.4 per 100,000 in this industry.[926, 927]

- April 10, 2015 – In a study that was inclusive of fracking-based extraction but not specific to it, NIOSH researchers updated their investigation into the sudden deaths of nine oil and gas extraction workers found near hatches where hydrocarbons were stored. All nine victims died between 2010 and 2014 and were unobserved or working alone at the time of their deaths. The first report attributed the fatalities to "inhalation of volatile petroleum hydrocarbons."[928] The update noted that when workers open hatches on production tanks, a plume of hydrocarbon gases and vapors can be rapidly released due to high internal pressure. Exposure to high concentrations of these low-molecular-weight hydrocarbons creates asphyxiation and explosive hazards and can have narcotic effects, resulting in disorientation, dizziness, and light-headedness. The authors cited reports of other sudden deaths following butane and propane inhalation, exposure to which can induce irregular heartbeat, insufficient oxygen supply, and respiratory depression.[929] As reported by the *Denver Post*, most of the death certificates listed natural causes or heart failure as the cause likely because medical examiners can easily miss signs of toxic inhalation during a routine autopsy. The nomadic nature of the industry presents obstacles to proper training in tank handling techniques.[930] NIOSH issued recommendations for worker protections, including respiratory protection training and engineering controls for remote gauging and venting.[931]

- February 15, 2015 – Burn injuries among North Dakota workers surged to more than 3,100 over the past five years as the area has become the epicenter of a massive drilling and fracking boom, as reported by the *Star Tribune*. Despite the flammability of Bakken crude oil and the danger of oil rig work, North Dakota has no burn centers, and burn victims must be transported out of state, typically to the Minneapolis-St. Paul area some 600 miles away. The article also covered the severe, debilitating, costly, and sometimes fatal aspects of these occupational injuries.[932]

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926 AFL-CIO, "Death on the Job: The Toll of Neglect, 25th Edition," April 22, 2015, https://aflcio.org/reports/death-job-2016.
927 Jana Kasperkevic, "About 150 US Workers Are Killed on the Job Every Day – Report," *The Guardian*, April 29, 2015, sec. US news, http://www.theguardian.com/us-news/2015/apr/29/north-dakota-deadliest-state-workers-third-year-running.
928 NIOSH, "Suspected Inhalation Fatalities Involving Workers during Manual Tank Gauging, Sampling, and Fluid Transfer Operations on Oil and Gas Well Sites, 2010-2014," March 15, 2015, https://www.cdc.gov/niosh/topics/fog/SpecialTopic2015.html.
929 Bradley King et al., "UPDATE: Reports of Worker Fatalities during Manual Tank Gauging and Sampling in the Oil and Gas Extraction Industry," *NIOSH Science Blog* (blog), April 10, 2015, https://blogs.cdc.gov/niosh-science-blog/2015/04/10/flowback-3/.
930 Monte Whaley, "Toxic Vapors Suspected in Deaths of Three Colorado Oil and Gas Workers," *The Denver Post*, May 17, 2015, https://www.denverpost.com/2015/05/17/toxic-vapors-suspected-in-deaths-of-three-colorado-oil-and-gas-workers/.
931 The Associated Press, "9 Oil Well Deaths Lead to Warning about Inhaling Chemicals," *The Coloradoan*, May 18, 2015, https://www.coloradoan.com/story/news/2015/05/18/oil-deaths-lead-warning-inhaling-chemicals/27562991/.
932 Maya Rao, "Twin Cities Hospitals Are Front Line in Treating Bakken Burn Victims," *Star Tribune*, February 15, 2015, https://www.startribune.com/twin-cities-hospitals-are-front-line-in-treating-bakken-burn-victims/291967611/.

- February 13, 2015 – NIOSH reported that while silicosis death rates declined between 2001 and 2010, silicosis deaths were still occurring among young persons aged 15 to 44 years old, indicating extremely high exposures to respirable silica dust. Among emerging new settings that put workers at risk for silicosis, the authors named oil and gas extraction industry workers.[933]

- January 14, 2015 – The *Charleston Gazette-Mail* reported that, due to an increase in workplace deaths that has accompanied the boom in natural gas drilling and production from the Marcellus Shale fields in Northern West Virginia, the Governor there has called for a study aimed at reversing that trend. "Between 2009 and 2013, as the industry boomed in the Marcellus region, 15 natural gas workers died on the job in West Virginia, according to the federal data. During the previous five-year period, from 2004 to 2008, three workers died in West Virginia's oil and gas industry, according to the [U.S. Bureau of Labor Statistics]."[934]

- January 12, 2015 – Oil and gas production employs less than one percent of the U.S. workforce, but in the past five years it has had more than ten percent of all workplace fatalities from fires and explosions. A review by *EnergyWire* of federal labor statistics last year found the industry had more deaths from fires and explosions than any other private industry. The only "industry" with more fire and explosion fatalities than oil and gas was firefighting, the report stated. These statistics are inclusive of deaths related to fracking operations but are not specific to them.[935]

- December 26, 2014 – A report in the *Houston Chronicle* illustrated the difficulties oil and gas workers encounter when injured on the job. In one case a worker fell from a rig, injuring his head. Supervisors did not record the accident. After he became too ill to work, he was shifted to other jobs and soon after, sent home. His daughter filed a Worker's Compensation claim, which was denied for "late reporting, no knowledge of injury by employer and no medical reports." The article noted that oilfield injuries are generally undercounted nationally. These include injuries related to drilling and fracking operations as well as those linked to other techniques of extraction.[936]

- December 4, 2014 – Benzene, a naturally occurring component of crude oil and natural gas, is a known carcinogen, with no known threshold of safety. Although the American Petroleum Institute in 1948 stated that "the only absolutely safe concentration … is zero," the organization since then undertook an intensive campaign to combat strict exposure limits. An investigation by the Center for Public Integrity found that, "[f]or decades, the

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933 Ki Moon Bang et al., "Silicosis Mortality Trends and New Exposures to Respirable Crystalline Silica — United States, 2001–2010," *Morbidity and Mortality Weekly Report* 64, no. 5 (February 13, 2015): 117–20.
934 Ken Ward Jr., "Tomblin Calls for Study of Increased Deaths from Gas-Drilling Boom," *Charleston Gazette-Mail*, January 14, 2015, https://www.wvgazettemail.com/news/politics/tomblin-calls-for-study-of-increased-deaths-from-gas-drilling/article_21d6342f-c5dd-54ee-bd91-534ece13373a.html.
935 Mike Soraghan, "At Least 16 Drilling Industry Workers Died in Fires, Explosions Last Year," January 12, 2015, https://web.archive.org/web/20150623023615/http://www.eenews.net/stories/1060011452.
936 Lise Olsen, "Many Oilfield Injuries Go Unreported," *Houston Chronicle*, December 26, 2014, sec. Houston, https://www.houstonchronicle.com/news/houston-texas/houston/article/Many-oilfield-injuries-go-unreported-5980350.php.

petrochemical industry spent millions on science seeking to minimize the dangers of benzene.… Taken together, the documents—put in context by interviews with dozens of lawyers, scientists, academics, regulators and industry representatives—depict a 'research strategy' built on dubious motives, close corporate oversight and painstaking public relations."[937]

- December, 2014 – In a report intended to inform employers and workers about the known hazards that result from hydraulic fracturing and flowback operations, OSHA noted that there is no publicly available worker injury, illness, or fatality data specific for fracking or flowback operations. At the same time, more workers are exposed to fracking- and flowback-related hazards due to the huge increase in the numbers of these operations over the past ten years. "In light of this, OSHA has determined that additional information concerning hydraulic fracturing and flowback operations hazards should be provided to educate and protect workers."[938]

- November 11, 2014 – University of Wisconsin toxicologist Crispin Pierce documented super-fine dust drifting from facilities that process silica sand for fracking operations. Pierce and his team detected silica dust in ambient air near frac sand operations at levels that exceed EPA air quality standards by a factor of four. Occupational exposure to respirable crystalline silica is linked in adult workers to silicosis, lung cancer, and pulmonary tuberculosis. Health threats to the general public from frac sand-related air pollution have not yet been studied directly. One of the first investigations of silica dust levels in the community environment, the Wisconsin study will appear next year in the *Journal of Environmental Health*.[939] (See entry for November 6, 2015 in Sand mining and processing.)

- November 11, 2014 – A high-pressure water line ruptured, killing one worker and seriously injuring two others during the hydraulic fracturing of an oil well in Weld County, Colorado.[940]

- October 13, 2014 – A legal news publication described the multiple lawsuits alleging that drilling rig workers were not made aware of and protected from asbestos in drilling muds. "Various plaintiffs have testified that they were made to work in an environment where there was asbestos drilling mud dust everywhere from the powder, and that no guidance

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937 Kristen Lombardi, "Benzene and Worker Cancers: 'An American Tragedy,'" Center for Public Integrity, December 4, 2014, https://publicintegrity.org/environment/benzene-and-worker-cancers-an-american-tragedy/.
938 U.S. Department of Labor, Occupational Safety and Health Administration, "Hydraulic Fracturing and Flowback Hazards Other than Respirable Silica," Guidance Document, 2014, https://www.osha.gov/sites/default/files/publications/OSHA3763.pdf.
939 Rich Kremer, "High Levels Of Super-Fine Dust Are Detected Around Wisconsin Frac Sand Mines," *Wisconsin Public Radio*, November 11, 2014, https://www.wpr.org/high-levels-super-fine-dust-are-detected-around-wisconsin-frac-sand-mines.
940 J. Paul, "Brighton Man ID'd as Victim in Fatal Weld County Fracking Blast," *The Denver Post*, November 11, 2014, https://www.denverpost.com/2014/11/14/brighton-man-idd-as-victim-in-fatal-weld-county-fracking-blast/.

or protective gear was provided."[941] Breathing asbestos is definitively linked to asbestosis, lung cancer, and mesothelioma of the pleura.

- October 6, 2014 – Toxicologist Peter Thorne, chair of University of Iowa's Department of Occupational and Environmental Health, warned the Winneshiek County Board of Supervisors about potential community impacts and cancer risks of silica exposure from sand used for fracking operations. Thorne's ongoing investigation, which involves air sampling, risk assessments, and inhalation toxicology studies, focuses on the public health hazards of mining, processing, and storing sand. His team has documented spikes in silica particulate matter related to the transport of the silica sand by rail. The study aims to determine if mining poses an "unacceptable exposure" to the public and quantify the level of risk. For silica-exposed workers, NIOSH continues to identify needed heath protections. Thorne noted, "Workers handling materials should be using respirators, but most are not."[942]

- September 25, 2014 – The Civil Society Institute's Boston Action Research, in cooperation with Environmental Working Group and Midwest Environmental Advocates, issued a report on the hazards of silica mining. The report noted that frac sand mining is expanding rapidly in the United States and poses a little-understood threat to public health, the environment, and local economies. Given the pace of the drilling and fracking boom, silica extraction could spread to a dozen other states with untapped or largely untapped sand deposits, including Illinois, Maine, Massachusetts, Michigan, Missouri, New York, North Carolina, South Carolina, Pennsylvania, Tennessee, Vermont, and Virginia. The *International Business Times* published a summary of the findings.[943, 944]

- August 29, 2014 – In a peer-reviewed study, NIOSH partnered with oil and gas operators and service companies to evaluate worker exposures to, and internal uptake of, volatile organic chemicals at six sites in Colorado and Wyoming where wells were being prepared for production. The study found benzene in the urine of well pad workers. Benzene is "naturally present in flowback fluids and the time spent working around flowback and production tanks … appears to be the primary risk factor for inhalation exposures." In some cases, airborne concentrations of benzene exceeded the NIOSH Recommended Exposure Limit concentrations and, in a few instances, the American

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[941] Gordon Gibb, "Major Oil Drilling Enterprise References Drilling Mud Lawsuits in Q2 Report," *LawyersandSettlements.Com*, October 13, 2014, https://www.lawyersandsettlements.com/legal-news/asbestos-drilling-mud/drilling-mud-asbestos-lawsuit-24-20169.html.
[942] "U of I Researcher Informs Supervisors about Frac-Sand Impact," *Driftless Journal*, October 6, 2014, https://decorahnewspapers.com/Content/Home/Home/Article/U-of-I-researcher-informs-supervisors-about-frac-sand-impact/-2/-2/35735.
[943] Emily Chapman et al., "Communities At Risk: Frac Sand Mining in the Upper Midwest A Report by Boston Action Research" (Civil Society Institute, September 25, 2014), https://www.civilsocietyinstitute.org/NEWCSI/2014CommunitiesatRiskFracSandMiningintheUpperMidwest.pdf.
[944] Maria Gallucci, "US Oil & Gas Fracking Boom Could Drive Silica Sand Mining Operations In 12 More States, Environmental Groups Say," *International Business Times*, September 25, 2014, sec. Business, https://www.ibtimes.com/us-oil-gas-fracking-boom-could-drive-silica-sand-mining-operations-12-more-states-1695246.

Conference of Governmental Industrial Hygienists' Threshold Limit Value, "when workers performed work tasks near a point source for benzene emissions."[945]

- July 29, 2014 – As part of an investigation into the health impacts of drilling and fracking on animal health, veterinarian Michelle Bamberger and Cornell biochemist Robert Oswald, published an interview with a twenty-year oil and gas industry worker about his experiences and worker safety. His account included injuries, 16-hour workdays, fatigue, exposure to chemicals, and inadequate health and safety training. "No one out there tells you about stuff that has latency. That is the last thing they are going to do is tell you that something that you are handling will take you out in 20 years or 10 years or cause you some kind of ailment, or you can potentially drag this home to your family."[946]

- July 14, 2014 – As part of an analysis of safety and research needs associated with drilling and fracking, researchers at the Colorado School of Public Health and the College of Health Sciences at the University of Wyoming documented high injury and on-the-job mortality rates among gas and oilfield workers. The occupational fatality rate was 2.5 times higher than that of the construction industry and seven times higher than that of general industry. By contrast, injury rates were lower than the construction industry, suggesting that injuries are underreported. Researchers documented crystalline silica levels above occupational health standards and identified the existence of other hazards, including particulate matter, benzene, noise, and radiation. The team called for exposure assessments for both chemical hazards and physical hazards that lead to occupational illness (noise, radioactivity); screening and surveillance systems to assess incidence and prevalence of occupational illness; industry/academic collaboration to conduct occupational epidemiologic studies; and assessment of the effectiveness of industry interventions to reduce exposures.[947]

- July 2014 – The British labor journal *Hazards* identified health concerns in the drilling and fracking industry: increased rate of death on the job, toxic releases, silica exposure, and exposure to hydrocarbons and endocrine disruptors. The union that organizes the construction, rig, and transport workers, on which fracking would rely, agreed at its July 2014 national conference to lobby for a moratorium on fracking because "[d]elegates want union members to be made aware of the dangers of fracking and be advised not to work on fracking sites."[948]

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[945] Eric J. Esswein et al., "Evaluation of Some Potential Chemical Exposure Risks During Flowback Operations in Unconventional Oil and Gas Extraction: Preliminary Results," *Journal of Occupational and Environmental Hygiene* 11, no. 10 (2014): D174–84, https://doi.org/10.1080/15459624.2014.933960.
[946] Michelle Bamberger and Robert Oswald, "The Shale Gas Revolution from the Viewpoint of a Former Industry Insider," *New Solutions: A Journal of Environmental and Occupational Health Policy* 24, no. 4 (February 2015): 585–600, https://doi.org/10.2190/NS.EOV.1.
[947] Roxana Z. Witter et al., "Occupational Exposures in the Oil and Gas Extraction Industry: State of the Science and Research Recommendations: Occupational Exposure in Oil and Gas Industry," *American Journal of Industrial Medicine* 57, no. 7 (July 2014): 847–56, https://doi.org/10.1002/ajim.22316.
[948] R. O'Neill, "Chemicals, Dust and Deaths and the New Rush for Oil and Gas," *Hazards Magazine*, 2014, https://www.hazards.org/oil/fracking.htm#top.

- June 29, 2014, and August 31, 2014 – An initial report and follow-up analysis in *The Columbus Dispatch* examined fire hazards at well pads. In one notable case, malfunctioning hydraulic tubing allowed a well pad fire in Monroe County, Ohio to spread rapidly, prompting evacuations. Local firefighters had neither the correct equipment nor did they know the chemicals they were trying to extinguish. One firefighter was treated for smoke inhalation.[949, 950]

- May 19, 2014 – Underscoring the dangerous nature of chemicals used in fracking operations, NIOSH reported that at least four gasfield workers have died since 2010 from acute chemical exposures during flowback operations and warned that flowback operations can "result in elevated concentrations of volatile hydrocarbons in the work environment that could be acute exposure hazards." The agency further noted that such volatile hydrocarbons "can affect the eyes, breathing, and the nervous system and at high concentrations may also affect the heart causing abnormal rhythms."[951, 952]

- May 16, 2013 – A NIOSH study revealed that worker exposure to crystalline silica dust from sand used in fracking operations exceeded "relevant occupational health criteria" at all eleven tested sites, and the magnitude of some exposures exceeded NIOSH limits by a factor of 10 or more. "[P]ersonal respiratory protection alone is not sufficient to adequately protect against workplace exposures." Inhalation of crystalline silica can cause incurable silicosis, lung cancer, chronic obstructive pulmonary disease, kidney disease and autoimmune diseases.[953] Although community exposures distant from mines are possible, there are no federal or state standards for silica in ambient air.[954]

- May 8, 2014 – A report by the AFL-CIO found that the fracking boom has made North Dakota the most dangerous state for U.S. workers—with a fatality rate five times higher than the national average—and that North Dakota's fatality rate has doubled since 2007. The AFL-CIO called North Dakota "an exceptionally dangerous and deadly place to work." U.S. Secretary of Labor Thomas E. Perez called the rising rate of workplace deaths suffered in the oil and gas sector "unacceptable."[955]

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949 Jennifer Smith Richards, "Glitch Sparks Smoky Fire at Gas Well," *The Columbus Dispatch*, June 29, 2014, https://www.dispatch.com/article/20140629/NEWS/306299873.
950 Laura Arenschield, "Fracking Fire Points out Failings," *The Columbus Dispatch*, August 31, 2014, https://www.dispatch.com/article/20140831/NEWS/308319916.
951 John Snawder et al., "Reports of Worker Fatalities during Flowback Operations," *NIOSH Science Blog* (blog), May 19, 2014, https://blogs.cdc.gov/niosh-science-blog/2014/05/19/flowback/.
952 Robert Iafolla, "Four Fatalities Linked to Used Fracking Fluid Exposure During 'Flowback,' NIOSH Reports," *Bloomberg BNA*, May 20, 2014, https://perma.cc/M5RY-QPZA.
953 Eric J. Esswein et al., "Occupational Exposures to Respirable Crystalline Silica During Hydraulic Fracturing," *Journal of Occupational and Environmental Hygiene* 10, no. 7 (July 2013): 347–56, https://doi.org/10.1080/15459624.2013.788352.
954 University of Iowa Environmental Health Sciences Research Center, "Exposure Assessment and Outreach to Engage the Public on Health Risks from Frac Sand Mining," 2012, https://web.archive.org/web/20140530144336/http://cph.uiowa.edu/ehsrc/fracsand.html.
955 Aimee Picchi, "The Most Dangerous U.S. State for Workers," *CBS News*, May 8, 2014, https://www.cbsnews.com/news/the-most-dangerous-us-state-for-workers/.

- April 24, 2014 – A University of Texas San Antonio report commissioned by the Methodist Healthcare Ministries found that many oil and gas field workers in the Eagle Ford Shale are uninsured or underinsured and that "the most noticeable health impacts so far are work-related illnesses and injuries: heat exhaustion, dehydration, sleep deprivation, exposure to oil and gas spills and accidents." The study also noted that oil and gas production has put strain on healthcare facilities.[956]

- April 10, 2014 –West Virginia University researcher Michael McCawley reported that some of the nation's highest rates of silicosis are in heavily drilled areas within the Northern Panhandle of West Virginia and southwestern Pennsylvania. A disease that hardens the lungs through inflammation and development of scar tissue, silicosis is entirely attributable to exposure to silica dust, a known occupational hazard at drilling and fracking operations. Two years earlier, OSHA and NIOSH issued a joint "Hazard Alert" to warn fracking workers of the health hazards of exposure to silica dust, including silicosis.[957]

- February 25, 2014 – A year-long investigation by the *Houston Chronicle* found that fracking jobs are deadly, with high fatality rates and high rates of serious injury. Within just one year in Texas, 65 oil and gas workers died, 79 lost limbs, 82 were crushed, 92 suffered burns and 675 broke bones. From 2007 to 2012, at least 664 U.S. workers were killed in oil and gas fields.[958, 959]

- December 27, 2013 – National Public Radio (NPR) reported spiking rates of fatalities related to oil and gas drilling operations, which had increased more than 100 percent since 2009. NPR noted that in the previous year, 138 workers were killed on the job, making the fatality rate among oil and gas workers nearly eight times higher than the average rate of 3.2 deaths for every 100,000 workers across all industries.[960]

- October 30, 2012 – In a policy statement, the American Public Health Association (APHA) asserted that, high volume horizontal hydraulic fracturing (HVHF) "poses potential risks to public health and the environment, including groundwater and surface water contamination, climate change, air pollution, and worker health." The statement

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[956] Y. Ghahremani, "Fractured Healthcare: Pumping Resources Back Into the Eagle Ford Shale Communities," Executive Summary (Methodist Healthcare Ministries and Center for Community and Business Research at the University of Texas San Antonio, April 2014), http://mhm.org/images/stories/pdf/Fractured%20Healthcare%20ExecSumm_FINAL.pdf.
[957] "Gas Workers at Risk of Silica Exposure," *The Weirton Daily Times*, April 10, 2014, https://www.weirtondailytimes.com/news/local-news/2014/04/gas-workers-at-risk-of-silica-exposure/.
[958] Lise Olsen, "Drilling Boom, Deadly Legacy," *Houston Chronicle*, February 22, 2014, sec. Special Reports, https://www.houstonchronicle.com/news/special-reports/article/Houston-Chronicle-exclusive-Drilling-boom-5259311.php.
[959] Steven Hsieh, "Why Are So Many Workers Dying in Oil Fields?," February 25, 2014, https://www.thenation.com/article/archive/why-are-so-many-workers-dying-oil-fields/.
[960] Andrew Schneider and Marilyn Geewax, "On-The-Job Deaths Spiking As Oil Drilling Quickly Expands," *NPR*, December 27, 2013, sec. Business, https://www.npr.org/2013/12/27/250807226/on-the-job-deaths-spiking-as-oil-drilling-quickly-expands.

also noted that the public health perspective has been inadequately represented in policy processes related to HVHF.[961] The policy statement added:

> [H]ydraulic fracturing workers are potentially exposed to inhalation health hazards from dust containing silica. There may also be impacts on workers and communities affected by the vastly increased production and transport of sand for HVHF. Inhalation of fine dusts of respirable crystalline silica can cause silicosis. Crystalline silica has also been determined to be an occupational lung carcinogen.

- 2005 – A researcher at Stanford University examined hazards associated with oil and gas extraction from exposure to radiation and determined that inhalation of high levels of radon gas is a serious concern to workers and those living nearby. Because the boiling point of radon lies between those of propane and ethane, gaseous radon (222Rn) will concentrate in ethane and propane fractions. "Elevated Rn activity concentration values have been measured at several processing plant sites…. It is well known that the radiological impact of the oil and gas-extracting and processing industry is not negligible."[962]

- May 9, 2003 – A New York Medical College study re-evaluated the chest X-rays of patients with exposure to silica who died from various respiratory problems and found that more than eight percent had undiagnosed silicosis. The study suggested that occupational lung disease may be undercounted in high-risk occupations. The authors of this study said that improved OSHA standards, with ongoing exposure monitoring and medical surveillance, would significantly improve the recognition of cases and justify more stringent preventive measures to reduce exposure. They further noted that practitioners need skills in taking an occupational exposure history. Although ten years have passed since this study was published, both recommendations have yet to be implemented.[963]

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[961] American Public Health Association, "The Environmental and Occupational Health Impacts of High-Volume Hydraulic Fracturing of Unconventional Gas Reserves," APHA, October 30, 2012, https://www.apha.org/policies-and-advocacy/public-health-policy-statements/policy-database/2014/10/02/15/37/hydraulic-fracturing.
[962] F. Steinhäusler, "Radiological Impact on Man and the Environment from the Oil and Gas Industry: Risk Assessment for the Critical Group," in *Radiation Safety Problems in the Caspian Region*, ed. Mohammed K. Zaidi and Islam Mustafaev, vol. 41, Nato Science Series: IV: Earth and Environmental Sciences (Dordrecht: Kluwer Academic Publishers, 2005), 129–34, https://doi.org/10.1007/1-4020-2378-2_19.
[963] Susan S. Goodwin et al., "Previously Undetected Silicosis in New Jersey Decedents," *American Journal of Industrial Medicine* 44, no. 3 (September 2003): 304–11, https://doi.org/10.1002/ajim.10260.

Public health effects, measured directly

By several measures, increasing evidence for fracking-related health problems has emerged across the United States and Canada.

In multiple states, studies of pregnant women in regions of intensive unconventional oil and gas extraction point to reproductive and developmental risks, including low birth weight, preterm births, and birth defects. In Oklahoma, Texas, and Colorado, birth defects were elevated among infants whose mothers lived near drilling and fracking sites while pregnant. In Texas, mothers who lived near active flare stacks while pregnant suffered higher rates of preterm birth. Also in Texas, living near fracking wells during pregnancy increased risks of preterm birth, reduced gestational age, and reduced birth weight, with Hispanic women disproportionately harmed. In California's San Joaquin Valley, women who lived with the highest exposure to oil and gas wells in early pregnancies were eight to 14 percent more likely to experience preterm births. A 2019 study in Oklahoma found evidence that drilling and fracking activities harm infant health by several measures. In British Columbia, pregnant indigenous women living near fracking sites had elevated levels of the developmental toxicants barium and strontium in their hair and urine.

Fracking has been linked to cancers in at least two states. In Colorado, children and young adults with leukemia were 4.3 times more likely to live in an area dense with oil and gas wells. A 2017 study in Pennsylvania found elevated rates of bladder and thyroid cancers among residents living in areas of fracking activity. In southwestern Pennsylvania, dozens of children and young adults were diagnosed with a rare cancer, Ewing sarcoma, as well as other rare cancers, in a six-county area where more than 3,500 fracking wells have been drilled.

As shown by multiple studies in Pennsylvania, as the number of gas wells increase in a community, so do rates of hospitalization, and community members experience sleep disturbance, headache, throat irritation, stress/anxiety, cough, shortness of breath, sinus problems, fatigue, wheezing, and nausea. Also in Pennsylvania, hospitalizations for pneumonia among the elderly are elevated in areas of fracking activity.

Drilling and fracking operations in multiple states are variously correlated with increased rates of asthma; increased hospitalizations for pneumonia and kidney, bladder, and skin problems; high blood pressure and signs of cardiovascular disease; elevated motor vehicle fatalities; symptoms of depression and anxiety; ambulance runs and emergency room visits; and incidence of sexually transmitted diseases.

Benzene levels in ambient air surrounding drilling and fracking operations are sufficient to elevate risks for future cancers in both workers and nearby residents, according to studies. Animal studies show numerous threats to fertility and reproductive success from exposure to various concentrations of oil and gas chemicals at levels representative of those found in drinking water. At least 43 chemicals used in drilling and fracking operations are classified as known or presumed human reproductive toxicants, while 31 others are suspected human reproductive toxicants. Two dozen chemicals commonly used in fracking operations are known endocrine disruptors that can variously disrupt organ systems, lower sperm counts, and cause reproductive harm. Endocrine disrupting chemicals have also been identified in fracking wastewater. Tissue culture and animal studies show endocrine-disrupting effects in response to

exposures to mixtures of fracking chemicals that reflect concentrations found in fracking wastewater.

- April 17, 2021 – A Stanford, Berkeley, and Columbia medical and public health science team identified a link between fracking-related air pollution and migraine headache as part of a study of long-term exposure to nitrogen dioxide (NO_2) and methane from industrial "super-emitters." One of two categories of methane super-emitters in the study included power plants, refineries, oil and gas production sites, wastewater treatment facilities, and oil and gas distribution infrastructure, such as compressors stations and distribution lines. The study also found that living within ten kilometers of any active oil and gas well was associated with increased frequency of outpatient neurologist visits, frequency of migraine-specific urgent care visits, and odds of at least one migraine-specific emergency room visit per person-year of follow-up. (This measurement takes into account the number of people in the study and the amount of time each person is in the study.) This study, the first to uncover a potential link between exposure to methane super-emitters and migraine, used a Northern California electronic health record data set of nearly 90,000 migraine cases between 2014 and 2018 and compared them to matched controls. It also documented a link between annual average NO_2 and fine particulate matter exposure and migraine headache severity. In addition to emitted air pollutants as risk factors, authors also noted that super-emitters such as oil and gas wells produce noise pollution, and both noise and odors are consistently linked with migraine headache.[964]

- March 31, 2021 – Fracking operations shorten lifespans and otherwise represent significant risks to the public health in Oklahoma, according to a unique study using a comprehensive health profile of the population across 76 counties, over twenty years (1998–2017). This research demonstrated that an increase in the number of fracking wells in a county has a detrimental effect on life expectancy. On average, a one percent increase in the number of fracking wells in a county leads to a 4.2 percent reduction in life expectancy. Researchers found analogous trends with other health outcomes. A one percent increase in the number of fracking wells led to a 7.9 percent increase in cancer incidence, a 7.3 percent increase in cardiac diseases, and a 5.9 percent increase in respiratory diseases. Researchers recommended that policymakers "dismiss fracking as a viable option and promote energy technologies that can have less harmful effects on health," and that "the public health risks results presented in this study can be beyond any effective regulation in which case prevention becomes a major policy option."[965]

- March 29, 2021 – Living near urban oil drilling sites in South Los Angeles was linked with reduced lung function among residents in a community-driven epidemiological study led by a University of Southern California and Occidental College team. The

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[964] Holly Elser et al., "Air Pollution, Methane Super-Emitters, and Oil and Gas Wells in Northern California: The Relationship with Migraine Headache Prevalence and Exacerbation," *Environmental Health* 20, no. 45 (2021), https://doi.org/10.1186/s12940-021-00727-w.

[965] Nicholas Apergis, Ghulam Mustafa, and Sayantan Ghosh Dastidar, "An Analysis of the Impact of Unconventional Oil and Gas Activities on Public Health: New Evidence Across Oklahoma Counties," *Energy Economics* 97 (2021), https://doi.org/10.1016/j.eneco.2021.105223.

researchers obtained 747 valid spirometry tests of residents living less than 1000 meters from two oil well sites (one active, one idle) in the Las Cienagas oil field, measuring FEV1 (forced expiratory volume in the first second of exhalation) and FVC (forced vital capacity). These are measures of lung capacity and lung strength, and they are both predictors of serious health problems, as well as of early death. The study found that living fewer than 200 meters from oil operations was associated with on average −112 mL lower FEV1 and −128 mL lower FVC compared to those living more than 200 meters from the sites. Further, residents living downwind and less than 200 meters from oil operations had on average −414 mL lower FEV1 and −400 mL lower FVC, compared to residents living upwind and more than 200 meters away from the wells. Researchers adjusted for factors including but not limited to proximity to freeway, smoking status, and asthma status. Researchers wrote that the impacts on lung function they found among non-asthmatic participants indicated that the drilling "may have adverse effects on otherwise healthy people." A second part of the study, which included the collection of self-reported acute health symptoms, indicates that residents living near the active drilling site had a greater prevalence of symptoms, including wheezing, sore throat, chest tightness, dizziness, and eye or nose irritation compared to residents near the idle well site. Authors said that their urban findings are similar to those found in studies of rural residents near gas fracking sites. The area where this study was situated "is among the top 10% most disproportionately-environmentally burdened in the state."[966] In media coverage addressing a failed state legislative effort to enact 2,500-foot buffer between drilling sites and schools, home and playgrounds, lead study author Jill Johnston of USC said that the link between worse lung function and the drilling sites found in the communities where her research took place "shows this is a real public health hazard."[967]

- March 1, 2021 – High levels of fracking-related chemicals were found in the bodies of residents living in five southwestern Pennsylvania households located near fracking operations. None of the households included smokers and each included at least one child.[968] An investigative journalist and her colleagues with *Environmental Health News*, in consultation with scientific advisors, collected 59 urine samples, 39 air samples, and 13 water samples, which were subsequently analyzed in a University of Missouri lab. (Raw data by family and compound is available in the referenced link.)[969] This pilot study was the first to document the body burden of fracking-related chemicals in Pennsylvanians and represents one of very few biomonitoring studies of these chemicals. Findings included very high levels of chemicals known to be released from fracking sites in the bodies of a family living within 1.5 miles of six wells. This family had benzene, toluene, naphthalene, and 15 other chemicals in their urine samples. These chemicals are

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[966] Jill E. Johnston et al., "Respiratory Health, Pulmonary Function and Local Engagement in Urban Communities Near Oil Development," *Environmental Research* 197 (2021), https://doi.org/10.1016/j.envres.2021.111088.
[967] Janet Wilson, "California Bill to Ban Fracking Dies, But Other Oil Regulation Measures Win Votes," *Desert Sun*, April 13, 2021, https://www.desertsun.com/story/news/environment/2021/04/13/california-bill-ban-fracking-dies-senate-committee-buffer-zones/7212190002/.
[968] Kristina Marusic and EHN Staff, "Fractured: The Body Burden of Living Near Fracking," *Environmental Health News*, March 1, 2021, https://www.ehn.org/fractured-series-on-fracking-pollution-2650624600/fractured-fracking.
[969] Charles Minshew, "EHN- A Family's Chemical Exposure," January 4, 2021, https://public.tableau.com/app/profile/charles.minshew2414/viz/EHN-AFamilysChemicalExposure/FamilyDashboard.

all known to have negative health impacts, including reproductive harm and cancer risk. A biomarker for toluene in a 9-year-old child in the family was 91 times as high as that of the average American. Each of the family's sample levels exceeded the U.S. 95th percentile for mandelic acid, a biomarker of ethylbenzene and styrene, and more than half of the family's samples exceeded the U.S. 95th percentile for phenylglyoxylic acid, another biomarker for ethylbenzene and styrene, as well as for trans, transmuconic acid, a biomarker for benzene. These U.S. percentiles for comparison were drawn from the Centers for Disease Control and Prevention's National Health and Nutrition Examination Survey. Overall, families in the investigation that lived closer to fracking operations had higher levels of several chemicals than those living further away. Highlighting this investigation, 35 members of the Pennsylvania House and Senate responded by publicly requesting that the Pennsylvania governor "direct adequate funding to thoroughly study the full and complete health impacts of fracking."[970]

- February 11, 2021 – An investigation of fracking and heart attack risk found that long-term exposure to fracking operations was associated with increased acute myocardial infarction (AMI) hospitalization rates and increased AMI death rates in a study that compared Pennsylvania and New York counties atop the Marcellus Shale, from 2005–2014. This study design was made possible by the natural experiment created by New York's statewide ban on fracking and the opposing decision by Pennsylvania to pursue shale gas extraction enthusiastically. Specifically, one hundred cumulative fracking wells drilled in a county was linked with 1.4–2.8 percent increases in AMI hospitalizations, depending on age and sex, and with a 5.4 percent increase in AMI deaths among men age 45 to 54. Of these findings, the authors wrote, "To put this into perspective, three Pennsylvania counties – Bradford, Washington, and Susquehanna… – each had over a thousand unconventional wells by the end of 2014, with hundreds more drilled since then. Not coincidentally, these three counties are the ones with the most individual cardiovascular health complaints submitted to the Pennsylvania Department of Health between 2011 and February 2018." Noting that their findings are consistent with a few previous studies on fracking and cardiovascular hospitalizations, the authors concluded that these results "suggest that bans on hydraulic fracturing can be protective for public health."[971]

- December 15, 2020 – A major study published in the *Journal of the American College of Cardiology* documented a link between fracking and heart failure. Using a case-control analysis and data on more than 12,000 patients from health records in an integrated health system across the state of Pennsylvania, researchers from Johns Hopkins University found that heart failure patients living near fracking sites were significantly more likely to become hospitalized. The results showed strong associations between fracking activity and two types of heart failure, with older heart-failure patients particularly vulnerable to adverse health impacts from fracking activity. Heart failure patients exposed to the

[970] Sara Innamorato, "Pennsylvania House and Senate Elected Officials Strongly Urge Governor Wolf to Investigate Serious Health Impacts Associated with Fracking" (PA House of Reps., March 18, 2021), https://www.pahouse.com/Innamorato/InTheNews/NewsRelease/?id=118917.
[971] Alina Denham et al., "Acute Myocardial Infarction Associated with Unconventional Natural Gas Development: A Natural Experiment," *Environmental Research* 195 (2021), https://doi.org/10.1016/j.envres.2021.110872.

highest intensity of fracking activity were more likely to be hospitalized for heart failure compared with those who were in the lowest intensity of exposure.[972] "These associations can be attributed to the environmental impacts of fracking, including air pollution, water contamination, and noise, traffic, and community impacts" with possible underlying mechanisms including systemic inflammation, autonomic dysfunction, prothrombotic pathways, and epigenomic changes, all of which are known to contribute to heart failure.[973]

- November 24, 2020 – Pregnant women living near fracking sites in Texas had increased risk for serious birth defects in their infants, including neurological defects, heart defects, and gastroschisis, according to a case-control study that compared nearly 53,000 cases with birth defects to 642,399 controls, from 1999 to 2011. Gastroschisis is an abnormality of the abdominal wall that allows the baby's intestines (and sometimes other organs) to protrude outside of the body. Specifically, researchers found links between maternal addresses within one kilometer (0.6 miles) of the highest fracking site density and the following birth defects: anencephaly, spina bifida, gastroschisis (for births from older mothers), aortic valve stenosis, hypoplastic left heart syndrome, and pulmonary valve atresia or stenosis. Based on these geographic patterns, the research team suggests that neural tube defects may be linked to "acute, frequent, and concentrated airborne exposures from high-intensity" fracking activities. Almost always fatal, anencephaly is a neural tube defect in which a large part of the skull is absent along with parts of the brain; spina bifida is a neural tube condition that affects the spine and spinal cord and can create paralysis. In addition, researchers found significant increased risk of congenital heart defects at all three maternal address distances to fracking that the study analyzed, radii of of 1, 3, and 7.5 kilometers. Because this type of risk was consistent across the three different distances, the researchers suggest that exposures linked with congenital heart defects might be due to groundwater contamination of a public supply serving an extended geographic area. An additional component of the study showed an increased risk for ventricular septal defects and atrial septal defects over time, possibly reflecting the increasing fracked well numbers around the state. Researchers wrote that their study supports previous research investigating fracking and birth defects, and that their analyses suggest that vulnerable populations near fracking sites, particularly minority and lower socioeconomic status (terms used by the authors) mothers, may be at greater risk for birth defects.[974]

- November 20, 2020 – A study appearing in the journal *Public Health Nursing* found a correlation between oil development and gonorrhea rates in North Dakota between the fracking boom years of 2002 to 2016. Previous research has documented the link between

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[972] Tara P. McAlexander et al., "Unconventional Natural Gas Development and Hospitalization for Heart Failure in Pennsylvania," *Journal of the American College of Cardiology* 76, no. 24 (2020): 2862–74, https://doi.org/10.1016/j.jacc.2020.10.023.
[973] Barrak Alahmad and Haitham Khraishah, "Unconventional Natural Gas Development and Heart Failure: Accumulating Epidemiological Evidence," *Journal of the American College of Cardiology* 76, no. 24 (2020): 2875–77, https://doi.org/10.1016/j.jacc.2020.10.040.
[974] Ian W. Tang, Peter H. Langlois, and Verónica M. Vieira, "Birth Defects and Unconventional Natural Gas Developments in Texas, 1999–2011," *Environmental Research* 194 (2021): 110511, https://doi.org/10.1016/j.envres.2020.110511.

sexually transmitted infections (STIs) and fracking in Ohio and Pennsylvania, but, heretofore, North Dakota has been far less studied. A second part of the study evaluated the state's public health infrastructure and ability to respond to the STI-related needs of North Dakota's growing transient population during that same period. Researchers found wide-ranging deficits, including lack of primary care services, limited STI testing, limited funding, large service areas, and lack of confidentiality. The authors recommended expanding the role of public health nurses in North Dakota to implement STI screening, which would allow for comprehensive reporting and treatment. This study documented increased STI rates across the state during the fracking boom without evidence of greater infection rates in oil-producing counties than in others. Authors posit this is due to factors unique to North Dakota such as the public health infrastructure deficits mentioned above, as well as factors such as workers traveling to oil-producing counties for work and returning home to more urban areas, where STI rates are documented to be higher.[975]

- September 30, 2020 – In a study that corroborates earlier findings from Pennsylvania on an association between asthma and fracking activities, researchers reported links between childhood asthma hospitalizations and both unconventional and conventional gas development in Texas. The team used a database of inpatient hospitalizations between 2000 and 2010, and zip code-level information including gas drilling type, production volumes, and gas-flaring volumes. They found increasing production volumes tracked with increased childhood asthma hospitalizations, following an exposure-response pattern. This study found inconsistent associations with gas flaring, but the authors noted that the available data on flaring was only "reasonable for inferring if flaring occurred, but the relative magnitude of flaring is more difficult to determine," and that flaring activity peaked in 2018 (beyond the years covered in the study). Hence, this study may have underestimated the impact of exposure to flaring. This study also has important environmental justice dimensions. Researchers found communities with lower income and more non-White population had higher odds of childhood asthma hospitalizations. Authors noted, "the U.S. Department of Energy is specifically instructed to monitor the impact of the energy sector on these communities, and the current study provides evidence that drilling exposures seem to be inequitably distributed in Texas."[976]

- August 18, 2020 – A modeling study that used a retrospective analysis and a novel method to quantify exposures from fracking wells in southwest Pennsylvania found that respiratory, neurological, and muscular symptoms tracked with cumulative well density around residential areas. The results suggest that living in proximity to wells may be associated with health symptoms. These findings also indicate that an estimation of exposure that relies on proximity to fracking wells alone may be simplistic, particularly in communities with increasing density of wells. The authors suggest that future research

[975] Andrea L. Huseth-Zosel et al., "Associations Between Oil Development and Sexually Transmitted Infections: Public Health Nurse Perspectives," *Public Health Nursing* 38, no. 1 (2021): 4–12, https://doi.org/10.1111/phn.12836.
[976] Mary Willis et al., "Natural Gas Development, Flaring Practices and Paediatric Asthma Hospitalizations in Texas," *International Journal of Epidemiology* 49, no. 6 (2020): 1883–96, https://doi.org/10.1093/ije/dyaa115.

should examine how the aggregation of exposures from fracking wells and potency of exposures at the residence levels affects health.[977]

- July 15, 2020 – Maternal proximity to flaring, the open combustion of natural gas, was linked to a fifty percent increased chance of preterm birth in a study of 23,487 birth records from 2012 to 2015 in the Eagle Ford Shale of south Texas.[978] The USC and UCLA researchers used satellite data on flaring activity to determine how much flaring took place during the pregnancies, within five kilometers of the maternal residence. They defined a "high" amount as ten or more nightly flare events within three miles of the residence. The researchers statistically adjusted for other known pregnancy risks, also including numbers of oil and gas wells in their analyses, "suggesting the effects of flaring on the length of gestation are independent of other potential exposures related to oil and gas wells." In addition to the flaring exposure effects, the study also found that living within five kilometers of oil and gas wells was independently linked to a higher chance of preterm birth, reduced gestational age, and reduced birth weight. In this first study to address the human health effects of flaring, offspring of Hispanic women were especially impacted. The researchers stated that this finding suggests theirs was "the first study to document greater health impacts associated with [oil and gas development] among women of color." Researchers expressed environmental justice concerns, given that approximately 50 percent of residents living within five kilometers of an oil or gas well are people of color. In an interview with *Environmental Health News,* a lead author said, "Historically, much of the waste disposal in the U.S. is concentrated in communities of color… One theory is that we're seeing the same pattern with flaring, which is essentially another type of waste disposal."[979] Authors called for measures to protect the health of infants, including reducing reliance on fossil fuels.

- July 10, 2020 – Researchers found inconsistent links between density/proximity to fracking wells during pregnancy and lower birthweight, and limited evidence of a link with increased risk of preterm birth, in the first epidemiological study of its kind in Northeastern British Columbia. They analyzed over 6,000 births at one hospital between December 30, 2006 and December 29, 2016, and the density and proximity of fracking wells in areas of 2.5, 5, and 10 kilometers (1.5, 3.1, and 6.2 miles) around the pregnant women's postal codes. Precise maternal addresses were not available to the researchers. The study found increased risk of preterm birth among women in the second quartile of well density/proximity of the 2.5-kilometer category. The researchers noted that a key limitation was their relatively small sample size compared to other epidemiological

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[977] Blinn et al., "Exposure Assessment of Adults Living near Unconventional Oil and Natural Gas Development and Reported Health Symptoms in Southwest Pennsylvania, USA."
[978] Lara J. Cushing et al., "Flaring from Unconventional Oil and Gas Development and Birth Outcomes in the Eagle Ford Shale in South Texas," *Environmental Health Perspectives* 128, no. 7 (July 2020): 077003, https://doi.org/10.1289/EHP6394.
[979] Kristina Marusic, "Babies Born Near Gas Flaring Are 50 Percent More Likely To Be Premature," *The Daily Climate*, July 15, 2020, https://www.dailyclimate.org/fracking-preterm-births--2646412309/particle-4.

studies of fracking and birth outcomes, "which can decrease precision in our effect estimates."[980]

- June 5, 2020 – San Joaquin Valley, California women who lived with the highest exposure to oil and gas wells in the first and second trimesters of their pregnancies were eight to 14 percent more likely to experience a spontaneous preterm birth at 20 to 31 weeks' gestation, according to Stanford University research.[981] The women studied did not have maternal comorbidities for preterm birth, such as gestational or pregestational diabetes, gestational hypertension, and preeclampsia/eclampsia. The researchers analyzed data on 27,913 preterm births and 197,461 comparison term births between 1998 and 2011, with data for 83,559 wells in preproduction or production during the same period, establishing four "exposure quantiles" (no exposure up to the highest exposure). Most of these California wells were drilled using conventional methods. The harmful birth impacts of living near oil and gas wells were strongest among the women who were Hispanic, Black, or had fewer than 12 years of education. In a secondary analysis, the researchers determined that exposure to wells in preproduction was associated with higher concentrations of particulate matter. Though they found a link between preterm birth and exposure to both new and active wells, researchers were not able to determine whether exposure to wells in either stage presents more risk.

- June 3, 2020 – Living near active oil and gas wells during pregnancy was found to increase the risk of low-birthweight babies, specifically in rural areas, according to the largest study of its kind and the first in California.[982] The UC Berkeley-led study found that pregnant people who lived within 0.62 miles (one kilometer) of the highest producing oil and gas wells (more than 100 barrels of oil or the natural gas equivalent) were 40 percent more likely to have low birth weight babies. Further, among full-term births from mothers with the same proximity to highest producing wells, 20 percent were more likely to have babies who were small for their gestational age. The researchers used nearly 3 million birth certificates of babies born to mothers living within ten kilometers of at least one active or inactive well from 2006 to 2015, in the Sacramento Valley, San Joaquin Valley, South Central Coast and Los Angeles Basin. Mothers in the study group exposed to high production volume had an average of 160 inactive wells and 32 active wells within one kilometer. For urban areas, the group within one kilometer of high production volume, compared to no exposure, showed increased odds of small for gestational age babies. They also found modest impacts on birth outcomes linked to proximity to inactive wells, and suggested a possible role of emissions from inactive wells such as methane and residual off-gassing of BTEX contaminants. Certain factors that the researchers could not take into account, such as maternal occupation, housing

[980] Élyse Caron-Beaudoin et al., "Density and Proximity to Hydraulic Fracturing Wells and Birth Outcomes in Northeastern British Columbia, Canada," *Journal of Exposure Science & Environmental Epidemiology* 31, no. 1 (2021): 53–61, https://doi.org/10.1038/s41370-020-0245-z.
[981] David J. X. Gonzalez et al., "Oil and Gas Production and Spontaneous Preterm Birth in the San Joaquin Valley, CA: A Case–Control Study," *Environmental Epidemiology* 4, no. 4 (August 2020): e099, https://doi.org/10.1097/EE9.0000000000000099.
[982] Kathy V. Tran et al., "Residential Proximity to Oil and Gas Development and Birth Outcomes in California: A Retrospective Cohort Study of 2006–2015 Births," *Environmental Health Perspectives* 128, no. 6 (June 2020): 067001, https://doi.org/10.1289/EHP5842.

quality, and indoor air quality, may have contributed to differences between findings in rural and urban populations. Though the study could not account for maternal changes of residence during pregnancy, researchers suggested that because they saw similar effects across trimesters, "any bias resulting from maternal residential and occupational mobility is likely non- differential across trimesters." Authors concluded that prenatal exposure to active oil and gas production using the range of conventional and unconventional techniques employed in California was associated with adverse birth outcomes. Co-author Kathy Tran said to the *Guardian*, "Because researchers don't have direct access to the actual oil and gas sites, it's hard to get a good estimate of what people actually experience… The more in-depth exposure assessment we can get, the more we can really understand why we are seeing the [birth outcome] effects that we see."[983]

- May 27, 2020 – A fracking chemical called Genapol-X100 can interfere with normal activity of the male hormones, according to research performed by University of California toxicologists.[984] The scientists ranked 60 fracking chemicals used in California, based on their potential to interfere with androgens' ability to bind with living human cells. Their assessment found five fracking chemicals with the highest potential to interfere with this process, subsequently identifying Genapol-X100 as a significant androgen disruptor. In their discussion they said that exposure to these chemicals "can affect the normal physiology of androgen pathways such as male reproduction health," and have other related adverse outcomes. Previous research in 2016 reported that Genapol-X100 was used as a chemical constituent in well stimulation treatments more than 500 times, but authors stated that the levels of this chemical in humans and wildlife is not well documented. They wrote that their findings demonstrate this chemical "may pose significant environmental and health risks as it noncompetitively inhibits [human androgen receptor] and alters the expression of androgenic genes at relatively low concentrations."

- May 8, 2020 – A water disinfection byproduct (DBP), monohalogenated iodoacetic acid (IAA), disrupted each major level of the female reproductive axis in an animal model experiment by University of Illinois scientists.[985] DPBs arise when chemicals used to for water decontamination combine with organic material and they have been linked to reproductive disfunction. IAA forms when iodide reacts with a disinfectant. The researchers noted, "not only is iodide widely present in the water supply, especially in coastal communities and those near fracking sites, but IAA has been found to be one of the most cyto- and genotoxic DBPs." Their study linked exposure to IAA to disruptive expressions of key endocrine genes related to reproductive function.

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[983] Nina Lakhani, "Living near Oil and Gas Wells Linked to Low Birthweight in Babies," *The Guardian*, June 3, 2020, sec. Environment, http://www.theguardian.com/environment/2020/jun/03/living-near-oil-and-gas-wells-linked-to-low-birthweight-in-babies.
[984] Phum Tachachartvanich et al., "Structure-Based Discovery of the Endocrine Disrupting Effects of Hydraulic Fracturing Chemicals as Novel Androgen Receptor Antagonists," *Chemosphere* 257 (October 2020): 127178, https://doi.org/10.1016/j.chemosphere.2020.127178.
[985] Rachel Gonzalez et al., "Adult Exposure to Iodoacetic Acid Leads to Abnormal Expression of Key Genes Related to Hypothalamic and Pituitary Control of Reproductive Function," *Journal of the Endocrine Society* 4, no. Supplement_1 (May 8, 2020): SUN-241, https://doi.org/10.1210/jendso/bvaa046.1083.

- March 4, 2020 – Exposures to a mixture of fracking chemicals commonly found in wastewater caused effects on diverse physiological systems though hormone disruption, according to a set of coordinated studies carried out collaboratively by an interdisciplinary team.[986] (See also July 25, 2019 and May 22, 2019 entries below.) These studies, conducted in laboratory animals and human tissue culture cells, used four different doses of a 23-chemical mixture which reflected realistic concentrations ranging from those found in surface and ground water in fracking-dense regions, to concentrations found in fracking wastewater. In human tissue culture cells, exposures to the chemical mixture showed "potent antagonist activity" for the estrogen, androgen, glucocorticoid, progesterone, and thyroid hormone receptors. In animal models, developmental exposures "profoundly impacted" pituitary hormones, reduced sperm counts, and altered maturation of the ovarian follicle. These exposures also altered the mammary gland ductal density and produced precancerous lesions. Finally, exposure additionally had effects on energy expenditure, behavior, and the immune system. The team concluded, "Taken together, these data suggest a strong need to examine the impacts of residential and occupational UOG exposure in humans and other wildlife in drilling areas."

- March 2, 2020 – University of Illinois environmental economists documented a causal link between fracking-related trucking and fatal traffic crashes in the Bakken Formation in North Dakota from 2006-2014.[987] The researchers found that each additional post-fracking well within six miles of a road segments led to eight percent more fatal crashes and over seven percent higher per-capita costs in accidents. In their study, post-fracking wells were those horizontal wells completed in the previous month from which post-fracking wastewater flowback is a hauled to disposal sites. They extrapolated from their data "that an additional 17 fatal crashes occurred every year due to the fracking operations near the sampled 225 road segments… representing a 49% increase relative to the 2006 baseline crash counts of the eighteen drilling counties in North Dakota." They noted that an increase in alcohol-involved crash drivers was most likely "due to their vulnerability to heavier fracking- induced traffic rather than more alcohol-involved truck drivers near the fracking sites."

- January 27, 2020 – Pressured by families affected with rare childhood cancers in southwestern Pennsylvania, Governor Tom Wolf announced that his administration will spend $3 million to fund two studies to investigate the possible link between fracking and childhood cancers. Although an initial analysis had determined no "cancer cluster" existed in Washington County, it had had considered only three cases of the six cases known within a single school district. Nine preschoolers and students in the Canon-McMillan school district were diagnosed with rare cancers in the 2018-2019 school year. The state's chief epidemiologist, Sharon Watkins, said the results of the earlier analysis could change after more recent data is included. The first study will review existing

[986] S.C. Nagel et al., "Developmental Exposure to a Mixture of Unconventional Oil and Gas Chemicals: A Review of Experimental Effects on Adult Health, Behavior, and Disease," *Molecular and Cellular Endocrinology* 513 (August 2020): 110722, https://doi.org/10.1016/j.mce.2020.110722.
[987] Minhong Xu and Yilan Xu, "Fraccidents: The Impact of Fracking on Road Traffic Deaths," *Journal of Environmental Economics and Management* 101 (May 2020): 102303, https://doi.org/10.1016/j.jeem.2020.102303.

literature on general health harms of fracking. The second will investigate whether young cancer patients had higher exposures to fracking than the general population.[988] From 2006-2017, 31 people in four counties in southwestern Pennsylvania had been diagnosed with Ewing's sarcoma, a rare bone cancer. This represents a 40 percent jump from 1995-2005, a period prior to the arrival of drilling and fracking activities in the area.[989] (See entry for May 14, 2019 below.)

- January 23, 2020 – Oil and gas development does not improve the "rural mortality penalty" according to an analysis of a large sample U.S. mortality rates from 2000-2016 and county-level counts of active wells.[990] The rural mortality penalty is the phenomenon in which those living in rural locations have higher mortality rates than those in suburban and urban places. This began to be the case approximately a half century ago, increasing over time, with a further 75 percent increase between 2004 and 2016. Though fracking may increase job growth and earnings in some places, the author concluded, "Importantly, [unconventional oil and gas development] does not seem to improve mortality rates, suggesting that UOGE cannot address this unique problem. This raises several questions of justice and fairness, as host communities do not seem to retain all the potential benefits of UOGE."

- January 9, 2020 – Rates of two sexually transmitted infections, gonorrhea and chlamydia, were respectively fifteen and ten percent higher in Texas counties with high levels of fracking compared to those without, in a Yale School of Public Health study.[991] The researchers considered the reported cases of these diseases, plus syphilis, from 2000-2016 in Texas, Colorado, and North Dakota. They sought to add to previous research on the link between increases in migrating and/or non-local workers and increased rates of sexually transmitted infections in host communities. Previous research took place in the Marcellus Shale formation states. Authors wrote, "Associations between shale drilling and chlamydia and gonorrhea in Texas are consistent with the previously observed associations in the Marcellus Shale, and may reflect increased risk in areas with greater drilling activity and increased proximity to major metropolitan areas." They expressed concern in the rise of both of these diseases; with gonorrhea due to the rise antibiotic-resistant infections, and chlamydia because asymptomatic people may not be treated.

- October 17, 2019 – Exposure to chemicals used in oil and gas development, such as benzene, may cause short-term negative health impacts including headaches, dizziness, respiratory effects, and skin and eye irritation at distances from 300 to 2000 feet from a

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[988] Chaffin, "Pennsylvania Governor Funds Research Examining Potential Fracking Health Impacts."
[989] Kris Maher, "After String of Rare Cancer Cases, Pennsylvania Investigates Potential Link to Fracking," *The Wall Street Journal*, December 20, 2019, sec. US, https://www.wsj.com/articles/after-string-of-rare-cancer-cases-pennsylvania-investigates-potential-link-to-fracking-11576837802.
[990] Adam P. Mayer, "Can Unconventional Oil and Gas Reduce the Rural Mortality Penalty? A Study of U.S. Counties," *Journal of Rural and Community Development* 14, no. 4 (2019), https://journals.brandonu.ca/jrcd/article/view/1712.
[991] Nicholaus P. Johnson et al., "A Multiregion Analysis of Shale Drilling Activity and Rates of Sexually Transmitted Infections in the United States," *Sexually Transmitted Diseases* 47, no. 4 (April 2020): 254–60, https://doi.org/10.1097/OLQ.0000000000001127.

well pad, concluded Colorado's state-funded human health risk assessment.[992, 993]The study used actual emissions data from oil and gas operations in the state, to model exposures and risks of health impacts. The study did not use actual health impacts. This contracted assessment followed the state's 2017 small health impacts study, which called for further research into the possible health effects and exposures for people living close to wells. A peer-reviewed summary of this 2019 assessment was published in the *Journal of the Air & Waste Management Association*.[994] *The Denver Post* reported, "While benzene has been linked to cancer, state officials said the study, based on measuring of emissions and computer modeling, did not find a basis for predicting long-term health harm."[995] The regulating agency, Colorado Oil and Gas Conservation Commission, said that though they were not previously involved in testing air around residents' homes, they will "immediately begin reviewing more strictly all industry applications to drill new wells within 2,000 feet of homes and start measuring air emissions around industry sites." The study only addressed the scenario of a single well pad, not the risks for those living near large, multi-well pads.

- October 11, 2019 – The first analysis of infant health at birth and proximity to fracking in Oklahoma counties found a clear, detrimental relationship, by several measures.[996] The analysis used 590,780 birth records across all 76 Oklahoma counties, from 2006–2017. Oklahoma's fracking boom began in 2006. Researchers determined distance between maternal residence and fracking wells, and their measures of infant health were total weight, low weight, and a composite health index of overall infant health. Researchers determined that 121,862 births took place within one kilometer of fracking wells, 148,783 births within five kilometers, 157,664 within ten, and 128,485 within 20 kilometers. The harmful effects of fracking wells on infant health were found for total birth weight and for the composite health index. For total birth weight, the results were significant within five kilometers and strongest within one kilometer. For the composite health index, the findings were significant across all distances, with the strongest impact taking place for maternal residence within one kilometer of fracking wells. These researchers also ran comparison analyses for conventional drilling, which constituted about 29 percent of Oklahoma drilling in the study period. They found more minor impacts, and at distances up to one kilometer only, concluding, "These findings provide

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[992] Ed Carr et al., "Final Report: Human Health Risk Assessment for Oil & Gas Operations in Colorado" (ICF International for the Colorado Department of Public Health & Environment, 2019), https://www.fcgov.com/oilandgas/files/20191017-cdphe-healthimpactsstudy.pdf.
[993] Jessica Bralish, "State Health Department Publishes Oil and Gas Health Risk Study | Department of Public Health & Environment," Press Release (Colorado Department of Public Health & Environment, October 17, 2019), https://cdphe.colorado.gov/press-release/state-health-department-publishes-oil-and-gas-health-risk-study.
[994] Chris Holder et al., "Evaluating Potential Human Health Risks from Modeled Inhalation Exposures to Volatile Organic Compounds Emitted from Oil and Gas Operations," *Journal of the Air & Waste Management Association* 69, no. 12 (December 2, 2019): 1503–24, https://doi.org/10.1080/10962247.2019.1680459.
[995] Bruce Finley, "Colorado to Tighten Oversight of Oil and Gas Sites near Homes in Wake of Study Finding Possible Short-Term Health Effects," *The Denver Post*, October 17, 2019, https://www.denverpost.com/2019/10/17/colorado-oil-gas-health-risks-study/.
[996] Nicholas Apergis, Tasawar Hayat, and Tareq Saeed, "Fracking and Infant Mortality: Fresh Evidence from Oklahoma," *Environmental Science and Pollution Research* 26, no. 31 (November 2019): 32360–67, https://doi.org/10.1007/s11356-019-06478-z.

supportive evidence to the substantial (negative) role of fracking drilling activities for infants' health status."

- August 15, 2019 – Building on their previous work that considered health-related symptoms of those living near fracking wells, researchers developed a study that added processing plants and compressor stations, while also creating the first such study to incorporate weather and atmospheric conditions in their exposure estimates. They analyzed respiratory health outcomes in a sample of 87 people living near fracking sites who participated in a Southwest Pennsylvania Environmental Health Project data collection project between February 1, 2012 and December 31, 2017. Seventy-two percent of the people studied reported at least one respiratory symptom "that began or worsened after the onset of drilling activity and could not be plausibly attributed to pre-existing or current medical conditions, or practices such as smoking."[997] Forty percent reported sore throat, 36 percent reported both cough and shortness of breath, 26 percent reported sinus problems, and 16 percent report wheezing. Seventy-seven percent of those studied lived within two kilometers of at least one source, 29 percent within one to nine sources, one quarter within 10 to 19 sources, and 23 percent of those studied lived within two kilometers of 20 or more fracking-related exposure sources. Results showed some of the sources studied linked specifically to cough, shortness of breath, and "any respiratory symptom."

- July 25, 2019 – In this set of experimental studies in human tissue culture cells and laboratory animals, exposure to a mixture of fracking chemicals was linked to potent hormone disrupting activity.[998] This paper presented results that were part of a set of coordinated studies carried out collaboratively by an interdisciplinary team using four different doses of a 23-chemical mixture, reflecting realistic concentrations ranging from those found in surface and ground water in fracking-dense regions, to concentrations found in fracking wastewater (see March 4, 2020 entry above and May 22, 2019 below). In the human tissue culture cells, exposure to the mixture was linked to "potent antagonist activity for the estrogen, androgen, glucocorticoid, progesterone, and thyroid receptors." In a laboratory mouse model, the fracking chemical mixture given in pregnancy led to profound impacts on health and behavior in the developing and adult offspring. Offspring had reduced sperm counts, altered ovarian follicle development, and precancerous lesions. The mixture impacted energy expenditure, exploratory and risk-taking behavior, and the immune system. The research also found immune system effects in a frog model. Using these different model systems and demonstrating various physiological impacts, the researchers concluded that fracking "may be an important source of human [endocrine disrupting chemical] exposure and altered health parameters."

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[997] David R. Brown et al., "Assessing Exposure to Unconventional Natural Gas Development: Using an Air Pollution Dispersal Screening Model to Predict New-Onset Respiratory Symptoms," *Journal of Environmental Science and Health, Part A* 54, no. 14 (December 6, 2019): 1357–63, https://doi.org/10.1080/10934529.2019.1657763.
[998] Victoria D. Balise et al., "Developmental Exposure to a Mixture of Unconventional Oil and Gas Chemicals Increased Risk-Taking Behavior, Activity and Energy Expenditure in Aged Female Mice After a Metabolic Challenge," *Frontiers in Endocrinology* 10 (July 25, 2019): 460, https://doi.org/10.3389/fendo.2019.00460.

- July 23, 2019 – Researchers found 4.3 additional cases of prenatal anxiety or depression per 100 women, among mothers who lived amid the most fracking activity during their pregnancies, compared to those who lived around less.[999] The study included 7,715 mothers without anxiety or depression at the time of conception, who delivered their babies at Geisinger Health System in central and northeast Pennsylvania, between January 2009 and January 2013. It included women who gave birth to single babies, without serious birth defects, and of viable weight and gestational age. In the highest quartile of the fracking activity metric developed for this study there were an average of 130 wells within 20 kilometers of the mothers' home, compared to 10 wells for mothers in the other three quartiles. The prevalence of anxiety or depression during pregnancy was 15 percent in the highest quartile, and 11 percent in the lower three quartiles. Researchers determined that the risk was greatest among low income women, among whom there were 5.6 additional cases of anxiety or depression per 100. In this study, researchers did not find a relationship between anxiety or depression during pregnancy and preterm birth and reduced term birth weight, though the same team found a link between proximity to fracking and these adverse birth outcomes.

- July 18, 2019 – Colorado mothers living in areas with the most intense levels of oil and gas activity were 40 to 70 percent more likely to have children with congenital heart defects (CHDs) in a study 3,324 of infants born in the state from 2005-2011.[1000] University of Colorado researchers developed a measure of the monthly intensity oil and gas well activity around mothers' residences from three months prior to conception through the second month of pregnancy, including the phase of oil and gas development, the size of well sites, and production volumes. These considerations as well as other features of this study, such as additional checks on the infants' diagnoses, built on previous research documenting the link between proximity to oil and gas and CHDs. Some of the most common hazardous air pollutants emitted from drilling and fracking sites are "suspected teratogens that are known to cross the placenta." CHDs are a leading cause of developmental problems, brain injury, and death among infants with birth defects. The four specific defects addressed were aortic artery and valve (AAVD), pulmonary artery and valve (PAVD), conotruncal (CTD), and tricuspid valve (TVD) defects. Authors concluded that the study provided further evidence of a link between maternal proximity to drilling and fracking and several types of CHDs, particularly in rural areas, where chances of an infant born with AAVD, CTD, or TVD were 2.6 to 4.6 times more likely in the high exposure group compared to the low exposure group. With regard to urban areas, authors wrote that it is likely that other sources of air pollution obscured possible links.

- July 12, 2019 – The driver of a tractor-trailer rig and four oil field workers riding in a pickup truck were killed in a head-on crash along New Mexico State Route 128, one of

[999] Joan A. Casey et al., "Unconventional Natural Gas Development and Adverse Birth Outcomes in Pennsylvania: The Potential Mediating Role of Antenatal Anxiety and Depression," *Environmental Research* 177 (October 2019): 108598, https://doi.org/10.1016/j.envres.2019.108598.
[1000] Lisa M. McKenzie, William Allshouse, and Stephen Daniels, "Congenital Heart Defects and Intensity of Oil and Gas Well Site Activities in Early Pregnancy," *Environment International* 132 (November 2019): 104949, https://doi.org/10.1016/j.envint.2019.104949.

several highways experiencing increased crashes in "the busiest oil and gas region in the United States.[1001] Crashes along this route, as well as New Mexico State Route 31 and U.S. 285, have increased over the last year, as upkeep, patrols, and interventions such as safety corridors do not keep pace with the significant increase in traffic and driver behavior issues brought by the fracking boom.

- June 26, 2019 – The investigative journalism organization *Searchlight New Mexico* examined trends in fracking-region highway deaths, their circumstances, and community reactions, reporting, "Locals have a new name for the section of US 285 where [local men] Ponce and Martinez perished: Death Highway."[1002] In 2018, there were 49 crashes, up from 31 crashes in 2017. There were five deaths resulting from the crashes along this highway in 2017 and two in 2018. "For local residents—especially those living in rural areas—the combination of congestion, roads thick with truck traffic, unsafe driver behavior, poorly maintained vehicles and deteriorating pavement can make even a routine trip to the farm supply store a white-knuckle obstacle course." According to research by an Albuquerque engineering and planning firm, most of the crashes were caused by speeding. Another group said that a scarcity of local qualified drivers, and many drivers hired by oil companies unfamiliar with the region, are key to the problem. Finally, government funding for needed road improvements is inadequate, according to the *Searchlight* report.

- May 22, 2019 – Exposure of laboratory mice to an environmentally relevant mixture of 23 fracking chemicals altered developmental programming, resulting in changed energy expenditure and activity in adult female offspring.[1003] Part of an ongoing set of studies examining the endocrine disruption effects of this mixture using laboratory animals and human tissue culture cells (see also March 4, 2020 and July 25, 2019, above), this was the first study to examine these direct developmental effects of exposure to fracking chemicals. Researchers exposed female mice the mixture of five weeks prior to mating, and from the first day of gestation day to the 21st day postnatally. Pre- and post-natal exposure to the fracking chemical mixture decreased total and resting energy expenditure in some of the groups, but it was not linked with altered body weight or body composition in the adult females. Researchers wrote that although "one would typically expect higher body mass or fat mass to track with lower energy expenditure, this is not always the case."

- May 14, 2019 – A pilot study in northeastern British Columbia reported elevated levels of barium and strontium in urine and hair samples of pregnant indigenous women living in an area of intense fracking activity. These trace metals, released during hydraulic fracturing, are known developmental toxicants. The researchers cited the need for

[1001] Susan Montoya Bryan, "Police: Texas Oilfield Workers, Truck Driver Killed in Fiery Crash," *Midland Reporter-Telegram*, July 12, 2019, sec. News, https://www.mrt.com/news/article/State-Police-5-dead-in-collision-in-southeastern-14091816.php.
[1002] April Reese, "Death Highway," *Searchlight New Mexico*, June 27, 2019, https://searchlightnm.org/death-highway/.
[1003] Victoria D. Balise et al., "Preconceptional, Gestational, and Lactational Exposure to an Unconventional Oil and Gas Chemical Mixture Alters Energy Expenditure in Adult Female Mice," *Frontiers in Endocrinology* 10 (May 22, 2019): 323, https://doi.org/10.3389/fendo.2019.00323.

systematic water monitoring program in the region, and, following this small pilot study, they intend to "carry out a multi-faceted study to assess exposure to contaminants including trace metals with more precision."[1004]

- May 14, 2019 – An investigation by the *Pittsburgh Post-Gazette* documented 27 cases of Ewing's sarcoma, a rare bone cancer that tends to strike children and young adults, in four counties in southwestern Pennsylvania (Fayette, Greene, Washington, and Westmoreland) that are at the heart of the Marcellus fracking boom and where more than 3,500 wells have been drilled since 2008.[1005] Six cases occurred in the same school district. (The typical rate is 250 cases of Ewing's sarcoma per year in the United States as a whole.) This cancer has no known cause but does not appear to have hereditary links. There are also high numbers of other rare cancers in the region, which is home to several polluting legacy industries. The *Post-Gazette* documented ten such rare cancers Washington County's Canon-McMillan School District alone and tallied 13 childhood and young adult cancer deaths in the region since 2011, including three since 2015 in the West Greene School District. In April 2019, the Pennsylvania Department of Health reported "no conclusive findings" of a cancer cluster in the Canon-McMillan School District and Washington County.[1006] Subsequently, additional cases came to light, and public calls for more comprehensive investigations continued.[1007, 1008, 1009, 1010]

- April 15, 2019 – Overall, oil and gas booms had very modest effects on local alcohol consumption in a U.S.-wide study using county-level data, but the effects varied greatly across states and by gender.[1011] Taken as a whole, oil and gas production slightly

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[1004] Élyse Caron-Beaudoin et al., "Urinary and Hair Concentrations of Trace Metals in Pregnant Women from Northeastern British Columbia, Canada: A Pilot Study," *Journal of Exposure Science & Environmental Epidemiology* 29, no. 5 (September 2019): 613–23, https://doi.org/10.1038/s41370-019-0144-3.
[1005] David Templeton and Don Hopey, "Are the 27 Cases of Ewing's Sarcoma near Pittsburgh a Cluster?," *Pittsburgh Post-Gazette*, May 14, 2019, https://newsinteractive.post-gazette.com/blog/ewing-sarcoma-cancer-cluster-pittsburgh-washington-westmoreland/.
[1006] Pennsylvania Department of Health, "Ewing's Family of Tumors, Childhood Cancer, and Radiation-Related Cancer Incidence Review for Washing County and Canon-McMillan School District in Pennsylvania" (Bureau of Epidemiology, Division of Community Epidemiology, April 22, 2019), https://www.documentcloud.org/documents/5975464-Ewings-Washington-Fmt.html.
[1007] Reid Frazier, "'Something's Wrong Here': Washington County Parents Want Pa. to Look Deeper at Whether Fracking Could Be Related to Cancer Cases," *State Impact Pennsylvania*, June 28, 2019, https://stateimpact.npr.org/pennsylvania/2019/06/28/somethings-wrong-here-washington-county-parents-want-pa-to-look-deeper-at-whether-fracking-could-be-related-to-cancer-cases/.
[1008] Deb Erdley, "Southwestern Pennsylvania Residents Renew Calls for Research on Possible Health Impact of Fracking," October 12, 2019, https://triblive.com/local/regional/southwestern-pennsylvania-residents-renew-calls-for-research-on-possible-health-impact-of-fracking/.
[1009] David Templeton and Don Hopey, "The Human Toll-Risk and Exposure in the Gas Lands," *Pittsburgh Post-Gazette*, May 14, 2019, https://newsinteractive.post-gazette.com/childhood-cancer-pittsburgh-pennsylvania-canon-mcmillan-pollution/.
[1010] Editorial Board, "Young Lives at Stake: Rural Areas Deserve Answers on Child Cancers," *Pittsburgh Post-Gazette*, May 22, 2019, https://www.post-gazette.com/opinion/editorials/2019/05/22/childhood-cancer-pittsburgh-pennsylvania-canon-mcmillan-pollution-rural-areas-greene-fayette-washington-westmoreland/stories/201905220064.
[1011] Adam Mayer and Shawn Olson Hazboun, "Does Fracking Drive You to Drink? Unconventional Oil and Gas Production and Alcohol Consumption in U.S. Counties," *The Extractive Industries and Society* 6, no. 3 (2019): 823–30, https://doi.org/10.1016/j.exis.2019.04.002.

increased heavy drinking for males and slightly decreased binge drinking for females. Researchers recommended that data be gathered at smaller spatial scales rather than by county, and that hospital admissions or arrest records could provide further insight into this question.

- January 21, 2019 – Increased hospitalizations for diseases of the genitourinary system, such as urinary tract infections, kidney infections, and kidney stones, were "strongly and positively associated with cumulative [unconventional natural gas] well density" in Pennsylvania.[1012] The strongest association for the genitourinary hospitalization rates was for women aged 20 to 64, particularly for kidney infections, stones in the ureter, and urinary tract infections. The researchers compared yearly hospitalization rates for each of Pennsylvania's 67 counties with the number of new fracking wells drilled, the total number of wells, and the density of wells by land area for each county by year, from 2003-2014. Noting that hospitalizations, in contrast with outpatient physician visits, reflect acute illness or serious exacerbations of chronic disease, the research team pointed out that these same health problems addressed in an outpatient setting, or not addressed at all, were likely also rising but would not have been counted in this study. The findings also revealed a link between cumulative gas well exposure measures and hospitalization rates for skin problems, particularly among men aged 20 to 64.

- December 12, 2018 – University of Oklahoma public health scientists found a significantly increased prevalence of neural tube defects among children whose birth residence was located within two miles of a drilling and fracking site, compared to those which were not.[1013] The researchers examined records of all 476,600 singleton births and congenital anomalies in Oklahoma from 1997 through 2009, together with historical location and production data on active natural gas wells for each year of the study. No stillbirths were included in this study. Hence, as the researchers note, the link they found would likely be an underestimate "if natural gas activity is related to severe anomalies with high prenatal mortality."

- December 6, 2018 – Early signs of cardiovascular disease—including high blood pressure, changes in the stiffness of blood vessels, and markers of inflammation—occurred more often in people who live in communities with more intense oil and gas development, according to a study of 97 adults living in northeastern Colorado between October 2015 and May 2016.[1014] Artery stiffness, as measured by augmentation index, was highest among people living in areas with the greatest drilling and fracking activity, as was systolic and diastolic blood pressure (for those not taking prescription medications). This was the first study to evaluate, with direct measurements, indicators of

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[1012] A. Denham et al., "Unconventional Natural Gas Development and Hospitalizations: Evidence from Pennsylvania, United States, 2003–2014," *Public Health* 168 (2019): 17–25, https://doi.org/10.1016/j.puhe.2018.11.020.
[1013] Amanda E. Janitz et al., "The Association between Natural Gas Well Activity and Specific Congenital Anomalies in Oklahoma, 1997–2009," *Environment International* 122 (2019): 381–88, https://doi.org/10.1016/j.envint.2018.12.011.
[1014] Lisa M. McKenzie et al., "Relationships between Indicators of Cardiovascular Disease and Intensity of Oil and Natural Gas Activity in Northeastern Colorado," *Environmental Research* 170 (2019): 56–64, https://doi.org/10.1016/j.envres.2018.12.004.

cardiovascular disease and the intensity of oil and gas activity. The results are consistent with previous research showing increased rates of cardiology inpatient hospital admission in these areas.

- August 28, 2018 – The top 10 oil and gas producing counties in Colorado had higher truck accident rates than the remaining 54 counties in an analysis by Colorado School of Public Health researchers. Researchers also performed an additional geospatial study technique called a "grid level analysis" using the Colorado Oil and Gas information System (COGIS), census population information, and home locations. These results showed that grid cells with more homes and/or wells were associated with more truck accidents, as well as with more multi-vehicle truck accidents with an injury.[1015]

- August 13, 2018 – Babies in Pennsylvania whose mothers lived near at least one gas well during their pregnancies were at higher risk for adverse birth outcomes, according to a study published in the *Journal of Health Economics.* This investigation examined state-based data on the locations of 2,459 natural gas wells drilled between 2006 and 2010 together with restricted-access birth and mortality data for the years 2003–2010.[1016] Mothers living within 2.5 kilometers (1.5 miles) of gas wells gave birth to infants with increased incidence of low birth weight and small for gestational age (SGA). SGA generally increases with exposure to environmental pollution and helps determine immediate health care needs, as well as predicting long-term adverse health outcomes. In addition, the study found term birth weight for these infants was lower on average, and the prevalence of APGAR scores less than eight was increased by 26 percent. APGAR scores are used to evaluate the health of infants immediately after birth. This study builds on growing evidence that air pollution from shale gas development damages infant health and stands out for thoroughly controlling for predictors of infant health and for estimating the extensive and intensive margins of drillings. Within the intensive margin (which includes an estimation of the impact of well density), one additional well was associated with a seven percent increase in low birth weight, a five gram reduction in term birth weight, and a three percent increase in premature birth. Each of these adverse outcomes carries high associated medical costs. The author conservatively estimated the added cost associated with one low birth weight infant to be $96,500 in the first year alone, not counting any loss of parent income. The author noted that these impacts are "likely to persist throughout these children's lives."

- August 10, 2018 – A study of Pennsylvania counties focusing on the period 2003–2012 found that counties with fracking activities have higher rates of gonorrhea and chlamydia infections (up 7.8 percent and 2.6 percent, respectively), as well as a 19.7 percent higher rate of prostitution-related arrests.[1017] Authors found no evidence that confounding

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[1015] Benjamin Blair et al., "Truck and Multivehicle Truck Accidents with Injuries Near Colorado Oil and Gas Operations," *International Journal of Environmental Research and Public Health* 15, no. 9 (2018): 1861, https://doi.org/10.3390/ijerph15091861.
[1016] Elaine L. Hill, "Shale Gas Development and Infant Health: Evidence from Pennsylvania," *Journal of Health Economics* 61 (2018): 134–50, https://doi.org/10.1016/j.jhealeco.2018.07.004.
[1017] Trinidad Beleche and Inna Cintina, "Fracking and Risky Behaviors: Evidence from Pennsylvania," *Economics & Human Biology* 31 (2018): 69–82, https://doi.org/10.1016/j.ehb.2018.08.001.

factors such as opioid prescription rates, viral hepatitis deaths, or drug abuse arrests influenced these results. These findings provide "strong evidence that unconventional or shale gas development poses significant risks to public health and that unconventional or shale gas development has policy implications beyond the economic and environmental impacts often cited."

- July 28, 2018 – Road fatalities in the Permian Basin region of west Texas have risen and fallen with the price of oil, according to an investigative piece in *Bloomberg* using New York Mercantile Exchange and Texas Department of Transportation data.[1018] Interviewees in the article pointed to inexperienced and exhausted drivers, sinkholes, oversized trucks on roads not designed for the amount of traffic they now carry, and other factors as reasons for the ongoing fatalities.

- July 27, 2018 – In this study of almost 5,000 Pennsylvanians, a team of medical and public health scientists found a link between living closer to more and bigger unconventional shale gas wells and increased symptoms of depression. This is the first epidemiologic study to address a mental health outcome with regard to proximity to fracking and related operations. The researchers combined information from a mailed questionnaire, electronic health record data, and residential proximity to more and bigger wells, using well data from three agencies. Size of wells was ascertained by combining data on total well depth and volume of natural gas produced. Researchers concluded that drilling and fracking activities "may be associated with adverse mental health in Pennsylvania" and called for including potential mental health consequences in future risk-benefit calculations.[1019]

- June 21, 2018 – Using individual inpatient data for the whole state of Pennsylvania from 2003 through 2014, researchers found consistent associations between childhood asthma hospitalizations and nearby drilling and fracking activity. When they compared unexposed children to children in the top third of patients exposed to shale gas drilling, the research team found that, during the same calendar quarter a gas well was drilled, the odds of children and adolescents being hospitalized for asthma increased by 25 percent. If there was ever a well drilled within a zip code, the odds of these pediatric asthma-related hospitalizations increased by 19 percent. This finding demonstrates that the increased risk remains for years after wells are drilled.[1020] This study is notable because it is the first to control for 180 pre-existing respiratory health risks. Researchers also considered specific air emissions from drilling and fracking sites. They found that increased levels of 2,2,4-trimethylpentane, carbon dioxide, formaldehyde, nitrous oxide, volatile organic compounds (VOCs), and x-hexane were associated with increased risks of pediatric

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[1018] Ryan Collins and Rachel Adams-Heard, "`Death Highway' Is Where Oil Prices, Truck Fatalities Intersect," *Bloomberg.Com*, July 28, 2018, https://www.bloomberg.com/news/articles/2018-07-28/-death-highway-is-where-oil-prices-truck-fatalities-intersect.
[1019] Joan A. Casey et al., "Associations of Unconventional Natural Gas Development with Depression Symptoms and Disordered Sleep in Pennsylvania," *Scientific Reports* 8, no. 1 (2018): 11375, https://doi.org/10.1038/s41598-018-29747-2.
[1020] Mary D. Willis et al., "Unconventional Natural Gas Development and Pediatric Asthma Hospitalizations in Pennsylvania," *Environmental Research* 166 (2018): 402–8, https://doi.org/10.1016/j.envres.2018.06.022.

asthma hospitalizations across age groups, as well as links for younger children to additional pollutants.

- May 21, 2018 – Using the most stringent classification within and across countries internationally, researchers examined reproductive toxicity among chemicals used in drilling and fracking operations for oil and gas. They found that 43 chemicals are classified as known or presumed human reproductive toxicants, while 31 others are suspected human reproductive toxicants. The team, which included Yale School of Medicine and School Public of Health researchers, further analyzed the 43 reproductive toxicants for their carcinogenic and mutagenic properties and found that seven reproductive toxicants doubled as carcinogens and mutagens. They are potassium dichromate, cadmium, benzene, ethylene oxide, nickel sulfate, N,N-dimethylformamide, and lead. Of these, benzene and lead are found in both fracking fluid and in fracking wastewater. Researchers noted that their study was limited to 157 chemicals previously identified as having evidence of reproductive toxicity, which is only a fraction of the more than 1000 chemicals identified as being present in fracking fluid, fracking wastewater, and fracking-related air emissions. They recommended that their framework be extended to all those chemicals.[1021] (See also entry for January 6, 2016 in Water Contamination.)

- May 1, 2018 – In a laboratory study, prenatal exposure to fracking-related chemicals triggered immune problems in mice, especially females. All three immune system illnesses tested—a house dust mite-induced allergic disease, influenza A virus, and a disease similar to multiple sclerosis—were impaired in mice exposed in the womb to a mixture of fracking chemicals.[1022] Using a chemical mixture "laced with chemicals at levels similar to those found in groundwater near fracking sites" and already demonstrated to have harmful developmental and reproductive effects, the researchers found sex-linked effects.[1023] The exposed female mice showed more severe damage to their immune systems and ability to resist disease. In addition, the multiple scleroris-like disease, experimental autoimmune encephalomyelitis, developed earlier and more severely in female mice as compared to male mice. Authors concluded, "These observations suggest that developmental exposure to complex mixtures of water contaminants, such as those derived from [drilling and fracking] operations, could contribute to immune dysregulation and disease later in life."

- March 23, 2018 – Yale University public health scientists investigated possible connections between shale gas drilling and sexually transmitted diseases in Ohio. They found that, compared to counties with no shale gas activity, counties with high activity

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[1021] Salmaan H. Inayat-Hussain et al., "Prioritization of Reproductive Toxicants in Unconventional Oil and Gas Operations Using a Multi-Country Regulatory Data-Driven Hazard Assessment," *Environment International* 117 (2018): 348–58, https://doi.org/10.1016/j.envint.2018.05.010.
[1022] L. A. Boulé et al., "Developmental Exposure to a Mixture of 23 Chemicals Associated With Unconventional Oil and Gas Operations Alters the Immune System of Mice," *Toxicological Sciences* 163, no. 2 (2018): 639–54, https://doi.org/10.1093/toxsci/kfy066.
[1023] Beth Adams, "Exposure to Chemicals Used in Fracking Impairs Immune System of Mice in URMC Study," *WXXI News*, May 1, 2018, https://www.wxxinews.org/post/exposure-chemicals-used-fracking-impairs-immune-system-mice-urmc-study.

had 21 percent increased rates of chlamydia and 19 percent increased rates of gonorrhea.[1024] They classified all 88 counties in the state as having none, low, and high shale gas activity in each year from 2000 through 2016, using Ohio Department of Natural Resources data. Their findings showed magnitude of effect for the association with gonorrhea that is similar to a prior analysis, adding strength to observed associations. Speaking to the *Columbus Dispatch*, the lead author noted, "Although there has been a decrease in new permits in recent years, [sexually transmitted infection] rates continue to climb because once a disease is introduced… it can be exchanged within the communities even after the workers leave."[1025]

- March 20, 2018 – In the Texas Barnett Shale, women with homes within a half-mile radius of the most dense gas drilling activity or gas production activity at the time of their child's birth had, respectively, 20 percent and 15 percent higher risk of preterm birth, compared with women with no such activity near their residence. The greatest proximity-related risk was for extremely premature births (prior 28 weeks gestation): mothers living near the densest drilling activity and the densest production activity were, respectively, 100 percent and 53 percent more likely to give birth to extremely premature babies.[1026, 1027] For purposes of this study, the drilling phase included drilling of the wellbore, installation of casing, and fracking, whereas the production phase, which can last for years, included the flowback of gas, condensate, and produced water, as well as possible on-site storage of these materials. Researchers noted that they did not have access to information that would have allowed more refined classification of phases. The study included 13,332 preterm birth cases and 66,933 term births in the 24-county Barnett Shale region between 2010 and 2012. The study also addressed trimester-specific differences in risk, finding little evidence for that factor. (See also entry for September 19, 2017.)

- March 13, 2018 – A research team found higher rates of hospitalizations for pneumonia among individuals ages 65 and older in Pennsylvania counties with drilling and fracking operations compared to those without. This result is consistent with other studies reporting links between respiratory problems and air pollution. This study, which used enhanced county-specific data from 2001 to 2013, expands on earlier research in its geographical reach and longer time horizon. The research team also found higher average hospitalization rates for other air pollution-sensitive diseases (acute myocardial infarction, chronic obstructive pulmonary disease, asthma, and upper respiratory

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[1024] Nicole C. Deziel et al., "Shale Gas Activity and Increased Rates of Sexually Transmitted Infections in Ohio, 2000–2016," ed. Jaymie Meliker, *PLoS ONE* 13, no. 3 (2018): e0194203, https://doi.org/10.1371/journal.pone.0194203.
[1025] Abbey Marshall, "Study Suggests Potential Link between Fracking Industry and Increased Sexually Transmitted Infections," *The Columbus Dispatch*, July 22, 2018, https://www.dispatch.com/news/20180722/study-suggests-potential-link-between-fracking-industry-and-increased-sexually-transmitted-infections.
[1026] Kristina Walker Whitworth, Amanda Kaye Marshall, and Elaine Symanski, "Drilling and Production Activity Related to Unconventional Gas Development and Severity of Preterm Birth," *Environmental Health Perspectives* 126, no. 3 (2018): 037006, https://doi.org/10.1289/EHP2622.
[1027] Lindsey Konkel, "Drilling into Critical Windows of Exposure: Trimester-Specific Associations between Gas Development and Preterm Birth," *Environmental Health Perspectives* 126, no. 10 (2018): 104002, https://doi.org/10.1289/EHP3762.

infections) in counties containing unconventional natural gas wells than in those without wells, but those links were not as strong statistically as for pneumonia among the elderly. Noting that their study design may actually underestimate the impact of natural gas development on pneumonia, the research team stated that their study "helps establish a consistent link between unconventional natural gas extraction and higher rates of disease."[1028]

- February 7, 2018 – Female mice exposed to a mixture of 23 fracking chemicals during early life developed dose-specific abnormalities in their mammary glands. The researchers saw changes in tissue morphology, cell proliferation, "and the induction of unique intraductal hyperplasias."[1029] (Intraductal hyperplasia is an overgrowth of cells that is considered a marker for future breast cancer risk.) Researchers used four doses; the lower two used were equivalent to concentrations found in drinking water in fracking regions and the highest dose represented concentrations that have been measured in industry wastewater. Mammary gland effects varied for each the doses, but all groups developed intraductal hyperplasia. According to a co-author, "This study shows that a mixture of [fracking] chemicals can affect the long-term health of the mouse mammary gland, even after low level exposures in the womb."[1030]

- January 15, 2018 – A study of urban oil drilling in two Los Angeles neighborhoods found elevated asthma rates among residents living within 1,500 feet of oil wells. Researchers compared diagnosed asthma rates in these areas to a representative comparison area (the California Health Interview Survey's "SPA6" in South Los Angeles) and to Los Angeles County as a whole.[1031] The diagnosed asthma rates in the two study areas were statistically significantly higher (16.1 percent and 23.6 percent) than the comparison area (9.8 percent). Asthma prevalence in one of the two study areas was significantly higher than that in Los Angeles County as a whole. Households with smokers were excluded from the analysis. This interdisciplinary team worked in partnership with the local residents to conduct this community-based survey with limited resources and urged further studies with more complex scientific design.

- December 13, 2017 – A team of health economists analyzed fracking's health impacts on infants. They examined birth certificates for all 1.1 million infants born in Pennsylvania between 2004 and 2013 and combined these data with maps showing when and where gas wells were drilled in the state. Their results indicated that the introduction of fracking "reduces health among infants born to mothers living within 3 km (1.9 miles) of a well

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[1028] Lizhong Peng, Chad Meyerhoefer, and Shin-Yi Chou, "The Health Implications of Unconventional Natural Gas Development in Pennsylvania," *Health Economics* 27, no. 6 (2018): 956–83, https://doi.org/10.1002/hec.3649.
[1029] Sarah A Sapouckey et al., "Prenatal Exposure to Unconventional Oil and Gas Operation Chemical Mixtures Altered Mammary Gland Development in Adult Female Mice," *Endocrinology* 159, no. 3 (2018): 1277–89, https://doi.org/10.1210/en.2017-00866.
[1030] University of Massachusettsat Amherst, "Changes in Mouse Breast Tissue after Exposure to Fracking Chemicals: UMass Amherst, University of Missouri Led First Study of Such Effects," *ScienceDaily*, February 7, 2018, https://www.sciencedaily.com/releases/2018/02/180207090108.htm.
[1031] Bhavna Shamasunder et al., "Community-Based Health and Exposure Study around Urban Oil Developments in South Los Angeles," *International Journal of Environmental Research and Public Health* 15, no. 1 (2018): 138, https://doi.org/10.3390/ijerph15010138.

site during pregnancy." For mothers living within one kilometer (.6 miles), they found a 25 percent increase in the probability of low birth weight, "significant declines" in average birth weight, as well as declines in other measures of infant health. They also observed reductions in infant health when mothers lived within one to three kilometers of a fracking site; these were about one-third to one-half of the declines of those mothers living closer.[1032] The researchers estimated that "about 29,000 out of the nearly 4 million U.S. births (0.7 percent) annually occur within 1 kilometer of a fracking site and 95,500 are born within 3 kilometers." "For policymakers weighing the costs and benefits of fracking before deciding whether to allow it in their communities, this study provides a clear cost: an increase in the probability of poorer health for babies born near these sites."[1033]

- November 6, 2017 – As part of a pilot project, a team of Montreal-based public health researchers evaluated exposure of pregnant mothers to VOCs in an area of intensive fracking in northeastern British Columbia. At least 28,000 unconventional natural gas wells had been drilled to date in the Peace River Valley. Analyzing the urine of 29 pregnant women, researchers found high concentrations of muconic acid, which is a degradation product of benzene, a widely studied developmental toxicant and an air contaminant in the vicinity of gas wells. The median concentration of this chemical was approximately 3.5 times higher in the study group than in the general Canadian population. In five of the 29 women, the concentration of muconic acid exceeded an exposure index by the American Conference of Governmental Industrial Hygienists that was designed for workplace settings. (No guidelines for the public exist.) By design, this small pilot study sets the groundwork for more extensive biomonitoring and environmental analysis.[1034]

- September 19, 2017 – University of Texas Health Science Center researchers conducted a case-control study nested within their larger cohort of women with single births (see entry for July 21, 2017, below) in the 24-county Barnett Shale between November 30, 2010 and November 29, 2012. Its specific purpose was to consider timing of unconventional gas development activity "during potentially sensitive windows of exposure," as well as "potential differences in risk by UGD drilling phase," with regard to preterm births. Results suggest a link between maternal residential proximity to UGD-activity and preterm births, which were similar by drilling phase and "slightly stronger in the first two trimesters of pregnancy."[1035]

[1032] Janet Currie, Michael Greenstone, and Katherine Meckel, "Hydraulic Fracturing and Infant Health: New Evidence from Pennsylvania," *Science Advances* 3, no. 12 (2017): e1603021, https://doi.org/10.1126/sciadv.1603021.
[1033] Janet Currie, Michael Greenstone, and Katherine Meckel, "Hydraulic Fracturing and Infant Health: New Evidence from Pennsylvania," Research Summary (Energy Policy Institute at the University of Chicago, 2017), https://epic.uchicago.edu/wp-content/uploads/2019/07/Research-Summary-5.pdf.
[1034] Élyse Caron-Beaudoin et al., "Gestational Exposure to Volatile Organic Compounds (VOCs) in Northeastern British Columbia, Canada: A Pilot Study," *Environment International* 110 (2018), https://doi.org/10.1016/j.envint.2017.10.022.
[1035] Amanda Marshall, Elaine Symanski, and Kristina Whitworth, "The Association Between Unconventional Gas Development and Preterm Birth: Evaluating Drilling Phases and Critical Windows of Susceptibility," *Annals of Epidemiology* 27, no. 8 (2017): 530.

- September 14, 2017 – Researchers reviewed health assessments taken between February 2012 and October 2015 of adults in Pennsylvania communities with intense unconventional natural gas development (UNGD). The most frequently reported symptoms were sleep disturbance, headache, throat irritation, stress/anxiety, cough, shortness of breath, sinus problems, fatigue, wheezing, nausea, each occurring in over 20 percent of the sample. Over 43 percent of the sample reported sleep disturbance. To meet the inclusion criteria, as developed and implemented by a physician and nurse practitioner, the symptoms were reviewed to ensure no plausible cause relating to "past medical and surgical history, concurrent medical conditions, family and social history, and environmental exposures unrelated to UNGD. For example, if the social history indicated a ½ pack/day smoking history, the symptom of 'difficulty breathing' was not included." Independently, the timing of the exposure for each symptom that met the inclusion criteria was determined, using the beginning drilling date for each unconventional natural gas well within one kilometer (.6 miles) of the patient's residence; records were excluded if it was not possible to verify at least one gas well within this distance.[1036]

- August 21, 2017 – Using county-level data from 2003 to 2013, researchers found that, all together, counties in the Marcellus Shale region that experienced a boom in hydraulic fracturing showed a 20 percent increase in the incidence rate of gonorrhea.[1037]

- July 21, 2017 – A University of Texas Health Science Center School of Public Health team assessed the links between the residential proximity of pregnant mothers to unconventional natural gas development activity and various newborn health problems: preterm birth, small-for-gestational age (SGA), fetal death, and low birth weight. They found evidence of a "moderate positive association" between residential proximity to UGD-activity and increased odds of preterm birth, and a "suggestive association" with fetal death. Nearly 159,000 births and fetal deaths from November 30, 2010 to November 29, 2012 in the 24-county Barnett Shale area were considered.[1038]

- February 15, 2017 – A study from the University of Colorado School of Public Health and Anschutz Medical Campus showed that children and young adults between the ages of 5 and 24 with acute lymphocytic leukemia (ALL) were 4.3 times more likely to live in area dense with active oil and gas wells. The researchers did not find such a link with ALL cases in 0-4 year olds, or with incidence of non-Hodgkin lymphoma. The study focused on rural areas and towns in 57 Colorado counties and did not include cities of more than 50,000 people. Authors wrote, "Because oil and gas development has potential

[1036] Beth Weinberger et al., "Health Symptoms in Residents Living near Shale Gas Activity: A Retrospective Record Review from the Environmental Health Project," *Preventive Medicine Reports* 8 (2017): 112–15, https://doi.org/10.1016/j.pmedr.2017.09.002.
[1037] Tim Komarek and Attila Cseh, "Fracking and Public Health: Evidence from Gonorrhea Incidence in the Marcellus Shale Region," *Journal of Public Health Policy* 38, no. 4 (2017): 464–81, https://doi.org/10.1057/s41271-017-0089-5.
[1038] Kristina W. Whitworth, Amanda K. Marshall, and Elaine Symanski, "Maternal Residential Proximity to Unconventional Gas Development and Perinatal Outcomes among a Diverse Urban Population in Texas," ed. Jaymie Meliker, *PLoS ONE* 12, no. 7 (2017): e0180966, https://doi.org/10.1371/journal.pone.0180966.

to expose a large population to known hematologic carcinogens, such as benzene, further study is clearly needed to substantiate both our positive and negative findings."[1039]

- October 26, 2016 – A study that investigated possible links between fracking and cancer incidence in southwest Pennsylvania found elevated rates of bladder and thyroid cancers in six counties with shale gas activity.[1040] Bladder cancer was elevated in both males and females, with a 10 percent increase in the number of observed cases from 2000 to 2012. Over the same time period, thyroid cancer jumped even more dramatically. "There was a huge 91.2% increase in the number of observed cases from 2000 to 2012." Patterns of leukemia incidence were less clearly related to shale gas activity. The author expressed caution in attributing these trends solely to shale gas development due to "the multiple sources of potentially toxic, harmful exposures in southwest Pennsylvania, many dating back decades," the long latency time required for many cancers to develop, and possible synergisms between exposures from shale gas development and past toxic exposures.

- August 25, 2016 – Researchers found that Pennsylvanians residing near intensive unconventional gas well activity were significantly more likely to experience chronic rhino sinusitis (at least three months of nasal and sinus symptoms), migraine headaches, and higher levels of fatigue than residents who do not live near such activity.[1041] Data were gathered from nearly 8,000 patients of Geisinger Health System from 40 counties in north and central Pennsylvania, and matched with the proximity of respondents to all phases of gas drilling activity and intensity, using information from the Pennsylvania Departments of Environmental Protection (PA DEP) and Conservation and Natural Resources, as well as satellite imagery. According to lead author Aaron W. Tustin, MD, MPH, resident physician in the Department of Environmental Health Sciences at the Johns Hopkins Bloomberg School of Public Health, "[t]hese three health conditions can have debilitating impacts on people's lives… In addition, they cost the health care system a lot of money."[1042]

- July 18, 2016 – Living near fracking operations significantly increases asthma attacks, according to a Johns Hopkins University study of 35,000 medical records of people with asthma in north and central Pennsylvania, from 2005 to 2012.[1043] The data show that those who live near a higher number of, or larger, active gas wells were 1.5 to 4 times more likely to suffer from asthma attacks compared to those who live farther away, with

[1039] Lisa M. McKenzie et al., "Childhood Hematologic Cancer and Residential Proximity to Oil and Gas Development," ed. Jaymie Meliker, *PLoS ONE* 12, no. 2 (2017): e0170423, https://doi.org/10.1371/journal.pone.0170423.
[1040] M.L. Finkel, "Shale Gas Development and Cancer Incidence in Southwest Pennsylvania," *Public Health* 141 (2016): 198–206, https://doi.org/10.1016/j.puhe.2016.09.008.
[1041] Aaron W. Tustin et al., "Associations between Unconventional Natural Gas Development and Nasal and Sinus, Migraine Headache, and Fatigue Symptoms in Pennsylvania," *Environmental Health Perspectives* 125, no. 2 (2017): 189–97, https://doi.org/10.1289/EHP281.
[1042] Susan Phillips, "New Study Links Gas Drilling to Migraines, Fatigue and Chronic Sinus Symptoms," *State Impact Pennsylvania*, August 25, 2016, https://stateimpact.npr.org/pennsylvania/2016/08/25/new-study-points-to-association-between-gas-drilling-to-migraines-fatigue-and-chronic-sinus-symptoms/.
[1043] Sara G. Rasmussen et al., "Association Between Unconventional Natural Gas Development in the Marcellus Shale and Asthma Exacerbations," *JAMA Internal Medicine* 176, no. 9 (2016): 1334, https://doi.org/10.1001/jamainternmed.2016.2436.

the closest group having the highest risk. There was increased risk in all three types of exacerbations defined: mild (new oral corticosteroid medication order), moderate (emergency department encounter), or severe (hospitalization). In addition, researchers identified increased risk during all four phases of well development: pad preparation, drilling, stimulation (fracking), and production. The study was praised for its "rigorous research methods," by a scientist not part of the team.[1044]

- July 5, 2016 – Researchers from five universities and the U.S. Geological Survey (USGS) identified a link between exposure to fracking and drilling chemicals and adverse reproductive and developmental outcomes in laboratory mice. The study used 23 oil and gas chemicals in four different concentrations, representing concentrations found in drinking water and groundwater, to higher concentrations found in oil and gas industry wastewater. Offspring of pregnant laboratory mice consuming these mixtures were compared to those that did not. Results suggested "numerous potential threats to fertility and reproductive success … including altered pituitary hormone levels, reproductive organ weights, and disrupted ovarian follicle development." Researchers observed these negative outcomes even in the offspring exposed to the lowest dose of chemicals. Building on previous research showing reduced sperm counts in male offspring, they also reported on "tentative mechanistic information for the observed adverse health effects."[1045]

- February 9, 2016 – An exploratory study of hospitalization rates for three study areas in Queensland, Australia showed rates for specific types of hospital admissions increased more quickly in a coal seam gas study area than in other study areas (a coal mining area and a rural/agricultural area). Coal seam gas is the methane trapped in pores and fractures in underground coal deposits; its exploitation is a form of unconventional natural gas development. A portion of coal seam gas extraction uses fracking. This preliminary study found the strongest link between increased hospitalization rates over time in a coal seam gas area to be for the category of 'Blood/immune' diseases.[1046]

- October 14, 2015 – Using an animal model, an interdisciplinary research team measured the endocrine-disrupting activities of 24 chemicals used and/or produced by oil and gas operations, finding that 23 of them "can activate or inhibit the estrogen, androgen, glucocorticoid, progesterone, and/or thyroid receptors, and mixtures of these chemicals can behave synergistically, additively, or antagonistically." Further, the researchers tested prenatal exposures to the chemicals and found effects on multiple organs, including

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[1044] Nicholas Kusnetz, "Increased Asthma Attacks Tied to Exposure to Natural Gas Production," *Inside Climate News*, July 18, 2016, https://insideclimatenews.org/news/18072016/asthma-study-marcellus-shale-pennsylvania-natural-gas-fracking/.
[1045] Christopher D. Kassotis et al., "Adverse Reproductive and Developmental Health Outcomes Following Prenatal Exposure to a Hydraulic Fracturing Chemical Mixture in Female C57Bl/6 Mice," *Endocrinology* 157, no. 9 (2016): 3469–81, https://doi.org/10.1210/en.2016-1242.
[1046] Angela K. Werner et al., "All-Age Hospitalization Rates in Coal Seam Gas Areas in Queensland, Australia, 1995–2011," *BMC Public Health* 16, no. 1 (2015): 125, https://doi.org/10.1186/s12889-016-2787-5.

adverse reproductive effects on the matured offspring.[1047] This study is the first to demonstrate that endocrine-disrupting chemicals, which are commonly used in fracking operations, can harm the reproductive health of mice, at levels of exposure that are realistic for humans. The study's senior author told *ScienceDaily,* "In addition to reduced sperm counts, the male mice exposed to the mixture of chemicals had elevated levels of testosterone in their blood and larger testicles. These findings may have implications for the fertility of men living in regions with dense oil and/or natural gas production."[1048]

- October 8, 2015 – Pregnant women who live near active fracking operations in Pennsylvania were at a 40 percent increased risk of giving birth prematurely and at a 30 percent increased risk for having obstetrician-labeled high-risk pregnancies, according to a study by Johns Hopkins Bloomberg School of Public Health and other researchers. High-risk pregnancies were those that included hypertension, high pre-pregnancy body mass index, and asthma. The study used data from the Geisinger Health System on 9,384 pregnant women and their 10,496 newborns between January 2009 and January 2013; Geisinger covers 40 counties in north and central Pennsylvania. Researchers developed an index for proximity to fracking wells based on distance from the women's homes, stage of drilling and depth of wells dug, and the amount of gas that was produced at those wells during the pregnancies. The highest-activity quartile had the highest rates of premature births and high-risk pregnancies.[1049, 1050]

- July 22, 2015 – Using a mammal model, New York University School of Medicine scientists, together with other U.S. and Chinese researchers, demonstrated cancerous changes linked to exposure to wastewater from Marcellus fracking operations. Their study also documented elevated levels of barium and strontium in exposed animal cells. The wastewater studied originated in Pennsylvania and was stored for a time to allow radioactivity and levels of short-lived VOCs to decline. The results suggest that "even aged flow back water could pose substantial health threats to exposed humans."[1051]

- July 15, 2015 – A study by University of Pennsylvania and Columbia University researchers found that drilling and fracking activity was associated with increased rates of hospitalization in Pennsylvania. During a period of dramatic increase in drilling and fracking activity between 2007 and 2011, inpatient prevalence rates surged for people living near shale gas wells. Cardiology inpatient prevalence rates were significantly associated with number of wells per zip code and their density, while neurology inpatient

[1047] Christopher D. Kassotis et al., "Endocrine-Disrupting Activity of Hydraulic Fracturing Chemicals and Adverse Health Outcomes After Prenatal Exposure in Male Mice," *Endocrinology* 156, no. 12 (2015): 4458–73, https://doi.org/10.1210/en.2015-1375.
[1048] Endocrine Society, "Fracking Chemicals Tied to Reduced Sperm Count in Mice," *ScienceDaily*, October 14, 2015, https://www.sciencedaily.com/releases/2015/10/151014134533.htm.
[1049] Joan A. Casey et al., "Unconventional Natural Gas Development and Birth Outcomes in Pennsylvania, USA," *Epidemiology* 27, no. 2 (2015): 163–72, https://doi.org/10.1097/EDE.0000000000000387.
[1050] Johns Hopkins Bloomberg School of Public Health, "Study: Fracking Industry Wells Associated With Premature Birth," October 8, 2015, https://publichealth.jhu.edu/2015/study-fracking-industry-wells-associated-with-premature-birth.
[1051] Yixin Yao et al., "Malignant Human Cell Transformation of Marcellus Shale Gas Drilling Flow Back Water," *Toxicology and Applied Pharmacology* 288, no. 1 (2015): 121–30, https://doi.org/10.1016/j.taap.2015.07.011.

prevalence rates were significantly associated with density of wells. Hospitalizations for cancer, skin conditions, and urological problems also rose significantly. During the same time period, no such increase in health problems was observed in a control Pennsylvania county without any drilling and fracking activity. In communities with the most wells, the rate of cardiology hospitalizations was 27 percent higher than in control communities with no fracking. "While the clinical significance of the association remains to be shown, [fracking] has just begun in Pennsylvania, and thus observing a significant association over this short time is striking.… Our study also supports the concept that health care utilization should be factored into the value (costs and benefits) of hydraulic fracturing over time."[1052] In a related *Newsweek* story, lead researcher Reynold Panettieri, Jr. said, "At this point, we suspect that residents are exposed to many toxicants, noise and social stressors due to hydraulic fracturing near their homes and this may add to the increased number of hospitalizations."[1053]

- July 9, 2015 – As part of a scientific assessment of well stimulation treatments, including fracking, the California Council on Science and Technology studied the potential impacts of well stimulation on human health in California. The risk factors directly attributable to well stimulation stem largely from the use of a very large number and quantity of stimulation chemicals. The unknown number and toxicity of chemicals that are mixed together in well stimulation fluids made it difficult to fully quantify risk to the environment and to human health, but the study highlighted the potential health risks from exposure to fracking-related air pollution for the people of Los Angeles, 1.7 million of whom live or work within one mile of an active oil or gas well.[1054] Jane Long, co-author, said, "officials should fully understand the toxicity and environmental profiles of all chemicals before allowing them to be used in California's oil operations," according to the *Los Angeles Times*.[1055]

- June 22, 2015 – A longtime midwife reported her personal analysis of an ongoing spike in infant deaths, miscarriages, and placental abnormalities in Utah's Uintah Basin that has followed the advent of drilling and fracking activity there and appears linked to air pollution episodes.[1056]

- June 3, 2015 – A University of Pittsburgh study linked fracking to low birthweight in three heavily drilled Pennsylvania counties. The more exposure a pregnant woman had to gas wells, the higher her risk for a smaller-than-normal baby. Exposure was determined as proximity and density of wells in relation to the residence of the pregnant woman. Compared to mothers whose homes had the fewest surrounding gas wells, mothers whose

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[1052] Thomas Jemielita et al., "Unconventional Gas and Oil Drilling Is Associated with Increased Hospital Utilization Rates," ed. Jaymie Meliker, *PLoS ONE* 10, no. 7 (2015): e0131093, https://doi.org/10.1371/journal.pone.0131093.
[1053] Zoë Schlanger, "Living Near Fracking Wells Linked to Increased Hospitalization Rates," Newsweek, July 15, 2015, https://www.newsweek.com/living-near-fracking-wells-linked-increased-hospitalization-rates-354093.
[1054] Shonkoff et al., "Chapter 6: Potential Impacts of Well Stimulation on Human Health in California."
[1055] Julie Cart, "Water and Wildlife May Be at Risk from Fracking's Toxic Chemicals, Panel Finds," *Los Angeles Times*, July 10, 2015, sec. California, https://www.latimes.com/local/lanow/la-me-california-science-panel-warns-that-fracking-poses-unknown-risk-20150709-story.html.
[1056] Paul Solotaroff, "What's Killing the Babies of Vernal, Utah?," *Rolling Stone*, June 22, 2015, https://www.rollingstone.com/culture/culture-news/whats-killing-the-babies-of-vernal-utah-33666/.

homes were nearest to a high density of wells were 34 percent more likely to have babies who were "small for gestational age," meaning they weighed significantly less than expected for the number of weeks of pregnancy. Although the study did not investigate mechanisms, researchers identified air as the likely route of exposure. They supported this argument by referencing another study done in Western Pennsylvania where airborne particulate pollution correlated with low birth weight and by noting that particulates are established shale gas infrastructure emissions.[1057, 1058] Low birth weight is a leading cause of infant mortality.

- March 3, 2015 – A follow-up study of 21 case studies from five states found that the distribution of symptoms in animals and humans affected by nearby fracking operations was, since 2012, unchanged for humans and companion animals. In food animals, reproductive problems decreased over time while respiratory problems and growth problems increased. "This longitudinal case study illustrates the importance of obtaining detailed epidemiological data on the long-term health effects of multiple chemical exposures and multiple routes of exposure that are characteristic of the environmental impacts of unconventional drilling operations."[1059]

- March 3, 2015 – A cross-sectional study by Yale University School of Medicine researchers using companion animals as sentinels of human exposure to fracking-related chemicals investigated possible associations between reported health conditions of companion and backyard animals in Southwest Pennsylvania and household proximity to drilling and fracking operations. Among dogs living in households located less than one kilometer from a gas well, risks for health problems were elevated, especially for dermal conditions, compared to animals living more than two kilometers from a well.[1060]

- January 1, 2015 – A Yale-led team studied the relationship between household proximity to drilling and fracking operations and reported health symptoms in Washington County, Pennsylvania where 624 gas wells were in active operation, most of which had been drilled in the past five to six years. Researchers found that health symptoms reported by residents increased in frequency as distance between household and gas wells decreased. Among persons living less than one kilometer from drilling and fracking operations, rashes and upper respiratory problems were more prevalent. The authors of this study, the largest to date on the link between reported symptoms and natural gas drilling activities, say that their findings are "… consistent with earlier reports of respiratory and dermal conditions in persons living near natural gas wells." They also cite literature

[1057] Shaina L. Stacy et al., "Perinatal Outcomes and Unconventional Natural Gas Operations in Southwest Pennsylvania," ed. Jaymie Meliker, *PLoS ONE* 10, no. 6 (2015): e0126425, https://doi.org/10.1371/journal.pone.0126425.
[1058] Robert Preidt, "'Fracking' Linked to Low Birth Weight Babies," WebMD, accessed September 17, 2021, https://www.webmd.com/baby/news/20150603/fracking-linked-to-low-birth-weight-babies.
[1059] Michelle Bamberger and Robert E. Oswald, "Long-Term Impacts of Unconventional Drilling Operations on Human and Animal Health," *Journal of Environmental Science and Health, Part A* 50, no. 5 (2015): 447–59, https://doi.org/10.1080/10934529.2015.992655.
[1060] I. B. Slizovskiy et al., "Reported Health Conditions in Animals Residing near Natural Gas Wells in Southwestern Pennsylvania," *Journal of Environmental Science and Health, Part A* 50, no. 5 (2015): 473–81, https://doi.org/10.1080/10934529.2015.992666.

demonstrating the biological plausibility of a link between oil and gas extraction activities and both categories of health effects reported.[1061]

- December 17, 2014 – As part of a lengthy review that became the foundation for New York State's ban on high volume hydraulic fracturing, the New York State Department of Health (NYS DOH) identified environmental problems associated with fracking that could contribute to adverse public health impacts. Among them: air pollution (particulate matter, ozone, diesel exhaust, and VOCs) that could affect respiratory health; drinking water contamination from underground migration of methane and/or fracking chemicals associated with faulty well construction or seismic activity; drinking water contamination from inadequate water treatment of fracking waste or from surface spills of fracking chemicals or wastewater; earthquakes and the creation of fissures; increased vehicle traffic; increased noise; increased demand for housing and medical care; and public health problems related to climate change impacts from methane and other greenhouse gas emissions into the atmosphere. The NYS DOH Public Health Review also discussed findings from surveys of health symptoms among residents living near high volume hydraulic fracturing activities. These included skin rash, nausea or vomiting, abdominal pain, breathing difficulties, cough, nosebleed, anxiety, stress, headache, dizziness, eye irritation, and throat irritation in populations living near drilling and fracking operations. The NYS DOH Public Health Review noted that ongoing studies by both government agencies and several academic institutions were exploring the public health risks and impacts of fracking but that many of these studies were years from completion. The review concludes:

  > … significant gaps exist in the knowledge of potential public health impacts from [high volume hydraulic fracturing]…. The existing science investigating associations between [high volume hydraulic fracturing] activities and observable adverse health outcomes is very sparse and the studies that have been published have significant scientific limitations. Nevertheless, studies are suggestive of potential public health risks related to [high volume hydraulic fracturing] activity that warrant further careful evaluation.

  In an accompanying letter to the New York State Department of Environmental Conservation, Health Commissioner Howard Zucker, MD, concluded,

  > … the overall weight of the evidence from the cumulative body of information contained in this Public Health Review demonstrates that there are significant uncertainties about the kinds of adverse health outcomes that may be associated with [high volume hydraulic fracturing], the likelihood of the occurrence of adverse health outcomes and the effectiveness of some of the mitigation measures in reducing or preventing environmental impacts which could adversely affect public health. Until the science provides sufficient information to determine the level of risk to public health from [fracking] to all New Yorkers and whether the

[1061] Peter M. Rabinowitz et al., "Proximity to Natural Gas Wells and Reported Health Status: Results of a Household Survey in Washington County, Pennsylvania," *Environmental Health Perspectives* 123, no. 1 (2015): 21–26, https://doi.org/10.1289/ehp.1307732.

risks can be adequately managed, DOH recommends that high volume hydraulic fracturing should not proceed in NYS.[1062]

- October 13, 2014 – According to the North Dakota Health Department, the number of HIV and AIDS cases in North Dakota more than doubled between 2012 and 2014, and cases were shifting to the state's western oil fields, where 35-40 percent of all new cases occurred. Previously, only 10 percent of cases were in that region.[1063] This trend followed on the heels of an upsurge in sexually transmitted chlamydia cases in the same region. The North Dakota state director of disease control, Kirby Kruger, attributed the uptick in HIV cases to the drilling and fracking industry and attempted to spread HIV prevention messages at the "man camps" that house young male workers in the oil industry.[1064] Human trafficking for purposes of prostitution accompanied the fracking boom, but there was a shortage of medical professionals to address this public health crisis, according to Kruger, who noted that it was difficult to hire nurses and medical staff who could live in the area on a public health wage.

- October 2, 2014 – According to researchers from the University of Pennsylvania's Center of Excellence in Environmental Toxicology, an increasing number of gas wells in Pennsylvania is significantly correlated with inpatient rates of hospitalization. The research team collected data from seven different insurance providers for three counties; the study's publication is forthcoming.[1065]

- September 11, 2014 – In Texas, commercial vehicle accidents have increased more than 50 percent since 2009 when the state's ongoing drilling and fracking boom began, according to an investigation by the *Houston Chronicle* and Houston Public Media News 88.7. "For six decades, highway deaths have dropped steadily all across the United States…. But in Texas all motor vehicle fatalities – and accidents involving commercial trucks – have turned back upward since the state's oil drilling and fracking boom began in 2008." This rising motor vehicle death toll is especially felt in formerly rural counties in the Eagle Ford and Permian Basin, now places of heavy drilling and fracking. A new Department of Public Safety "Road Check" program finds annually, "27 to 30 percent of Texas' commercial trucks shouldn't be operating at all due to potentially life-threatening

[1062] New York State Department of Health, "A Public Health Review of High Volume Hydraulic Fracturing for Shale Gas Development," December 17, 2014, http://www.health.ny.gov/press/reports/docs/high_volume_hydraulic_fracturing.pdf.
[1063] Associated Press, "North Dakota HIV/AIDS Rate Rises with Population Growth," *The Billings Gazette*, October 13, 2014, https://billingsgazette.com/news/state-and-regional/montana/north-dakota-hiv-aids-rate-rises-with-population-growth/article_a939fed6-f737-5cfb-957f-ab800673f4d7.html.
[1064] Andy Birkey, "Around the Region: HIV Rates Skyrocket in North Dakota," *The Column*, October 6, 2014, http://thecolu.mn/13773/around-region-hiv-rates-skyrocket-north-dakota.
[1065] Elizabeth Skrapits, "Study: More Gas Wells in Area Leads to More Hospitalizations," *Wilkes-Barre Citizens' Voice*, accessed September 17, 2021, https://www.citizensvoice.com/news/study-more-gas-wells-in-area-leads-to-more-hospitalizations/article_31eec203-76fc-5b9e-9a8a-f4a552bdd4f6.html.

safety problems like defective brakes, bald tires, inoperable safety lights and unqualified, unfit or intoxicated drivers."[1066, 1067]

- August 3, 2014 – Hospitals in the Bakken Shale region reported a sharp rise in ambulance calls and emergency room visits after 2006. "Mercy Medical Center in Williston and the Tioga Medical Center in neighboring Williams County saw their ambulance runs increase by more than 200 percent. Tioga's hospital saw a staggering leap in trauma patients by 1,125 percent. Mercy had a 373 percent increase." Drugs (including overdoses of prescription drugs, methamphetamine, and heroin) explain many of the cases, with oilfield related injuries such as "fingers crushed or cut off, extremity injuries, burns and pressure burns" accounting for 50 percent of the cases in one of the region's hospital emergency rooms.[1068]

- May 21, 2014 – Raising questions about possible links to worsening air pollution from the Uintah Basin's 11,200 oil and gas wells, health professionals reported that infant deaths in Vernal, Utah, rose to six times the normal rate over the past three years. Physician Brian Moench said, "We know that pregnant women who breathe more air pollution have much higher rates of virtually every adverse pregnancy outcome that exists…. And we know that this particular town is the center of an oil and gas boom that's been going on for the past five or six years and has uniquely high particulate matter and high ozone."[1069] Although it formerly had pristine air quality, Uintah County, Utah received a grade "F" for ozone in the American Lung Association's 2013 State of the Air Report.[1070]

- January 28, 2014 – Congenital heart defects, and possibly neural tube defects in newborns, were associated with the density and proximity of natural gas wells within a 10-mile radius of mothers' residences in a study of almost 25,000 births from 1996 to 2009 in rural Colorado. The researchers note that natural gas development emits several chemicals known to increase risk of birth defects (teratogens).[1071]

- January 4, 2014 – Preliminary data from researchers at Princeton University, Columbia University, and MIT showed elevated rates of low birthweight among infants born to mothers living near drilling and fracking operations during their pregnancies.[1072]

1066 Lise Olsen, "Fatal Truck Accidents Have Spiked during Texas' Ongoing Fracking and Drilling Boom," *Houston Chronicle*, September 11, 2014, sec. News, https://www.houstonchronicle.com/news/article/Fracking-and-hydraulic-drilling-have-brought-a-5747432.php.
1067 Andrew Schneider, "In Texas, Traffic Deaths Climb Amid Fracking Boom," *NPR*, October 12, 2014, sec. National, https://www.npr.org/2014/10/02/352980756/in-texas-traffic-deaths-climb-amid-fracking-boom.
1068 K. J. Bryan, "Drugs, Oilfield Work, Traffic Pushing More People through Doors of Watford City ER," *Bakken Today*, August 3, 2014, http://www.bakkentoday.com/event/article/id/37101/.
1069 Zoë Schlanger, "In Utah Boom Town, a Spike in Infant Deaths Raises Questions," *Newsweek*, May 21, 2014, https://www.newsweek.com/2014/05/30/utah-boom-town-spike-infant-deaths-raises-questions-251605.html.
1070 American Lung Association, "American Lung Association State of the Air 2013," 2013.
1071 Lisa M. McKenzie et al., "Birth Outcomes and Maternal Residential Proximity to Natural Gas Development in Rural Colorado," *Environmental Health Perspectives* 122, no. 4 (2014): 412–17, https://doi.org/10.1289/ehp.1306722.
1072 Mark Whitehouse, "Study Shows Fracking Is Bad for Babies," *Bloomberg*, January 4, 2014, https://www.bloomberg.com/opinion/articles/2014-01-04/study-shows-fracking-is-bad-for-babies.

- August 26, 2013 – Medical experts at a rural clinic in heavily-drilled Washington County, Pennsylvania reported case studies of 20 individuals with acute symptoms consistent with exposure to air contaminants known to be emitted from local fracking operations.[1073, 1074]

- May 2, 2013 – A community-based participatory research study in Pennsylvania tested air and water quality and surveyed self-reported health symptoms of more than 100 residents living near drilling and fracking operations. The team detected a total of 19 VOCs in ambient air sampled outside of homes. The reported health symptoms closely matched the established effects of chemicals detected through air and water testing at those nearby sites. Moreover, those symptoms occurred at significantly higher rates in households closer to the gas facilities than those farther away.[1075] Indicative of the growing prevalence of such health impacts in the state, a poll showed that two-thirds of Pennsylvanians support a moratorium on fracking because of concern about negative health impacts.[1076]

[1073] Lindsay Abrams, "Fracking's Real Health Risk May Be from Air Pollution," *Salon*, August 26, 2013, sec. News, https://www.salon.com/2013/08/26/frackings_real_health_risk_may_be_from_air_pollution/.
[1074] Larysa Dyrszka, Kathleen Nolan, and Sandra Steingraber, "Statement on Preliminary Findings from the Southwest Pennsylvania Environmental Health Project Study," Press Release (Concerned Health Professionals of NY, August 27, 2013), https://concernedhealthny.org/2013/08/statement-on-preliminary-findings-from-the-southwest-pennsylvania-environmental-health-project-study/.
[1075] Nadia Steinzor, Wilma Subra, and Lisa Sumi, "Investigating Links between Shale Gas Development and Health Impacts through a Community Survey Project in Pennsylvania," *New Solutions: A Journal of Environmental and Occupational Health Policy* 23, no. 1 (2013): 55–83, https://doi.org/10.2190/NS.23.1.e.
[1076] Susan Phillips, "Poll Shows Support for a Drilling Moratorium in Pennsylvania," *State Impact Pennsylvania*, May 14, 2013, https://stateimpact.npr.org/pennsylvania/2013/05/14/poll-shows-support-for-a-drilling-moratorium-in-pennsylvania/.

Noise pollution, light pollution, and stress

Drilling and fracking operations and ancillary infrastructure expose workers and nearby residents to continuous noise and light pollution that is sustained for periods lasting many months. Chronic exposure to light at night is linked to adverse health effects, including breast cancer.

Sources of fracking-related noise pollution include blasting, drilling, flaring, generators, compressor stations, and truck traffic. Noise-mitigating sound barriers do not always resolve complaints of nearby residents. Exposure to environmental noise pollution is linked to cardiovascular disease, cognitive impairment, and sleep disturbance. In Colorado, noise measured during construction and drilling of a large, multi-well pad in a residential area exceeded levels knowns to increase the risk of cardiovascular diseases and hypertension.

Denton, Texas residents reported increased levels of stress and anxiety compared to periods of time prior to the arrival of drilling fracking in their community. In rural Canada, residents living near drilling and fracking operations experienced community upheaval and showed multiple signs of trauma. Oil and gas production noise may be disrupting wildlife health in protected areas. Workers and residents whose homes, schools, and workplaces are in close proximity to well sites are at risk from these exposures as well as from related stressors. Existing "setback distances" may not be adequate to reduce public health threats, especially for vulnerable populations. A UK Health Impact Assessment (HIA) identified stress and anxiety resulting from drilling-related noise—as well as from a sense of uncertainty about the future and eroded public trust—as key public health risks related to fracking operations. These results are corroborated by research in the United States showing links between fracking-related stress, lower self-reported health, a sense of helplessness, and distrust in regulatory agencies.

- May 5, 2021 – Induced earthquakes linked to gas extraction and related activities have caused structural damage to housing in the Netherlands. Using previously validated health measures, the first study to address the long-term, stress-related effects on residents experiencing this kind of property damage found evidence of negative health impacts over time. Self-rated health, mental health, and other stress-related health impacts were all greater in a study group of people who had experienced this kind of damage to their homes when compared to a control group whose members did not. These negative impacts increased over time. Those whose homes had repeated damage were 1.60 times more likely to report poor health, 2.11 times more likely to report negative mental health, and 2.84 times more at risk of elevated stress-related health symptoms. The study population was drawn from 25,000 residents of Groningen, Netherlands from a complete registry of all legal residents, and the resulting groups completed questionnaires at five time-points over two years. These findings, the researchers concluded, "suggest that for chronic disasters/hazards, negative effects can accumulate over time, presumably because the recurrent threat and poor crisis response leads to an accumulation of stress."[1077]

- January 19, 2021 – Drilling and fracking significantly increased light pollution in rural areas of the United States from 2000 to 2012, while in these same areas, residents experienced increased levels of insufficient sleep, according to a study that found a dose-response relationship between the number of horizontal wells and measures of insufficient sleep. Residents in counties with more than 100 wells were three percentage points more likely to report insufficient sleep, and six percentage points more likely to report sleep fewer than seven hours sleep per night. Light pollution has established links to human health: disruptions to melatonin levels and circadian rhythm are linked with mood regulation, depression and sleeping disorders, in addition to metabolic disease and cancer. This study also found that, in areas that had minimal light pollution prior to the shale gas boom, drilling increased the dispersion of nighttime lights by over 100 percent. Urging further research on light pollution from the shale gas industry, authors note that many drilling and fracking operations are sited within International Dark Sky Places where work practices continue around the clock and are dependent on intense artificial lighting and gas flaring.[1078]

- March 14, 2020 – Living in a community with extensive fracking was linked with lower self-rated health, according to an interdisciplinary research team.[1079] The team designed and carried out survey research with three northern Colorado communities with different historical and current levels of fracking: Greeley, Fort Collins, and Windsor. Self-rated health, the researchers explained, has been used successfully across multiple disciplines in thousands of studies. Research has shown there is a strong link between self-rated health and actual health status. Living in Greeley, surrounded by some 21,000 active drilling locations in 2015-2016 when the study was carried out, was associated with lower self-rated health compared to Fort Collins, which voted for a (subsequently overturned) ban on fracking, and has little drilling in the community. Perceived stress from fracking was also linked to lower self-rated health. A third finding was that trust in regulatory agencies improved self-rated health. Authors noted, "Recalling that people in our study who reported the least satisfaction with their health were low-income and also experiencing stress from [unconventional oil and gas extraction], we may see links to environmental injustice and specifically procedural inequity, regarding people's (lack of) control over their local environment and their perceived health impacts."

- March 4, 2020 – More than 300 residents filed noise complaints about new fracking activity near Broomfield, Colorado's northeast side, between fall 2019 and publication of

[1077] Katherine Stroebe et al., "Chronic Disaster Impact: The Long-Term Psychological and Physical Health Consequences of Housing Damage Due to Induced Earthquakes," *BMJ Open* 11 (2021), https://doi.org/10.1136/bmjopen-2020-040710.
[1078] Andrew Boslett, Elaine Hill, and Lujia Zhang, "Rural Light Pollution from Shale Gas Development and Associated Sleep and Subjective Well-Being," *Resource and Energy Economics* 64 (2021), https://doi.org/10.1016/j.reseneeco.2021.101220.
[1079] Adam Mayer et al., "Understanding Self-Rated Health and Unconventional Oil and Gas Development in Three Colorado Communities," *Society & Natural Resources* 34, no. 1 (2020): 60–81, https://doi.org/10.1080/08941920.2020.1734702.

this *KUNC* piece.[1080] The radio station obtained the information through a public records request, finding the community had not gotten relief, despite an overnight noise ordinance that went into effect in late January: "…the noise drones on, according to resident complaints." A municipal judge was, at time of publication, determining whether the new ordinance applied to the oil and gas operator responsible for the noise, as the company maintained they were in compliance with a previous agreement.

- February 13, 2020 – Residents of Denton, Texas reported increased stress and anxiety compared to periods of time prior to the introduction of fracking in the area.[1081] Defining "socio-psychological health" as "one's well-being pertaining to dimensions of both their mental (including emotional) and social health," the researchers sought to build on previous research identifying socio-psychological impacts from fracking, through in-depth, semi-structured interviews. Specific socio-psychological features of participants' experiences included concerns about the environmental health of the community, increased prevalence of personal ailments and physical disorders, and feelings of helplessness linked to lack of response from government officials. Areas where study results were mixed included optimism versus pessimism, and various measures of social cohesion. On the one hand, the "us versus them" construct was a common theme, and on the other, the participants, who were recruited via a town hall meeting, also reported instances of community members brought closer together through their concern and activism.

- January 15, 2020 – The Broomfield, Colorado, City Council "unanimously approved an emergency noise ordinance that will return the onus to a person or company to prove noise generated during restricted hours is below Broomfield's decibel standards."[1082] The ordinance does not specifically address the oil and gas industry but followed a spike in noise complaints from residents near an 18 gas well site. Hundreds of complaints included specific health symptoms that residents linked to the noise, including headaches, difficulty sleeping, and anxiety and stress.

- December 12, 2019 – The City of Broomfield, Colorado issued a statement reacting to the breaching of noise standards by an oil and gas company operating in the city. "We hear you, we acknowledge the impact and we are taking the steps to pursue all legal options to keep our community safe… Our residents are enduring continuous impacts which now includes disturbing noise, sometimes in the middle of the night. Immediate action is necessary," said City and County Manager Jennifer Hoffman addressing city residents in the press release.[1083] The City received over 35 official noise complaints and

[1080] Matt Bloom, "Broomfield Tried Limiting Oil And Gas Noise. Now A Company Is Pushing Back," *KUNC*, March 4, 2020, sec. Oil and Gas, https://www.kunc.org/oil-and-gas/2020-03-04/broomfield-tried-limiting-oil-and-gas-noise-now-a-company-is-pushing-back.

[1081] Mehmet Soyer, Kylen Kaminski, and Sebahattin Ziyanak, "Socio-Psychological Impacts of Hydraulic Fracturing on Community Health and Well-Being," *International Journal of Environmental Research and Public Health* 13, no. 17 (2020): 1186, https://doi.org/10.3390/ijerph17041186.

[1082] Jennifer Rios, "Broomfield Passes Emergency Noise Ordinance," *Broomfield Enterprise*, January 15, 2020, https://www.broomfieldenterprise.com/2020/01/15/broomfield-passes-emergency-noise-ordinance-oil-and-gas/.

[1083] Jennifer Hoffman, "Broomfield Notifies Extraction Oil and Gas That It Has Breached Its Operator Agreement by Exceeding Noise Standards," Press Release (City of Broomfield, Colorado, December 12, 2019), verified that there were over 80 noise level readings above the established thresholds in the previous two-week period.

- September 16, 2019 – Residents of Brooke County, West Virginia expressed dissatisfaction with "sound walls" put up to mitigate noise surrounding a local gas well pad. "Residents say one thing that is particularly concerning is the hours that the noise is most bothersome; when they are trying to sleep. It is affecting their sleep and in turn, their health."[1084] The company responsible, Southwestern Energy, stated that noise was not exceeding the levels set by county ordinance and that it would "continue to monitor the situation and work with elected officials."

- May 28, 2019 – Noise levels exceeded World Health Organization guidelines for two types of measurements, A-weighted and C-weighted noise, at four residences in Weld County, Colorado, during all four unconventional oil and gas development phases at a nearby 22-well pad with "sound walls" in place.[1085] This study also included air pollution and truck traffic measurements, finding the highest pollution levels (particulate matter and black carbon) and the greatest number of heavy trucks trip per hour during the fracking phase of operations. During daytime hours on weekdays, one of these measures at one of the four residential sites exceeded the guideline for A-weighted decibels at least 73 percent of the time for each well development phase, drilling, fracking, flowback, and production. During "the high impact phases" of drilling, fracking, and flowback, the second guideline, for C-weighted noise, was exceeded 65 more than half of the time "regardless of whether it was a weekday/weekend or a daytime/nighttime," except at one of the sites. Authors wrote, "The cumulative health effects from multiple stressors for individuals living near these facilities is not known. Furthermore, excessive noise levels and increased truck traffic during the night, when people are home and trying to sleep, could have compounding effects on health and quality of life."

- April 24, 2019 – Northern Colorado communities experienced disturbance including vibration from "massive thumper trucks doing seismic exploration" for the best sites to drill.[1086] One community member said, "Actually made me gasp because it was shaking so loudly… I've felt earthquakes in California and I would say it was similar to that." The company did not provide notification to the targeted neighborhoods until the Colorado Oil and Gas Conservation Commission sent a cease-and-desist letter. After complying with notification requirements, the company was allowed to move forward with the estimated four to six weeks of exploration.

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https://docs.google.com/document/d/1R2qrVSwPls5bI8dKhZ4GG5OrFia76TwGlC09P_JMD1o/mobilebasic?urp=gmail_link.

[1084] Julianna Furfari, "Residents Fed Up With Fracking Noise Push for Change," *WTOV9*, September 16, 2019, https://wtov9.com/news/local/residents-fed-up-with-fracking-noise-push-for-change.

[1085] William B. Allshouse et al., "Community Noise and Air Pollution Exposure During the Development of a Multi-Well Oil and Gas Pad," *Environmental Science & Technology* 53, no. 12 (2019): 7126–35, https://doi.org/10.1021/acs.est.9b00052.

[1086] Jennifer Kovaleski, "Oil and Gas 'Thumping Trucks' Rattle Colorado Homeowners," *TheDenverChannel.Com*, April 24, 2019, https://www.thedenverchannel.com/news/contact7/oil-and-gas-thumping-trucks-rattle-colorado-homeowners.

- October 8, 2018 – Researchers collected noise measurements from residential areas, inside and outside homes, near two different gas well pads and a compressor station, north and south of Pittsburgh, Pennsylvania. Measurements from all of the outside areas had at least some decibel levels exceeding the recommended limits of the U.S. Environmental Protection Agency (EPA), and one indoor measurement near the compressor station exceeded the recommended level for noise measured inside homes. An accompanying survey documented that 96 percent of respondents were "worried about their overall health as a result of the noise." Fifty-seven percent were bothered "a great deal" by the noise, and slightly more than half of respondents said that their sleep was disturbed "a great deal" by the noise.[1087]

- October 4, 2018 – In the month following one or more earthquakes greater than magnitude 4 experienced in an Oklahoma county, motor vehicle crashes increased 4.6 percent. Anxiety-inducing life events increase the risk of motor vehicle crashes, and earthquakes are known to increase anxiety. University of California, Berkeley public health researchers used data on Oklahoma earthquakes between 2010 and 2016, known to have drastically increased in the state due to fracking wastewater injection, and county-level monthly vehicle crash counts. Authors noted "the high economic and social costs of such vehicle crashes," which were $2.9 billion in Oklahoma in 2010.[1088]

- May 30, 2018 – Anxiety-related Google searches increased 5.8 percent during months when there was more than one magnitude 4 or higher earthquake experienced in Oklahoma, from January 2010 to May 2017. Google searches for anxiety peaked three weeks after magnitude 4 or higher quakes, University of California, Berkeley public health researchers found. Oil and gas wastewater injection has dramatically increased seismicity in Oklahoma; in the study period, there were 8,908 earthquakes across the state of Oklahoma, an average of 218 earthquakes per month. Authors noted, "excessive anxiety… may disable individuals and has long-term implications for health and functioning," and that "excessive symptoms of anxiety occur more readily in response to a recurrent and unpredictable stressor, such as the Oklahoma earthquakes included in our study."[1089]

- May 11, 2018 – Over 40 percent of daytime and 23.6 percent of nighttime audible noise measurements taken during construction and drilling of a large, multi-well pad in a residential area were found to exceed the level that research has demonstrated to increase the risk of health effects, such as cardiovascular diseases and hypertension. When the researchers used an additional measurement that captures low frequency noise levels, these results showed that 97.5 percent of daytime and 98.3 percent of nighttime

[1087] Cynthia M. Richburg and Jeremy Slagley, "Noise Concerns of Residents Living in Close Proximity to Hydraulic Fracturing Sites in Southwest Pennsylvania," *Public Health Nursing* 36, no. 1 (2018): 3–10, https://doi.org/10.1111/phn.12540.
[1088] Joan A. Casey et al., "Increased Motor Vehicle Crashes Following Induced Earthquakes in Oklahoma, USA," *Science of the Total Environment* 10, no. 650 (Part 2) (2019): 2974–79, https://doi.org/10.1016/j.scitotenv.2018.10.043.
[1089] Joan A. Casey, Sidra Goldman-Mellor, and Ralph Catalano, "Association between Oklahoma Earthquakes and Anxiety-Related Google Search Episodes," *Environmental Epidemiology* 2, no. 2 (2018): e016, https://doi.org/10.1097/EE9.0000000000000016.

measurements exceeded the level "recommended to minimize impacts such as nausea and headaches." The measurements collected during this study were from four locations, over three months, in residential areas with oil and gas development in Colorado. Researchers concluded that the distances from the well pad at which some of their measurements were taken, highlight "that homes in closer proximity to operations will likely experience noise exposure at levels of concern even with the implementation of sound mitigation best management practices."[1090]

- December 29, 2017 – Every participant reported experiencing effects in one or more of five categories—psychological stress, social stress, environment, physical health, and traffic—in a study of how residents of two adjacent counties in Ohio are impacted by unconventional natural gas development. Most respondents reported impacts in three or more of the five categories. Types of psychological stress reported included general stress and uncertainty about the future; feeling frustrated and manipulated after interactions with the oil and gas industry; experiencing stress from noise or light pollution; and regional displacement. Researchers found that experiences of social stress extended to include divisions among family or community; fears of, or direct experiences of, environmental health harms; observing dying, unhealthy trees; and traffic-related effects. Nearly all residents interviewed had experienced dangerous encounters with oil and gas truck drivers and observed that damaged roads had become increasingly common.[1091]

- July 28, 2017 – A Canadian case study of the social impacts of fracking in a conservative, upper middle class, rural region of southern Alberta found that residents experienced "complete upheaval in their beliefs, and for many, their experiences with contamination, and fears of future exposure, dominate their lives."[1092] Participants described acute impacts to their own health, to family members' health, to their livestock (including fertility problems), and to their land (included disrupted crop production and abrupt changes to the landscape). The study further reported that authorities failed to respond, "in a manner expected by the victims" to these problems. In addition, "corrosion of community" occurred at a time when victims needed community support the most. The author posited, following a consideration of the literature on toxic contamination and trauma, that her interviewees had experienced the three key indications of trauma: loss of agency, hyperarousal, and ontological insecurity linked to the negative effects on normal daily routines, a sense of order and continuity, and human dignity. The author noted that the contamination experienced by the interviewees reflected a "new normal of non-conventional fossil fuel industries."

[1090] Benjamin D. Blair et al., "Residential Noise From Nearby Oil and Gas Well Construction and Drilling," *Journal of Exposure Science & Environmental Epidemiology* 28 (2018): 538–47, https://doi.org/10.1038/s41370-018-0039-8.
[1091] Michael P. Fisher et al., "Psychosocial Implications of Unconventional Natural Gas Development: Quality of Life in Ohio's Guernsey and Noble Counties," *Journal of Environmental Psychology* 55 (2018): 90–98, https://doi.org/10.1016/j.jenvp.2017.12.008.
[1092] Debra J. Davidson, "Evaluating the Effects of Living With Contamination From the Lens of Trauma: A Case Study of Fracking Development in Alberta, Canada," *Environmental Sociology* 48, no. 2 (2017): 196–209, https://doi.org/10.1080/23251042.2017.1349638.

- May 5, 2017 – Oil and gas production was one of the main anthropogenic noise sources (though the proportion for which it was responsible was not determined) in a study that quantified the degree and extent of noise pollution in U.S. protected areas (PAs) and critical habitat for endangered species. Authors "compared noise pollution among land management and protection status and investigated sources responsible for generating noise across PAs." The team of biologists and engineers found that human-caused noise doubled background sound in 63 percent of U.S. protected areas, and produced a tenfold or greater increase in 21 percent of protected areas. These levels are "known to interfere with human visitor experience and disrupt wildlife behavior, fitness, and community composition." Researchers also found a 10-fold increase in sound levels in 14 percent of critical habitats of endangered species.[1093]

- April 3, 2017 – A University of Maryland team conducted a pilot study of noise pollution at eight homes located less than a half mile (750 meters) from natural gas compressor stations in West Virginia and compared decibel levels to those collected from homes located further away. They found that daytime and nighttime noise levels were higher at properties located closer to a compressor, as measured both inside and outside the homes. Five of six homes that were monitored for a full 24-hour period had combined day-night indoor average noise levels that exceed 60 decibels (dBA), which exceeds both EPA's recommended limits for chronic noise exposure as well those recommended by the World Health Organization. To date, no federal noise standards exist for oil and gas operations. Noting that noise exposure has been associated in previous studies with sleep disruption, poor academic performance, and hypertension, the authors conclude, "Findings indicate that living near natural gas compressor stations could potentially result in high environmental noise exposures. Larger studies are needed to confirm these findings and evaluate potential health impacts and protections measures."[1094]

- December 9, 2016 – A review analyzing the relevant scientific literature on the potential public health impacts of ambient noise related to unconventional oil and gas development found that "oil and gas activities produce noise at levels that may increase the risk of adverse health outcomes, including annoyance, sleep disturbance, and cardiovascular disease." The team of environmental and occupational health scientists collected available measurements of noise levels at oil and gas operations and analyzed the data with established noise standards. Authors stated that many noise sources from fracking operations are similar to those of conventional oil and gas development, but that high-volume hydraulic fracturing activities present additional noise risks. These arise from conditions including four to five times the length of time needed to drill the well, and the much greater volume of water and higher pressures needed, compared to a traditional vertical well. They described the complexity of noise associated with oil and gas operations, including both intermittent and continuous noise, varying in intensities. The review included focus on vulnerable populations, including children, the elderly, and the chronically ill. Authors noted that existing "setback distances" – already often the result

[1093] Rachel T. Buxton et al., "Noise Pollution Is Pervasive in U.S. Protected Areas," *Science* 356, no. 6337 (2017): 531–33, https://doi.org/10.1126/science.aah4783.
[1094] Meleah D. Boyle et al., "A Pilot Study to Assess Residential Noise Exposure Near Natural Gas Compressor Stations," *PLoS ONE* 12, no. 4 (2017): e0174310, https://doi.org/10.1371/journal.pone.0174310.

of political compromise and not evidence-based – may be insufficient to reduce public health threats, and that maximum allowable noise levels should be lower for schools and hospitals.[1095]

- July 9, 2015 – As part of its assessment of potential health impacts, the California Council of Science and Technology looked at the impacts of noise and light pollution from oil and gas operations in California. The researchers noted that a number of activities associated with drilling and fracking generated noise at levels considered dangerous to public health. Noise is a biological stressor that can aggravate or contribute to the development of hypertension and heart problems. In California, noise from well stimulation was associated with both sleep disturbance and cardiovascular disease in a dose-response relationship. Exposure to artificial light at night has been linked to breast cancer in women, although almost no research has been conducted on the public health implications of light pollution from oil and gas extraction specifically.[1096]

- December 17, 2014 – The New York State Department of Health (NYS DOH) identified community impacts related to noise as a potential contributor to a variety of negative health impacts from drilling and fracking operations but noted that considerable scientific uncertainty remains on the issue of noise exposure per se as a risk factor. Noise, air pollution, traffic, vibration, odors, and nighttime lighting may all increase together as proximity to a drilling site decreases.[1097]

- December 1, 2014 – Range Resources Corporation warned supervisors in Pennsylvania's Donegal Township that a "big burn" natural gas flare will continue for as long as a week and "will produce a continuous noise of as much as 95 decibels at the well pad. Sustained decibel levels between 90 and 95 can result in permanent hearing loss, but workers will be equipped with ear protection." Township supervisor Doug Teagarden expressed concern for residents, saying, "They told us the flare would be double the size of other well flares, and the noise will be like a siren on a firetruck…. There are houses within a couple of hundred yards of the well pad, and those folks are going to hear it."[1098]

- November 6, 2014 – Sakthi Karunanithi, Director of Public Health in Lancashire, UK, reported on a Health Impact Assessment (HIA) of the two proposed shale gas exploration sites in Lancashire. Karunanithi's study determined that key risks to the health and well-being of the residents who live near the two proposed sites in Lancashire include stress and anxiety from uncertainty that could lead to "poor mental wellbeing," and noise-

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[1095] Jake Hays, Michael McCawley, and Seth B. C. Shonkoff, "Public Health Implications of Environmental Noise Associated With Unconventional Oil and Gas Development," *Science of the Total Environment* 580 (2017): 448–56, https://doi.org/10.1016/j.scitotenv.2016.11.118.
[1096] Shonkoff et al., "Chapter 6: Potential Impacts of Well Stimulation on Human Health in California."
[1097] New York State Department of Health, "A Public Health Review of High Volume Hydraulic Fracturing for Shale Gas Development."
[1098] Don Hopey, "Gas Flare to Light up Part of Washington County," *Pittsburgh Post-Gazette*, December 1, 2014, http://powersource.post-gazette.com/powersource/companies-powersource/2014/12/01/Gas-flare-to-light-up-part-of-Washington-County/stories/201411250224.

related health effects due to continuous drilling. The HIA also noted a lack of public trust and confidence.[1099, 1100]

- September 2014 – The Ohio Shale Country Listening Project, a collaborative effort to solicit, summarize, and share the perspectives and observations of those directly experiencing the shale gas build out in eastern Ohio, found that the more shale gas wells a community has, the less popular the oil and gas industry becomes. Many residents reported that they had not experienced the economic benefits promised by the oil and gas industry. They complained of increased rents and costs of gas and groceries, an influx of out-of-state workers, more vehicular accidents, road destruction from large trucks, and damaged landscape and cropland. Locals reported feeling less secure and more financially strapped.[1101]

- June 20, 2014 – In its discussion of "Oil and Gas Drilling/Development Impacts," the U.S. Office of Indian Energy and Economic Development detailed noise pollution from bulldozers, drill rigs, diesel engines, vehicular traffic, blasting, and flaring of gas. "If noise-producing activities occur near a residential area, noise levels from blasting, drilling, and other activities could exceed the U.S. Environmental Protection Agency (EPA) guidelines. The movement of heavy vehicles and drilling could result in frequent-to-continuous noise…. Drilling noise would occur continuously for 24 hours per day for one to two months or more depending on the depth of the formation."[1102] Exposure to chronic noise can be deadly. The World Health Organization has documented the connection between environmental noise and health effects, including cardiovascular disease, cognitive impairment, sleep disturbance, and tinnitus. At least one million "healthy life years" are lost every year from traffic-related noise in the western part of Europe.[1103]

- February 24, 2014 – In a review of the health effects from unconventional gas extraction published in the journal *Environmental Science & Technology*, leading researchers noted, "Noise exposure is a significant hazard due to the presence of multiple sources, including heavy equipment, compressors, and diesel powered generators. Loud continuous noise

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[1099] Sakthi Karunanithi, "Potential Health Impacts of the Proposed Shale Gas Exploration Sites in Lancashire" (Item 9 on the Agenda, Report of the Director of Public Health, Lancashire County Council Cabinet, 2:00 pm in Cabinet Room "B" County Hall, Preston,Lancashire County, UK, November 6, 2014), ://council.lancashire.gov.uk/documents/b11435/Potential%20Health%20Impacts%20of%20the%20Proposed%20Shale%20Gas%20Exploration%20Sites%20in%20Lancashire%2006th-Nov-2014%2014.pdf?T=9.

[1100] Elaine Dunkley, "Fracking in Lancashire 'May Affect Mental Health', Report Finds," *BBC News*, November 7, 2014, sec. Lancashire, http://www.bbc.com/news/uk-england-lancashire-29944212.

[1101] Ohio Organizing Collaborative (OOC)'s Communities United for Responsible Energy (CURE), with support from the Ohio Environmental Council (OEC), FracTracker.org, and Laborers Local 809 of Steubenville, "Ohio Shale Country Listening Project," September 2014, https://web.archive.org/web/20150206015846/http://carrollconcernedcitizens.org/uploads/2014_Shale_Report__small_.pdf.

[1102] Office of Indian Energy and Economic Development, "Oil and Gas Drilling/Development Impacts," Tribal Energy and Environmental Information Clearinghouse, 2014, https://web.archive.org/web/20141008163453/http://teeic.indianaffairs.gov/er/oilgas/impact/drilldev/index.htm.

[1103] Guénaël R. M. Rodier, "Burden of Disease From Environmental Noise: Quantification of Healthy Life Years Lost in Europe" (WHO, June 1, 2011), https://www.euro.who.int/__data/assets/pdf_file/0008/136466/e94888.pdf.

has health effects in working populations. It is likely that exposure to noise is substantial for many workers, and this is potentially important for health because drilling and servicing operations are exempt from some sections of the Occupational Safety and Health Administration noise standard." They noted that research should investigate stressors such as noise and light in the context of drilling and fracking operations in order to understand the overall effect of chemical and physical stressors together.[1104]

- May 30, 2014 – The *Denver Post* reported that in order to help meet Colorado's noise limits for fracking operations in suburban neighborhoods (and partially block the glare of floodlights), Encana Oil and Gas erected 4-inch-thick polyvinyl walls up to 32 feet high and 800 feet long. Residents said that the plastic walls do not completely solve the problem.[1105]

- October 25, 2013 – An analysis of well location and census data by the *Wall Street Journal* revealed that at least 15.3 million Americans now live within a mile of a well that has been drilled since 2000. According to this investigation, the fracking boom has ushered in "unprecedented industrialization" of communities across wide swaths of the nation and, with it, "24/7" industrial noise, stadium lighting, earth-moving equipment, and truck traffic.[1106]

- April 16, 2013 – In a presentation on oil field light pollution for a conference on "Sustainable Environment and Energy: Searching for Synergies," Roland Dechesne of the Royal Astronomical Society of Canada described problems of "light trespass," glare, and poorly-aimed fixtures in oil fields in Alberta. He described resulting "mass waterfowl mortality" linked to artificial illumination and other biochemical impacts of light pollution on wildlife, as well as the possibility of these effects on humans, including circadian disruption, melatonin suppression, and possible resulting hormonally-linked diseases.[1107] Known to have ecological impacts, outdoor light pollution from drilling and fracking operations may also be linked to artificial light-associated health effects documented in humans, including breast cancer.[1108]

- April 2013 – Led by the University of Pittsburgh Graduate School of Public Health, a study of community members living in proximity to Marcellus Shale drilling in Pennsylvania found adverse impacts to mental health, with stress the most frequently reported symptom. At least half of all respondents in each set of interviews reported these specific stressors, including: being taken advantage of; health concerns;

[1104] John L. Adgate, Bernard D. Goldstein, and Lisa M. McKenzie, "Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development," *Environmental Science & Technology* 48, no. 15 (2014): 8307–20, https://doi.org/10.1021/es404621d.
[1105] Bruce Finley, "Oil and Gas Industry Building Giant Walls to Try to Ease Impact," *The Denver Post*, May 29, 2014, sec. Environment, http://www.denverpost.com/ci_25859469/oil-and-gas-industry-building-giant-walls-try.
[1106] Russell Gold and Tom McGinty, "Energy Boom Puts Wells in America's Backyards," *The Wall Street Journal*, October 25, 2013, http://online.wsj.com/news/articles/SB10001424052702303672404579149432365326304.
[1107] Roland Dechesne, "Limiting Oil Field Light Pollution for Safety and the Environment," in *Sustainable Environment and Energy CPANS 2013 Conference*, 2013.
[1108] Ron Chepesiuk, "Missing the Dark: Health Effects of Light Pollution," *Environmental Health Perspectives* 117, no. 1 (2009): A20–27, https://doi.org/10.1289/ehp.117-a20.

concerns/complaints ignored; corruption; denied information or provided with false information. Many also reported the desire to move or leave community, estrangement from community, and financial damages. Researchers noted that stress can result in direct health impacts.[1109] Notably, mounting evidence indicates that chronic stress magnifies individuals' susceptibility to effects of pollution; for children, this interactive effect can begin during prenatal life.[1110]

- September 7, 2011 – A study by researchers at Boise State University and Colorado State University at Fort Collins modeled the potential impacts of compressor station noise from oil and gas operations on Mesa Verde National Park in Colorado. The study found the sound of 64 compressors outside Mesa Verde elevated the sound level within the park by 34.8 decibels on average, and by 56.8 decibels on the side of the park located closest to the compressors. According to the EPA, 55 decibels is the highest "safe noise level" to avoid damage to the human ear.[1111]

1109 Kyle J. Ferrar et al., "Assessment and Longitudinal Analysis of Health Impacts and Stressors Perceived to Result From Unconventional Shale Gas Development in the Marcellus Shale Region," *International Journal of Occupational and Environmental Health* 19, no. 2 (2013): 104–12, https://doi.org/10.1179/2049396713Y.0000000024.

1110 Catherine M. Cooney, "Stress–Pollution Interactions: An Emerging Issue in Children's Health Research," *Environmental Health Perspectives* 119, no. 10 (2011): a430–35, https://doi.org/10.1289/ehp.119-a430.

1111 Jesse R. Barger et al., "Anthropogenic Noise Exposure in Protected Natural Areas: Estimating the Scale of Ecological Consequences," *Landscape Ecology* 26 (2011): 1281, https://doi.org/10.1007/s10980-011-9646-7.

Earthquakes and seismic activity

As shown in an increasing number of studies from Canada, China, the United Kingdom, and the United States, fracking has triggered earthquakes. In November 2019, the UK government declared a moratorium on fracking after an agency report on fracking-related earthquakes in Lancashire concluded that it was not possible to predict their likelihood or size.

Definitive evidence from Ohio, Arkansas, Texas, Oklahoma, Kansas, and Colorado links fracking wastewater disposal wells to earthquakes of magnitudes as high as 5.8, in addition to swarms of minor earthquakes. Both the U.S. Geological Survey (USGS) and state geological agencies such as the Oklahoma Geological Survey now acknowledge that earthquakes can be caused by wastewater injection into disposal wells. Between 2017 and 2020, the number of earthquakes linked to fracking wastewater injection more than tripled in Oklahoma, Texas, Louisiana, and New Mexico. Current trends in this region show increasing frequency of fracking-related earthquakes as well as increasing strength.

Many recent studies focus on the mechanical ability of pressurized fluids to trigger seismic activity by unclamping stressed faults. Fracking wastewater does not always stay put after it is injected into a disposal well. Because briny wastewater can be denser than other fluids within geological formations, it can continue sinking after disposal, finding its way into deeper geological layers, creating pressure fronts that can risk the rupture of deeper faults that are linked to higher-magnitude quakes.

Emerging evidence suggests that frequency of induced earthquakes can continue to rise for years after waste injection, that these earthquakes can take place at distances far from the site of waste injections, and that earthquake risks cannot be prevented through "proper" fracking protocols or by solely limiting the rate or volume of injected fluid. 2021 studies from Canada show that elevated earthquake activity in heavily fracked regions continued during a period of industry quiescence brought on by the COVD-19 pandemic.

Injecting fracking waste into shallower zones is one method for reducing earthquake risk, but shallow injection raises the risk for groundwater contamination. The question of what to do with fracking wastewater remains a problem with no viable, safe solution.

- June 10, 2021 – According to Norwegian energy research firm Rystad Energy, earthquakes attributed to fracking waste disposal in Oklahoma, Texas, Louisiana, and New Mexico more than tripled in frequency over a three-year period. In 2020, 938 earthquakes above magnitude 2.0 were recorded in the region, up from 242 in 2017. This 3.85-fold increase in seismic activity coincides with a period of steadily increasing volumes of wastewater pumped into underground injection wells. Injection volumes in the United States have increased almost 50 percent over the past decade to 11.3 billion barrels last year, more than double the volume of oil that was produced. Some oil companies report recycling the wastewater, for use in additional oil drilling, crop irrigation, or other purposes, but in 2020, only 1.5 billion barrels of wastewater (less than 15 percent of barrels produced) were recycled, according to Rystad. "Around 570 similar induced tremors have been recorded through the first five months of 2021, meaning we may see a new record this year if the trend continues," the report read. "The trend appears to be moving not only to more frequent, but also larger events."[1112]

- May 26, 2021 – An analysis of trends based on detailed records of 2,865 wells and 439 earthquakes in the Peace River region prompted a former senior scientist with British Columbia's oil and gas commission, Allen Chapman, to predict that induced earthquakes of magnitude 5.0 or greater will very likely to occur in the future if current fracking activities in the region continue unabated. In an rebuke of reliance on so-called "traffic light" protocols as a form of earthquake management, Chapman warned that fracking-induced earthquakes of large magnitudes can and do occur without precursor warning and thus represent significant risks to public safety and infrastructure. Noting the likelihood of industry unwillingness to alter their practices due to the necessity of a "high degree of brute force" to hit production goals and financial targets, Chapman recommended the establishment of "frack-free zones proximal to populations and critical infrastructure."[1113]

- May 17, 2021 – Researchers in the United Kingdom used detailed microseismic data from a single fracking site in Lancashire to conclude that pore pressure increases are the likely mechanism for the earthquakes induced at the site, with "each operation activat[ing] different faults with different orientations." Despite examining a single site in detail with extensive data from prospective monitoring, the researchers stress that establishing the causative processes for induced seismicity is a complex and challenging computational task because multiple physical processes during hydraulic fracturing act in tandem to reactivate faults.[1114]

- May 10, 2021 – Increases in the pressures of fluid within the pores of deep geological strata is commonly invoked as the main driver for induced earthquakes triggered by the injections of fracking wastewater. However, a comprehensive investigation of a surge of earthquakes in the Delaware Basin in Texas from 1993 to 2020 revealed that changes in poroelastic stresses that can refer to other hydraulically isolated rock layers, rather than changes in pore pressure per se, can be the dominant stress change that induces earthquakes in some cases. Poroelastic stresses refer to fluid-mediated deformation of solid materials. That is, human activities in shallow geological strata can cause poroelastic stresses that trigger unexpected, unpredictable, and uncontrollable responses in isolated, sometimes distant, tectonic regions, especially if major faults are present, and sometimes after long time delays. "We show that the widespread deep seismicity is mainly driven by shallow wastewater injection through the transmission of poroelastic stresses assuming that unfractured shales are hydraulic barriers over decadal time scales."

[1112] Ryan Hassler, "Treating the US Oil Industry's Dark Water: As Earthquakes Increase, Billions Needed to Switch Course" (Rystad Energy, June 10, 2021), https://www.rystadenergy.com/newsevents/news/press-releases/treating-the-us-oil-industrys-dark-water-as-earthquakes-increase-billions-needed-to-switch-course/.
[1113] Allan R Chapman, "Hydraulic Fracturing, Cumulative Development and Earthquakes in the Peace River Region of British Columbia, Canada," *Journal of Geoscience and Environment Protection* 9 (2021): 55–82, https://doi.org/10.4236/gep.2021.95006.
[1114] Tom Kettlety and James P. Verdon, "Fault Triggering Mechanisms for Hydraulic Fracturing-Induced Seismicity From the Preston New Road, UK Case Study," *Frontiers in Earth Science* 9 (2021), https://doi.org/10.3389/feart.2021.670771.

Relying on industrial, seismic, geodetic, and geological data to develop new, integrated models of induced seismicity led researchers to conclude that "induced seismic hazard can be minimized by injecting fluids into porous sediments rather than a low-porosity basement."[1115]

- April 1, 2021 – A fracking wastewater injection well in Youngstown, Ohio caused a magnitude 4.0 earthquake on December 31, 2011, just prior to ceasing operation. Now abandoned and with no identifiable owner, the 9,200-foot-deep well was ordered sealed two years ago and yet remains open, with the well's former operators in prison and the company charged with plugging the well in bankruptcy.[1116]

- March 31, 2021 – During the early months of the global Covid-19 pandemic, from April to August 2020, fracking and wastewater disposal operations virtually halted in Alberta and northeast British Columbia, yet seismic stations recorded 389 earthquakes in those two Canadian provinces. Researchers observed that seismic events during this period of industry quiescence seem to share many characteristics with seismicity generated during fracking operations. According to their analysis 65 percent of the seismicity detected during the lockdown period is attributable to latent ongoing geological processes related to prior fluid injection. They posit mechanisms such as aseismic slip, with fault and fracture weakening over extended distances, to explain how an elevated background seismicity rate has become the "new normal" with earthquake activity continuing even during a period of temporarily ceased fracking and wastewater disposal activities.[1117]

- March 21, 2021 – Citing research from 2018 demonstrating that injected wastewater can cause sufficient pressure to trigger earthquakes more than 55 miles away [Note for authors: fn # 924 in V7 of Compendium], regulators in Kansas reversed their original interpretation of the origin of a series of more than a dozen earthquakes occurring in Wichita at the end of 2020. Additional earthquakes in 2021 pointed to injection of wastewater as the likely cause of the earthquake swarm. According to Rick Miller, senior scientist and seismologist at Kansas Geological Survey, the oil and gas industry accounts for a majority of wastewater wells in Kansas, although other industries, such as chemical, petrochemical, and food processing, also dispose of wastewater in underground wells. Which industry is responsible for inducing the large increase in earthquakes in Kansas in 2020 and 2021 remains unknown.[1118]

[1115] Guang Zhai, Manoochehr Shirzaei, and Michael Manga, "Widespread Deep Seismicity in the Delaware Basin, Texas, Is Mainly Driven by Shallow Wastewater Injection," *PNAS* 118, no. 20 (2021), https://doi.org/10.1073/pnas.2102338118.
[1116] Justin Dennis, "A Quake-Causing Injection Well in Youngstown Remains Unsealed 2 Years After Its Deadline. Here's Why," *Mahoning Matters*, April 1, 2021, https://www.mahoningmatters.com/local-news/a-quake-causing-injection-well-in-youngstown-remains-unsealed-2-years-after-its-deadline-heres-why-3595487.
[1117] Rebecca O. Salvage and David W. Eaton, "Unprecedented Quiescence in Resource Development Area Allows Detection of Long-Lived Latent Seismicity," *Solid Earth* 12 (2021): 765–83, https://doi.org/10.5194/se-12-765-2021.
[1118] Sarah Spicer, "State Said Wichita Earthquakes Were Likely Natural. New Evidence Suggests Otherwise," *The Wichita Eagle*, March 21, 2021, https://www.kansas.com/news/politics-government/article250044639.html.

- November 11, 2020 – An examination of more than 40 years of data from California demonstrated extremely high correlations between oilfield waste injection and the occurrence of earthquakes near the San Andreas Fault. As in Oklahoma, the size of the spatial footprint of induced seismicity is quite large, in California reaching to distances up to 24 kilometers (almost 15 miles). Researchers observed deformation of the surface of the earth in close proximity to the wastewater injection wells, with significant surface uplift.[1119] Separately, a co-author of this study argued that California's natural earthquake activity may have been masking industry-induced quakes.[1120] However, this new research reveals that fluid-injection operations, even though they take place near seismically active, well-known faults in California, are activating smaller unmapped faults and elevating injection-induced seismic hazards. The authors note that injection of waste directly above the geological basement layer, high-rate, broadscale injection into permeable zones, and the presence of tectonically stressed faults are likely all contributing factors and suggest that operators look for more stable regions in which to inject wastewater.

- September 2, 2020 – Seismic hazard risk assessment has until recently focused almost exclusively on risk exposure related to naturally occurring tectonic earthquakes. However, the timing and location of induced earthquakes offer unique opportunities for intervention because they are functions of economic forces as well as public policy decisions. Hence, earthquakes are an environmental justice issue. In Oklahoma, investigators found that induced seismicity disproportionately impacts communities with "low-income, female-headed and African-American households, workers employed in the primary economic sector, and Hispanic populations of employed men." Moreover, vulnerable populations may have decreased ability to participate in the generation of mitigation plans or to choose to move elsewhere. Authors recommend targeting areas of high exposure to earthquake exposures and high social vulnerability for measures to lessen risk, reduce social vulnerability, or both.[1121]

- August 5, 2020 – Researchers studied the characteristics of wastewater, particularly pressure, temperature, and composition, to identify whether fluid properties can contribute to the generation of induced seismicity in laboratory simulations. They found that oilfield wastewater with higher concentrations of total dissolved solids than are present in the fluids held within subsurface basement layers can result in density-driven pressure gradients that, along with fracture permeability, contribute to the generation of induced earthquakes. These findings help to explain the observed transfer of high pressure from wastewater injection across long distances (exceeding 10 to15 kilometers, or approximately 6 to 9 miles). In some modeled scenarios, fluid pressure could be expected to increase locally below injection wells for up to 20 years after the end of

[1119] Goebel and Shirzaei, "More than 40 Yr of Potentially Induced Seismicity Close to the San Andreas Fault in San Ardo, Central California."
[1120] Thomas H. Goebel, "Oil Field Operations Likely Triggered Earthquakes in California a Few Miles From the San Andreas Fault," *The Conversation*, November 10, 2020, https://theconversation.com/oil-field-operations-likely-triggered-earthquakes-in-california-a-few-miles-from-the-san-andreas-fault-149207.
[1121] Sahar Derakhshan, Michael E. Hodgson, and Susan L. Cutter, "Vulnerability of Populations Exposed to Seismic Risk in the State of Oklahoma," *Applied Geography*, 2020, https://doi.org/10.1016/j.apgeog.2020.102295.

injections. Injecting high-density brines into geologic formations with "seismogenic" basements (typically characterized by low-density brines) creates conditions that may result in fluid pressure transients sufficient to trigger earthquakes.[1122]

- July 14, 2020 – Geologists in Alberta investigated a swarm of earthquakes that persisted over 10 months following the cessation of fracking activities in western Canada and determined persistent aseismic slip to be the likely primary causative mechanism rather than fluid migration or other mechanisms. Their model posits that increased pore pressure from fracked wells loads faults in unstable regions, causing seismicity with lateral confinement of the creeping region eventually resulting from increased pore pressure. Some swarms (both induced and naturally occurring) previously ascribed to a pore pressure migration model might better be understood as generated by aseismic slip. This model suggests that current mitigation strategies, such as "traffic light protocols," for mitigating induced seismicity caused by fracking may be "sub-optimal" because these protocols "assume that a larger magnitude earthquake is preceded by smaller precursory events, and that changes in operations … have an immediate effect on the source process of induced events." These assumptions are not borne out by current evidence.[1123]

- May 31, 2020 – An analysis of USGS earthquake catalogs for 17 major fracking locations across the United States for the period from 1998 to 2018 shows statistical associations between fracking locations (including wastewater disposal sites) and increased earthquake activity. The association between fracking activities and earthquakes is particularly strong in Texas, Oklahoma, and Kansas.[1124]

- May 7, 2020 – It is not currently possible to confidently forecast the occurrence or maximum size, of a fracking-induced earthquake, nor are retrospective strategies sufficient "to protect critical or vulnerable infrastructure that have unacceptable failure consequences," according to a review published in *Nature Reviews Earth & Environment*. The review by three Canadian geoscientists determined that induced earthquakes, once triggered, are similar to their natural counterparts, although their hazards "might greatly exceed the natural earthquake hazard in regions of low to moderate seismicity." "Traffic light protocols," in which fracking operators reduce injection for an amber light or stop injection for a red light in response to predefined thresholds of quakes and population density, have not been successful, according to the review.[1125] Referring to this work, a Canadian investigative report outlined the deficits of

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[1122] Ryan M. Pollyea et al., "A New Perspective on the Hydraulics of Oilfield Wastewater Disposal: How PTX Conditions Affect Fluid Pressure Transients That Cause Earthquakes," *Energy & Environmental Science* 13 (2020): 3014–31, https://doi.org/10.1039/D0EE01864C.
[1123] Thomas S. Eyre et al., "A Long-Lived Swarm of Hydraulic Fracturing-Induced Seismicity Provides Evidence for Aseismic Slip," *Bulletin of the Seismological Society of America* 110, no. 5 (2020): 2205–15, https://doi.org/10.1785/0120200107.
[1124] Valeria Villa and Ramesh P. Singh, "Hydraulic Fracturing Operation for Oil and Gas Production and Associated Earthquake Activities Across the USA," *Environmental Earth Sciences* 79 (2020): 271, https://doi.org/10.1007/s12665-020-09008-0.
[1125] Gail M. Atkinson, David W. Eaton, and Nadine Igonin, "Developments in Understanding Seismicity Triggered by Hydraulic Fracturing," *Nature Reviews Earth & Environment* 1, no. 5 (2020): 264–77, https://doi.org/10.1038/s43017-020-0049-7.

British Columbia's practice of limiting fracking only after earthquakes have been triggered, adding to decades-long concern about the troubled Site C dam project in northeastern British Columbia, in a region of increasing earthquakes.[1126] Increasing understanding of the mechanisms by which induced seismicity can destabilize previously stable geologic formations also contributes to concerns about Site C dam. The review states that "it is clear that hazard mitigation, via the use of forecasting models to control the magnitude of the largest possible event, is in its infancy," and cannot, for example, account for the unpredictable nature of fault propagations possibly related to rupture of entire fault plains. Thus, limiting (yellow light) or stopping (red light) fracking activities upon the occurrence of small, induced earthquakes may not prevent future and possibly larger earthquakes from occurring.

- April 21, 2020 – Researchers employed satellite-based InSAR (Interferometric Synthetic Aperture Radar) to monitor surface deformation to study three sites in western Texas. They then correlated observed patterns of deformation with earthquake distributions and other factors to distinguish the causes of deformation. Groundwater withdrawals appear to have played a role in geologic changes, including subsidence, while wastewater injection (disposal) probably played a dominant role at two sites. Similarities and differences at the three studied sites "suggest the importance of local rock structures and properties in determining seismic behavior and sensitivity to injection."[1127]

- March 10, 2020 – Comparing the ground motion and damage potential of naturally occurring and induced earthquakes based on instrumental data and felt reports, a Canadian geologist concluded that both types of seismic activity have "significant damage potential within 10 km [over six miles]," at magnitude 5.0, while events of magnitude 5.5 would have "damage potential to a distance of 20 km [over 12 miles]." Detailing damage from induced earthquakes around the globe, the author noted damage in Oklahoma to brick buildings with accompanying soil liquefaction and slumping; injury to 135 people in Korea, with damage to 57,000 structures; and collapse of houses, landslides, and injuries to 19 people in China. To preclude earthquake damage, the author wrote, hazard mitigation measures must aim to prevent the occurrence of induced earthquakes of magnitude 3.5 or greater within approximately 5 kilometers (3 miles) of vulnerable structures.[1128]

- February 25, 2020 – Scientists used a variety of seismological techniques to conclude with a newly emerging cluster of earthquakes in Alberta, Canada, are "almost certainly" the result of nearby hydraulic fracturing activities.[1129] The largest event ascribed directly

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[1126] Andrew Nikiforuk, "Thousands of Quakes, Tied to Fracking, Keep Shaking the Site C Dam Region," *The Tyee*, August 13, 2020, https://thetyee.ca/News/2020/08/13/Quakes-Fracking-Site-C-Dam-Region/.
[1127] Fanghui Deng, Timothy H. Dixon, and Surui Xie, "Surface Deformation and Induced Seismicity Due to Fluid Injection and Oil and Gas Extraction in Western Texas," *Journal of Geophysical Research: Solid Earth* 125, no. 5 (2020): e2019JB018962, https://doi.org/10.1029/2019JB018962.
[1128] Gail M. Atkinson, "The Intensity of Ground Motions from Induced Earthquakes with Implications for Damage Potential," *Bulletin of the Seismological Society of America* 110, no. 5 (2020): 2366–79, https://doi.org/10.1785/0120190166.
[1129] Ryan Schultz and Ruijia Wang, "Newly Emerging Cases of Hydraulic Fracturing Induced Seismicity in the Duvernay East Shale Basin," *Tectonophysics* 779 (2020): 228393, https://doi.org/10.1016/j.tecto.2020.228393.

to fracking measured magnitude 4.18 ML, believed to have resulted from thrust-slip on a fault underlying the target formation. In March 2019, Alberta introduced a new "traffic light" regulatory framework to interrupt fracking activities associated with earthquakes of increasingly high magnitude.

- January 9, 2020 – BC Hydro, the publicly owned Canadian electric utility in the province of British Columbia, knew for "well over a decade that its Peace Canyon dam is built on weak, unstable rock and that an earthquake triggered by a nearby natural gas industry fracking or disposal well operation could cause the dam to fail." This information, obtained through freedom of information legislation, had not been shared with various relevant governmental entities and panels, nor even a construction manager at the dam. Hundreds of emails, letters, memos and meeting notes documented concerns discussed at the highest levels, and that the utility's dam safety specialist wrote "email after email to his superiors expressing fear about how encroaching fracking operations could destabilize BC Hydro's Peace Canyon dams."[1130]

- December 14, 2019 – Researchers used improved catalogs of earthquake activity and multistation template matching to determine that while the vast majority of earthquakes in western and southern Texas between 2015 and 2018 were associated with wastewater disposal, "at least ~5% of the seismicity was induced directly by hydraulic fracturing." While geologic features may act to influence the occurrence and location of induced seismicity, fracking induced seismicity is pervasive in the neighboring state of Oklahoma, and the researchers suggest that the frequency of earthquakes and the number of earthquakes greater than magnitude 3 will continue to increase if industry operations continue unaltered.[1131]

- November 13, 2019 – Fracking induced 94 earthquakes with a magnitude greater than 2.0 from 2014 through 2018 in the Eagle Ford Shale.[1132] This included what may have been the largest fracking-related earthquake in the United States, a magnitude 4.0 quake that occurred near the site of a 4.8 quake that occurred in 2011, thought to be induced by fluid extraction. The research team wrote that their study "demonstrates that faults in this area are capable of producing felt and potentially damaging earthquakes due to ongoing [fracking]." In addition, they proposed that fracking by "simultaneous stimulation of multiple laterals" was three times more to cause earthquakes than a single well strategy.

- November 4, 2019 – Considerably expanding understanding of the history of the Pecos earthquake cluster in west Texas, researchers demonstrated that anomalous earthquakes began in 2009 and increased dramatically, with more than 2,000 earthquakes in 2017. The largest of these had a local magnitude of 3.7, but the overall activity pattern did not

[1130] Ben Parfitt, "Peace Canyon Dam at Risk of Failure From Fracking-Induced Earthquakes, Documents Reveal," *The Narwhal*, January 9, 2020, https://thenarwhal.ca/peace-canyon-dam-at-risk-of-failure-from-fracking-induced-earthquakes-documents-reveal/.
[1131] Robert J. Skoumal et al., "Induced Seismicity in the Delaware Basin, Texas," *Journal of Geophysical Research: Solid Earth* 125, no. 1 (2019), https://doi.org/10.1029/2019JB018558.
[1132] Shannon L. Fasola et al., "Hydraulic Fracture Injection Strategy Influences the Probability of Earthquakes in the Eagle Ford Shale Play of South Texas," *Geophysical Research Letters* 46, no. 22 (2019): 12958–67, https://doi.org/10.1029/2019GL085167.

rule out future earthquakes of larger magnitude. The team observed that seismic activity, petroleum production, fluid waste injection, and hydrofracturing activity all rose in tandem, suggesting that fracking-related activities may be responsible for inducing this unusual earthquake activity between 2009 and 2017. They did not speculate which specific activities may have led to the onset of the quakes in 2009, nor which of these activities are most responsible for the recent spike in their frequency.[1133]

- November 2, 2019 – The UK government declared a moratorium on fracking after an Oil and Gas Authority (OGA) report concluded that predicting the risk, size, and location of earthquakes linked to fracking operations is not possible. However, it left open the possibility that the temporary ban could be lifted if further scientific discoveries allowed fracking-induced seismicity to be managed.[1134] The OGA's report was based on an assessment of fracking operations taking place at Preston New Road in Lancashire in northwest England. It found that susceptibility to earthquakes depends on local geology but the precise geological characteristics creating that susceptibility are not sufficiently understood to serve as applicable predictors. "Methods for predicting the maximum magnitude that adopt a link between injected volume and the maximum magnitude of induced events lack convincing empirical evidence or proven theoretical basis." After repeated seismic events and a magnitude 2.9 earthquake, fracking operations were suspended at the Preston New Road site in August 2019. The OGA concluded that, based on the pattern of ground motion, the likely cause was a rupture of a previously unidentified strike-slip fault, and the "possibility of larger events could not be excluded."[1135]

- October 14, 2019 – Some earthquakes in west Texas are more likely due to fracking itself than frack waste disposal, according to a team that matched earthquake times and locations with those of fracking activities. A new seismic monitoring program of nearly 60 seismographs created in 2015 resulted in this "improvement in absolute location accuracy."[1136] This study is a first in challenging the view that the induced quakes are only caused by wastewater injection wells rather than the fracking process. The new program, TexNet, is funded by the state of Texas and its research arm, the Center for Integrated Seismicity Research, is funded by the state in partnership with oil and gas companies.[1137]

[1133] Cliff Frohlich et al., "Onset and Cause of Increased Seismic Activity Near Pecos, West Texas, United States, From Observations at the Lajitas TXAR Seismic Array," *Journal of Geophysical Research: Solid Earth* 125, no. 1 (2019): e2019JB017737, https://doi.org/10.1029/2019JB017737.
[1134] Aonghus Heatley, "UK Government Ends Its Support for Fracking in England (At Least for Now)," *The National Law Review*, November 4, 2019, https://www.natlawreview.com/article/uk-government-ends-its-support-fracking-england-least-now.
[1135] Oil and Gas Authority, "Interim Report of the Scientific Analysis of Data Gathered from Cuadrilla's Operations at Preston New Road," 2019, https://www.ogauthority.co.uk/media/6149/summary-of-pnr1z-interim-reports.pdf.
[1136] Anthony Lomax and Alexandros Savvaidis, "Improving Absolute Earthquake Location in West Texas Using Probabilistic, Proxy Ground-Truth Station Corrections," *Journal of Geophysical Research: Solid Earth* 124, no. 11 (2019): 11447–65, https://doi.org/10.1029/2019JB017727.
[1137] Sergio Chapa, "Study Linking Fracking to Permian Basin Earthquakes Stirs Public Debate," *Houston Chronicle*, October 15, 2019, sec. Energy, https://www.houstonchronicle.com/business/energy/article/Study-linking-fracking-to-Permian-Basin-14537085.php.

- August 28, 2019 – The mechanism by which fracking triggers earthquakes is an area of unsettled science. Calling into question earlier studies that ascribe a central role to pore pressure diffusion or poroelastic stress changes as the trigger of earthquakes caused by hydraulic fracturing, researchers from the University of Calgary in Alberta, Canada, instead invoke an alternative model. This team argues that fault activation is caused by progressive loading of distant, unstable regions of a fault by a phenomenon called "aseismic slip," in which displacement along a fault radiates out to a seismogenic area. Noting that key features of the fundamental processes of fault activation remain poorly understood and that so-called "traffic light protocols" rely on the assumptions that smaller seismic events precede large-magnitude earthquakes and that changes in injection operations will have immediate effects, the new model calls for a better characterization of rock properties and faults near fracking and disposal zones.[1138]

- August 26, 2019 – In accordance with a Hydraulic Fracturing Plan with a "traffic light system" modeled after ones used in Canada, fracking operations at the Preston New Road site in Lancashire, England were suspended after multiple earthquakes at the fracking site, including a 2.9 magnitude tremor that was felt at the surface.[1139]

- July 29, 2019 – As a first step in predicting future fracking-related earthquakes more accurately, a model must be able to account for the distribution, frequency, and historical time course of past earthquakes. Researchers using a "physics-based" forecasting model that includes consideration of both pore pressure and poroelastic stresses (the mechanical properties of rocks, such as elastic response to fluid pressures) have been able retroactively to simulate the observed pattern of induced seismicity in Oklahoma, where earthquake activity has increased 900-fold since 2008.[1140] According to the study's lead author, "An interesting finding… was that a tiny change in the rocks' elastic response to changes in fluid pressure can amplify the number of earthquakes by several times. It's a very sensitive factor."[1141] In addition, the model indicates that shutting down injection wells where fracking waste is disposed may not immediately alleviate the probability of large earthquakes as the underground diffusion of fluid continues even after injection stops.

- July 16, 2019 – Because briny oilfield wastewater is more dense than host rock fluids, it will continue to migrate downward long after it is injected into an underground well. Even when injection rates are significantly reduced as a technique to alleviate the risk of earthquakes, sinking wastewater can cause a pressure front to migrate downward at comparable rates. The result is elevated subsurface fluid pressures that persist for more

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1138 Thomas S. Eyre et al., "The Role of Aseismic Slip in Hydraulic Fracturing-Induced Seismicity," *Science Advances* 5, no. 8 (2019): eaav7172, https://doi.org/10.1126/sciadv.aav7172.
1139 Oil and Gas Authority, "Hydraulic Fracturing at Preston New Road Suspended," *News*, August 26, 2019, https://www.ogauthority.co.uk/news-publications/news/2019/hydraulic-fracturing-at-preston-new-road-suspended/.
1140 Guang Zhai et al., "Pore-Pressure Diffusion, Enhanced by Poroelastic Stresses, Controls Induced Seismicity in Oklahoma," *Proceedings of the National Academy of Sciences U.S.A.* 116, no. 33 (2019): 16228–33, https://doi.org/10.1073/pnas.1819225116.
1141 Arizona State University, "Predicting Earthquake Hazards From Wastewater Injection," *Phys.Org*, July 29, 2019, https://phys.org/news/2019-07-earthquake-hazards-wastewater.html.

than a decade and increase with depth.[1142] This phenomenon raises the risks for earthquakes of higher magnitude because deeper faults, which are under higher stress, can release more energy when they rupture.[1143] As a consequence, wastewater disposal via underground injection effectively creates a time bomb as the risk of high-magnitude earthquakes may continue to rise even as overall earthquake activity slows.

- May 3, 2019 – Researchers at Tufts University combined field data and modeling data in a study that found that fracking wastewater disposal can trigger earthquakes originating from zones far beyond where the fracking wastewater diffuses. Overturning previous assumptions, these results suggest that waste fluids can activate slippage in faults that then quickly outpaces the spread of fluid underground. That is, a rupture front can develop and accelerate ahead of regional pore-pressure increases caused by migrating fluids and, potentially, activate slippage in distant pre-existing faults. If so, these runaway ruptures might trigger earthquakes of magnitudes greater than predicted based on an assessment of fluid-pressurized volumes.[1144, 1145]

- March 27, 2019 – The USGS deployed additional seismometers in the area around south Alabama and the Florida Panhandle following the detection of five earthquakes in the course of a week. The earthquakes, ranging in magnitude from 2.1 to 3.7, occurred in an area flagged as likely experiencing more seismic activity over the past decade due to oil and gas operations in the area.[1146] In 1997, a series of earthquakes, including the second largest in Alabama's history (at magnitude 4.9), occurred in the same region and was tentatively linked to oil and gas drilling and two associated injection wells nearby.[1147]

- March 8, 2019 – Over a two-day period in February 2019, three earthquakes struck a farming community in an area of China's Sichuan Province that is experiencing a fracking boom. Two people were killed, 13 injured, 20,000 homes destroyed, and 1,600 people displaced. In response to citizen protests, fracking operations were suspended.[1148]

- March 1, 2019 – A USGS-led team monitored leakage and fluid pressure over time in a permeable bedrock formation used for disposal of fracking waste in Osage County, Oklahoma. By inserting specially designed instruments into an unused disposal well within this formation, the team demonstrated an overall trend of increasing fluid pressure.

[1142] Ryan M. Pollyea et al., "High Density Oilfield Wastewater Disposal Causes Deeper, Stronger, and More Persistent Earthquakes," *Nature Communications* 10, no. 3077 (2019), https://doi.org/10.1038/s41467-019-11029-8.
[1143] Anna Kuchment, "Even If Injection of Fracking Wastewater Stops, Quakes Won't," *Scientific American*, September 9, 2019, https://www.scientificamerican.com/article/even-if-injection-of-fracking-wastewater-stops-quakes-wont/.
[1144] Bhattacharya and Viesca, "Fluid-Induced Aseismic Fault Slip Outpaces Pore-Fluid Migration."
[1145] Tufts University, "Study Suggests Earthquakes ARe Triggered Well BEyond Fluid Injection Zones," *AAAS Eureka Alert*, May 2, 2019, https://www.eurekalert.org/pub_releases/2019-05/tu-sse050119.php.
[1146] Dennis Pillion, "Did Fracking Cause South Alabama Earthquakes? Federal Researchers Investigating," *AL.Com*, March 27, 2019, sec. Mobile Real-Time News, https://www.al.com/news/mobile/2019/03/did-fracking-cause-south-alabama-earthquakes-federal-researchers-investigating.html.
[1147] Joan Gomberg and Lorraine Wolf, "Possible Cause for an Improbable Earthquake: The 1997 Mw 4.9 Southern Alabama Earthquake and Hydrocarbon REcovery," *Geology* 27, no. 4 (1999): 367–70, https://doi.org/10.1130/0091-7613(1999)027<0367:<PCFAIE>2.3CO;2.
[1148] Myers, "China Experiences a Fracking Boom, and All the Problems That Go with It."

"The only conceivable source of this increase is due to the injection of wastewater." The results also showed evidence that fracking waste is leaking out of the reservoir where it is being injected "at a significant rate." The direction of the leakage appears mostly downward into the basement rock below. The authors note that disposal of fracking waste is the leading cause of pressure changes on faults in Oklahoma and that fluid pressure changes are, in turn, the leading cause of earthquakes in Oklahoma.[1149]

- December 12, 2018 – For six continuous years, hydraulic fracturing and related activities have triggered multiple earthquakes of varying magnitudes in northwestern Alberta and northeastern British Columbia, with the operations of one company linked to tremors that have jolted Fort St. John from 2012 to 2018.[1150] Between September 2013 and January 2015 alone, researchers in western Alberta, Canada detected than 900 seismic events, ranging in magnitude from 1 to 4. Real-time recordings of seismic activity were generally consistent with published empirical and point-source simulation models. Approximately 80 percent of the events in the compiled database occurred "in distinct clusters in time and space that are characteristic of induced events."[1151] These induced earthquakes pose hazards to roads, pipelines, dams, groundwater, and public safety. Canadian scientists question whether any regulatory system could effectively forecast, control, or prevent them. In some cases, cessation of injection activities following large, potentially damaging earthquakes appears to a sufficient response. However, in other cases, quakes occur months after injection activities, falling outside the windows of immediate intervention that most "traffic light systems" are put in place to address.[1152] Further, companies are allowed to continue their activities despite predictions that considerable seismic activity may result, including earthquakes of much greater magnitude than predicted.[1153]

- November 28, 2018 – Noting that fracking is a microseismic event, a research team investigated whether the activity of hydraulic fracturing itself, and not just the disposal of fracking waste, can trigger earthquakes and might be contributing to the dramatic increases in frequency of seismic events across the central and eastern United States. The team focused on Oklahoma where they identified roughly 700 fracking-induced earthquakes, including 12 with magnitude between 3 and 3.5. Previous reports had described only two fracking-induced earthquakes in Oklahoma. Results also confirmed that, in Oklahoma, proximity of an injection site to a critically stressed fault is a better predictor of induced seismicity than a more commonly accepted general approach based on proximity to the Precambrian basement layer. These results demonstrate that public

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[1149] Andrew J. Barbour et al., "Leakage and Increasing Fluid Pressure Detected in Oklahoma's Wastewater Disposal Reservoir," *Journal of Geophysical Research: Solid Earth* 124, no. 3 (2019): 2896–2919, https://doi.org/10.1029/2019JB017327.
[1150] Andrew Nikiforuk, "Company Linked to Tremors That Jolted Fort St. John Triggered Previous Quakes," *The Tyee*, December 12, 2018, https://thetyee.ca/News/2018/12/12/Fort-St-John-Tremors/.
[1151] Mark Novakovic and Gail M. Atkinson, "Preliminary Evaluation of Ground Motions from Earthquakes in Alberta," *Seismological Research Letters* 86, no. 4 (2015): 1086–95, https://doi.org/10.1785/0220150059.
[1152] Andrew Nikiforuk, "Fracking Linked to Quake That Jolted Fort St. John," *The Tyee*, December 4, 2018, https://thetyee.ca/News/2018/12/04/Fracking-Linked-Quake-Jolted-Fort-St-John/.
[1153] Simon Little, "Fort St. John Earthquakes Were Caused by Fracking: BC Oil and Gas Commission," *Global News*, December 22, 2018, sec. Economy, https://globalnews.ca/news/4789210/fort-st-john-frackqing-earthquakes/.

research provides far greater detail and accuracy than data and notifications voluntarily released by drilling operators.[1154]

- November 11, 2018 – In Lancashire, England, fracking has triggered at least 37 minor earthquakes. Regulations require suspension of fracking activities when seismicity exceeds magnitude 0.5. Energy company Cuadrilla, which had previously supported these limits, lobbied the government to relax the regulations in order to allow fracking to continue. These calls have been rejected by the energy minister.[1155]

- October 31, 2018 – A holistic analysis of fracking waste disposal practices and seismicity compared intensely drilled regions across the United States, including the Bakken, Eagle Ford, and Permian shale basins, as well as basins in Oklahoma. Results showed consistent links between increased seismicity and increased depth of wastewater injection, increased rate of injection, and increased regional injection volumes. Shallower disposal wells help lower the risk of earthquakes. However, they raise the risk of groundwater contamination as increased pressures can push fluids through "faults or fractures or through abandoned oil wells that have not been properly plugged." The researchers also noted that deep waste disposal carries the risk of introducing toxic fluids into karstified areas where there is "limited geologic characterization of the disposal zone." These deep, cave-like zones may transmit fluids in an unknown, unpredictable fashion.[1156]

- August 31, 2018 – To delineate possible mechanisms for the induction of earthquakes at unexpectedly large distances from injection wells, researchers looked at data in the public domain from around the world. They found two patterns. One type of seismicity, manifesting a "direct pressure effect," clusters near wells and tends to be shallow, of modest magnitude, and to decay abruptly. The second type of seismicity, potentially triggered by elastic stresses, tends to occur in deeper layers, decay slowly, and exhibit larger spatial footprints and magnitudes. Both shallow and deep formations present unique risks, and these should be included in mitigation strategies.[1157] With low to moderate-sized human-made earthquakes putting 1 in 50 people in the United States at risk according to a recent USGS analysis, injection practices for oil and gas wastewater are "creating a ripple effect far beyond … drilling locations."[1158]

[1154] Robert J. Skoumal et al., "Earthquakes Induced by Hydraulic Fracturing Are Pervasive in Oklahoma," *Journal of Geophysical Research: Solid Earth* 123, no. 12 (2018): 10918–35, https://doi.org/10.1029/2018JB016790.
[1155] Adam Vaughan, "Fracking Firm Boss Says It Didn't Expect to Cause Such Serious Quakes," *The Guardian*, November 11, 2018, https://www.theguardian.com/environment/2018/nov/11/fracking-firm-boss-says-it-didnt-expect-to-cause-such-serious-quakes-lancashire?fbclid=IwAR2BEOJ3ySPm-7WiigVilQQyyjdzqAxOHbZxYGEH4s9RFbObbUfPwKGW9dM.
[1156] Bridget R. Scanlon et al., "Managing Basin-Scale Fluid Budgets to Reduce Injection-Induced Seismicity from the Recent U.S. Shale Oil Revolution," *Seismological Research Letters* 90, no. 1 (2019): 171–82, https://doi.org/10.1785/0220180223.
[1157] Thomas H. Goebel and Emily Brodsky, "The Spatial Footprint of Injection Wells in a Global Compilation of Induced Earthquake Sequences," *Science* 361, no. 6405 (2018): 899–904, https://doi.org/10.1126/science.aat5449.
[1158] B. Guarino, "How Energy Companies Set Off Earthquakes Miles Away From Their Waste Dumps," *The Washington Post*, August 30, 2018, https://www.washingtonpost.com/science/2018/08/30/how-energies-companies-set-off-earthquakes-miles-away-their-waste-dumps/?utm_term=.ee67ec5d693a.

- April 27, 2018 – The use of fracking to enhance geothermal energy recovery activated two faults in a previously unknown fault system and triggered a magnitude 5.5 earthquake near Pohang, South Korea. Using primarily publicly available data, the researchers characterized the fault dimensions, faulting mechanism, and depth of earthquake activity, which correlated with surface deformation at the time of the earthquake activity. The earthquake's main shock caused extensive structural damage to buildings in and around Pohang and injured 70 people.[1159]

- March 16, 2018 – Utilizing satellite radar imagery, researchers observed and analyzed ground deformation, earthquake activity, and subsidence (depressions and sinkholes) that appear to be the result of "decades of oil activity and its effects on rocks below the earth's surface."[1160, 1161] Noting that West Texas has been "punctured like a pincushion with oil wells and injection wells since the 1940s," the team documented an "alarming rate" of heaving and sinking across a 4,000-square-mile area.[1162] The researchers documented visible surface-level and subsurface changes from fracking, fracking waste injection, carbon dioxide injection that is used to aid in oil and gas exraction, and abandoned and uncapped wells. Some data may help sort out why hazards manifest in one site rather than another. Satellite assessments of deformation can provide crucial safety information to protect roadways, homes, businesses, industrial facilities, pipelines, and people from "potential larger catastrophic events."

- February 27, 2018 – Since December 2016 in Oklahoma, 74 earthquakes of at least 2.5 magnitude have been linked directly to fracking. As a result, state regulators tightened mitigation protocols and required operators to use seismic arrays to detect underground movement and pause their work when earthquakes exceed magnitude 2.5.[1163] These changes make Oklahoma's new regulations tougher than Canada's, where "the industry holds the record for causing magnitude 4-plus earthquakes by high volume fracking."[1164] Described by industry sources as "a cautious move forward, limiting though not hamstringing [the] oil industry," the new regulations will be evaluated in the field for their effectiveness in reducing the frequency of earthquakes large enough to be felt at the surface.[1165]

[1159] F. Grigoli et al., "The November 2017 Mw 5.5 Pohang Earthquake: A Possible Case of Induced Seismicity in South Korea," *Science* 360, no. 6392 (2018): 1003–6, https://doi.org/10.1126/science.aat2010.
[1160] Jin-Woo Kim and Zhong Lu, "Association Between Localized Geohazards in West Texas and Human Activities, Recognized by Sentinel-1A/B Satellite Radar Imagery," *Scientific Reports* 8 (2018): 4727, https://doi.org/10.1038/s41598-018-23143-6.
[1161] Sydney Greene, "Large Portions of West Texas Sinking at Alarming Rate, New Report Finds," *The Texas Tribune*, March 22, 2018, https://www.texastribune.org/2018/03/22/report-says-large-portions-west-texas-counties-are-sinking-alarming-ra/.
[1162] Margaret Allen, "Radar Images Show Large Swath of West Texas Oil Patch Is Heaving and Sinking at Alarming Rates," *SMU Research News*, March 20, 2018, https://blog.smu.edu/research/2018/03/20/radar-images-show-large-swath-of-texas-oil-patch-is-heaving-and-sinking-at-alarming-rates/.
[1163] Oklahoma Corporation Commission, & Oklahoma Geological Survey, "Moving Forward: New Protocol to Further Address Seismicity in State's Largest Oil and Gas Play," News Release, February 27, 2018, https://oklahoma.gov/content/dam/ok/en/occ/documents/og/02-27-18protocol.pdf.
[1164] Andrew Nikiforuk, "Spooked by Quakes, Oklahoma Toughens Fracking Rules," *The Tyee*, March 9, 2018, https://thetyee.ca/News/2018/03/09/Oklahoma-Toughens-Fracking-Rules/.
[1165] Wethe, "Oklahoma Toughens Oil Fracking Rules after Shale Earthquakes."

- February 20, 2018 – Researchers in Kansas used high-precision data from an extensive seismometer network to detail features of a surge of earthquakes that they concluded were induced by wastewater injection in southern Kansas. Some areas were free from earthquakes, despite injection activities, suggesting that unknown local geological conditions play a role in determining seismic activity. Lack of seismic activity in these areas is "either due to a lack of fluid pathways to the basement [deep geological layer] or due to the absence of faults that are close to failing." Regional influences led to more prolonged seismicity and were observed from wastewater injection wells located 10 or more kilometers away.[1166]

- February 15, 2018 – In Kansas, swarms of earthquakes near oil wastewater disposal wells began in 2013. By 2017, the prodigious volumes of injected fluid created sufficient pressure to trigger earthquakes more than 50 miles away and form a "triggering front" that advanced at an average rate of nearly 10 miles per year along a permeable fault zone.[1167] A mapping project based on gravity loads, magnetic fields, and seismic activity dating to 1979 revealed a previously unidentified subsurface fault running from central Nebraska 200 miles southeast to Kansas.[1168]

- February 5, 2018 – Focusing their investigation on areas in Ohio that are isolated from fracking waste injection activities, researchers found that fracking itself induced earthquakes in two distinct manners. In some cases, earthquake activity occurred in shallow subsurface layers and was of short duration and small magnitude. In other, more troubling cases, earthquakes were more powerful and took place in very deep layers, far below the layers being fracked, even when fracking did not directly contact faults in the basement rock. At three of five sites, earthquake activity continued for over a month after fracking activities ceased. These results support a causal role for poroelastic stress, sometimes operating over long distances, in addition to more predictable pore fluid pressure changes, in the generation of earthquakes by fracking.[1169, 1170]

- January 19, 2018 – Some of the largest earthquakes related to fracking have occurred near Fox Creek, Alberta, in Canada. Using publicly available data, researchers studied earthquakes induced both by fracking waste injection and by hydraulic fracturing itself.

1166 Justin L. Rubinstein, William L. Ellsworth, and Sara L. Dougherty, "The 2013–2016 Induced Earthquakes in Harper and Sumner Counties, Southern Kansas," *Bulletin of the Seismological Society of America* 108, no. 2 (2018): 674–89, https://doi.org/10.1785/0120170209.
1167 Shelby L. Peterie et al., "Earthquakes in Kansas Induced by Extremely Far-Field Pressure Diffusion," *Geophysical Research Letters* 45, no. 3 (2018): 1395–1401, https://doi.org/10.1002/2017GL076334.
1168 Chris Dunker, "Spate of Nebraska Earthquakes Might Be Linked to Kansas Tremors, UNL Student Researcher Says," *Lincoln Journal Star*, June 8, 2021, https://journalstar.com/news/local/education/spate-of-nebraska-earthquakes-might-be-linked-to-kansas-tremors/article_b81d0bdc-5b0e-5c98-a155-5f6499356b4d.amp.html?__twitter_impression=true.
1169 Maria Kozłowska et al., "Maturity of Nearby Faults Influences Seismic Hazard from Hydraulic Fracturing," *Proceedings of the National Academy of Sciences* 115, no. 8 (2018): E1720–29, https://doi.org/10.1073/pnas.1715284115.
1170 Kathiann M. Kowalski, "Fracking in Shale Plays Could Trigger Earthquakes in Deeper Faults: Study," *Energy News Network*, February 7, 2018, http://energynews.us/2018/02/07/fracking-in-shale-plays-could-trigger-earthquakes-in-deeper-faults-study/.

In both cases, the volume of fluid injected, rather than injection rate or injection pressure, was most strongly correlated with seismic activity. Geologic factors also played a role, with earthquakes more likely if fracking and disposal activities were conducted closer to faulting and areas of stress. Combining injected volume with geologic factors, researchers developed a model that can predict 96 percent of the seismic variability in the region, improving hazard estimations. Calculating a "seismogenic activation potential," particularly if coupled with microseismic monitoring in real time to detect previously unknown faulting, may improve earthquake forecasting.[1171]

- November 24, 2017 – A team of geologists confirmed conclusively that recent earthquakes in Texas' Fort Worth Basin were induced by underground injection of fracking waste that caused deep, critically stressed faults to slip.[1172] The authors of this study employed a classical structural geology analysis that relied on high-resolution seismic reflection imaging, described in an interview with geophysical researcher Maria Magnani as "a little bit like an ultrasound."[1173] Maps of the seismically active faults in the Fort Worth Basin show no evidence of previous motion over the past millions of years and instead have been "sleeping" for approximately the past 300 million years until "awakened" at the start of the 2008 earthquake swarm associated temporally with extensive wastewater injection activities.[1174]

- October 21, 2017 – Extending the findings of two previous studies, an investigation of earthquakes in the Raton Basin along the border of New Mexico and Colorado identified wastewater injection wells as the cause of the quakes and identified a mechanism.[1175] All together, the location of the earthquakes, modeled pore pressures, and the direct correlation between cumulative volume of injected waste in nearby wells and the number of quakes show that seismicity in the Raton Basin is likely induced, and that elevated pore pressures deep underground are "well above earthquake-triggering thresholds."[1176]

- September 14, 2017 – An investigation by *Politico* found that the U.S. crude oil storage hub in Cushing, Oklahoma—the world's largest store of oil—was not designed with seismic considerations in mind, nor are there seismic regulations in place for its 250,000-barrel oil tanks, which are under the purview of the Department of Transportation's

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[1171] R. Schultz et al., "Hydraulic Fracturing Volume Is Associated with Induced Earthquake Productivity in the Duvernay Play," *Science* 359, no. 6373 (2018): 304–8, https://doi.org/10.1126/science.aao0159.
[1172] Maria Beatrice Magnani et al., "Discriminating between Natural versus Induced Seismicity from Long-Term Deformation History of Intraplate Faults," *Science Advances* 3, no. 11 (November 2017): e1701593, https://doi.org/10.1126/sciadv.1701593.
[1173] Ben Guarino, "Oil and Gas Industry Is Causing Texas Earthquakes, a 'Landmark' Study Suggests," *Washington Post*, November 24, 2017, https://www.washingtonpost.com/news/speaking-of-science/wp/2017/11/24/fracking-and-other-human-activities-are-causing-texas-earthquakes-study-suggests/.
[1174] Anna Kuchment, "Drilling Reawakens Sleeping Faults in Texas, Leads to Earthquakes," *Scientific American*, November 24, 2017, sec. Environment, https://www.scientificamerican.com/article/drilling-reawakens-sleeping-faults-in-texas-leads-to-earthquakes/.
[1175] J. S. Nakai et al., "A Possible Causative Mechanism of Raton Basin, New Mexico and Colorado Earthquakes Using Recent Seismicity Patterns and Pore Pressure Modeling: Earthquakes in the Raton Basin," *Journal of Geophysical Research: Solid Earth* 122, no. 10 (2017): 8051–65, https://doi.org/10.1002/2017JB014415.
[1176] Jim Scott, "Raton Basin Earthquakes Linked to Oil and Gas Fluid Injections," *CU Boulder Today*, October 24, 2017, https://www.colorado.edu/today/2017/10/24/raton-basin-earthquakes-linked-oil-and-gas-fluid-injections.

Pipeline and Hazardous Materials Safety Administration. Central Oklahoma, where Cushing is located, became seismically active about five years ago when “wastewater injection and other fracking-related activities changed the seismic face of Oklahoma in dramatic fashion.”[1177] (See also entry below for November 8, 2016.)

- August 11, 2017 – Using multiple lines of evidence, researchers in China determined that a series of high-magnitude earthquakes between 2014 and 2017 in Sichuan Basin was triggered by fracking activities that re-activated pre-existing faults. “The present study shows that short-term injections (continuing over several months) for shale gas hydraulic fracturing are … very likely to induce M_W 4–5 class earthquakes in sites with similar geological and tectonic conditions within the southern Sichuan Basin.”[1178]

- May 3, 2017 – Studying two patterns of fracking waste injection in Oklahoma, geologists observed a large, unexpected impact on seismic activity at sites where injection rates drastically changed in recent years, as compared with those whose injection volumes held steady. They demonstrated that, in addition to direct pore pressure effects, deformations due to fluid flows (“poroelastic effects”) play an important role in generating earthquake activity. Elevated risks for earthquakes can persist years after fracking waste is injected underground. Their findings also showed that the “magnitude of the initial change in injection rate is particularly important, but the opposite effect occurs in the transition to zero injection” (i.e., shut-in or closing a well). This result implies that “in certain faulting regimes it is theoretically possible to mitigate damaging effects of rapid shut-in by carefully tapering injection rates.”[1179] Geophysicist Andrew Barbour, lead author of the study, said that fluctuating injection rates likely have a “profound effect” on earthquake risk.[1180] These findings suggest that the 2016 Pawnee earthquake, the strongest earthquake ever recorded in Oklahoma, may have been triggered by pulses of underground oil and gas activity years earlier.[1181]

- April 27, 2017 – Recognizing that increased seismicity from both hydraulic fracturing and underground disposal of fracking wastewater poses a hazard to critical infrastructure, such as large dams, a Canadian geologist proposed strategies to keep the likelihood of

[1177] Kathryn Miles, “How Man-Made Earthquakes Could Cripple the U.S. Economy,” *Politico Magazine*, September 14, 2017, https://www.politico.com/magazine/story/2017/09/14/earthquakes-oil-us-economy-fracking-215602.
[1178] Xinglin Lei et al., “Fault Reactivation and Earthquakes with Magnitudes of up to Mw4.7 Induced by Shale-Gas Hydraulic Fracturing in Sichuan Basin, China,” *Scientific Reports* 7, no. 1 (2017): 7, https://doi.org/10.1038/s41598-017-08557-y.
[1179] Andrew J. Barbour, Jack H. Norbeck, and Justin L. Rubinstein, “The Effects of Varying Injection Rates in Osage County, Oklahoma, on the 2016 M_w 5.8 Pawnee Earthquake,” *Seismological Research Letters* 88, no. 4 (2017): 1040–53, https://doi.org/10.1785/0220170003.
[1180] Corey Jones, “USGS Study ‘Strongly Suggests’ Short-Term Variations in Disposal Volumes Served as Trigger for Pawnee Earthquake,” *Tulsa World*, May 7, 2017, https://tulsaworld.com/earthquakes/usgs-study-strongly-suggests-short-term-variations-in-disposal-volumes-served-as-trigger-for-pawnee/article_97de08d5-9327-505d-8b51-adbc716d6c69.html.
[1181] Joe Wertz, “Study Links Pulse of Oil-Field Wastewater to Oklahoma’s Strongest Earthquake,” *State Impact Oklahoma*, May 4, 2017, https://stateimpact.npr.org/oklahoma/2017/05/04/study-links-pulse-of-oil-field-wastewater-to-oklahomas-strongest-earthquake/.

high-failure consequences under one per ten thousand per year.[1182] The primary strategy is the creation of "no frack" exclusion zones with a 5-kilometer (3.1 mile) radius that would surround vulnerable, critical facilities. In a larger ring beyond the exclusion zone, to approximately 25 kilometers (15.5 miles), monitoring and response protocols would be used.[1183]

- March 1, 2017 – Despite decreases of up to 40 percent in the volume of fracking wastewater injected underground in Oklahoma, researchers from the USGS Earthquake Hazard Program forecasted that seismic hazards would remain significantly elevated there throughout 2017, with the odds of damage from induced earthquakes within the next year "similar to that of natural earthquakes in high-hazard areas of California." About three million people in Oklahoma and southern Kansas now live with continuing increased potential for damaging shaking from induced seismicity."[1184] According to Mark Petersen, chief of the USGS National Seismic Hazard Mapping Project, the hazard risk remains "hundreds of times higher than before man-made activity began."[1185]

- February 17, 2017 – Pennsylvania's Department of Environment Protection (PA DEP) announced that a series of small earthquakes in Lawrence County had been induced by fracturing of wells in the Utica Shale.[1186] PA DEP officials held a webinar to discuss the situation and formulate "procedures to reduce seismic risk going forward," but no formal report or regulatory changes have yet been made public.[1187]

- December 20, 2016 – In an attempt to reduced the risk of earthquakes caused directly by fracking, the Oklahoma Corporation Commission's Oil and Gas Conservation Division introduced monitoring and response guidelines that include provisions requiring oil producers to "implement mitigation plans following an earthquake of magnitude 2.5 or more and to suspend operations following a quake of magnitude 3.5 or greater."[1188]

- November 17, 2016 – A study of fault activation found a connection between fracking and earthquake activity in a region of Alberta, Canada that had previously been

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[1182] Gail M. Atkinson, "Strategies to Prevent Damage to Critical Infrastructure Due to Induced Seismicity," ed. Christoph E. Geiss, *FACETS* 2, no. 1 (2017): 374–94, https://doi.org/10.1139/facets-2017-0013.
[1183] Andrew Nikiforuk, "Earthquake Expert Proposes 'No Frack Zone' around Critical Infrastructure," *The Tyee*, July 24, 2017, https://thetyee.ca/News/2017/07/24/Critical-Infrastructure-No-Frack-Zone/.
[1184] Mark D. Petersen et al., "2017 One-Year Seismic-Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes," *Seismological Research Letters* 88, no. 3 (2017): 772–83, https://doi.org/10.1785/0220170005.
[1185] Adam Wilmoth, "Oklahoma Considered at 'significant Potential' for Damaging Earthquakes," *The Oklahoman*, March 1, 2017, https://oklahoman.com/article/5539785/oklahoma-considered-at-significant-potential-for-damaging-earthquakes/.
[1186] Laura Legere, "DEP Links Lawrence County Earthquakes to Fracking," *Pittsburgh Post-Gazette*, February 16, 2017, https://www.post-gazette.com/business/powersource/2017/02/16/DEP-Pennsylvania-Lawrence-County-earthquakes-appear-linked-to-fracking-Hilcorp-Energy/stories/201702160176.
[1187] Pennsylvania Department of Environmental Protection, "Advisory– Friday– Department of Environmental Protection to Hold Webinar on 2016 Lawrence County Seismic Events," Press Release, February 17, 2017, https://www.ahs.dep.pa.gov/NewsRoomPublic/articleviewer.aspx?id=21145&typeid=1.
[1188] Hampton, "Oklahoma's New Fracking Guidelines Aim to Reduce Quake Risk," *Reuters*, December 20, 2016, https://www.reuters.com/article/us-oklahoma-quake-rules-idUSKBN1492R6.

seismically quiescent. The researchers demonstrated that new earthquake activity in the Fox Creek area was tightly spatially correlated with hydraulic fracturing activities. Their findings further suggested that seismic activity resulted from "stress changes due to the elastic response of the rockmass to hydraulic fracturing," as well as "pore-pressure changes due to fluid diffusion along a permeable fault zone."[1189] In contrast to the central United States, where induced seismic activity is primarily caused by massive underground disposal of fracking waste, these findings pointed to the fracking process itself as the trigger. In an interview with the *New York Times,* co-author David Eaton compared fracking to a series of "small underground explosions" that travel into the rock formation and "rapidly change the stress patterns within." These stress changes can be sufficient to trigger a slip at a critically stressed, previously undetected fault.[1190]

- November 17, 2016 – An investigation by the *Dallas Morning News* chronicled a pattern of corruption and regulatory failings at the Texas Railroad Commission, the state agency charged with overseeing the oil and gas industry, in its disregard of evidence linking fracking waste disposal to earthquakes in North Texas.[1191]

- November 8, 2016 – On November 6, 2016, a magnitude 5.0 earthquake struck Cushing, Oklahoma near the oil hub where 60 million barrels of crude oil were stored. The quake injured one, damaged more than 40 buildings, closed a school, and triggered evacuations. Oil infrastructure was not damaged.[1192] (See also entry above for September 14, 2017.)

- October 7, 2016 – The EPA recommended a moratorium on the underground injection of fracking wastewater in certain earthquake-prone parts of Oklahoma after a 5.8 earthquake struck near Pawnee on September 3, 2016.[1193] The strongest in Oklahoma's history, the Pawnee earthquake was felt by residents in five states and prompted a state of emergency declaration as well as an order from state regulators to shut down 67 wastewater disposal wells in the area.[1194, 1195]

- September 22, 2016 – A study using satellite-based radar imagery found that the earth's surface rose, by 3 millimeters per year, in areas of fracking waste injection. Underground pore pressures for this area exceeded those known to trigger earthquakes. These findings

[1189] Xuewei Bao and David W. Eaton, "Fault Activation by Hydraulic Fracturing in Western Canada," *Science* 354, no. 6318 (2016): 1406–9, https://doi.org/10.1126/science.aag2583.
[1190] Henry Fountain, "In Canada, a Direct Link Between Fracking and Earthquakes," *The New York Times*, November 17, 2016, sec. Science, https://www.nytimes.com/2016/11/18/science/fracking-earthquakes-alberta-canada.html.
[1191] Steve Thompson and Anna Kuchment, "Seismic Denial? Why Texas Won't Admit Fracking Wastewater Is Causing Earthquakes," *Dallas News*, November 17, 2016, http://interactives.dallasnews.com/2016/seismic-denial/#_ga=2.247990020.202656599.1515906987-1750807308.1515724730.
[1192] Matthew Philips, "Why Oklahoma Can't Turn Off Its Earthquakes," *Bloomberg Businessweek*, November 8, 2016, https://www.bloomberg.com/news/articles/2016-11-08/why-oklahoma-can-t-turn-off-its-earthquakes.
[1193] Mike Soraghan, "EPA Suggests Partial Disposal Moratorium in Okla," *E&E EnergyWire*, October 7, 2016, https://subscriber.politicopro.com/article/eenews/1060043991.
[1194] U.S. Geological Survey, "M 5.8 - 14 Km NW of Pawnee, Oklahoma," September 3, 2016, https://earthquake.usgs.gov/earthquakes/eventpage/us10006jxs/executive#executive.
[1195] Oklahoma Corporation Commission, "Latest Action Regarding Pawnee Area," Media Advisory, September 12, 2016, https://oklahoma.gov/content/dam/ok/en/occ/documents/ajls/news/2016/09-12-16pawnee-advisory.pdf.

provide proof that the migration of fracking wastewater into faults increased pressures in ways that triggered a 4.8 magnitude earthquake in east Texas in 2012. The researchers emphasized that pore pressure elevation and propagation from fracking wastewater injection may evolve over periods of months to years before affecting critically stressed faults.[1196]

- September 14, 2016 – Researchers from the USGS used a newly deployed seismic monitoring network to document the rupture of a fault plane that set off a magnitude 4.9 earthquake in Milan, Kansas in 2014, immediately following a rapid increase in fracking wastewater injection nearby.[1197]

- June 30, 2016 – Using mathematical equations, researchers can replicate the pattern and intensity of naturally occurring (tectonic) earthquakes in the plots of earthquakes induced by hydraulic fracturing, wastewater disposal, enhanced geothermal stimulation, and subsurface injections for research purposes. In these retrospective examinations, the total number of induced earthquakes follows the volume of fluid injected, while the size of the largest earthquakes induced is not limited by fluid volumes but instead "whatever it is that limits earthquake magnitudes on tectonic faults…." That is, there is nothing intrinsic to the geophysics of induced earthquakes that prevents them from being as large or larger than previously observed naturally occurring earthquakes.[1198]

- May 2016 – In a study that has "far-reaching implications for assessment of induced-seismicity hazards," a Canadian team of researchers determined that hydraulic fracturing itself is linked to earthquake swarms in western Canada, in contrast to the central United States where disposal of fracking waste is the cause of most induced seismicity. Furthermore, lowering the volume of injected fluid may not be sufficient to prevent quakes. In the Western Canada Sedimentary Basin, "it appears that the maximum-observed magnitude of events associated with hydraulic fracturing may exceed the prediction of an often-cited relationship between the volume of injected fluid and the maximum expected magnitude…. Rather, we propose that the size of the available fault surface that is in a critical state of stress may control the maximum magnitude…. Our results indicate that the maximum magnitude of induced events for hydraulic fracturing may not be well correlated with net injected fluid volume."[1199]

- April 29, 2016 – Five small earthquakes in one 24-hour period originated in an area in Lawrence County, Pennsylvania near a fracking operation that was drilling into the deep Utica Shale at the time. Quoted in the *Pittsburg Post-Gazette*, researchers noted that it is

[1196] M. Shirzaei et al., "Surface Uplift and Time-Dependent Seismic Hazard Due to Fluid Injection in Eastern Texas," *Science* 353, no. 6306 (2016): 1416–19, https://doi.org/10.1126/science.aag0262.
[1197] George L. Choy et al., "A Rare Moderate-Sized (Mw 4.9) Earthquake in Kansas: Rupture Process of the Milan, Kansas, Earthquake of 12 November 2014 and Its Relationship to Fluid Injection," *Seismological Research Letters* 87, no. 6 (2016): 1433–41, https://doi.org/10.1785/0220160100.
[1198] Nicholas J. van der Elst et al., "Induced Earthquake Magnitudes Are as Large as (Statistically) Expected," *Journal of Geophysical Research: Solid Earth* 121, no. 6 (2016): 4575–90, https://doi.org/10.1002/2016JB012818.
[1199] Gail M. Atkinson et al., "Hydraulic Fracturing and Seismicity in the Western Canada Sedimentary Basin," *Seismological Research Letters* 87, no. 3 (2016): 631–47, https://doi.org/10.1785/0220150263.

very difficult for operators to avoid areas with faults because their locations are very often unknown.[1200]

- March 28, 2016 – A summary of the evidence linking drilling and fracking activities to earthquakes appeared in *Scientific American.* Emerging data suggests that pressure changes caused by fracking wastewater injection can migrate for years before encountering a geological fault and altering stresses in ways that allow for slippage. In this way, earthquake risks can spread out over both time and space—traveling for miles beyond the disposal well and persisting for a decade or more as injected fluids travel underground. In spite of increasing scientific clarity about these mechanisms, regulators have been slow to respond.[1201]

- February 1, 2016 – An article in the *Texas Journal of Oil, Gas, and Energy Law* exhaustively reviewed the literature on earthquake activity in areas of six states (Arkansas, Colorado, Kansas, Ohio, Oklahoma, and Texas) where fracking takes place or drilling wastes are disposed underground and concluded that courts should impose strict liability for earthquake damage caused either by fracking itself or by the underground injection of fracking fluids. "Earthquakes sometimes occur when subsurface formations are properly fractured. Likewise, the risk of earthquake damage is not substantially mitigated by the exercise of due care when frack fluids are injected into the ground."[1202]

- January 22, 2016 – An international research team investigated a swarm of earthquakes in California's Central Valley that occurred in 2005. Using hydrogeological modeling, the researchers concluded that the underground injection of wastewater from oil drilling operations had contributed to seismicity via changes in localized pressures along an active fault.[1203]

- January 12, 2016 – As reported by *CBC News*, a Canadian regulatory agency ordered a drilling and fracking operation in northwestern Alberta to shut down after a magnitude 4.8 earthquake struck nearby. The operator was fracking at the time the earthquake happened.[1204]

[1200] Laura Legere, "State Studying Link between Fracking, Lawrence County Earthquakes," *Pittsburgh Post-Gazette*, April 29, 2016, https://www.post-gazette.com/business/powersource/2016/04/29/State-studying-link-between-fracking-and-Lawrence-County-earthquakes/stories/201604290099.
[1201] Anna Kuchment, "Drilling for Earthquakes," *Scientific American*, March 28, 2016, https://doi.org/10.1038/scientificamerican0716-46.
[1202] Blake A. Watson, "Fracking and Cracking: Strict Liability for Earthquake Damage Due to Wastewater Injection and Hydraulic Fracturing," SSRN Scholarly Paper (Rochester, NY: Social Science Research Network, February 1, 2016), https://papers.ssrn.com/abstract=2735862.
[1203] T. H. W. Goebel et al., "Wastewater Disposal and Earthquake Swarm Activity at the Southern End of the Central Valley, California," *Geophysical Research Letters* 43, no. 3 (2016): 1092–99, https://doi.org/10.1002/2015GL066948.
[1204] CBC News, "Alberta Fracking Operation Closed Indefinitely after Earthquake," *CBC*, January 12, 2016, https://www.cbc.ca/news/canada/edmonton/fox-creek-fracking-operation-closed-indefinitely-after-earthquake-1.3400605.

- November 15, 2015 – A spokesperson for the Oklahoma Corporation Commission, which regulates the oil and gas industry in the state, said that Oklahoma now leads the world in earthquake frequency.[1205]

- October 29, 2015 – The Kansas Corporation Commission extended limits on the injection of wastewater from fracking operations after a drop in the frequency of earthquakes that followed an earlier order to limit such injections.[1206] Between 2013 and October 2015, Kansas recorded more than 200 earthquakes. Before that, the average rate was one earthquake every two years.

- October 23, 2015 – *Bloomberg* explored the national security risks that fracking-induced earthquakes in Oklahoma create for the nation's largest oil storage hub in Cushing, where aboveground tanks hold more than 60 million barrels of crude oil and serve as a way station for oil from North Dakota's Bakken Shale as it heads to Gulf Coast refineries. Earthquake swarms have hit within a few miles of Cushing and may be harbingers of larger quakes in the future. "Now that quakes appear to have migrated closer to Cushing, the issue of what to do about them has morphed from a state issue to one of national security…. Not only is Cushing crucial to the financial side of the oil market, it is integral to the way physical crude flows around the country."[1207]

- September 21, 2015 – An international team of geologists investigated possible causes of the Lusi mudflow, which began suddenly in 2006 when mud began erupting from the ground in a volcano-like fashion in an urban area of Java in Indonesia. The ongoing disaster has, as of 2015, displaced 39,700 people and cost nearly $3 billion in damages and disaster management. Looking at data on the emissions of subsurface gases before and after the eruption began, the team concluded that the likely cause was nearby gas drilling that forced fluid into the clay layer via the open well. "We therefore conclude that the Lusi eruption was not triggered naturally but was instead the consequence of drilling operations."[1208] In interviews with the *New York Times*, lead author Mark Tinjay said, "We are now 99 percent certain that the drilling hypothesis is valid," while other experts who were not authors of the paper expressed less certainty.[1209]

- July 27, 2015 – During a seven-day period in late July, the state of Oklahoma experienced 40 earthquakes. According to the USGS, three registered above magnitude 4.0, one of which was strong enough to be felt by 1.9 million people, including residents

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[1205] Jessica Miller, "Oklahoma World's No. 1 Earthquake Area," *Enidnews.Com*, November 11, 2015, https://www.enidnews.com/news/local_news/oklahoma-worlds-no-1-earthquake-area/article_69b145b8-c180-5065-8f99-b2a7ec7ce913.html.
[1206] Kansas Corporation Commission, "Kansas Corporation Commission Approves Order Extending Wastewater Injection Limits," News Release, October 29, 2015, https://kcc.ks.gov/news-10-29-15.
[1207] Matthew Philips, "Oklahoma Earthquakes Are a National Security Threat," *Bloomberg*, October 23, 2015, https://www.bloomberg.com/news/articles/2015-10-23/oklahoma-earthquakes-are-a-national-security-threat.
[1208] M. R. P. Tingay et al., "Initiation of the Lusi Mudflow Disaster," *Nature Geoscience* 8, no. 7 (2015): 493–94, https://doi.org/10.1038/ngeo2472.
[1209] Rachel Nuwer, "Indonesia's 'Mud Volcano' and Nine Years of Debate About Its Muck," *The New York Times*, September 21, 2015, sec. Science, https://www.nytimes.com/2015/09/22/science/9-years-of-muck-mud-and-debate-in-java.html.

of several surrounding states.[1210] In response, gas and oil operators voluntarily shut down two nearby wastewater injection wells and reduced operations by half at a third well.[1211] According to the Oklahoma Geological Survey, the recent quakes are occurring along a fault line that extends north of Oklahoma City and signal greater potential for a larger earthquake.[1212] Ten days before the voluntary shutdowns, the Oklahoma Corporation Commission, which regulates the oil and gas industry, put 211 wastewater disposal wells under extra review.[1213] The next month, Oklahoma regulators, acknowledging that previous efforts have been unsuccessful in reducing seismic activity, asked operators of 23 injection wells to decrease the amount of wastewater injected by 38 percent and signaled that more sweeping regulatory actions may follow.[1214]

- July 1, 2015 – Two researchers, from the USGS and the Geological Survey of Canada, offered a summary of the history, basic geology, and engineering of fracking fluid injection and induced seismicity. Noting that since 2001 Oklahoma had experienced two earthquakes of very large magnitude (5.0 and 5.3), the authors called for "a detailed understanding of the physical processes involved in inducing large magnitude events and a detailed understanding of the geology and hydrology at the site of the earthquakes." They also noted that many important parameters are either unknown or not easily constrained, making it "difficult to determine the wells that will induce earthquakes and those that will not."[1215]

- June 30, 2015 – The Oklahoma Supreme Court ruled that homeowners who have sustained injuries or property damage that they believe is due to earthquakes caused by oil and gas operations can sue for damages in state trial courts. The number of earthquakes with magnitude 3.0 or higher has skyrocketed in Oklahoma, with 1,100 predicted to occur in 2015. Earlier this year, scientists at the state's geological survey reversed prior views and embraced the conclusion that the majority of the recent earthquakes in central and north-central Oklahoma were "very likely triggered" by underground wastewater disposal. Industry lawyers have complained that liability for such damages will be economically unsustainable. A separate class action lawsuit is

[1210] U.S. Geological Survey, "M 4.5 - 4 Km NNE of Crescent, Oklahoma," July 27, 2015, https://earthquake.usgs.gov/earthquakes/eventpage/us200030gd/executive#impact_pager.
[1211] Oklahoma Corporation Commission, "New Actions Taken in Response to Earthquake Activity in Crescent Area," Media Advisory, July 28, 2015.
[1212] Sean Murphy, "2 Injection Wells Shut down after Oklahoma Quakes," *Santa Cruz Sentinel*, July 28, 2015, https://www.santacruzsentinel.com/2015/07/28/2-injection-wells-shut-down-after-oklahoma-quakes/.
[1213] Oklahoma Corporation Commission, "OCC Announces Next Step in Continuing Response to Earthquake Concerns," Press Release, July 17, 2015.
[1214] Michael Wines, "Oklahoma Acts to Limit Earthquake Risk at Oil and Gas Wells," *The New York Times*, August 5, 2015, sec. U.S., https://www.nytimes.com/2015/08/05/us/oklahoma-acts-to-limit-earthquake-risk-at-oil-and-gas-wells.html.
[1215] Justin L. Rubinstein and Alireza Babaie Mahani, "Myths and Facts on Wastewater Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity," *Seismological Research Letters* 86, no. 4 (2015): 1060–67, https://doi.org/10.1785/0220150067.

planned.[1216]

- June 19, 2015 – By compiling a database of 187,570 injection wells in the central and eastern United States, University of Colorado Boulder and USGS researchers were able to test for associations between fracking waste disposal and earthquakes. Results showed far more injection wells were potentially related to earthquakes than had previously been realized, and active disposal-only wells were more than 1.5 times more likely than active oil extraction wells to be associated with an earthquake. In addition, high-rate injection wells, receiving more than 300,000 barrels of fluid per month, were much more likely than lower-rate wells to be associated with an earthquake, while other factors, including wellhead injection pressure, appeared unrelated to increased earthquake activity. The study called for managing injection rates as "a useful tool to minimize the likelihood of induced earthquakes." The researchers did not address the impact of hydrofracturing activities *per se* as a potential confounding variable.[1217, 1218]

- June 18, 2015 – Close examination of several areas in Oklahoma by Stanford University geophysicists revealed that dramatic increases in recent earthquake activity followed 5- to 10-fold increases in deep-well injection of briny "produced water," the highly salty fluid that rises to the surface from water-bearing oil reserves and requires disposal. The rate of earthquake occurrence, which began to increase in 2009, is now 600 times higher than it was before the onset of widespread fracking in the state. The disposal of this type of waste in Oklahoma mostly occurs via injection into geological formations that appear to be in hydraulic communication with potentially active faults in the crystalline basement. The study proposed that increasing pressure, spreading away from injection wells over time, could eventually trigger slips on critically stressed faults, resulting in earthquake activity. It is likely that, "even if injection from many wells were to stop immediately, seismicity would continue as pressure continues to spread out from past injection."[1219]

- June 12, 2015 – Researchers in France uncovered an unexpected mechanism by which subsurface fluid injections, such as those used in high volume hydrofracturing, can cause earthquakes. They found that injection of pressurized water can cause fault lines to "creep" rather than slip suddenly as occurs during earthquakes. Earthquakes did follow this slow movement but took place in a portion of the fault outside the pressurized zone. This research demonstrated that subsurface injection of fluids under pressure can cause

[1216] Richard A. Oppel Jr., "Oklahoma Court Rules Homeowners Can Sue Oil Companies Over Quakes," *The New York Times*, July 1, 2015, sec. U.S., https://www.nytimes.com/2015/07/01/us/oklahoma-court-rules-homeowners-can-sue-oil-companies-over-quakes.html.
[1217] M. Weingarten et al., "High-Rate Injection Is Associated with the Increase in U.S. Mid-Continent Seismicity," *Science* 348, no. 6241 (2015): 1336–40, https://doi.org/10.1126/science.aab1345.
[1218] Julia Rosen, "Pumped up to Rumble," *Science* 348, no. 6241 (2015): 1299–1299, https://doi.org/10.1126/science.348.6241.1299.
[1219] F. Rall Walsh and Mark D. Zoback, "Oklahoma's Recent Earthquakes and Saltwater Disposal," *Science Advances* 1, no. 5 (2015): e1500195, https://doi.org/10.1126/sciadv.1500195.

primary gradual slippage of fault planes leading to secondary sudden seismic activity.[1220, 1221]

- June 11, 2015 – As reported by the Vancouver news magazine *The Tyee,* seismic events of magnitude greater than 2.0 (but less than 4.0) in the Fox Creek area were reported in Alberta, Canada since the initiation in February of a novel "traffic light system" for responding to measured seismic activity. The system requires varying responses according to the magnitude of the event, ranging from no action up to ceasing operations and informing the Alberta Energy Regulator for events at magnitudes greater than 4.0. Experts noted that the system does not work well when the largest event in the sequence is the first event. Moreover, once a sequence of earthquakes is initiated, the sequence may continue, sometimes with larger earthquakes, long after potentially causally related drilling or injection activities have ceased.[1222]

- June 1, 2015 – In a data-rich presentation, a team of researchers from St. Louis University, Colorado State University, and USGS concluded that "a fundamental change in the earthquake-triggering process has occurred" in central Oklahoma. Using advanced field monitoring and high-performance software, computer models illustrate active earthquake sequences associated with long fault structures "that might be capable of supporting large earthquakes (M 5 to 6)" and possibly cascades of earthquakes, which could occur near population centers and expensive infrastructure associated with the oil and gas industry, such as a large underground crude-oil storage facility.[1223]

- May 11, 2015 – A series of directives from the Oklahoma Corporation Commission revealed a slowly evolving approach to the regulation of disposal well operations in that state, and the gradual tightening of a "traffic light system" introduced in 2013 to determine whether disposal wells for fracking waste should be permitted, permitted only with special restrictions and requirements, or not permitted, in light of the now-proven connection between the injection of liquid waste and the soaring frequency of earthquakes in Oklahoma. Since 2013, earthquake activity in Oklahoma has continued to increase in rate and intensity.[1224, 1225]

- April 23, 2015 – In a first-of-its-kind approach, the USGS is updating its National Seismic Hazard Model to address the rapidly increasing, highly variable, and difficult-to-

[1220] Y. Guglielmi et al., "Seismicity Triggered by Fluid Injection-Induced Aseismic Slip," *Science* 348, no. 6240 (2015): 1224–26, https://doi.org/10.1126/science.aab0476.
[1221] Scott K. Johnson, "Making Tiny Earthquakes to Understand Fracking-Driven Quakes," *Ars Technica*, June 11, 2015, https://arstechnica.com/science/2015/06/making-tiny-earthquakes-to-understand-fracking-driven-quakes/.
[1222] Andrew Nikiforuk, "More Industry Linked Earthquakes Recorded in Alberta," *The Tyee*, June 11, 2015, http://thetyee.ca/News/2015/06/11/More-Fracking-Earthquakes/.
[1223] D. E. McNamara et al., "Efforts to Monitor and Characterize the Recent Increasing Seismicity in Central Oklahoma," *The Leading Edge* 34, no. 6 (2015): 628–39, https://doi.org/10.1190/tle34060628.1.
[1224] Oklahoma Corporation Commission, "OCC Continuing Response to Triggered Seismicity Concerns," May 11, 2015, https://oklahoma.gov/occ/news/news-releases/news-archives/2015-news-releases.html.
[1225] Oklahoma Corporation Commission.

predict hazards of induced earthquakes.[1226] This initial report identified 17 areas within eight states (Alabama, Arkansas, Colorado, Kansas, New Mexico, Ohio, Oklahoma, and Texas) with increased rates of induced seismicity, including many areas experiencing earthquakes of large magnitude.[1227] Two days before the release of this report, Oklahoma's state government acknowledged for the first time that wastewater disposal related to oil and gas drilling is "very likely" to blame for the huge surge of earthquakes in many areas of Oklahoma, the *New York Times* reported.[1228] Several states have developed protocols to shut down existing wells and halt drilling of new disposal wells following an upsurge in earthquake activity.

- April 21, 2015 – Analyzing the unusual increase of seismicity in north Texas since 2008, researchers from Southern Methodist University, the USGS, and University of Texas at Austin concluded that observed earthquake swarms were associated both with extraction (of gas and brine formation waters) and injection (of fracking wastewater), via significant stress changes at earthquake depths. The research team noted that baseline pressure monitoring data, though easy to obtain and routinely collected by industry at well sites, were currently "neither required nor typically available for analysis." Greater transparency and cooperation in regional seismic monitoring is needed to generate more comprehensive data sets that are necessary for robust earthquake hazard analysis, they asserted.[1229, 1230]

- April 21, 2015 – In a statement reporting on an increase in earthquakes in Oklahoma of greater than magnitude 3.0 from less than two per year historically to over two per day in 2015, the Oklahoma Geological Society acknowledged that that the primary, suspected source of "triggered seismicity" is the injection and disposal of produced water associated with oil and gas production.[1231]

- March 30, 2015 – *Bloomberg Business* reported that Oklahoma state seismologists had received pressure from oil industry representatives to downplay the evidence linking fracking wastewater disposal to the soaring frequency of earthquakes in the state.[1232]

[1226] Mark D. Petersen et al., "Incorporating Induced Seismicity in the 2014 United States National Seismic Hazard Model—Results of 2014 Workshop and Sensitivity Studies," Open-File Report, Open-File Report, 2015.
[1227] U.S. Geological Survey, "New Insight on Ground Shaking from Man-Made Earthquakes," Open-File Report, Open-File Report (USGS Newisroom, April 23, 2015).
[1228] Richard Pérez-Peña, "U.S. Maps Pinpoint Earthquakes Linked to Quest for Oil and Gas," *The New York Times*, April 23, 2015, sec. U.S., https://www.nytimes.com/2015/04/24/us/us-maps-areas-of-increased-earthquakes-from-human-activity.html.
[1229] Matthew J. Hornbach et al., "Causal Factors for Seismicity near Azle, Texas," *Nature Communications* 6, no. 1 (2015): 6728, https://doi.org/10.1038/ncomms7728.
[1230] Marice Richter, "Small North Texas Quakes Likely Linked to Oil, Gas Operations - Study," *Reuters*, April 21, 2015, sec. Commodities, https://www.reuters.com/article/us-usa-texas-earthquake-idUSKBN0NC2DY20150421.
[1231] Richard D. Andrews and Austin Holland, "Statement on Oklahoma Seismicity" (Oklahoma Geological Survey, April 21, 2015).
[1232] Ben Elgin and Matthew Philips, "Big Oil Pressured Scientists Over Fracking Wastewater's Link to Quakes," *Bloomberg*, March 30, 2015, https://www.bloomberg.com/news/articles/2015-03-30/big-oil-pressured-scientists-over-fracking-wastewater-s-link-to-quakes.

- March 6, 2015 – A careful and detailed analysis of historical data coupled with onsite, real-time measurements of seismic activity in central Oklahoma via rapidly deployed seismic sensors revealed that reactivated ancient faults responsible for thousands of earthquakes in Oklahoma are capable of causing larger seismic events. Current hazard maps did not include induced seismicity and therefore underestimate earthquake hazard, the USGS reported. Until new hazard maps become available, providing information about the type, length, and location of these reactivated faults could provide guidance to the oil and gas industry and help inform public policy decisions.[1233] In addition, noted lead author Dan McNamara, such information can "aid in adapting building codes to ensure that structures can withstand more damaging earthquakes.[1234]

- February 20, 2015 – Scientists with the USGS reported in *Science* about grappling with an unexpected increase in injection-related seismic activity across the middle of North America. In 2014, the number of measured earthquakes with magnitude of 3 or greater in Oklahoma exceeded that in California, and observations increasingly suggested that the effects of fluid injection were not confined to the target formation but instead were communicated, sometimes to greater depths, along pre-existing faults. Making hazard modeling more difficult, "most of these faults are only detected when they are imaged by well-located induced earthquakes." Consequently, predicting and controlling such seismic activity may not be possible, leading to a recommendation that injection projects should be sited away from population centers.[1235]

- February 5, 2015 – Citing an association between increased water use and fracking-induced seismic activity, a research scientist at the Geological Survey of Canada offered the quantity of water injected underground as his hypothesis for an observed increase in the frequency and magnitude of earthquake activity in areas near fracking wells. Although the Council of Canadian Academies in 2014 called for more monitoring and data collection, there are only ten monitoring stations in British Columbia, overseeing the operations of thousands of fracking wells, reported the *Vancouver Observer*.[1236]

- January 29, 2015 – The industry-funded Alberta Energy Regulator confirmed that the location of an earthquake of magnitude 4.4 near Fox Creek, Alberta, was "consistent with being induced by hydraulic fracturing operations," making it the largest felt earthquake yet believed to be related to fracking. Despite claims from industry that tremors related to

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[1233] D. E. McNamara et al., "Earthquake Hypocenters and Focal Mechanisms in Central Oklahoma Reveal a Complex System of Reactivated Subsurface Strike-Slip Faulting: Earthquake Source Parameters in Oklahoma," *Geophysical Research Letters* 42, no. 8 (2015): 2742–49, https://doi.org/10.1002/2014GL062730.
[1234] H. Koontz, "Reawakened Oklahoma Faults Could Produce Larger Future Events," Press Release (U.S. Geological Survey, March 6, 2015), https://www.usgs.gov/news/reawakened-oklahoma-faults-could-produce-larger-future-events#:~:text=Reawakened%20Oklahoma%20Faults%20Could%20Produce%20Larger%20Future%20Events,Survey%20research%20published%20today%20in%20Geophysical%20Research%20Letters.
[1235] A. McGarr et al., "Coping with Earthquakes Induced by Fluid Injection," *Science* 347, no. 6224 (2015): 830–31, https://doi.org/10.1126/science.aaa0494.
[1236] Derek Leahy, "Fracking-Induced Earthquake Puts B.C. Gas Bonanza on Shaky Ground," *Vancouver Observer*, February 5, 2015, https://web.archive.org/web/20150207085334/http://www.vancouverobserver.com/news/fracking-induced-earthquake-puts-bc-gas-bonanza-shaky-ground.

deep-level fracking could never reach magnitudes that would allow them to be felt on the surface, Gail Atkinson, who holds the Canada Research Chair in Induced Seismicity Hazards at Western University in Ontario, noted, "With fracking, the magnitudes have been increasing every year."[1237]

- January 6, 2015 – Using a specialized program, Miami University researchers analyzed data from multiple seismic stations and determined that a cluster of 77 earthquakes in Poland Township, Ohio, which occurred over the course of a little more than a week, was related temporally and spatially to active hydraulic fracturing operations. When the fracturing operations were shut down, the rate of earthquake activity declined to only 6 events in the next 12 hours and only a single event over approximately the next two months. Among this cluster of seismic activity, an earthquake of magnitude 3.0 ranks as one of the largest earthquakes in the United States to be induced by hydraulic fracturing. The mechanism for these earthquakes appears to be induction of slip along a pre-existing fault or fracture zone. Because "no known fault or historical seismicity had been [previously] identified in the area," regulations prohibiting fracturing within three miles of a known fault would not have been protective.[1238, 1239]

- December 18, 2014 – In Canada, an investigation by the British Columbia Oil and Gas Commission found that induced seismicity in the Horn River Basin could be attributed both to wastewater disposal and to hydraulic fracturing operations. The Commission recommended mitigation of induced seismicity from wastewater disposal by "reducing injection rates, limiting the increase in [subsurface] reservoir pressure, and locating distal from faults," among other mitigation techniques.[1240, 1241]

- October 23, 2014 – Researchers from USGS and the Global Seismological Services in Golden, Colorado, linked a 2011 magnitude 5.3 earthquake in Colorado, which damaged the foundations of several homes, to underground disposal of fracking wastewater. The study determined that the earthquake ruptured an 8-10 kilometer-long segment of normal faults—an unexpectedly long length for a magnitude 5.3 earthquake—suggesting that wastewater disposal may have triggered a low stress drop.[1242] Lead author Bill Barnhart, a USGS geophysicist, told *Reuters*, "We saw a big increase in seismicity starting in 2001,

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[1237] Andrew Nikiforuk, "Did Alberta Just Break a Fracking Earthquake World Record?," *The Tyee*, January 29, 2015, http://thetyee.ca/News/2015/01/29/Alberta-Fracking-Earthquake/.
[1238] Robert J. Skoumal, Michael R. Brudzinski, and Brian S. Currie, "Earthquakes Induced by Hydraulic Fracturing in Poland Township, Ohio," *Bulletin of the Seismological Society of America* 105, no. 1 (2015): 189–97, https://doi.org/10.1785/0120140168.
[1239] Michael Wines, "New Research Links Scores of Earthquakes to Fracking Wells Near a Fault in Ohio," *The New York Times*, January 8, 2015, sec. U.S., https://www.nytimes.com/2015/01/08/us/new-research-links-scores-of-earthquakes-to-fracking-wells-near-a-fault-in-ohio.html.
[1240] BC Oil and Gas Commission, "Investigation of Observed Seismicity in the Montney Trend," Technical Report, 2014, https://www.bcogc.ca/files/reports/Technical-Reports/investigation-observed-seismicity-montney-trend.pdf.
[1241] Andrew Nikiforuk, "Fracking Industry Shakes Up Northern BC with 231 Tremors," *The Tyee*, January 10, 2015, https://doi.org/10/Fracking_Industry_Shakes_Up_Northern_BC/.
[1242] W. D. Barnhart et al., "Seismological and Geodetic Constraints on the 2011 M_w 5.3 Trinidad, Colorado Earthquake and Induced Deformation in the Raton Basin: 2011 Trinidad, CO Earthquake," *Journal of Geophysical Research: Solid Earth* 119, no. 10 (2014): 7923–33, https://doi.org/10.1002/2014JB011227.

including magnitude 5 earthquakes, in many locations in the basin, and that coincided with a surge in gas production and injection of wastewater."[1243]

- September 23, 2014 – Youngstown State University geologist Ray Beiersdorfer described increased seismic activity in Youngstown, Ohio in an essay that explores how fracking and fracking-related processes are causing "earthquake epidemics" across the United States.[1244]

- September 15, 2014 – Researchers at the National Energy Technology Laboratory teamed up with researchers from industry and academia to publish data and analysis from a closely watched project that involved field monitoring of the induced fracturing of six horizontal Marcellus Shale gas wells in Greene County, Pennsylvania. Touted in earlier media reports as demonstrating that, during short-term follow-up, fracking chemicals injected into these six wells did not spread to overlying aquifers[1245], the study's most notable finding is striking documentation of fractures from three of the six wells extending vertically to reach above an overlying rock layer previously thought to create an impenetrable "frac barrier" (that is, an upper barrier to fracture growth). In one case, a fracture extended vertically 1,900 feet, a surprisingly far distance. No pre-existing fault had been detected at this location, suggesting that small "pre-existing fractures or small-offset (sub-seismic) faults may have focused the energy of hydraulic fractures on certain areas…." Perhaps because of the extremely small sample size and a design focused primarily on monitoring for potential gas and fluid migration, the study's analysis includes no discussion of the seismic relevance of extremely long, vertical induced fractures.[1246]

- September 15, 2014 – Scientists from USGS ascribed causality to wastewater injection wells from coal-bed methane production for increases in seismic activity in New Mexico and Colorado and, in particular, for an earthquake that measured magnitude 5.3 in Colorado in 2011—the second largest earthquake to date for which there is clear evidence that the earthquake sequence was induced by fluid injection.[1247]

- September 6, 2014 – The Ohio Department of Natural Resources suspended operations at two deep-injection wells for fracking wastewater near Warren in northeastern Ohio after discovering evidence that the operation possibly caused a magnitude 2.1 earthquake. The

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[1243] Laura Zuckerman, "Gas Wastewater Likely Triggered 2011 Quake in Colorado: USGS," *Reuters*, October 30, 2014, sec. Environment, https://www.reuters.com/article/us-usa-earthquake-colorado-idUSKBN0II2NP20141029.
[1244] Ray Beiersdorfer, "View: On Fracking, Earthquakes and Indian Point," *The Journal News*, accessed September 19, 2021, https://www.lohud.com/story/opinion/contributors/2014/09/23/view-geologist-warns-fracking-ties-earthquakes/16100755/.
[1245] Kevin Begos, "DOE Study: Fracking Chemicals Didn't Taint Water," *USA Today*, July 19, 2013, https://www.usatoday.com/story/money/business/2013/07/19/doe-study-fracking-didnt-taint/2567721/.
[1246] R. Hammack et al., "An Evaluation of Fracture Growth and Gas/Fluid Migration as Horizontal Marcellus Shale Gas Wells Are Hydraulically Fractured in Greene County, Pennsylvania," Technological Report (U.S. Department of Energy, 2014).
[1247] Justin L. Rubinstein et al., "The 2001-Present Induced Earthquake Sequence in the Raton Basin of Northern New Mexico and Southern Colorado," *Bulletin of the Seismological Society of America*, 2014, https://doi.org/10.1785/0120140009.

injection well operator, American Water Management Services, had recently received permission to increase pressures at the site of the wells. In 2012, Governor John Kasich had halted disposal of fracking wastewater surrounding a well site in the same region after a series of earthquakes were tied to a deep-injection well. The company that ran that well has disputed the link. The state placed seismic-monitoring devices in the Warren area under protocols adopted after the series of earthquakes in nearby Youngstown.[1248]

- September 1, 2014 – Explaining the need for increased seismic monitoring, Andrew Beaton, Director of the Alberta Geological Survey, stated that over a long period of time, stresses increase in and around an injection wellbore. Seismic movement can be caused if the rate of injection is too fast or if there is a geological feature, such as a fault or fracture in nearby areas. Although Albertans in rural areas have been reporting for years that they can feel tremors under their feet near oil and gas activity, especially around areas of fracking, the Alberta Energy Regulator noted that deep well injections have been shown to create more of an earthquake hazard than hydraulic fracturing. Alberta experienced 819 earthquakes between 1918 and 2009. In comparison, Saskatchewan recorded 13 in the same time period and British Columbia recorded more than 1,200 earthquakes in 2007 alone. There are currently 24 seismic monitors in Alberta, which are tied into other networks, such as those belonging to Environment Canada, University of Calgary, and University of Alberta.[1249]

- August 26, 2014 – In a first-of-its-kind lawsuit, a resident of Prague, Oklahoma, sued two energy companies after rocks fell from her chimney and injured her leg during an earthquake of greater than magnitude 5. The lawsuit claims that underground injection of fracking wastewater conducted by New Dominion LLC and Spess Oil Company has caused shifts in fault lines that have resulted in earthquakes.[1250]

- July 31, 2014 – William Ellsworth, a research geophysicist at the USGS Earthquake Science Center, reported that USGS is developing a hazard model that takes induced earthquakes into account. In addition, residents of Oklahoma, where a sharp spike in earthquake activity has been noted over the past decade, are showing an increased interest in obtaining earthquake insurance.[1251]

- July 3, 2014 – Using data from the Oklahoma Corporation Commission, a team of researchers led by Cornell University geophysicist Katie Keranen found that a steep rise in earthquakes in Oklahoma can be explained by fluid migration from wastewater

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[1248] J. C. Smyth, "Ohio Halts Injections at Two Wells for Fracking Wastewater after Quake," *The Columbus Dispatch*, September 6, 2014, https://www.dispatch.com/article/20140906/NEWS/309069872.
[1249] Rachel Maclean, "Earthquake Hazard Linked with Deep Well Injection in Alberta," *CBC News*, September 1, 2014, https://www.cbc.ca/news/canada/calgary/earthquake-hazard-linked-with-deep-well-injection-in-alberta-1.2751963.
[1250] Leslie Rangel, "Prague Resident Files Lawsuit against Two Okla. Energy Companies Following Earthquake Injury," *KFOR.Com Oklahoma City*, August 26, 2014, https://kfor.com/news/prague-resident-files-lawsuit-against-two-okla-energy-companies-following-earthquake-injury/.
[1251] Joe Eaton, "Oklahoma Grapples With Earthquake Spike—And Evidence of Industry's Role," *National Geographic*, August 2, 2014, sec. Science, https://www.nationalgeographic.com/science/article/140731-oklahoma-earthquake-spike-wastewater-injection.

disposal wells. Moreover, injected fluids in high volume wells triggered earthquakes over 30 kilometers (over 18 miles) away. All of the wells analyzed were operated in compliance with existing regulations. Similar mechanisms may function in other states with high volumes of underground injection of wastewater from unconventional oil and gas production.[1252] Reporting on the study and the increase in earthquakes across the United States and the link to fracking and wastewater disposal, the *Associated Press* noted that some states, including Ohio, Oklahoma, and California, have introduced new rules compelling drillers to measure the volumes and pressures of their injection wells as well as to monitor seismicity during fracking operations.[1253]

- July 1, 2014 – Seismologists linked the emergence of a giant sinkhole that formed in August 2012 near Bayou Corne in southeast Louisiana to tremors (earthquakes) caused by high-pressure pulses of either natural gas or water charged with natural gas. The surges of natural gas that caused the explosive tremors (earthquakes) may have weakened an adjacent salt cavern and caused its collapse. Alternatively, part of the salt cavern may have collapsed, causing a nearby gas pocket to give off surges of gas, later followed by the complete collapse of the salt cavern. These findings help illuminate the role of pressurized fluids in triggering seismic events.[1254]

- June 24, 2014 – Following two earthquakes within a one-month period, the Colorado Oil and Gas Conservation Commission directed High Sierra Water Services to stop disposing wastewater into one of its Weld County injection wells. Monitoring by a team of seismologists from the University of Colorado had picked up evidence of continuing low-level seismic activity near the injection site, including a magnitude 2.6 event less than a month following a magnitude 3.4 earthquake that shook the Greeley area on May 31, 2014.[1255]

- May 6, 2014 – The USGS and Oklahoma Geological Survey (OGS) jointly issued an official earthquake warning for Oklahoma, pointing out that the number of earthquakes in the state has risen 50 percent since just October—when the two agencies had issued a prior warning. The advisory stated that this dramatic increase in the frequency of small earthquakes "significantly increases the chance for a damaging quake in central Oklahoma." Injection wells used for the disposal of liquid fracking waste have been implicated as the presumptive cause of the earthquake swarm. According to the OGS, about 80 percent of the state of Oklahoma is closer than ten miles from an injection

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[1252] K. M. Keranen et al., "Sharp Increase in Central Oklahoma Seismicity since 2008 Induced by Massive Wastewater Injection," *Science* 345, no. 6195 (2014): 448–51, https://doi.org/10.1126/science.1255802.
[1253] Emily Schmall and Justin Jouzapavicius, "Answers on Link between Injection Wells and Quakes," *AP NEWS*, July 14, 2014, sec. Hydraulic fracturing, https://apnews.com/article/hydraulic-fracturing-oklahoma-earthquakes-wastewater-fort-worth-fc32049fda854eaa9982818d149fec26.
[1254] A. Nayak and D. S. Dreger, "Moment Tensor Inversion of Seismic Events Associated with the Sinkhole at Napoleonville Salt Dome, Louisiana," *Bulletin of the Seismological Society of America* 104, no. 4 (2014): 1763–76, https://doi.org/10.1785/0120130260.f
[1255] John Tomasic, "Colorado Drilling Regulators Halt Injection-Well Activity in Reaction to Greeley Quake," *The Colorado Independent*, June 24, 2014, https://www.coloradoindependent.com/2014/06/24/colorado-drilling-regulators-halt-injection-well-activity-in-reaction-to-greeley-quake/.

well.[1256] Since the joint earthquake advisory was released in May, the number of earthquakes in Oklahoma has continued to rise. During the first four months of 2014, Oklahoma had experienced 109 earthquakes of magnitude 3 or higher on the Richter scale. By mid-June, the number of earthquakes had topped 200, exceeding the frequency of earthquakes in California.[1257]

- May 2, 2014 – At the annual meeting of the Seismological Society of America, leading geologists warned that the risks and impacts of earthquakes from fracking and injection wells are even more significant than previously thought, pointing out that such earthquakes could occur tens of miles away from wells themselves, including quakes greater than magnitude 5.0. Justin Rubinstein, a research geophysicist at the USGS said, "This demonstrates there is a significant hazard. We need to address ongoing seismicity."[1258] Seismologist Gail Atkinson reported, "We don't know how to evaluate the likelihood that a [fracking or wastewater] operation will be a seismic source in advance."[1259]

- April 11, 2014 – State geologists reported a link between fracking and a spate of earthquakes in Ohio, prompting the Ohio Department of Natural Resources to place a moratorium on drilling in certain areas and to require greater seismic monitoring.[1260]

- April 3, 2014 – Researchers linked earthquakes in Mexico to fracking in the Eagle Ford Shale, which extends beneath both southern Texas and northern Mexico. They also noted a statistical correlation between seismic activity and fracking, particularly in the border state of Nuevo Leon, which registered at least 31 quakes between magnitude 3.1 and 4.3.[1261]

- April 2014 – Researchers from the University of Alberta and the Alberta Geological Survey published a study in the *Journal of Geophysical Research* that found wastewater injection in Alberta is highly correlated with spikes of seismic activity between October

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[1256] U.S. Geological Survey, "Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes," Press Release, May 6, 2014, https://www.usgs.gov/news/record-number-oklahoma-tremors-raises-possibility-damaging-earthquakes.
[1257] Hailey Branson-Potts, "Oklahoma Coming to Terms with Unprecedented Surge in Earthquakes," *Los Angeles Times*, June 18, 2014, sec. World & Nation, https://www.latimes.com/nation/la-na-oklahoma-earthquakes-20140618-story.html.
[1258] Bryan Walsh, "The Seismic Link Between Fracking and Earthquakes," *Time*, May 1, 2014, https://time.com/84225/fracking-and-earthquake-link/.
[1259] Patrick J. Kiger, "Scientists Warn of Quake Risk From Fracking Operations," *National Geographic*, May 2, 2014, sec. Science, https://www.nationalgeographic.com/science/article/140502-scientists-warn-of-quake-risk-from-fracking-operations.
[1260] Paresh Dave, "Ohio Finds Link between Fracking and Sudden Burst of Earthquakes," *Los Angeles Times*, April 12, 2014, sec. World & Nation, https://www.latimes.com/nation/nationnow/la-na-nn-ohio-finds-link-fracking-earthquakes-20140411-story.html.
[1261] Emilio Godoy, "Fracking, Seismic Activity Grow Hand in Hand in Mexico," *Inter Press Service*, April 3, 2014, sec. Development & Aid, http://www.ipsnews.net/2014/04/fracking-seismic-activity-grow-hand-hand-mexico/.

2006 and March 2012.[1262] On November 13, 2014, *CBC News* reported on a more recent increase in earthquakes, which may also be linked to injection wells.[1263]

- March 7, 2014 – USGS researchers published a study confirming that Oklahoma's damaging magnitude 5.7 earthquake in 2011 was caused by fracking wastewater injection.[1264] One of the authors of the study, seismologist Elizabeth Cochran, noted, "Even if wastewater injection only directly affects a low-hazard fault, those smaller events could trigger an event on a larger fault nearby."[1265]

- January 30, 2014 – A USGS research team linked the rise in earthquakes in Colorado to fracking wastewater injection wells and announced that a study will be published in six to nine months.[1266]

- December 12, 2013 – The *New York Times* detailed the growing link between fracking wastewater injection wells and earthquakes, as well as between fracking itself and earthquakes, with a focus on Oklahoma and a recent magnitude 4.5 earthquake there. As the *New York Times* noted, "Oklahoma has never been known as earthquake country, with a yearly average of about 50 tremors, almost all of them minor. But in the past three years, the state has had thousands of quakes. This year has been the most active, with more than 2,600 so far, including 87 last week…. State officials say they are concerned, and residents accustomed to tornadoes and hail are now talking about buying earthquake insurance."[1267]

- November 19, 2013 – *Reuters* reported that a series of Oklahoma earthquakes in September of 2013 damaged several homes, and that more scientists in a number of states are concerned about earthquakes related to oil and gas development. Seismologist Austin Holland with the University of Oklahoma said, "This is a dramatic new rate of seismicity."[1268]

[1262] Ryan Schultz, Virginia Stern, and Yu Jeffrey Gu, "An Investigation of Seismicity Clustered near the Cordel Field, West Central Alberta, and Its Relation to a Nearby Disposal Well," *Journal of Geophysical Research: Solid Earth* 119, no. 4 (2014): 3410–23, https://doi.org/10.1002/2013JB010836.
[1263] Kim Trynacity, "'Industrial Activities' Could Trigger Earthquakes in Alberta, Researcher Says," *CBC News*, November 10, 2014, https://www.cbc.ca/news/canada/edmonton/fracking-linked-to-alberta-earthquakes-study-indicates-1.2829484.
[1264] Danielle F. Sumy et al., "Observations of Static Coulomb Stress Triggering of the November 2011 *M* 5.7 Oklahoma Earthquake Sequence," *Journal of Geophysical Research: Solid Earth* 119, no. 3 (2014): 1904–23, https://doi.org/10.1002/2013JB010612.
[1265] Becky Oskin, "Wastewater Injection Triggered Oklahoma's Earthquake Cascade," *Live Science*, March 7, 2014, https://www.livescience.com/43953-wastewater-injection-earthquake-triggering.html.
[1266] Lesley McClurg, "Earthquakes in Southern Colorado Linked to Oil and Gas Production," *Colorado Public Radio*, January 30, 2014, https://www.cpr.org/show-segment/earthquakes-in-southern-colorado-linked-to-oil-and-gas-production/.
[1267] Henry Fountain, "Experts Eye Oil and Gas Industry as Quakes Shake Oklahoma," *The New York Times*, December 12, 2013, sec. Science, https://www.nytimes.com/2013/12/13/science/earth/as-quakes-shake-oklahoma-scientists-eye-oil-and-gas-industry.html.
[1268] Carey Gillam, "In Oklahoma, Water, Fracking - and a Swarm of Quakes," *Reuters*, November 19, 2013, sec. Environment, https://www.reuters.com/article/us-usa-earthquakes-fracking-oklahoma-idUSBRE9AI12W20131119.

- July 19, 2013 – A study from the Lamont-Doherty Earth Observatory linked 109 earthquakes in Youngstown, Ohio to fracking wastewater disposal.[1269, 1270]

- July 11, 2013 – A study in *Science* by Columbia University's Lamont-Doherty Earth Observatory showed that deep-well injection of fracking waste can stress geological faults in ways that make them vulnerable to slipping. The research shows that distant natural earthquakes triggered swarms of smaller earthquakes on critically stressed faults. The researchers wrote, "The fluids [in wastewater injection wells] are driving the faults to their tipping point…. Areas with suspected anthropogenic earthquakes are more susceptible to earthquake-triggering from natural transient stresses generated by the seismic waves of large remote earthquakes."[1271]

- April 2013 – A group of British researchers stated that hydraulic fracturing itself was the likely cause of at least three earthquakes powerful enough to be felt by human beings at the surface. The researchers proposed that increases in the fluid pressure in fault zones were the causal mechanism for these three known instances of "felt seismicity" in the United States, Canada, and the United Kingdom. The largest of these earthquakes was a magnitude 3.8 in the Horn River Basin, Canada.[1272]

- March 26, 2013 – Scientists from the University of Oklahoma, Columbia University and USGS linked a 2011 swarm of earthquakes in Oklahoma to fracking waste disposal in that state.[1273] This included a magnitude 5.7 earthquake—possibly the largest ever triggered by wastewater injection—that injured two people, destroyed 14 homes, and was felt across 17 states.[1274] The research team concluded in a paper in the journal *Geology* that their data called into question the previously predicted maximum size of injection-induced earthquakes.[1275, 1276]

- December 14, 2012 – At a 2012 American Geophysical Union meeting, scientists presented data and concluded that some U.S. states, including Oklahoma, Texas and

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[1269] Won-Young Kim, "Induced Seismicity Associated with Fluid Injection into a Deep Well in Youngstown, Ohio," *Journal of Geophysical Research: Solid Earth* 118, no. 7 (2013): 3506–18, https://doi.org/10.1002/jgrb.50247.
[1270] B. Chameides, "Fracking Waste Wells Linked to Ohio Earthquakes," *Scientific American*, September 5, 2013, https://www.scientificamerican.com/article/fracking-waste-wells-linked-to-ohio-earthquakes/.
[1271] Sharon Begley, "Study Raises New Concern about Earthquakes and Fracking Fluids," *Reuters*, July 11, 2013, sec. Environment, https://www.reuters.com/article/us-science-fracking-earthquakes-idUSBRE96A0TZ20130711.
[1272] Richard Davies et al., "Induced Seismicity and Hydraulic Fracturing for the Recovery of Hydrocarbons," *Marine and Petroleum Geology* 45 (2013): 171–85, https://doi.org/10.1016/j.marpetgeo.2013.03.016.
[1273] Mark Drajem and Jim Efstathiou Jr., "Oklahoma Quake Tied to Drilling Wastes Adds Pressure for Rules," *Bloomberg*, March 27, 2013, https://www.bloomberg.com/news/articles/2013-03-26/oklahoma-earthquake-in-2011-tied-to-wastewater-wells-in-fracking.
[1274] Michael Behar, "Fracking's Latest Scandal? Earthquake Swarms," *Mother Jones*, April 2013, https://www.motherjones.com/environment/2013/03/does-fracking-cause-earthquakes-wastewater-dewatering/.
[1275] Katie M. Keranen et al., "Potentially Induced Earthquakes in Oklahoma, USA: Links between Wastewater Injection and the 2011 Mw 5.7 Earthquake Sequence," *Geology* 41, no. 6 (2013): 699–702, https://doi.org/10.1130/G34045.1.
[1276] Francie Diep, "Study: Wastewater Injection Caused Oklahoma's Largest-Ever Earthquake," *Popular Science*, March 18, 2019, https://www.popsci.com/science/article/2013-03/largest-earthquake-ever-linked-lightly-regulated-wastewater-wells/.

Colorado, have experienced a significant rise in seismic activity coinciding with a boom in gas drilling, fracking and wastewater disposal. Scientists further found that Oklahoma has seen a significant increase in earthquakes linked to wastewater injection, that a 5.3 earthquake in New Mexico was linked to wastewater injection, and that earthquakes were increasingly common within two miles of injection wells in the Barnett Shale region of Texas. Art McGarr, a researcher at the USGS Earthquake Science Center, concluded that, "The future probably holds a lot more in induced earthquakes as the gas boom expands."[1277]

- November 30, 2012, January 11, 2012, December 22, 2009 – In three different sets of comments on proposed fracking guidelines and regulations, citing scientific reports linking oil and gas infrastructure to seismic activity, the New York City Department of Environmental Protection (NYC DEP) raised serious concerns about the impacts of potential seismic activity from fracking-related activities on New York City's water supply infrastructure. Between 2009 and 2012, the NYC DEP consistently raised concerns that seismic activity surrounding New York City's aquifers and watershed infrastructure could threaten the city's drinking water supply by triggering microseismic events and small induced earthquakes that, in turn, could threaten the integrity of the aging, 100-mile-long aqueducts that carry drinking water from the Catskill Mountains into the New York City metropolitan area. The agency expressed specific concerns about the ability of hydraulic fracturing fluids to migrate underground and to intercept and reactivate faults miles away.[1278, 1279, 1280]

- September 6, 2012 – The British Columbia Oil and Gas Commission determined that fracking itself causes earthquakes, pointing to the results of a probe into 38 seismic events near fracking operations in the Horn River Basin. The report noted that no quakes had been recorded in the area prior to April 2009, before fracking began. The report recommended that the link between fracking and seismic activity be further examined.[1281]

- March 29, 2012 – The USGS found that between 2001 and 2011, there was a six-fold increase in earthquakes greater than magnitude 3.0 in the middle of the United States that

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[1277] Jessica Leber, "Studies Link Earthquakes to Wastewater from Fracking," *MIT Technology Review*, December 14, 2012, https://www.technologyreview.com/2012/12/14/181149/studies-link-earthquakes-to-wastewater-from-fracking/.
[1278] New York City Department of Environmental Protection, "New York City Comments on: Draft Supplemental Generic Environmental Impact Statement (DSGEIS) on the Oil, Gas and Solution Mining Regulatory Program – Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs," December 22, 2009, https://www.state.nj.us/drbc/library/documents/dockets/stone-energy/NYCDEP-DSGEIScomments122209.pdf.
[1279] New York City Department of Environmental Protection, "Comments on the Revised Draft Supplemental Generic Environmental Impact Statement," January 11, 2012.
[1280] New York City Department of Environmental Protection, "Comments on the Revised High-Volume Hydraulic Fracturing Regulations," November 30, 2012.
[1281] The Canadian Press, "Fracking Causes Minor Earthquakes, B.C. Regulator Says," *CBC News*, September 6, 2012, https://www.cbc.ca/news/canada/british-columbia/fracking-causes-minor-earthquakes-b-c-regulator-says-1.1209063.

"are almost certainly manmade." The agency further reported that the increase appears to be linked to oil and gas production and deep injection of drilling wastewater.[1282, 1283]

- July 31, 2011 – Numerous earthquakes in Arkansas motivated the Arkansas Oil and Gas Commission to shut down a disposal well and enact a permanent moratorium on future disposal wells in a nearly 1,200 square-mile area of the Fayetteville Shale.[1284]

- March 10, 2010 – In Texas, a 2008-2009 swarm of earthquakes in the Dallas-Fort Worth area was linked to produced water disposal wells.[1285]

- June 12, 2009 – *The Wall Street Journal* reported that earthquakes shook Cleburne, Texas, a small town at the epicenter of fracking activity. More earthquakes were detected during that period of fracking activity than in the previous 30 years combined.[1286]

1282 William L. Ellsworth et al., "Are Seismicity Rate Changes in the Midcontinent Natural or Manmade?," 2011, https://www.researchgate.net/publication/281538802_Are_seismicity_rate_changes_in_the_midcontinent_natural_or_manmade_Abstract.
1283 Mike Soraghan, "'Remarkable' Spate of Man-Made Quakes Linked to Drilling, USGS Team Says," *E&E News*, March 29, 2012, https://web.archive.org/web/20130708085615/http://www.eenews.net/stories/1059962190.
1284 Caroline Zilk, "Permanent Disposal-Well Moratorium Issued," *Arkansas Online*, July 31, 2011, https://www.arkansasonline.com/news/2011/jul/31/permanent-disposal-well-moratorium-issued-20110731/.
1285 C. Frohlich et al., "The Dallas-Fort Worth Earthquake Sequence: October 2008 through May 2009," *Bulletin of the Seismological Society of America* 101, no. 1 (2011): 327–40, https://doi.org/10.1785/0120100131.
1286 Ben Casselman, "Temblors Rattle Texas Town," *Wall Street Journal*, June 12, 2009, sec. Business, https://www.wsj.com/articles/SB124476331270108225.

Abandoned and active wells as pathways for gas and fluid migration

Individually or together, abandoned and active wells can serve as underground conduits for the migration of fluid and vapors. The most probable pathway of contaminant transport takes place outside the well casing, allowing leaks to migrate upward within the well, contaminating soil or groundwater and emitting methane into the atmosphere. A 2020 investigation in Pennsylvania identified uncemented sections of well casings as the most common cause of water contamination incidents.

The proportion of active wells that leak gas and fluids is unknown, but a 2021 study that examined the records of more than 100,000 oil and gas wells in three states estimates an overall leakage of 14.4 percent with fracked and horizontal wells showing a higher frequency of leaks than vertical wells (30.3 percent versus 11 percent). The cost of remediating fracked wells at the end of their lifespan is also significantly higher than for conventional wells, with costs that can exceed $100,000 per well.

Most fracking operations take place in oil and gas fields with a long history of conventional drilling and therefore with many abandoned wells. Multiple lines of evidence reveal that abandoned wells can and do allow pressurized fluids and gases to migrate to the surface and, in some cases, intersect active wells. Whether plugged or unplugged, abandoned wells are a significant source of methane leakage into the atmosphere and, based on findings from New York and Pennsylvania, may exceed cumulative total leakage from oil and gas wells currently in production. No state or federal agency routinely monitors methane leakage from abandoned wells. A 2021 study found that annual methane emissions from abandoned oil and gas wells might be underestimated by as much as 150 percent in Canada and 20 percent in the United States.

The location and status of most abandoned wells are not recorded in state databases, and many remain unplugged. Of the approximately 4,700,000 oil and gas wells in the United States, close to 3 million are no longer in production and an estimated 2.6 million are unplugged. These numbers are likely underestimates because of poor recordkeeping. As many as 750,000 to 1 million abandoned wells are orphaned: their owners either cannot be located at all or are unable pay the costs of decommissioning them. In Pennsylvania alone, an estimated 200,000 wells are orphaned. In California, 5,540 wells are orphaned or at high risk of becoming orphaned. In the United States, the number of abandoned wells increased by over 12 percent since the onset of the fracking boom in 2008. According to a 2021 study, the number of orphaned wells in the United States is expected to increase as the economy transitions to renewables.

$300 billion is the estimated cost of cleaning up and remediating of the entire U.S. inventory of abandoned wells. This cost is likely to rise, according to a 2021 analysis, as newer abandoned wells tend to be fracked wells which are much deeper and more difficult and expensive to remediate.

Most abandoned wells are not adequately bonded, leaving the full cost of plugging them to state or federal taxpayers. The financial stress of continued low prices led to a 50 percent rise in bankruptcies in 2019 and a further increase in orphaned wells. Also in 2019, the U.S.

Government Accountability Office (GAO) reported that 84 percent of bonds for extraction of oil and gas on federal lands were insufficient to cover cleanup costs.
The federal Bureau of Land Management (BLM) lacks good methods for tracking idle oil and gas wells drilled on public lands, and funding is inadequate to plug those orphaned wells which have already been identified.

Various state and federal proposals have suggested public works projects that create jobs for laid-off oil and gas workers that involve locating and remediating abandoned and orphaned wells. These plans hinge on a conundrum: public funds allocated for clean-up represent and indirect subsidy for fracking operators who use bankruptcy declarations to shirk their responsibility for these wells. In 2021, two bills were proposed in California to help address the problem of bankruptcy loopholes and to compel operators to clean up orphaned wells.

- July 1, 2021 – As reported in the *Los Angeles Times*, an analysis by the National Parks Conservation Association (NCPA) identified almost 32,000 orphaned oil and gas wells within 30 miles of national parks nationwide. They are not productive, have not been properly plugged, and the owners are bankrupt or cannot be found. An interactive map of national parks and orphaned wells shows that about 5,700 of these wells are near the Santa Monica Mountains National Recreation Area. These leaky wells contribute to poor air quality, and aside from contributing to climate change, increase the threat of wildfires, contaminate aquifers, and harm the ecosystem. About 120,000 jobs could be created by the federal government by a national program to plug orphaned wells, potentially keeping oil and gas workers employed during the switch to renewables. And yet, as America Fitzpatrick, energy program manager at NPCA, noted, such public works projects represent indirect subsidies to the oil and gas industry. "It's really unfortunate that the American taxpayer has (had) to address the cleanup that these oil and gas companies should really be responsible for."[1287]

- June 25, 2021 – An analysis in the California newspaper *Desert Sun*, explicates how companies use bankruptcy protection to shift the clean-up costs of abandoned wells to taxpayers. Oil and gas companies are required to put up bonds for cleanup prior to the onset of drilling, but the required amounts are often grossly inadequate to cover the costs. Companies have no incentive to spend more money, and essentially walk away. Since 2015, over 260 oil and gas companies have filed for chapter 11 bankruptcy in North America, essentially reaping the profits of fossil fuel extraction but leaving the responsibility and costs to state and federal governments. Only $110 million in bonding has been set aside for remediating California's depleted oil and gas wells, while the cleanup costs are estimated to be in the billions. California state Senator Monique Limon commented that the problem of companies leaving California with a cleanup bill "absolutely is a systemic issue." Rincon Island, an artificial island built in the 1950s to drill for oil is a case in point. It has not produced oil since 2008, has been cited for

[1287] Sammy Roth, "How Many Abandoned Oil Wells Threaten Your Favorite National Park?," *Los Angeles Times*, July 1, 2021, https://www.latimes.com/environment/newsletter/2021-07-01/how-many-abandoned-oil-wells-threaten-your-favorite-national-park-boiling-point.

multiple violations, and has changed hands many times. Purchased in 2002 in a bankruptcy sale, the buyer then filed for bankruptcy and taxpayers were left with a $27 million tab.[1288]

- May 10, 2021 – Since the mid-1880s, over one quarter million wells have been drilled in Ohio. Identifying which ones have been properly plugged and which should be deemed orphans is difficult work. Many are found only after problems are reported. For example, one old well was discovered under the gym floor of an Ohio elementary school. Magnetometers mounted on drones can scan a large area and identify anomalies in the ground's magnetic field that signify the presence of a vertical well casing. In a recent study, this technique located almost 90 possible wells in an area where records had indicated only 39. Not all old wells retain their original metal casings; in these cases, the use of LIDAR (LIght Detection And Radar) technology may be needed. Ohio hopes to use these both techniques to identify orphan wells and is also planning to increase the rate of plugging them. The Ohio Department of Natural Resources has set a goal of locating and plugging at least 200 depleted wells a year, but, at this pace, hundreds of years would be required to plug all of them. Use of high-tech tools like magnetometers and drones could help by identifying wells nearby to an existing remediation site, thereby allowing contractors to batch plugging jobs together. According to proponents of this plan, plugging Ohio's abandoned wells could create at least 8,000 jobs over a 20-year period, a cost-effective measure that brings ecosystem benefits, especially when weighed against the social costs of greenhouse gas emissions.[1289]

- May 7, 2021 – In early 2020, Canada allocated $1.7 billion in federal funding to clean up orphaned and inactive oil and gas wells owned by companies that were financially incapable of doing so. The province of Alberta alone received $1 billion. An investigation by a nonprofit news organization, the *Narwhal*, found that half of the funding went to help clean up sites owned by eight of Canada's largest oil and gas companies. Sites owned by Canadian Natural Resources Limited were allocated over $102 million, despite the company having reported an average of $1.9 billion in annual net profits over the last decade and having increased shareholder dividends by 11 percent in March 2021. Among other findings: bonds required of companies in Alberta to ensure adequate funding of cleanup are inadequate, and no legislation indicates when wells must be sealed. Further, the current estimated cost of cleanup is about $30 billion, but only $216 million in bonds are held for this purpose. Morrigan Simpson-Marran, an analyst with the Pembina Institute, has urged a redirection of federal money to help smaller companies address their orphan well problem and regulations requiring larger companies to clean up their own wells.[1290]

[1288] Mark Olalde, "Oil Bankruptcies Leave Environmental Cleanup Bills to California Taxpayers," *Desert Sun*, June 25, 2021, https://www.desertsun.com/in-depth/news/environment/2021/06/25/oil-bankruptcies-leave-environment-cleanup-california-taxpayers/4977647001/.
[1289] Kathiann M. Kowalski, "Thousands of Abandoned Ohio Oil and Gas Wells May Be Hidden. Drones Could Help Find Them," *Energy News Network*, May 10, 2021, https://energynews.us/2021/05/10/thousands-of-abandoned-ohio-oil-and-gas-wells-may-be-hidden-drones-could-help-discover-them/.
[1290] Sharon J. Riley, "$100 Million in Federal Funding for Cleanup of Alberta Oil and Gas Wells Went to Sites Licensed to CNRL," *The Narwhal*, May 7, 2021, https://thenarwhal.ca/cnrl-alberta-oil-gas-wells-cleanup/.

- May 2, 2021 – A proposed $30 million project to plug 1,600 oil wells in Pennsylvania's Allegheny National Forest has been plagued with delays, possible fraud, and allegations of criminal felonies. Resources Preservation, legally responsible for plugging the wells, created a partnership with AquaPower Holdings, which has floated a complex plan that requires the purchase of a decommissioned power plant and wastewater treatment facility. Sand would be transported in one direction, and salt would be transported back. Coal fly ash would be mixed into concrete to be used for new roads and well pads, while fracking wastewater would be turned into road salt and other salable products that would then pay to plug old wells. The legal agreement with the Pennsylvania Department of Environmental Protection (DEP) required Resources Preservation to plug at least 10 wells and return 60 abandoned wells to production by the end of 2020. However, 15 months after the agreement, there has been no progress, and Resources Preservation has stated that it lacks financial resources to proceed, and blames AquaPower, which has not made required payments to Resources Preservation totaling $600,000. The state of Pennsylvania has subpoenaed financial records and plans to use forensic accountants to evaluate the issue. Financial hardship does not excuse the company from its obligations, as noted by EPA enforcement officer Leah Zedella. "Compliance with the Safe Drinking Water Act is required without contingencies." At the time of publication Resources Preservation had plugged only one well and paid for it by selling equipment.[1291]

- April 28, 2021 – There are approximately 4,700,000 oil and gas wells in the United States and 790,000 in Canada. About 60 percent of these are inactive but only one in three of the inactive wells are plugged. The number of wells no longer in production is likely an underestimate because of poor recordkeeping of older wells. Inactive wells pose environmental hazards related to air pollution, greenhouse gas emissions, groundwater contamination, and ecosystem damage. They can leak underground even if there is no surface leak and substances may reach the surface through complex pathways. The number of orphaned wells, which are abandoned wells for which no responsible party exists, is expected to increase as the economy transitions to renewables. This study evaluated oil and gas data from the United States and Canada in order to identify policies that could address environmental problems related to inactive wells. It identified barriers to plugging and the potential for leaks, and urged further research on the potential for plugged wells to leak. Oil and gas industry bonds for well-plugging and site restoration are inadequate, and possible additional sources of funding, such as carbon credits and repurposing land for wind and solar, can augment these. The benefits of well-plugging when including carbon pricing, the social cost of greenhouse gas emissions, and restoration of ecosystem impacts could offset much of the cost. The authors provide a list of policy recommendations for monitoring and managing abandoned wells and recommend further studies on the environmental impacts of abandoned wells and plugging.[1292]

[1291] Anya Litvak and Laura Legere, "Project to Plug 1,600 Oil Wells in Allegheny National Forest Faces Delays, Doubt — Even an Arrest Warrant," *Pittsburgh Post-Gazette*, May 2, 2021, https://www.post-gazette.com/business/powersource/2021/05/02/A-project-to-plug-1-600-wells-is-almost-ready-to-launch-and-has-been-for-six-years/stories/202105020101.

[1292] Mary Kang et al., "Orphaned Oil and Gas Well Stimulus—Maximizing Economic and Environmental Benefits," *Elementa: Science of the Anthropocene* 9, no. 1 (2021), https://doi.org/10.1525/elementa.2020.20.00161.

- April 25, 2021 – An analysis of financial inequity related to oil and gas wells at the end of their productive lifespans described the ways in which the cost of clean-up is transferred to taxpayers. When production at an oil or gas well falls, a large corporation often will sell it to a smaller one, along with the responsibility for cleanup. Bonds are required to cover the cost of clean-up prior to drilling but in most states the bonds cover only about two percent of the actual clean-up cost. Companies are also allowed to buy "blanket bonds," which allow an unlimited number of wells for one price. When production falls below profitability, many smaller companies find it easier to file for bankruptcy or leave the state rather than clean up. This is the point at which the cost of cleanup falls to taxpayers. For example, the estimated cost of plugging all orphaned wells in Louisiana is now over $200 million. An Abandoned Well Act that would create a federal Abandoned Well Administration and set realistic bonding requirements may be necessary. In addition, the author suggests that oil and gas companies should start paying now for their prior 150 years of damage to the environment.[1293]

- April 16, 2021 – Oil and gas companies are attempting to sell off over $110 billion worth of assets to compensate for financial losses in 2020 and to show apparent reductions of their carbon footprints. Regulations regarding the decommissioning and environmental liabilities of offshore assets are tougher than onshore; selling an offshore asset does not relieve a company from the responsibility of the cost of decommission as it does with onshore wells. This discrepancy has caused sale prices of offshore assets to fall significantly. For example, Exxon sold its North Sea assets for only half of the original price, likely related to the high projected cost of decommissioning. Onshore rules for decommissioning wells are, by contrast, much more lax, allowing gas and oil companies to simply abandon unprofitable wells, leaving taxpayers on the hook for the cost of decommissioning.[1294]

- April 14, 2021 – An analysis of President Biden's plan to plug orphaned oil and gas wells estimated the number of documented unplugged well at 2.6 million with another 1.2 million undocumented unplugged wells. The cost for cleaning up all of them could reach $300 billion. Further, this cost is likely to rise, as newer abandoned wells tend to be fracked wells which are much deeper and more difficult to remediate. States require bonds to cover the cost of well plugging, but estimates suggest that the required bonds would cover only about one percent of cleanup costs. Companies therefore frequently abandon the wells when production falls and taxpayers are left with the bill. The American Jobs Plan would invest $16 billion to begin cleanup of orphaned wells, but the ongoing concern is how to avoid creating incentives for more well abandonment.

[1293] Bob Marshall, "Oil Companies Made a Mess. Will Taxpayers Clean It Up?," Nola.com, April 25, 2021, https://www.nola.com/opinions/article_e3d315b4-a3bb-11eb-8acc-7b0a5eebdbdb.html.
[1294] Justin Mikula, "Fossil Fuel Companies' Tough Sell: Oil and Gas Sites with Costly Environmental Clean-Up," *DeSmog*, April 16, 2021, https://www.desmog.com/2021/04/16/fossil-fuel-companies-tough-sell-oil-gas-sites-environmental-clean-up/.

Proposals are under consideration to add stricter financial requirements for oil and gas producers that would limit the likelihood of well abandonment.[1295]

- April 6, 2021 – The proportion of active gas and oil wells in the United States that leak is unknown. Fluid leaks can migrate upward within the well, often through a poorly cemented well annulus, contaminating soil or groundwater and emitting methane. A team of researchers investigating the frequency of leaks in active oil and gas wells looked at oil and gas regulatory databases of 33 states but were only able to obtain adequate information for analysis from three: Colorado, New Mexico and Pennsylvania. From the records of these three states, the team created a dataset of almost 475,000 tests of leakage on over 105,000 oil and gas wells. These tests were of two types: sustained casing pressure (SCP) tests and casing vent flow (CVF) tests of well integrity. SCP testing is done by measuring annular pressure buildup after an initial "bleeding off" of pressure, whereas CVF testing involves observation for leakage through an open annular valve. By combining these records, the researchers estimated that 14.4 percent of the tested wells had exhibited leakage. Deviated or horizontal wells showed a higher frequency of leaks than vertical wells (30.3 percent versus 11 percent). A combination of well construction information and SCP testing was used as a proxy to identify wells with a potential for gas migration into groundwater. The findings indicated that directional wells were more likely than vertical ones to have a potential for gas migration in Colorado and Pennsylvania, although this pattern was not seen in New Mexico and was less apparent in Pennsylvania for wells drilled after 2011. The dataset included only about 10 percent of the active wells in the United States. The authors suggest a standardized testing protocol to identify well integrity issues and allow better planning of remediation or abandonment of wells.[1296]

- March 19, 2021 – British Columbia has dedicated a $100 million fund to clean up dormant oil and gas wells. The funds cover 50 percent of the cost of restoration, up to $100,000 per well. An investigation by *The Tyee* found that much of the money is going to financially secure major oil and gas companies. One quarter of the first $50 million will be used to clean up sites owned by Canadian Natural Resources, Ltd, a company worth $45 billion. Shanghai Energy Corp., of which the Chinese Communist Party has an ownership stake, is another recipient of funding. Supporters of this plan highlight job creation and environmental benefits. Critics argue that companies benefiting from oil and gas extraction in British Columbia should be fully responsible for cleaning up their sites.[1297]

- January 29, 2021 – No U.S. federal regulations govern the remediation of orphaned wells, a task that falls to state governments. A study of how states manage this problem

[1295] Alexander Sammon, "Biden's Promising, Problematic Plan to Plug Orphaned Oil and Gas Wells," *The American Prospect*, April 14, 2021, https://prospect.org/environment/bidens-promising-problematic-plan-plug-orphaned-oil-gas-wells/.
[1296] Greg Lackey et al., "Public Data from Three US States Provide New Insights into Well Integrity," *PNAS* 118, no. 14 (2021), https://doi.org/10.1073/pnas.2013894118.
[1297] Andrew MacLeod, "Governments Are Making Taxpayers Subsidize Corporate Cleanup of Oil and Gas Wells," *The Tyee*, April 19, 2021, https://thetyee.ca/News/2021/03/19/Governments-Make-Taxpayers-Subsidize-Corporate-Cleanup-Oil-Wells/.

examined underlying factors that influence state policies regarding the financial risks of abandoned and orphaned wells. The researchers tested combinations of five variables, including the adequacy of bonding requirements and the use of fees and taxes to cover the costs. They added the state governor's party as well as the Forbes Green Index and the stringency of state oil and gas regulations regarding oil and gas production to the assessment. Binary values were assigned to the variables and ordinary least squares regression was used to correlate them. The findings showed that that states with more restrictive oil and gas rules and which are less reliant on oil and gas revenues had stronger financial assurance policies. There was no correlation with the state governor's political party or with anticipated cleanup costs. Overall, their model accounted for about 60 percent of the variability between states. The authors recommend avenues for future research, including better data collection and reporting of the number of orphan wells and the costs of remediation. Notably, the cost of remediating orphaned and abandoned oil and gas wells is much higher for fracked wells and can exceed $100,000 per well.[1298]

- January 12, 2021 – Writing in *Current Affairs*, energy market analyst Megan Milliken Biven proposed the development of a national Abandoned Well Administration to directly employ displaced oil and gas workers, to identify and remediate the millions of abandoned wells in the United States, and to establish a national monitoring and safety response program. She also recommended the establishment of an abandoned well tax on all well owners to begin paying for cleanup. The cost of plugging and site remediation is high; an estimated $280 billion would be needed to properly plug the 2.6 million documented wells in the United States. With a lack of federal oversight, oil and gas companies strongly influence local tax and zoning laws and the cost of bonding required to clean up wells at the end of their productive life. Companies often avoid the cost of plugging by delaying abandonment or by offloading the wells to smaller firms, which are less likely to afford well closures. Taxpayers end up shouldering the costs in violation of the "polluter pays" principle. An Abandoned Well Administration would also redress a humanitarian issue arising from the failure to link federal allocations to clean up wells with requirements to hire or retain workers. In Louisiana, prisoners are used by the oil and gas industry for this purpose and work long hours for minimal pay.[1299]

- January 3, 2021 – An historical analysis of oil and gas records in Michigan, where drilling began in 1859, showed that about 60,000 oil and gas wells have been drilled in the state, with the location of many older wells unknown and the number of orphaned wells growing, similar to the situation across the United States. Michigan regulations require oil and gas companies to notify the Michigan Department of Environment, Great Lakes, and Energy about non-producing or dry wells and to pay for plugging themselves. The agency also administers specific plugging instructions for each well. The process is expensive, but blanket bonds for cleanup at well end-of-life, covering all of a company's wells in the state, range from $100,000 to $250,000. This amount is grossly inadequate.

[1298] Steven Nelson and Jonathan M. Fisk, "End of the (Pipe)Line? Understanding How States Manage the Risks of Oil and Gas Wells," *Review of Policy Research* 38, no. 2 (2021): 203–21, https://doi.org/10.1111/ropr.12411.
[1299] Megan Milliken Biven, "The Wreckage of the Last Energy Epoch: Abandoned Wells and Workers," *Current Affairs*, July 12, 2021, https://www.currentaffairs.org/2020/01/the-wreckage-of-the-last-energy-epoch-abandoned-wells-and-workers/.

A 2017-2018 orphaned well report indicated that it cost Michigan over $1 million to plug just six wells in difficult locations. An orphan well fund in Michigan collects two percent of a severance tax from the oil and gas industry but these funds are also insufficient to cover the cost of plugging. Michigan regulators, as opposed to most other states, have the authority to examine the receiving company's assets to see if they would have the ability to pay for remediation. This makes it much harder for oil and gas companies to walk away from financial responsibility in the state. Municipalities in Michigan are not allowed to pass zoning laws limiting drilling, and the state requires a setback of only 1,320 feet from homes.[1300]

- December 15, 2020 – A McGill University team collected data on methane emissions from almost 600 abandoned wells in the United States and Canada, across seven states and two provinces, and used estimates of the number of abandoned wells in both countries to extrapolate a cumulative total of methane leakage from this source. Regional variations, plugging status, and well type (gas, combined oil and gas, and unknown) were considered in the analysis, and five different scenarios were used to see how different approaches would affect the estimates. The results showed that 96 percent of cumulative emissions come from 10 percent of wells, with unplugged gas wells serving as the highest emitters. Abandoned gas wells emitted almost double the emissions of abandoned combined oil and gas wells. The findings indicate that, for both the United States and Canada, methane emissions from abandoned wells are significantly higher than previously estimated (by 20 percent in the United States and by as much as 150 percent in Canada) and that there remains a great deal of uncertainty about the actual quantity of these emissions. Less than 0.01 percent of abandoned oil and gas wells in the United States and Canada have been measured for leakage, and the actual number of such wells also remains unclear. These results also suggest that emissions could be markedly reduced by plugging abandoned wells and by locating "super emitters."[1301, 1302] Commenting on the study, David Risk, a professor of earth sciences at St. Francis Xavier University said, "But if there's one thing that oversight studies have taught us, it's that when we measure more, we often find more. I think there's a strong possibility that emissions are larger than expressed here."[1303]

- October 30, 2020 – California has over 124,000 abandoned oil and gas wells and 38,000 so-called idle wells: unplugged wells that have not produced oil or gas for two more years. The wells can continue to leak methane, which is not only a climate threat but presents an explosion risk and can contaminate groundwater. Methane is also involved in

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[1300] Stacy Gittleman, "'Orphaned' Oil, Gas Wells and Threat to the Climate," *Downtown News Magazine*, January 3, 2021, https://www.downtownpublications.com/single-post/orphaned-oil-gas-wells-and-threat-do-the-climate.
[1301] James P. Williams, Amara Regehr, and Mary Kang, "Methane Emissions from Abandoned Oil and Gas Wells in Canada and the United States," *Environmental Science & Technology* 55 (2021): 563–70, https://doi.org/10.1021/acs.est.0c04265.
[1302] James P. Williams, Amara Regehr, and Mary Kang, "Correction to "Methane Emissions from Abandoned Oil and Gas Wells in Canada and the United States"," *Environmental Science & Technology* 55 (2021): 3449–3449, https://doi.org/10.1021/acs.est.0c04265.
[1303] Natasha Bulowski, "Canada Needs to Plug Methane Pollution from Abandoned Wells," *National Observer*, May 10, 2021, https://www.nationalobserver.com/2021/05/10/news/canada-needs-more-data-abandoned-oil-and-gas-wells.

the formation of ozone, and benzene and toluene can be co-contaminants. A research team evaluating methane emissions from abandoned wells in California used a combination of methods that allowed more sensitive measurements than those collected by the California Methane Survey. Looking at a representative sample of abandoned oil and gas wells in California, the researchers found a wide range of leakage rates, with unplugged idle wells leaking more than plugged abandoned wells and with the worst culprits leaking enough to substantially impact California's methane budget. Extrapolating the data suggests that the leakage rate might increase the California Methane Survey's estimate of emissions by 31 percent. The authors recommend further samples of idle and active wells at a low detection limit and additional measurements in areas where groundwater pumping has caused high levels of subsidence.[1304]

- August 10, 2020 – "Stripper" wells are oil or gas wells near the end of their lifespans that produce less than 15 barrels of oil equivalent. They are typically not profitable to operate but, because the cost of decommissioning them can be greater than the cost of keeping them running, they remain online or at the ready. Stripper wells are the most abundant type of oil and gas well, with more than 700,000 of these low-producing, marginal wells in the United States, and they appear to represent a disproportionately large source of methane emissions relative to their production, sometimes leaking more gas than is extracted, captured, and sent to market. Making direct measurements of emissions from marginal oil and gas wells in the Appalachian Basin of southeastern Ohio, a research team from University of Cincinnati showed that emissions of both methane and volatile organic compounds followed a skewed distribution, with many wells having zero or low emissions and a few wells responsible for the majority of emissions. Follow-up measurements at five wells indicated high emissions were not episodic. Some wells were emitting all or more of their reported production gas into the atmosphere. The authors surmised that stochastic processes, such as maintenance, may be the main driver of emissions. "This makes marginal wells a disproportionate greenhouse gas emissions source compared to their energy return, and a good target for environmental mitigation."[1305]

- June 22, 2020 – The bonds that states require of companies to cover plugging of orphan oil and gas wells are grossly inadequate, according to an *E&E News* report.[1306] Orphan oil and gas wells are unplugged abandoned wells the owners of which either cannot be located or cannot afford to properly plug them. Abandoned wells have been implicated in ground water contamination and can leak methane, a potent greenhouse gas. The Interstate Oil and Gas Commission identified 57,000 confirmed orphan wells in the United States, up to an additional 750,000 "potential" orphans, and up to 3 million abandoned and idle wells that have an identifiable owner. Further, more recent wells are deeper and are at higher pressures than older ones. The estimated cost of plugging a

[1304] Eric D. Lebel et al., "Methane Emissions from Abandoned Oil and Gas Wells in California," *Environmental Science & Technology* 54, no. 22 (2020): 14617–26, https://doi.org/10.1021/acs.est.0c05279.
[1305] Deighton et al., "Measurements Show That Marginal Wells Are a Disproportionate Source of Methane Relative to Production."
[1306] Mike Lee, "Should Feds Plug 'Orphan' Wells? States Offer a Warning," *E&E News*, June 22, 2020, https://web.archive.org/web/20200622133846/https://www.eenews.net/stories/1063430105.

(fracked) shale well is about $300,000, versus $40,000 to $50,000 for a conventional well. The piece reported on Congress considering using federal stimulus funds to help cover the cost of plugging orphan wells, providing jobs for oil field workers and pollution reduction. The limited number of skilled workers and specialized equipment for is a challenge already experienced in Ohio.

- June 16, 2020 – A *Reuters* review of government data and interviews with scientists, regulators, and United Nations officials estimated that globally there are 29 million abandoned oil and gas wells, leaking about 2.5 million tons of methane yearly.[1307] The wells "pose a serious threat to the climate that researchers and world governments are only starting to understand," according to the review. Groundwater and soil contamination have also been linked to these wells, and, in rare cases, leaking gas has caused explosions. In the United States, the number of abandoned wells increased by over 12 percent since the onset of the fracking boom in 2008. Continued low oil prices putting financial stress on the industry led to a 50 percent in rise bankruptcies in 2019, likely to result in a further increase in abandoned wells. The upfront bonds required of drillers to cover future cleanup and well plugging are markedly inadequate: "the rules are patchwork, with wildly differing requirements, and they seldom leave governments adequately funded," according to the report. Referencing the US Government Accounting Office estimate of $20,000 to $145,000 per abandoned well clean up and plugging, it would cost between $60 billion to $435 billion to clean up all of the United States' abandoned wells.

- June 11, 2020 – The president of the Northwest Landowners Association in North Dakota, Troy Coons, questioned why the state was using $33.1 million from the CARES Act to plug abandoned wells, rather than have the "bad actor" oil and gas companies fulfill their obligations, according to the *Williston Herald.*[1308] There are 358 wells on the state's list for confiscation but the actual number of abandoned wells is likely much higher. 2,161 inactive wells had been identified in North Dakota as of May 2020. Coons believes that plugging will be more expensive than the state estimates, and that if the state does not adjust bonding requirements to cover the actual cost of well decommissioning, the burden will continue to fall on taxpayers and landowners.

- May 5, 2020 – COVID-19 pandemic-related economic impacts on the oil and gas sector could add thousands to the already over three million abandoned oil and gas wells in the United States, reported *E&E News*. If a solvent responsible party cannot be found, the cost of cleanup falls to state or federal taxpayers. States such as Louisiana, New Mexico, Oklahoma, and Wyoming have instituted policies to help stressed oil and gas companies remain solvent. The federal BLM offered guidance to companies on how to suspend leases. An energy finance analyst, however, said that the poor financial shape and

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[1307] Nichola Groom, "Special Report: Millions of Abandoned Oil Wells Are Leaking Methane, a Climate Menace," *Reuters*, June 16, 2020, sec. Commodities News, https://www.reuters.com/article/us-usa-drilling-abandoned-specialreport-idUSKBN23N1NL.
[1308] Renée Jean, "NWLA Blasts North Dakota's Handling of Abandoned Wells in Confiscated Wells Testimony," *Williston Herald*, July 19, 2021, https://www.willistonherald.com/news/farm_and_ranch/nwla-blasts-north-dakotas-handling-of-abandoned-wells-in-confiscated-wells-testimony/article_06b8f7c2-ac25-11ea-b30c-77a8a8a13091.html.

structural weakness of the shale industry already create a "'perfect storm' for a cleanup crisis."[1309]

- April 19, 2020 – An audit by the Louisiana Legislative Auditor's office noted a 50 percent increase in orphaned oil and gas wells in the state, and that it would take an estimated 20 years and $128 million to plug the nearly 4,300 wells. "Rock-bottom" oil prices will force more firms out of business, leading to the number of orphaned wells further rising. *Nola.com* reported that only about two-thirds of the state's wells have financial security guarantees, and the actual cost of plugging was significantly higher than these guarantees. The audit recommended that the Louisiana legislature adjust fees to cover plugging costs. *Nola.com* covered some improvements with state regulation since a "scathing" 2014 audit, but serious financial risks to the state persist. Further, only about half of active wells with a major violation had undergone a required reinspection, and the Department of Natural Resources Office of Conservation had not forced companies to plug almost two thirds of those wells beyond a 90-day requirement and not on an extended closure schedule.[1310]

- April 3, 2020 – There are about 200,000 orphaned wells in Pennsylvania, all with the potential to leak oil and gas to the surface, pollute water, and create explosion hazards, according to a Pittsburgh *Post-Gazette* feature.[1311] At the rate and cost at which the state's Department of Environmental Protection (DEP) is sealing old wells, it would take 17,500 years and $6.6 billion to complete. The state requires operators to seal their wells at the end of production but does not require them to demonstrate that they have adequate financial resources. The feature highlighted the story of ARG resources, owner of 1,600 wells, 150 miles of road, and many buildings and tanks in the Allegheny National Forest. The company closed operations in 2019 because of lack of funds, abandoning wells and leaving nine spills unresolved. According to the DEP, ARG had earned enough during its period of profitability to pay for the cleanup: "plugging and restoration costs should not have been insurmountable." Taxpayers should not have been left with the bill, a DEP supervisor said. Rather than pursue lengthy legal proceedings, DEP signed a consent order involving a revenue-sharing arrangement between ARG and a chemical company, AquaPower, to clean brine wastewater and turn it into commercial salt and synthetic gypsum on ARG's property, with a portion of the proceeds dedicated to abandoned well cleanup. The plan is seen as a potential model to pay for abandoned well management, though AquaPower, at the time of publication, was delinquent in its deposits to begin the operation.

- March 6, 2020 – There are nearly 1,000 orphaned oil and gas wells across Los Angeles County, "deserted by their owners and left to the state to clean," determined a "first-of-

[1309] Heather Richards, "Coronavirus Could Drive 'Mass Abandonment' of Oil Wells," *E&E News*, May 5, 2020, https://web.archive.org/web/20200507051045/https://www.eenews.net/stories/1063049965.
[1310] Mark Schleifstein, "Number of 'orphaned' Wells Increased by 50 Percent, Could Cost State Millions: Audit," *The New Orleans Advocate*, April 19, 2020, https://www.nola.com/news/business/article_313d8dd2-7a9d-11ea-b4a4-e7675d1484f7.html.
[1311] Laura Legere and Anya Litvak, "Unplugged: Pennsylvania Faces a New Wave of Abandoned Oil and Gas Wells," *Post-Gazette*, April 3, 2020, https://newsinteractive.post-gazette.com/unplugged-pennsylvania-faces-new-wave-abandoned-oil-gas-wells/.

its-kind analysis of state records" by the *Los Angeles Times* and the Center for Public Integrity.[1312] Los Angeles mandates that oil or gas wells be restarted or shuttered if inactive for one year but has been delinquent in enforcement. The investigation determined that there was only one full time well inspector until recently, and that the city had not consistently employed a full time "petroleum administrator" despite the city code requiring it to do so. Industry and labor groups have challenged the city's authority to enforce cleanup, as community groups press for closure of old wells and residents nearby, often low-income and Latino, have reported nosebleeds, headaches, and nausea. "Eight hundred oil companies have dissolved over the years without scheduling wells for cleanup or paying state fees," according to the California Geologic Energy Management Division, and bond requirements have not been updated in about 60 years and are inadequate, reported the city controller.

- February 26, 2020 – Uncemented sections of well casings provide pathways for methane to flow from intermediate subterranean zones to shallow aquifers, according to a review of EPA investigations by Maryland Department of the Environment and Penn State scientists.[1313] The researchers evaluated EPA investigations in Dimock, Pennsylvania, Parker-Hood County, Texas, Pavilion, Wyoming, and Sugar Run, Pennsylvania and other studies, regarding the impact of methane migration on water resources. They reviewed various potential causes of methane migration identifying uncemented sections of well casings as the most common cause of contamination incidents from active wells. They noted that they were working with "relatively few, detailed, site-specific studies," and that "the actual scope of the problem is difficult to demonstrate, since impacts to water supplies due to migration of fugitive gases are often adjudicated between operators and homeowners involving nondisclosure agreements." The authors noted that less than half of the attempts to address this problem by "squeeze cementing" were successful. They suggested collecting predrilling samples to determine if methane concentrations increase later on, and recommended forensic methods including isotope analysis of gases to accurately determine fugitive gas sources. The studies did not address potential water resource contamination by hydraulic fracking fluids.

- January 23, 2020 – Plugging the approximately 5,540 oil and gas wells that are orphaned or at high risk of becoming orphaned in California would cost the state over $500 million, estimated the California Council on Science and Technology, a nonpartisan, nonprofit organization created by the state's Legislature, in a report requested by the Division of Oil, Gas, and Geothermal Resources.[1314] The report identified another 69,425 economically stressed wells that produce less than five barrels of oil daily and are at risk of becoming orphaned, which would bring the cost to an estimated $5 billion. According

[1312] Mark Olalde and Ryan Menezes, "Deserted Oil Wells Haunt Los Angeles with Toxic Fumes and Enormous Cleanup Costs," *Los Angeles Times*, March 5, 2020, sec. Climate & Environment, https://www.latimes.com/environment/story/2020-03-05/deserted-oil-wells-los-angeles-toxic-fumes-cleanup-costs.
[1313] Patrick A. Hammond et al., "Gas Well Integrity and Methane Migration: Evaluation of Published Evidence during Shale-Gas Development in the USA," *Hydrogeology Journal* 28, no. 4 (2020): 1481–1502, https://doi.org/10.1007/s10040-020-02116-y.
[1314] Judson Boomhower et al., "Orphan Wells in California - An Initial Assessment of the State's Potential Liabilities," Press Release (Californai Council of Science and Technology, January 23, 2020), https://ccst.us/wp-content/uploads/CCST-Orphan-Wells-Press-Release.pdf.

to the report, plugging all 107,000 wells in the state would cost more than $9 billion, and there are also wells that are plugged but may need to be replugged. Though legally required to pay for plugging of their wells, the bonds collected by the state from industry only totaled $107 million at the time of the report. The report makes several recommendations to help limit the state's financial and environmental liability. These include investigation of environmental impacts of orphan wells and evaluating potential changes to bonding rules.

- June 13, 2019 – Both plugged and unplugged abandoned oil and gas wells continue to emit methane, and some categories of plugged wells are high emitters. When the social costs of methane pollution were considered, mitigation of abandoned high-emitting wells was cost-effective, according to a Canadian-U.S. research team.[1315] Social costs were defined as air quality, climate, and human/ecosystem impacts. The authors cited estimates of the social cost of methane emissions as $1143 to $4822 per ton. The study evaluated strategies and costs of mitigating methane emissions. The mitigation options reviewed for high emitting abandoned wells included plugging without venting, or alternatively with venting and flaring, or with venting and usage of the emitted gas. Flaring or usage without plugging address methane pollution but not groundwater contamination, a social cost. The researchers found savings were possible for all mitigation strategies when the full social cost of methane was considered. Because state bonding requirements across the U.S. show that most are insufficient to cover the average plugging cost, they recommended the inclusion of methane emission reduction from abandoned wells in climate and energy policies, and "increased government funding at state/provincial and federal levels to manage the growing number of AOG wells in the US, Canada, and abroad."

- December 8, 2019 – There are an estimated 93,000 inactive and orphaned gas and oil wells in Alberta, Canada, and a rising number of these are owned by companies that are under financial stress and which cannot afford to clean them up. "One of the primary barriers to a clear understanding of the problem appears to be the absence of a credible and transparent assessment of cleanup costs," according to a University of Calgary law professor, writing in the *Globe and Mail*.[1316] In Alberta, the Orphan Well Association is responsible for inactive and orphaned wells, and the levy on industry for cleanup is insufficient to cover the average per well cleanup cost of $27,000 to $34,000 that can also run as high as $210,000. The writer recommended "an independent inquiry into the extent of the oil and gas sector's underfunded environmental liabilities," addressing the problem that, in a worst-case scenario, could triple within a generation from its current $80 billion.

- November 7, 2019 – Many shallow wells were drilled off the coast of Santa Barbara County in the early 1900's, later abandoned, and never plugged properly. This history, on

[1315] Mary Kang et al., "Reducing Methane Emissions from Abandoned Oil and Gas Wells: Strategies and Costs," *Energy Policy* 132 (2019): 594–601, https://doi.org/10.1016/j.enpol.2019.05.045.
[1316] Martin Olszynski, "Opinion: Alberta Ignores the Ticking Time-Bomb of Orphaned Oil and Gas Wells at Its Own Peril," *The Globe and Mail*, December 8, 2019, https://www.theglobeandmail.com/opinion/article-alberta-ignores-the-ticking-time-bomb-of-orphaned-oil-and-gas-wells-at/.

through present activity of the oil and gas industry in the region, was the focus of an *E&E* piece.[1317] Adding to natural seeps in the area, oil leaks from legacy wells and oil spills and pipeline ruptures have polluted beaches and four state marine conservation areas. The California State Lands Commission leads the inventory process and has identified 200 "high priority" orphaned offshore wells. The state passed legislation allocating two million dollars yearly for 10 years, "to take inventory of the orphaned wells, plug them when they are leaking, and clean up jetties and piers." More recent oil and gas industry bankruptcies also threatened to leave wells abandoned. The piece described Exxon nearly walking away from responsibilities for an offshore platform, later agreeing to a cost share with California. The legislated funding is likely to fall far short: in 2018 it cost $1.2 million to plug one offshore well alone. Exxon continues to try to obtain trucking permits in order to continue producing oil offshore in Santa Barbara County.

- November 6, 2019 – Houston Oil and Gas, based in Calgary, Alberta, ceased operations and left an estimated $81.5 million cleanup liability.[1318] It held 1264 wells, 41 facilities, and 251 pipelines. Some of the wells have already been transferred to Alberta's Orphan Well Association, essentially transferring the burden to taxpayers. The Houston Oil and Gas website, however, states that the company will manage its end-of-life liabilities. Other Alberta oil and gas companies have also shut down or are in financial difficulty since oil prices crashed in late 2014.

- October 22, 2019 – The federal Bureau of Land Management (BLM) does not have a good way of tracking the thousands of idle oil and gas wells on federal land. Funding is inadequate to plug those orphan wells which have already been identified. Aside from the cost to taxpayers, the wells pose a risk of groundwater pollution from hydrocarbons. The federal oil and gas program was included on a 2011 U.S. Government Accountability Office (GAO) list of "high risk" programs vulnerable to fraud, abuse, and mismanagement. In 2019 the GAO reported that 84 percent of bonds (the security that industry pays in advance for cleanup liability) for federal oil and gas development were inadequate to cover cleanup costs. *E&E* reported that despite multiple government investigations, federal data is difficult to obtain, and it is states dealing with orphan wells that "sometimes provide a clearer picture of the challenge."[1319] Wyoming, for example, estimated that there are 2,200 wells on federal land in that state that appear to be orphaned. BLM may be making improvements. The article reported that the agency had collected 16 percent of the additional bonding it has deemed needed for end-of-life well cleanup. BLM lacks authority to directly charge oil and gas operators for cleanup.

- October 1, 2019 – The magnitude and duration of barometric pressure changes directly influenced the natural gas emissions from wells, discovered a team of scientists from the

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[1317] Heather Richards, "Leaking 'Legacy' Oil Wells Pollute Calif. Beaches, Stir Fears," *E&E News*, November 7, 2019, https://web.archive.org/web/20191107180034/https://www.eenews.net/stories/1061482825.
[1318] Kyle Bakx, "Calgary-Based Houston Oil & Gas Ceases Operations, Leaving Almost 1,300 Wells Needing Cleanup," *CBC News*, November 6, 2019, https://www.cbc.ca/news/business/houston-calgary-oilpatch-orphan-wells-1.5348828.
[1319] Heather Richards, "Thousands of 'Orphan Wells' Spark Safety, Cleanup Fears," *E&E News*, October 22, 2019, https://web.archive.org/web/20191023203001/https://www.eenews.net/stories/1061342691.

University of British Columbia.[1320] At least seven percent of oil and gas wells show some loss of well bore integrity. Natural gas release from leaking oil and gas wells can cause aquifer contamination, explosive conditions, and greenhouse gas emissions. Complex processes are involved in gas migration and emission. High barometric pressure inhibits the release of soil gas, and the opposite occurs with low pressure, determined the study. The most significant effect seemed to occur in areas with deep water tables. The study used controlled release of natural gas injected 12 meters below ground level in an attempt to quantify the effect of atmospheric pressure on fugitive gas emissions. The findings of barometric pressure impacts on emissions indicates that "snapshot" measurements of emissions at well pads may not be accurate. Continuous monitoring over longer time periods is therefore required "to accurately detect and quantify fugitive gas emissions at oil and gas sites with a deep water table."

- September 18, 2019 – A GAO report to Congress identified 2,294 oil and gas wells on federal land which had not produced in over ten years and had not been reclaimed, and warned about the risks from insufficient bonds to reclaim these wells.[1321] The investigation found that BLM identified 89 new orphaned wells between July 2017 and April 2019. The average value of oil and gas bonds the BLM held in 2018 was $2122 per well, slightly lower than in 2008, according to the GAO analysis. Bonds are set at their regulatory minimum and the values have not been adjusted in about 60 years. They do not account for well depth, nor the number of wells covered, factors which greatly influence the cost of cleanup. GAO recommendations included providing the BLM with the authority to assess user fees for reclamation costs and establishing a mechanism to obtain those fees from operators. Congress had not done so as of the time of publication. The BLM should also adjust bond levels to cover expected reclamation costs. The BLM continues to collect and analyze data, but its analysis is not expected to be ready until the first quarter of fiscal year 2021.

- September 6, 2019 – *NPR* featured an overview of the orphaned oil and gas well situation nationwide.[1322] Given the one million orphaned oil and gas wells in the United States as estimated by the EPA in 2018, responsibility for which typically falls to the states, markedly inadequate bonding to cover well cleanup is a growing problem. Colorado, Alabama, Ohio, and Pennsylvania have dramatically increased state funds allocated for well cleanup. The backlog of wells, however, is very large, with an estimated 560,000 abandoned wells in Pennsylvania alone. Industry has pushed back on the suggestion that companies pay the full price of plugging before drilling starts.

- August 10, 2019 – In 2016 San Francisco passed a climate-related ordinance requiring that no city-owned property be used for oil production, specifically to address a lease that

[1320] Olenka N. Forde et al., "Barometric-Pumping Controls Fugitive Gas Emissions from a Vadose Zone Natural Gas Release," *Scientific Reports* 9, no. 1 (2019): 14080, https://doi.org/10.1038/s41598-019-50426-3.
[1321] U.S. Government Accountability Office, "Oil and Gas: Bureau of Land Management Should Address Risks from Insufficient Bonds to Reclaim Wells," September 18, 2019, https://www.gao.gov/products/gao-19-615.
[1322] Matt Bloom, "Cleaning Up Abandoned Wells Proves Costly To Gas And Oil Producing States," *NPR*, September 6, 2019, sec. Energy, https://www.npr.org/2019/09/06/758284873/cleaning-up-abandoned-wells-proves-costly-to-gas-and-oil-producing-states.

Chevron held in Kern County on the city's behalf. *Bakersfield.com* provided an update on ongoing negotiations on covering the costs of decommissioning the wells.[1323] The cost of decommissioning the wells is estimated to be between one million and five million dollars, as a best-case scenario. San Francisco wants Chevron to cover the cost of decommissioning the wells. According to the senior real estate project manager for the City and County of San Francisco, "While I can't get into specifics of our negotiations with Chevron, we believe our lease assigns decommissioning responsibilities to the tenant, in this case, Chevron."

- July 2, 2019 – Many fossil fuel extraction sites have been abandoned in the Atlantic Canadian Provinces since extraction began in the early 1600s. Multiple pathways can lead to methane emissions from these wells, including improper abandonment practices, compromised well bore integrity, and subsurface fluid migration. This study used multiple sampling methods to measure methane emissions from abandoned coal mine openings in Nova Scotia as well as from a legacy oil field (abandoned prior to 1952, when abandonment protocols were begun).[1324] A small percentage of sites accounted for the majority of methane emissions. Overall, low emission intensity and frequency were documented compared with other studies. Time after abandonment may have played a role. Emissions may have peaked early after abandonment and may have decreased over time.

- June 23, 2019 – 22,000 deserted oil and gas wells have been identified in Kansas, reported the *Hutchinson News*.[1325] Over 19,000 of the abandoned wells are in Eastern Kansas. The Kansas Corporation Commission (KCC) has prioritized 25 percent of those for cleanup, because of their risk for groundwater contamination. The KCC created a fund in 1996 to finance plugging of abandoned wells, financed by the oil industry. According to the article, the KCC and industry are optimistic about the commitment to plug all the wells, but community members and environmental groups, noting that industry has deep political influence on the Kansas legislature and the KCC and project, are far less satisfied with progress and commitment. Further, the KCC does not have the resources to track all owners of idle wells, and there reportedly are not enough contractors willing to bid on plugging.

- May 20, 2019 – Within the nation's largest regional concentration of abandoned oil and gas wells, the estimate of abandoned oil and gas wells in Pennsylvania alone ranges from 200,000 to 750,000, according to *E&E News*.[1326] Those wells are estimated to cause between five and eight percent of the state's human-caused methane emissions, in

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[1323] John Cox, "Well-Plugging Costs Add Wrinkle to San Francisco's Planned Oil Pullout," *The Bakersfield Californian*, August 10, 2019, https://www.bakersfield.com/news/well-plugging-costs-add-wrinkle-to-san-franciscos-planned-oil-pullout/article_9a43b724-bad7-11e9-8ea8-137db2d851d9.html.
[1324] James P. Williams et al., "Methane Emissions from Abandoned Coal and Oil and Gas Developments in New Brunswick and Nova Scotia," *Environmental Monitoring and Assessment* 191, no. 8 (2019): 479, https://doi.org/10.1007/s10661-019-7602-1.
[1325] Tim Carpenter, "Kansas Regulators Struggle with Record-High 22K Abandoned Oil, Gas Wells," *The Hutchinson News*, June 23, 2019, https://www.hutchnews.com/news/20190623/kansas-regulators-struggle-with-record-high-22k-abandoned-oil-gas-wells.
[1326] Lee, "Millions of Abandoned Wells Spark Climate, Safety Fears."

addition to presenting other risks including explosion hazards and environmental contamination from leaking oil. The piece reviewed the inadequacy of available funds for cleanup by states as well as on public lands. "Most [states] don't have enough funds to clean up the legacy wells left from the oil industry's first century, and most aren't ready to clean up the tens of thousands of wells drilled during the first decades of the shale drilling boom. Pennsylvania, for example, only has enough money to plug a dozen or so each year." Pennsylvania has allocated about $400,000 per year for well plugging, which at the current rate would require 17,500 years to complete the work. Colorado is planning to update bonding requirements, and Ohio has voted to increase the amount of oil and gas production taxes the state spends on well plugging. Ohio's tax on energy production, however, is one of the lowest in the country.

- March 11, 2019 – There are roughly 200,000 abandoned oil and gas wells in Pennsylvania left over from more than a century of drilling. Most are not mapped. Alabama-based Diversified Gas & Oil, which now owns about 23,000 gas wells in the state, reached an agreement with the PA DEP to plug 1,400 abandoned wells over the next 15 years—or bring them back into production. The agreement requires the company to submit a $7 million performance bond to cover the costs of plugging. In 2018, the company plugged 41 wells across its entire operating area.[1327]

- March 5, 2019 – There are 30,000 abandoned oil wells in California, with 1,850 in Los Angeles County. The state is currently not required to report to the public on toxic air emissions from these wells before, during, or after they are plugged, even when idle wells are located within densely populated residential communities. The process of capping wells can itself release harmful gases. Legislation has been proposed to remediate this oversight.[1328]

- February 21, 2019 – While preparing to mine over a natural gas storage field in Greene County, Pennsylvania, a coal company discovered dozens of undisclosed abandoned gas wells at the site, according to a report by the *Pittsburgh Post-Gazette.* "Pennsylvania's history of fossil fuel extraction, combined with modern operations harvesting coal, oil and gas at different depths, makes it a particularly thorny place to work underground."[1329]

- January 25, 2019 – Colorado Governor John Hickenlooper signed an executive order to force the "plugging, remediation and reclamation of all medium- and high-priority orphaned wells and orphaned sites." There are roughly 55,000 oil and gas wells in

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[1327] Laura Legere and Anya Litvak, "Pa. Strikes Well-Plugging Deal with Largest Conventional Oil and Gas Operator in Appalachia," *Pittsburgh Post-Gazette*, March 11, 2019, https://www.post-gazette.com/business/powersource/2019/03/11/Diversified-Gas-and-Oil-abandoned-wells-plugging-settlement-Pennsylvania-DEP/stories/201903080130.

[1328] Steve Scauzillo, "What Toxins Are Being Emitted from LA County's Abandoned Oil Wells? A Lawmaker Wants to Find Out," *San Gabriel Valley Tribune*, March 5, 2019, https://www.sgvtribune.com/2021/09/01/bill-that-would-eliminate-blood-slave-donor-dogs-in-california-on-way-to-governors-desk/.

[1329] Laura Legere, "Pa. DEP Threatened to Shut down a Gas Storage Field, Fearing Risks to Approaching Coal Mine," *Pittsburgh Post-Gazette*, February 21, 2019, https://www.post-gazette.com/business/powersource/2019/02/21/coal-mine-natural-gas-storage-abandoned-wells-Pennsylvania-Equitrans-Consol/stories/201902200130.

Colorado. At least 260 are orphaned, which means that the well's owner cannot be identified, usually because of bankruptcy. Inactive wells that are orphaned become the responsibility of the state.[1330]

- December 21, 2018 – Most fracking operations take place in oil and gas fields with a long history of conventional drilling and therefore with many abandoned wells. The possibility of hydraulic fractures intercepting these old wells and opening a pathway for rapid vertical transport for fluids to the surface or to groundwater aquifers depends on multiple variables. A University of Goettingen-led team used modeling to explore the relevant factors that predict long-term flow and transport of fracking fluids into groundwater aquifers through a leaky, abandoned well. The results showed that wellbore integrity of the abandoned well and its distance from the fracking operation are the two most influential parameters determining the vertical transport of fracking fluid through an abandoned well. The most probable pathway of contaminant transport takes place outside the well casing. Hydraulic fracking fluid tends to spread laterally when sediment layers are permeable, decreasing upward movement of fluid and decreasing contamination distribution in the aquifer. When freshwater aquifers are shallow, the short-term probability of contamination is negligible even in the presence of a leaky, abandoned well. "Model results show that hydraulic fracturing fluid reaches the aquifer three years after production."[1331]

- December 15, 2018 – A University of Vermont-led team explored the ability of various predictive models to forecast fluid migration from and through abandoned wells in Alberta, Canada. Although all the models "performed better than random guessing," none of them perfectly predicted which wells would leak in part because of incomplete data. In Alberta, wells that do not leak at the time they are drilled are not retested until they are abandoned. Continuous monitoring of wells in a small area would allow the models to be retrained with more accurate information. Consistent with previous findings, the models did show that the most important features in predicting whether an abandoned well will leak is the deviation of the well from vertical and the year the well was constructed.[1332]

- November 20, 2018 – An investigation by WPXI, an NBC-affiliated television station in Pittsburgh, reported that Pennsylvania lacks funds to locate, plug, and remediate all potentially dangerous abandoned wells in the state. "Overall the problems could cost the state close to $4 billion, so it is responding to the most critical cases first."[1333]

[1330] Anna Staver, "Hickenlooper Signs Order to Release the Locations of Orphan Wells, Sets Deadline to Cap Them," *The Denver Post*, July 18, 2018, https://www.denverpost.com/2018/07/18/hickenlooper-executive-order-orphan-wells/.
[1331] Reza Taherdangkoo et al., "Modeling Fate and Transport of Hydraulic Fracturing Fluid in the Presence of Abandoned Wells," *Journal of Contaminant Hydrology* 221 (2019): 58–68, https://doi.org/10.1016/j.jconhyd.2018.12.003.
[1332] James A. Montague, George F. Pinder, and Theresa L. Watson, "Predicting Gas Migration through Existing Oil and Gas Wells," *Environmental Geosciences* 25, no. 4 (2018): 121–32, https://doi.org/10.1306/eg.01241817008.
[1333] WPXI, "Abandoned Oil Wells Hidden under Thousands of Local Properties," November 20, 2018, https://www.wpxi.com/news/top-stories/abandoned-oil-wells-hidden-under-thousands-of-local-properties/875732284/.

- November 20, 2018 – There are an estimated 12,000 abandoned wells in West Virginia, of which 4,000 are orphaned and have no owners, according to a story in the *Charleston Gazette-Mail* that reported how gas companies are saving money by leaving depleted wells behind instead of plugging them.[1334]

- September 5, 2018 – An investigation of abandoned wells on Native American lands in the San Juan Basin found that the Bureau of Land Management (BLM), responsible for monitoring oil and gas wells on most tribal lands, has routinely failed to require operators to file paperwork on abandoned wells, lacks a clear strategy for identifying them, and does not prioritize cleaning up or remediating them.[1335]

- May 16, 2018 – The GAO reported to Congress that BLM needs to improve its oversight of abandoned oil and gas wells. Companies are supposed to provide bonds up front to cover the costs of plugging abandoned wells and reclaiming the sites, but if they don't, or if the costs exceed expectations, BLM can be liable and taxpayers can shoulder the clean-up costs. "Reclamation costs and potential liabilities likely increased since 2010, but we couldn't determine how much because BLM does not systematically track the data." The GAO recommended that, among other things, the director of BLM should systematically track the actual costs that the agency incurs when reclaiming orphaned wells, the number of orphaned and abandoned wells over time, and the information needed to determine the agency's potential liabilities. The BLM concurred with the GAO's recommendations. There are roughly 94,000 oil and gas wells on federal lands overseen by BLM.[1336]

- Dec 26, 2017 – In 1965, a blowout at a gas well in northeastern Netherlands caused the formation of quicksand, which swallowed up an entire drill rig. Eventually, the area was turned into a park. More than 50 years later, a team of researchers discovered that the site is still leaking methane. They found in the groundwater high levels of methane with an isotopic composition that matched that of the gas reservoir. An analysis of groundwater flow conditions showed that this methane is not a remnant of the blowout but the result of ongoing leakage. "Combined, the data reveal the long-term impact that underground gas well blowouts may have on groundwater chemistry, as well as the important role of anaerobic oxidation in controlling the fate of dissolved methane."[1337, 1338]

[1334] Kate Mishkin, "Drilling Companies Avoiding Responsibility to Plug Orphan Wells, Group Says," *Charleston Gazette-Mail*, November 20, 2018, https://www.wvgazettemail.com/news/drilling-companies-avoiding-responsibility-to-plug-orphan-wells-group-says/article_c423997f-d011-5e8a-a54f-13e54d3c0985.html.
[1335] Rebecca Clarren, "Idle Oil, Gas Wells Threaten Indian Tribes While Energy Companies, Regulators Do Little," *Investigate West*, September 5, 2018, https://www.invw.org/2018/09/05/idle-oil-gas-wells-threaten-indian-tribes-while-energy-companies-and-regulators-do-little/.
[1336] U.S. Government Accountability Office, "Oil and Gas Wells: Bureau of Land Management Needs to Improve Its Data and Oversight of Its Potential Liabilities," Report to Congressional Requesters, May 16, 2018.
[1337] Gilian Schout et al., "Impact of an Historic Underground Gas Well Blowout on the Current Methane Chemistry in a Shallow Groundwater System," *Proceedings of the National Academy of Sciences* 115, no. 2 (2018): 296–301, https://doi.org/10.1073/pnas.1711472115.
[1338] Bob Yirka, "Methane Still Leaking from the Ground at Site of Gas Explosion Decades Ago," *Phys.Org*, December 29, 2017, https://phys.org/news/2017-12-methane-leaking-ground-site-gas.html.

- June 28, 2017 – *The Tyee* made public the results of an unreleased 2016 report by the Alberta Energy Regulator (AER) showing that 36 of 335 abandoned oil and gas wells that are located close to occupied buildings in urban areas of Alberta are leaking methane. Six abandoned wells were leaking at levels (10,000 ppm) that pose explosion risks and are considered life-threatening. (Natural background level is about 1.9 ppm.) Based on these findings, the report also estimated that 17,000 of 170,000 abandoned wells in rural Alberta were likely also leaking. The author of the unreleased report said in an interview with *The Tyee* that AER, a corporation that functions in part as a regulatory agency, does not have the capacity to evaluate the potential threat to public health and safety. "The expertise to assess the health risk of abandoned wells really doesn't exist in house."[1339, 1340]

- March 27, 2017 – In an experimental study, Canadian researchers injected methane gas into a shallow sand aquifer over a 72-day period and monitored methane migration for eight months. After 72 days, they found that half of the methane had vented into the atmosphere and half remained in the groundwater, traveling laterally a greater distance than expected and degrading at a rate less than expected. "Our findings demonstrate that even small-volume releases of methane gas can cause extensive and persistent free phase and solute plumes."[1341, 1342]

- December 21, 2016 – The *Texas Tribune* investigated abandoned oil wells in Texas where the Texas Railroad Commission, which is charged with regulating the oil and gas industry, has tracked and mapped 6,628 unplugged, orphaned wells. The commission is struggling with a ballooning inventory of inactive, leaking wells and decreasing clean-up funds to deal with them. The most recent oil boom, involving horizontal drilling with fracking, added to the problem as drillers cut corners in the rush to bring oil to market. "Just drill the well as fast as possible, because they were under such pressure to get cash flow going," according to a geoscientist interviewed for the story who had recently retired as a groundwater advisor for the Railroad Commission.[1343]

- November 14, 2016 – Methane emissions from abandoned wells vary widely, with a few high emitters responsible for a disproportionately large share of the problem. Using new field measurement and data mining techniques, a Stanford University-led team investigated gas leaks at 88 inactive wells in Pennsylvania in an attempt to identify the characteristics of these "super-emitters." Their results showed that unplugged gas wells

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[1339] Andrew Nikiforuk, "Energy Industry Legacy: Hundreds of Abandoned Wells Leaking Methane in Alberta Communities," *The Tyee*, June 28, 2017, https://thetyee.ca/News/2017/06/28/Energy-Industry-Legacy/.
[1340] Andrew Nikiforuk, "Alberta Failing on Risk From Leaking Oil and Gas Wells, Says Expert," *The Tyee*, July 4, 2017, https://thetyee.ca/News/2017/07/04/Alberta-Failing-Leaking-Oil-Gas-Wells-Risk/.
[1341] Aaron G. Cahill et al., "Mobility and Persistence of Methane in Groundwater in a Controlled-Release Field Experiment," *Nature Geoscience* 10, no. 4 (2017): 289–94, https://doi.org/10.1038/ngeo2919.
[1342] Andrew Nikiforuk, "Methane Leaks from Energy Wells Affects Groundwater, Travels Great Distances, Study Confirms," *The Tyee*, April 11, 2017, https://thetyee.ca/News/2017/04/11/Methane-Leaks-from-Energy-Wells-Affects-Groundwater/.
[1343] Jim Malewitz, "Abandoned Texas Oil Wells Seen as 'Ticking Time Bombs' of Contamination," *The Texas Tribune*, December 21, 2016, https://www.texastribune.org/2016/12/21/texas-abandoned-oil-wells-seen-ticking-time-bombs-/.

and wells located in coal areas had the highest methane flow rates. Well plugging does not always reduce methane emission, especially when the wells are vented. In many areas with extensive coal layers, decommissioning requirements for wells included mandatory venting. Using comprehensive databases, the team also estimated the number of abandoned wells in Pennsylvania to be between 470,000 and 750,000, considerably more than previous estimates of 300,000 to 500,000. The research team calculated that, all together, Pennsylvania's abandoned wells contribute 5-8 percent of the state's annual greenhouse gas emissions.[1344, 1345]

- June 20, 2016 – Pennsylvania's attorney general began reviewing regulations requiring drillers to document abandoned oil and gas wells within 1,000 feet of a new fracking site. According to a *Bloomberg* investigation, "This puts Pennsylvania among states such as California, Texas, Ohio, Wyoming and Colorado confronting the environmentally catastrophic legacy of booms as fracking and home development expand over former drilling sites. As the number of fracked wells increases, so does the chance they might interact with lost wells." As noted by *Bloomberg,* state databases document only about 10 percent of the nation's 2.6 million abandoned oil and gas wells; the whereabouts of the vast majority are unknown. Current efforts in Pennsylvania to increase documentation on the location and status of inactive wells rely on "citizen scientists" equipped with GPS and methane sniffers, as well as home and farm-owners living on top of abandoned wells. Over a period of three decades, PA DEP has located and plugged only about 3,000 abandoned wells.[1346]

- May 30, 2016 – New developments of houses, schools, and shopping centers are being built over abandoned oil and gas wells, according to a report by Wyoming Public Media. In most states there is no requirement for homeowners to be notified about abandoned wells on their properties, and these wells are not systematically monitored for leaks, nor are their locations well mapped. A builder who worked in the oil and gas industry for decades and suffered cardiac arrest when methane from an abandoned well he was inadvertently working atop exploded, said that there were "no signs" that a well was there.[1347]

- January 26, 2016 – Researchers tested soil methane levels at 102 United Kingdom decommissioned oil and gas wells between 8 and 79 years old. Thirty percent of the wells had methane at the soil surface that was significantly higher than their control samples in

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[1344] Mary Kang et al., "Identification and Characterization of High Methane-Emitting Abandoned Oil and Gas Wells," *Proceedings of the National Academy of Sciences* 113, no. 48 (2016): 13636–41, https://doi.org/10.1073/pnas.1605913113.
[1345] Ker Than, "Study of Abandoned Oil and Gas Wells Reveals New Ways of Fixing the Worst Methane Emitters," *Stanford News*, November 14, 2016, sec. Science & Technology, https://news.stanford.edu/2016/11/14/study-abandoned-oil-gas-wells-reveals-new-ways-fixing-worst-methane-emitters/.
[1346] Jennifer Oldham, "In the Birthplace of U.S. Oil, Methane Gas Is Leaking Everywhere," *Bloomberg*, June 20, 2016, https://www.bloomberg.com/news/articles/2016-06-20/in-the-birthplace-of-u-s-oil-methane-gas-is-leaking-everywhere.
[1347] Stephanie Joyce, "Danger Below? New Properties Hide Abandoned Oil And Gas Wells," *Wyoming Public Radio*, May 30, 2016, https://www.northcountrypublicradio.org/news/npr/474100388/danger-below-new-properties-hide-abandoned-oil-and-gas-wells.

nearby fields. Thirty-nine percent of well sites had significantly lower surface soil methane than their respective controls. Researchers suggested several explanations for the latter results, including replaced soils.[1348]

- October 19, 2015 – Abandoned oil and gas wells near fracking sites can be conduits for methane escape that is not currently being measured, according to University of Vermont researchers. Fractures in the surrounding rock may connect to existing unused oil and gas wells in the area during fracking processes, thus providing a pathway for methane to migrate to the surface. The study used a mathematical model based on the large part of southern New York State underlain by the Marcellus Shale, incorporating "the depth of a new fracturing well, the vertical growth of induced fractures, and the depths and locations of existing nearby wells." The researchers concluded the probability that new fracking-induced fractures would connect to a pre-existing well to be .03 percent to 3 percent. Density of nearby abandoned wells was the largest factor, and researchers pointed out the continuing problem of undocumented abandoned wells.[1349] As noted in an accompanying press release, probabilities are likely much higher: "Industry-sponsored information made public since the paper was published vastly increased assumptions about the area impacted by a set of six to eight fracking wells known as a well pad – to two square miles – increasing the probabilities cited in the paper by a factor of 10 or more."[1350]

- July 9, 2015 – As part of an extensive, peer-reviewed assessment of fracking in California, the California Council on Science and Technology identified leakage through failed, inactive wells as a known mechanism for fracking-related water contamination in other states, including Texas and Ohio, and said that it is not known whether abandoned wells in California likewise function as conduits for groundwater contamination and gas leakage. In California, there are more inactive than active wells. Of the state's nearly one-quarter million oil and gas wells, more than half (116,000) have been plugged and abandoned, while another 1,800 inactive wells are "buried" with only an approximate location known. The locations of another 338 old wells are entirely unknown. California also has 110 orphaned wells, that is, abandoned wells with no owners. Most of California's abandoned wells (53 percent) are located in Kern County.[1351]

- May 15, 2015 – *CBC News* reported that falling gas and oil prices have prompted many smaller companies to abandon their operations in Alberta, Canada, leaving the provincial government to close down and dismantle their wells. In the past year alone, the number of orphaned wells in Alberta increased from 162 to 702. At the current rate of work,

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[1348] I.M. Boothroyd et al., "Fugitive Emissions of Methane from Abandoned, Decommissioned Oil and Gas Wells," *Science of The Total Environment* 547 (2016): 461–69, https://doi.org/10.1016/j.scitotenv.2015.12.096.
[1349] James A. Montague and George F. Pinder, "Potential of Hydraulically Induced Fractures to Communicate with Existing Wellbores," *Water Resources Research* 51, no. 10 (2015): 8303–15, https://doi.org/10.1002/2014WR016771.
[1350] University of Vermont, "Dirty Pipeline: Methane From Fracking Sites Can Flow to Abandoned Wells, New Study Shows," *News Wise*, October 19, 2015, https://www.newswise.com/articles/dirty-pipeline-methane-from-fracking-sites-can-flow-to-abandoned-wells-new-study-shows.
[1351] Stringfellow et al., "Chapter Two: Impacts of Well Stimulation on Water Resources."

deconstructing the inventory of wells abandoned just in the past year alone will be a 20-year task.[1352]

- April 27, 2015 – In a peer-reviewed study, researchers with the U.S. Fish and Wildlife Service documented 5,002 wells located on National Wildlife Refuge System units, in addition to 1,339 miles of pipeline. Almost half of the wells were inactive, while one-third were active and the remainder either plugged and abandoned or with status unknown. Highlighting the impacts of leaks, spills, and routine operation and maintenance on wildlife conservation efforts, the authors called for regular on-site ecological assessments, improved efforts to plug inactive wells and restore inactive well sites, and a "consolidated and robust regulatory framework" to protect the public's interests.[1353]

- March 24, 2015 – Analyzing data from 42 abandoned oil and gas wells in western Pennsylvania, a Princeton and Stanford team documented a wide range of leakage potentials. As a group, gas wells have higher permeability than oil wells. Among gas wells, methane flow rates are positively correlated with permeability. Subterranean temperatures and temperatures, along with well depth, are all variables that can influence leakage potentials of abandoned wells. The leakage potential of wells drilled prior to 1960 is moderate to high, and plugged wells, as well as unplugged wells, can leak. The authors note that cement plugs are imperfect barriers that can develop defects that allow fluids to flow through gaps between the plug and surrounding hole, through pores or fissures within the plug itself, or directly through cracks in the well casing.[1354]

- December 8, 2014 – A Princeton University team found that abandoned oil and gas wells in Pennsylvania, left over from prior decades of conventional drilling, leak significantly more methane than previously thought. Between 300,000 and 500,000 abandoned oil and gas wells are located in Pennsylvania, and many go unchecked and unmonitored for leaks. Nearly three-quarters are unplugged. Based on direct measurements of methane flow from 19 such wells, most of which were a half century old or older, the researchers estimated that the methane leaks from abandoned wells alone could account for between 4 and 7 percent of human-caused methane emissions in the state. Based on these measurements of positive methane flow from decades-old wells, the authors concluded that cumulative emissions from these abandoned wells "may be significantly larger than the cumulative leakage associated with oil and gas production, which has a shorter lifetime of operation." Further, methane flow rates from plugged wells measured in this study were not consistently lower than unplugged wells and indeed were sometimes higher, even though wells are plugged for the precise purpose of limiting the escape of gases. The authors noted that an estimated three million abandoned oil and gas wells are

[1352] Tracy Johnson, "Alberta Sees Huge Spike in Abandoned Oil and Gas Wells," *CBC News*, May 15, 2015, https://www.cbc.ca/news/canada/calgary/alberta-sees-huge-spike-in-abandoned-oil-and-gas-wells-1.3032434.
[1353] Pedro Ramirez and Sherri Baker Mosley, "Oil and Gas Wells and Pipelines on U.S. Wildlife Refuges: Challenges for Managers," ed. Stephen J. Johnson, *PLoS ONE* 10, no. 4 (2015): e0124085, https://doi.org/10.1371/journal.pone.0124085.
[1354] Mary Kang et al., "Effective Permeabilities of Abandoned Oil and Gas Wells: Analysis of Data from Pennsylvania," *Environmental Science & Technology* 49, no. 7 (2015): 4757–64, https://doi.org/10.1021/acs.est.5b00132.

scattered across the United States and likely represent "the second largest potential contribution to total US methane emissions above US Environmental Protection Agency estimates." In the United States, no regulatory requirements for monitoring methane leaks from abandoned wells exist.[1355, 1356]

- December 1, 2013 – An analysis of reports from the NYS DEC found that three-quarters of the state's abandoned oil and gas wells were never plugged. New York State has approximately 48,000 such wells; many of their locations remain unknown.[1357]

- Aug. 4, 2011 – A report from the EPA to Congress in 1987—and discovered by the *New York Times*—concluded that abandoned natural gas wells may have served as a pathway for hydraulic fracturing fluids to migrate underground from a shale gas well to a water well in West Virginia. In noting that the water well was polluted due to hydraulic fracturing and that such contamination was "illustrative" of contamination from oil and natural gas drilling, the report suggested that additional cases of groundwater contamination from hydraulic fracturing may exist.[1358]

- April 4, 2011 – *ProPublica* reported that abandoned wells have caused problems across the nation including contamination of drinking water in Colorado, Kentucky, Michigan, New York, Texas, and other states. *ProPublica* also found that a draft report from the Pennsylvania DEP described a 2008 incident in Pennsylvania in which a person died in an explosion triggered by lighting a candle in a bathroom after natural gas had seeped into a septic system from an abandoned well. The same draft report documented at least two dozen additional cases in which gas leaked from old wells, and three in which gas from new wells migrated into old wells, seeping into water supplies and requiring the evacuation of homes.[1359]

- May 20, 2010 – The British Columbia Oil and Gas Commission issued a safety advisory after hydraulic fracturing caused a large "kick," or unintentional entry of fluid or gas, into a nearby gas well. The commission reported that it knew of 18 incidents in British Columbia and one in Western Alberta in which hydraulic fractures had entered nearby gas wells. "Large kicks resulted in volumes up to 80 cubic meters [about 100 cubic yards] of fluids produced to surface. Invading fluids have included water, carbon dioxide, nitrogen, sand, drilling mud, other stimulation fluids and small amounts of gas." These cases occurred in horizontal wells with a distance between wellbores of up to 2,300 feet. The Commission wrote, "It is recommended that operators cooperate through

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[1355] Mary Kang et al., "Direct Measurements of Methane Emissions from Abandoned Oil and Gas Wells in Pennsylvania," *Proceedings of the National Academy of Sciences* 111, no. 51 (2014): 18173–77, https://doi.org/10.1073/pnas.1408315111.
[1356] Bobby Magill, "Derelict Oil Wells May Be Major Methane Emitters," *Climate Central*, June 19, 2014, https://www.climatecentral.org/news/abandoned-oil-wells-methane-emissions-17575.
[1357] Ronald E. Bishop, "Historical Analysis of Oil and Gas Well Plugging in New York: Is the Regulatory System Working?," *New Solutions: A Journal of Environmental and Occupational Health Policy* 23, no. 1 (2013): 103–16, https://doi.org/10.2190/NS.23.1.g.
[1358] Urbina, "A Tainted Water Well, and Concern There May Be More."
[1359] Nicholas Kusnetz, "Danger in Honeycomb of Old Wells," *Pittsburgh Post-Gazette*, April 4, 2011, https://www.post-gazette.com/news/nation/2011/04/04/Danger-in-honeycomb-of-old-wells/stories/201104040149.

notifications and monitoring of all drilling and completion operations where fracturing takes place within 1000m [3,280 feet] of well bores existing or currently being drilled." Such communication between active wells raises the potential that similar communication can occur between active wells and abandoned wells.[1360]

- 2010 – The NYS DEC cautioned that "abandoned wells can leak oil, gas and/or brine; underground leaks may go undiscovered for years. These fluids can contaminate ground and surface water, kill vegetation, and cause public safety and health problems." As the agency reported, "DEC has at least partial records on 40,000 wells, but estimates that over 75,000 oil and gas wells have been drilled in the State since the 1820s. Most of the wells date from before New York established a regulatory program. Many of these old wells were never properly plugged or were plugged using older techniques that were less reliable and long-lasting than modern methods."[1361] The agency published similar comments in 2008 and 2009.

- January 2009 – In a presentation before the Society of Petroleum Engineers, industry consultant Michael C. Vincent reported on evidence that fractures from hydraulically fractured wells can communicate with nearby oil and gas wells. In spite of numerous examples of fractures intersecting with adjacent wellbores, the industry is reluctant to publish reports documenting these cases because "such information could unnecessarily alarm regulators or adjacent leaseholders." Vincent added, "Although computing tools have improved, as an industry we remain incapable of fully describing the complexity of the fracture, reservoir, and fluid flow regimes." These findings raise the possibility that there could be similar communications between existing fracked wells that are fractured and abandoned wells and that operators cannot accurately predict how these will interact.[1362]

- 2005 – M.K. Fisher, Vice President of Business Management at Pinnacle, a service of Halliburton that specializes in hydraulic fracturing, reported in an article published by the Society of Petroleum Engineers that a single fracture produced during a fracking operation in the Texas Barnett Shale had unexpectedly spread 2,500 feet laterally in two directions. He also described fractures in the Barnett Shale as "extremely complex."[1363] These findings raise the possibility that well communication over very large distances could occur due to fractures that spread "unexpectedly."

- October 1999 – The U.S. Department of Energy reported that there were approximately

[1360] British Columbia Oil & Gas Commission, "Safety Advisory: Communication during Fracture Stimulation," Safety Advisory, May 20, 2010, https://www.bcogc.ca/node/5806/download.
[1361] New York State Department of Environmental Conservation, "New York Oil, Gas and Mineral Resources 2010," 2010.
[1362] Mike Vincent, "Examining Our Assumptions – Have Oversimplifications Jeopardized Our Ability to Design Optimal Fracture Treatments?" (Hydraulic Fracturing Technology Conference, Society of Petroleum Engineers, The Woodlands, TX, January 19, 2009), http://www.spe.org/dl/docs/2010/MikeVincent.pdf.
[1363] Marc Kevin Fisher et al., "Integrating Fracture Mapping Technologies To Improve Stimulations in the Barnett Shale," *SPE Production & Facilities* 20, no. 02 (2005): 85–93, https://doi.org/10.2118/77441-PA.

2.5 million abandoned oil and gas wells in the U.S.[1364]

- Early 1990s – An underground waste disposal well in McKean County, Pennsylvania, contaminated groundwater when the wastewater traveled up a nearby abandoned, unmapped, and unplugged oil well. Owners of private water wells that were contaminated by the incident eventually had to be connected to a public water system.[1365]

- July 1989 – In the past, the investigative agency for Congress, the U.S. General Accounting Office (now the Government Accountability Office—GAO) studied oil and natural gas underground injection disposal wells and found serious cases of contamination. The agency reported that, in several cases, wastewater from oil and natural gas operations had migrated up into abandoned oil and natural gas wells, contaminating underground water supplies. The GAO found that "if these abandoned wells are not properly plugged—that is, sealed off —and have cracked casings, they can serve as pathways for injected brines [waste fluids from natural gas and oil drilling] to enter drinking water…. Because groundwater moves very slowly, any contaminants that enter it will remain concentrated for long periods of time, and cleanup, if it is technically feasible, can be prohibitively costly."[1366]

- December 1987 – The EPA submitted a report to Congress on oil and natural gas wastes in which the agency cautioned that abandoned wells must be plugged with cement in order to avoid "degradation" of ground and surface waters as a result of pressurized brine or injected waste from wastewater disposal wells migrating into to aquifers, rivers, or streams.[1367] While the EPA did not address the potential for contamination through abandoned wells as a result of hydraulic fracturing, both hydraulic fracturing and underground injection disposal wells require underground injection of fluid under pressure, raising the potential that there is a similar risk of groundwater contamination when hydraulic fracturing occurs near abandoned wells.

- 1985 – In an investigation of 4,658 complaints due to oil and natural gas production, the Texas Department of Agriculture found that "when a water well is experiencing an oilfield pollution problem (typically, high chlorides), the pollution source is often difficult to track down. The source could be a leak in the casing of a disposal well, leakage behind the casing due to poor cement bond, old saltwater evaporation pits, or, most often, transport of contaminants through an *improperly plugged abandoned well*" (emphasis in original). The agency found more than a dozen confirmed or suspected

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1364 U.S. Department of Energy, Office of Fossil Energy, "Environmental Benefits of Advanced Oil and Gas Exploration and Production Technology," Technical Report (USDOE Office of Fossil Energy, Washington, DC (US), October 1, 1999), https://doi.org/10.2172/771125.

1365 Don Hopey, "Wastewater Disposal Wells under Scrutiny Following Irvin Leak," *Pittsburgh Post-Gazette*, January 3, 2012, https://www.post-gazette.com/news/environment/2012/01/03/Wastewater-disposal-wells-under-scrutiny-following-Irvin-leak/stories/201201030332.

1366 U.S. Government Accountability Office, "Drinking Water: Safeguards Are Not Preventing Contamination From Injected Oil and Gas Wastes."

1367 U.S. Environmental Protection Agency, "Report to Congress: Management of Wastes from the Exploration, Development, and Production of Crude Oil, Natural Gas, and Geothermal Energy," December 1987, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=20012D4P.pdf.

cases in which pollutants had migrated up abandoned wells and contaminated groundwater. In one case, drilling wastewater migrated up an abandoned well a half mile away from where the wastewater was injected underground for disposal.[1368]

- November 1978 – In a report later cited by the EPA in its 1987 report to Congress (cited above), the state of Illinois Environmental Protection Agency found that oil and natural gas wastes injected underground could migrate through abandoned oil and natural gas wells and contaminate groundwater. The agency wrote, “In old production areas, abandoned wells may pose a serious threat to ground water quality. Unplugged or improperly plugged wells provide possible vertical communication between saline and fresh water aquifers.”[1369]

[1368] Texas Department of Agriculture, “Agricultural Land and Water Contamination: From Injection Wells, Disposal Pits, and Abandoned Wells Used in Oil and Gas Production” (Department of Natural Resources, 1985).
[1369] Illinois Environmental Protection Agency, “Illinois Oil Field Brine Disposal Assessment,” Staff Report (Water Quality Management Planning, November 1978), http://static.ewg.org/reports/2011/fracking/pdf/ILReport1978.pdf.

Flood risks

Fracking exacerbates flood risks in two ways. First, massive land clearing and forest fragmentation that necessarily accompany well site preparation increase erosion, run-off, and risks for catastrophic flooding. The construction of access roads, easements for pipelines, and build-out of other related infrastructure further contribute to the problem. Compared to an acre of forest or meadow, an acre of land subject to fracking construction activity releases 1,000-2,000 times more sediment during rainstorms. In addition, in some cases, operators choose to site well pads on flood-prone areas in order to have easy access to water for fracking, to abide by setback requirements intended to keep well pads away from inhabited buildings, or to avoid productive agricultural areas.

Second, the vulnerability of fracking sites to flooding increases the known dangers of unconventional gas extraction, heightening the risks of contamination of soils and water supplies, the overflow or breaching of containment ponds, and the escape of chemicals and hazardous materials. Storage tanks on oil and gas sites appear particularly vulnerable to flood-related damage resulting in toxic spills. A 2019 study documented over 600 hazardous chemical releases from gas installations and offshore oil facilities and pipelines triggered by Hurricanes Rita and Katrina. During Hurricane Harvey flooding in Texas in 2017, Eagle Ford operators reported 31 spills at oil and gas wells, storage tanks, and pipelines. A 2021 study found that such flood-related toxic incidents in the greater Houston area were disproportionately higher in impoverished communities.

Rising sea levels, more powerful hurricanes, and increased storm surges in coastal areas, all consequences of climate change, are expected to represent an increasing threat to oil and gas infrastructure, especially along the Gulf coast. According to a 2018 study, natural gas processing plants in U.S. coastal areas are among the energy infrastructure most vulnerable to inundation by sea level rise. So-called natural hazard-triggered technical disasters, or "natech events" are the focus of a growing area of research.

- April 19, 2021 – The concentration of oil and gas waste facilities, petroleum and natural gas facilities, and petroleum bulk terminals was greatest in the lower socioeconomic status (SES) areas of the greater Houston metropolitan area, and the majority of incidents at toxic sites occurred at petroleum and natural gas facilities, according to the first study addressing disparities in exposure to toxic incidents following Hurricane Harvey in 2017. This Mount Sinai School of Medicine-led analysis demonstrated that low SES areas were more likely to have a toxic release, even after taking into account the greater number of toxic sites in lower SES areas. The actual flooding was highest in the second-lowest quintile of SES and lowest in the highest SES quintile of the study areas. But because flooding was not found to be a significant predictor of an incident at a toxic site related to the hurricane, researchers wrote that this suggests "there are other unmeasured variables that contribute to incidents occurring in lower SES areas," possibly including "lower maintenance or upkeep of facilities, gaps in safety measures, encompassing an overall absence of resiliency to natural disasters." After petroleum and natural gas facilities, other site types with high numbers of incidents were chemical facilities and superfund sites.[1370]

- December 16, 2020 – Of the major storms impacting southeast Texas from 2001 through 2019, Hurricane Harvey had by far the most serious effect on the oil and gas sector, including impacts on employees. Lamar University researchers analyzed industry practices related to resilience and recovery, using a participatory methodology. As expressed by industry representatives, unmet needs included the modernization of flood gauges; availability of high-water vehicles; revised regulations allowing for the use of drones for emergency response; revised labor standards to ease labor shortages following emergencies; and improved logistics and communications, as flooded roadways impeded the ability to receive cargo, including spare parts, from the airport. Rainfall during Harvey exceeded the internal drainage capacity of the oil and gas facilities. At one plant, corrosion of equipment remained unremediated for more than a year after the flood. The study also looked at industry changes made in the aftermath of Harvey. These included the physical raising of facilities and equipment. The study reported that nearly half of oil and gas industry employees were affected personally by the flood, and employees' family safety and damaged homes impeded their return to work. Employees on site at the time of the hurricane could not go home, and lack of food and medication on site were identified as problems. Some companies reported considering purchasing high-water vehicles with 40-inch tires to move personnel in these emergencies.[1371]

- April 29, 2020 – Fracking should be designated an "unacceptable use" of the floodplains of Australia's western Queensland channel country, according to the report of an independent scientific panel commissioned by that state's government that was blocked from public release.[1372] *Guardian Australia* obtained the panel's report which said it "wanted the state to establish a designated wetland and floodplain precinct in which fracking would be banned, and gas wells restricted from frequently flooded areas."

- December 24, 2019 – Hurricane Harvey in 2017 resulted in "extraordinary damage" to onshore industrial facilities, including oil and gas infrastructure, and storage tanks were the most frequently damaged pieces of equipment, according to an investigation using government incident databases documenting accidents involving hazardous chemicals. Researchers found that fully 42 percent of the hurricane-related accidents involved storage tanks, thus adding data and evidence to previous research that had identified storage tanks as highly vulnerable to catastrophic damage from storms and floods. Storage tanks released hundreds of thousands of kilograms of their hazardous contents during Harvey. No plans were in place to deal with the volume of rain that fell during this

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[1370] Wil Lieberman-Cribbin et al., "Socioeconomic Disparities in Incidents at Toxic Sites During Hurricane Harvey," *Journal of Exposure Science & Environmental Epidemiology* 31, no. 3 (2021): 454–60, https://doi.org/10.1038/s41370-021-00324-6.
[1371] Gevorg Sargsyan et al., "Analysis of Risk Management Practices of the Oil and Gas Industry in Southeast Texas During Hurricane Harvey," *Journal of Applied Business and Economics* 22, no. 12 (2020), https://doi.org/10.33423/jabe.v22i12.3882.
[1372] Ben Smee, "Scientific Advice Recommending Ban on Fracking in Lake Eyre Basin Kept Secret and Ignored," *The Guardian*, April 29, 2020, sec. Australia news, https://www.theguardian.com/australia-news/2020/apr/29/scientific-advice-recommending-ban-on-fracking-in-lake-eyre-basin-kept-secret-and-ignored.

category 4 hurricane. Calling this an "unforeseen new failure mode," and acknowledging the role of climate change in causing more frequent and more severe disasters, researchers called for review and updating of design standards of floating roof storage tanks. At least 400 storage tanks in the Houston region have this type of roof.[1373]

- November 5, 2019 – Noting that floods will be increasing in frequency and severity due to climate change, researchers studied the impact of flood water on natural gas pipeline transmission valves to identify possible threats to safety and demonstrated that flooding presents risks of corrosion beyond routine threats. The chemical composition of flood waters, which can vary widely, "had an aggressive effect on the metals." Flood waters may also scour the surrounding land, leading to loss of mechanical stability of gas pipelines, particularly at various parts including valves. Specifically, this study found that the loss of stability of a gas pipeline would be most dangerous for flange connections, due to the additional forces of the underwater environment, and can also be the result of "force moments," which can trigger changes in the load balance. Flange connections comprise some valve connections in aboveground gas pipelines. This study provides additional evidence and detail to previous research demonstrating the long-term negative impact of flood waters on the operation of transmission systems. "[T]here is often a conflict between economic conditions and ensuring the appropriate safety of transmission systems," researchers wrote.[1374]

- August 5, 2019 – The oil and gas industry is "both a victim and a perpetrator" of the landslides and sinkholes linked to the industry's Pennsylvania activity and infrastructure, according to the Pittsburgh *Post-Gazette*.[1375] "With hundreds of well pads and thousands of miles of pipelines newly added to the ground in Pennsylvania over the past decade, the industry's development disturbs the surface and eliminates some trees and vegetation that would otherwise absorb rainfall. Then the rain, in turn, floods culverts, soaks the ground and moves soil without regard for what pipelines may be relying on its support." The article also covered the "precipitation spikes" in the state, noting the twelve months previous to publication were the rainiest on record, with nearly two feet more rain than an average year for the last century. According to an engineering professor quoted in the piece, very few of the industry's infrastructure standards have been updated to account for this climate change impact.

- May 29, 2019 – A George Washington University research team described the "potential disastrous and growing" public health risks that the combination of increasingly extreme weather, chemical facilities, and vulnerable populations presents. They present findings

[1373] Rongshui Qin, Nima Khakzad, and Jiping Zhu, "An Overview of the Impact of Hurricane Harvey on Chemical and Process Facilities in Texas," *International Journal of Disaster Risk Reduction* 45 (2020): 101453, https://doi.org/10.1016/j.ijdrr.2019.101453.
[1374] Mariusz Łaciak et al., "Impact of Flood Water on the Technical Condition of Natural Gas Transmission Pipeline Valves," *Journal of Loss Prevention in the Process Industries* 63 (2020): 103998, https://doi.org/10.1016/j.jlp.2019.103998.
[1375] Anya Litvak and Laura Legere, "Too Much Rain Is Messing with Pipeline Operators' Infrastructure Plans | Pittsburgh Post-Gazette," *Pittsburgh Post-Gazette*, August 5, 2019, https://www.post-gazette.com/business/bop/2019/08/05/Too-much-rain-is-messing-with-pipeline-operators-infrastructure-plans/stories/201908040010.

on recent natural hazard-triggered technical disasters, or "natech" events, which are the focus of a growing area of research. Natech events include the "over 600 hazardous material releases from gas installations and offshore oil facilities and pipelines," triggered by Hurricanes Rita and Katrina.[1376] Their own research identified 872 highly hazardous chemical facilities within 50 miles of the hurricane-prone U.S. Gulf Coast, and 4,374,000 people, 1,717 schools, and 98 medical facilities within 1.5 miles of these facilities.

- March 5, 2019 – In the aftermath of Hurricane Harvey, which brought record rainfall and widespread flooding to Houston and Galveston, the state of Texas and the U.S. Environmental Protection Agency (EPA) prohibited a National Aeronautics and Space Administration (NASA) plane "equipped with the world's most sophisticated air samplers" to fly over chemical spills, fires, flooded storage tanks, damaged plants, and flooded Superfund sites. Instead, a single-prop plane was used by the EPA to gather information on about two dozen air pollutants, whereas the NASA jet could have analyzed more than 450. At the same time, the Texas governor began a seven-month suspension of state air pollution emissions rules. A subsequent investigation by the Associated Press and the *Houston Chronicle* showed there was "widespread, unreported pollution and environmental damage in the region. The team identified more than 100 storm-related toxic releases, including a cloud of hydrochloric acid that leaked from a damaged pipeline and a gasoline spill from an oil terminal that formed 'a vapor cloud.'"[1377]

- November 30, 2018 – According to the *Miami Herald*, a new Florida Power & Light gas plant, replacing an existing one, will be raised 11.5 feet "to protect from sea level rise, a growing threat caused by emissions from fossil fuel plants." The region is expected to see 14 to 34 inches of sea level rise by 2062. Testimony at a public hearing, following an outpouring of public opposition to the project, included objections to further investments in fossil fuel projects. "What will you tell residents when the last of their personal possessions wash out to sea and the plant that fuels that tide stands above them?"[1378]

- November 29, 2018 – Storm protections will not be coming nearly as quickly as the planned tens of billions of dollars in new natural gas processing and chemical facilities along the Texas gulf, explained a collaborative investigative article in the *Texas Tribune*. "Many of the proposed, under-construction or recently built facilities along the Texas Gulf are in areas that felt [Hurricane] Harvey's bite." Harvey dropped more rain than any storm on U.S. record and led to chemical spills, contaminant releases to the air, and explosions at oil, gas, and chemical facilities. "Extensive storm modeling by top Texas

[1376] Susan C. Anenberg and Casey Kalman, "Extreme Weather, Chemical Facilities, and Vulnerable Communities in the U.S. Gulf Coast: A Disastrous Combination," *GeoHealth* 3, no. 5 (2019): 122–26, https://doi.org/10.1029/2019GH000197.
[1377] Susanne Rust and Louis Sahagun, "Post-Hurricane Harvey, NASA Tried to Fly a Pollution-Spotting Plane over Houston. The EPA Said No," Los Angeles Times, March 5, 2019, https://www.latimes.com/local/california/la-me-nasa-jet-epa-hurricane-harvey-20190305-story.html.
[1378] Alex Harris and Samantha J. Gross, "FPL to Build New Fossil Fuel Plant — and Elevate It 11 Feet to Protect from Sea Rise," *Miami Herald*, November 30, 2018, https://www.miamiherald.com/news/local/community/broward/article222435610.html?fbclid=IwAR3mbqV7WBYvpGOzmLpbz1R6q1gxZQJzwXQ84fmx0RBocfyaG93M6bsZGws.

scientists has shown that if a hurricane hit near the southern end of Galveston Island outside Houston… storm surge would pour into the Port of Houston, dislodging thousands of storage tanks full of crude oil and hazardous chemicals."[1379]

- September 14, 2018 – In Beaver County, Pennsylvania, a landslide following heavy rains and flooding caused an explosion of a new section of Energy Transfer Partners' Revolution Pipeline one week after it was operational, according to an investigative piece in *Environmental Health News*. The explosion destroyed a house, other structures, and vehicles, and forced evacuations. A few months earlier, a TransCanada natural gas pipeline in Marshall County, West Virginia exploded due to landslide. In its recent permit application, Shell Pipeline Company identified 25 locations prone to landslides along the route of its proposed Falcon Ethane Pipeline through Pennsylvania, Ohio, and West Virginia.[1380]

- September 11, 2018 – Pipeline construction guidelines are based on standards that do not account for recent changes in weather patterns, and flood risks are particularly exacerbated along the Mountain Valley Pipeline route, which passes through extraordinarily rugged terrain. In a mountainous area of Virginia, pipeline construction workers were compelled to rush preparations for catastrophic rain from Hurricane Florence in summer 2018 as the abnormally wet summer overcame efforts to prevent runoff and erosion.[1381]

- August 22, 2018 –The state of Texas sought at least $12 billion, nearly all of it coming from public funds, to build a nearly 60-mile "spine" of concrete seawalls, earthen barriers, floating gates, and steel levees on the Texas Gulf Coast. This region is home to one of the world's largest concentrations of petrochemical facilities, including most of Texas' 30 refineries. Facilities that would be protected by this project include those owned by the Saudi-controlled Motiva, Chevron, DuPont, and others. Scaled back from earlier proposals, the current one focused on refineries, according to the Associated Press.[1382]

- April 28, 2018 – In their assessment of coastal energy infrastructure at risk along the Gulf Coast, scholars at Louisiana State University concluded that natural gas processing plants in the United States are particularly vulnerable to inundation by sea level rise compared

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[1379] Jamie Smith Hopkins and Kiah Collier, "Surge of Oil and Gas Flowing to Texas Coastline Triggers Building Boom, Tensions," *The Texas Tribune*, November 29, 2018, https://www.texastribune.org/2018/11/29/oil-and-gas-surge-texas-coastline-triggers-building-boom-tensions/.

[1380] Kristina Marusic, "25 Zones along the Proposed Shell Falcon Pipeline Are at Risk of Explosions Due to Landslides," *Environmental Health News*, September 14, 2018, https://www.ehn.org/here-are-the-25-zones-along-the-proposed-shell-falcon-pipeline-at-risk-of-explosions-due-to-landslides-2604629860.html.

[1381] G. S. Schneider, "Hurricane Could Devastate Virginia Pipeline Project That Is Already Struggling with Changing Weather," *Washington Post*, September 11, 2018, sec. Virginia Politics, https://www.washingtonpost.com/local/virginia-politics/hurricane-could-devastate-virginia-pipeline-project-that-is-already-struggling-with-changing-weather/2018/09/11/572d0ef8-b5cf-11e8-94eb-3bd52dfe917b_story.html.

[1382] Will Weissert, "Big Oil Asks Government to Protect It from Climate Change," *AP News*, April 28, 2021, sec. U.S. News, https://apnews.com/article/us-news-ap-top-news-houston-climate-change-port-arthur-4adc5a2a2e6b45df953ebcba6b63d171.

to other energy infrastructure, with up to eight percent of natural gas processing capacity at risk. Tidal flooding is known to be an ancillary effect of sea level rise. Hence, apart from sea level rise itself, "storm surges and flooding from extreme weather-related events often increase the current exposure of these facilities to near-term damage."[1383] Fifteen natural gas processing plants were in the potential inundation zones of the study's various sea level rise scenarios, with nine plants projected to be inundated under all three scenarios.

- December 29, 2017 – Flooding was a central theme in an internationally focused review of energy critical infrastructures at risk from climate change. Potential flood impacts on oil and gas infrastructure take many forms: storm surge flooding damaging aboveground fuel storage tanks; flood-related soil erosion exposing buried underground oil and gas pipelines; and inundation of oil refineries. The authors noted that as climate change "leads to an increase in atmospheric moisture content, the likelihood of extreme precipitation and the risk of flooding increase with associated physical impacts" on infrastructure such as power plants and gas pipelines.[1384]

- September 15, 2017 – Hurricane Harvey and its resulting flooding affected various parts of metropolitan Houston's vast oil and gas operations, as well as the Eagle Ford shale region of South Texas. *Reuters* reviewed company reports to the U.S. Coast Guard on the various releases of petrochemicals around the time of Harvey's hit and subsequent flooding. In addition to more than 22,000 barrels of crude oil, gasoline, diesel, drilling wastewater, and petrochemicals spilled from refineries, storage terminals, and other facilities in the days after the storm, 27 million cubic feet (765,000 cubic meters) of natural gas was released.[1385] Pipeline operators are required to report oil and gas, but not drilling wastewater, spills to the Texas Railroad Commission. An environmental organization retrieved and listed this data, finding 31 spills at oil and gas wells, storage tanks, and pipelines during the hurricane's flooding. The group notes that though the data contains many "produced water" spills, they are likely underreported since they are not mandatory.[1386] More than half the fracking rigs running in the region were estimated to have shut down. "Given that much of oil and gas activity occurs in areas only accessible via dirt roads, the heavy rainfall usually makes the movement of trucks and supplies much more difficult…The trucking and rail of sand, chemicals, and personnel to the well

[1383] David E. Dismukes and Siddhartha Narra, "Sea-Level Rise and Coastal Inundation: A Case Study of the Gulf Coast Energy Infrastructure," *Natural Resources* 09, no. 04 (2018): 150–74, https://doi.org/10.4236/nr.2018.94010.
[1384] Cleo Varianou Mikellidou et al., "Energy Critical Infrastructures at Risk from Climate Change: A State of the Art Review," *Safety Science* 110 (2018): 110–20, https://doi.org/10.1016/j.ssci.2017.12.022.
[1385] Emily Flitter and Richard Valdmanis, "Oil and Chemical Spills from Hurricane Harvey Big, but Dwarfed by Katrina," *Reuters*, September 15, 2017, https://www.reuters.com/article/us-storm-harvey-spills/oil-and-chemical-spills-from-hurricane-harvey-big-but-dwarfed-by-katrina-idUSKCN1BQ1E8.
[1386] Environment Texas, "Environmental and Health Concerns About Oil and Gas Spills After Hurricane Harvey," Fact Sheet, September 12, 2017, https://environmenttexas.org/sites/environment/files/reports/Harvey%20Oil%20Gas%20Spills%20-%20Env%20TX%20-%209.22.17.pdf.

site will all take more time given the likely nasty condition of many Eagle Ford access roads," according to an energy analyst.[1387]

- May 25, 2016 – The removal of photos of flood-related oil spills on a Texas state-run website appears to be an effort to hide visuals that "don't portray the energy business in a flattering light," according to the *El Paso Times* Editorial Board. The photos revealed potential environmental damage caused by flooding at fracking sites.[1388] As earlier reported by the *El Paso Times*, many of the photos shot during Texas' recent floods "show swamped wastewater ponds at fracking sites, presumably allowing wastewater to escape into the environment—and potentially into drinking-water supplies."[1389]

- May 1, 2016 – Spring floods across Texas inundated oil wells and fracking sites, tipped over storage tanks, and flushed crude oil and fracking chemicals into rivers, as documented in an Associated Press story that referenced dozens of aerial photographs showing flooded production sites along the Sabine River on the Texas-Louisiana border. (The photographs were later removed from direct public access; see above.) Past president of the American Public Health Association Walter Tsou, MD, called the situation "a potential disaster."[1390]

- June 12, 2015 – At the beginning of 2015, after a month of record-breaking rainfall, Fish and Wildlife Service officials at the Hagerman National Wildlife Refuge in Texas found that floodwaters flowing through oil production well pads in the refuge had inundated dozens of jackpumps, pipelines, and other oil and gas infrastructure, leaving bubbling, oily water and a gassy stench. In 1989, the U.S. Government Accountability Office (GAO) called for "bold action" to address fossil fuel production activities incompatible with the mission of the refuge system. Subsequent reforms have been exceedingly slow, according to a report from *Greenwire*. In most cases, the Fish and Wildlife Service does not know how much fossil fuel is produced or spilled on refuges, and remediation efforts are inadequate. Severe weather events are expected to increase in frequency and severity as climate change progresses, amplifying flood related concerns.[1391]

- June 20, 2014 – The *Coloradoan* reported that Noble Energy storage tanks damaged by spring flooding in Colorado dumped 7,500 gallons of crude oil, fracking chemicals, and fracking wastewater into the Cache la Poudre River, which is both a National Heritage area and a habitat for Colorado's only self-sustaining population of wild trout. Recent high river flows had undercut the bank where the oil tank was located, which caused the

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[1387] David Wethe, "Harvey's Floods Could Delay 10% of U.S. Fracking: Analyst," *Bloomberg*, August 31, 2017, https://www.bloomberg.com/news/articles/2017-08-31/harvey-s-floods-could-delay-10-percent-of-u-s-fracking-analyst.
[1388] Editorial Board, "Editorial: Hiding Bad News from Texans," *El Paso Times*, May 25, 2018, https://www.elpasotimes.com/story/opinion/editorials/2016/05/25/editorial-hiding-bad-news-texans/84937054/.
[1389] Schladen, "Flooding Sweeps Oil, Chemicals Into Rivers."
[1390] Chris Siron, "Texas Floods Washing Fracking Chemicals, Crude Oil into Rivers," *The Dallas Morning News*, May 1, 2016, sec. News, https://www.dallasnews.com/news/2016/05/01/texas-floods-washing-fracking-chemicals-crude-oil-into-rivers/.
[1391] Corbin Hiar, "Wildlife Refuges: Floods Expose Weakness in FWS's Oil and Gas Oversight," *E&E News*, June 12, 2015, https://web.archive.org/web/20150617000047/http://www.eenews.net/stories/1060020169.

tank to drop and break a valve.[1392]

- March 2014 – An extraordinary flood that struck the Front Range of Colorado killed ten people, forced the evacuation of 18,000 more, destroyed more than 1,850 homes, and damaged roads, bridges, and farmland throughout the state. More than 2,650 oil and gas wells and associated facilities were also affected, with 1,614 wells lying directly within the flood impact zone. Many of these storm-damaged facilities and storage tanks leaked uncontrollably. In a later accounting, Matt Lepore, Director of the Colorado Oil and Gas Conservation Commission, estimated the flooding had resulted in the release to the environment of 48,250 gallons of oil or condensate and 43,479 gallons of fracking wastewater from 50 different spill sites across the state. In Colorado, more than 20,850 oil and gas wells lie within 500 feet of a river, stream, or other drainage. According to Director Lepore, setback requirements that keep drilling and fracking operations away from residential areas inadvertently encourage operators to drill in unoccupied floodplains. At the same time, oil and gas operators prefer locations close to supplies of water for use in fracking. These twin factors result in a clustering of drilling and fracking operations in low-lying areas prone to catastrophic flooding.[1393]

- 2004-2013 – In 2004, 2005, 2006, 2009, 2011, and 2013, several counties targeted for shale gas drilling in New York State experienced serious flooding. These include the counties of Albany, Broome, Cattaraugus, Chautauqua, Chenango, Delaware, Erie, Greene, Madison, Orange, Otsego, Schoharie, Sullivan and Ulster. In 2004, 2005, 2006, 2009 and 2011, floods exceeded 100-year levels in at least some of the counties.[1394, 1395, 1396, 1397, 1398, 1399, 1400]

- February 7, 2013 – In its 2012 annual report to investors, oil and gas drilling company

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1392 Ryan Maye Handy, "Crude Oil Spills into Poudre near Windsor," *The Coloradoan*, June 20, 2014, https://www.coloradoan.com/story/news/local/2014/06/20/crude-oil-spills-poudre-near-windsor/11161379/.
1393 Matt Lepore, "The Colorado Oil and Gas Conservation Commission and the Floods of September 2013—The Response So Far" (Colorado Oil & Gas Conservation Commission, May 20, 2014), https://iogcc.ok.gov/sites/g/files/gmc836/f/coloradofloodsv3_20140520.pdf.
1394 Lloyd T. Brooks, "Flood of September 18-19, 2004 in the Upper Delaware River Basin, New York," USGS Numbered Series, *Flood of September 18-19, 2004 in the Upper Delaware River Basin, New York*, vol. 2005–1166, Open-File Report (Reston, VA: U.S. Geological Survey, 2005), https://doi.org/10.3133/ofr20051166.
1395 Thomas P. Suro and Gary D. Firda, "Flood of April 2–3, 2005, Neversink River Basin, New York," Open-File Report (U.S. Geological Survey, 2006), https://pubs.usgs.gov/of/2006/1319/.
1396 Thomas P. Suro, Gary D. Firda, and Carolyn O. Szabo, "Flood of June 26–29, 2006, Mohawk, Delaware and Susquehanna River Basins, New York," Open-File Report (U.S. Geological Survey, 2009), https://pubs.usgs.gov/of/2009/1063/pdf/ofr2009-1063.pdf.
1397 Carolyn O. Szabo, William F. Coon, and Thomas A. Niziol, "Flash Floods of August 10, 2009, in the Villages of Gowanda and Silver Creek, New York," Scientific Investigations Report (U.S. Geological Survey, 2010).
1398 L. Szabo, "REMOVE THIS" (United States Geological Survey, 2011).
1399 Sistina Giordano, "Several Eastern Counties in Central New York under Water after Heavy Flooding," *Syracule Post-Standard*, June 29, 2013, sec. Central NY News, https://www.syracuse.com/news/2013/06/several_eastern_counties_in_ce.html.
1400 New York State Department of Environmental Conservation, "Supplemental Generic Environmental Impact Statement (SGEIS) on the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs," Technical Report (NYSDEC, 2011).

Noble Energy stated, "Our operations are subject to hazards and risks inherent in the drilling, production and transportation of crude oil and natural gas, including … flooding which could affect our operations in low-lying areas such as the Marcellus Shale."[1401]

- September 7, 2011 – The New York State Department of Environmental Conservation's (NYS DEC) draft shale gas drilling plan recommended that drilling be prohibited within 100-year floodplains but acknowledged that many areas in the Delaware and Susquehanna River basins that were affected by flooding in 2004 and 2006 were located outside of officially designated flood zones.[1402] In 2004, 2005, 2006, 2009, and 2011, flooding in New York exceeded 100-year levels in at least some of the counties where drilling and fracking may occur.

- 1992 – In its Generic Environmental Impact Statement (GEIS) for oil and natural gas drilling, which was predicated on conventional drilling, the NYS DEC raised concerns that storage tanks holding drilling wastewater, spent hydraulic fracturing fluid, or other contaminants could be damaged by flooding and leak. At the time, the GEIS called for at least some of these tanks to be properly secured.[1403] Shale gas extraction via horizontal fracking would require many more storage tanks for fracking fluids and wastewater than conventional drilling operations anticipated in 1992 when the agency estimated that oil and gas wells in the state would each require 20,000-80,000 gallons of fracking fluid.[1404] As of 2011, the agency anticipated that high volume, horizontally fracked shale gas wells in New York State would each require 2.4-7.8 million gallons of fluid—roughly 100 times the 1992 estimate.[1405]

[1401] Noble Energy, "Annual Report (Form 10-K)," February 7, 2013.
[1402] New York State Department of Environmental Conservation, "Supplemental Generic Environmental Impact Statement (SGEIS) on the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs," Technical Report (NYSDEC, 2011).
[1403] New York State Department of Environmental Conservation, "Supplemental Generic Environmental Impact Statement (SGEIS) on the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs," Technical Report (NYSDEC, 2011).
[1404] New York State Department of Environmental Conservation, "Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program," 1992, http://www.dec.ny.gov/docs/materials_minerals_pdf/dgeisv1ch8.pdf.
[1405] New York State Department of Environmental Conservation, "Supplemental Generic Environmental Impact Statement (SGEIS) on the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs," Technical Report (NYSDEC, 2011).

Threats to agriculture, soil quality, and forests

Drilling and fracking operations pose risks to farming, soil, and forests. In California, fracking wastewater illegally injected into aquifers threatens crucial irrigation supplies to farmers in a time of severe drought. Fracking wastewater reused for irrigation and livestock watering in California's San Joaquin Valley may contain at least ten known or suspected chemical carcinogens, as well as over a dozen chemicals with no available toxicological data and many unidentified compounds currently classified as "trade secrets." A 2020 study found elevated levels of sodium and boron in California soils irrigated with wastewater. Agricultural uses of wastewater, as well as flowback water spills, raise questions about direct exposure of affected soils, contamination of food crops via bioabsorption through plant roots, and impacts on livestock due to ingestion. Soil degradation, lower crop yields and microbial diversity were seen in land irrigated with oil and gas wastewater.

Studies and case reports from across the country have highlighted instances of deaths, neurological disorders, aborted pregnancies, and stillbirths in farm animals that have come into contact with wastewater. In Pennsylvania, ingestion of farm water contaminated with fracking chemicals has been linked to dysphagia, an extremely rare birth defect of the neuromuscular control of swallowing, among horses.

Additionally, farmers have expressed concern that nearby fracking operations can hurt the perception of agricultural quality and invalidate value-added organic certification.

Land use changes and transport of invasive species by drilling and fracking operations have led to documented harm to forests and natural areas. In forested areas of Pennsylvania, drilling and fracking operations have greatly reduced canopy covers and thereby diminished the carbon storage capacity of photosynthesizing forest trees. Soil compaction in cleared areas is detrimental to new plant growth and encourages the growth of invasive species. Sharp declines in the abundance and diversity of songbirds in Appalachian forest interiors accompany the arrival of fracking development activities even at low levels of forest loss.

Loss of farmland in areas with multiple wells is exacerbated by potentially permanent soil contamination. Planting tree cover could lead to a triple return on investment, but remediation is hampered by inadequate bond requirements, which leaves wells abandoned and opportunities for potential carbon sequestration squandered.

- April 14, 2021 – A study in an area of New Mexico with intense and continuous natural gas drilling activities found that elevated sound levels from gas wells and associated compressor stations impeded the growth and maturation of juniper and pinion pine seedlings. This study also found that noise directly altered the community of seed-dispersing animals upon which both tree species depend for reproduction, resulting in a decline in these foundational species. "We found support for long-term negative effects of noise on tree seedling recruitment, evenness of wood plants and increasingly dissimilar vegetation communities with differences in noise levels…Our results add to the limited evidence that noise has cascading ecological effects."[1406]

- April 9, 2021 – Before proceeding with production-scale fracking, South Africa can learn important lessons about surface impacts to rural and natural areas from the experience of fracking in North Dakota's agricultural Bakken region, according to a South African and North Dakota-based research team. The researchers noted that "energy sprawl" is the largest driver of land-use change in the United States, and that South Africa is unprepared to deal with these impacts. The research was based on the apt comparison of the Bakken to eastern South Africa: the mix of dryland farming and cattle ranching, rural towns, areas of Native lands, and federal conservation lands. A primary lesson learned in this analysis was the necessity to prioritize environmental integrity from the outset in order to prevent the kind of impacts seen in the Bakken. Researchers wrote that Bakken landowners eventually learned strategies to improve outcomes from the industry's soil and vegetation restoration projects, by, for example, writing into their contracts the imperative to use native grasses rather than exotic and annual species for revegetation. By contrast, however, restoring natural grassland is simply not currently feasible in South Africa because commercial seed harvesting and processing are not available at a volume or scale sufficient to support widespread restoration projects.[1407]

- April 9, 2021 – A study of landcover changes and forest structural changes in the Muskingum River Watershed in Appalachian Ohio found extreme damage to forest ecosystems in two areas—Carroll-Harrison counties and Belmont-Guernsey-Monroe-Noble counties—where intensive drilling and fracking activities took place during a boom that reached its peak in 2014 and slowed down by 2018. The loss of core forest was over 14 percent in regions where fracking operations were most dense and also included pipeline rights-of-way. High-resolution aerial images and other remote sensing techniques revealed that about two-thirds of the core forest was lost during the rising phase of the boom, while one-third occurred during the declining phase. The study documented a range of complex ecological damage, including break-up of the forest canopy; conversion of large continuous forest zones into small, isolated forest zones; irreversible changes in microclimate conditions; and the fragmentation and altered movement of wildlife populations.[1408]

- March 15, 2021 – A journalistic investigation found that the pipeline company Cheniere and its construction contractors have trucked away valuable topsoil from Oklahoma farms, flooded fields, and left construction debris and unrepaired swaths cut through soil.

[1406] Jennifer N. Phillips, Sarah E. Termondt, and Clinton D. Francis, "Long-Term Noise Pollution Affects Seedling Recruitment and Community Composition, with Negative Effects Persisting After Removal," *Proceedings of the Royal Society B* 288 (2021), https://doi.org/10.1098/rspb.2020.2906.
[1407] Devan Allen McGranahan and Kevin Peter Kirkman, "Be Proactive on Energy Sprawl: South Africa Must Anticipate Surface Impacts of Fracking in Rural Areas," *Resources Policy* 72 (2021), https://doi.org/10.1016/j.resourpol.2021.102081.
[1408] Yang Liu, "Remote Sensing of Forest Structural Changes Due to the Recent Boom of Unconventional Shale Gas Extraction Activities in Appalachian Ohio," *Remote Sensing* 13, no. 8 (2021), https://doi.org/10.3390/rs13081453.

Cheniere cited an economic downturn, cost overruns, and the pandemic as reasons for the lack of reconstruction of the farmers' lands.[1409]

- March 12, 2021 – A proposed 12-mile natural gas pipeline to be built by Louisville Electric and Gas (LG&E) will cut through Kentucky's Bernheim Research Forest and Arboretum's Cedar Grove wildlife corridor, which includes habitat for endangered species, including Kentucky glade cress, which grows nowhere else in the world. A media investigation revealed that Beam Suntory, the parent company of Jim Beam Bourbon, would be the sole recipient of the gas for the first five years.[1410]

- March 8, 2021 – Fracking harms natural landscapes in ways that are not limited to its infrastructure footprint alone. An Arkansas-based research team estimated restoration costs on land currently occupied by 400,000 restoration-eligible, non-producing well sites. These sites are largely located on temperate deciduous forest, grassland and pasture, and agricultural lands. The team then also calculated the economic benefits of restoration, including carbon sequestration and agricultural sales. The results showed that the value of carbon sequestration and agricultural benefits from the restoration, accrued over 50 years, was $21.3 billion in 2018 dollars. By contrast, the cost of restoration was $6.9 billion. Thus, the benefit-cost ratio of restoration exceeds 3:1. While the restoration of all abandoned fossil fuel lands in the United States showed economic benefits in this study, the restoration of deciduous forests, grasslands, and Mediterranean ecoregions had the biggest value.[1411]

- February 23, 2021 – Fracking in the Permian Basin of west Texas and New Mexico takes place in arid and semi-arid landscapes. A study that evaluated 1300 cross-sectional parcels of land in this region using high-resolution remote sensing research found significant harm to shrubland and grassland/pasture, with damage to shrubland most pronounced. The impacts were more strongly associated with the shale oil and gas production volume than with the number of wells drilled. The results showed that fracking activities affect vegetation cover in two ways: direct land-use change by clearing vegetation and, secondarily, from spillover impacts on nearby vegetation, as when fracking waste creates surface salt formation. These secondary impacts are more difficult to determine and take more time to assess.[1412]

- February 1, 2021 – Benzene from a pipeline leak contaminated soil over four acres and at 20-foot depths on a farm in western Weld County, Colorado. Landowners Julie and Mark Nygren were ultimately forced to remove the soil and demolish their house after discovering that liquid hydrocarbons had pooled beneath it. In April 2019, after years of

[1409] Mike Soraghan, "Angry Okla. Farmers Fight Pipeline Builder — and FERC," *E&E News*, March 15, 2021, https://web.archive.org/web/20210315220815/https://www.eenews.net/stories/1063727417.
[1410] Ryan Van Velzer, "LG&E Records Show Bernheim Pipeline Would Primarily Benefit Jim Beam," 89.3 WFPL, March 12, 2021, https://wfpl.org/lge-records-show-bernheim-pipeline-would-primarily-benefit-jim-beam/.
[1411] William Haden Chomposy et al., "Ecosystem Services Benefits from the Restoration of Non-Producing US Oil and Gas Lands," *Nature Sustainability* 4 (2021): 547–54, https://doi.org/10.1038/s41893-021-00689-4.
[1412] Haoying Wang, "The Impact of Shale Oil and Gas Development on Rangelands in the Permian Basin Region: An Assessment Using High-Resolution Remote Sensing Data," *Remote Sensing* 13, no. 4 (2021), https://doi.org/10.3390/rs13040824.

observing trees dying off on their property, they found green liquid floating in a ditch 130 feet from their house in a discovery that led to a determination that an underground "gathering line" had breached below their farm. As described by Julie Nygren, the resulting clean-up has created ongoing upheaval on their farm including the challenge of "planning to maneuver around the heavy equipment and the trucks that haul as many as 100 loads of contaminated soil to a landfill each day."[1413]

- January 22, 2021 – From 2012 to 2017, the core forest in the karst region of southwestern China decreased by 5.7 percent due to drilling and fracking activities, as determined by high-resolution, remote-sensing images. Though shale gas development was not the main driver of deforestation in this region, which has been experiencing other kinds of development as well, its impact will likely accelerate as shale gas industry development ramps up. Of all the various shale gas activities studied, pipeline construction had the greatest impact on core forest landscape.[1414]

- January 15, 2021 – In a study of North Dakota's four core shale-producing counties and two peripheral counties, researchers using GIS technology found that the footprints of both single wells and multi-well pads were significantly higher than industry estimates. The average single-well pad required 5.26 acres, while the average multi-well pad footprint was 8.60 acres. In the six counties, 23,077 acres of farmland were lost when they were converted by the fracking industry to 3,577 well pads plus access roads that service them. Authors estimated that 22.57 farms were lost with the six affected counties, with an estimated income loss of $4.45 million per year. In addition to farmland, 440 wetlands and 154.68 acres of native woodlands were impacted by well pads and access roads.[1415]

- December 29, 2020 – In some states, fracking wastewater is re-used to irrigate food crops. To determine if the plants can absorb some of the chemicals known to be present in the waste stream, researchers irrigated wheat with four fracking chemicals known to be linked to health risks, in a greenhouse experiment. They found significant uptake into both the wheat grain and stems for two of the chemicals, diethanolamine and tetramethylammonium chloride (TMAC), compared to the control plants. They found the third chemical, acrylamide, in statistically higher concentrations in the stems only, while didecyldimethylammonium chloride, the fourth chemical, was not detected in grain or stems. To reflect a worst-case scenario situation, researchers used in their experiment the maximum concentrations of the fracking fluid chemicals as reported in the FracFocus database. Results indicated that consuming the wheat with study levels of TMAC, a biocide, would present elevated health risks in both adults and children. Researchers

[1413] Judith Kohler, "Natural Gas Pipeline Leak Spurs Landowners to Assail Colorado's 'Subterranean Toxic Spaghetti,'" *The Denver Post*, February 1, 2021, https://www.denverpost.com/2021/02/01/colorado-farmers-oil-gas-pipeline-leak-dcp-lawsuit/.

[1414] Yu Guo et al., "Influence of Shale Gas Development on Core Forests in the Subtropical Karst Region in Southwestern China," *Science of the Total Environment* 771 (2021), https://doi.org/10.1016/j.scitotenv.2021.145287.

[1415] Felix N. Fernando and Jon A. Stika, "Exploration of Unconventional Oil and Gas (UOAG) Development on Farmland: Findings from the Bakken Shale of North Dakota," *Extractive Industries and Society* 8, no. 1 (2021): 400–412, https://doi.org/10.1016/j.exis.2021.01.001.

acknowledged that their experimental design did not represent the true chemical complexity of fracking fluids that might potentially be used for agricultural irrigation. They recommended evaluation of more complex chemical mixtures, at various levels, on other plant species. They noted that the expense and resources needed for the research to address the data gaps are significant.[1416]

- June 26, 2020 – "Landscape alteration" is likely to increase by approximately 42 percent under a "low-impact" oil and gas development scenario and by as much as about 299 percent under a "high-impact" scenario, in the Permian Basin of Texas and New Mexico.[1417] Researchers determined through these low-, medium-, and high-impact scenarios that, under each respectively, 60,000, 180,000, and 430,000 new well pads could be constructed through 2050. The Chihuahuan Desert, the largest portion of the study area, was determined to have the largest area of alterations, approximately 70, 200, and 500 percent under the three scenarios. The study's projections only include well pad development, not infrastructure, such as pipelines, compressor stations, and new roads, and authors cited research documenting these developments "can double the amount of alteration caused by well pads alone."

- June 4, 2020 – If reclamation took place on Arkansas lands with abandoned Fayetteville Shale oil and gas infrastructure, researchers estimated a gain of over $2 million annually in agricultural, timber, and carbon sequestration benefits, with benefits far outweighing the costs. The study used an ecosystem services approach, measuring changes using a monetary calculation of the value of natural resources beneficial to humans. Restoring lands to their original habitat, the researchers wrote, would have profound benefits to species requiring contiguous habitat as well as providing an important carbon sink. Almost 20 percent of wells in the Fayetteville Shale are currently non-producing, and as of 2017 only about 20 percent of those had been reclaimed. Nearly all wells in the Fayetteville Shale will be abandoned by 2050, according to the researchers. As the number of active wells declines, the cumulative costs would continue to increase while any oil and gas economic benefits decrease. The study suggested that there would be a two- to four-year break-even period after which regained ecosystem services benefits following reclamation would offset the reclamation costs. The researchers appealed for public education to understand the benefits and to support reclamation, with agricultural benefits an "especially efficacious as a way to communicate to the Arkansas public," as the public "might be especially receptive to programs that improve agricultural output, and subsequently the value of private property." Public support of policy changes would be necessary since the state's bonding requirements are inadequate.[1418]

[1416] Linsey Shariq et al., "Irrigation of Wheat with Select Hydraulic Fracturing Chemicals: Evaluating Plant Uptake and Growth Impacts," *Environmental Pollution* 273 (2021), https://doi.org/10.1016/j.envpol.2020.116402.
[1417] Jon Paul Pierre et al., "Projected Landscape Impacts from Oil and Gas Development Scenarios in the Permian Basin, USA," *Environmental Management* 66, no. 3 (2020): 348–63, https://doi.org/10.1007/s00267-020-01308-2.
[1418] Varenya Nallur, Maureen R. McClung, and Matthew D. Moran, "Potential for Reclamation of Abandoned Gas Wells to Restore Ecosystem Services in the Fayetteville Shale of Arkansas," *Environmental Management* 66 (2020): 180–90, https://doi.org/10.1007/s00267-020-01307-3.

- May 12, 2020 – Soil irrigated by “oilfield produced water” (OPW) in Kern County, California had systematically higher boron and sodium levels than soil irrigated by groundwater, in a study by a team of California and North Carolina researchers.[1419] Researchers concluded that long-term utilization of this blend of oilfield wastewater and surface water could induce boron and sodium toxicity and threaten crops in the long term. The study focused on inorganic chemistry and naturally occurring radioactive materials (NORM), “aiming to evaluate the long-term impact from irrigation with blended OPW as compared to local groundwater.” Results indicated that the blended OPW was of comparable quality to the groundwater, with constituents measured below drinking water and irrigation standards. But the findings of elevated boron and sodium, the researchers concluded, pose “long-term risks to soil sodification [excess sodium], groundwater salinization, and plant health.” The continued use of OPW for irrigation will require planting of boron-tolerant crops to avoid boron toxicity.

- May 5, 2020 – Research performed by a team from three veterinary research centers found a link between farm water contaminated with fracking chemicals and dysphagia, an extremely rare birth defect involving the neuromuscular control of swallowing, in horses.[1420] Dysphagic foals have difficulty suckling effectively. In 2014, veterinarians at the Cornell University Hospital for Animals found five out of ten foals born on one farm in Pennsylvania (PA) carried this defect. The research team that responded analyzed dysphagia cases in neonatal foals born between 2014 and 2016 on that farm, as well as on an unaffected New York (NY) farm with the same owner, evaluating biological data and environmental exposures on each. The PA farm is located in the northeast region of the Marcellus shale formation and has 28 fracking wells within 10 kilometers. Of the 69 foals born during the study period, 17 were dysphagic and all born in PA, and 48 were normal (11 born in PA, 37 born in NY). Several mares that were on the PA farm for the first half of pregnancy had healthy offspring after being moved to the NY farm mid-pregnancy, and several mares starting off in NY and moving to the PA farm gave birth to dysphagic foals. Both farms used the same feed and hay. The study’s environmental analysis found the PA well water to contain higher levels of several polyaromatic hydrocarbons (PAHs) compared to the NY farm water, including 3,6-dimethylphenanthrene, fluoranthene, pyrene, and triphenylene. The study’s analysis supported nearby fracking activities as the possible contamination source. The installation of a water treatment system reducing the PAHs in the PA water to NY levels eliminated the occurrences of dysphagia. Noting that a “similar study of these environmental variables would be nearly impossible to undertake in humans,” the researchers state that “domestic large animals such as horses can serve as important sentinels for human health risks” linked to fracking.

- April 27, 2020 – Forest interior songbird numbers declined “at relatively low levels of overall forest loss” associated with shale gas in Marcellus-Utica shale area landscapes

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[1419] Andrew J Kondash et al., “The Impact of Using Low-Saline Oilfield Produced Water for Irrigation on Water and Soil Quality in California,” *Science of The Total Environment* 733 (2020): 139392, https://doi.org/10.1016/j.scitotenv.2020.139392.
[1420] Kathleen R. Mullen et al., “Environmental Surveillance and Adverse Neonatal Health Outcomes in Foals Born near Unconventional Natural Gas Development Activity,” *Science of The Total Environment* 731 (August 2020): 138497, https://doi.org/10.1016/j.scitotenv.2020.138497.

within Pennsylvania, West Virginia, and eastern Ohio, a team of forest and wildlife ecologists determined.[1421] Their study consisted of 2,589 bird surveys at 190 sites across this region over two years. They found that some forest interior species "decreased abruptly in abundance and frequency of occurrence above a threshold of 17.0% overall forest loss." Some more sensitive species similar declined at lower thresholds, from 8.7 to 15.9 percent forest loss. Whereas research has shown that some highly adaptive bird species can increase with human disturbance, this study found that species in these other habitat categories did not increase in landscapes with more than 30.5–36.5 percent forest loss from shale gas development. Researchers concluded that their findings of "declines in abundance and richness of forest interior birds in response to anthropogenic forest disturbance at relatively low levels of forest loss" were consistent with previous findings, and warned that the time period is which shale gas development has taken place in the region would not yet allow for science to have observed "the full range of successional impacts to affected forests, or the full response of species to ongoing changes."

- April 10, 2020 – A case study considered the "misalignment of conservation objectives" by analyzing the effects of fracking in the Bakken shale on North Dakota's Theodore Roosevelt National Park (TRNP).[1422] Authors discussed the potential for conflict between federal oversight of shale oil and gas reserves development with the federal obligation "to preserve designated areas of 'wilderness,' as well as protect social and cultural significance, ecosystem services, recreational benefits, and inherent beauty," with particular attention to the Trump administration's executive orders weakening and repealing pertinent protections. Twelve national parks contain active oil and gas wells within their boundaries, while others, including TRNP, do not, but effects of surrounding oil and gas development have included air pollution, noise pollution, and land fragmentation. Documented "evidence of encroachment" included "noticeable changes to viewscape and soundscape." The authors posit that the Trump administration's steps toward weakening protections and prioritizing oil and gas development over conservation "conflicts with the original intent to set aside TRNP and other federal parklands for current and future generations." They ask, "In regulating fracking and conservation, can the federal government be both the gamekeeper and the poacher?"

- March 27, 2020 – West Virginia wildlife researchers found sex-specific genetic changes in Louisiana waterthrush linked to shale gas development, concluding these changes "may affect long-term population survival and fitness" of the species.[1423] This was the first study relating shale gas development to a molecular-level, epigenetic response in a wildlife population. This species is known to be sensitive to changes in ecological conditions and is of conservation concern. It has a specialized habitat and its core breeding range overlaps the Marcellus-Shale region. The researchers' previous six-year

[1421] Laura S. Farwell et al., "Threshold Responses of Songbirds to Forest Loss and Fragmentation across the Marcellus-Utica Shale Gas Region of Central Appalachia, USA," *Landscape Ecology* 35, no. 6 (2020): 1353–70, https://doi.org/10.1007/s10980-020-01019-3.
[1422] Miriam R. Aczel and Karen E. Makuch, "Shale Resources, Parks Conservation, and Contested Public Lands in North Dakota's Theodore Roosevelt National Park: Is Fracking Booming?," *Case Studies in the Environment* 4, no. 1 (2020): 1–13, https://doi.org/10.1525/cse.2019.002121.
[1423] Mack W. Frantz et al., "Epigenetic Response of Louisiana Waterthrush *Parkesia Motacilla* to Shale Gas Development," *Ibis* 162, no. 4 (2020): 1211–24, https://doi.org/10.1111/ibi.12833.

study determined that shale gas development negatively impacted the Louisiana waterthrush population. Here, the researchers studied the epigenetic response—DNA changes, or, methylation variation, in response to environmental exposures that may be inherited by future generations—of this species, comparing those in shale gas development regions to those without disturbance from shale gas development. Researchers wrote that their study "adds to existing evidence that methylation varies with pollutant concentrations," and was the first to show a differing pattern of methylation between males and females in a wildlife population. Females had more "methylated restriction sites" than males, which authors proposed may be due to their different use and movement patterns within their territories. Researchers also correlated methylation to the accumulation in feathers of barium and strontium, two heavy metals linked to fracking and already documented to be higher in waterthrush feathers in fracking areas.

- March 14, 2020 – Researchers found degraded soil health, lower wheat yields, and loss of microbial diversity in a greenhouse experiment that involved treating wheat with various dilutions of wastewater from oil and gas production in an effort to determine if it can safely be used as a viable water source for agricultural irrigation. Using a soil health index that reflected chemical, biological, physical, and nutrient properties, the team found irrigation with wastewater from oil and gas production significantly reduced soil health as compared to the soil receiving the control irrigation water. Both dilutions led to lower wheat yields. Further, the microbial community within the soil was significantly different between irrigation treatments in ways that may affect biochemical cycling.[1424]

- November 19, 2019 – Expanding oil and gas well pads and infrastructure covered 2.5 percent and nearly eleven percent of two priority greater sage-grouse population habitat management area zones within the Parachute-Piceance-Roan, according to study by Colorado Parks and Wildlife researchers.[1425] Oil and gas infrastructure developed during the 2005-2015 study period included 195 new well pads, 930 hectares of new pipelines, and 230 kilometers of new roads. The total oil and gas "footprint" within the greater sage-grouse range in this location more than doubled in the study period, with the rate of new energy development slowing from 2009 to 2015. The researchers predicted, however, that oil and gas will continue to be the main source of greater sage-grouse habitat loss and change in this area over the next few decades. The greater sage-grouse is a "species of concern," that "has experienced historical population declines, especially in peripheral populations" such as the Parachute-Piceance-Roan, and energy development has been widely cited, including by the U.S. Fish and Wildlife Service, as one of the main concerns. This study sought to remedy the "lack the comprehensive, accurate, time-stamped spatial data layers needed to rigorously quantify effects of energy infrastructure" in a greater sage-grouse population. Researchers chose Parachute-Piceance-Roan, which overlays large shale reserves, for its increasing oil and gas development and concern

[1424] Hannah Miller et al., "Reusing Oil and Gas Produced Water for Agricultural Irrigation: Effects on Soil Health and the Soil Microbiome," *Science of the Total Environment* 722 (2020), https://doi.org/10.1016/j.scitotenv.2020.137888.
[1425] Brett L. Walker et al., "Quantifying Habitat Loss and Modification from Recent Expansion of Energy Infrastructure in an Isolated, Peripheral Greater Sage-Grouse Population," *Journal of Environmental Management* 255 (2020): 109819, https://doi.org/10.1016/j.jenvman.2019.109819.

about long-term population viability. Within the study area researchers found that the same topographic constraints that lead to oil and gas development in gentler topography, hold true for the greater sage-grouse habitat preference.

- September 23, 2019 – Farmers in the path of the Spire Inc. STL gas pipeline in Illinois said access to their fields has been blocked, their topsoil damaged, and fields flooded by the construction.[1426] The farmers' claims were backed up by an 80-page inspection report by the Illinois Environmental Protection Agency, linked in the *E&E News* piece, and a consulting firm working on behalf of some of the farmers filed at least 25 complaints with the Federal Energy Regulatory Commission (FERC) on their behalf. Fifty farmers in the pipeline's path had denied easements; the company subsequently employed a legal process called "quick take" to gain access to the properties.

- August 7, 2019 – Between 1975 and 2017, four British Columbian shale gas plays together lost over one percent of their forest cover, due to the construction of well pads, access roads, and pipelines.[1427] The Canadian and U.S. research team combined a geospatial approach with metrics from landscape ecology. Authors suggested that forest cover loss was held to the degree found due to the International Boreal Conservation Science Panel recommendation that "at least fifty percent of the intact boreal forest of Canada should be conserved," but that increased understanding is needed of "specific forest conservation or land management context of each of these shale gas plays."

- June 11, 2019 – Drilling and fracking activities decreased the abundance of forest interior-dependent songbird populations in central Appalachia, according to a study of the relationship between 27 bird species and their distance from shale gas construction in northern West Virginia from 2008 to 2017.[1428] Ovenbird species populations declined 35 percent and cerulean warblers by 34 percent. Over the study period the footprint of shale gas increased tenfold, with a larger increase in new "forest edges." Though other, highly adaptable species may benefit from forest disturbance, the researchers noted that species negatively affected include those of "conservation concern." The researchers stated that their findings of losses to populations of edge-avoiding, forest interior bird declines near shale gas development is consistent with other studies of energy development impacts on birds.

- April 9, 2019 – Shale gas development impacted "site fidelity," or breeding site return rates, of the Louisiana waterthrush, according to a six-year study by West Virginia

[1426] Mike Soraghan, "'A Muddy Mess.' Ill. Landowners Fight FERC over Pipeline," *E&E News*, September 23, 2019, https://web.archive.org/web/20191226021302/https://www.eenews.net/energywire/stories/1061140891.
[1427] J. Oduro Appiah, C. Opio, and S. Donnelly, "Quantifying, Comparing, and Contrasting Forest Change Pattern from Shale Gas Infrastructure Development in the British Columbia's Shale Gas Plays," *International Journal of Sustainable Development & World Ecology* 27, no. 2 (2020): 114–28, https://doi.org/10.1080/13504509.2019.1649313.
[1428] Farwell et al., "Proximity to Unconventional Shale Gas Infrastructure Alters Breeding Bird Abundance and Distribution."

wildlife researchers.[1429] This species is of "conservation concern" because of its specialized habitat, and because most of its core breeding range is within the Marcellus-Utica shale region. Previous research by the team showed diminished waterthrush habitat quality, nest survival, and productivity, and this study turned its focus to site fidelity, typically high among Louisiana waterthrush. This is important, as researchers explained, because "site fidelity can directly influence fecundity and survival of individuals." Specifically, the study analyzed waterthrush annual site fidelity, factors that might affect annual site fidelity, and apparent annual survival across 14 headwater streams with varying amounts of shale gas disturbance in the Lewis Wetzel Wildlife Management Area in West Virginia. Shale gas disturbance on streams varied greatly within each year of the study, but on average streams had more than one-fifth of their length disturbed by fracking development, and there were no undisturbed streams. Results showed that the males had very high site fidelity initially, returning to areas despite lowered habitat quality, but females were less likely to return, had a higher number of breeding attempts, and lowered productivity. The disruptions to the birds' normal behaviors, such as maintaining pair bonds from one year to the next, "may affect the population's long-term persistence," according to the researchers, and their study "adds to previous evidence that shale gas disturbed areas may serve as sink habitats." In sink habitats, death rates exceed birth rates.

- September 15, 2018 – Drilling and fracking operations and their associated infrastructure removed a large volume forest canopy in the upper Susquehanna River basin of New York and Pennsylvania from 2006 to 2013. This loss can be considered permanent, according to U.S. Geological Survey (USGS) scientists. Using "lidar" (light detection and ranging) remote sensing technology, the research team assessed three-dimensional volumetric change of forest loss, as opposed to two-dimensional areal loss. Because trees capture carbon dioxide on the surfaces of their canopy leaves during photosynthesis, three-dimensional measurements allow for the assessment of the carbon storage capacity that is sacrificed to gas development via tree removal. The researchers found that a total of 991,326,760m^3 of forest canopy was removed by oil and gas activities in the upper Susquehanna River watershed area studied. New York's loss was "relatively low" because of the state's fracking moratorium during the study period. The largest losses in forest volumes took place in the Pennsylvania counties of Lycoming, Tioga, Sullivan, Bradford, Wyoming, and Susquehanna. Although timber operations removed more canopy overall, that loss was concentrated in a smaller area.[1430]

- September 7, 2018 – Cleared areas around fracking well pads in Pennsylvania state forests are subjected to soil compaction equivalent to that in parking lot construction, according to researchers quoted in a *StateImpact* article. Although not used once the well is in production, these cleared areas are not typically repaired or replanted. Further, this

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[1429] Mack W. Frantz et al., "Louisiana Waterthrush (Parkesia Motacilla) Survival and Site Fidelity in an Area Undergoing Shale Gas Development," *The Wilson Journal of Ornithology* 131, no. 1 (2019): 84, https://doi.org/10.1676/18-6.
[1430] John Young et al., "Canopy Volume Removal from Oil and Gas Development Activity in the Upper Susquehanna River Basin in Pennsylvania and New York (USA): An Assessment Using Lidar Data," *Journal of Environmental Management* 222 (2018): 66–75, https://doi.org/10.1016/j.jenvman.2018.05.041.

level of compaction is detrimental to new plant growth as the soil has fewer pores to store water or gases needed for plant survival. Experimenting with repair for these areas, Penn State University soil scientist Patrick Drohan said, "A lot of our native species, especially the grasses, are very deeply rooted. So if they can get down through 20 inches of loosened soil they're going to be able to develop really deep, nice root systems." Though involved with these experiments and resulting step-by-step repair directions, the Pennsylvania Department of Conservation and Natural Resources is "not proposing to make any of these methods mandatory."[1431]

- July 18, 2018 – A USGS study on the Colorado Plateau investigated vegetation cover at inactive well sites. Researchers found that on half of plugged and abandoned oil and gas well sites, the median vegetation cover after five years was 26 percent, while sites with high vegetation cover were dominated by invasive, non-native species. Using satellite-based Landsat time series analysis, the scientists looked at three to six years of vegetation regrowth at 365 well sites in Utah, Colorado, and New Mexico, drilled in 1985 or after and abandoned in 1997 or after. Vegetation recovery generally slowed over time and was related to moisture conditions year to year. Recovery was lower on abandoned well sites in shrublands or evergreen woodlands, which produced only about half the regrowth of well sites in grasslands. The grassland recovery, however, was dominated by invasive annuals such as cheatgrass and Russian thistle. There are currently over 26,000 abandoned and 63,000 active well pads on the Colorado Plateau.[1432]

- July 17, 2018 – A simulation study that applied actual fracking wastewater to local soils in the Denver area investigated how fracking spills might affect the growth of crops. Spills of fracking wastewater resulted in metal contamination at environmentally relevant concentrations as well as a dramatic decrease in water infiltration rate in ways that could have "severe impact on crop production."[1433] Many of the metals studied, including copper, lead, and iron, "met or approached water quality standards and could have important environmental and human health impacts."

- April 13, 2018 – Grasslands and row crop habitats were most affected in a predictive modeling study of vegetation conversion and landscape fragmentation that would result from future drilling and associated well pad construction in the Eagle Ford Shale. The study, which used "energy production outlook" predictions, found that these impacts increased in spatial extent and magnitude as oil prices increased. The study anticipated that up to 83,000 wells would be drilled through the year 2045 and include as many as 45,500 well pads. In this scenario, between 26,485 and 70,623 hectares (65,446 to 174,513 acres) would undergo vegetative conversion. These results are consistent with findings from related studies. The authors cautioned that their model did not include

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[1431] Reid Frazier, "Bringing the Forest Back after Shale Gas," *State Impact Pennsylvania*, September 7, 2018, https://stateimpact.npr.org/pennsylvania/2018/09/07/bringing-the-forest-back-after-shale-gas/.
[1432] Eric K. Waller et al., "Landsat Time Series Analysis of Fractional Plant Cover Changes on Abandoned Energy Development Sites," *International Journal of Applied Earth Observation and Geoinformation* 73 (2018): 407–19, https://doi.org/10.1016/j.jag.2018.07.008.
[1433] Karl Oetjen et al., "Simulation of a Hydraulic Fracturing Wastewater Surface Spill on Agricultural Soil," *Science of The Total Environment* 645 (2018): 229–34, https://doi.org/10.1016/j.scitotenv.2018.07.043.

future locations of associated infrastructure, such as surface water impoundments and compressor stations. If they were included, "doubling land-change results of this study… would result in a reasonable estimate of overall footprint of all hydrocarbon extractive infrastructure."[1434]

- July 20, 2017 – Penn State Unversity researchers identified a direct correlation between the spread of invasive, non-native plants in Pennsylvania's northern forests and specific aspects of fracking operations. Researchers surveyed 127 Marcellus Shale gas well pads and adjacent access roads in seven state forest districts in the Allegheny National Forest. The study "found that within less than a decade invasive non-native plants have spread to over half of the 127 well pads in our survey, and for the 85% of the pads that were less than 4 years old it occurred in a much shorter period of time." Gravel shipments and mud on the tires and undercarriages of trucks carry and deposit seeds and propagules of invasive plants. "Given the fact that on average 1235 one-way truck trips delivering fracturing fluid and proppant are required to complete an unconventional well, the potential to transport invasive plant propagules is significant."[1435] "The spread of invasive non-native plants could have long-term negative consequences for the forest ecosystem in a region where the ubiquitous woods provide timbering revenue, wildlife habitat, and ecotourism, warns team member David Mortensen, professor of weed and applied plant ecology."[1436]

- May 15, 2017 – By 2015, the annual ecological cost of fracking in the United States reached over $272 million per year, according to a team of biologists from Hendrix College in Arkansas. They reached this value by estimating the impact of land-use changes on "ecosystem services," the benefits that natural habitats provide to humans, such as carbon sequestration, flood mitigation, food security, ecotourism revenue, and genetic diversity. Authors considered this estimate to be conservative. In addition, they wrote, "[d]epending on future well-drilling rates, cumulative ecosystem services costs projected to the year 2040 range from US$9.4 billion to US$31.9 billion." Their results showed, "that temperate grassland and deciduous forest are being disproportionately impacted by unconventional oil and gas development. Temperate grasslands are some of the most imperiled ecosystems in North America." They found "considerable variation in ecosystem services costs between different plays, with Haynesville, Bakken/Three Forks, and Fayetteville showing the highest annual costs."[1437]

[1434] Brad D. Wolaver et al., "An Improved Approach for Forecasting Ecological Impacts from Future Drilling in Unconventional Shale Oil and Gas Plays," *Environmental Management* 62, no. 2 (2018): 323–33, https://doi.org/10.1007/s00267-018-1042-5.
[1435] Kathryn M. Barlow et al., "Unconventional Gas Development Facilitates Plant Invasions," *Journal of Environmental Management* 202 (2017): 208–16, https://doi.org/10.1016/j.jenvman.2017.07.005.
[1436] Jeff Mulhollem, "Shale Gas Development Spurring Spread of Invasive Plants in Pa. Forests | Penn State University," *Penn State News*, July 20, 2017, https://news.psu.edu/story/475225/2017/07/20/research/shale-gas-development-spurring-spread-invasive-plants-pa-forests.
[1437] Matthew D Moran et al., "Land-Use and Ecosystem Services Costs of Unconventional US Oil and Gas Development," *Frontiers in Ecology and the Environment* 15, no. 5 (2017): 237–42, https://doi.org/10.1002/fee.1492.

- April 2, 2017 – Nearly four percent of "core forest" was lost within six years of shale gas development in Lycoming County, Pennsylvania, from 2010 to 2016. Pipelines were the largest contributor to the industry's spatial footprint and were identified as the major fragmenting feature. "Linear infrastructure" (pipelines and roads) led to 3.2 percent loss of core forest, whereas well pad infrastructure (well pad, water impoundment, compressor station, etc.) resulted in 0.9 percent loss of core forests. "Limiting loss of core forest and fragmentation is of particular importance in Pennsylvania and central Appalachia due to potential impacts to area sensitive species."[1438]

- November 29, 2016 – A study by engineers and environmental scientists from China, the U.K., and the Republic of Korea investigated the impact of contaminated fracking flowback water on soil health, using soils from representative shale gas areas in China. They also performed a preliminary human health risk assessment of exposure to the arsenic found in such soils. The solutions they tested were representative of flowback water from various stages following a fracked well's establishment, and their study found that the temporal change in the composition of these wastewaters "leads to different environmental implications." They tested heavy metal mobility and bioaccessibility, finding that even though mobility was reduced by high ionic strength of flowback water, the metals maintained relatively high bioaccessibility. Soil toxicity moderately increased after a month "aging" with the flowback water treatment. Arensic, one of the metals included in the testing, is a known human carcinogen and therefore the focus of the human health risk assessment. Results indicated "a low level of cancer risk through exposure via ingestion."[1439]

- October 4, 2016 – A research team from Lawrence Berkeley National Laboratory, University of California Berkeley, and University of the Pacific released preliminary results from a first-ever hazard assessment of chemicals used in California oil drilling operations that reuse wastewater for livestock watering and other agricultural purposes in the San Joaquin Valley. This evaluation, compiled as a technical report by PSE Healthy Energy and Lawrence Berkeley National Laboratory, revealed that more than one-third of the 173 chemicals used are classified as trade secret and their identities are therefore unknown. Of the remainder, ten are classified as either carcinogenic or possibly carcinogenic in humans, 22 are classified by the state of California as toxic air contaminants, and 14 had no ecotoxicity or mammalian toxicity data available. "It is difficult or impossible to estimate risks to consumers, farmworkers or the environment," the authors concluded, "when identification of chemical additives remains in trade secret form and/or lacks toxicity and environmental profile information."[1440]

[1438] Lillie A. Langlois, Patrick J. Drohan, and Margaret C. Brittingham, "Linear Infrastructure Drives Habitat Conversion and Forest Fragmentation Associated with Marcellus Shale Gas Development in a Forested Landscape," *Journal of Environmental Management* 197 (2017): 167–76, https://doi.org/10.1016/j.jenvman.2017.03.045.
[1439] Season S. Chen et al., "Potential Impact of Flowback Water from Hydraulic Fracturing on Agricultural Soil Quality: Metal/Metalloid Bioaccessibility, Microtox Bioassay, and Enzyme Activities," *Science of The Total Environment* 579 (2017): 1419–26, https://doi.org/10.1016/j.scitotenv.2016.11.141.
[1440] Seth B. C. Shonkoff, William T. Stringfellow, and Jeremy K. Domen, "Hazard Assessment of Chemical Additives Used in Oil Fields That Reuse Produced Water for Agricultural Irrigation, Livestock Watering, and Groundwater Recharge in The San Joaquin Valley of California: Preliminary Results," Technical Report (PSE

- June 1, 2016 – "Co-contaminant interaction effects" can occur when multiple chemicals are involved in spills of oil and gas wastewater on agricultural soils, according to a study by a Colorado State University research team. Through simulations, researchers analyzed how degradation was affected when combinations of three fracking-related organic chemicals spilled, alone or together: polyethylene glycol, a commonly used surfactant; glutaraldehyde, a biocide to prevent pipe corrosion from microbial activity; and polyacrylamide, a friction reducer. In addition to interactions between the chemicals, they analyzed the role of naturally occurring salts. Results showed that polyethylene glycol surfactants alone can break down in topsoil within 42−71 days, but, in the presence of the biocide glutaraldehyde or salt concentrations typical of fracking wastewater, their biodegradation was impeded or halted altogether. Authors emphasized that the interactions they studied account for only a fraction of the hundreds of fracking chemicals in use, but that their results "show a complex picture of co-contaminant fate and toxicity" that has, so far, been ignored.in the regulatory process.[1441]

- December 12, 2015 – A research team at the University of Aberdeen found high levels of selenium, molybdenum, and arsenic in rock samples collected from a region in northern England that has been targeted for fracking. The finding is important due to the possible risk that these toxic elements will be released into groundwater during shale gas operations. Selenium poisoning has occurred among Irish horses confined to pastures underlain by black shale. While small amounts of selenium are essential for metabolism, high levels (which, in the case of human consumption, is above 400 μg/day) are toxic. Possible consequences include neurotoxicity, cancer and diabetes."[1442]

- November 23, 2015 – Gas-related impacts on Pennsylvania farmers may include pipelines criss-crossing fields and forests, as well as jeopardization of organic certification, according to a report covering a State Agriculture Department spokesman's presentation, on the Potter County government website. The spokesman said, "steps should be taken to steer this development in ways that diminish impact on soil quality and fragmentation." "With trees and other vegetation being cleared from pipeline rights-of-way, he noted, it's important for the acreage to be replanted with plant species that are beneficial to agriculture—pollinating plants, as an example."[1443]

- October 25, 2015 – More than 180 million gallons of wastewater from oil and gas operations spilled from 2009 to 2014, according to an Associated Press analysis of data

Healthy Energy, September 2016), https://www.psehealthyenergy.org/wp-content/uploads/2017/04/Preliminary_Results_13267_Disclosures_FINAL-1.pdf.

[1441] Molly C. McLaughlin, Thomas Borch, and Jens Blotevogel, "Spills of Hydraulic Fracturing Chemicals on Agricultural Topsoil: Biodegradation, Sorption, and Co-Contaminant Interactions," *Environmental Science & Technology* 50, no. 11 (2016): 6071–78, https://doi.org/10.1021/acs.est.6b00240.

[1442] John Parnell et al., "Selenium Enrichment in Carboniferous Shales, Britain and Ireland: Problem or Opportunity for Shale Gas Extraction?," *Applied Geochemistry* 66 (2016): 82–87, https://doi.org/10.1016/j.apgeochem.2015.12.008.

[1443] Potter County Today, "Shale Gas Impact on Agriculture 'Profound,'" November 23, 2015, https://web.archive.org/web/20151206011350/http://today.pottercountypa.net/shale-gas-impact-on-agriculture-profound/.

from leading oil- and gas-producing states (Texas, North Dakota, California, Alaska, Colorado, New Mexico, Oklahoma, Wyoming, Kansas, Utah and Montana). A *Dallas Morning News* report focused on how the resulting contamination of groundwater and soils has affected agricultural and ranching. In one case, wastewater from pits seeped beneath a cotton and nut farm near Bakersfield, California and forced the grower to remove 2,000 acres from production. In western Texas, pipeline failures and illegal dumping of frack waste contaminated ranches and pastures.[1444]

- May 2, 2015 – The *Los Angeles Times* reported that farmers in Kern County, California purchased over 21 million gallons per day of treated oil field wastewater to use for crop irrigation. The article identified lingering questions about chemicals remaining after treatment and their potential impact both on the crops and those who consume them. Independent testing identified chemicals including acetone and methylene chloride, along with oil, in the treated irrigation water.[1445] Acetone and methylene chloride are powerful industrial solvents that are highly toxic to humans, and samples of the wastewater contained concentrations of both that were higher than those seen at oil spill disaster sites. (Chevron's own report confirmed the presence of acetone, benzene, and xylene, though in lesser concentrations; Chevron did not appear to test for methylene chloride.[1446]) Broader testing requirements involving chemicals covered under California's new fracking disclosure regulations went into effect June 15, 2015.[1447]

- April 24, 2015 – Unconventional technologies in gas and oil extraction facilitated the drilling of an average of 50,000 new fractured wells per year in North America over the past 15 years. An interdisciplinary study published in *Science* demonstrated that the accumulating land degradation has resulted in continent-wide impacts, as measured by the reduced amount of carbon absorbed by plants and accumulated as biomass. This is a robust metric of essential ecosystem services, such as food production, biodiversity, and wildlife habitat, and its loss "is likely long-lasting and potentially permanent." The land area occupied by well pads, roads, and storage facilities built during this period is approximately three million hectares, roughly the land area of three Yellowstone National Parks. The authors concluded that new approaches to land use planning and policy are "necessary to achieve energy policies that minimize ecosystem service losses."[1448]

- January 26, 2015 – Two Colorado scientists performed a detailed analysis of vegetative patterns—followed chronologically—over a selected group of well pads in Colorado

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[1444] J. Flesher, "Fatal Flow: Brine from Oil, Gas Drilling Fouls Land, Kills Wildlife at Alarming Rate," *The Dallas Morning News*, October 25, 2015, sec. News, https://www.dallasnews.com/news/2015/10/25/fatal-flow-brine-from-oil-gas-drilling-fouls-land-kills-wildlife-at-alarming-rate/.
[1445] Julie Cart, "Central Valley's Growing Concern: Crops Raised with Oil Field Water," *Los Angeles Times*, May 2, 2015, sec. California, https://www.latimes.com/local/california/la-me-drought-oil-water-20150503-story.html.
[1446] Amec Foster Wheeler Environment & Infrastructure, Inc., "Reclaimed Water Impoundments Sampling, Cawelo Water District Ponds, Kern River Oil Field, Kern County, California, Prepared for Chevron U.S.A. Inc.," Technical Report, June 15, 2015.
[1447] Daniel Ross, "Has Our Food Been Contaminated by Chevron's Wastewater?," *Truthout*, June 19, 2015, sec. Environment, https://truthout.org/articles/has-our-food-been-contaminated-by-chevron-s-wastewater/.
[1448] B. W. Allred et al., "Ecosystem Services Lost to Oil and Gas in North America," *Science* 348, no. 6233 (2015): 401–2, https://doi.org/10.1126/science.aaa4785.

managed by the U.S. Bureau of Land Management, including two undisturbed reference sites. They documented the disturbance of plant and soil systems linked to contemporary oil and gas well pad construction, and found that none of the oil and gas well pads included in the study returned to pre-drilling condition, even after 20-50 years. Full restoration may require decades of intensive effort.[1449]

- October 14, 2014 – State documents obtained by the Center for Biological Diversity show that almost three billion gallons of fracking wastewater have been illegally dumped into central California aquifers that supply drinking water and farming irrigation. The California Water Board confirmed that several oil companies used at least nine of 11 injection wells that connect with high-quality water sources for disposal of fracking wastewater, which included high levels of arsenic, thallium, and nitrates. The California Division of Oil, Gas and Geothermal Resources has shut down 11 oil field injection wells and is scrutinizing almost 100 others for posing a "danger to life, health, property, and natural resources." At least one farming company has sued oil producers in part for contaminating groundwater that farms use for irrigation.[1450]

- September 6, 2014 – *Al Jazeera America* examined the challenges that North Dakota farmers are facing in light of wastewater spills from oil and gas development. Notably, in heavily drilled Bottineau County, some levels of chloride, from sites where an estimated 16,800-25,200 gallons of wastewater had seeped into the ground, were so high that they exceeded the levels measurable with the North Dakota Department of Health's test strips. State records, testimonies from oil workers and various residents, and the decades-long failure of contaminated fields to produce crops indicate that wastewater spills are a significant hazard in the current fracking boom.[1451]

- August 6, 2014 – The Pennsylvania Department of Environmental Protection (PA DEP) found that leaks of fracking wastewater from three impoundments contaminated soil and groundwater. The findings prompted the state to issue a violation and increase testing.[1452]

- August 5, 2014 – Michelle Bamberger, a veterinarian and researcher, and Robert Oswald, a professor of molecular medicine at Cornell University, published a book that describes their research into the impacts of drilling and fracking on agriculture and animal health. They detail results of 24 case studies from six gas drilling states, including follow-up on

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[1449] Tamera J. Minnick and Richard D. Alward, "Plant–Soil Feedbacks and the Partial Recovery of Soil Spatial Patterns on Abandoned Well Pads in a Sagebrush Shrubland," *Ecological Applications* 25, no. 1 (2015): 3–10, https://doi.org/10.1890/13-1698.1.
[1450] Sandy Dechert, "Fracking Wastewater Spoils California Drinking, Farm Supplies," CleanTechnica, October 14, 2014, https://cleantechnica.com/2014/10/14/fracking-wastewater-spoils-california-drinking-farm-supplies/.
[1451] Laura Gottesdiener, "In Shadow of Oil Boom, North Dakota Farmers Fight Contamination," *Al Jazeera America*, September 6, 2014, http://america.aljazeera.com/articles/2014/9/6/north-dakota-wastewaterlegacy.html.
[1452] Don Hopey, "State: Fracking Waste Tainted Groundwater, Soil at Three Washington County Sites," *Pittsburgh Post-Gazette*, August 6, 2014, https://www.post-gazette.com/local/washington/2014/08/06/Pa-finds-tainted-water-soil-at-three-Washington-County-shale-sites/stories/201408050198.

cases they previously published in the peer-reviewed literature, raising concerns about the effects of drilling and fracking on agriculture and the health of animals.[1453]

- August 1, 2014 – At least 19,000 gallons of hydrochloric acid spilled during completion of a fracking well on an alfalfa farm in Kingfisher County, Oklahoma. The Oklahoma Corporation Commission reported concerns about rain pushing chemical runoff into a nearby creek that flows into the town of Hennessey's water system. The responsible company, Blake Production, planned to pay for the alfalfa crop for six years. The landowner and a neighbor were pursuing litigation.[1454]

- May 3, 2014 – In an analysis of state data from Colorado, the *Denver Post* reported that fracking related to oil and gas drilling is putting soil quality and farmlands at risk due to significant amounts of toxic fluids penetrating the soil. According to report, 578 spills were reported in 2013, which means that, on average in the state, a gallon of toxic liquid penetrates the ground every eight minutes. Colorado State University soil scientist Eugene Kelly, said that the overall impact of the oil and gas boom "is like a death sentence for soil."[1455]

- November 28, 2012 – In conjunction with the Food & Environment Reporting Network, *The Nation* reported that serious risks to agriculture caused by fracking are increasing across the country and linked these concerns to risks to human health.[1456]

- January 2012 – A study of gas drilling's impacts on human and animal health concluded that the drilling process may lead to health problems. The study reported and analyzed a number of case studies, including dead and sick animals in several states that had been exposed to drilling or hydraulic fracturing fluids, wastewater, or contaminated ground or surface water.[1457] The researchers cited 24 cases in six states where animals and their owners were potentially affected by gas drilling. In one case, a farmer separated 96 head of cattle into three areas, one along a creek where fracking wastewater was allegedly dumped and the remainder in fields without access to the contaminated creek; the farmer found that, of the 60 head exposed to the creek, 21 died and 16 failed to produce, whereas the unexposed cattle experienced no unusual health problems. In another case, a farmer reported that of 140 head of cattle exposed to fracking wastewater, about 70 died, and there was a high incidence of stillborn and stunted calves in the remaining cattle.[1458]

[1453] Michelle Bamberger and Robert Oswald, *The Real Cost Of Fracking: How America's Shale Gas Boom Is Threatening Our Families, Pets, and Food* (Beacon Press, 2015).
[1454] Kim Passoth, "Major Oil Field Spill in Kingfisher Co.," *KOCO News 5 ABC*, August 2, 2014, sec. News, https://www.koco.com/article/major-oil-field-spill-in-kingfisher-co/4299547.
[1455] Bruce Finley, "Colorado Faces Oil Boom 'Death Sentence' for Soil, Eyes Microbe Fix," *The Denver Post*, May 3, 2014, https://www.denverpost.com/2014/05/03/colorado-faces-oil-boom-death-sentence-for-soil-eyes-microbe-fix/.
[1456] Elizabeth Royte, "Fracking Our Food Supply," *The Nation*, November 28, 2012, https://www.thenation.com/article/archive/fracking-our-food-supply/.
[1457] Michelle Bamberger and Robert E. Oswald, "Impacts of Gas Drilling on Human and Animal Health," *New Solutions: A Journal of Environmental and Occupational Health Policy* 22, no. 1 (2012): 51–77, https://doi.org/10.2190/NS.22.1.e.
[1458] Krishna Ramanujan, "Study Suggests Hydrofracking Is Killing Farm Animals, Pets," *Cornell Chronicle*, March 7, 2012, https://news.cornell.edu/stories/2012/03/reproductive-problems-death-animals-exposed-fracking.

- January 2011 – U.S. Forest Service researchers reported dramatic negative effects on vegetation caused by the drilling and fracking of a natural gas well in an experimental forest in northeastern West Virginia. In June 2008, the researchers found browning of foliage near the well pad, a lack of ground foliage, and that many trees nearby had dropped their foliage. They attributed these impacts to the loss of control of the wellbore on May 29, 2008, which caused an aerial release of materials from the well. Trees showed no apparent symptoms the following summer. However, the researchers also found "dramatic impacts on vegetation" where drilling and fracking wastewater had been sprayed on the land as a disposal technique following completion of the well. Just after the spraying of approximately 60,000 gallons of wastewater at the first disposal site, the Forest Service researchers found 115 damaged trees and other evidence of harm. This figure grew to 147 trees almost a year later. At a second site, where about 20,000 gallons of wastewater was sprayed, the damage was less dramatic, yet the researchers still found "considerable leaf browning and mortality of young northern red oak seedlings." The researchers concluded that the spraying of the drilling fluids resulted in an "extreme" dose of chlorides to the forest.[1459]

- May 2010 – Pennsylvania's Department of Agriculture quarantined 28 cows in Tioga County after the animals wandered through a spill of drilling wastewater and may have ingested some of it. The Department was concerned that beef eventually produced from the cows could be contaminated as a result of any exposure. In May 2011, only ten yearlings were still quarantined, but the farmer who owned the cows, Carol Johnson, told National Public Radio that of 17 calves born to the quarantined cows in the spring of 2011, only six survived, and many of the calves that were lost were stillborn. "They were born dead or extremely weak. It's highly unusual," she said, continuing, "I might lose one or two calves a year, but I don't lose eight out of eleven."[1460]

- March 2010 – A Pennsylvania State Extension analysis of dairy farms in the state found a decline in the number of dairy cows in areas where fracking was prevalent. Pennsylvania counties that had both more than 10,000 dairy cows and more than 150 Marcellus Shale wells experienced a 16-percent decline in dairy cows between 2007 and 2010.[1461]

- April 28, 2009 – Seventeen cows in Caddo Parish, Louisiana died within one hour after apparently ingesting hydraulic fracturing fluids spilled at a well that was being fractured. "It seemed obvious the cattle had died acutely from an ingested toxin that had drained from the 'fracking' operation going on at the property," Mike Barrington, a state veterinarian said in a document obtained from the state Department of Environmental

[1459] Mary Beth Adams et al., "Effects of Development of a Natural Gas Well and Associated Pipeline on the Natural and Scientific Resources of the Fernow Experimental Forest," General Technical (U.S. Department of Agriculture, January 2011), https://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs76.pdf.
[1460] Susan Phillips, "Burning Questions: Quarantined Cows Give Birth to Dead Calves," *State Impact Pennsylvania*, September 27, 2011, https://stateimpact.npr.org/pennsylvania/2011/09/27/burning-questions-quarantined-cows-give-birth-to-dead-calves/.
[1461] Penn State Extension, "Pennsylvania Dairy Farms and Marcellus Shale, 2007-2010," *Penn State Extension*, March 2010, https://extension.psu.edu/pennsylvania-dairy-farms-and-marcellus-shale-2007-2010.

Quality by the *Times-Picayune*.[1462, 1463]

- August 1977 – A paper in the *Journal of Arboriculture* described how natural gas leaks in soil can damage plants and crops. The paper notes that vegetation dies in the vicinity of natural gas leaks. Due to the oxidation of methane by methane-consuming bacteria, gas leaks drive down the oxygen concentration to extremely low levels and cause carbon dioxide concentration to rise. The resulting low oxygen concentration is the greatest contributing factor in the death of trees and other vegetation near natural gas leaks.[1464]

1462 KSLA, "Cows in Caddo Parish Fall Dead near Gas Well," *KSLA News*, April 29, 2009, https://www.ksla.com/story/10268585/cows-in-caddo-parish-fall-dead-near-gas-well/.
1463 Mark Schleifstein, "Haynesville Natural Gas Field Is the Most Productive in the U.S.," *The New Orleans Advocate*, March 27, 2011, https://www.nola.com/news/politics/article_fbdcb467-382d-52a8-90e7-7dc667edecb4.html.
1464 Spencer H. Davis Jr., "The Effect of Natural Gas on Trees and Other Vegetation," *Journal of Arboriculture* 3, no. 8 (1977): 153–54.

Threats to the climate system

Natural gas is not a climate-friendly fuel. Methane, which escapes from all parts of the natural gas extraction and distribution system, is a powerful greenhouse gas that traps 86 times more heat than carbon dioxide over a 20-year time frame. According to the best available evidence, fuel-switching that replaces coal with natural gas to generate electricity offers no clear climate benefits and likely represents a step backwards. As is now documented in many studies, fugitive methane emissions from U.S. drilling and fracking operations, storage, and ancillary infrastructure are omnipresent and much higher than previously supposed. The science is settled on these facts.

A significant proportion of these methane leaks are not preventable through engineering fixes. Indeed, some represent intentional venting during routine maintenance or during attempts to control pressure and prevent explosions during malfunctions. Venting takes place at all points along the supply chain, from well pads, pipelines, and compressor stations to liquefied natural gas (LNG) export terminals. Storage tanks, compressor stations, and unlit flare stacks are emerging as significant sources of methane emissions, according to 2021 studies published in both Canada and the United States. The problem of methane leakage appears to be getting worse rather than better with newer fracking sites in the Permian Basin leaking more methane than older sites. A 2018 analysis of methane emissions from the U.S. oil and gas supply chain that used a combination of measurement methodologies found leakage rates 60 percent higher than reported by the U.S. Environmental Protection Agency (EPA) and concluded that natural gas is just as damaging as coal for the climate over a 20-year time frame. Collectively, a range of studies disprove the claim that natural gas is a transitional "bridge" fuel that can lower greenhouse gas emissions while renewable energy solutions are developed.

A sharp rise in global atmospheric methane concentrations began in 2007 and has accelerated since 2014. The causes for this spike are not yet fully understood and likely include both biogenic sources (livestock, agriculture, wetlands, landfills, forest fires) and fossil fuel sources. As both satellite and ground measurements reveal, U.S. methane emissions are responsible for 30-60 percent of the recent upsurge in global atmospheric methane concentrations. Most of this excess methane appears to represent fugitive emissions from U.S. oil and gas operations, which underwent its own surge in activity during the same time period.

Although the science is not yet settled on the relative importance of the various sources of this methane, several lines of evidence point to the important role of drilling and fracking operations in driving greenhouse gas emissions upward. These include the atmospheric pattern of increased methane concentrations directly over intensively fracked areas of the United States; sharp upticks in global methane and co-occurring ethane levels that correspond to the advent of the U.S. shale gas and oil boom; and documentation of large pulses of methane released from storage facilities and other "super-emitting" sites. A major study from the National Aeronautics and Space Administration (NASA) in 2017 found that methane from biomass sources, such as fires, decreased over the time period 2001-2016 while fossil fuel sources of methane increased. Reducing atmospheric methane is key to reducing the rate of global warming and limiting temperature rise to 1.5 ^{o} C according to a May 2021 assessment from the United Nations, which identified the fossil fuel industry as the sector with the greatest potential to cut methane emissions rapidly.

The widely touted claim that the U.S. shale gas and oil boom has contributed to recent declines in carbon dioxide emissions in the United States has been invalidated by research showing that almost all the reductions in CO_2 emissions between 2007 and 2009 were the result of economic recession rather than coal-to-gas fuel switching. Other lines of research show that expanded use of natural gas impedes rather than encourages investments in, and deployment of, renewable energy infrastructure. In sum, fracking, which enables the extraction of oil and gas from shale, is a major driver of rising methane emissions, is incompatible with climate stability, and stands as an obstacle to rapid decarbonization that the goal of climate stability requires.

- July 12, 2021 – Combining two different methods of measurement, Canadian researchers found that methane emissions from oil and gas extraction operations in British Columbia are 1.6 to 2.2 times higher than estimated by Canada's current federal inventory. Their results showed that more than half of emissions could be attributed to three main sources: tanks (24 percent); compressors (15 percent); and unlit flares (13 percent). The researchers wrote, "In particular, tank emissions appear much more important than current inventories suggest and unlit flares are a second important gap, bolstering observations from recent helicopter measurements in the Permian basin." This new combined-measurement approach, which matched optical gas imaging (OGI) cameras on the ground with aerial surveys, greatly improved accuracies in sites where OGI surveys alone are unreliable. Total emissions measured by the aerial survey were 18 times higher than those recorded by the OGI cameras. In the case of leaking tanks, for example, disparities between ground and aerial measurements of methane emission rates differ by a factor of more than 40: whereas the ground survey mean rate, as estimated by OGI, was 1.3 kg/h, the rate estimated by aerial surveys was 48.3 kg/h. Further, methane emissions from unlit flairs are inherently difficult to capture by OGI camera, and this study's aerial measurements showed that they were a significant contributor to methane emissions. Similarly, the study found that "unburned methane entrained in natural gas engine-driven compressor exhaust," also not easily measurable with OGI, is responsible for much of the total emissions at compressor stations. Conversely, the aerial survey identified 10-fold fewer total sources of emissions than did OGI, suggesting that the two methodologies are prone to different types of inaccuracies in data collection. The research team concluded that "policy and regulations that rely on OGI surveys alone risk missing a significant portion of total emissions."[1465]

- June 30, 2021 – The Permian Basin is now the largest oil and gas-producing basin in the United States. Using high-resolution satellite measurements collected over several days, an international team of researchers identified 37 different "extreme" methane plumes (that is, those emitting more than 500 kg of methane per hour) and attributed them to specific types of infrastructure. The results showed that newer facilities—those starting production in 2018 or later—contributed more extreme emissions than older facilities. Specifically, extreme emissions occurred 2.6 times more frequently for new facilities

[1465] David R. Tyner and Matthew R. Johnson, "Where the Methane Is: Insights from Novel Airborne LiDAR Measurements Combined with Ground Survey Data," *Environmental Science & Technology* 55 (2021): 9773–83, https://doi.org/10.1021/acs.est.1c01572.

than old, and the amount of methane emitted by new facilities is twice that of older facilities. "This result supports the speculation that recently developed wells and infrastructure associated with these wells are the major methane emitters in the Permian basin, which is likely due to a faster development of gas extraction methods than of storage and processing capabilities." The results showed that fully half of all methane emissions originated from compressor stations, 24 percent from tank batteries, 21 percent from flaring, and 6 percent from wells themselves. The high proportion of emissions (21 percent in terms of both number of plumes and amount of methane emitted) that come from flare stacks was a surprising discovery. "Such high emission rates can only be explained by inefficient or malfunctioning flaring operations…. Our results suggest that the rapid installation of new O&G production facilities in the Permian basin might not be counterbalanced by sufficient parallel development of gas gathering and processing infrastructure, which would lead to a high concentration of extreme emissions in the region due to issues such as unlit associated gas flares."[1466]

- June 24, 2021 – At least 123 oil and gas sites in Austria, Czech Republic, Germany, Hungary, Italy, Poland and Romania emit methane, according to data released by the international nonprofit organization Clean Air Task Force (CATF) and reported by Reuters. At the time of reporting, the European Union did not regulate methane leaks and vents to the atmosphere and reporting requirements were limited to only some of the individual nation states. Hence, no laws were broken by companies responsible for these emissions. According to James Turitto, who filmed the emissions for CATF, 90 percent of the sites visited in the Czech Republic, Hungary, Italy, Poland, and Romania were emitting methane, while the frequency of leaking sites in Germany and Austria was lower. Using independent experts to review a selection of the CATF infrared thermography, Reuters reported that a significant proportion of these emissions was avoidable with commercially available measurement and abatement technology. While the omnipresence of leaks in Europe's gas system currently resembles that of the United States, said Reuters, proposed EU restrictions on venting and flaring methane have put energy companies on notice. These rules will not go into force until 2023 or thereafter.[1467]

- June 15, 2021 – Newly launched and soon to be deployed satellites will continue to sharpen identification of methane leaks from oil and gas operations, filling gaps left by ground-based sensors and aerial surveys, according to an analysis by *Yale Environment 360*. While earlier generations of satellites were consistently unable to link specific sources with emissions data, newer satellites have been able, despite the pandemic, to match recent rises in methane releases to their origins in Russia, Turkmenistan, and Canada.[1468]

[1466] Itziar Irakulis-Loitxate et al., "Satellite-Based Survey of Extreme Methane Emissions in the Permian Basin," *Science Advances* 7, no. 27 (2021): eabf4507, https://doi.org/10.1126/sciadv.abf4507.
[1467] Kate Abnett and Shadia Nasralla, "EXCLUSIVE: Gas Infrastructure Across Europe Leaking Planet-Alarming Methane," Reuters, June 24, 2021, https://www.reuters.com/business/environment/exclusive-gas-infrastructure-across-europe-leaking-planet-warming-methane-video-2021-06-24/.
[1468] Cheryl Katz, "In Push to Find Methane Leaks, Satellites Gear Up for the Hunt," Yale Environment 360, June 15, 2021, https://e360.yale.edu/features/in-push-to-find-methane-leaks-satellites-gear-up-for-the-hunt.

- June 2, 2021 – A report funded by Bank of America and developed by the energy consultancy M.J. Bradley & Associates—in collaboration with the non-profit organizations Ceres and the Clean Air Task Force—looked at the relationship between methane emissions and oil and gas extraction volumes. An analysis of 295 oil and gas producers that report data to the EPA under its Greenhouse Gas Reporting Program showed that the magnitude of methane emissions was not a function of a company's production levels.[1469] Indeed, the largest methane emitter in the United States, Hilcorp Energy, emitted 50 percent more methane from its operations than did Exxon Mobil, even though Hilcorp pumps far less oil and gas. Four other relatively unknown companies—Terra Energy Partners, Flywheel Energy, Blackbeard Operating and Scout Energy—each self-reported more methane emissions than many top producers. As further described in reporting by the *New York Times* small, privately held drilling companies that are buying up high-polluting assets from larger companies are rapidly becoming the nation's highest emitters of methane and other greenhouse gases. In this way, oil and gas majors are able to remove highly leaky facilities from their books. "Hilcorp's methane emissions intensity, or leak rate, was almost six times higher than the average of the top 30 producers, largely caused by high emissions from its aging San Juan operations."[1470]

- June 1, 2021 – After a brief pandemic-related drop, fracking activities in the Permian Basin in West Texas once again rebounded and now represent the number one source of methane emissions in the United States. Continued expansion of these operations threatens "any credible US response to the climate crisis," according to investigative reporter Rebecca Leber, who described several formidable obstacles to reining in this "ticking time bomb." Sited on land entirely state-owned or privately held, Permian Basin fracking operations are not governed by future regulations that might restrict new federal leasing. Further, economic incentives do not constrain methane emissions. Permian producers, for whom oil brings a bigger profit, largely consider natural gas a waste product and, hence, intentionally release methane via unlit or burning flares in the absence of any state-based regulation. Leber notes that the EPA could be authorized to intervene but has limited resources for doing so. Another strategy, which goes beyond limiting emissions to addressing production, seeks to interrupt industry's export plans, on which the industry is relying in light of US market "saturation." Declaring a climate emergency, Leber wrote, may be the federal administration's only option to "cut off producers from their global customers" if Congress does not enact appropriate climate measures. "There is a narrow pathway to do this. In 2015, Congress lifted a crude-oil export ban but kept a 'get-out' clause. It allows a president to suspend these exports by declaring a national emergency. Other kinds of exports, like liquefied natural gas, would require permitting from FERC, an independent energy regulatory agency, and the Department of Energy."[1471]

[1469] Robert LaCount et al., "Benchmarking Methane and Other GHG Emissions of Oil & Natural Gas Production in the United States" (M.J. Bradley & Associates, June 2021), https://www.mjbradley.com/sites/default/files/OilandGas_BenchmarkingReport_2021.pdf.
[1470] Hiroko Tabuchi, "Here Are America's Top Methane Emitters. Some Will Surprise You," *The New York Times*, June 2, 2021, https://www.nytimes.com/2021/06/02/climate/biggest-methane-emitters.html?referringSource=articleShare.
[1471] Rebecca Leber, "There's a Ticking Climate Time Bomb in West Texas," *Vox*, June 1, 2021, https://www.vox.com/22407581/gas-texas-biden-climate-change-methane-permian-basin.

- May 27, 2021 – Episodic releases of methane from various types of fracking infrastructure create monitoring challenges. Researchers investigated the potential impact of variations over time in emissions from known "super-emitter" sites by performing 17 methane audits at one such natural gas extraction site over a four-year time period, from 2016 to 2020. Results revealed high temporal variability, with minimum and maximum levels varying by a factor of 560. These results suggest that substantial methane emissions may go undetected by infrequent audits. "These data highlight that single snapshots in time from direct methane quantification audits could significantly overpredict or underpredict methane emissions on an annual basis." The results also highlighted the importance of storage tanks as a potential source of methane emissions. At this super-emitting facility, tank emissions represented the majority of emissions for eight audits (54.7−99.7 percent by mass) and overall represented 91 percent of all measured methane emissions.[1472]

- May 6, 2021 – Reducing atmospheric methane is key to reducing the rate of global warming and limiting temperature rise to 1.5° C, and the fossil fuel industry has the greatest potential to cut methane emissions rapidly, according to the latest United Nations assessment report. The assessment found the fossil fuel industry is responsible for 35 percent of human-caused emissions and identified "readily available targeted measures" that could reduce emissions 30 percent by 2030. The industry could implement up to 80 percent of these measures at negative or low cost. The report states that methane mitigation must take place even alongside decarbonization strategies, and that "expansion of natural gas infrastructure and usage is incompatible with keeping warming to 1.5° C." In addition to the climate-related urgency of reducing this powerful, short-lived climate pollutant, the report points to other reasons for global action on methane, including its contribution to the formation of ground-level ozone. The assessment "found that every million tonnes (Mt) of methane reduced prevents approximately 1,430 annual premature deaths due to ozone globally."[1473]

- May 4, 2021 – A U.S. team of researchers analyzed the climate benefits of rapidly reducing methane emissions across all known sectors, which would improve the ability to limit climate damages in the near term. Using a validated model for assessing greenhouse gas-induced climate change, they found that pursuing all known mitigation measures now could slow the global-mean rate of near-term warming by around 30 percent within the decade and so avoid a quarter of a degree centigrade of additional warming by midcentury. Such an approach would create a path that could prevent a rise in mean global temperatures that would exceed more than half a degree centigrade by end of this century. Conversely, a slow implementation of measures to limit methane may well result in an additional tenth of a degree of warming by midcentury and a five percent faster

[1472] Derek Johnson and Robert Heltzel, "On the Long-Term Temporal Variations in Methane Emissions from an Unconventional Natural Gas Well Site," *ACS Omega* 6, no. 22 (2021): 14200–207, https://doi.org/10.1021/acsomega.1c00874.
[1473] United Nations Environment Programme and Climate and Clean Air Coalition, "Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions" (United Nations Environment Programme, May 2021), https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions.

warming rate when compared to rapid action. Waiting to pursue these measures until midcentury may result in an additional two tenths of a degree centigrade by midcentury and 15 percent faster warming rate. The researchers also note that existing mitigation measures across all sectors (rice, livestock, oil and gas, coal mining, landfills, wastewater), if deployed now, could cut expected 2030 methane emissions in half, with a quarter of these at no net cost. "We find that full deployment of these available mitigation measures by 2030 can slow the rate of global-mean warming over the next few decades by more than 25 percent."[1474]

- April 30, 2021 – In response to announced plans by the Mexican government to reduce oil and gas related methane emissions in the country by 40-45 percent by year 2025 (relative to 2012 levels), a research team used satellite imagery of areas overlying onshore and offshore oil and gas facilities in eastern Mexico to quantify the current magnitude of emissions and better understand the location of their key sources. Data showed substantial methane concentrations along the eastern coastal areas and in Mexico City, with enhanced concentrations of nitrous oxide, attributable to gas flaring, also observed over both onshore and offshore production areas. Estimates of methane emissions from satellite data were nearly double those estimated by ground-based, facilities-level emission inventories. The research team calculated an overall methane loss rate of 4.7 percent for oil and gas extraction operations in eastern Mexico (as compared to a 3.7 percent loss rate in the Texas Permian basin gas and oil fields). High loss rates reveal that Mexico's oil and gas basins have "strong mitigation potential," especially at production sites and processing plants.[1475]

- April 24, 2021 – Reducing methane emissions is required to ward off the worst effects of climate change, according to a *New York Times* review of a forthcoming UN report (see May 6, 2021 entry above). According to the summary obtained by the *Times* in advance, the report will single out the fossil fuel industry as the sector which can make the easiest cuts to methane emissions, at little or no cost. The report will also state that expanding the use of natural gas is very likely incompatible with keeping global warming to 1.5^{o} C.[1476]

- March 22, 2021 – Using satellite observations of atmospheric methane across the entire United States and Mexico, an international team discovered that anthropogenic (human-caused) emissions increased between 2010-2015, rather than decreased, as had been estimated by the EPA. For the oil and gas sector, measured methane emissions were almost twice the level estimated by the EPA's greenhouse gas inventory, with the increase largely driven by the rapid growth of fracking operations in the eastern United States. Emissions from oil and gas production facilities in Mexico were also higher than

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[1474] Ilissa B. Ocko et al., "Acting Rapidly to Deploy Readily Available Methane Mitigation Measures by Sector Can Immediately Slow Global Warming," *Environmental Research Letters* 16, no. 5 (2021): 054042, https://doi.org/10.1088/1748-9326/abf9c8.
[1475] Lu Shen et al., "Unravelling a Large Methane Emission Discrepancy in Mexico Using Satellite Observations," *Remote Sensing of the Environment* 260 (2021), https://doi.org/10.1016/j.rse.2021.112461.
[1476] Hiroko Tabuchi, "Halting the Vast Release of Methane Is Critical for Climate, U.N. Says," *New York Times*, April 24, 2021, https://www.nytimes.com/2021/04/24/climate/methane-leaks-united-nations.html.

in the nationally reported inventory. The discrepancies between satellite-generated estimates in this study and the national inventories are likely due to an undercount of all potential sources of emissions and high variability of leakage rates within those sources.[1477] The EPA calculates total emissions by estimating methane leaks from specific types of processes and equipment and then extrapolating, based on the numbers of pieces of that kind of equipment operating across the country. This method, noted lead author Joannes Maasakkers, "makes it really hard to get estimates for individual facilities because it is hard to take into account every possible source of emission." Maasakkers also emphasized that "we shouldn't wait until we fully understand these emissions to start trying to reduce them."[1478]

- January 26, 2021 – Combining satellite data with estimates of methane emissions as determined by aircraft-based measurements above onshore and offshore facilities in Mexico, an international research team calculated methane leakage rates and compared these findings with estimates from Mexico's national greenhouse gas inventory. Estimates of offshore emissions were an order of magnitude lower than the official inventory estimate, but onshore emission estimates were more than an order of magnitude higher. The results showed that a large proportion of emissions is attributable to flaring. One single facility—an onshore gas-processing complex that receives offshore gas—was responsible for greater emissions than the entirety of the largest offshore production region, "suggesting that offshore-produced associated gas is being transported onshore where it is burned and in the process some released to the atmosphere." The majority of those emissions are from flaring and represents "a substantial waste of gas, enough to cover half the natural gas consumption for the national residential section during 2018." The low combustion efficiency of gas flaring operations also makes them a locally important source of unhealthful air pollutants, including volatile organic compounds, polycyclic aromatic hydrocarbons, carbon monoxide, nitrogen oxides, sulfur oxides, and soot. The researchers urge a greater reliance on empirically estimated methane emissions, along with more effective mitigation policies, especially when communities live in proximity to oil and gas production regions.[1479]

- December 15, 2020 – The U.S. natural gas supply chain is leaking substantially more methane than previously presumed, according to the nonprofit organization Global Energy Monitor's "Gas Index." Compiling data from dozens of studies that have measured methane emissions from all components of the U.S. natural gas system—from oil and gas extraction wells to urban distribution pipelines and within homes and businesses—this analysis calculated full life-cycle methane leakage for 71 U.S. cities. The results showed that, in all cases, methane leakage is more extensive across the system than in many earlier estimates, including the EPA's Greenhouse Gas Inventory, with some cities showing leakage rates over four times higher than EPA estimates. City-

[1477] Joannes D. Maasakkers et al., "2010–2015 North American Methane Emissions, Sectoral Contributions, and Trends: A High-Resolution Inversion of GOSAT Observations of Atmospheric Methane," *Atmospheric Chemistry and Physics* 21 (2021): 4339–56.
[1478] Leah Burrows, "Oil and Natural Gas Production Emit More Methane than Previously Thought," Phys.org, March 26, 2021, https://phys.org/news/2021-03-oil-natural-gas-production-emit.html.
[1479] Daniel Zavala-Araiza et al., "A Tale of Two Regions: Methane Emissions from Oil and Gas Production in Offshore/Onshore Mexico," *Environmental Research Letters* 16 (2021), https://doi.org/10.1088/1748-9326/abceeb.

by-city results highlight where efforts to fix the gas system can be most effective and how cities can achieve large reductions in emissions by switching homes and other buildings from natural gas to electricity, especially for heating systems. "Electrifying building heating would lead to emissions reductions in many cases… replacing gas heaters with efficient electric heat pumps would lead to emissions cuts in every city evaluated." The ten cities with the leakiest gas supplies are Indianapolis, Los Angeles, Phoenix, Miami, Oklahoma City, Orlando, Boston, Little Rock, Reno, and Tampa.[1480]

- November 5, 2020 – Satellite maps compiled in 2014 revealed an anomalous methane hot spot over the intensely drilled and fracked San Juan Basin that straddles the Colorado and New Mexico border. As part of a follow-up study led by the University of Colorado and the National Oceanographic and Atmospheric Administration's Earth System Research Laboratory in Boulder, a research team investigated daily wind patterns in the region and collected both ground-based and airborne atmospheric data on levels of methane, ethane, and other light-chain carbon concentrations to identify and characterized the sources of the emissions. The results revealed that fossil fuel sources are collectively responsible for the vast majority (72-85 percent) of the observed methane and ethane over the San Juan Basin, with emissions from coalbed methane and natural gas operations alone contributing 66-75 percent of the methane in the hot spot and with 75 percent of the detected methane originating from operations in New Mexico. Moreover, ground-based measurements and meteorological data illustrate that local methane sources are especially influencing surface air composition at night and in the early morning "when limited air circulation leads to the pooling of emissions near sources, especially in low elevation portions of the basin." While mean leakage rates appear to be comparable to other basins in the United States, emissions in some parts of the San Juan Basin are essentially trapped due to topography. Noting that the background air quality in and near Durango, Colorado is likely being harmed by emissions from oil and gas operations in the San Juan Basin, these researchers cite the need for "rapid and deep" mitigation, with "much bolder emission cuts necessitating substantial and industry transformations" in order to meet global climate goals.[1481]

- October 15, 2020 – A team led by University of Wyoming researchers determined that methane emissions from oil and gas well pads in the western Permian Basin are 5.5-9.0 times greater the EPA has estimated. Using a mobile laboratory that collects ground-level data, researchers obtained measurements of methane 40-200 meters downwind of 71 oil and gas facilities in the Permian Basin of western Texas and southeastern New Mexico. Methane emissions in the Permian Basin had not previously been studied in ground-based fashion, and most of the basin is difficult to study with aerial approaches. Detailed analysis of the data revealed differences between "simple" sites, with no or minimal processing equipment and storage of liquids on-site, and "complex" sites that stored and processed liquids at or near the well pad. The emission profile of the simple sites was distinct, with far more simple sites registering methane levels below detection thresholds. Disaggregating these two types of sites in the data analysis can lead to greater accuracy in

[1480] Mason Inman, "The Gas Index" (Global Energy Monitor, December 15, 2020), https://thegasindex.org/.
[1481] Gabrielle Pétron et al., "Investigating Large Methane Enhancements in the U.S. San Juan Basin," *Elementa Science of the Anthropocene* 8 (2020), https://doi.org/10.1525/elementa.038.

evaluating the high end of the emission distribution where complex sites account for 91 percent of total emissions and also allows for more meaningful statistical analysis, with better fit of data in commonly used probability plots. Total estimated emission rates for the New Mexico portion of the Permian Basin, as calculated by these methods, ranged from approximately 520,000 to 610,000 tons per year.[1482]

- September 19, 2020 – Researchers at the California Air Resources Board developed and deployed a novel measurement system for mobile sampling of methane emissions with the intent of identifying and fixing unexpected fugitive leaks. Measurements from a highly instrumented sport utility vehicle (the Mobile Measurement Platform) correlated with and extended inventory-based estimates when used for monitoring emissions at 86 natural gas well pads, including 20 idle well pads. Within approximately 100 meters downwind of emission sources, the system was able to detect low-level emissions, making the system potentially much easier to use than Optical Gas Imaging cameras, which require close proximity to a source (approximately 3-10 meters) for detection of methane at similar and lower levels. The mobile system documented a highly skewed distribution. For active well pads, the top 10 percent of leaking wells were responsible for 80 percent of total emissions, and the top 20 percent were responsible for roughly 90 percent of total emissions. Findings for the idle well pads showed a similar distribution pattern but at much smaller magnitudes. These results demonstrate that using a mobile measuring system as a screening tool may lead to real-time detections of previously overlooked sources of large, potentially avoidable emissions of methane and "suggest that controlling a small number of large emitters can significantly reduce methane emissions."[1483]

- July 21, 2020 – A lawsuit brought by 15 states, spearheaded by Massachusetts and New York, led to the release of email messages that documents a successful, coordinated effort by oil and gas industry leaders to compel the White House to cancel nationwide methane reporting requirements. The suit alleges that the EPA engineered the repeal of the requirements without any internal analysis, illegally delaying the development of additional regulations to reduce methane emissions.[1484]

- July 15, 2020 – Continuing a "living review" of global methane emissions, an interdisciplinary consortium of scientists working under the rubric of the Global Carbon Project conducted a three-year update of their meta-analysis of data relevant to the global methane cycle. These data were gleaned from hundreds of individual studies. Incorporating regional atmospheric measurements, they calculated global methane emissions at 576 teragrams per year (range of 550-594), with 60 percent of global methane emissions coming from anthropogenic sources of all kinds. According to their analysis, mean annual emissions continue to rise with oil and gas production accounting

[1482] Anna M. Robertson et al., "New Mexico Permian Basin Measured Well Pad Methane Emissions Are a Factor of 5−9 Times Higher Than U.S. EPA Estimates," *Environmental Science & Technology* 54 (2020): 13926–34.
[1483] Xiaochi Zhou et al., "Mobile Sampling of Methane Emissions from Natural Gas Well Pads in California," *Atmospheric Environment* 244 (2021), https://doi.org/10.1016/j.atmosenv.2020.117930.
[1484] Lisa Friedman, "New Emails Show How Energy Industry Moved Fast to Undo Curbs," *The New York Times*, July 21, 2020, https://www.nytimes.com/2020/07/21/climate/trump-methane-climate-change.html?smid=tw-share.

for approximately 35 percent (range 30-42 percent) of total global anthropogenic emissions.[1485]

- July 14, 2020 − Stanford-led researchers estimated methane emissions by combining "top down" measurements of atmospheric methane emissions with a "bottom up" analysis of comprehensive global inventories to attribute emissions by sector. ("Top down" methods involve using aircraft to measure methane levels over an entire region. "Bottom up" approaches measure methane emissions on the ground from a representative sample of equipment.) They concluded that methane emissions reached a record high in 2017, the last year for which complete data are available.[1486] "Throughout the study period, agriculture [primarily cattle and sheep ranching] accounted for roughly two-thirds of all methane emissions related to human activities; fossil fuels contributed most of the remaining third. However, those two sources have contributed in roughly equal measure to the increases seen since the early 2000s."[1487]

- July 12, 2020 – An investigation by Hiroko Tabuchi of the *New York Times* revealed that many oil and gas companies were hurtling toward bankruptcy, potentially leaving wells untended and leaking planet-warming methane, with the costs of clean up left to local communities. Rystad Energy, an analytics company, noted that almost 250 oil and gas companies could file for bankruptcy protection by the end of next year, more than the previous five years combined. As these businesses collapse, millions of dollars often flow to executive compensation.[1488]

- June 9, 2020 – Methane leaking from its natural gas infrastructure is increasing Israel's overall greenhouse gas emissions by eight percent and is threatening its international climate change commitments. The estimation of methane leakage addressed "the entire chain of production and distribution of Israel's Tamar and Leviathan gas wells, up to its arrival at gas-fired power stations." The more comprehensive national estimate reflects emissions that are routinely neither measured nor reported. Israel reported 7,000 tons of methane to the UN Framework Convention on Climate Change in 2018, but the report calculated that the Tamar and Leviathan wells 372,672.2 tons.[1489]

[1485] Marielle Saunois et al., "The Global Methane Budget 2000–2017," *Earth System Science Data* 12, no. 3 (2020): 1561–1623, https://doi.org/10.5194/essd-12-1561-2020.
[1486] R. B. Jackson et al., "Increasing Anthropogenic Methane Emissions Arise Equally From Agricultural and Fossil Fuel Sources," *Environmental Research Letters* 15, no. 7 (2020), https://doi.org/10.1088/1748-9326/ab9ed2.
[1487] Stanford's School of Earth, Energy & Environmental Sciences, "Global Methane Emissions Soar to Record High, Even As Pandemic Has Reduced Carbon Emissions," *Sci Tech Daily*, July 14, 2020, https://scitechdaily.com/global-methane-emissions-soar-to-record-high-even-as-pandemic-has-reduced-carbon-emissions/.

[1488] Hiroko Tabuchi, "Fracking Firms Fail, Rewarding Executives and Raising Climate Fears," *The New York Times*, July 12, 2020, https://www.nytimes.com/2020/07/12/climate/oil-fracking-bankruptcy-methane-executive-pay.html#:~:text=Fracking%20Firms%20Fail%2C%20Rewarding%20Executives%20and%20Raising%20Climate, methane%20%28which%20is%20invisible%20to%20the%20naked%20eye%29.
[1489] Sue Surkes, "Methane From Natural Gas Boosts Annual Global Warming Gases by 8% – Study," *The Times of Israel*, June 9, 2020, https://www.timesofisrael.com/methane-from-natural-gas-boosts-annual-global-warming-gases-by-8-study/.

- May 13, 2020 – Pennsylvania gas drillers released more than 1.1 million tons of methane into 2017, 16 times the amount they reported to the state, according to an online report building on an earlier, peer-reviewed study. (See June 21, 2018 entry.) The updated data showed that fugitive emissions from fracked wells alone totaled 543,000 tons for 2017, not the 70,150 tons reported to the state Department of Environmental Protection (DEP). A similar amount was calculated from older, conventionally drilled wells, data that is not collected by the state. The total is more than 15 times higher than what oil and gas companies reported.[1490]

- May 1, 2020 – A helicopter survey of the Permian Basin employing infrared cameras found that 1 in 10 flares burning at oil and gas sites was unlit or malfunctioning and venting methane gas straight into the atmosphere. These unlit flares may be responsible for more than 10 percent of the Permian's overall methane emissions.[1491]

- April 22, 2020 – Satellite analysis from a Harvard-led study using high-resolution instrumentation showed that methane is leaking from Permian Basin wells into the atmosphere at a rate of 3.7 percent.[1492, 1493] This leakage rate is approximately 60 percent higher than the national leakage rate of 2.3 ± 0.3 percent, a discrepancy that the authors attribute to the practice of extensive venting and flaring in the Permian oil fields. The Delaware sub-basin, part of the larger Permian, demonstrated an even higher rate than the average for the Basin, at 4.1 percent. Authors wrote, "with the rescinding of U.S. federal requirements on gas capture and fugitive emissions in 2018, current regulations on O/G methane emissions in the Permian Basin are less stringent at both federal and state levels… All these factors may increase the incentive for operators to vent and flare their product."

- April 17, 2020 – In 2020, the U.S. EPA began collecting emissions estimates from individual pieces of equipment, walking back an Obama-era method of estimating emissions drawn from "gathering stations," facilities that transport and control the flow of natural gas to processing plants and transmission pipelines. The new method can omit very large intermittent emissions and emissions from super-emitting sites. Environmental analysts contend that the new method may under-report methane emissions by as much as 40 percent. The old method reported 2.2 million metric tons of methane emissions in

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1490 Don Hopey, "Methane Leaks Much Worse than Previously Thought, Study Says," *Pittsburgh Post-Gazette*, May 13, 2020, https://www.post-gazette.com/news/environment/2020/05/13/Methane-leaks-much-worse-than-previously-thought/stories/202005120163.
1491 Rachel Adams-Heard and Akshat Rathi, "When Flames Go Out, the Permian's Methane Problem Worsens," *Houston Chronicle*, May 1, 2020, https://www.houstonchronicle.com/business/energy/article/When-the-Flames-Go-Out-the-Permian-s-Methane-15239528.php.
1492 Yuzhong Zhang et al., "Quantifying Methane Emissions From the Largest Oil-Producing Basin in the United States From Space," *Science Advances* 6, no. 17 (2020): eaaz5120, https://doi.org/10.1126/sciadv.aaz5120.
1493 Adam Vaughan, "Fracking Wells In the US Are Leaking Loads of Planet-Warming Methane," *New Scientist*, April 22, 2020, sec. Environment, https://www.newscientist.com/article/2241347-fracking-wells-in-the-us-are-leaking-loads-of-planet-warming-methane/.

2017, whereas the new method measured only 1.3 million metric tons of leaking methane even though production had increased.[1494]

- April 13, 2020 – Using technology previously used to detect methane emissions from land-based fossil fuel development, researchers found an "effective loss rate" of 2.9 percent over offshore oil and gas platforms in the Gulf of Mexico.[1495] Authors wrote that onshore methane emissions are large and often underestimated, while offshore methane emissions have not been closely examined. Gulf of Mexico drilling represented three percent of U.S. gas production in 2017. The study findings suggest the federal government's calculations of such emissions are too low, and "analogous to the highest emitting onshore basins." Large shallow-water central hub facilities are particularly likely to be related to "disproportionately high emission events."

- April 9, 2020 – Using Pennsylvania's unique quarterly mechanical inspection reports, researchers determined that methane emissions from abandoned and active wells were at least 15 percent higher than previously thought.[1496] The researchers used 589,175 operator reports on methane leaks from both fracked and conventional oil and gas wells in the state from 2014 to 2018. The rate of flow of escaping methane from fracked wells (18.5 percent) was great than that from conventional wells. Extrapolating these findings to the nation as a whole, where over three million wells are in operation, shows that methane escaping from oil and gas wells undermine efforts to address climate change. "Another 15 percent of methane going into the atmosphere that we didn't know about is very significant for climate change in the short term," professor emeritus of engineering at Cornell and the study's lead author Anthony Ingraffea told *Environmental Health News*.[1497]

- April 7, 2020 – The International Energy Agency (IEA) cautioned that a sharp decline in oil and gas revenues during the pandemic may lead some companies to cut expenses by failing to fix leaks in gas pipes or cut losses by increasing the venting and flaring of unwanted gas. If so, atmospheric methane emissions may increase during the pandemic even as demand for natural gas falls off. A *Scientific American* report documents exactly this. The composition of greenhouse gases changed markedly the early months of 2020 and included a 10 percent reduction in carbon dioxide and a 50 percent reduction in carbon monoxide, as measured in New York City in March 2020 by researchers at Columbia University. In contrast to the carbon dioxide declines, attributable to the

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[1494] Stephen Lee, "EPA Estimate Undercounts Methane Emissions: Environmentalists," *Bloomberg Law*, April 17, 2020, https://news.bloomberglaw.com/environment-and-energy/epa-approach-undercounts-methane-emissions-environmentalists.
[1495] Alan M. Gorchov Negron et al., "Airborne Assessment of Methane Emissions from Offshore Platforms in the U.S. Gulf of Mexico," *Environmental Science & Technology* 54 (2020): 5112–20, https://doi.org/10.1021/acs.est.0c00179.
[1496] Anthony R. Ingraffea et al., "Reported Methane Emissions from Active Oil and Gas Wells in Pennsylvania, 2014–2018," *Environmental Science & Technology* 54, no. 9 (2020): 5783–89, https://doi.org/10.1021/acs.est.0c00863.
[1497] Kristina Marusic, "Oil and Gas Methane Emissions in US Are at Least 15% Higher than We Thought," *Environmental Health News*, April 23, 2020, https://www.ehn.org/fracking-methane-leaks-2645817287.html?rebelltitem=2#rebelltitem2.

temporary slowdown in transportation and other industries, methane levels did not fall. However, lack of reliable data from global oil and gas producers, make the understanding of these trends difficult.[1498]

- April 6, 2020 –Since 1983, the National Oceanic and Atmospheric Administration's (NOAA) has tracked atmospheric methane levels through a globally distributed network of air sampling sites. In 2019, its Trends in Atmospheric Methane data project documented a dramatic leap in airborne methane levels.[1499] This project does not distinguish between the various natural and human-generated sources. However, commenting on the data, climate scientist Drew Shindell said, "The easiest way to stem methane pollution… is to limit its release from oil and gas drilling sites…. You see the benefits in the first decade or two that you make cuts. You see fewer people dying from heat waves. You see less powerful storms and all of the stuff that comes from climate change."[1500]

- March 31, 2020 – Pointing toward its online "Methane Tracker" as a tool to encourage both governments and the oil and gas industry to make proactive changes to reduce the emission of methane and other global greenhouse gases, the IEA highlighted the importance of new measuring capabilities provided by satellite and aircraft and the cost-effectiveness of reducing leakage during periods of reduced gas prices. The IEA wrote that methane trends held more uncertainty than carbon dioxide trends, and that "a drop in methane emissions from oil and gas cannot be taken for granted, even if oil and gas consumption falls." It is possible that a decline in revenues from oil and gas operations would lead to less effort to decrease emissions, and that low gas prices may lead to increases in flaring or venting.[1501]

- March 30, 2020 – Using an innovative, off-site approach, researchers mounted methane-measuring equipment on a nearby, downwind tower just prior to unconventional well drilling and fracturing. They documented large, frequent spikes of methane escaping from the observed well site, especially during the vertical drilling phase (316 percent greater amplitude than baseline) and the hydraulic stimulation phase (509 percent greater amplitude than baseline). Measurements of carbon-13 isotopes confirmed that the source of the methane emissions was geological. The researcher recommends this approach for passive, offsite measurement of methane leaks that can enable researchers and

[1498] John Fialka, "As CO2 Emissions Drop During Pandemic, Methane May Rise," *Scientific American*, April 7, 2020, https://www.scientificamerican.com/article/as-co2-emissions-drop-during-pandemic-methane-may-rise/.
[1499] E. Roston and N. S. Malik, "Methane Emissions Hit a New Record and Scientists Can't Say Why," *Bloomberg Green*, April 6, 2020, https://www.bloomberg.com/news/articles/2020-04-06/methane-emissions-hit-a-new-record-and-scientists-can-t-say-why.
[1500] Jeremy Deaton, "Methane Levels Reach an All-Time High," *Scientific American*, April 12, 2020, https://www.scientificamerican.com/article/methane-levels-reach-an-all-time-high/.
[1501] Christophe McGlade, K. C. Michaels, and Tim Gould, "Global Methane Emissions From Oil and Gas: Insights From the Updated IEA Methane Tracker," *International Energy Agency*, March 31, 2020, https://www.iea.org/articles/global-methane-emissions-from-oil-and-gas.

community members to obtain a clearer picture of the time-course of emissions at particular sites.[1502]

- March 6, 2020 – An international team of researchers used isotopic analysis and a published data set to assess what proportion of the ongoing global surge in atmospheric methane emissions is attributable to oil and gas extraction, especially from shale, as opposed to other sources of atmospheric methane, such as wetlands and cattle. They concluded that methane from shale gas and conventional natural gas do not greatly differ in their carbon-13 composition, suggesting that the isotopic signal now observable in the atmosphere is not consistent with that from fossil fuel-derived methane. This assessment contests Cornell University researcher Robert Howarth's earlier attribution of increasing global methane emissions to North American fracking operations, which is premised on the existence of an isotopic difference between shale gas and conventional gas caused by fractionation as methane slowly migrates from inside shale formations to conventional gas reserves. (See entry for August 14, 2019.) The authors stress nonetheless that "oil and gas industry expansion remains a significant factor in the complex patterns of global atmospheric methane emissions and concentrations."[1503]

- February 29, 2020 – Annual emissions from fracking operations in Australia's Northern Territory could be as large as 22 percent of the nation's current annual emissions, according to government records obtained by the Australia Institute.[1504] Obtained under Freedom of Information procedures, the documents revealed that high production scenarios in the Territory would be "worse than the emissions of Australia's coal fleet across the National Energy Market (NEM) in 2030, and require more offsets each year than have ever been issued in Australia to date," threatening Australia's ability to meet international emissions reduction obligations. In the documents, government officials stated that emissions from fracking "could reach 39 million tonnes of carbon dioxide equivalent (MtCO2e) per year under one production scenario, and up to 117 MtCO2e per year under larger scale production."

- February 27, 2020 – Researchers at the International Institute for Applied Systems Analysis explored technical solutions for curbing methane emissions and transitioning to carbon-free energy alternatives and their costs. While technical solutions and alternative exist, adoption of new methods, policies, and approaches is only feasible through regulation or "if the future price of gas become[s] high enough to make gas recovery

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[1502] Sarah J. Russell et al., "Quantifying CH4 Concentration Spikes Above Baseline and Attributing CH4 Sources to Hydraulic Fracturing Activities by Continuous Monitoring at an Off-Site Tower," *Atmospheric Environment* 228 (2020): 117452, https://doi.org/10.1016/j.atmosenv.2020.117452.
[1503] Alexei V. Milkov et al., "Using Global Isotopic Data to Constrain the Role of Shale Gas Production in Recent Increases In Atmospheric Methane," *Scientific Reports* 10 (2020): 4199, https://doi.org/10.1038/s41598-020-61035-w.
[1504] Tom Swann, "All It's Fracked Up to Be" (The Australia Institute, February 2020), https://australiainstitute.org.au/wp-content/uploads/2020/12/P875-All-its-Fracked-Up-to-Be-WEB.pdf.

profitable." Specifically, extensive technical opportunities exist to control emissions "from waste and wastewater handling and from fossil fuel production and use."[1505]

- February 21, 2020 – Using measurements of carbon-14 and its isotopes from ice cores reflecting the most recent prior deglaciation period on earth (approximately 18,000 to 8,000 years before present), a team of researchers discovered that relatively little methane was emitted from "old carbon" sources, such as permafrost and methane hydrates under ice sheets.[1506] Instead, "old methane is often rapidly consumed by microorganisms living in sediments, soils, and water, which convert it to carbon dioxide before it can be released to the atmosphere."[1507] A similar pattern may hold as present global temperatures increase. Thus, the paper's lead author said, "we need to be more concerned about the anthropogenic emissions—those originating from human activities—than the natural feedbacks."[1508]

- February 19, 2020 – A University of Rochester-led team conducted an isotopic analysis of pre-industrial ice cores. The results showed that naturally occurring methane emissions from geological sources are relatively small (1.6 million tons per year) and contribute far less to global methane emissions than has been estimated (30 million to 60 million tons). Instead, human activities that liberate methane from geological formations—namely, fossil fuel extraction, distribution, and use—make a far greater contribution to global methane emissions and have heretofore been underestimated by 25 to 40 percent. Accordingly, reducing anthropogenic methane emissions is a firm target for mitigating climate change.[1509, 1510]

- February 12, 2020 – Researchers used drones to sample methane emissions downwind from a single fracking operation, demonstrating the utility of this method for a rapid response, highly precise, "snap shot" study in settings where access for other forms of monitoring may be restricted or where the study area is too small for satellite or high altitude aerial surveillance. High levels of methane emissions were correlated to venting at the fracking site. Such sampling can complement and supplement other methods for compiling inventories of methane emissions and can be used to study relative

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[1505] Lena Höglund-Isaksson et al., "Technical Potentials and Costs for Reducing Global Anthropogenic Methane Emissions in the 2050 Timeframe –Results from the GAINS Model," *Environmental Research Communications* 2, no. 2 (2020): 025004, https://doi.org/10.1088/2515-7620/ab7457.

[1506] M. N. Dyonisius et al., "Old Carbon Reservoirs Were Not Important In the Deglacial Methane Budget," *Science* 367, no. 6480 (2020): 907–10, https://doi.org/10.1126/science.aax0504.

[1507] Joshua F. Dean, "Old Methane and Modern Climate Change," *Science* 367, no. 6480 (2020): 846–48, https://doi.org/10.1126/science.aba8518.

[1508] Lindsey Valich, "To Combat Climate Change, Human Activities More Important than Natural Feedbacks," *University of Rochester Newscenter*, February 21, 2020, https://www.rochester.edu/newscenter/combat-climate-change-human-activities-more-important-natural-feedbacks-416672/.

[1509] Benjamin Hmiel et al., "Preindustrial 14CH4 Indicates Greater Anthropogenic Fossil CH4 Emissions," *Nature* 578 (2020): 409–12, https://doi.org/10.1038/s41586-020-1991-8.

[1510] Warren Cornwall, "Humans Are a Bigger Source of Climate-Altering Methane, New Studies Suggest," *Science Magazine*, February 20, 2020, https://www.sciencemag.org/news/2020/02/only-humans-can-create-climate-altering-methane-burns-new-studies-suggest.

contributions to emissions of differing phases of fracking, including flow-back, venting, storage, and compression.[1511]

- February 3, 2020 – According to data available through the federal Energy Information Administration (EIA), flaring and venting of methane by the oil and gas industry increased in 2019 for a third year in a row. Compared to 2018 levels, flaring and venting rose by seven percent in the Permian Basin underlying Texas and New Mexico, while the volumes of gas released or burned in North Dakota's huge Bakken oil field increased by 36 percent. Many states allow the practice, and few enforce regulations that are in place.[1512]

- January 28, 2020 – Researchers extended the use of the high-resolution, satellite-based instrumentation to measure methane emissions in multiple basins in the United States, including the Central Valley of California, the Uintah Basin in Utah, several basins in Texas, and a range of other states, including Florida. After corroborating their findings with findings from ground-based and airborne measurements, they suggest the possibility of greater accuracy, completeness, and utility through "future determination of regional methane emissions [via satellite] with a high time resolution and soon after the time of emission" in both the United States and internationally.[1513]

- January 11, 2020 – A report issued by New Mexico's Methane Advisory Panel, appointed by the Governor, suggests that methane venting and flaring have increased, despite conflicting claims from industry and declining numbers in EPA inventories, following changes in reporting methods. Compiling comments from multiple interested parties, "the report lays out comprehensive technical recommendations meant to guide environmental regulators as they craft a new methane rule involving everything from leaks in oil and gas storage tanks to pneumatic pumps."[1514]

- December 16, 2019 – Methane escapes from all parts of the extraction, distribution, and storage system for natural gas. Quantifying these emissions is difficult and yet dictates how quickly further investments in natural gas should end in order to meet greenhouse gas reduction targets. Researchers from the Massachusetts Institute of Technology calculated that reductions in leakage rates from natural gas infrastructure on the order of 30 to 90 percent would be required in order to meet proposed climate targets for 2030. The team projected out multiple scenarios to show the impact of differing approaches to reaching that goal, as well as the potential benefits and importance of identifying and targeting methane super-emitters. Given the difficulties of both measuring and mitigating

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[1511] Adil Shah et al., "Unmanned Aerial Vehicle Observations of Cold Venting From Exploratory Hydraulic Fracturing in the United Kingdom," *Environmental Research Communications* 2, no. 2 (2020): 021003, https://doi.org/10.1088/2515-7620/ab716d.

[1512] Nichola Groom and Jennifer Hiller, "U.S. Oil Fields Flared and Vented More Natural Gas Again in 2019-Data," *Thomson Reuters Roundation News*, February 3, 2020, http://news.trust.org/item/20200203112531-yoq0j/.

[1513] Joost A. de Gouw et al., "Daily Satellite Observations of Methane from Oil and Gas Production Regions in the United States," *Scientific Reports* 10 (2020): 1379, https://doi.org/10.1038/s41598-020-57678-4.

[1514] Michael Gerstein, "Report: Methane Venting, Flaring in Permian Doubled Since 2017," *Santa Fe New Mexican*, February 15, 2021, https://www.santafenewmexican.com/news/local_news/report-methane-venting-flaring-in-permian-doubled-since-2017/article_819dc5ac-3313-11ea-96ff-3f3802aff8b0.html.

methane emissions and given that virtually all scenarios for meeting greenhouse gas reduction targets call for ultimately phasing out natural gas by mid-century, further investments in natural gas infrastructure raise questions.[1515] "A certain amount of investment probably makes sense to improve and make use of current infrastructure, but if you're interested in really deep reduction targets, our results make it harder to make a case for that expansion right now," according to author Jessika Trancik.[1516]

- December 16, 2019 – Positing that lack of reliable measurements of accidental methane releases and intermittent emissions from high-volume point sources (super-emitters) in the oil and gas industry leads to omission of such data from emission inventories and reporting, researchers enlisted the use of a space-borne instrument to detail an extremely large methane plume observed in 2018, traceable to a natural gas well blowout in Ohio.[1517] Satellite records put the emission rate of the event in Ohio at 120 metric tons per hour, double the widely reported leak from the Aliso Canyon storage facility in California in 2015, yet its full extent had gone undetected prior to investigation of the satellite's records, despite health complaints among residents closest to the well that included "throat irritation, dizziness, breathing problems."[1518] The extent of the methane released had also escaped the state's routine greenhouse gas accounting systems. Estimates of the total methane from the event, which lasted approximately 20 days, put that single source at roughly 60 kilotons of methane, equivalent to a quarter of Ohio's reported annual methane emissions and the total reported emissions of some countries. These results reinforce other recent findings that methane emissions from drilling and fracking operations are bigger and more problematic than previously assumed. The researchers urge the expanded use of such observations to identify methane hot spots in order to record these events and target them for intervention.

- December 10, 2019 – Thermal imaging equipment has allowed the nonprofit organization Earthworks to document billowing plumes of methane at oil and gas production sites in New Mexico, made visible through the infrared lens, according to the *Albuquerque Journal*.[1519] Clouds of gas emissions can signal open vents or malfunctioning equipment. Earthworks uses the information to seek reductions in emissions and, if necessary, reports emissions violations to the New Mexico Environment Department. Some measured emissions of methane in the Permian Basin in New Mexico are five times higher than EPA estimates. These findings have helped pushed Governor Michelle Lujan Grisham to

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[1515] Magdalena M. Klemun and Jessika Trancik, "Timelines for Mitigating the Methane Impacts of Using Natural Gas for Carbon Dioxide Abatement," *Environmental Research Letters* 14, no. 12 (2019): 124069, https://doi.org/10.1088/1748-9326/ab2577.
[1516] David L. Chandler, "The Uncertain Role of Natural Gas in the Transition to Clean Energy," *MIT News*, December 16, 2019, http://news.mit.edu/2019/role-natural-gas-transition-electricity-1216.
[1517] Sudhanshu Pandey et al., "Satellite Observations Reveal Extreme Methane Leakage From a Natural Gas Well Blowout," *Proceedings of the National Academy of Sciences* 116, no. 52 (2019): 26376–81, https://doi.org/10.1073/pnas.1908712116.
[1518] Hiroko Tabuchi, "A Methane Leak, Seen From Space, Proves to Be Far Larger Than Thought," *The New York Times*, December 16, 2019, sec. Climate Change, https://www.nytimes.com/2019/12/16/climate/methane-leak-satellite.html.
[1519] Theresa Davis, "Methane Emissions a Numbers Game in New Mexico," *Albuquerque Journal*, December 10, 2019, https://www.abqjournal.com/1399538/methane-emissions-a-numbers-game-in-new-mexico-ex-an-advisory-panel-will-discuss-what-regulations-would-be-practical-and-effective-for-the-state.html.

pursue a first-of-its-kind state partnership with a commercial laboratory "to measure methane—accurately and in real time—using satellite tech and weather patterns."

- December 5, 2019 – After proclaiming publicly that Colorado would adopt aggressive climate goals, cut down on methane emissions through strict regulations, and keep pressure on the oil and gas industry for improved practices, elected officials were confronted with inaccuracies in the state-funded system to collect data and verify reductions in emissions. The state has declined to hire or to use data from other in-state sources such as aerial surveys by NOAA or private companies like Scientific Aviation, that can do precise real-time monitoring.[1520]

- December 4, 2019 – An international team of researchers examined the growing dependency on fossil fuels around the globe, "amidst declarations of planetary emergency and reports that the window for limiting climate change … is rapidly closing."[1521] They determined that the ongoing natural gas boom is serving a major barrier to rapid decarbonization. Natural gas is the fastest growing fossil fuel in the world. While it has indeed displaced coal—the use of coal in the United States has fallen by half over the past 15 years—the use of natural gas has soared so fast that the methane emissions from burning it have more than offset the decline in carbon dioxide emissions from the dwindling use of coal. The result is that carbon dioxide (or CO_2-equivalent) emissions from fossil fuels grew each year from 2017-2019. The low costs of natural gas, and new methods for transporting it, such as LNG tankers, are keeping the use of fossil fuels high even as renewable energy sources are also growing. As a result, the carbon intensity of global energy production has remained essentially unchanged since 1990. The study calls for "accelerated energy efficiency improvements and reduced consumption, rapid deployment of electric vehicles, carbon capture and storage technologies, and a decarbonized electricity grid, with new renewable capacities replacing fossil fuels," assisted by stronger global commitments and carbon pricing. "I have strong concerns about the pace of our natural gas build-out in the United States and globally because those facilities will be producing pollution for many decades," said lead author and Stanford University earth system scientist Rob Jackson.[1522]

- November 26, 2019 – Meteorologists used measurements from airborne instruments to model methane emissions across multiple oil and gas regions in Arkansas, Texas, Louisiana and Oklahoma that are estimated to contribute 40 percent of the oil and gas

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[1520] Grace Hood, "Colorado Talks A Mean Game On Methane. Bad Data, No Best Practices Say Otherwise," *Colorado Public Radio News*, December 5, 2019, https://www.cpr.org/2019/12/05/colorado-talks-a-mean-game-on-methane-bad-data-no-best-practices-say-otherwise/.
[1521] R. B. Jackson et al., "Persistant Fossil Fuel Growth Threatens the Paris Agreement and Planetary Health," *Environmental Research Letters* 14, no. 12 (2019): 121001, https://doi.org/10.1088/1748-9326/ab57b3.
[1522] Nicholas Kusnetz, "Natural Gas Rush Drives a Global Rise in Fossil Fuel Emissions," *Inside Climate News*, December 4, 2019, sec. Fossil Fuels, https://insideclimatenews.org/news/03122019/fossil-fuel-emissions-2019-natural-gas-bridge-oil-coal-climate-change.

produced in the United States.[1523, 1524] These aerial data confirm other research showing that 1.1 to 2.5 times as much methane is being emitted by oil and gas activities than is estimated by inventories collected on the ground, such as those compiled by the EPA. Tracers, including ethane, allowed researchers to segregate methane emissions originating from the oil and gas sector from biogenic sources, such as livestock and manure. They also found that flying through massive methane plumes concentrated by regional weather front boundaries allowed them to measure methane emissions from a wide area.

- November 6, 2019 – Researchers employed the "Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG)" to detect, geolocate, and quantify point sources of less than 10 meters in diameter that emit methane, with a focus on identifying super-emitting landfills, livestock facilities, and oil and gas infrastructure. Their results allowed the team to estimate that the emissions from point sources were equivalent to 34-46 percent of the state's 2016 methane inventory. They also found super-emitters among every sector of point sources, with 10 percent of them accounting for roughly 60 percent of point-source emissions.[1525] Regular scans for such emissions are needed, especially since sharing data about these localized "puffs" of methane with collaborating infrastructure operators in some cases led to mitigation.[1526]

- October 25, 2019 – High-resolution satellite instrumentation detected an unexpectedly large, persistent methane source in Central Asia, along with additional nearby sources of high emission.[1527] The amount of methane detected equaled the "total emissions from the Aliso Canyon disaster—the largest accidental release of greenhouse gases in U.S. history."[1528] While the exact cause of the emissions cannot be determined, venting (blowdowns) from a gas compressor station or malfunction of a valve on a pipeline seem likely. The researchers compared and confirmed their results with observations from another satellite based measuring instrument. The results point toward a potential strategy for monitoring in which "instruments with global coverage at coarse spatial resolution can first identify methane hot spots and then instruments with fine spatial resolution but limited coverage can zoom in to identify the facilities responsible for the hot spots."

[1523] A. R. Barkley et al., "Forward Modeling and Optimization of Methane Emissions in the South Central United States Using Aircraft Transects Across Frontal Boundaries," *Journal of Geophysical Research: Atmospheres* 46, no. 22 (2019): 13564–73, https://doi.org/10.1029/2019GL084495.
[1524] David Kubarek, "Airborne Measurements Point to Low EPA Methane Estimates in South Central US," *Penn State News*, January 27, 2020, https://news.psu.edu/story/605629/2020/01/27/research/airborne-measurements-point-low-epa-methane-estimates-south-central.
[1525] Riley M. Duren et al., "California's Methane Super-Emitters," *Nature* 575 (2019): 180–84, https://doi.org/10.1038/s41586-019-1720-3.
[1526] Leslie Nemo, "'Super-Emitters' In California Release A Third Of The State's Methane," *Discover*, November 5, 2019, https://www.discovermagazine.com/environment/super-emitters-in-california-release-a-third-of-the-states-methane.
[1527] D. J. Varon et al., "Satellite Discovery of Anomalously Large Methane Point Sources From Oil/Gas Production," *Geophysical Research Letters* 46, no. 22 (2019): 13507–16, https://doi.org/10.1029/2019GL083798.
[1528] Carlos Anchondo, "Satellite Discovers 'Anomalously Large' Methane Plume," *E&E News*, November 26, 2019, https://web.archive.org/web/20191128174408/https://www.eenews.net/energywire/stories/1061647835.

- October 16, 2019 – Despite pledges from oil and gas industry executives to curb the energy-wasting practice of flaring off excess natural gas, rates of flaring have significantly increased in recent years, along with rates of venting unburned gas. In 2018, operators across three basins (the Eagle Ford and Permian basins in the Southwest and the Bakken Formation at the Canadian border) flared or vented a record 320 million cubic feet of gas, more than 40 percent above levels seen just five years ago. Oil producers often treat natural gas as a liability, flaring it rather than paying to pipe it away for sale. "Last year in Texas, venting and flaring in the Permian Basin oil field alone consumed more natural gas than states like Arizona and South Carolina use in a year."[1529]

- August 14, 2019 –Isotopic analysis can distinguish methane produced from microbes (biogenic methane) from methane emissions arising from oil and gas operations (thermogenic methane). During the final 20 years of the 20th century, as atmospheric methane concentrations rose, isotopic analysis allowed scientists to conclude that fossil fuels and not microbes were driving the increase. During a second methane surge, beginning in 2009, the isotopic evidence led some researchers to conclude that biogenic sources, such as tropical wetlands, rice culture, or animal agriculture were the most likely driver of the observed methane increases. (See entry for March 10, 2016.) However, Cornell University biogeochemist Robert Howarth proposes an alternative view, noting that previous studies did not explicitly consider shale gas, which has a lighter isotopic signature that more closely resembles that of microbial methane. Correcting the earlier analyses for this difference, Howarth concluded that shale gas production in North America over the past decade may have contributed "more than half of all of the increased emissions from fossil fuels globally and approximately one-third of the total increased emissions from all sources globally over the past decade." In other words, the North American fracking boom is globally important in the current rise in global methane levels and "may well be the leading cause of the increased flux."[1530] Stabilizing the climate by slashing methane emissions from the extraction, transport, storage, processing, and use of fossil fuels—particularly those obtained via fracking—is "the low-hanging fruit to slow global warming."[1531] (See also entry for March 6, 2020 above.)

- July 29, 2019 – To measure fugitive methane emissions from urban areas and identify the sources of those emissions, scientists used atmospheric observations of methane, carbon dioxide, carbon monoxide, and ethane downwind from six "old and leak-prone major cities" along the northeast coast of the United States. Their findings showed that these regions are leaking twice as much methane as indicated in EPA inventories. This discrepancy is possibly due to underestimates of natural gas leakage from urban

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[1529] Hiroko Tabuchi, "Despite Their Promises, Giant Energy Companies Burn Away Vast Amounts of Natural Gas," *The New York Times*, October 16, 2019, https://www.nytimes.com/2019/10/16/climate/natural-gas-flaring-exxon-bp.html.
[1530] Robert W. Howarth, "Ideas and Perspectives: Is Shale Gas a Major Driver of Recent Increase in Global Atmospheric Methane?," *Biogeosciences* 16 (2019): 3033–46, https://doi.org/10.5194/bg-16-3033-2019.
[1531] Ruth Schuster, "As Fracking Poisons the Air, Israeli Scientists Propose to Engineer Cows," *Haaretz*, August 14, 2019, sec. Science & Health, https://www.haaretz.com/science-and-health/as-fracking-poisons-the-air-israeli-scientists-propose-to-engineer-cows-1.7683463.

distribution sources or from lack of inclusion of end-use emissions, or both.[1532] The amount of methane emitted by these six cities is large ("well over triple the amount emitted by gas production in the Bakken shale formation in the U.S. Midwest") and preventable. Possible sources of the leaks include natural gas pipelines, pumps, valves, water treatment systems, gas-fired power plants, and leaks from within homes and businesses.[1533]

- July 15, 2019 – Measurements of methane from a remote sensing spectrometer located just outside Los Angeles documented a correlation between methane levels and consumption of natural gas by residential and commercial consumers in the city, with measured emissions more than twice the level of estimates derived from monitoring equipment on the ground. If a causal correlation exists between the greater amount of gas burned in cold weather and higher methane levels, then the study estimates that about 1.4 percent of the commercial and residential natural gas consumption in Los Angeles is released into the atmosphere.[1534] To meet mandated reductions in emissions in California, sources of emission must be identified and quantified—in this case, the entire urban distribution system, "from storage fields to pipelines to stoves and furnaces."[1535] This approach provides a simple and relatively inexpensive method to address an often-overlooked component of global methane pollution.

- July 2, 2019 – Venting and flaring events at fracking sites release not only the greenhouse gases carbon dioxide and methane but also toxic air pollutants, including hydrogen sulfide, formaldehyde, sulfur dioxide, benzene, and volatile aromatic hydrocarbons. These events are self-reported by the industry to state agencies. Because there is almost no independent auditing, the precision and accuracy of self-reported venting and flaring volumes remain unknown. A research team from Texas A&M working in the Permian and Eagle Ford basins therefore created and attempted to match detailed maps of flared gas from both self-reported data collected on-site by the operators and satellite aerial data. Their results revealed that flaring volumes measured by satellite were at least two time greater than self-reported volumes submitted by the operators to the state. The authors note that venting and flaring reports are not mandated until after the well is drilled, fracked, and hooked up to the pipeline and also enjoy other exemptions. "Self-

[1532] Genevieve Plant et al., "Large Fugitive Methane Emissions From Urban Centers Along the U.S. East Coast," *Geophysical Research Letters* 46, no. 14 (2019): 8500–8507, https://doi.org/10.1029/2019GL082635.
[1533] Sid Perkins, "Major U.S. Cities Are Leaking Methane at Twice the Rate Previously Believed," *Science*, July 19, 2019, https://www.sciencemag.org/news/2019/07/major-us-cities-are-leaking-methane-twice-rate-previously-believed.
[1534] Liyin He et al., "Atmospheric Methane Emissions Correlate With Natural Gas Consumption From Residential and Commercial Sectors in Los Angeles," *Geophysical Research Letters* 46, no. 14 (2019): 8563–71, https://doi.org/10.1029/2019GL083400.
[1535] Emily Velasco, "Natural-Gas Leaks Are Important Source of Greenhouse Gas Emissions in Los Angeles," *Caltech News*, August 12, 2019, https://www.caltech.edu/about/news/natural-gas-leaks-are-important-source-greenhouse-gas-emissions-los-angeles.

reported volumes significantly underestimate the volume of gas being vented or flared."[1536]

- June 7, 2019 – In a perspective published in *Science*, researchers from the National Institute of Water and Atmospheric Research in New Zealand considered the climate risks posed by rising global methane levels and their possible sources. In 2007, after a seven-year period of no change, the amount of methane in the atmosphere began to rise. The rate of increase then doubled from 2014 to the end of 2018, threatening to undermine the goals to limit planetary temperature increases, as set out in the Paris Agreement. The cause of this ongoing methane surge has four possible explanations, according to the authors: fossil fuel sources, biogenic sources, especially ruminant livestock; methane release from wetlands, particularly in the southern tropics, triggered by rising global temperatures; or a decline in the atmosphere's ability to break methane molecules apart, slowing the natural decay rate of methane.[1537]

- May 27, 2019 – In response to discussions about possible future fracking activities in Germany and the United Kingdom, researchers at the Institute for Advanced Sustainability Studies in Germany developed projections for emissions of greenhouse gases and associated local air pollutants, with a realistic scenario assuming "business-as-usual" activities and an optimistic scenario based on "the lowest emissions technically possible" including "full compliance with a stringent regulatory framework…."[1538] In addition to other harmful effects from fracking activities such as earthquakes and surface and groundwater contamination, projections of atmospheric impacts from drilling 480 wells annually in the two countries suggest that methane and carbon dioxide emissions with fracking are considerably higher than with conventional oil and gas production under the realistic scenario, with leakage rates only meeting current government figures under the 'optimistic' scenario, which the researchers acknowledge is "rather unlikely to be systematically employed or achieved." One of the reviewers suggested that "In light of the climate crisis, the environmental risks posed by gas emissions need to move quickly onto the agenda in policy making and in negotiations with the gas industry in order to keep the adverse effects of a European shale gas industry to an absolute minimum."[1539]

- March 12, 2019 – Using aircraft, a team of researchers from multiple universities and institutions estimated emissions from both coal mines and shale gas wells in southwestern Pennsylvania. For coal, their results largely aligned with EPA estimates. However, for natural gas wells, emissions were five times higher than EPA figures. Because the volume of gas extracted per well is higher than in other shale basins, production-scaled

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[1536] Katherine Ann Willyard and Gunnar W. Schade, "Flaring in Two Texas Shale Areas: Comparison of Bottom-Up With Top-Down Volume Estimates for 2012 to 2015," *Science of the Total Environment* 691 (2019): 243–51, https://doi.org/10.1016/j.scitotenv.2019.06.465.
[1537] Sara E. Mikaloff Fletcher and Hinrich Schaefer, "Rising Methane: A New Climate Challenge," *Science* 364, no. 6444 (2019): 932–33, https://doi.org/10.1126/science.aax1828.
[1538] Lorenzo Cremonese et al., "Emission Scenarios of a Potential Shale Gas Industry in Germany and the United Kingdom," *Elementa: Science of the Anthropocene* 7, no. 18 (2019), https://doi.org/10.1525/elementa.359.
[1539] Rachel Cordery, "Shale Gas Fracking Could Increase Emissions," *Power Technology*, July 25, 2019, sec. News, https://www.power-technology.com/news/shale-gas-increases-harmful-emissions/.

methane emissions were still comparatively low, with carbon dioxide emissions from combustion remaining the dominant source of greenhouse gas emissions.[1540]

- March 7, 2019 – Methane is a very strong greenhouse gas, with 120 times the power to trap heat than an equivalent amount of carbon dioxide. However, methane persists in the atmosphere for an average of only 12.4 years whereas carbon dioxide can linger for a century or more. Using a combination of approaches, a London team assessed the contribution of natural gas extraction to future greenhouse gas emissions in the United States, taking into account timing as well as magnitude of emissions and changing prices. They found that methane emitted further into the future—and therefore closer to the year where climate stabilization needs to take place—has a disproportionately large bearing on the overall climate impact of drilling and fracking activities, with long-lived gas fields having the most effect. "A key finding of this study is that the environmental and economic consequences of emissions are likely to rise with the age of a field, thus exposing long-lived assets to the greatest potential losses….Overall, our results suggest that future cumulative greenhouse gas emissions from existing US [gas] fields have a significant short-medium climate impact." The authors recommend carbon pricing as a strategy to shorten the lifetime of long-lived gas fields. They also report that 40 percent of carbon dioxide output from natural gas is directly related to drilling activities.[1541]

- February 28, 2019 – Australia's LNG export industry contributed significantly to rising carbon emissions from that country in the 12 months prior to September 2018, according to Australia's National Greenhouse Gas Inventory. Emissions from power plants fell during this same time period as the result of a 31 percent jump in renewable energy serving eastern Australia. These declines, however, were more than offset by soaring increases in industrial and fugitive emissions from Australia's LNG plants.[1542] LNG exports rose by one fifth in 2018.[1543] This jump represents the third consecutive year of rising greenhouse gas emissions from Australia. The expansion in LNG production and export was identified as the major contributor to this trend.[1544]

- February 27, 2019 – An international team investigated the climate and the public health harms attributable to fossil fuel combustion. Their global model estimated an avoidable excess mortality rate of 3.61 million deaths per year from air pollution alone. Air pollution also chemically reacts with dust to create aerosols that disrupt the hydrologic

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[1540] Z. R. Barkley et al., "Estimating Methane Emissions From Underground Coal and Natural Gas Production in Southwestern Pennsylvania," *Geophysical Research Letters* 46, no. 8 (2019): 4531–40, https://doi.org/10.1029/2019GL082131.
[1541] Daniel J. G. Crow et al., "Assessing the Impact of Future Greenhouse Gas Emissions From Natural Gas Production," *Science of the Total Environment* 668 (2019): 1242–58, https://doi.org/10.1016/j.scitotenv.2019.03.048.
[1542] Commonwealth of Australia Department of Environment and Energy, "Quarterly Update of Australia's National Greenhouse Gas Inventory for September 2018," 2018, https://www.industry.gov.au/data-and-publications/national-greenhouse-gas-inventory-for-september-2018.
[1543] Peter Hannam, "Annual Emissions Keep Rising as Gas Jump Counters Power Sector Drop," *The Sydney Morning Herald*, February 28, 2019, sec. Climage Change, https://www.smh.com.au/environment/climate-change/annual-emissions-keep-rising-as-gas-jump-counters-power-sector-drop-20190228-p510wu.html.
[1544] Lisa Cox, "Gas Boom Fuels Australia's Third Straight Year of Rising Emissions," *The Guardian*, May 14, 2018, https://www.theguardian.com/environment/2018/may/14/gas-fuels-australias-third-straight-year-of-rising-emissions.

cycle and impede rainfall patterns. If fossil fuel burning ended, not only would deaths due to air pollution be avoided but additional lives would be saved as water and food security improved in densely populated areas of India, northern China, and central America. In sum, "a rapid phaseout of fossil fuel-related emissions and major reductions of other anthropogenic sources are needed to save millions of lives, restore aerosol-perturbed rainfall patterns, and limit global warming to 2 Cº."[1545]

- February 12, 2019 – In southeastern Saskatchewan, Canada, conventional gas and oil drilling takes place side by side with unconventional drilling via fracking. In a first study of its kind, a St. Francis Xavier University research team directly compared methane emissions from both types of co-located wells. By conducting truck-based air sampling downwind from 645 conventional wells and 289 unconventional wells, the team found that 28 percent of conventional wells leaked methane compared to 32 percent of fracked wells. The bigger difference was in measures of mean emission intensities from the wells that were leaking. Leaking fracked wells emitted nearly three times as much methane (59 cubic meters of methane per day) as leaking conventional wells (20 cubic meters of methane per day). "Our results showed that unconventional sites in southeastern Saskatchewan emit about as often as nearby conventional sites, but with somewhat greater severity."[1546]

- February 5, 2019 – A team led by University of Maryland researchers conducted aircraft sampling in 2015 to assess leakage from drilling and fracking operations in the southwestern Marcellus Shale. Coalbeds were the likely source of more than 70 percent of the emitted methane. Of the methane that likely arose from shale gas wells, the estimated mean emission rate was 1.1 percent of the total natural gas extraction. These results were consistent with (but at the low end of) estimates determined by previous observational studies in this region. They indicate that the climate impact of natural gas combustion falls below that of coal. Nevertheless, the full range includes values up to 3.5 percent, which falls above the break-even point with coal over a 20-year time span.[1547]

- February 5, 2019 – Sampling air from remote locations all over the world, an international team of atmospheric scientists confirmed a sharp rise in global atmospheric methane. This spike began in 2007 and has accelerated since 2014. The causes for the increase are not fully understood. The research team also documented, over the same time period, a shift in the carbon isotope ratio, which may signal a shift in the relative proportions of emissions from different sources. (These various methane sources include, for example, gas leaks, microbes, livestock, landfills, biomass burning.) Alternatively—or additionally—it may signal a decline in the oxidative capacity of the atmosphere,

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[1545] J. Lelieveld et al., "Effects of Fossil Fuel and Total Anthropogenic Emission Removal on Public Health and Climate," *Proceedings of the National Academy of Sciences U.S.A.* 116, no. 5 (2019): 7192–97, https://doi.org/10.1073/pnas.1819989116.
[1546] Jennifer Baillie et al., "Methane Emissions From Conventional and Unconventional Oil and Gas Production Sites in Southeastern Saskatchewan, Canada," *Environmental Research Communications* 1, no. 1 (2019): 011003, https://doi.org/1088/2515-7620/ab01f2.
[1547] Xinrong Ren et al., "Methane Emissions From the Marcellus Shale in Southwestern Pennsylvania and Northern West Virginia Based on Airborne Measurements," *Journal of Geophysical Research: Atmospheres* 124 (2019): 1862–78, https://doi.org/10.1029/2018JD029690.

which breaks apart methane molecules. A change in the rate of methane destruction can also change the carbon isotope ratio. Either way, a sharp, ongoing increase in global methane concentrations was not predicted by the future greenhouse gas scenarios that were incorporated into the targets of the Paris Agreement. If the current increase continues, the goals of that treaty could be out of reach. “There is now urgent need to reduce methane emissions, especially from the fossil fuel industry… anthropogenic methane emissions are relatively very large and thus offer attractive targets for rapid reduction, which are essential if the Paris Agreement aims are to be attained.”[1548]

- February 4, 2019 – Permafrost is soil that remains frozen year-round. If it thaws, microbes turn the carbon contained in the soil into carbon dioxide and methane. Because such a vast amount of carbon is held in permafrost, warming Arctic temperatures may release a large pulse of climate-destabilizing methane and so trigger an uncontrolled positive feedback loop. A study by an international team looked at the fate of permafrost under different scenarios of greenhouse gas mitigation, including some in which no progress is made toward decreasing fossil fuel-based emissions and others in which the targets of the Paris Agreement are met. In their analysis, the team determined the highest level of natural methane emissions that can be released from the Arctic by 2100. This level is considerably lower than likely anthropogenic methane emission levels over the same time period, which indicates that human-made emissions can be reduced sufficiently to limit methane-causing climate warming by 2100 even if the permafrost undergoes an uncontrolled emission feedback—but only if a committed, global effort to reduce fossil fuel use takes place very soon.[1549] In a press release about this research, one of the authors of the study, Lena Högland-Isaksson, said, “It is important to put the two estimates alongside each other to point out how important it is to urgently address methane emissions from human activities, in particular through a phase out of fossil fuels. It is important for everyone concerned about global warming to know that humans are the main source of methane emissions and that if we can control humans’ release of methane, the problem of methane release from the thawing Arctic tundra is likely to remain manageable.”[1550]

- December 4, 2018 – Research firm Rystad Energy reported that gas flaring in the west Texas Permian Basin has doubled since 2017. Oil wells in the region pump out large volumes of associated natural gas. Without pipelines to bring the gas to burner tips, and in order to maintain the rapid pace of oil drilling, operators simply waste the gas—worth more than $1 million per day—by burning it off in flare stacks. Flaring permits are limited to 45 days but are now routinely extended for up to six continuous months.[1551]

[1548] E. G. Nisbet et al., “Very Strong Atmospheric Methane Growth in the 4 Years 2014–2017: Implications for the Paris Agreement,” *Global Biogeochemical Cycles* 33, no. 3 (2019): 318–42, https://doi.org/10.1029/2018GB006009.
[1549] Torben Røjle Christensen et al., “Tracing the Climate Signal: Mitigation of Anthropogenic Methane Emissions Can Outweigh a Large Arctic Natural Emission Increase,” *Scientific Reports* 9 (2019): 1146, https://doi.org/10.1038/s41598-018-37719-9.
[1550] International Institute for Applied Systems Analysis, “Diffusing the Methane Bomb: We Can Still Make a Difference,” Press Release, February 6, 2019, https://www.sciencedaily.com/releases/2019/02/190206104538.htm.
[1551] Jordan Blum, “Permian Basin Gas Flaring Has Nearly Doubled In a Year,” *Houston Chronicle*, December 4, 2018, sec. Energy, https://www.houstonchronicle.com/business/energy/article/Record-Permian-gas-flaring-has-nearly-doubled-in-13443024.php.

- November 23, 2018 – In a report commissioned by the Obama administration in 2016, the U.S. Geological Survey (USGS) provided estimates on greenhouse gas emissions associated with the extraction and combustion of fossil fuels produced from federal lands. Between 2005 and 2014, fully one-quarter of all U.S. carbon emissions come from fossil fuels that were extracted from public lands. The report found that forests on federal lands can offset some of these emissions but only by 15 percent. Fossil fuels are extracted from public lands in 28 states with more than half the total carbon emissions coming from Wyoming.[1552, 1553]

- October 29, 2018 – The Basin Methane Reconciliation Study was a large-scale field investigation that brought together more than 80 scientists from multiple institutions. They examined why different methods of accounting for methane emissions from natural gas drilling sites vary so widely across the United States. The study took place in 2015 in Arkansas' Arkoma Basin and utilized both bottom-up and top-down approaches, which is to say, measurements were taken on the ground at selected facilities as well as in the atmosphere over the region, via aircraft. This type of concurrent dual analysis had never been attempted before. The study revealed spikes of high emissions that occur during daytime maintenance operations, as when, for example, liquids are being removed from a well and natural gas is freely vented into the air for the duration of that process. The high temporal variability and episodic nature of methane emissions likely explain the persistent gap between the two accounting methods and mean that researchers who attempt to determine how much methane is escaping from drilling and fracking operations require "detailed activity data, unfettered and unbiased site access, and time-resolved operations data." This type of study necessarily requires cooperation with industry employees.[1554]

- August 1, 2018 – The Groningen natural gas field in the northern Netherlands is one of Europe's major gas fields where extraction, gas processing, and gas storage all take place. It is also a region with intensive agriculture and cattle operations. An international research team investigated methane emissions there with the intent of distinguishing between methane from fossil fuel sources and methane arising from livestock, wetlands, and agriculture. Using both ground and aircraft measurements, the researchers determined that emissions from oil and gas operations account for 20 percent of regional methane, with the remainder from biogenic sources. That figure for fossil fuel sources is, nevertheless, ten times higher than the 1.9 percent that was estimated by previous inventories. Ground-based measurements at extraction, processing, and storage sites found low emission rates compared to gas production facilities in the United States.

[1552] Matthew D. Merrill et al., "Federal Lands Greenhouse Gas Emissions and Sequestration in the United States: Estimates for 2005–14," *U.S. Geological Survey Scientific Investigations Report 2018-5131*, 2018, https://doi.org/10.3133/sir20185131.
[1553] Adam Aton, "Fossil Fuel Extraction on Public Lands Produces One Quarter of U.S. Emissions," *E&E News*, November 27, 2018, https://www.scientificamerican.com/article/fossil-fuel-extraction-on-public-lands-produces-one-quarter-of-u-s-emissions/.
[1554] Timothy L. Vaughn et al., "Temporar Variability Largely Explains Top-Down/Bottom-Up Difference in Methane Emission Estimates From a Natural Gas Production Region," *Proceedings of the National Academy of Sciences U.S.A.* 115, no. 46 (2018): 11712–17, https://doi.org/10.1073/pnas.1805687115.

Production volume was a poor predictor of emission rates. Even wells with no production still had emissions.[1555]

- August 1, 2018 – California's climate goals call for an 80 percent reduction in emissions by 2050. With this goal in mind, a Lawrence Berkeley National Laboratory team set out to estimate what fraction of California's greenhouse gas emissions represent methane emissions from residential homes, including leakage from gas pipes, stovetops, combustion appliance pilot lights, and forced air furnaces. Total methane emissions from California homes represent 15 percent of the total emissions from the natural gas sector in California and represent two percent of the state's total methane emissions, as calculated in the 2015 state inventory. The team also found that emissions from pilot lights constitute a significant fraction as do flames in domestic hot water heaters. "While methane emissions from houses are small compared to most sources, California's ambitious goals…suggest value in testing and repairing obvious leaks in residential gas lines, modernizing combustion appliances to move away from pilot lights, and gradually increasing the use of non-fossil fuel energy sources for residential space and hot water heating and cooking."[1556]

- July 10, 2018 – In 2015, as part of a follow-up study, a research team used helicopters to measure methane emission patterns at 353 well pads in North Dakota's Bakken Shale that had been surveyed in the same way in 2014. In the interim, 21 newly producing well pads were added to the sampling area. They found that the individual well pads that emitted methane in 2014 were far more likely to be still emitting in 2015 than would be expected by chance alone. The reasons for this persistent leaking were not identified but potentially include tanks without vapor recovery systems, overpressurization, undersized flaring systems, stuck or clogged valves, and "poorly designed equipment." Altogether, researchers quantified 33 plumes of methane and ethane arising from these well pads.[1557]

- June 21, 2018 – An analysis of methane leaks from the U.S. oil and gas supply chain found that natural gas is just as damaging as coal for the climate over a 20-year time frame. This study combined on-the-ground measurements of leaks at selected facilities (bottom-up methods) with data collected from the atmosphere via aircraft (top-down methods). Based on the results, the authors estimated that roughly 2.3 percent of all the natural gas extracted in the United States escapes into the air. This estimated level of leakage was 60 percent higher than the EPA's estimate of 1.4 percent. The authors believe their emissions estimate is the more accurate because they used helicopters to capture episodic releases of large plumes of methane caused by "abnormal operating conditions" and "failure-prone systems" that were likely missed by the sampling methods used for EPA's greenhouse gas inventory. Liquid storage tank hatches and vents were the

[1555] Tara I. Yacovitch et al., "Methane Emissions in the Netherlands: The Groningen Field," *Elementa Science of the Anthropocene* 6, no. 57 (2018), https://doi.org/10.1525/elementa.308.
[1556] Marc L. Fischer et al., "Natural Gas Methane Emissions From California Homes" (California Energy Commission, 2018), https://www.energy.ca.gov/publications/2018/natural-gas-methane-emissions-california-homes.
[1557] Jacob G. Englander et al., "Aerial Interyear Comparison and Quantification of Methane Emissions Persistence in the Bakken Formation of North Dakota, USA," *Environmental Science & Technology* 52, no. 15 (2018): 8947–53, https://doi.org/10.1021/acs.est.8b01665.

source of most of acute incidents.[1558]

- December 20, 2017 – A major study led by NASA researchers concluded. that fossil fuel sources are driving the sharp uptick in global atmospheric concentrations of methane since 2006. Using satellite measurements and isotopic analysis, the team showed that methane from biomass sources, such as fires, decreased over the time period 2001-2016 while fossil fuel sources of methane increased. These findings helped reconcile conflicting results from other previous studies.[1559]

- October 17, 2017 – Using planes, an international team of researchers measured regional airborne methane and ethane emission rates from the Alberta oil and gas fields in Canada. They compared these results to emissions reported by the industries themselves, as part of an accounting system that requires operators to report flaring and venting volumes, and found large discrepancies. Based on the amounts of methane and ethane detected in the atmosphere above the oil and gas fields, the reported industry emissions in this region should be 2.5 ± 0.5 times higher. Such large discrepancies between actual methane emissions and industry-provided data represent a "reporting gap" and present a critical challenge when determining policy. Proposed regulations in Canada currently call for reducing methane emissions from Canadian fracking operations by 45 percent. However, these data indicate that most of the methane emissions from these operations arise from fugitive leaks that are not being measured at all and/or from episodes of unreported venting.[1560]

- July 18, 2017 – A team of 15 climate scientists led by James Hansen at Columbia University conducted a study on the growth rate of greenhouse gas climate forcing, which has accelerated by 20 percent in the past decade. (Climate forcing is the difference between the amount of the sun's energy that is absorbed by the Earth and amount that radiates back into space.) The authors note that methane (CH_4) is the largest climate-forcing gas after carbon dioxide. With an atmospheric lifetime of only about ten years, "there is potential to reduce climate forcing rapidly if CH_4 sources are reduced." However, "there is a danger of increased leakage with expanded shale gas extraction." Noting that the speed of ice sheet melting and sea level rise are difficult to predict, the authors assert that targets for limiting global warming should aim to keep global temperatures close to the preindustrial Holocene range rather than allow them to rise to those found during the prior Eemian period, when sea levels were 6-9 meters higher than today. Such targets require immediate phase-out of fossil fuel emissions, along with profound changes in farming and forestry practices. A delay in taking these measures to minimize irreversible climate impacts means that the next generation will be required to undertake risky, expensive, large-scale CO_2 extraction practices, such as carbon capture.

[1558] Ramon A. Alvarez et al., "Assessment of Methane Emissions From the U.S. Oil and Gas Supply Chain," *Science* 361, no. 6398 (2018): 186–88, https://doi.org/10.1126/science.aar7204.
[1559] John R. Worden et al., "Reduced Biomass Burning Emissions Reconcile Conflicting Estimates of the Post-2006 Atmospheric Methane Budget," *Nature Communications* 8 (2017): 2227, https://doi.org/10.1038/s41467-017-02246-0.
[1560] Matthew R. Johnson et al., "Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector," *Environmental Science & Technology* 51, no. 21 (2017): 13008–17, https://doi.org/10.1021/acs.est.7b03525.

"If high fossil fuel emissions continue, a great burden will be placed on the young. . . . Continued high fossil fuel emissions unarguably sentences young people to either a massive, implausible cleanup or growing deleterious climate impacts or both."[1561]

- July 8, 2017 – An investigative report from the Inter Press Service News Agency examined the climate impacts of methane emissions from Mexico, which is sixth among the world's nations in technically recoverable shale gas reserves (after China, Argentina, Algeria, the United States, and Canada). Mexico's current energy policy, introduced in 2014, emphasizes the exploitation of shale gas using fracking. Using data from the state-owned energy company Petroleos Mexicanos (PEMEX), the Inter Press Service story documents that as of 2017, more than 900 wells, located in six of Mexico's 32 states, have been drilled and fracked. High volumes of methane are emitted during venting, and methane emissions have been increasing sharply. In 2016, the total methane emissions from Mexico's PEMEX Exploration and Production operations were 641,517 metric tons, 38 percent higher than the previous year. According to researcher Ramón Torres, of the National Autonomous University of Mexico, who is quoted in the story, "Current regulations are based on best practices, but the philosophy of environmental protection has been abandoned. Exploitation is deepening inequities in a negative way, such as environmental impact. It is irresponsible to auction reserves without a proper evaluation of environmental and social impacts."[1562]

- June 19, 2017 – A study that measured methane emissions from various components of drilling and fracking equipment on well pads located in four different shale basins in Colorado, Utah, Arkansas, and Wyoming found widely varying results. In Colorado and Utah, a small percentage of well pads leaked the vast majority of methane, whereas leakage was more equitably distributed among wells in Wyoming. The research team also found variations that were dependent on oil/gas/water content as well as on the numbers of wells per well pad. In sum, emissions from well pads contributed significantly to basin-wide methane emissions but varied depending on location. [Note: the authors identify XTO Energy as a cost share partner in this study.][1563]

- April 18, 2017 – San Juan Basin in the four-corner region of Utah, Arizona, New Mexico, and Colorado, is one of the largest coal-bed methane producing regions in North America. Between 2003 and 2015, natural gas production declined, and yet, as revealed by atmospheric sampling from aircraft flying over the basin, methane emissions did not decrease during this same time period. These results confirm earlier findings from a satellite study that also showed no declines in regional methane concentrations in spite of significant declines in natural gas production. According to the authors, the likely

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[1561] James Hansen et al., "Young People's Burden: Requirement of Negative CO2 Emissions," *Earth System Dynamics* 8 (2017): 577–616, https://doi.org/10.5194/esd-8-577-2017.
[1562] Emilio Godoy, "Mexico's Methane Emissions Threaten the Environment," *Inter Press Service News Agency*, July 8, 2017, sec. Energy, http://www.ipsnews.net/2017/07/mexicos-methane-emissions-threaten-environment/.
[1563] Anna M. Robertson et al., "Variation in Methane Emission Rates from Well Pads in Four Oil and Gas Basins with Contrasting Production Volumes and Compositions," *Environmental Science & Technology* 51, no. 15 (2017): 8832–40, https://doi.org/10.1021/acs.est.7b00571.

explanation for the region's persistent, elevated methane levels is increased oil drilling in the basin.[1564]

- February 9, 2017 – Using ground-based monitoring methods, a team led by Drexel University researchers monitored a range of emissions, including methane, in two intensively drilled regions of the Marcellus Shale basin in Pennsylvania. The goal was to understand the concentrations and sources of relevant air pollutants that had previously been reported as impacts of drilling and fracking operations. Airborne methane concentrations were higher in southwestern Pennsylvania as compared to northeastern Pennsylvania. The authors conclude that urban-like levels of air pollutants in rural Pennsylvania are likely due to emissions from oil and gas operations in the Marcellus Shale basin.[1565]

- January 9, 2017 – A modeling study found that short-lived greenhouses gases, such as methane, contribute to thermal expansion of the ocean over much longer time scales than their brief atmospheric lifetimes might otherwise predict. "Actions taken to reduce emissions of short-lived gases could mitigate centuries of additional future sea-level rise."[1566]

- December 12, 2016 – As part of the interdisciplinary Global Carbon Project, a consortium of scientists undertook a meta-analysis that synthesizes many hundreds of individual studies in order to better understand the global methane cycle. Integrating atmospheric measurements with ground-based data, the researchers found more uncertainty in the emissions from natural sources than from human activities. For the 2003–2012 decade, global methane emissions were 558 teragrams per year (range of 540–568), with 60 percent of global methane emissions attributed to anthropogenic sources of all kinds and with a significant contribution (likely at least 39 percent) from oil and gas production operations.[1567]

- December 12, 2016 – An editorial published in *Environmental Research Letters* by an international team of scientists urges immediate attention to quantify and reduce methane emissions. "Unlike CO2, atmospheric methane concentrations are rising faster than at any time in the past two decades and, since 2014, are now approaching the most greenhouse-gas-intensive scenarios." The authors present methods of evaluating anthropogenic and

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[1564] Mackenzie L. Smith et al., "Airborne Quantification of Methane Emissions over the Four Corners Region," *Environmental Science & Technology* 51, no. 0 (2017): 5832–37, https://doi.org/10.1021/acs.est.6b06107.

[1565] J. Douglas Goetz et al., "Analysis of Local-Scale Background Concentrations of Methane and Other Gas-Phase Species in the Marcellus Shale," *Elementa: Science of the Anthropocene* 5, no. 1 (2017), https://doi.org/10.1525/elementa.182.

[1566] Kirsten Zickfeld, Susan Solomon, and Daniel M. Gilford, "Centuries of Termal Sea-Level Rise Due to Anthropogenic Emissions of Short-Lived Greenhouse Gases," *Proceedings of the National Academy of Sciences U.S.A.* 114, no. 4 (2017): 657–62, https://doi.org/10.1073/pnas.1612066114.

[1567] Marielle Saunois et al., "The Global Methane Budget 2000-2012," *Earth System Science Data* 8 (2016): 697–751, https://doi.org/10.5194/essd-8-697-2016.

biogenic sources of methane, as from agricultural practices and project future methane emissions.[1568]

- November 8, 2016 – The government of Scotland released a report confirming that the pursuit of unconventional oil and gas extraction would make more difficult the nation's goal of meeting its climate targets on greenhouse gas emissions.[1569]

- November 1, 2016 – A life cycle analysis of greenhouse gas emissions from fracking operations in the Marcellus Shale region found that upstream activities associated with the use and transportation of chemicals, water, and sand mining contributed relatively lower emissions than downstream phases of the fracking process, which include gas combustion, methane leakage, venting, and flaring.[1570]

- October 5, 2016 – A new inventory of worldwide methane emissions from various sources finds that methane emissions from the fossil fuel industry are 20-60 percent higher than previously thought.[1571] This discovery, based on isotopic fingerprinting of methane sources, has prompted researchers to call for revisions to current climate prediction models and for a renewed emphasis on reducing methane emissions as a necessary tool for combating climate change.[1572]

- September 26, 2016 – In ratifying the Paris Climate Agreement, the United States pledged to reduce its greenhouse gas emissions 26-28 percent by 2025 as compared to 2005 levels. A research team from Lawrence Berkeley National Laboratory found that the United States is on track to miss this target, in large part because of soaring methane emissions.[1573, 1574]

- September 12, 2016 – Using isotopic analysis and archived air samples collected from 1977 to 1998, as well as more contemporary data, a team of researchers from Oregon presented "strong evidence" that methane emissions from fossil fuel sectors were

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[1568] Marielle Saunois et al., "The Growing Role of Methane in Anthropogenic Climate Change," *Environmental Research Letters* 11, no. 12 (2016): 120207, https://doi.org/10.1088/1748-9326/11/12/120207.
[1569] Committee on Climate Change, "Unconventional Oil and Gas: Compatibility With Scottish Greenhouse Gas Emissions Targets," Research and Analysis (Energy and Climate Change Directorate, Scotland, November 8, 2016), http://www.gov.scot/Resource/0050/00509324.pdf.
[1570] Christopher Sibrizzi and Peter LaPuma, "An Assessment of Life Cycle Greenhouse Gas Emissions Associated With the Use of Water, Sand, and Chemicals in Shale Gas Production of the Pennsylvania Marcellus Shale," *Journal of Environmental Health* 79, no. 4 (2016): 8–15.
[1571] Stefan Schwietzke et al., "Upward Revision of Global Fossil Fuel Methane Emissions Based on Isotope Database," *Nature* 538 (2016): 88–91, https://doi.org/10.1038/nature19797.
[1572] Adam Vaughan, "Fossil Fuel Industry's Methane Emissions Far Higher Than Thought," *The Guardian*, October 5, 2016, https://www.theguardian.com/environment/2016/oct/05/fossil-fuel-industrys-methane-emissions-far-higher-than-thought.
[1573] Jeffery B. Greenblatt and Max Wei, "Assessment of the Climate Commitments and Additional Mitigation Policies of the United States," *Nature Climate Change* 6 (2016): 1090–93, https://doi.org/10.1038/nclimate3125.
[1574] Chris Mooney, "The U.S. Is on Course to Miss Its Emissions Goals, and One Reason Is Methane," *The Washington Post*, September 26, 2016, sec. Climate and Environment, https://www.washingtonpost.com/news/energy-environment/wp/2016/09/26/the-u-s-is-on-course-to-miss-its-emissions-goals-and-one-reason-is-methane/?utm_term=.80df24676a21.

approximately constant in the 1980s and 1990s but then increased significantly between 2000 and 2009. Over the same time period, methane emissions from biomass burning, rice cultivation, and wetlands decreased. These results contradict the findings of earlier studies that used atmospheric ethane as a marker for methane and had concluded that fugitive fossil fuel emissions fell during much of that period. (More recent studies show that ethane emissions are increasing again.)[1575, 1576, 1577]

- July 11, 2016 – A group of 130 environmental and health organizations signed a formal complaint with the Inspector General of the U.S. Environmental Protection Agency (EPA) about a pivotal 2013 study that was published in the *Proceedings of the National Academies of Sciences* and which was led by University of Texas chemist David T. Allen. The letter accused Allen of "systemic fraud, waste, and abuse" for his reliance on an inaccurate measurement device that was known to underestimate methane levels. Partially funded by the oil industry, Allen's study reported very low methane emission rates as part of a large survey of 190 drilling and fracking sites across the nation. That flawed study was influential, said complainants, in preventing EPA from recognizing the magnitude of methane leakage from drilling and fracking operations.[1578] (See also the entry below for March 24, 2015.)

- June 17, 2016 – A comparative assessment of emerging methods for measuring methane emissions from different sources recommends combining analytic methods with chemical mass balance (CMB) methods. The CMB system is currently used in the Barnett Shale oil and gas production region in Texas as an approach to tracing methane emissions back to their sources.[1579]

- May 25, 2016 – As part of the first field study to directly measure methane emissions from the heavily drilled Bakken Shale formation in northwestern North Dakota, a team led by atmospheric chemist Jeff Peischl at NOAA flew research aircraft over the region in May 2014. The researchers derived a methane emission rate of 275,000 tons of methane per year, which is similar to the rate of methane leakage in the Front Range area of Colorado but significantly lower than previous studies of the Bakken area that relied on satellite remote sensing data during an earlier time period (2006-2011). Analyzing the chemical composition of air samples, the NOAA team determined that almost all of the methane originated with oil and gas operations, rather than with natural or agricultural

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[1575] A. L. Rice et al., "Atmospheric Methane Isotopic Record Favors Fossil Sources Flat in 1980s and 1990s With Recent Increase," *Proceedings of the National Academy of Sciences U.S.A.* 113, no. 39 (2016): 10791–96, https://doi.org/10.1073/pnas.1522923113.
[1576] C. Harvey, "Scientists May Have Solved a Key Mystery About the World's Methane Emissions," *The Washington Post*, September 13, 2016, sec. Climate and Environment, https://www.washingtonpost.com/news/energy-environment/wp/2016/09/13/the-answer-to-the-global-methane-mystery-fossil-fuels-a-study-finds/?utm_term=.64a94b9abf4e.
[1577] Camille von Kaenel, "Debate Rises over Real Source of Higher Methane Emissions," *Scientific American*, September 13, 2016, sec. Environment, https://www.scientificamerican.com/article/debate-rises-over-real-source-of-higher-methane-emissions/.
[1578] Jeff Johnson, "Pivotal Study on Methane Leaks From U.S. Oil and Natural Gas Wells Under Fire," *Chemical & Engineering News*, July 11, 2016, http://cen.acs.org/articles/94/i28/Pivotal-study-methane-leaks-US.html.
[1579] David Allen, "Attributing Atmospheric Methane to Anthropogenic Emission Sources," *Accounts of Chemical Research* 49, no. 7 (2016): 1344–50, https://doi.org/10.1021/acs.accounts.6b00081.

sources, and estimated a leakage rate of 4.2-8.4 percent.[1580] Scaled to production, this emission rate is slightly lower than that estimated by EPA in its recently revised inventory.[1581, 1582] (See April 15, 2016 entry below.)

- April 15, 2016 – In its 21st annual greenhouse gas inventory, which includes 2014 data, the EPA increased its leakage assessment from oil and gas operations by 34 percent. For oil production alone, the EPA more than doubled its estimates of methane emissions. Further, in an admission that the agency had been historically underestimating methane leaks, the EPA also retroactively increased estimates of past emissions from the fossil fuel sector as expressed in prior inventories.[1583, 1584] In an accompanying news release, the agency said, "Data on oil and gas show that methane emissions from the sector are higher than previously estimated. The oil and gas sector is the largest emitting-sector for methane and accounts for a third of total U.S. methane emissions."[1585] Past EPA inventories had identified livestock as the number one source of U.S. methane. These annual inventories fulfill the EPA's obligations under the United Nations Framework Convention on Climate Change, signed and ratified by the United States in 1992, and attempt to identify and quantify U.S. anthropogenic sources and sinks of greenhouse gases for the time period 1990 and forward. The upward revision in both past and current inventories is a reflection of changing methodologies for measuring methane leaks.[1586] Older methods included the incorporation of "bottom-up" data supplied by the oil and gas industry, without attention to high-emitting or super-emitting sources or possible sources of error introduced by flawed measuring equipment. In addition, the use of a Global Warming Potential multiplier of 25 for methane, which is based on a 100-year time horizon, rather than 86 for a 20-year time horizon, has come under sustained criticism given the urgency of the climate crisis.[1587, 1588]

[1580] Jeff Peischl et al., "Quantifying Atmospheric Methane Emissions From Oil and Natural Gas Production in the Bakken Shale Region of North Dakota," *Journal of Geophysical Research: Atmospheres* 121, no. 10 (2016): 6101–11, https://doi.org/10.1002/2015JD024631.
[1581] National Oceanic and Atmospheric Administration, "North Dakota's Bakken Oil and Gas Field Leaking 275,000 Tons of Methane per Year," Press Release (U.S. Department of Commerce, May 10, 2016), http://www.noaa.gov/news/north-dakota-s-bakken-oil-and-gas-field-leaking-275000-tons-of-methane-year.
[1582] James MacPherson, "A New Study Says the Oil-Producing Region of North Dakota and Montana Leaks 275,000 Tons of Methane Annually," *U.S. News*, May 11, 2016, http://www.usnews.com/news/science/articles/2016-05-11/study-bakken-oil-field-leaks-275-000-tons-of-methane-yearly.
[1583] U.S. Environmental Protection Agency, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014," April 15, 2016, https://www.epa.gov/sites/production/files/2016-04/documents/us-ghg-inventory-2016-main-text.pdf.
[1584] Jeff Johnson, "Oil, Natural Gas Operations Now Top U.S. Methane Emitters," *Chemical & Engineering News*, April 25, 2016, http://cen.acs.org/articles/94/i17/Oil-natural-gas-operations-top.html?type=paidArticleContent.
[1585] U.S. Environmental Protection Agency, "EPA Publishes 21st Annual U.S. Greenhouse Gas Inventory," Press Release, April 15, 2016, https://archive.epa.gov/epa/newsreleases/epa-publishes-21st-annual-us-greenhouse-gas-inventory.html.
[1586] Chris Mooney, "The U.S. Has Been Emitting a Lot More Methane Than We Thought, Says EPA.," *The Washington Post*, April 15, 2016, sec. Climate and Environment, https://www.washingtonpost.com/news/energy-environment/wp/2016/04/15/epa-issues-large-upward-revision-to-u-s-methane-emissions/?utm_term=.eca9c599ff09.
[1587] Thomas Sumner, "EPA Underestimates Methane Emissions," *Science News*, April 14, 2016, sec. Environment, https://www.sciencenews.org/article/epa-underestimates-methane-emissions.
[1588] Tim Profeta, "Study, EPA Spotlight Methane Emissions From Oil and Gas Industry," *National Geographic*, March 3, 2016.

- April 7, 2016 – Since 2009, corresponding to the advent of the U.S. shale gas boom, North American ethane emissions have increased by 5 percent per year. This trend represents a reversal of a previous multi-decade decline (mid-1980s until the end of the 2000s) in the abundance of atmospheric ethane that had been attributed to the reduction of fugitive emissions from fossil fuel sources. These are the findings of an international research team, which analyzed remote sensing data gathered by the Network for the Detection of Atmospheric Composition Change at globally distributed ground-based sites. Ethane is a volatile organic compound (VOC) that readily reacts with nitrogen oxides in the presence of sunlight to create ground-level ozone (smog). Also a potent greenhouse gas, ethane is co-released along with methane from drilling and fracking sites. The source of two-thirds of the ethane in Earth's atmosphere is leakage from natural gas wells and pipelines. Because ethane is co-emitted with methane and can serve as a marker for it, this documentation of a sharp, recent uptick in atmospheric ethane is part of a larger body of evidence suggesting that U.S. drilling and fracking operations are driving up global methane levels.[1589] (See also entry dated June 13, 2016 in Air Pollution section].)

- April 5, 2016 – Helicopter-based infrared camera surveys of more than 8,000 oil and gas wells in seven U.S. regions found that well pads emit considerably more methane and VOCs than captured by earlier inventories. Moreover, these emissions were widely and unpredictably variable from site to site and from well to well. Between 1 and 14 percent of oil and gas well pads surveyed were high emitters of hydrocarbons and VOCs, with the greatest number observed in oil-producing areas and in areas with horizontal drilling. Further, while some leakage was intentional or part of routine maintenance operations, unplanned releases from malfunctioning equipment were also common, as were combustion emissions from flares and compressor engine exhaust. Over 90 percent of total airborne emissions from well pads originated with vents and hatches on aboveground storage tanks. These findings deeply undercut the assumption in the EPA's Oil & Gas Emission Estimation Tool that tank control systems offer 100 percent capture efficiency. The overall inability to predict which sites were super-emitters (meaning that they leaked into the air more than 200 cubic feet of methane and VOCs per hour) demonstrates that continuous, site-specific monitoring would be required to identify and remediate methane leaks from drilling and fracking operations.[1590] In a comment about the findings to *Inside Climate News*, Cornell University engineer Anthony Ingraffea, who was not an author of the paper, said, "It makes regulation very difficult. If you have all these possible sites where you can have leaks, you can never have enough inspectors with

[1589] Bruno Franco et al., "Evaluating Ethane and Methane Emissions Associated With the Development of Oil and Natural Gas Extraction in North America," *Environmental Research Letters* 11 (2016): 044010, https://doi.org/10.1088/1748-9326/11/4/044010.
[1590] David R. Lyon et al., "Aerial Surveys of Elevated Hydrocarbon Emissions from Oil and Gas Production Sites," *Environmental Science & Technology* 50 (2016): 4877–86, https://doi.org/10.1021/acs.est.6b00705.

all the right equipment being in all the right places at all the right times. It's too complex a system."[1591]

- March 10, 2016 – Attempting to explain a methane plateau between 1999 and 2006 within otherwise almost continuously increasing levels of atmospheric methane since the dawn of the industrial revolution, an international team of atmospheric scientists reconstructed the global history of methane and used isotopic carbon fingerprinting to parse the sources of its emission. Thermogenic emissions were assumed to result from fossil-fuel sources, while biogenic sources were assumed to arise from wetlands and agricultural operations. Based on a geographic distribution of methane revealed by remote sensing, the authors concluded that agricultural emissions, especially increases in livestock inventories and rice cultivation, were the most likely drivers of observed global methane increases from 2006 to 2014.[1592] These results stand in contrast to other contemporaneous and recent studies that have supplied evidence for the role of oil and gas extraction in the recent upsurge in atmospheric methane.[1593] (See entry for February 16, 2016 below.)

- February 16, 2016 – A Harvard-led team used both satellite retrievals and surface observations to estimate that methane emissions in the United States increased by more than 30 percent over the past twelve years. These findings, which contradict the 10 percent decline reported by the EPA, suggest that the United States could be responsible for 30-60 percent of the recent global spike in atmospheric methane.[1594, 1595] Since 2015, research on atmospheric methane has frequently relied on an "inverse method" to optimize emission estimates by combining "bottom-up" and "top-down" data, yet data from different sources have not yielded consistent estimates of methane emissions and levels. Three major sources (Wecht et al. [2014], Miller et al. [2013], and Turner et al. [2015]) all found maximum emissions in the South Central United States, with spatial overlaps that made separating livestock sources from oil and gas sources difficult. Taking into account the time period investigated by differing studies reveals an increasing trend in methane emissions, with an increase of 38 percent from 2004 to 2011, a period of greatly increasing drilling activity. This trend is confirmed by analyzing temporal trends in satellite data. While this account still differs from the EPA's inventory in 2014 showing a 3 percent decrease in oil and gas emissions over that same time period, the

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[1591] Phil McKenna, "Researchers Find No Shortcuts for Spotting Wells That Leak the Most Methane," Inside Climate News, April 8, 2016, https://insideclimatenews.org/news/08042016/big-methane-leaks-superemitters-oil-gas-production-climate-change-edf/.
[1592] Hinrich Schaefer et al., "A 21st-Century Shift From Fossil-Fuel to Biogenic Methane Emissions Indicated by 13CH4," *Science* 352, no. 6281 (2016): 80–84, https://doi.org/10.1126/science.aad2705.
[1593] Phil McKenna, "The Mystery of the Global Methane Rise: Asian Agriculture or U.S. Fracking?," *Inside Climate News*, March 10, 2016, sec. Fossil Fuels, https://insideclimatenews.org/news/10032016/mysterious-global-methane-rise-asian-agriculture-or-us-fracking.
[1594] A. J. Turner et al., "A Large Increase in U.S. Methane Emissions Over the Past Decade Inferred From Satellite Data and Surface Observations," *Geophysical Research Letters* 43, no. 5 (2016): 2218–24, https://doi.org/10.1002/2016GL067987.
[1595] Bobby Magill, "Study Ties U.S. to Spike in Global Methane Emissions," *Climate Central*, February 16, 2016, http://www.climatecentral.org/news/us-60-percent-of-global-methane-growth-20037.

EPA's data presumed better control of measured leaks, which may not correlate with better control of overall emissions.

- January 29, 2016 – Working in the Marcellus Shale Basin, a Carnegie Mellon research team compared methane emissions from older conventional gas wells (those that were vertically drilled) and newer, unconventional gas wells (those that combined fracking with horizontal drilling). Measured by facility, the mean emission rate for unconventional wells was 23 times higher than that of conventional wells. This difference, in part, was attributed to the larger size of unconventional well pads, which, typically, have multiple wells per pad, more ancillary equipment, and produce more gas. When corrected for production, the conventional wells leaked more—that is to say, they lost a comparably larger fraction of methane per unit of production—likely due to "unresolved equipment maintenance issues." All together, the authors concluded, these new emissions data show that the recently instituted Pennsylvania Department of Environmental Protection's (PA DEP) methane emissions inventory substantially underestimates facility-level methane emissions. Five unconventional well sites included in this study leaked 10-37 times more methane than estimated in the state inventory.[1596]

- January 25, 2016 – Cornell University scientists introduced an innovative methodology for assessing potential climate impacts of alternative choices and used it to demonstrate that emissions of the two most important greenhouse gases (carbon dioxide and methane), calculated as time-integrated radiative forcing, are lower with heat pump water heaters than any other means of heating water. Further, their calculations showed that heat pump water heaters powered by coal-generated electricity achieve greater net climatic benefit than heaters powered by natural gas, while even greater benefits may be achieved by combining heat pump water heaters with electricity generated by renewable sources. The authors proposed and justified a methane emission rate of 3.8 percent for conventional shale gas, which is therefore offered as a lower bound for future, tightly controlled methane emissions from unconventional gas activities. The authors also made their web-based tool for evaluating the greenhouse gas footprint of reference and alternative technologies and its source code available to the public (at http://www.eeb.cornell.edu/howarth/methane/tool.htm).[1597]

- December 22, 2015 – To reconcile troubling divergences in published estimates of methane emissions, in which "top-down" estimates, based on atmospheric or satellite sampling, often exceed "bottom-up" estimates, based on ground-level sampling or individual source reports, researchers used a combination of repeated mass balance measurements plus ethane fingerprinting to improve top-down estimates and incorporated a more complete and detailed count of facilities to improve bottom-up estimates.[1598] The

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[1596] Mark Omara et al., "Methane Emissions from Conventional and Unconventional Natural Gas Production Sites in the Marcellus Shale Basin," *Environmental Science & Technology* 50, no. 4 (2016): 2099–2107, https://doi.org/10.1021/acs.est.5b05503.
[1597] Bongghi Hong and Robert W. Howarth, "Greenhouse Gas Emissions From Domestic Hot Water: Heat Pumps Compared to Most Commonly Used Systems," *Energy Science & Engineering* 42, no. 2 (2016): 123–33, https://doi.org/10.1002/ese3.112.
[1598] Daniel Zavala-Araiza et al., "Reconciling Divergent Estimates of Oil and Gas Methane Emissions," *Proceedings of the National Academy of Sciences U.S.A.* 112, no. 51 (2015), https://doi.org/10.1073/pnas.1522126112.

results, as demonstrated in the Barnett Shale oil and gas-producing region of Texas, revealed a convergence of estimates to within 10 percent for fossil methane and 0.1 percent for total methane, with predicted methane emissions 90 percent larger than those estimated by the EPA's Greenhouse Gas Inventory. Exclusion of additional problematic studies might have resulted in even greater convergence and higher estimates.[1599] The agreement between top-down and bottom-up estimates demonstrates that well-designed surveys using either approach can be useful, with spatially resolved bottom-up estimates pointing toward production sites as the source of 53 percent of emissions, compressor stations 31 percent of emissions, and processing plants 13 percent of emissions. The Barnett shale emission rate of 1.5 percent calculated in this study is low enough (less than 3 percent) to suggest that gas fired electricity production in this region causes less climate forcing than coal-fired electricity, but it is high enough (greater than 1 percent) to argue against the conversion of diesel-powered freight trucks to compressed natural gas. Gas production practices and heavier activity in other basins may lead to higher emission rates, as may the storage and long-distance or very long-distance transmission of natural gas.

- December 22, 2015 – Climate scientists want the United Nations to stop expressing the heat-trapping potential of methane over a 100-year time frame and instead use a twenty-year time frame when generating global warming potential, the conversion factor that allows policymakers to compare methane's ability to trap heat with that of carbon dioxide. Methane is a far more potent heat-trapping gas than is carbon dioxide, but it is also shorter lived. By convention, policymakers have used a 100-year time frame when calculating global warming potentials. However, there is no scientific reason to do so, and many scientific critics argue that choosing this time scale veils the true climate impacts of natural gas and "makes the gas appear more benign than it is."[1600]

- November 25, 2015 – Using reports from countries and companies with proved reserves of recoverable oil, natural gas, and coal, an analysis published in *Global Environmental Change* shows that full production of these resources would use up 160 percent of the world's estimated remaining carbon budget (designed to restrict anthropogenic climate change to equal to or less than 2^{o} C). While 76 percent of reserves are owned by states or state entities, the relatively smaller amount of reserves owned by investors poses the greater immediate threat, since those companies are more likely poised to produce, refine, and deliver fossil fuels to global markets in the near term. However, exploitation of existing proved reserves controlled by the private sector alone does not lead to warming above the 2^{o} limit, if it is not accompanied by exploration for and development of new reserves. Future considerations of fossil fuel use should focus not only on reducing private sector contributions but also on reducing contributions from countries that have

[1599] Lisa Song, "Texas Fracking Zone Emits 90% More Methane Than EPA Estimated," *Inside Climate News*, December 7, 2015, https://insideclimatenews.org/news/07122015/methane-emissions-texas-fracking-zone-90-higher-epa-estimate.
[1600] Gayathri Vaidyanathan, "How Bad of a Greenhouse Gas Is Methane?," *Scientific American*, December 22, 2015, https://www.scientificamerican.com/article/how-bad-of-a-greenhouse-gas-is-methane/.

historically dominated or currently dominate emissions, and especially nation-states with large undeveloped reserves.[1601]

- November 9, 2015 – Including data available through 2014, the World Meteorological Organization (WMO) reported that globally averaged levels of carbon dioxide, methane, and nitrous oxide reached new highs in 2014, with values, respectively, "143%, 254% and 121% of pre-industrial (1750) levels." [1602, 1603] While the atmospheric increase in carbon dioxide has slowed, methane and nitrous oxide levels continue to increase. Measurements from the WMO's Global Watch Programme point to wetlands in the tropics and anthropogenic sources at mid-latitudes of the northern hemisphere as the sources of increased methane over the past decade.

- October 8, 2015 – As a foundation for policy recommendations, Cornell University biogeochemist Robert Howarth summarized and analyzed the evidence documenting the magnitude of methane emissions related to oil and gas development in the United States since 2007. With estimated emission rates ranging from 3.8-12 percent, the high radiative forcing of methane over a twenty-year period prevents natural gas from serving as a bridge fuel. Instead of further investments in natural gas, Howarth proposes a rapid transition to electric powered vehicles for transportation, high-efficiency heat pumps for space and water heating, and imposition of a methane tax that is roughly 86 times higher than currently proposed carbon taxes, which typical address only carbon dioxide.[1604] Howarth also noted that the EPA "has seriously underestimated the importance of methane emissions in general—and from shale gas in particular."[1605]

- August 4, 2015 – A developer of high flow sampling technology determined that a commonly used instrument to quantify methane leakage has unreliable sensors and malfunctions in ways that vastly underreport emissions by factors of three to five. More than 40 percent of the compiled national methane inventory may be affected by this measurement failure, according to the author of this study.[1606] The implications of this discovery for our understanding of system-wide methane leakage rates from drilling and fracking operations are not known, but they do call into question the results of at least

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1601 Richard Heede and Naomi Oreskes, "Potential Emissions of CO2 and Methane From Proved Reserves of Fossil Fuels: An Alternative Analysis," *Global Environmental Change* 36 (2016): 12–20, https://doi.org/10.1016/j.gloenvcha.2015.10.005.

1602 World Meteorological Organization, "The State of Greenhouse Gases in the Atmosphere Based on Global Observations Through 2014," WMO Greenhouse Gas Bulletin 11, November 9, 2015, https://library.wmo.int/doc_num.php?explnum_id=7243.

1603 Tom Miles, "CO2 Levels Hit Record High for 30th Year in a Row," *Scientific American*, November 9, 2015, https://www.scientificamerican.com/article/co2-levels-hit-record-high-for-30th-year-in-a-row/.

1604 Robert W. Howarth, "Methane Emissions and Climatic Warming Risk From Hydraulic Fracturing and Shale Gas Development: Implications for Policy," *Energy and Emission Control Technologies* 3 (2015): 45–54, https://doi.org/10.2147/EECT.S61539.

1605 "Two Studies Highlight Risks of Fracking-Released Methane," Weather.com, October 20, 2015, https://web.archive.org/web/20151021134023/https://weather.com/science/environment/news/studies-highlight-risks-of-methane-from-fracking.

1606 Touché Howard, "University of Texas Study Underestimates National Methane Emissions at Natural Gas Production Sites Due to Instrument Sensor Failure," *Energy Science & Engineering* 3, no. 5 (2015): 443–55, https://doi.org/10.1002/ese3.81.

one major study of methane emissions that relied on this device for collecting data. This is the second of two studies that finds that the primary tool approved by the EPA for measuring and reporting emissions of methane fails to function properly when used as directed by the manufacturer. (See also entry below dated March 24, 2015.)

- July 21, 2015 – An international team of researchers investigated the claim that the fracking boom, which has dramatically increased supplies of natural gas in the United States, is the main driver of the modest decline in carbon dioxide emissions since 2007. Conventional wisdom, as expressed by the Third National Climate Assessment of the U.S. Global Change Research Program, attributes the drop in emissions to a shift away from carbon dioxide-intensive coal and toward natural gas in power plants. But this team analyzed the sources of change in carbon dioxide emissions and, using a tool called input-output structural decomposition analysis, documented that the economic downturn, not fuel switching in the power sector, was the explanation for declining carbon dioxide emissions since 2007. The single biggest impact on U.S. emissions was changes in the volume of goods and services consumed. Between 2007 and 2013, driven by a huge drop in the volume of capital investment, emissions associated with capital formation decreased by almost 25 percent. During the same period, emissions related to household consumption decreased by 11 percent.[1607]

- July 7, 2015 – A scientific opinion piece by Environmental Defense Fund researchers involved in a group of 11 studies on methane emissions in Texas' Barnett Shale provided an overview and orientation to new research that either measured or estimated methane emissions from oil and gas operations. Research from both top-down estimates (based on measuring atmospheric methane or related compounds at regional or larger scales) and bottom-up measurements (made directly from components or at ground level near studied sites) demonstrated that methane emissions from oil and gas operations in the Barnett Shale region exceeded the emissions expected from the EPA's greenhouse gas inventory, which relies on industry self-reporting and excludes many compressor stations. The new research detailed the importance of addressing high-emitting landfills and natural gas facilities ("super-emitters") and malfunctioning equipment in efforts to control ongoing methane emissions.[1608]

- May 28, 2015 – A comprehensive working paper from the New Climate Economy initiative of the Global Commission on the Economy and Climate at Stockholm Environment Institute found that the experience in the United States of substituting natural gas for oil was unlikely to be replicated around the globe and probably will not provide climate benefits unless coupled with strict controls on methane leakage, limits on total energy use, and policies to prevent the displacement of non-fossil fuel energy by methane. Citing multiple studies of the net climate impact of "more abundant, cheaper natural gas supplies," the Commission concluded that "both globally and for the United

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[1607] Kuishuang Feng et al., "Drivers of the US CO2 Emissions 1997–2013," *Nature Communications* 6 (2015): 7714, https://doi.org/10.1038/ncomms8714.
[1608] Robert Harriss et al., "Using Multi-Scale Measurements to Improve Methane Emission Estimates from Oil and Gas Operations in the Barnett Shale Region, Texas," *Environmental Science & Technology* 49, no. 13 (2015): 7525–26, https://doi.org/10.1021/acs.est.5b02305.

States, the increase in emissions from the scale effect [from increased energy consumption boosted by cheap natural gas and loss of potentially more expensive lower carbon approaches] fully offsets the emission benefits from the substitution effect, net of methane leakage."[1609, 1610]

- March 24, 2015 – A University of Cincinnati researcher and independent engineers documented that the Bacharach Hi-Flow Sampler (BHFS)—one of the only tools approved by the EPA for measuring and reporting emissions of methane from natural gas transmission, storage, and processing facilities—failed to function properly when used as indicated by the manufacturer. The BHFS, unless recalibrated daily and running revised software (or taking measurements in a nearly pure methane environment, which is exceedingly rare in the field), misreported high levels of natural gas by as much as an order of magnitude lower than actual concentration. A reanalysis of 2011 results from the City of Fort Worth Air Quality Study revealed at least seven instances for which the BHFS indicated sample concentrations at or below 5 percent when more reliable canister methane readings indicated concentrations that ranged from 6.1 percent to 90.4 percent. Inaccurate measurements like these can contribute to the discrepancy between "top-down" and "bottom-up" measurements of methane, with ground-level measurements from the BHFS potentially producing reports of falsely low emissions.[1611] This study was followed by another that further documented malfunctions in the BHFS device and called into question the results of a landmark 2013 survey of methane emissions at 190 drilling and fracking sites across the United States. That 2013 survey, from the University of Texas, relied on the BHFS device for collecting data and found very low leakage rates.[1612] (See also entry above dated August 4, 2015.)

- March 20, 2015 – A team led by Bruno Franco from the University of Liege in Belgium discovered an abrupt uptick in ethane levels at a mountaintop station in the Swiss Alps that is far removed from local pollution sources.[1613] In a later comment about this discovery, Franco said, "Since 2009, we observed increases of 5% per year here—it was completely unexpected."[1614] The team attributed the trend reversal to the natural gas

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[1609] Michael Lazarus et al., "Natural Gas: Guardrails for a Potential Climate Bridge," New Climate Economy Contributing Paper (Stockholm Environment Institute, May 2015), https://mediamanager.sei.org/documents/Publications/Climate/NCE-SEI-2015-Natural-gas-guardrails-climate-bridge.pdf.
[1610] Simon Evans, "The Climate Benefits of a Gas Bridge Are Unlikely to Be Significant," *The Australian Business Review*, June 2, 2015, http://www.businessspectator.com.au/article/2015/6/2/policy-politics/climate-benefits-gas-bridge-are-unlikely-be-significant.
[1611] Touché Howard, Thomas W. Ferrara, and Amy Townsend-Small, "Sensor Transition Failure in the High Flow Sampler: Implications for Methane Emission Inventories of Natural Gas Infrastructure," *Journal of the Air & Waste Management Association* 65, no. 7 (2015): 856–62, https://doi.org/10.1080/10962247.2015.1025925.
[1612] David T. Allen et al., "Measurements of Methane Emissions at Natural Gas Production Sites in the United States," *Proceedings of the National Academy of Sciences* 110 (2013): 17768–73, https://doi.org/10.1073/pnas.1304880110.
[1613] Bruno Franco et al., "Retrieval of Ethane From Ground-Based FTIR Solar Spectra Using Improved Spectroscopy: Recent Burden Increase Above Jungfraujoch," *Journal of Qualitative Spectroscopy and Radiative Transfer* 160 (2015): 36–49, https://doi.org/10.1016/j.jqsrt.2015.03.017.
[1614] Environmental Research Web, "Ethane Emissions Back on the Rise," May 23, 2016, http://environmentalresearchweb.org/cws/article/news/65093.

boom in North America. Ethane is released together with methane from drilling and fracking operations and serves as a proxy for it. (See also the entry above for April 7, 2016.)

- March 9, 2015 – With specialized equipment in a mobile van, University of Colorado, NOAA, Environmental Defense Fund, and independent researchers continuously measured methane and ethane from public roads at sites downwind of potential emission sources, such as natural gas production wellheads, processing plants, and compressor stations. The sampling method and modeling allowed capture of multiple "accidental" plumes, acquired during long drives across the study region between planned measurements near large facilities. Sampling was not random but documented a large number of facilities with low methane emission rates (equal to or less than 10 kg/hr), with a smaller yet important number of facilities showing much higher emissions. Although the largest measured emission in this study (1,360 kg/hr) corresponded to approximately $1.2 million in lost revenue per year, the authors noted that, in this industry, the "leak fraction" or "proportional loss" levels they documented would generally translate into only a small proportion of lost revenue, probably not sufficient to prompt strong energy-sector self-regulation.[1615]

- March 1, 2015 – Using a simulation model, the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, writing for Germany's Federal Environmental Agency, found that shale gas was not a cheap option to reduce global greenhouse gas emissions. Multiple comparison simulations found that shale gas availability, especially in the short-term, tends to lead to higher emissions due to lower energy prices inducing higher use. The net result is higher costs to achieve compliance with climate targets. In this model, shale gas was also found to compete in an unhelpful way with renewable energy sources, resulting in reduced use of renewable energy sources and reduced investment in energy efficiency measures.[1616]

- January 8, 2015 – Using a single integrated modeling program that incorporates detailed estimates of the world's reserves of oil, gas, and coal and is consistent with a wide variety of prior modeling approaches, University College London researchers demonstrated that, around the world, "a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused from 2010 to 2050" in order to meet a target of less than or equal to a 2 degree Celsius rise in global temperature. In addition, "development of resources in the Arctic and any increase in unconventional oil production are incommensurate with efforts to limit average global warming" below the 2 degree threshold. Calling for a "stark transformation" of our understanding of fossil fuel availability, the authors noted that, in a climate-constrained world, fears of scarcity of

[1615] Tara I. Yacovitch et al., "Mobile Laboratory Observations of Methane Emissions in the Barnett Shale Region," *Environmental Science & Technology* 49, no. 13 (2015): 7889–95, https://doi.org/10.1021/es506352j.
[1616] Jan Kersting et al., "The Impact of Shale Gas on the Costs of Climate Policy" (Environmental Research of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, 2015), https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/climate_change_03_2015_the_impact_of_shale_gas_1.pdf.

fossil fuels must be superseded by a commitment to preventing overuse of existing resources and reserves.[1617]

- November 26, 2014 – Stanford University and independent researchers compared coal and natural gas for power generation and concluded that the question of "whether natural gas plants are better than coal plants cannot be answered in the general case." During the period of plant operation, "natural gas plants can produce greater near-term warming than coal plants, with the same power output." They found that over time, natural gas plants can produce some reduction in near-term warming, but only if life cycle methane leakage rates are low and power plant efficiency is high. Relative to coal, there is the potential that "deployment of natural gas power plants could both produce excess near-term warming (if methane leakage rates are high) and produce excess long-term warming (if the deployment of natural gas plants today delays the transition to near-zero emission technologies)."[1618]

- October 23, 2014 – Adding to the debate about natural gas and climate change, a multi-center, international research team used a sophisticated, integrated approach to the global energy-economy-climate systems question and found no climate benefit to natural gas over other fossil fuels. As summarized by the editor of *Nature*,

> The development of hydraulic fracturing technologies has led to rapid growth in the use of natural gas as an energy source. Some evidence has suggested that this growing adoption of natural gas might lead a reduced greenhouse gas burden and consequent mitigation of climate change. This collaboration between five energy–climate modelling teams show that instead—under a scenario of abundant natural gas availability—increased consumption will have little or no impact on climate change." The authors concluded, "although market penetration of globally abundant gas may substantially change the future energy system, it is not necessarily an effective substitute for climate change mitigation policy.[1619]

- October 6, 2014 – Utilizing satellite data for the Bakken and Eagle Ford formations, scientists from Germany, the United Kingdom, and the University of Maryland confirmed that higher "top-down" estimates of fugitive methane leaks from oil and gas fields (which are obtained via tall tower flask samples, aircraft measurements, and road surveys) are more accurate than lower "bottom-up" estimates (which are obtained by summing emissions from different types of known sources at sites provided by participating utility companies). According to "bottom-up" estimates, the average U.S. leakage rate ranges from 1.2-2.0 percent. But satellite data show much higher leakage rates: 10.1 percent (± 7.3 percent) and 9.1 percent (± 6.2 percent), for the Bakken and

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[1617] Christophe McGlade and Paul Ekins, "The Geographical Distribution of Fossil Fuels Unused When Limiting Global Warming to 2° C," *Nature* 517 (2015): 187–90, https://doi.org/10.1038/nature14016.
[1618] Xiaochun Zhang, Nathan P. Myhrvold, and Ken Caldeira, "Key Factors for Assessing Climate Benefits of Natural Gas Versus Coal Electricity Generation," *Environmental Research Letters* 9, no. 11 (2014): 114022, https://doi.org/10.1088/1748-9326/9/11/114022.
[1619] Haewon McJeon et al., "Limited Impact on Decadal-Scale Climate Change From Increased Use of Natural Gas," *Nature* 514 (2014): 482–482, https://doi.org/10.1038/nature13837.

Eagle Ford formations, respectively. These higher estimates indicate that current inventories likely underestimate fugitive emissions and call into question any immediate climate benefit from switching from coal to natural gas. Similar results were seen for the Marcellus shale region, but as a result of technical and geographical limitations, the authors declined to quantify their results, pending future studies with enhanced equipment.[1620]

- September 24, 2014 – According to a paper published by scientists from the University of California and Stanford University, "… without strong limits on [greenhouse gas] emissions or policies that explicitly encourage renewable electricity, abundant natural gas may actually slow the process of decarbonization, primarily by delaying deployment of renewable energy technologies." The study builds on previous research by examining natural gas in a range of supply curves, with a tested economic model, and across three different types and levels of climate policy. Researchers found that abundant natural gas, even with low rates of methane leakage, does little to reduce—and may increase—greenhouse gases. They conclude that delaying deployment of renewable energy technologies "may actually exacerbate the climate change problem in the long term."[1621]

- September 2, 2014 – Analyzing the level of greenhouse gas emissions attributable to electricity from natural-gas-fired power plants and coal-fired power plants, economist Chris Busch and physicist Eric Gimon conclude that, over short time frames and at high rates of leakage, natural gas offers little benefit compared to coal and could exacerbate global warming. Although Busch and Gimon acknowledge that natural gas offers some reductions in greenhouse gas emissions over longer time frames, they point out that such reductions are not large enough for natural gas to play an expanded role in efforts to manage emissions. They conclude that under the best of circumstances, natural gas-fired electric power offers a modest benefit toward abating climate change, while if poorly developed (i.e., with extensive methane leaks, estimated by these authors to be on the order of 4 percent or higher), or if used to displace energy efficiency or renewable energy, natural gas could seriously contribute to increased greenhouse gas emissions.[1622]

- August 5, 2014 – Reporting in *Scientific American,* the science news organization Climate Central outlined the natural gas-related factors that threaten any ability to achieve climate goals through the proposed Clean Power Plan. "No one has any idea how much methane is leaking from our sprawling and growing natural gas system. This is a major problem, because without a precise understanding of the leak rate natural gas could actually make climate change worse." Referring to an interactive Climate Central tool that runs various methane leakage scenarios, the article notes that, even given modest leak rates and an aggressive transition, "we could still end up with little or no climate

[1620] Oliver Schneising et al., "Remote Sensing of Fugitive Methane Emissions From Oil and Gas Production in North American Tight Geologic Formations," *Earth's Future* 2, no. 10 (2014): 548–58, https://doi.org/10.1002/2014EF000265.
[1621] Christine Shearer et al., "The Effect of Natural Gas Supply on US Renewable Energy and CO2 Emissions," *Environmental Research Letters* 9, no. 9 (2014): 094008, https://doi.org/10.1088/1748-9326/9/9/094008.
[1622] Chris Busch and Eric Gimon, "Natural Gas versus Coal: Is Natural Gas Better for the Climate?," *The Electricity Journal* 27, no. 7 (2014): 97–111, https://doi.org/10.1016/j.tej.2014.07.007.

benefits by 2030 after an enormous financial and political investment in natural gas."[1623]

- July 25, 2014 –EPA's Office of Inspector General reports that the agency "has placed little focus and attention on reducing methane emissions from pipelines in the natural gas distribution sector." According to this report, the EPA acknowledged in 2012 that leaks from natural gas pipelines "accounted for more than 13 million metric tons of carbon dioxide equivalent emissions," are almost 100 percent methane, and represent more than 10 percent of total methane emissions from natural gas systems in the United States. Nevertheless, as report went on to note, the EPA does not have the partnerships in place to begin controlling methane leaks, such as with the Pipeline and Hazardous Materials Safety Administration, nor has it conducted a comprehensive analysis of emissions factors, relying instead on a 1996 study with a "high level of uncertainty."[1624]

- May 15, 2014 – A recent review of existing data on life cycle emissions of methane from natural gas systems concluded that, as a strategy for addressing climate change, natural gas is a "bridge to nowhere." The review found that, over a 20-year time frame, natural gas is as bad as or worse than coal and oil as a driver of climate change.[1625] Referencing this review and other recent studies, *Bloomberg Business News* reported that the EPA has underestimated the impact of methane leakage resulting from the production, transmission, and distribution of natural gas and is using outdated estimates of methane's potency compared to more recent estimates from the Intergovernmental Panel on Climate Change (IPCC).[1626]

- April 25, 2014 – A reassessment of the heat-trapping potential of greenhouse gases revealed that current methods of accounting underestimate the climate-damaging impact of methane pollution from all sources, including drilling and fracking operations.[1627]

- April 14, 2014 – A study from researchers at Purdue University, NOAA, Cornell University, University of Colorado at Boulder, and Pennsylvania State University, published in *Proceedings of the National Academy of Sciences* found very high levels of methane emissions above many wells being drilled at fracking sites in Pennsylvania.

[1623] Climate Central, "Methane Leak Rate Proves Key to Climate Change Goals," *Scientific American*, August 5, 2014, http://www.scientificamerican.com/article/methane-leak-rate-proves-key-to-climate-change-goals/.
[1624] U.S. Environmental Protection Agency Office of Inspector General, "Improvements Needed in EPA Efforts to Address Methane Emissions From Natural Gas Distribution Pipelines," July 25, 2014, https://www.epa.gov/sites/default/files/2015-09/documents/20140725-14-p-0324_0.pdf.
[1625] Robert W. Howarth, "A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footpring of Natural Gas," *Energy Science & Engineering* 2, no. 2 (2014): 47–60, https://doi.org/10.1002/ese3.35.
[1626] A. Childers, "EPA Understimates Fracking's Impact on Climate Change.," *Bloomberg*, May 9, 2014, http://www.bloomberg.com/news/2014-05-09/epa-underestimates-fracking-s-impact-on-climate-change.html.
[1627] Morgan R. Edwards and Jessika E. Trancik, "Climate Impacts of Energy Technologies Depend on Emissions Timing," *Nature Climate Change* 4 (2014): 347–52, https://doi.org/10.1038/NCLIMATE2204.

Levels were 100-1,000 times above the estimates of federal regulators, who have always assumed very low methane emissions as wells are drilled.[1628, 1629]

- February 26, 2014 – The United Nations' top environmental official, Achim Steiner, argued that the shale gas rush is "a liability" in efforts to slow climate change and that a switch from coal to natural gas is delaying critical energy transition to renewables.[1630]

- February 13, 2014 – A major study in *Science* by Stanford University, Massachusetts Institute of Technology, and the U.S. Department of Energy found that methane leaks negate any climate benefits of natural gas as a fuel for vehicles, and that the EPA is significantly underestimating methane in the atmosphere.[1631] Lead author Adam R. Brandt told the *New York Times*, "Switching from diesel to natural gas, that's not a good policy from a climate perspective."[1632] This study also concluded that the national methane leakage rate is likely between 3.6 and 7.2 percent of production.

- January 15, 2014 – As reported by the *Guardian*, a new study by BP concluded that shale gas "…will not cause a decline in greenhouse gases" and will do little to cut carbon emissions.[1633]

- December 30, 2013 – An analysis of fracking-related truck transportation in the Susquehanna River Basin in Pennsylvania found that greenhouse gas emissions from frack water and waste hauling operations were 70-157 metric tons of CO_2 equivalent per gas well.[1634]

- November 11, 2013 – In a letter to California Governor Jerry Brown, twenty of the nation's top climate scientists warned that pro-fracking policies will worsen climate disruption and harm California's efforts to be a leader in reducing greenhouse gas

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1628 Dana R. Caulton et al., "Toward a Better Understanding and Quantification of Methane Emissions From Shale Gas Development," *Proceedings of the National Academy of Sciences*, 2014, https://doi.org/10.1073/pnas.1316546111.
1629 Neela Banerjee, "EPA Drastically Underestimates Methane Released at Drilling Sites," *Los Angeles Times*, April 14, 2014, sec. Science, http://www.latimes.com/science/sciencenow/la-sci-sn-methane-emissions-natural-gas-fracking-20140414,0,2417418.story.
1630 Suzanne Goldenberg, "Achim Steiner: Shale Gas Rush 'a Liability' in Efforts Slow Climate Change," *The Guardian*, February 26, 2014, http://www.theguardian.com/environment/2014/feb/26/achim-steiner-shale-gas-rush-climate-change-energy.
1631 Adam R. Brandt et al., "Methane Leaks from North American Natural Gas Systems," *Science* 343, no. 6172 (2014): 733–35, https://doi.org/10.1126/science.1247045.
1632 Coral Davenport, "Study Finds Methane Leaks Negate Benefits of Natural Gas as a Fuel for Vehicles," *The New York Times*, February 13, 2014, http://www.nytimes.com/2014/02/14/us/study-finds-methane-leaks-negate-climate-benefits-of-natural-gas.html?smid=tw-share.
1633 Fiona Harvey and Terry Macalister, "BP Study Predicts Greenhouse Emissions Will Rise by Almost a Third in 20 Years," *The Guardian*, January 1, 2014, http://www.theguardian.com/business/2014/jan/15/bp-predicts-greenhouse-emissions-rise-third?CMP=twt_gu.
1634 Kevin R. Gilmore, Rebekah Hupp, and Janine Glathar, "Transport of Hydraulic Fracturing Water and Wastes in the Susquehanna River Basin, Pennsylvania," *Journal of Environmental Engineering* 140, no. 5 (2014), https://doi.org/10.1061/(ASCE)EE.1943-7870.0000810.

emissions. The letter called on Governor Brown to place a moratorium on fracking.[1635] On November 21, 2013, a group of Governor Brown's former policy and campaign advisors made a similar request in light of concerns about the effects of fracking on climate change and water pollution. [1636]

- October 18, 2013 – A team of researchers from multiple institutions including Harvard, the University of Michigan, and NOAA reported that methane emissions due to drilling activities in the south-central U.S. may be almost five times greater than reported by the world's most comprehensive methane inventory. "These results cast doubt on the US EPA's recent decision to downscale its estimate of national natural gas emissions by 25-30 percent," the authors wrote.[1637] As the *New York Times* reported, "The analysis also said that methane discharges in Texas and Oklahoma, where oil and gas production was concentrated at the time, were 2.7 times greater than conventional estimates. Emissions from oil and gas activity alone could be five times greater than the prevailing estimate."[1638]

- October 18, 2013 – A major study spearheaded by Stanford University's Energy Modeling Forum concluded that fracking and the shale gas revolution will have no long-term climate benefit. The study brought together a working group of about 50 experts and advisors from companies, government agencies, and universities, and modeling teams from 14 organizations. The study also found that build-out of infrastructure for fracking and natural gas will discourage efforts to conserve energy and boost efficiency. The study did not examine methane leaks in order to weigh in on the short-term climate impacts of natural gas.[1639]

- October 11, 2013 – As reported in the *Guardian*, key climate scientists argued that the growth in fracking across the United States is hurting the United States' credibility on climate change.[1640]

- October 2, 2013 – Updated measurements from the IPCC determined that methane is even worse for the climate than previously thought. The IPCC determined that methane is

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[1635] Paul Rogers, "Top Climate Scientists Call for Fracking Ban in Letter to Gov. Jerry Brown," *The Mercury News*, November 12, 2013, http://www.mercurynews.com/ci_24509392/top-climate-scientists-call-fracking-ban-letter-gov.
[1636] Sharon McNary, "Former Advisors to Gov. Brown Request Fracking Ban," *Southern California Public Radio*, November 21, 2013, http://www.scpr.org/blogs/politics/2013/11/21/15248/former-advisors-to-gov-brown-request-fracking-ban/.
[1637] Scot M. Miller et al., "Anthropogenic Emissions of Methane in the United States," *Proceedings of the National Academy of Sciences* 110, no. 50 (2013): 20018–22, https://doi.org/10.1073/pnas.1314392110.
[1638] Michael Wines, "Emissions of Methane in U.S. Exceed Estimates, Study Finds," *The New York Times*, November 25, 2013, http://www.nytimes.com/2013/11/26/us/emissions-of-methane-in-us-exceed-estimates-study-finds.html?_r=0.
[1639] Hillard Huntington, "Changing the Game? Emissions and Market Implications of New Natural Gas Supplies," *Energy Modeling Forum*, 2013, https://emf.stanford.edu/publications/emf-26-changing-game-emissions-and-market-implications-new-natural-gas-supplies.
[1640] Bobby Magill, "Fracking Hurts US Climate Change Credibility, Say Scientists," *The Guardian*, October 11, 2013, http://www.theguardian.com/environment/2013/oct/11/fracking-us-climate-credibility-shale-gas.

34 times more potent as a greenhouse gas in the atmosphere than CO2 over a 100-year timeframe, and 86 times more potent over a 20-year timeframe.[1641]

- September 27, 2013 – The IPCC formally embraced an upper limit on greenhouse gases for the first time, warning that the world will exceed those levels and face irreversible climatic changes in a matter of decades unless steps are taken soon to reduce emissions. The IPCC reported that humanity faces a "carbon budget"—a limit on the amount of greenhouse gases that can be produced by industrial activity before irreversible, damaging consequences—of burning about a trillion metric tons of carbon. The world is on track to hit that by around 2040 at the current rate of energy consumption.[1642]

- August 12, 2013 – A *New Scientist* review of the science on fracking and global warming concluded that fracking could accelerate climate change rather than slow it.[1643]

- May 28, 2013 – A research team led by Jeff Peischl, an associate scientist at NOAA and the Cooperative Institute for Research in Environmental Sciences, estimated that methane leakage from Los Angeles-area oil and gas operations was about 17 percent.[1644, 1645]

- May 2013 – A group of scientists and journalists studying climate change, led by energy systems analyst Eric Larson of Princeton University and the news organization Climate Central, reported that the often-purported 50 percent climate advantage of natural gas over coal is unlikely to be achieved over the next three to four decades given methane leaks and other factors.[1646] The 50 percent claim is based on the fact that natural gas produces half as much carbon dioxide when burned than coal, but it ignores the significant greenhouse gas impacts of methane leakage that occurs throughout the life cycle of natural gas production, transmission, and distribution.

- January 2, 2013 – A NOAA study found methane emissions from oil and gas fields in Utah to be as high as nine percent of production. These levels are considered extremely damaging to the climate.[1647]

- November 2012 – A review by the United Nations Environment Programme found that emissions from fracking, as well as other unconventional natural gas extraction methods,

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[1641] Intergovernmental Panel on Climate Change, *Climate Change 2013 – The Physical Science Basis Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. T. F. Stocker et al. (Cambridge University Press, 2014).
[1642] Justin Gillis, "U.N. Climate Panel Endorses Ceiling on Global Emissions," *The New York Times*, August 12, 2013, http://www.nytimes.com/2013/09/28/science/global-climate-change-report.html?pagewanted=all.
[1643] Fred Pearce, "Fracking Could Accelerate Global Warming," *New Scientist*, August 12, 2013, http://www.newscientist.com/article/dn24029-fracking-could-accelerate-global-warming.html#.UpEWqsQ3uSo.
[1644] Jeff Peischl et al., "Quantifying Sources of Methane Using Light Alkanes in the Los Angeles Basin, California," *Journal of Geophysical Research: Atmospheres* 118, no. 10 (2013): 4974–90, https://doi.org/10.1002/jgrd.50413.
[1645] Stephanie Paige Ogburn, "Solving the Case of California's Extra Methane," *Scientific American*, May 15, 2013, sec. Environment, http://www.scientificamerican.com/article/solving-the-case-of-californias-extra-machine/.
[1646] Eric D. Larson, "Natural Gas & Climate Change" (Climate Central, May 2013), http://assets.climatecentral.org/pdfs/NaturalGas-and-ClimateChange.pdf.
[1647] Tollefson, "Methane Leaks Erode Green Credentials of Natural Gas."

could increase global warming in the short-term and be comparable to coal over a 100-year timeframe.[1648]

- November 2012 – The International Energy Agency (IEA) found that a large natural gas boom—even with improvements in place to reduce leakage—would eventually lead to greenhouse gas concentrations of 650 parts per million and a global temperature rise of 3.5° C, far exceeding the 2° C limit which is critical to avoid the most severe effects of climate change.[1649]

- May 29, 2012 – The *Guardian* summarized a special report on natural gas by the IEA: "A 'golden age of gas' spurred by a tripling of shale gas from fracking and other sources of unconventional gas by 2035 will stop renewable energy in its tracks if governments do not take action."[1650]

- February 2012 – A study published in *Environmental Research Letters* found that the carbon dioxide emitted from the burning of natural gas —even neglecting the impacts of methane leakage—contributes significantly to greenhouse gas emissions that are driving climate change.[1651]

- February 7, 2012 – A NOAA study of Colorado gas fields measured methane emissions of about four percent, a significant percentage that could be very damaging to the climate.[1652]

- December 29, 2011 – As reported by the *New York Times,* levels of methane in the atmosphere have been steadily rising since 2007—coinciding with the onset of the fracking boom and posing a serious threat to the Earth's climate.[1653]

- October 2011 – A study from the National Center for Atmospheric Research concluded that substituting the use of natural gas for coal will increase, rather than decrease, the rate of global warming for many decades.[1654]

[1648] Pascal Peduzzi and Ruth Harding, "Gas Fracking: Can We Safely Squeeze the Rocks?" (United Nations Environment Programme Global Environmental Alert Service, 2012), Gas fracking: Can we safely squeeze the rocks?
[1649] World Energy Outlook, "Golden Rules for a Golden Age of Gas," Special Report (International Energy Agency, November 2012), https://www.iea.org/reports/golden-rules-for-a-golden-age-of-gas.
[1650] Fiona Harvey, "'Golden Age of Gas' Threatens Renewable Energy, IEA Warns," *The Guardian*, May 29, 2012, http://www.theguardian.com/environment/2012/may/29/gas-boom-renewables-agency-warns.
[1651] Nathan P. Myhrvold and Ken Caldeira, "Greenhouse Gases, Climate Change and the Transition From Coal to Low-Carbon Electricity," *Environmental Research Letters* 7, no. 1 (2012): 014019, https://doi.org/10.1088/1748-9326/7/1/014019.
[1652] Jeff Tollefson, "Air Sampling Reveals High Emissions From Gas Field," *Nature* 482 (2012): 139–40.
[1653] Justin Gillis, "The Puzzle of Rising Methane," *The New York Times*, December 29, 2011, http://green.blogs.nytimes.com/2011/12/29/the-puzzle-of-rising-methane/.
[1654] Tom M. L. Wigley, "Coal to Gas: The Influence of Methane Leakage," *Climatic Change* 108 (2011): 601, https://doi.org/10.1007/s10584-011-0217-3.

- July 6, 2011 – According to the U.S. Energy Information Administration and other research, significant amounts of methane are leaking from aging gas pipelines and infrastructure.[1655]

- April 2011 – A comprehensive analysis of the greenhouse gas footprint of natural gas from shale formations found that between 3.6 percent to 7.9 percent of the methane from natural gas production wells escapes into the atmosphere, rather than being combusted, thereby undermining any climate benefits of gas over coal as a source of energy.[1656, 1657]

1655 Phil McKenna, "Thousands of Gas Leaks Under Boston and San Francisco," *New Scientist*, July 6, 2011, http://www.newscientist.com/article/mg21128203.800-thousands-of-gas-leaks-under-boston-and-san-francisco.html#.UpEbbMQ3uSp.

1656 Robert W. Howarth, Renee Santoro, and Anthony Ingraffea, "Methane and the Greenhouse-Gas Footprint of Natural Gas From Shale Formations," *Climatic Change* 106 (2011): 679, https://doi.org/10.1007/s10584-011-0061-5.

1657 Robert W. Howarth, Renee Santoro, and Anthony Ingraffea, "Venting and Leaking of Methane From Shale Gas Development: Response to Cathles et Al.," *Climatic Change* 113 (2012): 537–49, https://doi.org/10.1007/s10584-012-0401-0.

Threats from fracking infrastructure

The infrastructure for drilling and fracking operations is complex, widespread, and poses its own risks to public health and the climate. Beginning where silica sand is mined and processed and ending where gas is burned or liquefied for export, infrastructure includes pipelines, compressor stations, dehydrators, processing plants, flare stacks, gas-fired power plants, and storage depots through which oil or gas is moved, filtered, pressurized, warehoused, refined, and vented. It also includes injection wells and recycling facilities that dispose and treat the prodigious amounts of liquid waste that fracking generates. Air pollution is produced at every stage of the process. [Note: harm from flare stacks is included in Air Pollution and is not taken up in the sub-sections that follow.]

<u>Sand mining and processing</u>

Silica sand is used as an ingredient in fracking fluid to prop open the cracks and fissures created during the hydraulic fracturing process in order to allow bubbles of gas or oil to escape the rock. By 2015, the United States had become the world's largest producer of sand for fracking operations, with 70 percent of domestic frack sand mined in Wisconsin and Minnesota.

In the Upper Midwest, this boom in silica sand mining threatens both air and water quality. It has transformed rural areas into industrialized zones and introduced complex public health risks and occupational health risks that are not well understood. Silica dust is a well-known cause of disabling and potentially fatal lung diseases, including both lung cancer and silicosis, and represents a proven occupational health threat to workers so exposed in other industries.

Inhalation exposures to silica dust can occur in several ways: during sandstone mining and loading operations; from truck traffic to and from mines and sand storage depots; during crushing, washing, and drying processes; and whenever dust is visible. Precise exposures to downwind communities remain uncertain. A 2018 study found elevated levels of particulate air pollution in ambient air near two Wisconsin industrial silica sand operations at levels that may pose health risks to nearby residents. Mining operations in Wisconsin and Minnesota are now increasingly the subject of citizen lawsuits on the grounds of noise pollution, water contamination, silica dust exposure, and loss of property value. In January 2021, a county-wide ban on frack sand mining in Winona County, Minnesota was upheld by the U.S. Supreme Court.

By 2018, the center of U.S. frack sand mining had begun to shift from western Wisconsin to western Texas where sand mines in the Permian Basin have now become a major U.S. supplier of frack sand. Texas sand is considered inferior to Wisconsin sand, which is crush-resistant and ideally shaped to prop open fractures to allow oil and gas to flow up the borehole. However, Texas sand is up to 50 percent cheaper as it does not incur the cost of rail transport to reach the booming Permian Basin oil wells.

Like fracking itself, frack sand mining is a boom-and-bust industry that was hit hard by the downturn in oil and gas demand and crashing prices before and during the COVID-19 pandemic. In 2019-2020, silica sand mining companies in Wisconsin underwent a wave of bankruptcies, raising questions about whether the bonds set aside for mine restoration were sufficient. Although companies are responsible for returning their mines to farmland, prairie, or forest, the required bonds for the restoration work are sometimes backed up by subsidiary companies that may also go bankrupt. By July 2021, industry analysts were predicting growth in the global frack sand mining industry through 2025.[1658]

Frack sand dust generated during fracking operations is a more complex mixture of respirable particles than crystalline silica alone. In 2020, a multi-part study led by the National Institute of Occupational and Environmental Health, examined frack sand dust toxicity on several organ systems and reported a wide range of harms. These are described below. For more on the health threats of frack sand to fracking workers, see also "Occupational health and safety hazards."

- June 2, 2021 – In 2013, researchers with the National Institute for Occupational Safety and Health (NIOSH) published exposure assessment results for respirable silica dust among oil and gas workers conducting fracking operations. These results revealed, among other things, that occupational exposure limits for some fracking workers were being exceeded by a factor of ten. This paper describes the historical background of this research project, beginning in 2008 when NIOSH began a focused effort to understand the suite of occupational hazards among fracking industry workers that eventually led to the 2013 report. The authors also summarize the known risks of crystalline silica exposure for workers: lung cancer; chronic obstructive pulmonary disease; kidney disease; and incurable silicosis, which can either progress gradually or, in some cases, swiftly and fatally after only a few months of very intense exposure.[1659]

- May 24, 2021 – One of Wisconsin's biggest producers of sand for fracking, Hi-Crush Proppants, liquidated one of its four sand mines in the state after declaring bankruptcy last year.[1660]

- January 24, 2021 – The U.S. Supreme Court let stand a ban on the mining of sand for fracking operations in Winona County, Minnesota. The ban was first enacted in 2016 on the grounds that frack sand mining was incompatible with land stewardship and healthy communities. The ban was previously challenged by the industry in county and in state courts, both of which had upheld it.[1661]

[1658] Research and Markets, "The Worldwide Frac Sand Industry Is Expected to Grow by $1.59 Billion Between 2021 to 2025," Yahoo Finance, July 5, 2021, https://finance.yahoo.com/news/worldwide-frac-sand-industry-expected-103300557.html.
[1659] Eric J. Esswein, Bradley King, and Ryan Hill, "An Ancient Hazard in a 21st Century Workplace: The Power of Partnerships and Collaboration Investigating Respirable Crystalline Silica in Hydraulic Fracturing," NIOSH Science Blog, June 2, 2021, https://blogs.cdc.gov/niosh-science-blog/2021/06/02/oge-partnership/.
[1660] Rich Kremer, "Frac Sand Company Liquidating Western Wisconsin Mine," Wisconsin Public Radio, May 24, 2021, https://www.wpr.org/frac-sand-company-liquidating-western-wisconsin-mine.
[1661] Waterways Journal, "Supreme Court Upholds Winona Frac Sand Ban," *Waterways Journal*, January 24, 2021, https://www.waterwaysjournal.net/2021/01/24/supreme-court-upholds-winona-frac-sand-ban/.

- December 11, 2020 – A spate of lawsuits against frack sand mining operations in Wisconsin have targeted several proposed new mines as well as existing mines that have already been cited for multiple environmental violations, including spills of mine sludge into surface water and groundwater contamination.[1662]

- November 9, 2020 – Workers who service gas wells while they are being fracked are migratory, moving from one well pad to another after spending a few weeks at each well during the fracking stage. Because of the itinerant nature of their work, there is no registry of lung diseases in workers due to exposure to fracking sand dust. A multi-part investigation using a rat model attempted to understand whether inhalation of sand used at fracking sites could have adverse effects, even after short-term exposure bursts at concentrations that mimic those found at fracking well sites. This paper outlined the scope of the whole study. The organ systems studied included lungs, heart, kidney, brain, and the immune system. Cytotoxicity, inflammation, and molecular mechanisms were also explored. The findings showed that exposure to fracking sand dust has weaker biological effects than exposure to pure crystalline silica dust, but, nevertheless, harmful effects were seen across many organ systems even after short-term exposure.[1663]

- November 7, 2020 – As part of a multi-part investigation (see above), researchers studied the organ systems of rats exposed to fracking sand dust using an intratracheal instillation and inhalation exposure model in both living animals and in tissue studies. The major finding was that the toxicity of fracking sand dust extended to many organ systems—including the cardiovascular system, immune system, kidneys, and brain—which were harmed, for the most part, more severely than the lungs. The mechanism by which fracking sand provoked responses in organs distance from the lungs is not understood.[1664]

- October 22, 2020 – As part of a multi-part investigation (see above), researchers exposed rats to fracking sand dust and found changes in the brain. Specifically, acute inhalation of fracking sand dust altered the blood-brain barrier, elicited neuroinflammation, and caused changes in cells supporting the olfactory bulb, the hippocampus, and the cerebellum. The cerebellum also showed signs of synaptic injury.[1665]

- October 15, 2020 – As part of a multi-part investigation (see above), researchers compared the physico-chemicals properties of nine different samples of frack sand dust to pure respirable crystalline silica dust typically used in lab experiments. They also

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[1662] Mike Tighe, "Suits Balloon Against Frac Sand Mining 'Running Amok,' Onalaska Lawyer Says," News8000.com, December 11, 2020, https://www.news8000.com/suits-balloon-against-frac-sand-mining-operations-running-amok-onalaska-lawyer-says/.

[1663] Jeffrey S. Fedan, "Biological Effects of Inhaled Hydraulic Fracturing Sand Dust. I. Scope of the Investigation," *Toxicology and Applied Pharmacology* 409 (2020), https://doi.org/10.1016/j.taap.2020.115329.

[1664] Stacey E. Anderson and Mark Barger, "Biological Effects of Inhaled Hydraulic Fracturing Sand Dust. IX. Summary and Significance," *Toxicology and Applied Pharmacology* 409 (2020), https://doi.org/10.1016/j.taap.2020.115330.

[1665] Krishnan Sriram et al., "Biological Effects of Inhaled Hydraulic Fracturing Sand Dust VII. Neuroinflammation and Altered Synaptic Protein Expression," *Toxicology and Applied Pharmacology* 409 (2020), https://doi.org/10.1016/j.taap.2020.115300.

compared the pulmonary responses of rats exposed to both types of dust. The findings showed that both the physico-chemical characteristics and the biological effects of the two types of dust have distinct differences. Fracking sand dust samples had comparatively great amounts of non-silica minerals, the grains were less uniform in size, and the toxicity to lung tissue was less. Further, researchers documented significant differences in bioactivity among the various samples of frack sand dust.[1666]

- October 15, 2020 – As part of a multi-part investigation (see above), researchers examined the biological effects of inhaled fracking sand dust on the lung mechanics of laboratory rats. They found differences among nine different samples of dust collected at well pads during fracking operations. Some dusts caused temporary harm to various measures of breathing that appeared to resolve over time. A strong pro-inflammatory response, which is typical of silica dust exposure, was not evident in cases exposed to one of the nine different dust samples. However, the epithelial lining of the airways did show functional alterations.[1667]

- October 13, 2020 – In laboratory animals and humans alike, the deposition of silica dust in small airways of the lung, where they are ingested by macrophages, causes cell death and elicits dramatic and sustained inflammation. As part of a multi-part investigation (see above), researchers exposed rodent immune cells growing in culture to frack sand dust collected from a fracking site and looked for toxicity and inflammatory responses. The results confirmed that this particular sample of frack sand dust was toxic to mammalian lung cells, damaging their DNA and increasing inflammatory cytokine production.[1668]

- October 13, 2020 – As part of a multi-part investigation (see above), researchers examined the biological effects of inhaled fracking sand dust on the pulmonary inflammatory responses of laboratory rats and looked also for signs of toxicity and oxidative stress. Unexpectedly, the rats exposed via inhalation to frack sand dust showed only minimal signs of toxicity or changes in gene expression in their lung tissue. The researchers noted that the association of other minerals on the surfaces of the particles of this particular sample of frack sand dust may have "prevented, through masking, cellular interactions that would trigger an inflammatory response. It is of interest to determine whether frack sand dust collected from other hydraulic fracturing sites in the U.S. would, in this rat inhalation model, have a similar toxicity profile as the dust examined in the present study."[1669]

[1666] Jeffrey S. Fedan et al., "Biological Effects of Inhaled Hydraulic Fracturing Sand Dust. II. Particle Characterization and Pulmonary Effects 30 d Following Intratracheal Instillation," *Toxicology and Applied Pharmacology* 409 (2020), https://doi.org/10.1016/j.taap.2020.115282.
[1667] Kristen A. Russ et al., "Biological Effects of Inhaled Hydraulic Fracturing Sand Dust. IV. Pulmonary Effects," *Toxicology and Applied Pharmacology* 409 (2020), https://doi.org/10.1016/j.taap.2020.115284.
[1668] Nicole S. Olgun et al., "Biological Effects of Inhaled Hydraulic Fracturing Sand Dust. III. Cytotoxicity and Pro-Inflammatory Responses in Cultured Murine Macrophage Cells," *Toxicology and Applied Pharmacology* 408 (2020), https://doi.org/10.1016/j.taap.2020.115281.
[1669] Tina M. Sager et al., "Biological Effects of Inhaled Hydraulic Fracturing Sand Dust. V. Pulmonary Inflammatory, Cytotoxic and Oxidant Effects," *Toxicology and Applied Pharmacology* 408 (2020), https://doi.org/10.1016/j.taap.2020.115280.

- September 30, 2020 – As part of a multi-part investigation (see above), researchers examined the biological effects of inhaled fracking sand dust on immune responses of exposed laboratory rats. They found several impacts. Exposure to fracking sand dust significantly altered lymph node cellularity and frequency of T-cells, B-cells, and natural killer cells, among other endpoints. These changes all signal impairment of immune functioning.[1670]

- September 12, 2020 – As part of a multi-part investigation (see above), researchers examined the biological effects of inhaled fracking sand dust on the cardiovascular of exposed laboratory rats. The results showed constriction of arteries, decreased heart rate, and alterations in blood pressure. Also, of expressions of proteins in kidney tissue were indicative of injury. "Thus, it appears that inhalation of fracking sand dust does have some prolonged effects on cardiovascular and, possibly, renal function."[1671]

- July 14, 2020 – Three companies mining silica sand for fracking declared bankruptcy in the five weeks preceding this report by the *Houston Chronicle*.[1672] One of those companies described holds over $953 million of assets but carries over $699 million of debt. The pandemic was cited as dramatically cutting demand and forcing the closure of silica mines across the United States.

- June 27, 2020 – Hi-Crush Inc. closed three of its four Wisconsin silica sand mines including its largest, as a result of reduced demand. The company told the *Wisconsin State Journal* that it had reduced its workforce by about 60 percent in the past three months.[1673]

- May 18, 2020 – An update on the Atlas Sand Company's frack sand conveyer belt project appeared in the *Permian Basin Oil and Gas Magazine*.[1674] The magazine reported that public scoping process of the Bureau of Land Management (BLM) for the 16.6-mile-long conveyor belt system for moving frack sand from West Texas into Southeast New Mexico had taken place, and the BLM was preparing an environmental assessment. The BLM was "analyzing a range of alternatives and its associated environmental effects," and, once the environmental assessment was complete, a 30-day public comment period would commence. (BLM published the assessment and opened the comment period on

[1670] Stacey E. Anderson et al., "Biological Effects of Inhaled Hydraulic Fracturing Sand Dust. VIII. Immunotoxicity," *Toxicology and Applied Pharmacology* 408 (2020), https://doi.org/10.1016/j.taap.2020.115256.
[1671] Kristine Krajnak et al., "Biological Effects of Inhaled Hydraulic Fracturing Sand Dust. VI. Cardiovascular Effects," *Toxicology and Applied Pharmacology* 406 (2020), https://doi.org/10.1016/j.taap.2020.115242.
[1672] Sergio Chapa, "Pandemic Forces 3 Frac Sand Companies into Chapter 11 Bankruptcy," *Houston Chronicle*, July 14, 2020, sec. Energy, https://www.houstonchronicle.com/business/energy/article/pandemic-forces-bankrupt-frac-sand-company-houston-15405869.php.
[1673] Chris Hubbuch, "Frac Sand Producer Hi-Crush Pursuing Bankruptcy amid Flagging Sales," *Wisconsin State Journal*, June 27, 2020, https://madison.com/wsj/business/frac-sand-producer-hi-crush-pursuing-bankruptcy-amid-flagging-sales/article_f0c4157d-1e2c-5ee4-a984-a33d0fdd7145.html.
[1674] PBOG, "Belting It Out," *Permian Basin Oil and Gas Magazine*, May 18, 2020, https://pboilandgasmagazine.com/belting-it-out/.

Aug. 28, 2020, accepting comments through Sept. 28, 2020.[1675]) The plan's developer claimed the project would lead to a 47 percent reduction per year in frack sand hauling trucks on public roadways. Trucking plays a role in the sand transfers within the new project, with the 140-acre offloading facility plan calling for 24 truck loading lanes. Proposed health and safety precautions in the proposal include a cover for the belt to decrease noise, and "environmental awareness training… to instruct personnel on the protection of cultural, ecological, and other natural resources."

- April 29, 2020 – Frack sand mining plants in Wisconsin laid off workers as oil prices crashed as the pandemic took hold. Sand from western Wisconsin "has the shape and composition to be widely used in the process of extracting oil and gas from shale rock," and the mines and layoffs are concentrated there.[1676]

- January 9, 2020 – The company behind the frack sand mine proposed in Kane County, Utah announced that it was "stepping away" from the project, "citing the conclusions of 'feasibility assessments,'" reported *KUER* radio.[1677] Southern Red Sands released the announcement together with Best Friends Animal Society, a national animal shelter organization sharing a border with the company's mining claim. The animal sanctuary had been one of the project's "most vocal opponents." Other expressions of opposition to the frack sand mine included a petition that garnered over 12,000 signatures.

- January 8, 2020 – The Atlas Sand Company sought to construct a 16.5-mile conveyor belt to carry silica sand for fracking, from an offloading facility in rural West Texas to a proposed 140-acre loadout facility in southeast New Mexico.[1678] The plan was submitted in January 2020 to the Bureau of Land Management, from which the project would need a permanent, 70-foot-wide right of way across federal land. The conveyer belt would be in place of trucking, the main method of transporting sand to well sites.

- July 7, 2019 – A company proposing a massive frack sand mine in southern Utah sought 1,200 acre-feet of water per year, which would be needed to process the sand. Residents and organizations, including an animal sanctuary, expressed alarm at the Kanab City Council's water service agreement near finalization. Those opposed also addressed truck traffic and harmful impacts on tourism, telling the *Salt Lake City Tribune*, "such an operation is not a good fit for a county so rich in geological scenery and steeped in

[1675] Bureau of Land Management, "The Bureau of Land Management Invites Public to Comment on Proposed Kermit Overland Conveyor Project | Bureau of Land Management," U.S. Department of the Interior, August 28, 2020, https://www.blm.gov/press-release/bureau-land-management-invites-public-comment-proposed-kermit-overland-conveyor.
[1676] Joe Taschler, "Oil Price Destruction Makes Its Way to Wisconsin's Frac Sand Mines," *Milwaukee Journal Sentinel*, April 29, 2020, https://www.jsonline.com/story/money/business/2020/04/29/wisconsin-frac-sand-plants-lay-off-workers-amid-oil-price-crash/3044935001/.
[1677] Fuchs, D. (2020, January 9). BREAKING: Divisive Southern Utah sand mine project will not move forward. *KUER.org.* Retrieved from https://www.kuer.org/energy-environment/2020-01-09/breaking-divisive-southern-utah-sand-mine-project-will-not-move-forward
[1678] Associated Press, "Company Eyes Texas-New Mexico Fracking Sand Transport System," *Albuquerque Journal*, January 8, 2020, sec. Business, https://www.abqjournal.com/1407811/company-eyes-texas-new-mexico-fracking-sand-transport-system.html.

agricultural traditions," and "authorities seem too eager to facilitate a proposal that could have far-reaching consequences and undermine the area's amenity-based economy."[1679] (See January 9, 2020 entry for an update addressing the cancellation of this project.)

- May 13, 2019 – As another Wisconsin frack sand company faced bankruptcy, an industry analyst said that many of the 128 silica mines in the state that supply oil and gas producers might have to close due to oversupply.[1680] "Maybe half of these mines, maybe as much as 75 percent of these mines, might need to be retired or just permanently reclaimed and then it brings up the question of is there enough money set aside for reclamation and restoration," the analyst told *Wisconsin Public Radio*. Though companies are responsible for returning the land to either farmland, prairie or forest, the analyst cast said that the required bonds for the restoration, "could be suspect," because they are backed up by subsidiary companies that may also go bankrupt.

- March 7, 2019 – The Minnesota Supreme Court announced that it would hear oral arguments on the legality of Winona County's ban on the mining of silica sand for use in fracking operations. A Winona County judge, as well as a Minnesota Court of Appeals, sided against Minnesota Sands, LLC and ruled in favor of the county legislature.[1681] The ban prohibits mining sand for industrial purposes but allows mining for construction purposes. The county has argued that it is within its rights to protect the health of its citizens. Its original ordinance, passed on November 22, 2016, was the first countywide ban in the nation on the extraction of silica sand for use in drilling and fracking operations. It became the subject of a lawsuit by Minnesota Sands on the grounds that the ordinance violates the federal Commerce Clause of the U.S. Constitution.[1682, 1683]

- December 27, 2018 – Wisconsin's frack sand mining industry had a volatile year in 2018. Mines that had closed in 2016 due to market downturns reopened on news of increased drilling activity. However, later in the year, the price for sand dropped dramatically as sand mines opened in Texas to serve fracking operations in the nearby Permian Basin. Wisconsin sand companies then closed mines again, with one company laying off 37 employees.[1684]

[1679] Brian Maffly, "Worried about Truck Traffic and Losing Valuable Water, Southern Utah Residents Fight Plan to Mine Frack Sand," *The Salt Lake Tribune*, July 7, 2019, https://www.sltrib.com/news/environment/2019/07/07/worried-about-truck/.

[1680] Rich Kremer, "Frac Sand Producer In Wisconsin Faces Bankruptcy As Industry Shifts," *Wisconsin Public Radio*, May 13, 2019, https://www.wpr.org/frac-sand-producer-wisconsin-faces-bankruptcy-industry-shifts.

[1681] Winona Daily News Staff & Associated Press, "Challenge to Winona County's Frac Sand Ban to Be Heard by State Supreme Court next Month," *Winona Daily News*, March 7, 2019, https://www.winonadailynews.com/news/local/challenge-to-winona-county-s-frac-sand-ban-to-be/article_bd2474ea-e6a7-5f9f-8108-c957de307aad.html.

[1682] Chris Rogers, "Supreme Court Takes Frac Sand Case," *Winona Post*, October 31, 2018, https://www.winonapost.com/news/supreme-court-takes-frac-sand-case/article_2dd27a1a-e531-57d2-9be5-07297188b40e.html.

[1683] Dan Browning, "Appeals Court Upholds Winona County Ban on Frac Sand Mining," *Star Tribune*, July 30, 2018, https://www.startribune.com/minnesota-appeals-court-upholds-winona-county-ban-on-frac-sand-mining/489529801/.

[1684] Rich Kremer, "2018 Was A Roller-Coaster Year For Wisconsin's Frac Sand Industry," *Wisconsin Public Radio*, December 27, 2018, https://www.wpr.org/2018-was-roller-coaster-year-wisconsins-frac-sand-industry.

- July 17, 2018 – As part of an industry-funded study, a research team retrospectively assessed the silica dust exposure among workers in the industrial sand industry, which includes sand used for fracking. Workers who went on to develop silicosis had significantly more exposure to silica dust than those who did not. Results showed decreases in exposure throughout the industry over time, driven in part by the establishment of workplace regulations in the 1970s that helped accelerate silica dust control programs. Adjustment for use of respiratory protection showed only modest reductions in estimated exposures.[1685]

- May 11, 2018 – The dunes sagebrush lizard in western Texas is imperiled because of booming demand for frack sand. "It's really a new threat and it just sort of came in all at once and really has the potential to wipe out a lot of lizard habitat, if not controlled," said a petition to the U.S. Fish and Wildlife Service that urged the agency to add the dunes sagebrush lizard to the endangered species list.[1686] Sand mines in the Permian Basin of west Texas now provide one quarter of the total U.S. supply of frack sand. Texas sand is up to 50 percent cheaper than Wisconsin sand as it does not incur the cost of rail transport to reach the booming Permian Basin oil wells, although it is considered inferior to Wisconsin sand, which is crush-resistant and ideally shaped to prop open fractures to allow oil and gas to flow up the borehole.[1687]

- March 12, 2018 – Significantly higher $PM_{2.5}$ levels than background were identified in ambient air around two Wisconsin industrial silica sand operations, by a team of University of Wisconsin-Eau Claire researchers led by environmental public health toxicologist and silica sand researcher Crispin Pierce.[1688] Average $PM_{2.5}$ concentrations found both above and below the EPA standard were likely due to: "site-specific considerations such as degree of year-round activity; proximity to other sand facilities; rail traffic; and differences between mining, processing, and transport activities." Average PM_{10} levels at both sites were above the State of California and WHO annual average standard. Though PM_{10} is not as closely associated with human health effects as the finer $PM_{2.5}$, and though required by Clean Air Act, the Wisconsin Department of Natural Resources has not collected $PM_{2.5}$. Authors concluded, "Given that no known level of particulate exposure is considered harmless, that risk has been established down to at least 5 µg/m3, and that statistically significant increases in $PM_{2.5}$ were measured in this study, health risks may be increased for residents around frac sand facilities."

[1685] Roy J Rando et al., "Retrospective Assessment of Respirable Quartz Exposure for a Silicosis Study of the Industrial Sand Industry," *Annals of Work Exposures and Health* 62, no. 8 (2018): 1021–32, https://doi.org/10.1093/annweh/wxy064.
[1686] Natalie Krebs, "In West Texas, Fracking Companies Face A Tough Challenger – The Dunes Sagebrush Lizard," *Texas Standard*, May 11, 2018, https://www.texasstandard.org/stories/in-west-texas-fracking-companies-face-a-tough-challenger-the-dunes-sagebrush-lizard/.
[1687] David Wethe, "Why This Sand From Texas Is Suddenly Worth $80 a Ton," *Bloomberg*, July 10, 2018, https://www.yahoo.com/news/why-sand-texas-suddenly-worth-134140942.html.
[1688] Crispin Pierce et al., "Monitoring of Airborne Particulates near Industrial Silica Sand Mining and Processing Facilities," *Archives of Environmental & Occupational Health* 74, no. 4 (2019): 185–96, https://doi.org/10.1080/19338244.2018.1436036.

- August 7, 2017 – A University of Iowa team evaluated the impact of frack sand mining and processing on the concentration of particulate matter in the air of surrounding communities. Sampling in 17 homes located within 800 meters from sand mining activities, the team found that, overall, particulate matter and silica concentrations were lower than regulations and guidelines established to prevent silicosis but spiked when winds blew over the facility. They concluded that particulate matter levels from fracking sand mining and processing were "unlikely to cause chronic adverse health conditions." Sampling for this study, which took place in 2014, did not consider the impact of living near multiple adjacent frack sand operations. The industry in western Wisconsin has expanded considerably since that time.[1689]

- November 25, 2017 – In Minnesota, a district judge upheld Winona County's ban on the mining, processing, and loading of frack sand. In her decision, the judge referenced public health and safety threats, fragility of the water quality in the area, and evidence for harm from sand mines in other areas. Winona is the first county in the United States to pass a countywide ban on frack sand extraction. Efforts to replicate the ban are now ongoing in neighboring counties.[1690, 1691]

- July 5, 2016 – The Wisconsin Department of Natural Resources (DNR) released a *Strategic Analysis for Public Review* of the state's industrial sand mining industry that downplayed environmental health effects from air pollution. There are 128 industrial sand mine facilities in Wisconsin, including the mines themselves and processing and rail loading facilities. The DNR identified airborne particulate matter as a primary concern for industrial sand mining facilities and said that air quality monitors in western Wisconsin have not detected a problem.[1692] Researchers, organizations, and the native community involved in monitoring impacts of the frack sand industry challenged these findings, pointing to lack of data collection on the most dangerous kind of particulate matter called PM2.5, which represents fine particles that are less than 2.5 microns in width. These critics noted that the U.S. Environmental Protection Agency (EPA) had previously expressed concerns about the DNR's approach to regulating PM2.5.[1693] Regarding groundwater, the report described elevated levels of several metals in wastewater holding ponds at the sand mines, presenting a risk to groundwater quality.

[1689] Thomas M. Peters et al., "Community Airborne Particulate Matter from Mining for Sand Used as Hydraulic Fracturing Proppant," *Science of The Total Environment* 609 (2017): 1475–82, https://doi.org/10.1016/j.scitotenv.2017.08.006.
[1690] Matt McKinney, "Judge's Ruling on Winona County Ban of Frac Sand Mining Stirs Interest," *Minneapolis Star-Tribune*, November 25, 2017, https://web.archive.org/web/20171126004240/https://www.startribune.com/judge-s-ruling-on-winona-county-frac-sand-ban-stirs-interest/459974433/.
[1691] Chris Rogers, "District Court Upholds County Frac Sand Ban," *Winona Post*, November 22, 2017, https://www.winonapost.com/news/district-court-upholds-county-frac-sand-ban/article_4778c8d2-290b-5644-ab0d-7b608a482be1.html.
[1692] Wisconsin Department of Natural Resources, "Industrial Sand Mining in Wisconsin Strategic Analysis for Public Review," 2016, https://dnr.wi.gov/topic/EIA/documents/ISMSA/ISMSA.pdf.
[1693] Chris Hubbuch, "DNR Releases Frac Sand Analysis to Immediate Criticism from Environmental Group," *La Crosse Tribune*, July 6, 2016, https://lacrossetribune.com/news/local/dnr-releases-frac-sand-analysis-to-immediate-criticism-from-environmental-group/article_bce8ea56-fff1-52ae-97cb-c67cfb120a1f.html.

- March 25, 2016 – The Occupational Safety and Health Administration (OSHA) amended its existing standards for occupational exposure to respirable crystalline silica, "having determined that employees exposed to respirable crystalline silica at the previous permissible exposure limits face a significant risk of material impairment to their health."[1694] Key provisions include the reduction of the permissible exposure limit to 50 micrograms per cubic meter of air, averaged over an 8-hour shift. The standards cover many industries with some having two years to comply; the hydraulic fracturing industry is allowed an additional five-year extension for engineering controls, until June 23, 2021.[1695] The *New York Times* reported that safety experts have advocated for a tightening of silica exposure standards for the past forty years but that "progress was stymied for decades by resistance from affected companies and regulatory inaction." The article reported that many oil and gas companies in particular were not meeting the current silica exposure standard. The new rules, when fully in effect, are estimated to save 600 lives and prevent 900 new cases of silicosis per year.[1696]

- March 1, 2016 – University of Wisconsin anthropologist Thomas Pearson conducted in-depth interviews examining the impact of frack sand mining on sense of community, quality of life, and place in nearby residents. His findings indicated that the sudden influx of this heavy extractive industry has eroded residents' sense of place and belonging and that these experiences are rarely taken into account by policymakers. Residents report "significant anxiety and stress from truck traffic, noise, light pollution, and uncertainty about environmental health impacts," and distress caused by drastic changes to long-familiar landscapes over which they have no control. Pearson concluded that policymakers should pay closer attention to the uneven distribution of benefits and costs and "recognize that the costs go beyond quantifiable economic or environmental impacts."[1697]

- January 29, 2016 – The Institute for Wisconsin's Health, Inc. released its Health Impact Assessment (HIA) on frack sand mining operations in western Wisconsin, prepared with the participation of 15 local and tribal health departments. According to the report, the HIA was a collaborative effort. The scope of the report was limited to the potential for community-level health effects of industrial sand mining in western Wisconsin. Regarding air quality, the report concluded that health effects from the impact of industrial sand mining on community-level air quality related to particulate matter are unlikely, and that it was also unlikely that community members would be exposed to respirable crystalline silica from industrial sand mining as currently regulated. Regarding

[1694] Occupational Safety and Health Administration, "Occupational Exposure to Respirable Crystalline Silica," March 25, 2016, https://www.federalregister.gov/documents/2016/03/25/2016-04800/occupational-exposure-to-respirable-crystalline-silica.
[1695] Occupational Safety and Health Administration, "OSHA's Final Rule to Protect Workers from Exposure to Respirable Crystalline Silica," Final Rule, March 25, 2016, https://www.osha.gov/laws-regs/federalregister/2016-03-25-1.
[1696] Barry Meier, "New Rules Aim to Reduce Silica Exposure at Work Sites," *The New York Times*, March 24, 2016, sec. Business, https://www.nytimes.com/2016/03/24/business/new-rules-aim-to-reduce-silica-exposure-at-work-sites.html.
[1697] Thomas W. Pearson, "Frac Sand Mining and the Disruption of Place, Landscape, and Community in Wisconsin," *Human Organization* 75, no. 1 (2016): 47–58, https://doi.org/10.17730/0018-7259-75.1.47.

water quality, the report concluded that contamination is possible; however, health effects were unlikely. Quality of life effects were likely, but variable.[1698] Though it was a “Level 1 Partner” for the report, the Ho-Chunk Nation responded to the HIA with criticism, writing, “we are disappointed with the conclusions drawn in the report, particularly in the section on air quality impacts, and we believe a more robust assessment of the air quality impacts is required before such conclusions can be drawn.” They wrote that the HIA failed to provide an accurate and complete analysis of the health threats posed by this industry because of the limited scope, and “minimal discussion about fine particulate matter (or PM2.5), which likely presents the biggest threat from industrial sand mining operations.[1699] As reported by Rochester, Minnesota’s *Post-Bulletin*, Crispin Pierce, director of University of Wisconsin-Eau Claire’s environmental public health program, “believes the study ignored important air quality data collected by university students at sand mining sites at Bloomer, New Auburn and Augusta during the past 18 months,” which he described as “the only work that looked at these fine particles.”[1700]

- November 6, 2015 – According to findings from a pilot study led by Crispin Pierce (see entry above), levels of fine particulate matter (PM2.5) are not being adequately measured near frack sand operations. Air monitors set up by Pierce and his team consistently showed higher readings than detections measured by Wisconsin’s DNR.[1701] In some instances, PM2.5 levels exceeded the EPA guideline of 12 micrograms per cubic meter of air. In an accompanying news story, Pierce noted that the state’s air quality data largely comes from industry itself. “‘The DNR so far has continued to shy away from doing their own monitoring,’ he said. ‘The monitoring I’ve seen so far is inadequate. People aren’t looking at PM2.5, and they really should be—from unbiased sources.’”[1702]

- October 15, 2015 – *Inside Climate News* reported on the response of nearby communities to the “bust” cycle of the frack sand industry in Wisconsin and Minnesota. Reactions reported included ongoing concerns that the industry does not provide permanent economic prosperity. Municipalities and community organizations are using the lull to advance protections in advance of a possible upturn: “Towns in the region are also trying to strengthening their local zoning ordinances, such as adding rules to limit industrial

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[1698] A. Boerner, N. Young, and D. Young, “Health Impact Assessment of Industrial Sand Mining in Western Wisconsin” (Institute for Wisconsin’s Health, Inc., 2016), https://www.heartland.org/_template-assets/documents/publications/iwhi_industrial_sand_hia.pdf.
[1699] Ho-Chunk Nation, “Concerns about Air Quality Impacts and Human Health Remain After Release of Industrial Sand Mining Health Impact Assessment,” News Release, March 9, 2016, http://midwestadvocates.org/assets/resources/Frac%20Sand%20Mining/20160309HoChunkHIARelease.pdf.
[1700] E. Lindquist, “Report Downplays Frac Sand Link to Health Troubles,” *Post-Bulletin*, February 4, 2016, http://www.postbulletin.com/news/local/report-downplays-frac-sand-link-to-health-troubles/article_b3023c6c-fe74-5028-a7a4-6238fa035eaa.html.
[1701] Kristin Walters et al., “PM 2.5 Airborne Particulates Near Frac Sand Operations,” *Journal of Environmental Health* 78, no. 4 (2015): 8–12.
[1702] Ryan Schuessler, “Wisconsin Locals Fear Dust from Mines for Fracking Sand Even as Boom Wanes,” *Al Jazeera America*, 2015, http://america.aljazeera.com/articles/2015/11/6/wisconsin-locals-fear-frac-sand-mining.html.

noise and light pollution. In other cases, communities are trying to oust pro-sand advocates from office."[1703]

- June 30, 2015 – Because the amount of sand used per fracking well has increased, demand for silica sand by the oil and gas industry is still growing even though new drilling activity has taken a downturn. A global investment bank reported that fracking operations now require an average of 4.2 million pounds of sand per well. A few years ago, silica sand comprised 9.5 percent of fracking fluid but now is closer to 20 percent. Further "rising intensity" of sand use is expected.[1704]

- June 15, 2015 – An investigative report by *EnergyWire* documented self-reported health impacts among residents of southwestern Wisconsin who live near silica sand mining operations that service the fracking industry. Exposure to silica dust is a proven cause of silicosis and lung cancer. (See further entries on silica sand exposure among workers in the section, "Occupational Health and Safety Hazards.") Residents near frack sand mine operations reported exposure to dust pollution and respiratory problems. Air monitoring data from the Wisconsin DNR showed that none of the state's 63 active sand mines were in violation for particulate matter, but, as the author noted, the state measured particles only 10 micrometers in diameter or larger.[1705] Below this diameter, crystalline silica particles are small enough to bypass the body's natural clearance mechanisms and are likely to lodge deep in the lungs where they can initiate scarring, autoimmune reactions, and tumor formation.[1706]

- May 28, 2015 – The U.S. Geological Survey reviewed the geological and economic status of sand mining for hydraulic fracturing operations in the United States. More the 70 percent of the sand used in U.S. fracking operations originates from the Upper Midwest, especially in Wisconsin and Minnesota, where an ongoing sand mining surge has paralleled the national fracking boom. More than 40 different operators are involved in the mining, processing, transportation, and distribution of frac sand to a fast-growing domestic market. U.S. frack sand is also exported and shipped throughout the world.[1707]

[1703] Zahra Hirji, "In Fracking Downturn, Sand Mining Opponents Not Slowing Down," *Inside Climate News*, October 15, 2015, https://insideclimatenews.org/news/15102015/fracking-struggles-sand-mining-opponents-momentum-minnesota-wisconsin/.
[1704] Sergio Chapa, "Demand For Sand: Frac Sand Use per Well Goes up amid Low Oil Prices," *San Antonio Business Journal*, June 30, 2015, https://www.bizjournals.com/sanantonio/blog/eagle-ford-shale-insight/2015/06/demand-for-sand-frac-sand-use-per-well-goes-up.html.
[1705] Pamela King, "Frac Sand Towns Question Whether Rules Protect Them Against Silica Pollution," *E&E News*, June 15, 2015, https://web.archive.org/web/20150621073016/http://www.eenews.net/stories/1060020192.
[1706] U.S. Department of Labor, "Dust and Its Control," 1987, https://web.archive.org/web/20111018032206/https://www.osha.gov/dsg/topics/silicacrystalline/dust/chapter_1.html.
[1707] Mary Ellen Benson, Anna B. Wilson, and Donald L. Bleiwas, "Frac Sand in the United States: A Geological and Industry Overview" (U.S. Geological Survey, May 2015), https://pubs.er.usgs.gov/publication/ofr20151107.

Pipelines and compressor stations

More than 300,000 miles of natural gas transmission pipelines traverse the United States. They are serviced, every 40 to 100 miles, by compressor stations that maintain the pressure of the gas flowing through them. (Pump stations do the same for oil pipelines.)

Pipelines and compressor stations are significant sources of air pollutants, including benzene and formaldehyde, constituting potential health risks to those living nearby while offering no economic benefits. Instead, they are associated with loss of tax revenue and economic development for the communities where they are sited. A 2017 study identified 70 different air pollutants in compressor station emissions. A 2019 study found that 39 of the chemicals released are linked to cancer. A 2020 study found that proximity to higher amounts of volatile emissions from compressor stations were linked with higher death rates. A 2021 study found "alarming levels" of volatile organic compounds, including cancer-causing benzene, in the indoor air of homes located near a compressor station in Ohio.

Pipelines and compressor stations vent methane into the atmosphere as part of routine maintenance operations and represent a climate risk. Historically, the Federal Energy Regulatory Commission, which undertakes environmental reviews of proposed pipelines, has not considered climate impacts in its approval process. In 2021, the Commission signaled that it would begin considering greenhouse gas emissions as part of its permitting requirements but did not settle on a method for doing so.

Pipelines and compressor stations are also accident-prone. The Medical Society of the State of New York, the Massachusetts Medical Society, and the American Medical Association have each called for comprehensive health impact assessments regarding the health and safety risks associated with natural gas pipelines, which include fires, explosions, and leaks.

In addition to transmission pipelines, 450,000 miles of gathering lines carry raw oil and gas from the wellheads to collection and processing sites with the United States. These smaller-diameter, lower-pressure pipelines are regulated lightly or, in rural areas, not at all. In some cases, large, high-pressure gas pipelines legally qualify as gathering lines and so remain exempt from regulations despite their size. More than one-third of the nation's gathering lines are in Texas. In 2018, three gathering line explosions in Texas' Permian Basin killed several people, including a three-year-old child, and badly burned others. Nevertheless, in October 2019, the Texas Railroad Commission, which overseas oil and gas extraction in Texas, rejected a proposal to subject the state's rural gathering lines to regulation and set safety protocols.

A 2021 nationwide study found that gathering and transmission pipelines are disproportionately sited in socially vulnerable communities, especially Indigenous communities.

Distribution pipelines, which carry gas into individual homes and businesses, are an overlooked but significant source of methane emissions and a cause of urban tree death, according to emerging research. In October 2018, a Columbia Gas work crew in Massachusetts' Merrimack Valley over-pressurized a natural gas distribution system while replacing aging pipelines and triggered 80 simultaneous natural gas explosions, killing one teenager, injuring 23 people,

destroying or damaging 130 buildings, prompting a mass evacuation, and costing the company over $1 billion.

- July 15, 2021 – Two former pipeline inspectors became whistleblowers about hazards on an ethane pipeline carrying the highly volatile liquid from Marcellus Shale fracking wells in Ohio, Pennsylvania, and West Virginia to a new Shell petrochemical plant. Investigative reporting that relied on heavily redacted documents obtained through Freedom of Information Act requests documented several serious safety charges in the whistleblower complaint. Among the most serious are compromised pipeline coatings, a problem that increases the risk of corrosion. According to Pipeline and Hazardous Materials Safety Administration (PHMSA), corrosion is the cause of about 18 percent of pipeline accidents. Although the Shell contractors on the project fired the inspectors and the Occupational Safety and Health Administration (OSHA) dismissed the complaint, PHMSA investigators had, prior to the whistleblower complaint, "found that Shell had inadequate procedures for the company's inspectors to detect coating damage and other problems." The investigation documented a culture of clique behavior among the industry's inspectors—hired and paid by the industry—that effectively encouraged overlooking expensive problems but which the terminated inspectors, who are appealing OSHA's dismissal, had resisted.[1708]

- June 23, 2021 – The U.S. Court of Appeals for the District of Columbia Circuit, denied a certificate for the Spire STL pipeline in a strong opinion that criticized the Federal Energy Regulatory Commission (FERC) for failing to determine whether there was a need for the 65-mile natural gas pipeline from Illinois to Missouri. The previous year, FERC Chairman Richard Glick reopened a review of its Certificate Policy Statement, which dictates the process for determining whether a proposed pipeline is in the public interest and should therefore be approved. The federal court's ruling may have an impact on this review. However, there are precedent agreements that have historically been viewed by the commission as a proxy for pipeline need. Glick, who voted against FERC's 2019 decision to approve the Spire STL pipeline, has criticized the reliance on precedent agreements, particularly in cases where project applications only include agreements between affiliated companies.[1709]

- June 13, 2021 – Responding to community concerns, a research team investigated the relationship between proximity to a natural gas compressor station in eastern Ohio's Jefferson County and health risks to residents. The results showed that concentrations of volatile organic compounds (VOCs) were indeed elevated in the air inside of homes closer to the compressor station and had reached "alarming levels." Cancer-causing benzene was 2-17 times higher in homes located fewer than two kilometers from the

[1708] Mike Soraghan, "Whistleblowers Say 'Bad Seeds' Undermine Pipeline Safety," *E&E News*, July 15, 2021, https://web.archive.org/web/20210715124012/https://www.eenews.net/articles/whistleblowers-say-bad-seeds-undermine-pipeline-safety/.
[1709] Niina H. Farah, Mike Soraghan, and Miranda Willson, "Court's 'Historic' FERC Slap-Down Shifts Pipeline War," *E&E News*, June 23, 2021, https://web.archive.org/web/20210623133723/https://www.eenews.net/stories/1063735583.

compressor. Other VOCs were also detected in elevated quantities near the compressor and validated the residents' concerns. Authors recommended further study to explicate the specific pathways of exposure.[1710]

- June 3, 2021 – The Danish Environmental Protection Agency halted work on the Denmark of Baltic Pipe, a pipeline connecting Poland with Norwegian gas fields, and temporarily withdrew an environmental permit because of concerns over the impact on protected mice and bat species. The initial study had provided insufficient information on protection of the animals.[1711]

- June 1, 2021 – Using a questionnaire administered to pipeline operators, asset managers, and industry regulators in Nigeria, researchers determined the challenges to "Nigerian Pipeline Integrity Management Systems." Pipeline leaks result in environmental damage and economic loss. The results described in this peer-reviewed study showed that management plans are poorly implemented and that most pipeline failures were due to: forces such as corrosion, weather, and aging; human errors such as poor operation; and willful damage and vandalism. Authors found multiple reasons for the lack of effective implementation of pipeline integrity management in Nigeria. These included "shoddy" repair of pipelines and ancillary facilities, lack of management commitment to safety, high costs of pipeline integrity management procedures, and poor management of data.[1712]

- May 18, 2021 – As part of nationwide study, a research team found that people living in U.S. counties where gas infrastructure is located are at greater risk of exposure to water and air pollution, public health and safety issues, and other negative impacts. Further, counties with more socially vulnerable populations, especially Indigenous populations, had significantly higher densities of gathering and transmission pipelines than counties with less socially vulnerable populations. "Assuming natural gas gathering and transmission pipelines continue to be built, decision-makers and the general public should keep in mind that the network is already distributed inequitably with respect to social vulnerability, and that future projects can either maintain the inequitable status quo or shift the distribution in ways that will potentially exacerbate or ameliorate current disparities."[1713] The study's lead author said to *North Carolina Health News,* "This is what the communities themselves have been saying for a long time… For the first time,

[1710] Kaitlin A. Vollet Martin et al., "Survey of Airborne Organic Compounds in Residential Communities Near a Natural Gas Compressor Station: Response to Community Concern," *Environmental Advances* 5 (2021), https://doi.org/10.1016/j.envadv.2021.100076.
[1711] Reuters, "Concern Over Wildlife Halts Building of Norway-Poland Gas Link," Reuters, June 3, 2021, https://www.reuters.com/business/energy/denmark-halts-baltic-pipe-project-after-environmental-permit-withdrawn-2021-06-03/.
[1712] Sunday Kyrian Nsude et al., "Failures in Natural Gas Pipeline Systems: An Assessment of Pipeline Integrity Management Programs from Nigeria," *International Journal of Scientific Engineering and Applied Science* 7, no. 6 (2021), http://ijseas.com/volume7/v7i6/IJSEAS202106105.pdf.
[1713] Ryan E. Emanuel et al., "Natural Gas Gathering and Transmission Pipelines and Social Vulnerability in the United States," *GeoHealth* 5 (2021), https://doi.org/10.1029/2021GH000442.

we gathered all of this together and zoomed out and took a national look and said, 'You know what, these pipelines don't exist in a vacuum.'"[1714]

- March 19, 2021 – The Department of the Interior's Bureau of Safety and Environmental Enforcement (BSEE) has oversight of the approximately 8,600 miles of active offshore oil and gas pipelines located on the seafloor of the Gulf of Mexico. However, it does not have a robust oversight process for ensuring the integrity of these pipelines. BSEE has authorized industry to leave over 97 percent (about 18,000 miles) of all decommissioned pipeline mileage on the Gulf of Mexico seafloor since the 1960s. Further, if pipelines decommissioned-in-place are later found to pose risks, there is no funding source for removal. "GAO recommends that BSEE take actions to further develop, finalize, and implement updated pipeline regulations to address long-standing limitations regarding its ability to (1) ensure active pipeline integrity and (2) address safety and environmental risks associated with pipeline decommissioning. Interior agreed with this recommendation."[1715]

- March 19, 2021 – Following a certificate from FERC to begin operations at the Enbridge compressor station in Weymouth, Massachusetts, two incidents resulted in emergency shutdowns and large gas releases from the facility, at least one of them caused by equipment malfunction. Long-standing public opposition to the facility reflects concern about risks to public health and safety in this urban environment, environmental justice violations, and greenhouse gas emissions. In apparent response to this public pressure, the Commission voted in February 2021 to establish a "paper briefing process," a type of official comment period which has the goal of answering specific unresolved questions. This decision appeared to signal a rare instance of a willingness by the Commission to reexamine the approval of a facility already in service. More than 60 entities applied to be "intervenors," or participants, in this proceeding. On the side opposing the Enbridge compressor, applicants responded to this unusual "second chance," and the possibility of a FERC reversal of authorization for the project. Pediatric environmental health researcher Philip Landrigan, MD, said, "All of these groups are joining together and they're catalyzed by the recognition that a very poor job was done in the health impact assessment several years ago. There's a real opportunity against the background of this incomplete piece of work to overturn the decision." Brita Lundberg, MD, of Greater Boston Physicians for Social Responsibility said, "FERC specifically asked about what safety and environmental justice issues we know about now that we did not know about when the project was approved. … I find it a very hopeful sign that FERC is now offering to listen. … There is still the opportunity to do the right thing."[1716]

[1714] Greg Barnes, "New N.C. State Study Finds Socially Vulnerable Communities Bear Brunt of Pipelines," *North Carolina Health News*, June 2, 2021, https://www.northcarolinahealthnews.org/2021/06/02/new-n-c-state-study-finds-socially-vulnerable-communities-bear-brunt-of-pipelines/.
[1715] U.S. Government Accountability Office, "Offshore Oil and Gas: Updated Regulations Needed to Improve Pipeline Oversight and Decommissioning" (U.S. Government Accountability Office, March 19, 2021), https://www.gao.gov/products/gao-21-293.
[1716] Miriam Wasser, "Why A Federal Order in The Weymouth Compressor Case Has the Natural Gas World Worried," WBUR, March 19, 2021, https://www.wbur.org/news/2021/03/19/weymouth-compressor-ferc-precedent-enbridge-natural-gas.

- March 4, 2021 – Tracking methane emissions from pipelines has largely focused on structural defects and fugitive emissions. However, these sources are underestimates, as revealed by high resolution satellite monitoring that can capture episodic, intentional methane releases, including venting.[1717]

- February 24, 2021 –Members of the Massachusetts congressional delegation asked federal regulators to reconsider their decision to allow the Enbridge compressor station in Weymouth to go into service. “The site is located within a half mile of Quincy Point and Germantown – ‘environmental justice communities’ that suffer persistent environmental health disparities due to socioeconomic and other factors – as well as nearly 1,000 homes, a water treatment plant and a public park,” the legislators wrote in the letter. “An estimated 3,100 children live or go to school within a mile of the site, and more than 13,000 children attend school within three miles of the compressor station.”[1718]

- February 14, 2021 – A study tested whether key demographic and socioeconomic characteristics of a neighborhood’s population—racial composition, educational attainment, poverty rate, and rurality—are associated with the probability of a proposed pipeline running through it. The study addressed planned natural gas transmission pipelines in the United States for which researchers were able to discover proposed routes, combined with 2015 census data. It found only limited, and sometimes contradictory evidence of environmental injustice regarding these proposed pipelines. It is not clear whether systemic inequalities in environmental hazards hold true for existing pipelines, as their precise routes are kept confidential by the industry and the federal government, and therefore cannot be studied in this way. The study responded to the environmental justice community’s calls for an assessment of the environmental risks caused by the development of gas infrastructure, and whether those risks are equally distributed within the population. Authors of this study emphasized that their results “cannot be used as a verdict over the equity of specific pipelines without considering local contexts and group-specific experiences of marginalization.” They also stated that more realistic models are needed, that risks may go beyond the census tract of the pipeline, and that the study lacks precision in the large census tracts.[1719]

- February 5, 2021 – The Coastal GasLink project, a $6.6-billion pipeline designed to carry natural gas, continued, with more than 140 kilometers of pipe laid in northern British Columbia toward a $40-billion LNG terminal on the province’s North Coast for export to Asia. Although the hereditary Wet’suwet’en chiefs still oppose the pipeline, their priorities have shifted to caring for their elders during the pandemic. In British Columbia's north, First Nations people have been disproportionately hit with COVID-19,

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[1717] European Space Agency, “Monitoring Methane Emissions from Gas Pipelines,” Phys.org, March 4, 2021, https://phys.org/news/2021-03-methane-emissions-gas-pipelines.html.
[1718] Jessica Trufant, “Lawmakers Push Regulators to Reexamine Compressor Approval,” *The Patriot Ledger*, February 24, 2021, https://www.patriotledger.com/story/news/2021/02/24/lawmakers-push-regulators-reexamine-compressor-approval/4555468001/.
[1719] Johann Strube, Brian C. Thiede, and Walter E. “Ted” Auch, “Proposed Pipelines and Environmental Justice: Exploring the Association between Race, Socioeconomic Status, and Pipeline Proposals in the United States,” *Rural Sociology*, 2021, https://doi.org/10.1111/ruso.12367.

with double the confirmed cases compared to the rest of the population. There have also been outbreaks among industry employees and that has slowed construction.[1720]

- February 4, 2021 – Because of violations for erosion and sedimentation control, the Mountain Valley Pipeline has paid over a half a million dollars in fines by consent order of the West Virginia Department of Environmental Protection. Altogether there were 29 notices issued, and some of them contained multiple violations.[1721]

- February 3, 2021 – Natural gas pipelines have proliferated throughout Appalachia's Marcellus Shale region. In West Virginia alone, natural gas production increased four-fold in the past decade. Survey research on the effects of pipeline development in rural Appalachia found that residents live with the fear of disasters, toxic contamination, explosions, construction noise, and the anxiety of having no control over their own land.[1722]

- February 1, 2021 – Global Energy Monitor identifies, maps, describes, and categorizes oil and gas pipelines, and liquified natural gas (LNG) terminals throughout the world. Its online database, Global Fossil Infrastructure, shows that $1 trillion in capital expenditures are on a collision course with commitments by most large economies to transition to carbon neutrality by mid-century, representing risks for stranded assets. United States, as the world's leading developer of pipelines, is at particular risk, as is natural gas infrastructure in general: 18 of the 20 longest pipelines in development and 82.7 percent of all pipelines in development globally carry natural gas. Currently, only four major financial institutions have restricted investments in pipelines. At the same time, opposition from landowners, indigenous groups, and climate activists is causing the cancellation or delay of high-profile pipelines and is changing perceptions of pipelines as a good investment. "Closing the midstream policy gap at financial institutions is key to mitigating the effects of climate change and the increasing risk that, in a decarbonizing world, many of these midstream assets will soon be stranded."[1723]

- January 19, 2021 – Natural gas compressor stations emit loud, low-frequency noise that travels hundreds of meters and is audible to birds. A study that investigated its effects on bird reproduction introduced a recorded playback of compressor noise into nest boxes of eastern bluebirds and tree swallows. The authors measured reproductive output and success, including the number of eggs per nest, the proportion of eggs that hatched, the proportion of young that fledged, as well as proportion of eggs that produced fledglings.

[1720] Betsy Trumpener, "A Year After Wet'suwet'en Blockades, Coastal GasLink Pipeline Pushes on Through Pandemic," *CBC*, February 5, 2021, https://www.cbc.ca/news/canada/british-columbia/coastal-gaslink-pipeline-bc-wet-suwet-en-pandemic-1.5898219.
[1721] Laurence Hammack, "Mountain Valley Pipeline Cited Again for Erosion and Sedimentation Violations," *The Roanoke Times*, February 4, 2021, https://roanoke.com/news/local/mountain-valley-pipeline-cited-again-for-erosion-and-sedimentation-violations/article_496c5fd4-671c-11eb-a913-8b3e7d176b2b.html.
[1722] Erin Brock Carlson and Martina Angela Caretta, "Living with Natural Gas Pipelines: Appalachian Landowners Describe Fear, Anxiety and Loss," *The Conversation*, February 3, 2021, https://theconversation.com/living-with-natural-gas-pipelines-appalachian-landowners-describe-fear-anxiety-and-loss-152586.
[1723] James Browning et al., "Pipeline Bubble 2021: Tracking Global Oil and Gas Pipelines" (Global Energy Monitor, February 2021), https://globalenergymonitor.org/report/pipeline-bubble-2021/.

Incubation rates were lower in noisy boxes for both bluebirds and tree swallows. Also, for both species, the noise reduced hatching success by 9–15 percent compared to quiet boxes.[1724] A summary article reported that "compressor noise caused behavioral changes that led to reduced reproductive success for eastern bluebirds and tree swallows. The results indicate … that natural gas infrastructure can create an 'equal-preference ecological trap,' where birds do not distinguish between lower and higher quality territories, even when they incur reproductive costs."[1725]

- August 1, 2020 – A Michigan Technological University team collected publicly available fuel and emissions data from the entire extraction, transport, and combustion lifecycle to determine that oil and gas pipelines have the highest total embedded carbon emissions. Their method, introduced in this paper, considers all the emissions that a facility enables rather than only what it emits at a point-source, as conventional methods do. This "bottleneck method" showed that the top ten CO_2 emission bottlenecks in the U.S. are predominantly oil (47 percent) and natural gas (44 percent) pipelines.[1726] Commenting on their findings, the researchers expressed surprise at the large emissions contribution from natural gas. "For natural gas, the biggest emissions came from pipeline transport. The sheer length of pipelines—the Transcontinental Gas Pipeline (Transco) alone branches into more than 16,900 kilometers (10,500 miles) of pipeline from Texas to New York—means there are lots of places to emit gas."[1727]

- July 31, 2020 – In early May 2020, a cloud of methane 12 miles wide and drifting over five counties in Florida was picked up in an analysis of satellite data. For more than two months, its source remained a mystery until the state's Department of Environmental Protection confirmed that three hundred metric tons of methane had been intentionally released from a compressor station near Gainesville during an emergency shutdown. The facility is part of the Florida Gas Transmission Pipeline, a joint venture between Energy Transfer and Kinder Morgan.[1728]

- July 20, 2020 – The Dakota Access pipeline was ordered to cease operations by a federal judge after a ruling found that the U.S. Army Corps of Engineers had violated the National Environmental Policy Act in permitting it. In the same month, the lesser-known Tesoro High Plains pipeline was also ordered shut down for the first time in its 67 years of operation after a determination that the pipeline was trespassing on Native American

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[1724] Danielle P. Williams et al., "Experimental Playback of Natural Gas Compressor Noise Reduces Incubation Time and Hatching Success in Two Secondary Cavity-Nesting Bird Species," *Ornithological Applications* 123 (2021): 1–11, https://doi.org/10.1093/ornithapp/duaa066.
[1725] Jeff Mulhollem, "Songbirds' Reproductive Success Reduced by Natural Gas Compressor Noise," PennState News, February 18, 2021, https://news.psu.edu/story/647898/2021/02/18/research/songbirds-reproductive-success-reduced-natural-gas-compressor-noise.
[1726] Alexis S. Pascaris and Joshua M. Pearce, "U.S. Greenhouse Gas Emission Bottlenecks: Prioritization of Targets for Climate Liability," *Energies* 13, no. 15 (2020), https://doi.org/10.3390/en13153932.
[1727] Sarah Derouin, "The Surprising Source of Greenhouse Gas Emissions," *Eos*, March 1, 2021, https://eos.org/articles/the-surprising-source-of-greenhouse-gas-emissions.
[1728] Naureen S. Malik, "Florida Offers Pipeline Clue in Mystery of Giant Methane Leak - Bloomberg," *Bloomberg*, July 31, 2020, https://www.bloomberg.com/news/articles/2020-07-31/florida-offers-pipeline-clue-in-mystery-of-giant-methane-leak.

land.[1729] Together, the two pipelines ship over a third of fracked crude from the Bakken shale formation to market. "Their travails signal the ebbing of the oil industry's sway in the U.S. heartland and underscore the growing heft and savvy of challengers who've become emboldened to demand higher compensation and safeguards."

- July 17, 2020 – Subsidence and the development of sinkholes have occurred alongside pipeline construction for the transport of natural gas liquids from the Marcellus Shale fields in western Pennsylvania to an export terminal in Delaware County. Sunoco's Mariner East pipeline development had "catastrophic" potential, according to the state's Public Utility Commission in 2018, though they later changed that determination. Pipeline leaks of natural gas liquids can be more dangerous than methane leaks because the liquids turn into gases once they escape. Heavier than air, these gases then sink to the ground rather than dissipate, are highly volatile, and can easily explode.[1730]

- June 30, 2020 – The D.C. Circuit Court ruled that the Federal Energy Regulatory Commission (FERC) can no longer use "tolling orders" to prevent opponents of proposed pipeline projects from going to court while the Commission considers their appeals while allowing construction to proceed.[1731] Under the Natural Gas Act, landowner opponents of pipelines must file a petition at FERC and wait for the Commission to resolve it before going to court, which it must do within 30 days. But the agency routinely issues so-called tolling orders to extend that review period indefinitely while land seizures and construction often move forward. The DC Circuit Court decision coalesced around a simple conclusion: The Natural Gas Act didn't give FERC the authority to issue tolling orders and stall litigation.

- June 27, 2020 – A gas pipeline crew drilling horizontally under the Blanco River in Texas' Hill Country spilled 36,000 gallons of drilling fluid into the Trinity Aquifer, contaminating at least six water wells drawing from it. Reporting on the incident three months following, the *Houston Chronicle* interviewed residents whose wells were contaminated, including those who had opposed the 30-mile Permian Highway fracked gas pipeline from the time of its announcement. Those interviewed reported challenges for maintaining personal hygiene during the pandemic, dependency on bottled water, and startling results from water testing that turned up detections of arsenic, lead, and other metals at levels beyond maximum allowable concentrations in public drinking water supplies. Ultimately, Kinder Morgan offered to install a rainwater collection system on the properties. Some of the property owners have gone on to sue the company for

[1729] Catherine Ngai, "A Pipeline Is Quietly Ordered Shut in New Signal of Shale's Woes," *Bloomberg Green*, July 20, 2020, https://www.bloomberg.com/news/articles/2020-07-20/another-oil-pipeline-ordered-shut-signals-shale-s-woes.
[1730] Susan Phillips, "More Sinkholes Develop alongside Mariner East Construction in Chester County," *State Impact Pennsylvania*, July 17, 2020, https://stateimpact.npr.org/pennsylvania/2020/07/17/mariner-east-pipeline-construction-site-of-additional-sinkholes-in-chester-county/.
[1731] Ellen M. Gilmer, "'Kafkaesque' FERC Pipeline Process Needs Revamp, Court Says (3)," *Bloomberg Law*, June 30, 2020, https://news.bloomberglaw.com/environment-and-energy/kafkaesque-pipeline-review-process-needs-revamp-court-rules.

"injecting contaminants, including a 'cocktail of carcinogens,' into the aquifer that feeds their wells."[1732]

- June 25, 2020 – Satellite data is now being used by companies, academic researchers, and some energy producers to find large methane leaks.[1733] For example, energy consultancy Kayrros recently observed a leak spewing 93 metric tonnes of methane every hour from the Yamal pipeline that carries gas from Siberia to Europe. Kayrros said its analysis of the satellite data showed concentrations of methane around compressor stations along the pipeline. According to *Reuters*, satellite discoveries of methane leaks could also lead to "more stringent regulatory regimes targeting natural gas, once seen as a 'clean' fossil fuel, as governments seek to combat climate change."

- June 21, 2020 – New Jersey Natural Gas stopped work on its pipeline in Monmouth County following an "inadvertent return, or the unintended discharge of drilling mud to the surface through a natural crack or fissure in the bedrock being drilled."[1734] This inadvertent return damaged a home and flooded its basement by sending drilling mud into a fissure leading to the home's foundation. A statement from the homeowner read, "I was almost too terrified to investigate after what had felt like an explosion in my house… I discovered huge cracks in my foundation, my basement floor, and even my walls. As I watched in horror water and sludge came pouring in through the cracks, I ran to the construction site and begged them to stop." The sludge also flowed into a nearby stream. A 2018 lawsuit to overturn the pipeline's approvals was still pending in the Appellate Division of State Superior Court.

- June 19, 2020 – In Michigan, the Canadian company Enbridge reported additional damage to its Line 5 pipeline running through the Straits of Mackinac. That line has since been shut down. The damage included a damaged screw anchor support that had shifted from its original position, 150 feet from spots on the pipeline where protective coating had worn away, according to the Governor's office. The Michigan Attorney General's office issued a statement saying, "Yet again, Enbridge has confirmed what we already know—Line 5 is a clear and present danger to our Great Lakes and to the millions of Michiganders who rely on those lakes for recreation, business and tourism."[1735]

- June 10, 2020 – Using data collected from an advanced mobile leak detection (AMLD) platform in twelve metropolitan areas, a research team estimated methane emissions from local gas distribution systems. An historically underreported source of greenhouse gases,

[1732] Jay Root, "A Pipeline Poisons the Wells in Hill Country," *Houston Chronicle*, June 27, 2020, sec. Investigations, https://www.houstonchronicle.com/news/investigations/article/A-pipeline-poisons-the-wells-in-Hill-Country-15371071.php.
[1733] Shadia Nasralla, "Satellites Reveal Major New Gas Industry Methane Leaks," *Reuters*, June 25, 2020, sec. Environment, https://www.reuters.com/article/us-climatechange-methane-satellites-insi-idUSKBN23W3K4.
[1734] Steve Strunsky, "Drilling Work Halted on Natural Gas Pipeline after Mishap Damages N.J. Couple's House," *NJ.Com*, June 21, 2020, sec. Burlington, https://www.nj.com/burlington/2020/06/work-halted-on-natural-gas-pipeline-after-drilling-sludge-damages-nj-couples-house.html.
[1735] Melissa Frick, "Enbridge Reports 'Significant Damage' on Line 5 Pipeline to State," *MLive.Com*, June 20, 2020, sec. News, https://www.mlive.com/news/2020/06/enbridge-reports-significant-damage-on-line-5-pipeline-to-state.html.

distribution pipelines are the low-pressure network of service lines that carry natural gas into individual homes and business. The results of this study fill in an important data gap as most recent national assessments of methane emissions from the US gas supply chain did not take local gas distribution systems into account at all. The team found that the age and the material of the pipelines and their interaction affected leakage rate. Overall, emissions were far greater than those of previous studies. The mean of their emissions estimates was 0.55 teragrams of CO_2 equivalent per year, a value 3.85 times greater than the current EPA estimate.[1736]

- May 26, 2020 – A 30-inch diameter gas pipeline that runs between southern Mississippi and Pennsylvania exploded in Kentucky in August 2019, killing one person and injuring several others. A Pipeline Hazardous Materials Safety Administration (PHMSA) investigation found that the company had missed evidence of defects in the pipeline in 2011, the year of its last inspection. The pipeline is operated by Texas Eastern Transmission LP, a subsidiary of Enbridge.[1737]

- May 14, 2020 – The nation's gathering pipelines that carry raw natural gas from the wellhead to processing plants are served by gathering stations, each of which includes a compressor along with associated separators and tanks. Many include dehydrators, which remove water from the gas, and equipment to remove hydrogen sulfide gas and other contaminants. In a study funded by the oil and gas industry, a research team estimated the collective methane emissions from the nation's 5,200 gathering stations by compiling 85 hours of data from a representative sample of 180 stations, as provided to them by industry partners. Measurements were taken using optimal gas imaging cameras and Bacharach Hi Flow samplers. The team reported a 45 percent lower mean methane emissions rate than a previous study, likely because the gathering stations included in the current study were smaller and lower throughput. The authors argue that their sample was more representative of the gathering station population nationally. Their results also showed that the whole gas emission rates from the components on gathering stations were comparable to, although somewhat higher than, emission factors used by EPA's greenhouse gas reporting program. However, when the activity data of the gathering stations were factored in, the study's estimate of total methane emissions (1,290 gigagrams/year) was just 66 percent of the current estimates used in the EPA's Greenhouse Gas Inventory (1,955 gigagrams/year). The authors propose a replicable method that incorporates activity data to update emissions estimates from gathering stations. The field data and the EPA data together show that significantly more methane was released from gathering stations as part of normal operations (venting, flaring, compressor exhaust, maintenance blowdowns) than via accidental fugitive leaks from equipment.[1738]

[1736] Zachary D. Weller, Steven P. Hamburg, and Joseph C. von Fischer, "A National Estimate of Methane Leakage from Pipeline Mains in Natural Gas Local Distribution Systems," *Environmental Science & Technology* 54, no. 14 (2020): 8958–67, https://doi.org/10.1021/acs.est.0c00437.
[1737] Bill Estep, "Report: Gas Pipeline in Fatal Kentucky Explosion Had Defects Operator Had Not Found," *Lexington Herald Leader*, May 26, 2020, https://www.kentucky.com/news/state/kentucky/article242995236.html.
[1738] Daniel Zimmerle et al., "Methane Emissions from Gathering Compressor Stations in the U.S.," *Environmental Science & Technology* 54, no. 12 (2020): 7552–61, https://doi.org/10.1021/acs.est.0c00516.

- May 10, 2020 – Proximity to higher amounts of non-methane volatile organic compound (VOC) emissions from natural gas pipeline compressor stations were linked to higher death rates in a national, county-level ecological study.[1739] Twelve specific VOCs were also associated with significantly higher mortality rates, including styrene, 2,2,4-trimethylpentane, ethylene dichloride, and vinyl chloride. Studies of human health impacts from compressor stations have been almost completely absent from the literature, despite the expansion of natural gas infrastructure. The Indiana University team also found that counties with compressor station emissions had higher percentages of Hispanic populations and lower percentages of non-Hispanic White populations. Authors concluded that the "results of the current study, along with findings from other research, challenge the conventional wisdom that natural gas is a clean fuel that we may rely on to provide for our energy needs with little adverse effect."

- May 7, 2020 – When a Beaver County home was destroyed in a 2018 explosion, pipeline company ETC Northeast Pipeline LLC, a subsidiary of Energy Transfer, was fined a record $30 million. Subsequently, the Pennsylvania Department of Environmental Protection has issued hundreds of additional construction violation notices on the same pipeline for infractions such as slipping slopes along the pipeline route, failed erosion and sedimentation barriers, and sediment-laden water getting into streams, all violations of the company's clean water permits.[1740]

- April 27, 2020 – Public concerns about Kinder Morgan's storage of pipeline segments for the 428-mile Permian Highway Pipeline led to an investigative report by Austin, Texas radio station KXAN.[1741] Residents had noticed coated pipe segments lying out in the open despite manufacturer warnings that the epoxy coatings can degrade with prolonged exposure to sunlight. KXAN's investigation found no existing regulations that govern pipe coating exposure to UV radiation.

- April 17, 2020 – The proposed Northeast Supply Enhancement (NESE) pipeline would bring fracked gas from Pennsylvania to Long Island at a cost of a billion dollars. A report by the Institute for Energy Economics and Financial Analysis (IEEFA) described the lack of need for the gas and the significant cost to ratepayers in four New York boroughs. The report lead author called the proposal "unwise and high-risk with ratepayers expected to bear the brunt of the cost."[1742]

[1739] Michael Hendryx and Juhua Luo, "Natural Gas Pipeline Compressor Stations: VOC Emissions and Mortality Rates," *The Extractive Industries and Society* 7, no. 3 (2020): 864–69, https://doi.org/10.1016/j.exis.2020.04.011.
[1740] Reid Frazier, "The Revolution Pipeline Explosion Resulted in a Huge Fine for Energy Transfer. Now, DEP Says It's Found Hundreds of New Violations," *State Impact Pennsylvania*, May 7, 2020, https://stateimpact.npr.org/pennsylvania/2020/05/07/the-revolution-pipeline-explosion-resulted-in-a-huge-fine-for-energy-transfer-now-dep-says-its-found-hundreds-of-new-violations/.
[1741] Jody Barr, "PIPELINE EXPOSED: KXAN Investigation Uncovers Safety Concerns over Pipes Used in Kinder Morgan's Permian Highway Pipeline," *KXAN Austin*, April 27, 2020, https://www.kxan.com/investigations/pipeline-exposed-kxan-investigation-uncovers-safety-concerns-over-pipes-used-in-kinder-morgans-permian-highway-pipeline/.
[1742] Suzanne Mattei and Tom Sanzillo, "Proposed NESE Gas Pipeline May Stick New York Ratepayers with One Billion-Dollar+ Cost," *Institute for Energy Economics & Financial Analysis*, April 17, 2020, https://ieefa.org/ieefa-report-proposed-nese-gas-pipeline-may-stick-nys-ratepayers-with-one-billion-dollar-cost/.

- April 8, 2020 – A Nuclear Regulatory Commission (NRC) report concluded the Indian Point Energy Center nuclear power plant would remain safe even in case of a rupture on a nearby, newly installed 42-inch gas transmission pipeline.[1743] The study called a rupture "unlikely" and stated that even if one were to occur, "the nuclear power plant would remain protected." The study team, composed of NRC and external experts, did however criticize earlier "optimistic assumptions in analyzing potential rupture" and recommended follow up actions, stating, "**The NRC needs to improve its processes and practices for technical reviews, inspection support, petition reviews, pipeline analysis, and coordination with other agencies.**" (Emphasis in original.)[1744] Environmental groups expressed dissatisfaction with the NRC conclusion that "maintain(s) the status quo."[1745]

- April 3, 2020 – A study that investigated natural gas leaks and tree deaths found that fugitive methane exposure from leaky natural gas distribution systems threatens urban tree canopies. Researchers measured methane and oxygen concentrations in subsurface soil at the base of case (dead or dying) trees and control (healthy) trees in Chelsea, Massachusetts. About 25 percent of dead trees had increased methane in their base soil, as opposed to one percent of healthy trees. The research team found the greatest soil methane concentrations on the side of the tree pit closest to the street, nearest to where natural gas distribution pipelines are located, suggesting that "elevated soil methane may contribute to urban street tree decline and that the fugitive methane may be the result of leaking pipeline infrastructure beneath the street surface."[1746]

- March 19, 2020 – An x-ray technician working on the Mariner East pipeline in Pennsylvania was charged with fraud for falsifying documents recording x-rays of pipeline welds.[1747] The worker allegedly certified in writing that the welds had been properly x-rayed and were acceptable when these certifications were false. He eventually pled guilty in federal court.[1748] The Mariner East pipeline carries natural gas liquids, which can cause a catastrophic explosion if they leak.

[1743] U.S. Nuclear Regulatory Commission (NRC Staff, "Report of the U.S. Nuclear Regulatory Commission Expert Evaluation Team on Concerns Pertaining to Gas Transmission Lines Near the Indian Point Nuclear Power Plant," April 8, 2020, https://www.nrc.gov/docs/ML2010/ML20100F635.pdf.
[1744] Jeremy Dillon, "NRC Says Gas Pipeline Doesn't Pose Threat to Indian Point," *E&E News*, April 15, 2020, https://web.archive.org/web/20200423075240/https://www.eenews.net/eenewspm/2020/04/15/stories/1062883415.
[1745] Thomas C. Zambito, "NRC Says Gas Pipeline No Threat to Indian Point, Dashing Hopes for Shutdown by Groups," *The Journal News*, April 20, 2020, https://www.lohud.com/story/news/local/indian-point/2020/04/20/nrc-gas-pipeline-indian-point-reactors/5166749002/.
[1746] Claire Schollaert et al., "Natural Gas Leaks and Tree Death: A First-Look Case-Control Study of Urban Trees in Chelsea, MA USA," *Environmental Pollution* 263 (2020): 114464, https://doi.org/10.1016/j.envpol.2020.114464.
[1747] Susan Phillips, "Mariner East Worker Charged with Falsifying Documents Related to a Pipeline Weld," *State Impact Pennsylvania*, March 19, 2020, https://stateimpact.npr.org/pennsylvania/2020/03/19/mariner-east-worker-charged-with-falsifying-documents-related-to-a-pipeline-weld/.
[1748] Department of Justice U.S. Attorney's Office Western District of Pennsylvania, "Radiograph Technician on Natural Gas Pipeline Admits Falsifying Testing Results," Press Release, June 22, 2020, https://www.justice.gov/usao-wdpa/pr/radiograph-technician-natural-gas-pipeline-admits-falsifying-testing-results.

- March 9, 2020 – Residents living a quarter-mile from a compressor station in rural Washington County, Pennsylvania told the Pittsburgh *Post-Gazette* that the persistent low-frequency sound from the station "gives them headaches and feels like torture."[1749] The township does not regulate low-frequency noise. A member of the same family was recently diagnosed with multiple myeloma, a blood plasma cancer linked to benzene and other pollutants. This compressor station emitted 1.2 tons of benzene in 2018, "making it the third biggest source of the carcinogen in the seven-county southwestern Pennsylvania region," according to data obtained from the Pennsylvania Department of Energy Emissions Inventory. Washington County has 40 compressor stations pushing gas through the pipelines.

- February 13, 2020 – NRC's Office of Inspector General conducted an inquiry into NRC's hazard analysis of a natural gas pipeline then proposed to run through the grounds of the Indian Point nuclear power plant. The inquiry found that the NRC failed to properly analyze the safety impact of a potential rupture of that pipeline and did not provide an appropriate response to "relevant and on point" stakeholder concerns.[1750] Congresswoman Nita Lowey and Westchester County Executive George Latimer expressed disappointment and outrage about these failures. "NRC must immediately explain to our communities the risks they face as a result of the agency's faulty processes and take steps to protect the public from any dangers that have resulted from the pipeline's approval and installation," the congresswoman stated.[1751]

- December 3, 2019 – In a "first-of-its-kind dispute," a pipeline operator sued the Texas Railroad Commission, which regulates oil and gas drilling, over approval of gas flaring.[1752] Dallas-based Exco Operating Co. had requested and received permission to flare natural gas that comes up with the oil it pumps from the Eagle Ford Shale. Exco flared off the gas following its emergence from bankruptcy, claiming inability to afford the cost of pipeline transport of the gas. Although natural gas flaring has long been restricted in Texas, the Commission has granted exceptions with increasing frequency in the past years.

- October 24, 2019 – In a 2017 settlement with Exxon which was sealed but obtained by *Inside Climate News*, residents documented illnesses and property damage following the rupture of Exxon's Pegasus pipeline that sent heavy crude oil diluted with dangerous

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[1749] David Templeton and Don Hopey, "Next Door Noise: Washington County Residents Say Their Neighbor Is Noisy, Disruptive and a Pollutor," *Pittsburgh Post-Gazette*, March 9, 2020, https://newsinteractive.post-gazette.com/smith-township-compressor-station-three-brothers/.
[1750] Office of the Inspector General, "Concerns Pertaining to Gas Transmission Lines at the Indian Point Nuclear Power Plant" (United States Nuclear Regulatory Commission, 2020), https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML20056F095.
[1751] "Lowey, Latimer Blast NRC for 'Faulty Analysis' That Led to Approval of Gas Line near Indian Point," *Mid Hudson News*, February 28, 2020, https://midhudsonnews.com/2020/02/27/lowey-latimer-blast-nrc-for-faulty-analysis-that-led-to-approval-of-gas-line-near-indian-point/.
[1752] Kiah Collier, "Pipeline Giant Sues Railroad Commission, Alleging Lax Oversight of Natural Gas Flaring," *The Texas Tribune*, December 3, 2019, https://www.texastribune.org/2019/12/03/railroad-commission-sued-lax-oversight-natural-gas-flaring/.

solvents spilling into a subdivision in Mayflower, Arkansas.[1753] Residents subsequently filed a class action lawsuit against Exxon alleging negligence in its maintenance of the 69-year-old pipeline. They faced "significant risks" after being exposed to a cocktail of chemicals including benzene, a known carcinogen; cyclohexane; naphthalene; and toluene, according to an environmental consultant hired by the plaintiffs' lawyers. The residents reportedly were awarded between $2,000 and $15,000. Exxon denied liability, claiming it "acted in conformity with generally recognized, state-of-the-art standards in the industry."

- October 10, 2019 – The Texas Railroad Commission, which oversees the state's oil and gas activity, rejected specific safety proposals drafted by its own staff for rural gathering lines and opted instead for vaguer requirements. This decision was praised by pipeline operators.[1754] Gathering lines are typically small-diameter, low-pressure pipelines carrying oil and gas from wells to processing sites, but recently industry has been building larger and higher-pressure pipelines that legally qualify as gathering lines. This new ruling allows gathering lines to escape regulations in remote, rural areas despite their size.

- June 4, 2019 – At least six pipeline explosions were caused by landslides, sinking and caving of land, and other types of land movement in the steeply sloped Appalachian mountains.[1755] Among them: TransCanada Corp's Leach Xpress natural gas pipeline exploded and demolished a house in Moundsville, West Virginia after five months in operation; a landslide caused a pipeline explosion near Aliquippa, Pa., burning down a house; and a boy and his grandfather were injured in an explosion in southeastern Ohio. An *E&E* investigation examined the gaps in comprehensive oversight: while PHMSA is responsible for the safety of construction and adherence to the agency's minimum standards, they are not involved in pipeline routes. That is handled by a different agency, FERC, which reviews how the path selection will affect the environment. The commission defers on safety issues to PHMSA. Thus, no one entity is in charge of ensuring that pipelines are built in safe places.

- May 7, 2019 – University at Albany researchers investigated health harms associated with chemical emissions from natural gas compressor stations in New York State. Between 2008 and 2014, 18 gas compressor stations (out of 74 compressors in the state) released a total of 36.99 million pounds of air pollutants, excluding methane and carbon dioxide. Thirty-nine of the chemicals released were human carcinogens. The study also included a greenhouse gas inventory, with data available for ten of the compressors.

[1753] David Hasemyer, "6 Years After Exxon's Oil Pipeline Burst in an Arkansas Town, a Final Accounting," *Inside Climate News*, October 24, 2019, https://insideclimatenews.org/news/24102019/exxon-oil-spill-neighborhood-mayflower-arkansas-sealed-depositions-illnesses-fines/.
[1754] Mike Soraghan, "Texas Commissioners Scale Back Gathering Line Proposal," *E&E News*, October 10, 2019, https://web.archive.org/web/20191010213035/https://www.eenews.net/stories/1061235103.
[1755] Mike Soraghan, "Landslides, Explosions Spark Fear in Pipeline Country," *E&E News*, June 4, 2019, https://web.archive.org/web/20190607095016/https://www.eenews.net/stories/1060472727.

Those facilities released 6.1 billion pounds of greenhouse gases release in a single year.[1756] (See also entry for October 12, 2017 below.)

- May 2, 2019 – Eight months after heavy rains and landslides led to the rupture and explosion of Energy Transfer's natural gas liquids Revolution Pipeline in Beaver County, Pennsylvania, destroying a house and knocking down power lines, PHMSA issued an advisory bulletin for operators of gas and hazardous liquid pipelines to "remind" them of the potential for damage from flooding, landslides, subsidence and other geologic hazards.[1757] The advisory bulletin reviewed specific guidance for monitoring, risk identification, and preventative and mitigative measures, as well as the many recent geological-related pipeline failures, particularly in the eastern portion of the United States. Unlike a regulation, a federal advisory is not enforceable but serves as a warning and a reminder of the regulations that are associated with pipeline safety. (See also entry for September 10, 2018 below.)

- March 4, 2019 – *E&E News* investigated accidents involving "gathering lines," which are small diameter pipelines that carry oil or gas from wellheads to processing facilities. Nationally, there are 450,000 miles of gathering lines. However, only high-pressure gathering lines in urban areas are regulated, and these represent only 18,000 miles of pipeline. The Pipeline and Hazardous Materials Safety Administration (PHMSA) has no rules for the rest. Nor do most states. Hence, it is not known how many fatalities have occurred due to explosions of gathering lines because no records are kept in rural areas. Rural gathering lines "don't have to be marked, built to standards or regularly inspected. Unlike for transmission lines, operators don't have to have emergency response plans for when they leak or explode."[1758]

- February 20, 2019 – During a polar vortex on January 30, 2019, a compressor station at an underground gas storage depot in Macomb County, Michigan was destroyed by an explosion after an equipment malfunction triggered emergency venting of gas. The extremely low temperatures prevented the methane plume from dispersing, and high winds pushed it along the ground until the gas encountered heat from another compressor station and exploded. The resulting gas shortage necessitated a statewide emergency call to residents and businesses to voluntarily turn down thermostats and reduce natural gas use. General Motors in Flint suspended operations for three days.[1759]

[1756] Pasquale N. Russo and David O. Carpenter, "Air Emissions from Natural Gas Facilities in New York State," *International Journal of Environmental Research and Public Health* 16, no. 9 (2019): 1591, https://doi.org/10.3390/ijerph16091591.
[1757] Pipeline Hazardous Materials Safety Administration, "Pipeline Safety: Potential for Damage to Pipeline Facilities Caused by Earth Movement and Other Geological Hazards," *Federal Register*, May 2, 2019, https://www.federalregister.gov/documents/2019/05/02/2019-08984/pipeline-safety-potential-for-damage-to-pipeline-facilities-caused-by-earth-movement-and-other.
[1758] Mike Lee and Mike Soraghan, "Deadly Pipelines, No Rules," *E&E News*, March 4, 2019, https://web.archive.org/web/20190304182624/https://www.eenews.net/stories/1060123021.
[1759] Beth LeBlanc, "Consumers CEO: Two Natural Gas Plants Still down after Jan. 30 Fire," *The Detroit News*, February 20, 2019, https://www.detroitnews.com/story/news/local/michigan/2019/02/20/consumers-energy-two-plants-still-down-after-fire-emergency-appeal/2928041002/.

- January 1, 2019 – As part of the planned Atlantic Bridge pipeline project, which will ferry fracked natural gas from New Jersey through New England and into Canada, Calgary-based Enbridge Inc. (formerly Spectra Energy) applied to site a 7,700-horsepower compressor station in Weymouth, Massachusetts, south of Boston. The Enbridge compressor station in Weymouth would maintain pipeline pressure needed to push the gas north to Maine and Canada. In 2016, the company offered the town $47 million to drop its opposition to the plan, which would place the compressor station in a port area immediately adjacent to densely populated neighborhood, the highly utilized Fore River lift bridge, a power plant, a sewage pumping station, and a gas metering station. Instead, residents and local political leaders rejected this offer and demanded a Health Impact Assessment (HIA). Ordered by Governor Charlie Baker in July 2017 and released in January 2019, this study received considerable criticism from the public health community due to its deviation from standard HIA methodologies. The HIA showed that the Fore River Basin already suffered from levels of benzene, formaldehyde, and other air toxics that exceeded state guidelines for these carcinogens while concluding that adding another source of these same pollutants would have negligible impact on residents' health.[1760, 1761] Shortly thereafter, the Massachusetts Department of Environmental Protection issued an air quality permit for the compressor station. This decision—and the HIA's conclusion on which it was based—was immediately contested by independent public health researchers. In February 2019, Greater Boston Physicians for Social Responsibility (GBPSR) issued their own report on the health risks of the Weymouth compressor that outlined their concerns about the safety and emergency response hazards associated with the proposed compressor and rejected the "no health impact" conclusion of the HIA. While the HIA acknowledged that the residents of the Fore River Basin already experienced excess rates of lung disease, heart disease, and cancer, the GBPSR report argued that disproportionately health-burdened people "require greater, not lesser, environmental safeguards."[1762, 1763] At this writing, the air quality permit, which was greenlighted by the HIA's findings, is under appeal before the Massachusetts Department of Environmental Protection.

- December 18, 2018 – "Given that many pipelines transport volatile, flammable, or toxic oil and liquids, and given the potential consequences of a successful physical or cyber-attack, pipeline systems are attractive targets for terrorists, hackers, foreign nations, criminal groups, and others with malicious intent," according to a report from the U.S. Government Accountability Office that urged the U.S. Department of Homeland

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[1760] The Massachusetts Department of Environmental Protection, the Massachusetts Department of Public Health, & the Metropolitan Area Planning Council, "Health Impact Assessment of a Proposed Natural Gas Compressor Station in Weymouth, MA," January 1, 2019, https://www.mass.gov/files/documents/2019/02/14/Health-Impact-Assessment-Weymouth-Final-Report.pdf.

[1761] Jessica Trufant, "Regulators Issue Air Permit for Weymouth Compressor Station," *The Patriot Ledger, Quincy, MA*, January 11, 2019, https://www.patriotledger.com/news/20190111/regulators-issue-air-permit-for-weymouth-compressor-station.

[1762] Greater Boston Physicians for Social Responsibility, "Health Risks of A Proposed Compressor Station in Weymouth, Massachusetts," February 7, 2019, https://d279m997dpfwgl.cloudfront.net/wp/2019/02/GB-PSR-Report-on-Health-Risks-of-Proposed-Weymouth-Compressor-Station_Feb-7-2019.pdf.

[1763] Jessica Trufant, "Doctors' Group Challenges Report on Weymouth Compressor Station," *The Patriot Ledger, Quincy, MA*, February 7, 2019, https://www.patriotledger.com/news/20190207/doctors-group-challenges-report-on-weymouth-compressor-station.

Security's Transportation Security Administration (TSA) to address weaknesses in its management of pipeline security. TSA oversees the physical security and cybersecurity of the more than 2.7 million miles of gas, oil, and hazardous liquid pipelines in the United States.[1764]

- December 14, 2018 – The California Public Utilities Commission (CPUC) took action against Pacific Gas and Electric Company (PG&E) for what CPUC said are systemic violations of rules to prevent damage to natural gas pipelines during excavation activities. PG&E had been noncompliant with the law pertaining to the locating and marking of natural gas distribution pipelines, as well as related requirements to inform construction personnel and private persons on the location of PG&E's underground pipes and other natural gas infrastructure in a timely and accurate manner.[1765, 1766, 1767]

- December 10, 2018 – The Atlantic Coast Pipeline is a 600-mile project led by Dominion Energy that would extend from West Virginia to eastern North Carolina. Construction was halted when the U.S. Court of Appeals stayed a permit from the U.S. Fish and Wildlife Service that had authorized building the pipeline in critical habitat for four endangered species: the Indiana bat, the rusty-patched bumblebee, the clubshell mussel, and a shrimp-like crustacean called the Madison Cave isopod.[1768]

- November 15, 2018 – An *E&E News* analysis of interstate pipeline enforcement found that interstate pipelines have caught fire or exploded 137 times since 2010. In 90 percent of those disasters, no fines were levied by PHMSA (the federal agency that directly regulates 350,000 miles of pipelines, more than 400 natural gas storage facilities, and 26 liquefied natural gas facilities). PHMSA's reluctance to levy fines is a direct result of federal pipeline laws, which were largely drafted after 1994 when deregulation was a federal priority.[1769]

- November 1, 2018 – A Russian team used a cartographic model to assess the potential impact on health and environment of compressor station emissions during scheduled

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[1764] U.S. Government Accountability Office, "Critical Infrastructure Protection: Actions Needed to Address Significant Weaknesses in TSA's Pipeline Security Program Management," December 18, 2018, https://www.gao.gov/products/gao-19-48.
[1765] California Public Utilities Commission (CPUC), "Order Instituting Investigation and Order to Show Cause," December 14, 2018, https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M246/K120/246120841.PDF.
[1766] California Public Utilities Commission (CPUC), "CPUC Opens Case Against PG&E for Potential Natural Gas Safety Violations," Press Release, December 14, 2018, http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M250/K897/250897740.PDF.
[1767] Richard Gonzales, "PG&E Falsified Gas Pipeline Safety Records, Regulators Say," *NPR*, December 14, 2018, sec. National, https://www.npr.org/2018/12/14/677003961/pg-e-falsified-gas-pipeline-safety-records-regulators-say.
[1768] John Murawski, "Atlantic Coast Pipeline: Construction Halts for Endangered Species," *The News & Observer*, December 10, 2018, https://www.newsobserver.com/news/business/article222856155.html.
[1769] Mike Soraghan, "No Penalties for 90% of Pipeline Blasts," *E&E News*, November 15, 2018, https://web.archive.org/web/20181115220003/https://www.eenews.net/stories/1060106253.

outages and repairs. They described a method of gas flow redistribution that would obviate the need for large-scale venting of methane into the atmosphere.[1770]

- October 11, 2018 – Overpressurizing a natural gas distribution system while replacing aging pipelines triggered 80 simultaneous natural gas explosions in Massachusetts' Merrimack Valley on September 13, 2018. One teenager was killed, 23 were injured, 130 buildings were destroyed or damaged, and thousands evacuated from communities in Lawrence, Andover, and North Andover. The explosions cost Columbia Gas more than $1 billion.[1771]

- September 10, 2018 – A landslide triggered by four days of intense rain caused a pipeline explosion that burned down a house in Beaver County, Pennsylvania and prompted evacuations. This pipeline, built by Energy Transfer Partners (which merged with Sunoco in 2017), was part of the Mariner 2 East Pipeline that is intended to carry the liquid hydrocarbon, ethane, to coastal ports where it will be exported for plastics manufacturing abroad. In western Pennsylvania, ethane co-occurs with methane in the shale bedrock and is released during fracking operations.[1772, 1773, 1774]

- August 10, 2018 – A joint investigation by the *Charleston Gazette-Mail* and *ProPublica* found that pipeline operators continue to break environmental rules, and state and federal agencies continue to clear roadblocks to allow these projects to move forward despite serious unanswered questions.[1775]

- July 25, 2018 – The Attorneys General of six states (Massachusetts, Rhode Island, New Jersey, Maryland, Illinois, Washington) and the District of Columbia submitted comments to the Federal Energy Regulatory Commission (FERC) on how the Commission should revise its approach to certifying new natural gas transportation facilities. They recommended that the Commission assess need on a comprehensive, regional basis; consider environmental harm, including climate impacts that consider the social costs of carbon; and more heavily weigh the harm of eminent domain. They urged

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[1770] Alexey Strizhenok and Denis Korelskiy, "Estimation and Reduction of Methane Emissions at the Scheduled and Repair Outages of Gas-Compressor Units," *Journal of Ecological Engineering* 20, no. 1 (January 1, 2019): 46–51, https://doi.org/10.12911/22998993/93943.

[1771] National Transportation Safety Board, "Pipeline Over-Pressure of a Columbia Gas of Massachusetts Low-Pressure Natural Gas Distribution System," Accident report (National Transportation Safety Board, October 11, 2018), https://permanent.fdlp.gov/gpo111468/PLD18MR003-preliminary-report.pdf.

[1772] Kris Mamula and Anya Litvak, "Officials Believe Landslide May Have Triggered Massive Gas Pipeline Explosion in Beaver County | Pittsburgh Post-Gazette," *Pittsburgh Post-Gazette*, September 10, 2018, https://www.post-gazette.com/local/west/2018/09/10/gas-explosion-in-center-township-Beaver-County/stories/201809100067.

[1773] Anya Litvak, "Pipeline Ruptures Bring New Scrutiny to Pennsylvania Geology," *AP News*, October 27, 2018, sec. Pennsylvania, https://apnews.com/article/2e0005ec7db342a290199a4d8464b5a0.

[1774] Anya Litvak, "Who Gets to Say Where It's Safe to Build a Pipeline? | Pittsburgh Post-Gazette," *Pittsburgh Post-Gazette*, September 14, 2018, https://www.post-gazette.com/business/powersource/2018/09/14/Who-gets-to-say-where-it-s-safe-to-build-a-pipeline-natural-gas-beaver-county-explosion-DEP-Pennsylvania/stories/201809140058.

[1775] Kate Mishkin and Ken Ward Jr., "What Happens When a Pipeline Runs Afoul of Government Rules? Authorities Change the Rules.," *ProPublica*, August 10, 2018, https://www.propublica.org/article/west-virginia-halted-mountain-valley-pipeline?token=SstV5uby4K1aF_9o7uU0NxUx4Lmau-1g.

better incorporation of state and local land use policies. And they recommended that the Commission no longer issue partial notices to proceed with construction when rehearing requests are pending.[1776]

- May 24, 2018 – The Office of the Inspector General at the Department of Energy audited FERC's Natural Gas Certification Process. It found that FERC lacked a consistent process for tracking public comments on proposed pipeline projects, suggesting that all comments might not be reviewed. "In the absence of a consistent methodology, we did not verify to what degree comments received by FERC were considered, aggregated, and reflected in the environmental documents or final orders for the certificate applications during our review," the report concluded. "The lack of a consistent methodology could increase the risk that FERC may not address significant and impactful public comments in the environmental document or final order."[1777, 1778]

- May 16, 2018 – A team of researchers in Alberta, Canada investigated how noise from natural gas compressor stations and oil wells affected the behavior and communication of Savannah sparrows (*Passerculus sandwichensis*). The results showed that alarm responses and feeding visits were impaired by noise-producing infrastructure. Savannah sparrows were less vigilant when provisioning nestlings and distracted from their reproductive tasks when in the vicinity of compressor stations. "Our observation that Savannah sparrows are less responsive to anti-predator signals in the vicinity of natural gas compressor stations is of conservation concern and adds to a growing body of evidence that noisy anthropogenic structures have the potential to negatively affect birds by interfering with acoustic communication."[1779] Previous research in the same region found that the Savannah sparrow altered its song structure and song features when exposed to noise from oil and gas infrastructure, including compressor stations, and that these noise-altered songs were less effective at provoking responses from other birds.[1780, 1781]Similarly, researcher working in the San Juan Basin of New Mexico found that chronic noise from drilling and fracking operations, including compressor stations,

[1776] Federal Energy Regulatory Commission, "Comments of the Attorneys General of Massachusetts, Illinois, Maryland, New Jersey, Rhode Island, Washington, and the District of Columbia," Docket, July 25, 2018, https://www.mass.gov/files/documents/2018/07/26/Multistate%20Comments-FERC%201999%20PL%20Policy%20Review.pdf.
[1777] Phil McKenna, "Public Comments on Pipeline Plans May Be Slipping Through Cracks at FERC, Audit Says," *Inside Climate News*, May 31, 2018, https://insideclimatenews.org/news/31052018/public-comments-oil-gas-pipelines-ferc-review-energy-department-inspector-general-audit/.
[1778] Office of the Inspector General at the Department of Energy, "The Federal Energy Regulatory Commission's Natural Gas Certification Process," Audit Report, May 24, 2018, https://www.energy.gov/ig/downloads/audit-report-doe-oig-18-33.
[1779] Bridget Antze and Nicola Koper, "Noisy Anthropogenic Infrastructure Interferes with Alarm Responses in Savannah Sparrows (*Passerculus Sandwichensis*)," *Royal Society Open Science* 5, no. 5 (2018): 172168, https://doi.org/10.1098/rsos.172168.
[1780] Miyako H. Warrington et al., "Noise from Four Types of Extractive Energy Infrastructure Affects Song Features of Savannah Sparrows," *The Condor* 120, no. 1 (2017): 1–15, https://doi.org/10.1650/CONDOR-17-69.1.
[1781] Claire M. Curry et al., "Noise Source and Individual Physiology Mediate Effectiveness of Bird Songs Adjusted to Anthropogenic Noise," *Scientific Reports* 8, no. 1 (2018): 3942, https://doi.org/10.1038/s41598-018-22253-5.

affected levels of stress hormones in songbirds and masked critical acoustic cues in ways that decreased the birds' ability to survive and reproduce.[1782, 1783]

- April 26, 2018 – Studies that investigate the health impacts of drilling and fracking activities typically incorporate the distance between participants' home addresses and well pads and do not consider potential exposures to emissions from other ancillary pieces of infrastructure. A study led by Johns Hopkins University researchers working in Pennsylvania attempted to develop exposure metrics for air emissions from compressor stations, flare stacks, and impoundments. The research team identified 457 compressor stations in Pennsylvania and 1419 compressor station engines. Data on compressor stations engines were not available electronically, and only 361 stations could be confirmed as operational. The team found that compressor engines, impoundments, and flaring events are all potential sources of emissions related to drilling and fracking that have not previously been accounted for in epidemiological studies "in part because data are not readily available. The value of including these additional sources of information on [fracking], particularly in health studies, remains unknown."[1784]

- April 26, 2018 – Pipelines are inspected and cleaned through a process called pigging, in which devices are placed inside, and travel through, the pipe. Pigs can be used to force water or air through a pipeline, check for obstructions, detect leaks, scrape debris from the pipe wall, prevent corrosion, or apply coatings. Pigging is necessarily accompanied by venting of hydrocarbon gases into the air, including methane. A federal settlement acknowledged that the use of the maintenance pigging technique is a major source of harmful emissions in pipeline systems carrying fracked gas extracted from shale that also contains other hydrocarbons, such as natural gas liquids. "The settlement between the U.S. Department of Justice, Environmental Protection Agency and Pennsylvania Department of Environmental Protection and two MarkWest subsidiaries … alleges the company failed to apply for or comply with air pollution permits. As a result, the company unlawfully vented hundreds of tons of natural gas and volatile organic compounds."[1785]

- October 12, 2017 – Researchers at University of Albany's Institute for Health and the Environment prepared a 300-page technical report on the health effects of the emissions from 18 natural gas compressor stations in New York State. The team found that, collectively, these sites released 40 million pounds of 70 different contaminants over a seven-year period, making natural gas compressor stations the seventh largest point

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[1782] Nathan J. Kleist et al., "Chronic Anthropogenic Noise Disrupts Glucocorticoid Signaling and Has Multiple Effects on Fitness in an Avian Community," *Proceedings of the National Academy of Sciences* 115, no. 4 (2018): E648–57, https://doi.org/10.1073/pnas.1709200115.
[1783] University of Colorado at Boulder, "Noise from Oil and Gas Operations Stresses Birds, Hinders Reproduction," News Release (AAAS EurekAlert, January 8, 2018), https://www.eurekalert.org/news-releases/896481.
[1784] Kirsten Koehler et al., "Exposure Assessment Using Secondary Data Sources in Unconventional Natural Gas Development and Health Studies," *Environmental Science & Technology* 52, no. 10 (2018): 6061–69, https://doi.org/10.1021/acs.est.8b00507.
[1785] Brittany Patterson, "MarkWest Agrees to Pay Millions in Federal Settlement Over 'Pig' Emissions," *West Virginia Public Broadcasting*, April 26, 2018, sec. WVPB News, https://www.wvpublic.org/news/2018-04-26/markwest-agrees-to-pay-millions-in-federal-settlement-over-pig-emissions.

source of air pollution in the state. By volume, the largest emissions were nitrogen oxides, carbon monoxide, volatile organic compounds (VOCs), formaldehyde, and particulate matter. Exposure to these chemicals is linked to cancer, as well as cardiovascular, neurological, and developmental disorders. The authors noted, "The potential health impacts of the large volumes of pollutants generated by natural gas compressor stations have not been addressed, let alone answered, by those arguing for their construction and expansion."[1786]

- October 11, 2017 – A study of airborne methane emissions from assorted components of natural gas infrastructure in California, including compressor stations and storage facilities, confirmed earlier studies in finding widely variable leakages. The results suggested that a significant fraction of the methane emitted from storage facilities may, in fact, be escaping from their associated compressor stations.[1787]

- July 17, 2017 – A comprehensive investigation of the pipeline approval process by the Center for Public Integrity, *StateImpact Pennsylvania,* and National Public Radio found that FERC, which is charged with ensuring the public's interest, routinely assesses need based on company filings and functions as an agency captured by industry interests, concluding, "at every turn, the agency's process favors the pipeline companies." The result, according to this analysis of more than 500 pipeline cases, is that the financial interests of the gas industry, and not market demand or public necessity, is driving the ongoing pipeline build-out. In some cases, utility companies have complex financial ties to the pipeline companies that service them.[1788] Continuing this investigation, *Inside Climate News* then reviewed several large, new pipeline proposals in the Marcellus and Utica Shale regions, focusing on joint ventures and interlocking financial relationships between customers (state-regulated utilities) and suppliers (pipeline companies). Affiliate agreements that allow parent companies of utilities to seek federal certificates for interstate pipelines—which typically allow a 14 percent return on equity—contribute to the ongoing frenzy of pipeline construction even when natural gas demand is flat. Existing pipelines, the investigation noted, run at only slightly more than half capacity.[1789]

- July 12, 2017 – A Canadian study found that oil and gas infrastructure, including compressor stations, contributes to habit fragmentation and increases parasitism by

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[1786] D. O. Carpenter and P. N. Russo, "Health Effects Associated with Stack Chemical Emissions from NYS Natural Gas Compressor Stations: 2008-2014," Technical Report (Southwest Pennsylvania Environmental Health Project, n.d.), http://www.environmentalhealthproject-ny.org/uploads/3/8/5/9/38599771/ny_compressor_station_report_power_point_10.11.2017.pdf.
[1787] Shobhit Mehrotra et al., "Airborne Methane Emission Measurements for Selected Oil and Gas Facilities Across California," *Environmental Science & Technology* 51, no. 21 (2017): 12981–87, https://doi.org/10.1021/acs.est.7b03254.
[1788] Kristen Lombardi and Jamie Smith Hopkins, "Natural Gas Building Boom Fuels Climate Worries, Enrages Landowners," *NPR*, July 17, 2017, https://www.npr.org/2017/07/17/536708576/natural-gas-building-boom-fuels-climate-worries-enrages-landowners.
[1789] Phil McKenna, "Pipeline Payday: How Builders Win Big, Whether More Gas Is Needed or Not," *Inside Climate News*, August 3, 2017, https://insideclimatenews.org/news/03082017/natural-gas-pipeline-boom-corporate-profit-bubble-limited-demand-climate-emissions/.

cowbirds on Savannah sparrow nests in the Northern Great Plains. Populations of North American grassland songbirds, including the Savannah sparrow, are declining precipitously, mostly due to habitat loss and degradation. These results suggest that "brood parasitism associated with oil and natural gas infrastructure may result in additional pressures that reduce the productivity of this declining grassland songbird."[1790]

- May 16, 2017 – An analysis of records from state agencies revealed that low-pressure flow lines at oil and gas well sites are responsible for more than 7,000 spills, leaks, and accidents since 2009. Flow lines carry oil, gas, or wastewater from scattered pieces of equipment within a production site. Other than in New Mexico, operators are not required to report gas leaks from flow lines. A fatal explosion in April 2017 in a Firestone, Colorado home built on top of an oil field was triggered when an abandoned flow line seeped gas into a basement where it ignited. Two people were killed and one person was badly injured. Soon after, Colorado Governor John Hickenlooper ordered a statewide review of all oil and gas lines located near occupied buildings. Preliminary data showed that 16,000 wells across Colorado have flow lines that lie within 1,000 feet of homes. Corrosion is a leading cause of flow line failures.[1791, 1792]

- February 15, 2017 – A team of researchers from University of Texas investigated emissions from natural gas compressor stations throughout Pennsylvania and New York. They found that compressors emitted highly variable plumes of methane that spread downwind and were measurable a full mile away at levels that could expose nearby residents, especially during temperature inversions. The researchers concluded, "Our data indicate that compressor stations are likely sources of methane emissions and presumably co-emitted air contaminants, and can sporadically/episodically emit methane at relatively high levels…if such facilities are to be permitted to release specified amounts of contaminants, those amounts should be actively measured and verified. Without measurement there can be no assurance that permit conditions are being met."[1793]

- November 30, 2016 – A CityLab investigation used data from the Pipeline and Hazardous Materials Safety Administration to map all significant U.S. pipeline accidents between 1986 and 2016 and concluded, "wherever pipelines are extended, deadly accidents will follow." Pipeline accidents over the past 30 years have resulted in 548 deaths, more than 2,500 injuries, and over $8.5 billion in damages. Accidents are particularly common in Texas and Louisiana.[1794]

[1790] Jacy Bernath-Plaisted, Heather Nenninger, and Nicola Koper, "Conventional Oil and Natural Gas Infrastructure Increases Brown-Headed Cowbird (*Molothrus Ater*) Relative Abundance and Parasitism in Mixed-Grass Prairie," *Royal Society Open Science* 4, no. 7 (2017): 170036, https://doi.org/10.1098/rsos.170036.
[1791] Mike Soraghan, "Flow Lines Cited in More than 7K Spills," *E&E News*, May 16, 2017, https://web.archive.org/web/20170516233919/https://www.eenews.net/stories/1060054568.
[1792] Mike Lee, "Fatal Explosion Threatens More Upheaval over Drilling in Colo," *E&E News*, June 12, 2017, https://web.archive.org/web/20180828194551/https://www.eenews.net/stories/1060055846.
[1793] Bryce F. Payne et al., "Characterization of Methane Plumes Downwind of Natural Gas Compressor Stations in Pennsylvania and New York," *Science of The Total Environment* 580 (2017): 1214–21, https://doi.org/10.1016/j.scitotenv.2016.12.082.
[1794] George Joseph, "30 Years of Oil and Gas Pipeline Spills, Mapped - Bloomberg," *CityLab*, November 30, 2017, https://www.bloomberg.com/news/articles/2016-11-30/30-years-of-oil-and-gas-pipeline-spills-mapped.

- July 5, 2016 – The National Energy Board, Canada's pipeline watchdog, gave two of Canada's largest pipeline companies six months to fix severe deficiencies in pipelines, ultimately issuing an emergency safety order in February 2016. Newly released federal documents showed that Texas-based Kinder Morgan and Alberta-based Enbridge were both looking into the use of defective parts purchased from Thailand-based Canadoil Asia that recently went bankrupt. U.S. regulators warned of these deficiencies eight years prior. At least one Canadian pipeline with defective materials exploded during that period.[1795]

- June 10, 2016 – EPA Region 2 submitted comments to FERC on Docket Nos. PFI6-3, Eastern System Upgrade Project, which includes new natural gas compressor stations in Hancock and Highland, New York. The EPA submission suggested an analysis of whether this project was needed; clarification of what is meant by a loop system; evaluation of alternatives; a comprehensive analysis of cumulative, indirect, and secondary impacts; information on greenhouse gas emissions and climate change impacts; a Health Impact Assessment; the inclusion of all pollution prevention practices; and a consideration of environmental justice concerns.[1796] The company agreed to provide funding toward a health study but wished to retain the ability to determine the study parameters.[1797] Skeptical of the health study's funding and parameters, residents and potentially impacted towns objected to the company's dismissal of the towns' laws prohibiting the construction and operation of heavy industrial use facilities. The Deputy Supervisor of one of the affected towns "said he was encouraged by the federal Environmental Protection Agency's comments on the project's preliminary federal application. He said the EPA concerns were 'the same as ours.'"[1798]

- April 27, 2016 – In its report on two natural gas pipeline expansion projects in Appalachia, the Institute for Energy Economics and Financial Analysis demonstrated that the Atlantic Coast and Mountain Valley pipelines are "emblematic of the risks that such expansion creates for ratepayers, investors and landowners." The report concluded that pipelines out of the Marcellus and Utica region are being overbuilt, putting ratepayers at risk of paying for excess capacity, landowners at risk of losing their property to unnecessary projects, and investors at risk of loss. The report stated that FERC facilitates this building of excess pipeline capacity and its approach for assessing need is insufficient.[1799]

[1795] Mike De Souza, "How Canada's Pipeline Watchdog Secretly Discusses 'Ticking Time Bombs' with Industry," *Canada's National Observer*, July 5, 2016, sec. News, https://www.nationalobserver.com/2016/07/05/news/how-canada%E2%80%99s-pipeline-watchdog-secretly-discusses-ticking-time-bombs-industry.
[1796] US EPA Region 2, "Docket Nos. PFI6-3, Eastern System Upgrade Project," June 10, 2016, https://elibrary.ferc.gov/idmws/file_list.asp?document_id=14468753.
[1797] F. Mayer, "Millennium to Pay for Health Study," *The River Reporter*, April 27, 2016, https://riverreporter.com/stories/millennium-to-pay-for-health-study,1279.
[1798] David Hulse, "Highland Concerned about Study Underfunding," *The River Reporter*, June 22, 2016, https://riverreporter.com/stories/highland-concerned-about-study-underfunding,945.
[1799] Cathy Kunkel and Tom Sanzillo, "Risks Associated With Natural Gas Pipeline Expansion in Appalachia: Proposed Atlantic Coast and Mountain Valley Pipelines Need Greater Scrutiny" (Institute for Energy Economics

- April 22, 2016 – The federal Agency for Toxic Substances and Disease Registry (ATSDR) released a report on air quality near a natural gas compressor station in Brooklyn Township, Susquehanna County, Pennsylvania, finding levels of fine particulate matter (PM2.5) at levels that can damage human health in those with long-term exposure. Evaluating data from an 18-day EPA field air monitoring event, the report found that the average ambient 24-hour PM2.5 concentration observed at one residence (19 µg/m3) was higher than the nearest regional National Ambient Air Quality Standards (NAAQS) monitoring station (12.3 µg/m3) in Scranton, PA, over the same period. ATSDR concluded that there was evidence that long-term exposure to PM2.5 at the levels found can cause an increase in mortality, respiratory problems, hospitalizations, preterm births, and low birth weight. The agency said that in the short term, exposure could be harmful to sensitive populations, such as those with respiratory problems or heart disease. The agency recommended that sensitive individuals monitor air quality and limit activity accordingly, and that the PA DEP work to reduce other sources of PM and its precursors.[1800]

- April 3, 2016 – The Southwest Pennsylvania Environmental Health Project issued a *Technical Report* in response to the January 29, 2016 federal ATSDR report on the Brigich compressor station in Chartiers Township, Washington County, Pennsylvania. ATSDR detected chemicals that had been reported at gas sites previously, and this confirmation of their presence provided "an important acknowledgement that neighbors of such facilities are being exposed (often at very close range) to chemicals that bring with them the possibility of short- and long-term health effects." The report stated that, in conjunction with the monitoring work of the EPA, ATSDR "provided a solid set of data." However, due to the limitations of the methodologies available to them, the authors were "concerned that there was, in the end, an underestimate of risk to community members."[1801]

- April 1, 2016 – Kinder Morgan, the largest energy infrastructure company in North America, suspended construction of a $1 billion pipeline project that would have carried gasoline and diesel fuel across the southeastern United States. Construction was suspended after landowners protested the seizure of their property, a Georgia Superior Court judge upheld a decision denying a certificate that would have allowed the company

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and Financial Analysis, 2016), http://ieefa.org/wp-content/uploads/2016/04/Risks-Associated-With-Natural-Gas-Pipeline-Expansion-in-Appalachia-_April-2016.pdf.

[1800] U.S. Department of Health and Human Services, "Brooklyn Township PM2.5 Brooklyn Township, Susquehanna County, Pennsylvania," Health Consultation (Agency for Toxic Substances and Disease Registry, Division of Community Health Investigations, April 22, 2016), https://www.atsdr.cdc.gov/HAC/pha/BrooklynTownship/BrooklynTwnsp_pm2-5_HC_Final_04-22-2016_508.pdf.

[1801] Southwest Pennsylvania Environmental Health Project, "ATSDR Releases Investigation of Pennsylvania Compressor Station: Response to Governmental Action and Publication I," April 3, 2016, https://www.catskillcitizens.org/files/learnmore/brigichtechnicalreportfinal_1_.pdf.

to use eminent domain, and the state legislature passed legislation to block the property seizure.[1802]

- March 26, 2016 – According to a Boston University-led study, fugitive emissions from urban natural gas pipeline systems were the largest anthropogenic source of the greenhouse gas methane in the United States and contribute to the risk of explosions in urban environments, with 15 percent of leaks qualifying as potentially explosive.[1803] “All leaks must be addressed, as even small leaks cannot be disregarded as ‘safely leaking,’” concluded the report authors. In an interview with *Inside Climate News*, the lead author said that in addition to weighing the safety risks from gas leaks, regulators and utility companies must also consider the climate impact of leaks when determining priorities for repairing and replacing pipes.[1804]

- March 7, 2016 – A lawsuit filed against FERC in U.S. District Court in Washington, D.C challenged the agency’s relationship with industry, reported *Penn Live*: “The suit accuses the commission of regulatory capture, a situation in which corporations control regulators.” FERC receives all of its funding from the energy companies that it regulates and had never rejected a pipeline plan, which, according to the complainant, demonstrates “clear bias and corruption.”[1805]

- February 26, 2016 – Congressman Chris Gibson (NY-19), in response to citizen concerns, sent a letter to FERC regarding the proposed 41,000-horsepower compressor station in southern Rensselaer County, New York, part of the Northeast Energy Direct (NED) pipeline project. He discussed the inadequacy of federal exposure standards with regard to exposures at compressor sites and lack of medical expertise in these decisions. He requested public health expertise on all Environmental Assessment and Environmental Impact Statement teams, an independent panel to review the federal exposure standards around compressor stations, and “a transparent and effective review process.”[1806] His call was supported by other elected officials, as well as public health researcher David O. Carpenter, MD, who has studied compressor station pollutants.[1807]

[1802] Phil McKenna, “Property Rights Outcry Stops Billion-Dollar Pipeline Project in Georgia,” *Inside Climate News*, April 1, 2016, https://insideclimatenews.org/news/01042016/palmetto-pipeline-kinder-morgan-georgia-eminent-domain-oil-gas-republicans/.
[1803] Margaret F. Hendrick et al., “Fugitive Methane Emissions from Leak-Prone Natural Gas Distribution Infrastructure in Urban Environments,” *Environmental Pollution* 213 (2016): 710–16, https://doi.org/10.1016/j.envpol.2016.01.094.
[1804] Phil McKenna, “Methane Hazard Lurks in Boston’s Aging, Leaking Gas Pipes, Study Says,” *Inside Climate News*, March 31, 2016, https://insideclimatenews.org/news/31032016/boston-natural-gas-pipelines-leaking-methane-climate-change-explosion/.
[1805] Candy Woodall, “Federal Agency Funded by Energy Industry Has Never Rejected a Pipeline Plan,” *PennLive Patriot News*, March 7, 2016, sec. Pennsylvania Real-Time News, https://www.pennlive.com/news/2016/03/pipeline_fights_raise_big_ques.html.
[1806] Chris Gibson, “Compressor Station Needs Review,” *Sullivan County Democrat*, February 26, 2016, https://www.scdemocratonline.com/stories/compressor-station-needs-review,47706?
[1807] Brian Nearing, “Gibson: Federal Natural Gas Air Pollution Safety Standards May Be Obsolete,” *Times Union*, March 31, 2016, sec. Business, https://www.timesunion.com/business/article/Gibson-Federal-natural-gas-air-pollution-safety-7221271.php.

- January 29, 2016 – ATSDR, in collaboration with the EPA Region 3 Air Protection Division, conducted an exposure investigation to evaluate exposures of residents living near the Brigich natural gas compressor station in Chartiers Township, Washington County, Pennsylvania. ATSDR concluded that, although exposure to the levels of chemicals detected in the ambient air was not expected to harm the health of the general population, "some sensitive subpopulations (e.g., asthmatics, elderly) may experience harmful effects from exposures to hydrogen sulfide and PM 2.5 [and] [s]ome individuals may also be sensitive to aldehyde exposures, including glutaraldehyde." According to ATSDR, one of the study's limitations was that the sampling "may not have adequately captured uncommon but significant incidents when peak emissions (e.g. unscheduled facility incidents, blowdowns or flaring events) coincide with unfavorable meteorological conditions (e.g. air inversion)." ATSDR recommendations included reducing exposures to the chemicals of concern to protect sensitive populations, continued collection of emissions data for long-term and peak exposures, and air modeling to better understand ambient air quality.[1808]

- December 8, 2015 – The Niagara County Legislature, following the recommendations of the Medical Society of the State of New York, called for a Health Impact Assessment (HIA) on natural gas infrastructure, including compressor stations, and co-hosted a conference in Albany on the Medical Society's health findings. A compressor station with twin compressors, part of the "2016 Northern Access Plan" to transfer gas from Pennsylvania to Canada, is proposed for the county.[1809]

- November 9, 2015 – Following the 2010 heavy oil spill in Michigan's Kalamazoo River, Congress ordered an audit that spotlighted the industry's poor record of spotting leaks. *Politico* reported on the 2015 regulatory structure ultimately unveiled in response, determining the proposal "fails to patch that hole in the nation's pipeline safety net." "While the agency's proposed rule expands the number of pipelines that must have a leak-detection system in place, it sets no basic standards for how well that technology should work. Instead, safety advocates say, it lets pipeline operators decide for themselves whether they are adequately prepared."[1810]

- October 16, 2015 – The EPA urged FERC to consider "whether the Northeast Energy Direct pipeline could be combined with other projects, rather than constructing a new system that would have a host of environmental impacts," reported Oneonta, New York's *Daily Star*. The EPA also advised "that the gas demand addressed by NED's application

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[1808] U.S. Department of Health and Human Services, "Exposure Investigation, Natural Gas Ambient Air Quality Monitoring Initiative Brigich Compressor Station, Chartiers Township, Washington County, Pennsylvania," Health Consultation (Agency for Toxic Substances and Disease Registry, Division of Community Health Investigations, January 29, 2016), http://www.atsdr.cdc.gov/HAC/pha/Brigich_Compressor_Station/Brigich_Compressor_Station_EI_HC_01-29-2016_508.pdf.
[1809] Staff Reports, "County Lawmakers Call for Study on Compressor Health Risks," *Lockport Union-Sun & Journal*, December 8, 2015, https://www.lockportjournal.com/news/local_news/county-lawmakers-call-for-study-on-compressor-health-risks/article_932989cd-058a-594f-9ef2-e52827db85a6.html.
[1810] Elana Schor and Andrew Restuccia, "The Hole in Obama's Pipeline Safety Plan," *Politico*, November 9, 2015, https://www.politico.com/story/2015/11/obama-pipeline-safety-plan-oil-215617.

could be met by renewable forms of energy such as solar and wind power…"[1811] (Note: Kinder Morgan withdrew its NED pipeline application in April 2016.)

- September 17, 2015 – At a shale gas conference, industry representatives espoused the construction of new pipelines as necessary to re-invigorate the gas industry in the Marcellus. Speakers noted that FERC approval can be expected to now take longer, by about six months, blaming environmental groups for the delays.[1812]

- September 9, 2015 – New pipelines are failing at a rate on par with gas transmission lines installed before the 1940s, according to an analysis of federal data by the Pipeline Safety Trust, reported by *S&P Global Market Intelligence*. "The gas transmission lines installed in the 2010s had an annual average incident rate of 6.64 per 10,000 miles over the time frame considered, even exceeding that of the pre-1940s pipes. Those installed prior to 1940 or at unknown dates had an incident rate of 6.08 per 10,000 miles." The director of the National Transportation Safety Board's Office of Railroad, Pipeline and Hazardous Materials Investigations "agreed that the rapid construction of pipelines in the U.S. is likely a contributing factor."[1813]

- August 18, 2015 – Houston Advanced Research Center (HARC) scientists addressed "the commonly acknowledged sources of uncertainty which are the lack of sustained monitoring of ambient concentrations of pollutants associated with gas mining, poor quantification of their emissions, and inability to correlate health symptoms with specific emission events." They concluded that "more contemporary monitoring and data analysis techniques should take the place of older methods to better protect the health of nearby residents and maintain the integrity of the surrounding environment." "Real-time mobile monitoring, microscale modeling and source attribution, and real-time broadcasting of air quality and human health data over the World Wide Web" have been demonstrated, they wrote, by past, current, and planned future monitoring studies in the Barnett and Eagle Ford shale regions.[1814] Founded as a technology incubator in 1982 by Houston oilman George P. Mitchell, HARC later re-aligned to focus on sustainable development.

- August 14, 2015 – HARC scientists found that port operations involving petrochemicals may significantly increase emissions of air toxics, including peaks of carcinogenic benzene of up to 37 ppb. The scientists matched the benzene spikes with pipeline systems. The spikes were at levels much higher than those reported in the EPA's 2011 National Emissions Inventory. The authors recommended the use of updated methods for

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[1811] Joe Mahoney, "EPA: Can Local Pipeline Plans Merge?," *The Daily Star*, October 16, 2015, https://www.thedailystar.com/news/local_news/epa-can-local-pipeline-plans-merge/article_f2836510-a96b-5c2d-9892-755b94b1f640.html.

[1812] Dan Packel, "Energy Honchos Lament FERC Pipeline Approval Delays - Law360," *Law 360*, September 17, 2015, https://www.law360.com/articles/697120/energy-honchos-lament-ferc-pipeline-approval-delays.

[1813] Sarah Smith, "SNL: As US Rushes to Build Gas Lines, Failure Rate of New Pipes Has Spiked," *S&P Global*, September 9, 2015, https://www.snl.com/interactiveX/article.aspx?CDID=A-33791090-11060&ID=33791090&Printable=1.

[1814] Eduardo P. Olaguer et al., "Updated Methods for Assessing the Impacts of Nearby Gas Drilling and Production on Neighborhood Air Quality and Human Health," *Journal of the Air & Waste Management Association* 66, no. 2 (2016): 173–83, https://doi.org/10.1080/10962247.2015.1083914.

ambient monitoring.[1815] Lead scientist Jay Olaguer said in a related interview that "government regulators should wake up to the reality of the situation, that their methods of tracking air pollution need to be updated so that the samples are taken in real time and can catch it when toxic vapors of this magnitude are released."[1816]

- July 15, 2015 – Rensselaer County lawmakers passed a resolution asking the state of New York to freeze the approval process for the Northeast Energy Direct pipeline—which would carry fracked gas from Pennsylvania to Boston—until it conducts a comprehensive health impact assessment for natural gas pipelines.[1817]

- July 8, 2015 – Researchers from West Virginia University completed leak and loss audits for methane emissions at three natural gas compressor stations and two natural gas storage facilities, with a "leak" defined as an unintended release of natural gas due to malfunction of a component, and a "loss" defined as an intended release of natural gas. In terms of frequency, most emissions were leaks, but on a mass basis, losses were the dominant source of methane emissions (88 percent). The top loss emitters were engine exhausts (accounting for nearly half), packing vents, and slop tanks. Emissions from compressor blowdowns were not included.[1818] A related study by a University of Houston team found that emission rates from compressor stations in Texas' Barnett Shale were far higher than from well pads.[1819, 1820]

- July 7, 2015 – Seeking a method to bridge the gap between bottom-up and top-down methods of measuring methane emissions, Purdue University, University of Houston, the National Oceanic and Atmospheric Administration (NOAA), Environmental Defense Fund, and independent researchers surveyed eight high-emitting point sources in the Barnett Shale using an aircraft-based "mass balance" approach. Results from four gas processing plants and one compressor station highlighted the importance of addressing methane "super-emitters" and confirmed that self-reports from the Greenhouse Gas Reporting Program underestimated actual emission rates by a factor of 3.8 or higher, due to "underestimated facility emissions, temporal variability of emissions, and the exclusion of nonreporting facility emissions."[1821]

[1815] Eduardo P. Olaguer et al., "Source Attribution and Quantification of Benzene Event Emissions in a Houston Ship Channel Community Based on Real-Time Mobile Monitoring of Ambient Air," *Journal of the Air & Waste Management Association* 66, no. 2 (2016): 164–72, https://doi.org/10.1080/10962247.2015.1081652.
[1816] Dianna Wray, "Scientists Discover Pipelines Belching Benzene in East Houston," *Houston Press*, February 23, 2016, https://www.houstonpress.com/news/scientists-discover-pipelines-belching-benzene-in-east-houston-8181569.
[1817] Brian Nearing, "County: Put Study before Any Permit," *Times Union*, July 16, 2015, sec. News, https://www.timesunion.com/news/article/County-Put-study-before-any-permit-6387404.php.
[1818] Derek R. Johnson, April N. Covington, and Nigel N. Clark, "Methane Emissions from Leak and Loss Audits of Natural Gas Compressor Stations and Storage Facilities," *Environmental Science & Technology* 49, no. 13 (2015): 8132–38, https://doi.org/10.1021/es506163m.
[1819] Xin Lan et al., "Characterizing Fugitive Methane Emissions in the Barnett Shale Area Using a Mobile Laboratory," *Environmental Science & Technology* 49, no. 13 (2015): 8139–46, https://doi.org/10.1021/es5063055.
[1820] Lisa Song and Zahra Hirji, "Methane Emissions in Texas Fracking Region 50% Higher Than EPA Estimates," *Inside Climate News*, July 8, 2015, https://insideclimatenews.org/news/08072015/methane-emissions-texas-fracking-region-50-higher-epa-estimates-oil-gas-drilling-barnett-shale-environmental-defense-fund/.
[1821] Tegan N. Lavoie et al., "Aircraft-Based Measurements of Point Source Methane Emissions in the Barnett Shale Basin," *Environmental Science & Technology* 49, no. 13 (2015): 7904–13, https://doi.org/10.1021/acs.est.5b00410.

- July 7, 2015 – Using relatively easy-to-acquire and inexpensive stable isotopic and alkane ratio tracers, researchers are now able to distinguish methane arising from natural gas production and transport from agricultural and urban methane sources, and, in addition, to distinguish between methane released from shale gas as opposed to conventional wells. Initial research from the University of Cincinnati, University of California at Irvine, and the Environmental Defense Fund found that methane in the Barnett Shale hydraulic fracturing region near Fort Worth, Texas, represents a complex mixture of these sources. This new approach, used for ground-level measurements, can complement and extend top-down approaches, allowing for more accurate inventories of thermogenic and biogenic sources of methane emissions.[1822]

- July 1, 2015 – In New York State, Schoharie County supervisors and medical professionals demanded comprehensive health impact assessments as a precondition for permitting natural gas pipelines and compressor stations.[1823]

- June 12, 2015 – The Agency for Toxic Substances and Disease Registry investigated the health effects of ruptured gas pipelines in an analysis of data in a database on acute petroleum-related releases to which seven states contribute (Louisiana, New York, North Carolina, Oregon, Tennessee, Utah, and Wisconsin). From 2010 to 2012, there were 1,369 such incidents, which resulted in 259 injuries. More than three-quarters of these incidents were related to natural gas distribution. Equipment failure accounted for half of all incidents; human error accounted for 40 percent. The report noted the "continuing occurrence" of petroleum release incidents—including from natural gas pipeline ruptures—which have "the potential to cause mass casualties and environmental contamination."[1824]

- June 9, 2015 – The American Medical Association (AMA) adopted a resolution, "Protecting Public Health from Natural Gas Infrastructure," that was based on a resolution adopted by the Medical Society of the State of New York. (See below.) The resolution states, "Our AMA recognizes the potential impact on human health associated with natural gas infrastructure and supports legislation that would require a comprehensive Health Impact Assessment regarding the health risks that may be associated with natural gas pipelines."[1825]

- May 2, 2015 – The Medical Society of the State of New York adopted a resolution, "Protecting Public Health from Natural Gas Infrastructure," that recognizes the potential

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[1822] Amy Townsend-Small et al., "Integrating Source Apportionment Tracers into a Bottom-up Inventory of Methane Emissions in the Barnett Shale Hydraulic Fracturing Region," *Environmental Science & Technology* 49, no. 13 (2015): 8175–82, https://doi.org/10.1021/acs.est.5b00057.
[1823] Kyle Adams, "Schoharie County Officials Ask New Studies on Gas Lines," *The Daily Gazette*, July 1, 2015, https://dailygazette.wufoo.com/forms/k1mmje2u1rvcynr/.
[1824] Ayana R. Anderson, "Health Effects of Cut Gas Lines and Other Petroleum Product Release Incidents — Seven States, 2010–2012," *Morbidity and Mortality Weekly Report* 64, no. 22 (June 12, 2015): 601–5.
[1825] American Medical Association, "H-135.930 Protecting Public Health from Natural Gas Infrastructure, Resolution 519, A-15," 2015, https://www.ama-assn.org/sites/default/files/media-browser/public/hod/a15-hod-resolutions.pdf.

impact to human health and the environment of natural gas pipelines and calls for a governmental assessment of these risks.[1826]

- March 3, 2015 – Researchers with the Southwest Pennsylvania Environmental Health Project measured ambient levels of particulate and volatile air pollutants from fracking-related operations and calculated expected human exposures in Washington County, Pennsylvania. Extremely high exposures peaked at night when air was still. These fluctuating exposure events mimic, in frequency and intensity, the episodic nature of health complaints among residents. Over a one-year period, compressor stations were responsible for more extreme exposure events (118) than well pads or gas processing plants.[1827]

- February 24, 2015 – As part of a literature review on the health impacts of compressor stations, the Southwest Pennsylvania Environmental Health Project reported that peak emissions of fine particles tended to occur during construction time, that day-to-day emissions during operational time can fluctuate greatly, and that a compressor blowdown typically represented the single largest emission event during operations. Hence, documentation of these fluctuations cannot be captured by calculating yearly averages. A blowdown is an intentional or accidental release of gas through the blowdown valve that creates a 30- to 60-meter-high gas plume. Blowdowns, which are used to release pressure, can last as long as three hours. The authors noted that blowdowns result in periods of high levels of volatile organic compound releases and that anecdotal accounts associate blowdowns with burning eyes and throat, skin irritation, and headache.[1828] There is neither a national or state inventory of compressor station accidents nor a body of peer-reviewed research on the public health impacts of compressor stations.

- February 17, 2015 – A Boston study found that emissions from residential, end-use natural gas infrastructure was a significant source of atmospheric methane—two to three times larger than previously presumed—and accounted for 60 to 100 percent of methane, depending on the season. Of all the natural gas in the downstream component of the natural gas system, 2.7 percent was lost to the atmosphere.[1829]

- February 10, 2015 – A team of engineers from Pennsylvania and Colorado examined methane emissions from natural gas compressor stations and found that vents, valves, engine exhaust, and equipment leaks were also major emissions sources. There was

[1826] Medical Society of the State of New York, “2015 House of Delegates Actions: Public Health and Education,” 2015, http://www.mssny.org/Documents/HOD/Actions/ActionPHE.pdf.
[1827] David R. Brown, Celia Lewis, and Beth I. Weinberger, “Human Exposure to Unconventional Natural Gas Development: A Public Health Demonstration of Periodic High Exposure to Chemical Mixtures in Ambient Air,” *Journal of Environmental Science and Health, Part A* 50, no. 5 (2015): 460–72, https://doi.org/10.1080/10934529.2015.992663.
[1828] Southwest Pennsylvania Environmental Health Project, “Summary on Compressor Stations and Health Impacts,” February 24, 2015, https://sape2016.files.wordpress.com/2014/01/summary_report_compressor_stations_swpaehp.pdf.
[1829] Kathryn McKain et al., “Methane Emissions from Natural Gas Infrastructure and Use in the Urban Region of Boston, Massachusetts,” *Proceedings of the National Academy of Sciences* 112, no. 7 (2015): 1941–46, https://doi.org/10.1073/pnas.1416261112.

considerable variation in emissions among the 45 compressor stations measured. Surprisingly, substantial emissions were found even when compressors were not operating.[1830]

- December 27, 2014 – A *Pittsburgh Tribune-Review* investigation found that the vast majority of natural gas “gathering lines”—pipelines that take natural gas from rural well pads to processing plants—were regulated by neither federal nor state pipeline safety laws. The United States has nearly 230,000 miles of natural gas gathering lines that are unregulated, operating without safety standards or inspection. These pipelines are among the largest and highest-pressure pipes in use and carry gas at nearly three times the pressure of transmission lines, which transport the gas from the processing plants to urban distribution networks.[1831]

- November 11, 2014 – An analysis by a Carnegie Mellon University research team of 40,000 pipeline accidents from 1968 to 2009 found that comparatively few accidents accounted for a large share of total property damage, whereas a large share of fatalities and injuries were caused by numerous, small-scale accidents. There are 2.4 million miles of natural gas pipeline in the United States and 175,000 miles of hazardous liquid pipeline (which includes crude oil).[1832]

- October 30, 2014 – A research team led by David O. Carpenter at University at Albany found high levels of formaldehyde near 14 compressor stations in three states. In Arkansas, Pennsylvania, and Wyoming, formaldehyde levels near compressor stations exceeded health-based risk levels. The authors noted that compressor stations can produce formaldehyde through at least two routes: it is created as an incomplete combustion byproduct from the gas-fired engines used in compressor stations. It is also created when fugitive methane, which escapes from compressor stations, is chemically converted in the presence of sunlight. Formaldehyde is a known human carcinogen. Other hazardous air pollutants detected near compressor stations in this study were benzene and hexane. One air sample collected near a compressor station in Arkansas contained 17 different volatile compounds. (See entry for October 30, 2014 in Air Pollution.)

- October 15, 2014 – In comments to FERC, New York’s Madison County Health Department reviewed the literature on compressor station emissions and expressed concerns about associated health impacts, including documented correlations between health problems and residential proximity to compressor stations. It also reviewed health outcomes associated with exposures to chemicals known to be released from compressor stations, including VOCs, carbonyls and aldehydes, aromatics, and particulate matter. In addition, gas from fracking operations transiting through compressor stations may carry

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[1830] R. Subramanian et al., “Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol,” *Environmental Science & Technology* 49, no. 5 (2015): 3252–61, https://doi.org/10.1021/es5060258.
[1831] Mike Wereschagin, “Rural Gas Gathering Pipelines Kindle Concerns about Safety Laws | TribLIVE.Com,” *Trib Live*, December 27, 2014, https://archive.triblive.com/news/rural-gas-gathering-pipelines-kindle-concerns-about-safety-laws/#axzz3NAHfzYF8.
[1832] Kyle Siler-Evans et al., “Analysis of Pipeline Accidents in the United States from 1968 to 2009,” *International Journal of Critical Infrastructure Protection* 7, no. 4 (2014), https://doi.org/10.1016/j.ijcip.2014.09.002.

gaseous radon. The Health Department noted a troubling lack of information on the intensity, frequency, and duration of emission peaks that occur during the blowdowns and large venting episodes that are a normal part of compressor operations.[1833]

- September 16, 2014 – Noting the proximity of a proposed high-pressure pipeline to Indian Point Nuclear Facility, as well as the evidence linking compressor station emissions to negative health impacts, New York's Rockland County legislature adopted a resolution calling for a comprehensive Health Impact Assessment in regards to Spectra Energy's planned Algonquin Incremental Market (AIM) natural gas pipeline, compressor, and metering stations expansion project.[1834] This resolution follows on the heels of similar resolutions expressing health concerns about the AIM project from both Westchester and Putnam County legislatures.[1835, 1836]

- January 24, 2013 – A report prepared for the Clean Air Council by an independent consulting firm to evaluate air quality impacts from the Barto Compressor Station in Penn Township, Lycoming County, Pennsylvania predicted "large exceedances" of the nitrogen dioxide (NO_2) 1-hour NAAQS. Researchers used allowable emissions in the PA DEP permit, the 2006-2010 meteorological data and the latest EPA modeling guidance for the model's prediction. Three techniques were used, and for two of the techniques, NAAQS exceedances occurred within a mile of the plant. The report concluded, "NO_2 impacts from the Barto plant alone are very significant since its emissions cause large exceedances of the 1-hour NAAQS."[1837]

- July 14, 2011 – A Fort Worth air quality study assessed the impact of drilling and fracking operations, and ancillary infrastructure, on concentrations of toxic air pollutants in the city of Fort Worth, Texas. The study found that compressor stations were a significant source of fracking-related air pollution. The compressor engines were responsible for over 99 percent of the hazardous air pollutants emitted from compressor stations, of which 67 percent was formaldehyde.[1838]

[1833] New York State Madison County Health Department, "Comments to the Federal Energy Regulatory Committee Concerning Docket No. CP14-497-000, Dominion Transmission, Inc," October 15, 2014.

[1834] Rockland County Legislature, "Resolution No. 404 of 2014 Urging That Health, Safety and Planning Concerns Be Addressed and Mitigated in the Environmental Review and All Other Review Processes before Project Permissions Be Granted for Spectra Energy's Algonquin Incremental Market (AIM) Natural Gas Pipeline, Compressor and Metering Stations Expansion Project," September 16, 2014, https://sape2016.files.wordpress.com/2014/05/rockland-aim-resolution.pdf.

[1835] Board of Legislators County of Westchester, State of New York, "Resolution RES-2014-80 Algonquin Incremental Marketing Project Resolution," July 21, 2014, https://sape2016.files.wordpress.com/2014/05/080414-wcbol-resolution-no-80-2014-requesting-due-diligence-on-environment-p.pdf.

[1836] Putnam County Legislature, "Resolution #104, Resolution Regarding the Algonquin Incremental Market (AIM) Project," May 9, 2014, https://sape2016.files.wordpress.com/2014/05/putnam-county-resolutions-104-163-and-182-1.pdf.

[1837] Khanh T. Tran, "AERMOD Modeling of NO2 Impacts of the Barto Compressor Station," Final Report (AMI Environmental, January 24, 2013), https://crawler.dep.state.pa.us/Air/AirQuality/AQPortalFiles/Regulations%20and%20Clean%20Air%20Plans/AERMOD%20NO2%20Modeling%20of%20Barto%20Compressor%20Station%20-%20Jan%2024%202013.pdf.

[1838] Eastern Research Group, "Fort Worth Natural Gas Air Quality Study Final Report," July 14, 2011, https://www.fortworthtexas.gov/departments/development-services/gaswells/air-quality-study/final.

Gas storage

Gas storage facilities include not only manmade holding tanks but also geological formations, most notably, aquifers, abandoned salt caverns, mines, and depleted oil fields left over from drilling operations. These unlined cavities were not created with the intent to store pressurized hydrocarbon gases, nor are they engineered for this purpose. Leakage from these facilities has resulted in water contamination, air pollution and explosions.

The 3,600-acre Aliso Canyon gas storage facility, located in a depleted oil field in southern California, released more than 100,000 metric tons of methane into the air of the San Fernando Valley over a four-month period beginning in October 2015 before it was finally contained in February 2016. This massive methane leak—the largest in U.S. history—is the greenhouse gas equivalent of a half million cars driving for a year. The plume itself was visible from space. More than 8,000 families in the nearby community of Porter Ranch were evacuated and relocated, thousands were sickened, and two public schools closed. As determined by a 2019 final report, the root cause of the Aliso Canyon blowout was a corroded well casing and lack of a shut-off valve in a half-century-old well.

Data released in 2018 reveal that there are more than 10,000 Aliso-style storage wells with gas flowing through only a single unprotected pipe—that is, with a single point of failure. Of the nearly 400 natural underground storage facilities in the United States, 296 of them have one or more of these wells, and they are located in 32 states. Many natural gas storage facilities approached capacity in 2020 as low demand and low prices created an enduring supply glut.

While not as common as depleted oil fields, salt cavern gas storage facilities suffer a disproportionate number of serious problems, including loss of cavern integrity and consequent gas migration.

- May 20, 2021 –Nova Scotia's geology includes salt formations along the Shubenacadie River where Alton Gas is proposing to build a gas storage facility. Despite a centuries-old treaty which gives the indigenous Mi'kmaq people rights to this land and river, they were not consulted during the permitting process. Mi'kmaq elders objecting to the construction predict certain destruction of land and river life from construction and maintenance of the gas storage facility. Critics also fear dire safety issues for indigenous women living in the area and along the 85-mile corridor that is proposed to connect the storage facility to the proposed LNG terminal 85 miles away."[1839]

- April 30, 2021 – A $25 million public health research study on impacts of the 2015 gas leak at Aliso Canyon is the result of a $120 million settlement between Southern Gas California Co., Los Angeles County, the City of Los Angeles, and the state agencies. The

[1839] Karen Edelstein, "Gas Storage Plan vs. Indigenous Rights in Nova Scotia" (FracTracker Alliance, May 20, 2021), https://www.fractracker.org/2021/05/gas-storage-plan-vs-indigenous-rights-in-nova-scotia/.

Los Angeles *Daily News* reported widespread community dissatisfaction with the direction of the study, which was spearheaded by the public health department with guidance from a scientific oversight committee and a community advisory group (CAG). The public health department released a study draft identifying key areas the health study should address, which the CAG has described as too broad and underdeveloped. "The CAG unanimously agrees that the loose draft language of the study's goals and priorities invites a mediocre study by encouraging the use of data proxies and environmental abstractions," said Craig Galanti, a member of CAG. Criticizing a reliance on publicly available, utility-derived data for a modeling study, the group cited a 2018 report by the California Council on Science and Technology which concluded that such air quality monitoring missed the first few days of the blowout, when exposures to the highest concentrations likely occurred. In addition, the CAG expressed the need for a clinically-based, human-subject focused study. "CAG members say if the health study doesn't include the chemical list, a cancer surveillance study, accurate air monitoring and benzene exposure data, it wouldn't be complete."[1840]

- April 7, 2021 – A 2019 blowout of 100,000 cubic feet of natural gas from Southern California's Playa del Rey oilfield served as a reminder of the long legacy of fossil fuel extraction and storage on the west side of Los Angeles. Playa del Rey's sandstone formation thousands of feet underground holds natural gas in an operation similar to that of Aliso Canyon. Both storage fields, reported the *Los Angeles Times*, have a long history of leaks. Opposition to Playa del Rey's gas storage field is growing, including among elected officials, in the form of municipal resolutions to close the facility and a call from the Los Angeles County Board of Supervisors to study the feasibility of closure. Though it has less than three percent of the storage capacity of Aliso Canyon, 45,000 people live within a mile of Playa del Rey field, compared with 6,500 within a mile of Aliso. Four thousand people live directly above the Playa del Rey storage field. A 2019 Harvard study singled out the field as particularly risky. [See July 8, 2019 entry below.][1841]

- January 12, 2021 – A study of surface deformation caused by the convergence of multiple underground gas storage facilities focused on the increasing use of salt caverns for gas storage, and resultant changes in pressure inside those caverns due to injection, unloading, and additional leaching. These can cause significant cavern disruption which can lead to deformation and subsidence. The study described an effective multi-parameter method for determining changes in rock mass deformation for salt caverns, as well for predicting the surface deformation for a large field of salt caverns.[1842]

- October 28, 2020 – Using Bayesian analysis, researchers calculated the frequency of accidents, incidents, failures, and other problematic events at U.S. underground natural

[1840] Olga Grigoryants, "Residents, Activists Express No Confidence in L.A. County's Aliso Canyon Gas Leak Health Study," *Los Angeles Daily News*, April 30, 2021, https://www.dailynews.com/2021/04/30/residents-activists-express-no-confidence-in-l-a-countys-aliso-canyon-gas-leak-health-study/.
[1841] Sammy Roth, "The Next Aliso Canyon Could Happen on L.A.'s Westside," *Los Angeles Times*, April 7, 2021, https://www.latimes.com/business/story/2021-04-07/aliso-canyon-natural-gas-playa-del-rey.
[1842] Krzysztof Tajduś et al., "Surface Deformations Caused by the Convergence of Large Underground Gas Storage Facilities," *Energies* 14, no. 2 (2021), https://doi.org/10.3390/en14020402.

gas storage facilities for each of the 31 states that host such facilities. Depleted oil and gas fields, which are, by far, the most common type of underground gas storage facility in the United States and have been in operation for the longest time, showed the highest number of problematic occurrences. Aquifer storage, though not as common, has led to contamination of drinking water wells on neighboring properties. Many occurrences have been linked with salt-cavern storage over a relatively small number of facility-years, and these include serious problems such as loss of cavern volume, loss of cavern integrity, gas migration into adjacent brine caverns, and elevated cavern pressures, which can endanger surface wellheads and related infrastructure of the brine caverns. "States having the largest number of occurrences at the lowest, nuisance-group level of severity are California and Pennsylvania (for oil-and-gas storage), Iowa and Illinois (for aquifer storage), and Texas (for salt-cavern storage)." [See also entry below for November 5, 2019.][1843]

- July 29, 2020 – A natural gas storage facility exploded in Mont Belvieu, Texas after a contractor struck an underground pipeline.[1844] The facility belonging to Lone Star NGL, a subsidiary of Dallas-based Energy Transfer LP, stores and processes natural gas liquids, including propane, butane and ethane. Five hundred and thirty-five miles of pipeline from the Permian Basin, Barnett Shale and East Texas transport natural gas liquids to the Mont Belvieu storage and fractionation facility. A company spokeswoman said that the company planned an investigation.

- June 30, 2020 – SoCalGas executives sought to delay by six months the next round of mechanical integrity tests on wells used to access the Aliso Canyon gas storage field, site of the 2015 four-month blowout releasing 100,000 metric tons of methane.[1845] These tests were required after a root cause analysis had determined that the blowout was caused by a faulty well casing at the facility, linked to microbial corrosion caused by contact with groundwater. (See entry for May 16, 2019.) California regulators instituted new regulations following the disaster, including the requirement that all wells undergo mechanical integrity tests at least once every two years. SoCalGas asked the state to suspend the requirement, citing the pandemic. The request was denied.

- June 9, 2020 – Use of the SoCalGas Aliso Canyon gas storage field has vastly expanded during California Governor's Newsome's tenure, despite a stated commitment to close the facility following the 2015 massive blowout.[1846] SoCalGas withdrew 20 billion cubic

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[1843] Richard A. Schultz and David J. Evans, "Occurrence Frequencies and Uncertainties for US Underground Natural Gas Storage Facilities by State," *Journal of Natural Gas Science and Engineering* 84 (2020), https://doi.org/10.1016/j.jngse.2020.103630.
[1844] Julian Gill and Erin Douglas, "Natural Gas Storage Facility Explodes in Mont Belvieu," *Houston Chronicle*, July 29, 2020, sec. Houston, https://www.houstonchronicle.com/news/houston-texas/houston/article/Explosion-reported-at-Mont-Belvieu-industrial-15444117.php.
[1845] Sammy Roth, "Remember the Aliso Canyon Disaster? SoCalGas Just Tried to Delay Safety Tests," *Los Angeles Times*, June 30, 2020, sec. Climate & Environment, https://www.latimes.com/environment/story/2020-06-30/remember-the-aliso-canyon-disaster-socalgas-just-tried-to-delay-safety-tests.
[1846] Sammy Roth, "SoCalGas Ramps up Use of Aliso Canyon, Site of Worst Gas Leak in U.S. History," *Los Angeles Times*, June 9, 2020, sec. Climate & Environment, https://www.latimes.com/environment/story/2020-06-09/socalgas-ramps-up-use-of-aliso-canyon-site-of-worst-gas-leak.

feet of gas from the facility in winter 2019-2020, up from 14 billion the winter before, and one billion in 2017-2018. "The more the gas company uses the storage field, the higher the risk of additional leaks," said USC engineering professor Najmedin Meshkati, who authored a study examining the causes. (See December 1, 2017 entry.)

- May 20, 2020 – The *Texas Observer* reported on threats to the state's drinking water from changing oil and gas storage practices in Texas during a time of supply glut, negative prices for oil, and a growing scarcity of Gulf Coast storage tank capacity. As producers sought to store their excess oil and gas in underground salt caverns, in the same way the U.S. Strategic Petroleum Reserve stores their crude, the Texas Railroad Commission, which regulates oil and gas producers in that state, granted permission for such storage up for to five years. Commissioners also lifted the requirement to hold public hearings. Environmental groups and scientists decried the absence of formal opportunity for public comment, particularly concerned about the threat to the nine aquifers across Texas, which provide 60 percent of the state's water and underlie the oil fields. "Is it going to stay there and not leak into the aquifer?…The environmental concerns are the biggest issue here," according to Ramanan Krishnamoorti, petroleum engineer at the University of Houston.[1847] The agency's history of indifference toward potential contamination of aquifers is longstanding. "In 2014, the commission sided with Marathon Oil Company when a local groundwater conservation district raised concerns about the company injecting drilling waste into a productive South Texas aquifer. In its most recent annual report on groundwater contamination in Texas, a group of state agencies tasked with studying the issue found roughly 630 cases of groundwater contamination linked to 'total petroleum hydrocarbons' in 2018." *The Observer* noted that another risk of gas and oil storage in salt caverns is explosion. One such accident in 1992 in Brenham, TX killed a six-year-old boy and injured 13 others.

- May 18, 2020 – Gas storage has reached capacity as natural gas exceeds demand, and prices plummet, according to *Oilprice.com.*[1848] In Europe as in the United States, these trends have been exacerbated by mild weather in winter 2019-2020, more renewable energy production, and a crash in industrial demand for gas amid the pandemic. Although prospects for gas are better than oil because of the electrical generation industry, demand for gas will continue to decrease significantly if Europe embraces a green recovery and renewable energy sources are pressured to expand.

- April 15, 2020 – Using advanced remote sensing and in situ observations of near-surface atmospheric methane combined with wind data, researchers studied twelve active underground gas storage facilities in California, including Aliso Canyon, between January 2016 and November 2017 to determine net annual methane emissions.[1849] The

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[1847] Christopher Collins, "With Storage Space Evaporating, the Oil and Gas Industry Will Get to Put Its Products Back Underground," *The Texas Observer*, May 20, 2020, https://www.texasobserver.org/underground-storage-oil-rule-rollback/.
[1848] Irina Slav, "Natural Gas Drillers Face Price Meltdown As Storage Fills Fast," *OilPrice.Com*, May 18, 2020, https://oilprice.com/Energy/Crude-Oil/Natural-Gas-Drillers-Face-Price-Meltdown-As-Storage-Fills-Fast.html.
[1849] Andrew K Thorpe et al., "Methane Emissions from Underground Gas Storage in California," *Environmental Research Letters* 15, no. 4 (2020): 045005, https://doi.org/10.1088/1748-9326/ab751d.

team, consisting of scientists from CalTech, Stanford, Lawrence Berkeley National Laboratory, and other institutions, said their "analysis reveals significant discrepancies with the State's accounting of UGS emissions as well as under reporting by individual facilities which if unresolved could impede efforts to meet future mitigation targets," and they found this conclusion to be consistent for both of their estimation techniques. The study's 2016 estimations of net annual methane emissions for the seven facilities that did report were approximately five times higher than they reported. Methane has been targeted for emissions mitigation by the State of California, including legislation focused on natural gas leak detection and repair and identification of emission hotspots. This study's findings included that, even since the massive Aliso Canyon release, researchers found persistent venting from the shutdown stack and episodic venting from equipment. Results from other facilities included highly variable emissions, and this variability "remains one of the most challenging aspects of UGS emissions quantification, underscoring the need for more systematic and persistent methane monitoring."

- April 10, 2020 – Ethane, a byproduct of fracked shale gas and needed to produce plastics, is often stored in underground caverns. Cracker plants, which would use the ethane, are being constructed and proposed along the Ohio River around Pittsburgh, Pennsylvania, to use the wet fracked gas from Pennsylvania and Ohio. A 2017 an Appalachian Oil and Natural Gas Research Consortium study identified regions in West Virginia, Pennsylvania, and Ohio for constructing caverns in underground salt beds or limestone rock, as well as in abandoned gas fields, for storing natural gas liquids. An *Inside Climate News* piece provided this background, as well as the mechanics of underground gas storage, for examining the history and hazards of Mont Belvieu, 30 miles northeast of Houston, the world's largest natural gas liquids underground storage area.[1850] Mont Belvieu has a history of environmental calamities, and the complex's operator continues to be the target of enforcement actions. In view of that history, the Ohio River underground storage facilities are being promoted as very different from the accident-prone and violation-ridden Mont Belvieu. "We just want to be a warehouse," said David Hooker, president of Mountaineer NGL Storage, which is developing a site along the Ohio River in Monroe County.

- March 24, 2020 – In 2016 Nova Scotia's environment minister, Margaret Miller, permitted a gas storage facility on the banks of the Shubenacadie River. Alton Gas, a subsidiary of Calgary-based energy company AltaGas, proposed to store up to 10 billion cubic feet of natural gas in underground caverns. The Sipekne'katik First Nation sued to stop the project both because it is Aboriginal land and because the process would cause significant pollution of the river. The storage cavern would be created by flushing nearby salt deposits with water from the Shubenacadie River. As reported by the CBC, the Nova

[1850] James Bruggers, "For the Ohio River Valley, an Ethane Storage Facility in Texas Is Either a Model or a Cautionary Tale," *Inside Climate News*, April 10, 2020, https://insideclimatenews.org/news/10042020/ethane-plant-appalachia-mont-belvieu-texas/.

Scotia Supreme Court agreed to a delay of at least 120 days and has ordered the province to resume consultations with Sipekne'katik First Nation.[1851]

- March 20, 2020 – In 2016, Congress passed the Protecting our Infrastructure of Pipelines and Enhancing Safety (PIPES) Act requiring the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) to promulgate underground natural gas storage safety regulations following the massive 2015 Aliso Canyon gas leak. In February 2020, PHMSA issued its Final Rule, which weakened existing safety regulations applicable to underground natural gas storage facilities, including limiting the type of accidents or routine maintenance activities that had previously been deemed reportable. Only well plugging or abandonment or maintenance costing more than $200,000 now require reporting to PHMSA. According to the legal news digest, *JD Supra*, "the Final Rule provides clarifications to the Interim Final Rule in ways that should benefit storage operators," and the agency resisted in its rule "calls to impose additional safety requirements on storage operators at least for the foreseeable future."[1852]

- January 24, 2020 – Porter Ranch residents presented in Superior Court the damages they sustained from the massive Aliso Canyon gas storage site gas leak and the actions they would have taken to protect themselves and their property if SoCalGas had not delayed in notifying authorities and residents. A state appeals court panel had ruled that residents were entitled to this hearing addressing "whether petitioners can prove damages from the three-day delay in reporting the leak, as charged in the criminal complaint." At 2016 settlement talks between prosecutors and SoCalGas, residents complained of not being part of the proceedings and left unable to seek restitution. Many residents are still sick and property still contaminated, according to the residents' attorney.[1853]

- January 7, 2020 – *NBC Los Angeles* reported that Los Angeles County Board of Supervisors unanimously called on California Governor Gavin Newsom to expedite the closure of the Aliso Canyon natural gas storage facility in Porter Ranch, site of the largest methane leak in U.S. history.[1854] Supervisor Kathryn Barger said, "We do not know what the long-term impacts of the gas leak will be… The only way to preserve the health and safety of the residents around Aliso Canyon is for it to close." Operator of the site, SoCalGas continued to maintain that the site is needed to provide an affordable electric energy supply. Fearing expansion at another SoCalGas storage facility in the Los Angeles

[1851] Taryn Grant, "Siding with First Nation, N.S. Judge Overturns Alton Gas Approval | CBC News," *CBC*, March 24, 2020, https://www.cbc.ca/news/canada/nova-scotia/alton-gas-nova-scotia-supreme-court-appeal-decision-1.5508130.
[1852] James Bowe Jr. and William Rice, "PHMSA Issues Final Rule on Underground Natural Gas Storage Safety Establishing a Phased-in, Multi-Year Timeframe for Integrity Management," *JD Supra*, March 21, 2020, https://www.jdsupra.com/legalnews/phmsa-issues-final-rule-on-underground-60203/.
[1853] Tom Bray, "Aliso Canyon Gas Leak Victims Argue for Restitution; No Ruling Yet," *Daily News*, January 24, 2020, https://www.dailynews.com/2020/01/24/aliso-canyon-gas-leak-victims-argue-for-restitution-no-ruling-yet.
[1854] City News Service, "LA County Calls on Governor to Expedite Closure of Aliso Canyon," *NBC Los Angeles*, January 7, 2020, https://www.nbclosangeles.com/news/local/la-county-calls-on-governor-to-expedite-closure-of-aliso-canyon/2286869/.

area, a Supervisor successfully added an amendment to the Board's call to the governor, requesting a feasibility study of closing the Playa del Rey facility.

- November 19, 2019 – California Governor Gavin Newsom called on California's utilities regulator to identify ways to accelerate the pace to state reliance on renewables, with the objective of closing the Aliso Canyon gas storage facility. Renewable energy sources like solar and wind play increasing roles in California's energy landscape, but natural gas still accounts for the largest single source of in-state generation, at 46.5 percent. Environmental groups criticized the Governor's call for additional study, citing an independent energy consulting group's finding that natural gas injections at Aliso Canyon were not needed in the short-term. For the long-term, the report said that advances in energy efficiency and carbon-free storage will make Aliso Canyon obsolete. At the time of this San Diego *Tribune* report, Aliso Canyon gas storage was permitted at about 39 percent of maximum capacity, after the initial resumption in July 2017.[1855]

- November 5, 2019 – The first probabilistic analysis of natural gas accidents—variously referred to as events, incidents, accidents, or failures across studies—at underground gas storage facilities in the United States found in its review an occurrence rate "larger than has been previously reported."[1856] The researchers predicted, "The probability of one serious or catastrophic leakage occurrence to the ground surface within the next 10 years, assuming constant number of facilities, is approximately 0.1–0.3% for any facility type." Using a Bayesian statistical approach, an inference method that integrates new data with existing knowledge, researchers said that their study "demonstrates the value of collecting new historical data for occurrences as well as comparing the newly acquired data to earlier databases." The study's characterization of risks to plan improved risk management and regulatory policy of underground gas storage facilities included cause, severity, and uncertainty for depleted oil-and-gas field storage, aquifer storage, and solution-mined salt cavern storage. Depleted oil-and-gas field storage showed the largest probabilities and the smallest uncertainties for accidents.

- October 15, 2019 – As the October 2019 Saddleridge Fire burned and a fire broke out and burned for 24 hours next to the Aliso Canyon gas storage facility, residents of Porter Ranch, California prepared for mandatory evacuation, *Knock LA* reported.[1857] Since and before the oil field was repurposed for gas storage in 1973, fires have been frequent at and around the facility, some caused by ruptured gas lines and others triggered by earthquakes. Although the local department of health failed to warn residents to wear respirator masks until 12 hours after the evacuation, a physician in the area advised residents to use respirators for protection against particulate matter that included not only

[1855] Rob Nikolewski, "Newsom Looks to Accelerate Time Line for Closing Aliso Canyon Natural Gas Facility," *San Diego Union-Tribune*, November 20, 2019, sec. Energy, https://www.sandiegouniontribune.com/business/energy-green/story/2019-11-19/newsom-looks-to-accelerate-time-line-for-closing-aliso-canyon-natural-gas-facility.
[1856] Richard A. Schultz et al., "Characterization of Historical Methane Occurrence Frequencies from U.S. Underground Natural Gas Storage Facilities with Implications for Risk Management, Operations, and Regulatory Policy," *Risk Analysis* 40, no. 3 (2020): 588–607, https://doi.org/10.1111/risa.13417.
[1857] Patty Crost Glueck, "As The North SFV Burns, Worries About The Aliso Canyon Gas Storage Facility Ignites," *Knock LA*, October 15, 2019, https://knock-la.com/as-the-north-sfv-burns-worries-about-the-aliso-canyon-gas-storage-facility-ignites-ec12a3b38027/.

soot from burned vegetation, but also from burning contaminants released during the Aliso Canyon blowout. The piece referenced the recent study (See Jun 26, 2019 entry below) that found "a broad range of hazardous air pollutants (HAPs)" co-emitted during the Aliso Canyon blowout and during "final well kill attempts." Two deaths were reported in the aftermath of the fire: that of a park ranger and a Porter Ranch resident, both of heart attacks, known health consequences of particulate matter exposure.

- July 31, 2019 – A *ProPublica* investigation explored the political connections behind the proposed Appalachian Storage and Trading Hub, a $10 billion dollar mammoth underground storage facility for ethane and other byproducts used in plastics manufacturing.[1858] West Virginia state officials see the reserves that form the largest natural gas field in the world as "a path to renewed political and economic relevance for the Mountain State, which they envision rivaling the Gulf Coast as a center for processing natural gas and producing plastics." However, such a large facility is beyond what the region could support and carries a range of risks. West Virginia leaders sought a $1.9 billion federal loan guarantee, one of the largest ever considered, and which could leave taxpayers on the hook in the event the project fails, as well as looking to the federal government for a "streamlined" review process. The hub's prospects were considered weakened by "uncertainty and turmoil" of the U.S.-China trade war.

- July 8, 2019 – Tens of thousands of U.S. homes and residents are located within a proposed underground gas storage (UGS) "Wellhead Safety Zone" of active UGS wells, according to a multi-institution study comparing methods of estimating this hazard.[1859] In some cases homes and residents were within a state's oil and gas well surface setback distance. Lead author Drew Michanowicz, of the Center for Climate, Health and Global Environment at the Harvard T.H. Chan School of Public Health said to *West Virginia Public Radio*, "Our results were somewhat surprising in that a lot of these wells are in residential suburban areas, which in terms of the entire natural gas supply chain is definitely a unique kind of land use conflict."[1860] The researchers applied a new method of allocating an average person per household to geospatially-identified residential housing unit. This new method showed 65 percent of UGS wells occupying residential urban and suburban areas, and across the six states studied, 41 percent of underground storage wells were located within one city block of at least one home. As reported by *West Virginia Public Radio*, "in Ohio, more than half of the state's underground storage wells are located within one block of a residence" and "affected an estimated 12,000 Ohio homes and over 30,000 residents." The new method provided more precise estimates than the previous standard method, but by either benchmark, there is "a substantial degree of land use conflict between populations and UGS wells" in Ohio.

[1858] Keith Schneider, "West Virginia Bets Big on Plastics, and on Backing of Trump Administration," *ProPublica*, 2019, https://www.propublica.org/article/appalachian-storage-and-trading-hub-ethane-west-virginia-plastics-backing-of-trump-administration.
[1859] Drew R. Michanowicz et al., "Population Allocation at the Housing Unit Level: Estimates around Underground Natural Gas Storage Wells in PA, OH, NY, WV, MI, and CA," *Environmental Health* 18, no. 1 (December 2019): 58, https://doi.org/10.1186/s12940-019-0497-z.
[1860] Brittany Patterson, "Study Finds Thousands Live Near Underground Natural Gas Storage Wells," *WVPB*, July 9, 2019, sec. WVPB News, https://www.wvpublic.org/news/2019-07-09/study-finds-thousands-live-near-underground-natural-gas-storage-wells.

- Jun 26, 2019 – Scientists from the United Kingdom, China, and the United States conducted a study of links between particulate matter (PM), hazardous air pollutants (HAPS), and methane emissions, during the Aliso Canyon gas storage facility blowout.[1861] Samples obtained during the massive methane release showed a unique gas and particle concentration in ambient air and a characteristic "fingerprint" of metals in the indoor dust samples, similar to samples taken at the blowout site. These analyses, together with health surveys of several households, provided plausible explanations for health symptoms that persisted post-remediation. Various kill-well attempts were a source of multiple toxic air pollutants, such as various sizes of PM and volatile organic compounds (VOCs). Of note in their analyses, the researchers found that long-term averaged HAPs levels were normal, but short samplings, such as the individual 5-minute "trigger" samples, identified elevated concentrations, several above health benchmarks. Speaking to *CleanTechnica*, lead author UCLA environmental health scientist Diane A. Garcia-Gonzales said, "Our findings demonstrate that uncontrolled leaks or blowout events at natural gas storage facilities can release pollutants with the potential to cause not only environmental harm, but also adverse health consequences in surrounding communities."[1862] Adding to the complicated picture, researchers lacked baseline measurements, the full range of toxins emitted during the active blowout may not have been sampled, and the study may not have addressed all potentially biologically relevant pollutants; elevations in HAPs benzene, known to cause cancer, and hexane and xylene, neurotoxins also harmful to human health, all correlated with elevated methane levels.

- May 16, 2019 – A root cause analysis of the 2015 Aliso Canyon blowout determined that surface corrosion on the outside of well casing was the immediate cause of the disaster that sent uncontrolled releases of methane into the air for 111 days. Prolonged contact with groundwater and microbes, most likely methanogenic Archaea, was the underlying cause of the corrosion. Additional contributing factors identified in this final report include lack of detailed follow-up investigations after other failure events in the Aliso Canyon storage field; lack of investigations following the discovery of corrosion in other wells; lack of any form of risk assessment focused on wellbore integrity management; lack of understanding of groundwater depths; and lack of a dual mechanical barrier system in the wellbore.[1863]

- February 1, 2019 – An assessment of gas leakage from different types of natural gas storage facilities that established a mathematical model to predict leakage points showed that long-term periodic injection of gas and improper construction will lead to some

[1861] Diane A. Garcia-Gonzales et al., "Associations among Particulate Matter, Hazardous Air Pollutants and Methane Emissions from the Aliso Canyon Natural Gas Storage Facility during the 2015 Blowout," *Environment International* 132 (2019): 104855, https://doi.org/10.1016/j.envint.2019.05.049.
[1862] Charles W. Thurston, "New Study Calls For Monitoring Old Oil & Gas Wells For Air Emissions," *CleanTechnica*, June 27, 2019, https://cleantechnica.com/2019/06/27/new-study-calls-for-monitoring-old-oil-gas-wells-for-air-emissions/.
[1863] Blade Energy Partners, "Root Cause Analysis of the Uncontrolled Hydrocarbon Release from Aliso Canyon, SS-25," Main Report, May 16, 2019, https://www.socalgas.com/sites/default/files/SoCalGas-75-Served-03-15-21.pdf.

degree of gas leakage risks, no matter what kind of construction process is used to create the gas storage reservoir.[1864]

- December 17, 2018 – Plans by Alton Natural Gas to create a massive gas storage hub in salt caverns north of Halifax, Nova Scotia were delayed due to "project and regulatory planning," and the company has asked the Nova Scotia Utility and Review Board to extend its cavern construction permit. The plan involves hollowing out underground salt deposits using water from the tidal Shubenacadie River. The brine waste would then be dumped into the river, twice a day at high tide, over a two- to three-year period. Members of the Sipekne'katik First Nation argue that the project will harm the ecology of the tidal river, which runs through the middle of Nova Scotia. They have continuously occupied and protested at the site since 2014.[1865]

- August 20, 2018 – A research team investigated the geomechanics of an underground natural gas storage facility in China. They noted that geological factors and engineering factors can both contribute to leaks. Engineering factors include problems with casing integrity, cementing quality, and salt cavern operating pressure. Geological factors include challenges posed by the complexity of geological formations, imperfect sealing by the caprock, and the presence of faults. Using geological analysis, permeability tests, and CT scans, the authors determined that the risk of leakage in this salt cavern underground gas storage arises mainly from a failure of wellbore tightness within a mudstone interlayer.[1866]

- July 12, 2018 – The New York State Department of Environmental Conservation denied a permit for liquified petroleum gas storage (propane) in abandoned salt caverns on the shoreline of Seneca Lake. "The record demonstrates that the impacts of this project on the character of the local and regional community, including but not limited to the environmental setting and sensitivity of the Finger Lakes area and the local and regional economic engines (e.g., wine, agricultural and tourism industries), are significant and adverse and the project does not avoid or minimize those impacts to the maximum extent practicable. Furthermore, the significant adverse impacts on community character are not outweighed or balanced by social, economic or other considerations, and cannot be avoided or minimized to the maximum extent practicable by the proposed mitigation measures." Concerns were also raised about the structural integrity of the caverns following disclosure by the gas storage company that additional pressure testing in the

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[1864] Xiao Wei and Zhang Zhichao, "Study on the Production Mode and Leakage Risk of Gas Storage Well Completion," *IOP Conference Series: Earth and Environmental Science* 233 (2019): 042007, https://doi.org/10.1088/1755-1315/233/4/042007.
[1865] Michael MacDonald, "More Delays for Underground Cavern Gas Storage Plan North of Halifax," *CBC*, December 17, 2018, https://www.cbc.ca/news/canada/nova-scotia/delays-underground-cavern-gas-storage-alton-natural-gas-1.4949423.
[1866] Xiangsheng Chen et al., "Study on Sealing Failure of Wellbore in Bedded Salt Cavern Gas Storage," *Rock Mechanics and Rock Engineering* 52, no. 1 (2019): 215–28, https://doi.org/10.1007/s00603-018-1571-5.

caverns would be required to assess possible leaks.[1867, 1868]The previous year, a subsidiary of the same company scrapped a parallel plan to expand the storage of natural gas in adjacent salt caverns along the lake shore.[1869]

- June 22, 2018 – A research team undertook an analysis to determine why the roof of China's first salt cavern underground gas storage facility collapsed, as determined by a sonar test after just 1.3 years of use. They concluded that the main reasons for the collapse were the large-span flat roof, a too-rapid decrease in internal gas pressure, and localized damage that led to massive collapse. They also concluded that this cavern has a high risk of roof collapse taking place again. The study includes evaluations of other similar incidents worldwide. Using geomechanical modeling, the authors developed a "new failure prediction index, consisting of volume shrinkage, dilatancy safety factors, displacement, vertical stress, and equivalent strain."[1870]

- May 4, 2018 – A new Department of Transportation rule requires gas companies that operate storage facilities to disclose information about design, leaks, and repairs of their wells. According to data released on April 4, 2018 as part of this rule, more than 10,000 wells have gas flowing through only a single unprotected pipe—that is, with a single point of failure. Of the nearly 400 natural underground storage facilities in the United States, 296 of them have one or more of these wells, and they are in 32 states.[1871] These statistics update an earlier estimate by Harvard University researcher Drew Michanowicz, who, consulting earlier databases, had pegged the number of Aliso-type wells at about 2,700.[1872] (See also entry for May 24, 2017.)

- March 6, 2018 – Illinois has the largest amount of natural gas storage in salt formations in the nation. Some of these storage sites underlie the Mahomet Aquifer, which provides drinking water for 14 counties in east-central Illinois. Prompted by an October 2016 report by a federal task force in the aftermath of California's Aliso Canyon natural gas leak, a team from the University of Illinois' Prairie Research Institute created an

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[1867] State of New York Department of Environmental Conservation, "Finger Lakes LPG Storage, LLC - Decision of the Commissioner, Final Supplemental Environmental Impact Statement, and SEQRA Findings Statement, July 12, 2018," July 12, 2018, https://www.dec.ny.gov/hearings/114139.html.
[1868] Jeff Platsky, "Crestwood Acknowledges Possible Leaks in Proposed LPG Storage in Seneca Lake Mines," *Press & Sun-Bulletin*, May 21, 2018, https://www.pressconnects.com/story/news/local/2018/05/21/crestwood-seneca-lake-gas-storage/629768002/.
[1869] Jon Campbell, "Crestwood's Seneca Lake Propane Storage Facility Rejected by DEC," *Press & Sun-Bulletin*, July 12, 2018, https://www.pressconnects.com/story/news/2018/07/12/dec-rejects-plan-crestwood-propane-storage-facility-seneca-lake/779605002/.
[1870] Tongtao Wang et al., "Geomechanical Investigation of Roof Failure of China's First Gas Storage Salt Cavern," *Engineering Geology* 243 (2018): 59–69, https://doi.org/10.1016/j.enggeo.2018.06.013.
[1871] U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration, "Gas Distribution, Gas Gathering, Gas Transmission, Hazardous Liquids, Liquefied Natural Gas (LNG), and Underground Natural Gas Storage (UNGS) Annual Report Data | PHMSA," 2018, https://www.phmsa.dot.gov/data-and-statistics/pipeline/gas-distribution-gas-gathering-gas-transmission-hazardous-liquids.
[1872] Drew Michanowicz, "Op-Ed: The Aliso Canyon Gas Leak Was a Disaster. There Are 10,000 More Storage Wells out There Just like It," *Los Angeles Times*, May 14, 2018, sec. Opinion, https://www.latimes.com/opinion/op-ed/la-oe-michanowicz-aliso-canyon-gas-leak-20180514-story.html.

introductory guide to provide basic information about the Mahomet Aquifer and natural gas storage in east-central Illinois.[1873] (See also entry for October 18, 2016.)

- January 18, 2018 – The California Council of Science and Technology released a 910-page report analyzing the safety risks of all 14 facilities in the state that store gas in depleted oil fields. Among its findings: gas companies do not disclose the chemicals that are pumping underground; state regulators lack necessary information to assess risks; and many wells servicing the storage fields are 60 to 90 years old with no regulatory limit to the age of the well.[1874]

- December 1, 2017 – A University of Southern California-led team investigated the roots causes of the catastrophic Aliso Canyon gas storage blow-out, which began October 23, 2015 and continued for four months before being contained. Using methodology designed to capture both social and technological factors, the team concluded that corporate dysfunction and lack of government oversight were the driving forces responsible for the accident. “Risk analysis is vital for safe well operations and relies on analyzing prior data records, yet no national standards for well records were in place prior to the accident. There was no clear overarching agency that was in control of the accident’s intervention and aftermath.”[1875] In a subsequent news piece from the university, Najmedin Meshkati, senior author of the study, said, “SoCal Gas had lenient requirements for infrastructure record keeping, no comprehensive risk management plan, and no testing programs or plans in place to remediate substandard wells. The company needs to improve its safety culture.”[1876]

- November 22, 2017 – The U.S. Government Accountability Office (GAO) reported that, two years after the Aliso Canyon blow-out, the Pipeline and Hazardous Materials Safety Administration (PHMSA) is failing to inspect natural gas storage sites in a timely manner, as called for by the Department of Transportation’s interim standards. Until 2016, states set the standards for 211 of the nation’s 415 gas storage sites, while the 204 sites that were connected to interstate pipelines had no standards at all. Collectively, these 415 natural gas storage sites contain about 17,000 wells that inject or withdraw natural gas from the underground formations below, which include depleted oil and gas

[1873] R. Locke et al., “An Introductory Guide to the Mahomet Aquifer and Natural Gas Storage in East Central Illinois” (Prairie Research Institute, 2018), https://www.ideals.illinois.edu/bitstream/handle/2142/99145/PRI%20Intro%20Guide%20to%20the%20Mahomet%20Aquifer%20and%20Natural%20Gas%20Storage_02.22.2018_printed.pdf?sequence=2&isAllowed=y.
[1874] Jane C. S. Long et al., “Long-Term Viability of Underground Natural Gas Storage in California: An Independent Review of Scientific and Technical Information,” Technical Report (California Council of Science and Technology, January 18, 2018), https://ccst.us/reports/long-term-viability-of-underground-natural-gas-storage-in-california-an-independent-review-of-scientific-and-technical-information/.
[1875] Maryam Tabibzadeh et al., “A Systematic Framework for Root-Cause Analysis of the Aliso Canyon Gas Leak Using the AcciMap Methodology: Implication for Underground Gas Storage Facilities,” *Journal of Sustainable Energy Engineering*, 2017, https://doi.org/10.7569/JSEE.2017.629515.
[1876] Zen Vuong, “Who Should Be Held Responsible for the Aliso Canyon Gas Leak?,” *USC News*, February 15, 2018, https://news.usc.edu/136300/who-should-be-held-responsible-for-the-aliso-canyon-gas-leak/.

reservoirs, abandoned mines, depleted aquifers, and hard rock caverns. The GAO noted that more than 300 cities and towns are located near natural gas storage sites.[1877]

- June 21, 2017 – In response to requests from the oil and natural gas industry, the White House announced that it will delay implementation of a rule that would have set national standards for underground natural gas storage. Prompted by the 2015 disaster at Aliso Canyon and developed under the previous administration, this federal interim rule had called for phasing out single-point-of-failure, single-containment designs of the type that made impossible the task of swiftly shutting off the impaired Aliso Canyon well once it began leaking.[1878]

- May 24, 2017 – A national assessment of thousands of underground gas storage wells by a Harvard School of Public Health team found that more than 20 percent are similar in design to the well that failed at Aliso Canyon. These obsolete wells, with single failure points and a median age of 74 years, operate in 19 states and represent more than half of the working capacity for U.S. natural gas. More than 2,700 of these wells were not originally designed to hold gas and, as at Aliso Canyon, have been repurposed to do so. An estimated 210 of these repurposed wells (located in Pennsylvania, Ohio, New York, and West Virginia) are more than 100 years old and entirely lack cement zonal isolation methods. Study author Jonathan Buonocore said, "Partly because no federal safety regulations apply to natural gas storage wells or their operations (now pending), very little aggregate information was available. . . . After we identified this data gap, we realized we needed to build our own database to begin to assess this previously inapparent hazard." With the 50 percent increase in domestic natural gas production over the last ten years, natural gas storage is at an all time high and in demand.[1879, 1880]

- October 21, 2016 – The California Air Resources Board determined that the Aliso Canyon gas storage facility released 100,000 tons of methane, becoming the largest ever natural gas leak in U.S. history.[1881]

[1877] U.S. Government Accountability Office, "Natural Gas Storage: Department of Transportation Could Take Additional Steps to Improve Safety Enforcement Planning," Report to Congressional Requesters, November 22, 2017, https://www.gao.gov/assets/690/688553.pdf.
[1878] Rich Nemec, "PHMSA Pauses Stricter Natural Gas Storage Rules for Clarification," *Natural Gas Intelligence*, June 21, 2017, sec. Regulatory, https://www.naturalgasintel.com/phmsa-pauses-stricter-natural-gas-storage-rules-for-clarification/.
[1879] Drew R Michanowicz et al., "A National Assessment of Underground Natural Gas Storage: Identifying Wells with Designs Likely Vulnerable to a Single-Point-of-Failure," *Environmental Research Letters* 12, no. 6 (2017): 064004, https://doi.org/10.1088/1748-9326/aa7030.
[1880] Institute of Physics, "Study Uncovers Widespread Leak Risk for US Underground Natural Gas Storage Wells," *Phys.Org*, May 24, 2017, https://phys.org/news/2017-05-uncovers-widespread-leak-underground-natural.html.
[1881] California Air Resources Board, "Determination of Total Methane Emissions from the Aliso Canyon Natural Gas Leak Incident | California Air Resources Board," October 21, 2016, https://ww2.arb.ca.gov/resources/documents/determination-total-methane-emissions-aliso-canyon-natural-gas-leak-incident.

- October 18, 2016 – A federal task force issued a report with 44 recommendations intended to prevent another Aliso Canyon-style disaster. Chief among them is a phase-out of “single-point of failure” designs.[1882]

- July 13, 2016 – As reported by the *Los Angeles Daily News,* Los Angeles County health officials were prepared to go to court to ensure that the Southern California Gas Company complies with an order to pay for professional comprehensive cleaning in the homes of residents who were relocated due to the Aliso Canyon gas leak. The company had filed legal papers asking that the order “to remove dust and oily mist from up to 35,000 homes be nullified,” after their report of having cleaned 1,700 homes to date. The Los Angeles County Health Department said the company had done a poor job on these and did not follow protocol to remove the metal particles, including barium, manganese, vanadium, aluminum, and iron previously identified in household surface dust.[1883]

- July 9, 2016 – California’s South Coast Air Quality Management District and Southern California Gas Company were still at an impasse seven months after the company was given an abatement order that included a community health study on the potential impacts of exposures from the massive Aliso Canyon leak. The company was ordered to commit to paying “reasonable costs” for the study.[1884]

- June 22, 2016 – The first federal legislation of gas storage facilities was signed into law. The Protecting our Infrastructure of Pipelines and Enhancing Safety Act of 2016 includes a provision in response to the Aliso Canyon gas leak requiring PHMSA to develop regulations for the construction and operation of underground natural gas storage facilities.[1885] (See entry below, of February 8, 2016, for analysis of the likely shortcomings of these first federal regulations and their inability to prevent a leak such as that at Aliso Canyon.)

- June 20, 2016 – As reported in *Geophysical Research Letters*, an airborne instrument onboard a NASA satellite was able to detect and quantify the size and shape of the methane plume from the Aliso Canyon gas leak as the event occurred.[1886] This is the first

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[1882] U.S. Department of Energy and U.S. Department of Transportation’s Pipeline & Hazardous Materials Safety Administration, “Ensuring Safe and Reliable Underground Natural Gas Storage: Final Report of the Interagency Task Force on Natural Gas Storage Safety,” October 18, 2016, https://energy.gov/sites/prod/files/2016/10/f33/Ensuring%20Safe%20and%20Reliable%20Underground%20Natural%20Gas%20Storage%20-%20Final%20Report.pdf.

[1883] Susan Abram, “SoCalGas Slammed for Poor Cleanup of Porter Ranch Homes,” *Daily News*, July 13, 2016, https://www.dailynews.com/health/20160713/socalgas-slammed-for-poor-cleanup-of-porter-ranch-homes.

[1884] Dana Bartholomew, “Gas Company, Pollution Agency at Odds over Cost of Porter Ranch Health Study,” *Daily News*, July 9, 2016, https://www.dailynews.com/government-and-politics/20160709/gas-company-pollution-agency-at-odds-over-cost-of-porter-ranch-health-study.

[1885] Timothy Cama, “Obama Signs Pipeline Safety Bill,” *TheHill*, June 22, 2016, https://thehill.com/policy/energy-environment/284479-obama-signs-pipeline-safety-bill.

[1886] D. R. Thompson et al., “Space-based Remote Imaging Spectroscopy of the Aliso Canyon CH_4 Superemitter,” *Geophysical Research Letters* 43, no. 12 (2016): 6571–78, https://doi.org/10.1002/2016GL069079.

time a natural gas leak has been visible from space, according to the authors of the study.[1887]

- May 4, 2016 – Southern California Gas Company said that costs related to the Aliso Canyon natural gas storage facility leak reached an estimated $665 million. The utility company let the Securities and Exchange Commission know they carry policies with a combined limit available "in excess of $1 billion," but according to the *Los Angeles Times,* legal experts and lawyers said that $1 billion in insurance might not be enough for what they ultimately need.[1888]

- April 12, 2016 – California energy agencies issued a report indicating the threat of widespread summer power outages if no gas can be withdrawn from Aliso Canyon. The report was met with criticism. "Consumer groups and utility critics contend that the blackout warnings are an irresponsible scare tactic to ensure that Southern California Gas Company is allowed to keep storing gas at the facility and that ratepayers will pay for upgrades to store even more fuel there."[1889]

- April 6, 2016 – The *Los Angeles Times* reported that, though prices for homes in Porter Ranch adjacent to the Aliso Canyon gas storage leak held up, sales declined. After the leak that began October 23, 2015, sales from December 2015 to February 2016 declined 20 percent from the year before. Disclosures for homes in the area "now include a mention of the community's proximity to the gas field and the recent problems."[1890]

- March 18, 2016 – The California State Oil and Gas Division of the Department of Conservation issued penalties totaling $75,000 for three separate violations after finding incidents of intentional venting of gas at the Aliso Canyon gas field and malicious concealment of those acts. Both are violations of the state gas regulations.[1891] Following the Aliso Canyon gas storage leak, the California State Public Utilities Commission ordered a statewide survey of California's 12 natural gas storage fields and found 229 faulty valves, flanges and leaky wellheads and a 230th leak at an abandoned well; eight were deemed hazardous.[1892]

[1887] Chris Mooney, "This Gas Leak Was so Massive That NASA Saw It from Space," *Washington Post*, June 15, 2016, https://www.washingtonpost.com/news/energy-environment/wp/2016/06/15/this-gas-leak-was-so-massive-that-nasa-saw-it-from-space/.
[1888] Ivan Penn, "Costs Related to Aliso Canyon Leak Reach an Estimated $665 Million," *Los Angeles Times*, May 4, 2016, sec. Business, https://www.latimes.com/business/la-fi-aliso-canyon-costs-20160504-snap-story.html.
[1889] Ivan Penn, "'This Is a Threat. This Is Not a Report.' Critics Call Blackout Warnings a Scare Tactic to Keep Aliso Canyon Open," *Los Angeles Times*, April 12, 2016, sec. Business, https://www.latimes.com/business/la-fi-gas-field-20160412-story.html.
[1890] Andrew Khouri, "Gas Leak Disrupts Porter Ranch Housing Market," *Los Angeles Times*, April 6, 2016, sec. Real Estate, https://www.latimes.com/business/realestate/la-fi-porter-ranch-sales-20160406-story.html.
[1891] California Department of Conservation, "State Oil & Gas Division Issues $75,000 Fine to Operator for Illegally Venting Natural Gas," March 18, 2016, http://www.conservation.ca.gov/index/Documents/2016-06%20DOC%20fines%20oil%20operator%20$75,000.pdf.
[1892] Paige St. John, "229 Leaks Found in State's Underground Gas Storage Facilities, Most Considered Minor," *Los Angeles Times*, March 24, 2016, sec. California, https://www.latimes.com/local/lanow/la-me-ln-gas-leaks-storage-wells-20160322-story.html.

- March 14, 2016 – Methane and ethane emissions were measured to determine spatial patterns and source attribution of urban methane in the Los Angeles Basin. The surveys demonstrated the prevalence of fugitive methane emissions across the Los Angeles urban landscape and that fossil fuel sources accounted for 58–65 percent of methane emissions.[1893]

- February 25, 2016 – Measurements of methane and other chemicals were taken by aerial equipment following the October gas release from a faulty well in the Aliso Canyon storage field. The data demonstrated that the blowout of this single well created the largest known anthropogenic point source of methane in the United States. The leak lasted 112 days and released a total of 97,100 tons of methane and 7,300 tons of ethane into the atmosphere. This was equal to 24 percent of the methane and 56 percent of the ethane emitted each year from all other sources in the Los Angeles Basin combined.[1894] Aliso Canyon was already a major pollution source before the massive leak.[1895] As determined by the study and reported by major news outlets, the recent methane link is officially the worst in U.S. history.[1896, 1897]

- February 18, 2016 – Stanford and UCLA scientists reported to *Inside Climate News* that the lack of measurement data for the entire 100+ days of community exposures to the Aliso Canyon methane leak, combined with gaps in the science about many of the chemicals, hinders the ability to understand the health impacts of the leak. "'The first week is when we would expect the highest gas concentrations to reach the neighborhood because the pressures in the storage field were the highest,' said Robert Jackson, an earth system science professor at Stanford University who measured methane concentrations in nearby communities during the leak. 'And yet we don't have any information or data for that first week at least.'" Jackson noted that even after monitoring was initiated, it was intermittent rather than continuous.[1898]

- February 18, 2016 – Independent regional experts from USC and UCLA interviewed by Southern California Public Radio expressed skepticism that an industry-funded study ordered by the South Coast Air Quality Management District following the Aliso Canyon methane leak would be rigorously designed to answer specific questions about sub-

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1893 Francesca M. Hopkins et al., "Spatial Patterns and Source Attribution of Urban Methane in the Los Angeles Basin: Mobile Survey of LA Methane," *Journal of Geophysical Research: Atmospheres* 121, no. 5 (March 16, 2016): 2490–2507, https://doi.org/10.1002/2015JD024429.
1894 S. Conley et al., "Methane Emissions from the 2015 Aliso Canyon Blowout in Los Angeles, CA," *Science* 351, no. 6279 (2016): 1317–20, https://doi.org/10.1126/science.aaf2348.
1895 Ingrid Lobet and Mike Reicher, "Aliso Canyon Was Major Pollution Source before Massive Leak," *Inewsource.Org*, February 14, 2016, http://inewsource.org/2016/02/14/aliso-canyon-major-pollution/.
1896 Nsikan Akpan, "Los Angeles Methane Leak Was Officially the Worst in U.S. History, Study Says," *PBS NewsHour*, February 25, 2016, sec. Science, https://www.pbs.org/newshour/science/los-angeles-methane-leak-is-officially-the-worst-in-u-s-history.
1897 Amina Khan, "Porter Ranch Leak Declared Largest Methane Leak in U.S. History," *Los Angeles Times*, February 26, 2016, sec. Science, https://www.latimes.com/science/sciencenow/la-sci-sn-porter-ranch-methane-20160225-story.html.
1898 Phil McKenna, "What Will Be the Health Impact of 100+ Days of Exposure to California's Methane Leak?," *Inside Climate News*, February 18, 2016, https://insideclimatenews.org/news/18022016/health-impacts-aliso-canyon-porter-ranch-methane-leak-california-socal-gas/.

chronic, cumulative exposures, including hydrogen sulfide, which was measured in the nearby Porter Ranch community at levels far greater than the average across American cities.[1899]

- February 13, 2016 – The Los Angeles County Department of Health prepared a *Supplemental Report* for its Expanded Air Monitoring Plan concerning the Southern California Gas Company's Aliso Canyon storage facility long-term gas leak. The report addressed "chemicals of health concern" including toluene, ethylbenzene, xylene, hydrocarbons, VOCs, metals, and radon and concluded, "all results suggest that chemical exposures experienced by residents as a result of the gas leak are below the levels of concern that have been established by various regulatory agencies."[1900] Remaining challenges named by the report itself included possible gaps in data collection, other chemicals present for which no sampling occurred, and further study of the symptoms reported by the public. Many independent scientists did not concur with the Department of Health's ongoing statements that chemical exposures were below levels of concern. Issues raised included monitoring not initiated until a week after the leak began, lack of continuous monitoring, and reliance on "grab samples." Speaking to *Inside Climate News,* John Bosch, a retired air-monitoring expert with more than 30 years' experience at the EPA said, "Grab samples may be OK as a first-tier guestimate of what the problem is, but you really have to have continuous monitoring."[1901]

- February 8, 2016 – PHMSA announced that it might issue its first federal safety regulations for gas storage sites such as Aliso Canyon, while also suggesting site operators voluntarily follow guidelines that the proposed rules (which would likely take years to issue) will likely mirror. According to a report in *Inside Climate News*, these guidelines would not require systems to stop the flow of gas in an emergency or mandate redundancies to prevent methane from leaking into the environment." If PHMSA proceeds to adopt industry guidelines, the resulting rules "may not address two key issues that turned Aliso Canyon into a disaster: emergency shutoff valves and a safer configuration of pipes." Further, even with new regulations, storage units would most likely remain under state jurisdiction, "though state authorities may adopt any new federal rules."[1902] A subsequent story reported on members of Congress pressing PHMSA to create the first federal standards for the 418 underground gas storage facilities for which it has authority to set regulations. In the hearing before a subcommittee of the

[1899] Stephanie O'Neill, "Did the Porter Ranch Gas Leak Cause Long-Term Health Damage?," Archive.kpcc.org, February 18, 2016, https://archive.kpcc.org/news/2016/02/18/57666/did-the-porter-ranch-gas-leak-cause-long-term-heal/.
[1900] Los Angeles County Department of Health, "Aliso Canyon Gas Leak: Results of Air Monitoring and Assessments of Health," February 5, 2016, http://www.publichealth.lacounty.gov/media/docs/AlisoAir.pdf.
[1901] McKenna, "What Will Be the Health Impact of 100+ Days of Exposure to California's Methane Leak?"
[1902] Phil McKenna, "New Federal Gas Storage Regulations Likely to Mimic Industry's Guidelines," *Inside Climate News*, February 8, 2016, https://insideclimatenews.org/news/08022016/federal-gas-storage-regulations-likely-mimic-industry-guidelines-aliso-canyon-phmsa-api/.

House Committee on Transportation and Infrastructure, California representatives "spoke about their efforts to speed up PHMSA's rulemaking for underground gas storage."[1903]

- February 5, 2016 – As part of the Expanded Air Monitoring Plan, Los Angeles County Department of Health provided results for the primary chemicals of concern to assess health effects in residents, pets, and other animals in the community during the Southern California Gas Aliso Canyon storage facility leak. Those chemicals included methane, odorants, and benzene. The maximum level of methane detected was 4,340 ppm and the maximum level of benzene was 30.6 ppb. Early on, average weekly benzene levels that were close to the 1 ppb chronic exposure limit/ health protective level. "Methane levels have remained above normal, but have decreased substantially over time," the report summarized. It also stated that odorants "… remained below instrument detection limits throughout the entire period, including immediately after the leak, even at locations near the leaking well," and that "[b]enzene and other chemicals were originally detectable at levels above normal from within community sampling sites, but peak levels remained below acute exposure thresholds."[1904] While the Los Angeles County Department of Health concluded that "health effects resulting from the on-going leak should be limited to short-term effects resulting from exposure to the odorants," independent scientists, noting data gaps, have challenged these conclusions.

- January 25, 2016 – Some health experts and residents of Porter Ranch, California, adjacent to the Aliso Canyon gas field leak, expressed concern about long-term exposure to the odorous component of the gas, mercaptans, to which regulators attributed several symptoms of residents. Mercaptans are sulfurous chemicals that are added to natural gas to aid in the detection of leaks. Though California regulators have said the health problems, such as headaches, vomiting, and nosebleeds are temporary and will not lead to long-term damage, medical researchers described data gaps to *Inside Climate News.* There is "virtually no research on prolonged exposure to mercaptans." Further, some researchers suggest the health problems may have been caused by different chemicals in the gas, and that "regulators have downplayed the significance of other contaminants that are also present in the leak."[1905]

- January 19, 2016 – Peter Richman, MD, president of the Los Angeles County Medical Association told the *Los Angeles Daily News* that, at nearly three months after the Aliso Canyon methane leak began, physicians had yet to receive a formal statement from the Los Angeles County Department of Public Health about airborne chemical pollutants related to the gas leak or guidelines on how to answer questions from patients about long-term health effects. Richman expressed special concern about prolonged exposure to methane and trace chemicals known to be carcinogenic. Another area physician reported

[1903] Lisa Song, "U.S. Pipeline Agency Pressed to Regulate Underground Gas Storage," *Inside Climate News*, February 26, 2016, https://insideclimatenews.org/news/26022016/phmsa-pipeline-regulator-pressed-regulate-underground-natural-gas-storage-aliso-canyon-methane/.
[1904] Los Angeles County Department of Health, "Aliso Canyon Gas Leak: Results of Air Monitoring and Assessments of Health."
[1905] Lisa Song, "Mercaptans in Methane Leak Make Porter Ranch Residents Sick, and Fearful," *Inside Climate News*, January 25, 2016, https://insideclimatenews.org/news/25012016/porter-ranch-residents-health-effects-methane-leak-aliso-canyon-california/.

that, as of the interview date, his urgent care practice had seen a hundred patients whose symptoms were consistent with exposure to leak-related pollutants.[1906]

- January 14, 2016 – Boston University researcher Nathan Phillips and Bob Ackley of Gas Safety USA drove a high precision GIS-enabled gas analyzer through roads throughout California's San Fernando Valley adjacent to the Aliso Canyon gas leak in early January 2016. Early results showed methane levels elevated 2-67 times the background level.[1907]

- January 13, 2016 – Investigations into the possible cause of the gas leak in Aliso Canyon included the consideration that nearby fracking may have contributed to casing failure. In an email to the *Los Angeles Daily News*, California Department of Conservation Chief Deputy Jason Marshall said that their investigation will examine well records, including those pertaining to "well stimulation operations."[1908] According to a 2015 report prepared for the California Council on Science and Technology, hydraulic fracturing is used about twice yearly to enhance storage "mostly in one facility serving southern California (Aliso Canyon)."[1909]

- January 13, 2016 – "Aliso Canyon is a wake-up call," according to a *Rocky Mountain PBS News* investigative report on the state of U.S. natural gas infrastructure. Natural gas is no longer a cleaner fuel than coal when methane leakage rates exceeds 2-4 percent, but the vast size of the nation's interconnected natural gas storage and pipeline systems makes difficult the task of tallying all the micro-leaks spread across the entire network and answering fundamental questions about exactly how much methane is being lost. The PBS report also expressed concern about the age of many of the system's component parts. According to the piece, nearly half (46 percent) of the nation's transmission pipelines, designed to carry high-pressure gas over long distances, were built in the 50s and 60s and are now more than a half century old.[1910]

- December 30, 2015 – According to the *Los Angeles Daily News,* which unearthed November 2014 state regulatory filing documents, the Southern California Gas Company

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[1906] Susan Abram, "Doctors Treating Porter Ranch Residents Want More Gas-Leak Guidance," *Daily News*, January 19, 2016, https://www.dailynews.com/health/20160119/doctors-treating-porter-ranch-residents-want-more-gas-leak-guidance.

[1907] Dana Bartholomew, "'Plume Chaser' Researchers Fan out across San Fernando Valley to Map Reach of Porter Ranch Gas Leak," *Daily News*, January 14, 2016, https://www.dailynews.com/environment-and-nature/20160114/plume-chaser-researchers-fan-out-across-san-fernando-valley-to-map-reach-of-porter-ranch-gas-leak.

[1908] G. J. Wilcox, "Regulators Probing Whether Fracking Was Connected to Aliso Canyon Gas Well Leak," Daily News, January 14, 2016, https://www.dailynews.com/environment-and-nature/20160113/regulators-probing-whether-fracking-was-connected-to-aliso-canyon-gas-well-leak.

[1909] Jane C. S. Long et al., "An Independent Scientific Assessment of Well Stimulation in California, Volume I: Well Stimulation Technologies and Their Past, Present, and Potential Future Use in California" (California Council on Science and Technology, Lawrence Berkeley National Laboratory, Pacific Institute, 2015), https://ccst.us/publications/2015/2015SB4-v1.pdf.

[1910] J. Wirfs-Brock, "Vast California Methane Leak Is Dire but Not Unique in Aging Infrastructure," *Rocky Mountain PBS News*, January 13, 2016, https://web.archive.org/web/20160120174236/http://inewsnetwork.org/2016/01/13/vast-california-methane-leak-is-dire-but-not-unique-in-aging-infrastructure/.

knew about the corrosion and potential for leakage at Aliso Canyon prior to the massive blow-out. "In written testimony to the California Public Utilities Commission, [SoCalGas Director of Storage Operations Phillip] Baker described a reactive maintenance process that hinted at major leakage problems underground."[1911]

- November 20, 2015 – California state agencies collaborated with Aviation Scientific to measure methane emission rates at two early November dates, finding rates of 44,000±5,000 kilograms of methane per hour and 50,000±16,000 kilograms of methane per hour. The results indicated that the Aliso Canyon gas leak would have contributed about a quarter of California's methane emissions for the time period studied.[1912]

- November 20, 2015 – According to the *Los Angeles Times*, one month into the Aliso Canyon ongoing gas leak, Southern California Gas warned that it "might need several months" to plug the leak. An order from California's Division of Oil, Gas and Geothermal Resources, "stated that an 'uncontrolled flow of fluids' and gas was escaping and the operator had failed to fully inform state officials about the well's status. Steve Bohlen, the state oil and gas supervisor, also directed the company to submit a schedule for remediation work or for drilling a relief well."[1913]

- October 19, 2015 – *Houston Public Media* reported on the 125 caverns carved out of salt storing natural gas liquids (NGLs), thousands of feet under the city of Mont Belvieu, Texas, east of Houston. "There have been fiery accidents here. But nothing like what happened 23 years ago at a different [NGL] storage site 100 miles to the west. 'A bomb-like blast literally blew residents in this small community out of their beds this morning, said a reporter for Dallas's Channel 8 as he did a live report just outside the city of Brenham." That blast, which killed three and injured 21, was reportedly caused by the lack of an emergency shut-off valve. There are no federal standards in place for such requirements. Twenty-three years later, a month prior to the *Houston Public Media* report, "at a hearing held by the U.S. Senate Committee on Commerce, Science, & Transportation, Donald Santa, head of the Interstate Natural Gas Association of America, told the senators that it was only in recent weeks that the industry approved standards for storing natural gas." Texas did enact legislation a year after the deadly blast "and now requires emergency shutoff valves and inspections for leaks every five years."[1914]

[1911] Mike Reicher, "SoCalGas Knew of Corrosion at Porter Ranch Gas Facility, Doc Shows," *Daily News*, December 31, 2015, https://www.dailynews.com/general-news/20151230/socalgas-knew-of-corrosion-at-porter-ranch-gas-facility-doc-shows.
[1912] California Air Resources Board, "Report on Greenhouse Gas Emissions from Aliso Canyon Leak," *Los Angeles Times*, November 20, 2015, http://documents.latimes.com/report-greenhouse-gas-emissions-aliso-canyon-leak/.
[1913] T. Barboza, "Natural Gas Leak That's Sickening Valley Residents Could Take Months to Fix," *Los Angeles Times*, November 21, 2015, sec. California, https://www.latimes.com/local/california/la-me-1121-gas-leak-20151121-story.html.
[1914] Dave Fehling, "On Edge Of Houston, Underground Caverns Store Huge Quantities Of Natural Gas Liquids," *Houston Public Media*, sec. Energy & Environment, accessed September 22, 2021, https://www.houstonpublicmedia.org/articles/news/2015/10/19/124674/on-edge-of-houston-underground-caverns-store-huge-quantities-of-natural-gas-liquids/.

- October 5, 2011 – The federal district court in Topeka struck down Kansas gas-safety laws in 2010, and 11 underground storage sites with a capacity of more than 270 billion cubic feet of gas have gone uninspected, leaving thousands of Kansans to live on and around uninspected gas-storage fields.[1915]

- 2008 – When considering the possibility of storing natural gas in a variety of underground gas storage facilities, the UK government commissioned the British Geological Survey to identify the main types of facilities currently in operation worldwide along with any documented or reported failures and incidents which have led to release of stored product. The researchers found that California had the most incidents, but concluded that many of these problems and geological factors would not necessarily be applicable to the UK. The incidents most relevant to gas storage in the UK resulted from a failure of either the man-made infrastructure (well casings, cement, pipes, valves, flanges, compressors etc.), or human error, which has included overfilling of caverns and inadvertent intrusion. Extreme natural events, including earthquakes, also played a role. The researchers looked closely at incidents in salt caverns that had been repurposed to store gas. They reported that "early salt cavern storage in the US was done in brine wells that had been solution mined [in which salt deposits are melted away with hot water or steam] without consideration for subsequent storage in the depleted caverns. This practice sometimes resulted in later problems for storage operations in retrofitted brine caverns." The authors conclude that the rate for a geological failure of the storage cavity in an underground gas storage facility is of the order of 10^{-5} failures per well year.[1916]

<u>**Liquefied natural gas (LNG) facilities**</u>

Liquefied natural gas (LNG) is methane vapor that has been turned into liquid through a cryogenic process that lowers the temperature of the gas to its condensation point (– 259o F). Chilling natural gas to its liquid state shrinks its volume by a factor of 600, allowing LNG to be transported to places where pipelines don't reach, as when it is exported overseas on massive tanker ships. LNG is also sometimes used as vehicle fuel in, for example, long-haul trucks. LNG facilities encourage fracking by creating storage for the glut of gas that fracking has created, by enabling its export, and by driving up prices and profit margins. LNG facilities are capital-intensive and consist of liquefaction plants, import/export terminals, tanker ships, regasification terminals, and inland storage equipment.

LNG liquefaction requires immense energy in order to achieve the ultra-low temperatures required for condensation. An LNG facility typically requires its own power plant. Because they rely on evaporative cooling, LNG tanks are leaky by design: to maintain the liquid at super-chilled temperatures and prevent explosions, vaporized gas is vented from storage tanks directly

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[1915] Dion Lefler, "Lawsuit Leaves Large Gas Storage Fields in Kansas Unregulated," *The Wichita Eagle*, October 5, 2011, https://www.kansas.com/news/article1071558.html.

[1916] Deborah Keeley, "Failure Rates for Underground Gas Storage: Significance for Land Use Planning Assessments," Research Report (Health and Safety Laboratory, 2008), https://www.hse.gov.uk/research/rrpdf/rr671.pdf.

into the atmosphere. Larger tanks are engineered to capture boiled-off gas, but this process is not leak-proof. Before it is combusted or sent down a pipeline, LNG must be regasified via an energy-intensive process that requires massive infrastructure of its own, including periodic flaring to control pressure. Refrigeration, venting, leaks, flaring, and shipping make LNG more energy intensive than conventional natural gas. A recent analysis shows that exporting large quantities of LNG from the United States will likely cause global greenhouse gas emissions to rise not only because of its energy penalty but also because LNG exports add more fossil fuels to the global market and extend the lifespan of U.S. coal-fired plants.

LNG creates acute public safety risks. LNG explodes when spilled into water and, if spilled on the ground, can turn into rapidly expanding, odorless clouds that can flash-freeze human flesh and asphyxiate by displacing oxygen. If ignited at the source, LNG vapors can become flaming "pool fires" that burn hotter than other fuels and cannot be extinguished. LNG fires burn hot enough to cause second-degree burns on exposed skin up to a mile away. LNG facilities pose significant risks to nearby population centers and have been identified as potential terrorist targets.

Nevertheless, in June 2020, over the strong objections of the International Association of Firefighters, the National Association of Fire Marshalls, and the National Transportation Safety Board, the Trump administration, by executive order, lifted the nationwide ban on transporting LNG by rail to facilitate the planned construction of an LNG export terminal in Gibbstown, New Jersey. As of this writing, that executive order has not been lifted by the Biden administration. The Pipeline and Hazardous Materials Safety Administration (PHMSA) together with the Federal Railroad Administration have convened a task force to initiate rulemaking that would allow the transportation of LNG by re-designed rail cars. This work was largely finished in 2020. Concurrently, Congress directed the National Academies of Sciences, Engineering, and Medicine to convene a committee to study the transportation of LNG by rail and review the research and testing activities of the task force. The second phase of the committee's project, to be completed in mid-2022, will address a range of risk factors, including incidents caused by deliberate acts.

- July 2, 2021 – Calling its own project "impractical," Pieridae Energy said it will not proceed with its planned LNG processing and export facility in Nova Scotia with an estimated construction cost of $14 billion. Although the German government had offered the company a US $4.5 billion loan guarantee contingent on its ability to secure additional financing, the company failed to submit an application for for additional funds from the Canadian government by the ageed-upon deadline. The editor and publisher of the *Halifax Examiner* noted that the company could still alter the project—importing natural gas from Pennsylvania through existing pipelines rather than as originally planned from Alberta—but such a shift would create a dependency on the problem-plagued Enbridge compressor station in Weymouth, Massachusetts, throwing the viability of the project into doubt. "Natural gas's time has passed. The public hates it, governments won't finance it, and no one is buying."[1917]

[1917] Tim Bousquet, "The Goldboro LNG Plant Scheme Has Collapsed," *Halifax Examiner*, July 2, 2021, https://www.halifaxexaminer.ca/featured/the-goldboro-lng-plant-scheme-has-collapsed/.

- June 30, 2021 – Pieridae Energy, having missed a deadline to submit an application to the Canadian government for $925 million in grant, repayable contribution, or loan guarantee for its planned LNG facility in Nova Scotia, would still need to undergo environmental assessment and receive regulatory permissions even if all the necessary funding were secured. The plan's opponents are prepared to mount substantive challenges, out of concern that the LNG facility would prevent Nova Scotia from meeting emissions goals, that the large labor camp would threaten the safety of native Canadian women, and that the use of public funds to increase fossil fuel production in a time of accelerating renewable energy investments is inappropriate.[1918]

- June 22, 2021 – U.S. company New Fortress Energy (NFE) announced its intention to apply for permission for an LNG terminal in Ireland despite the country's May 2021 pause on all new LNG terminals. The project would include a power plant and battery storage facility, with an offshore LNG terminal in the Shannon estuary. A previous plan was put on hold in 2019 because of concerns over the import of fracked gas. Ireland has pledged to obtain 70 percent of energy from renewables by 2030 and has excluded the use of fracked gas. NFE claims that its project will not be dependent on fracked gas.[1919]

- June 16, 2021 – As part of the Further Consolidated Appropriations Act of 2020, PHMSA entered into an agreement with the Transportation Research Board, a major program of the National Academies of Sciences, Engineering, and Medicine (NASEM) to convene a committee of independent experts to critique the safety research and testing protocols undertaken by the task force engaged in the final rulemaking process for allowing the transportation of LNG by rail tank car. Among other concerns, the committee in its report asked for a clearer rationale for how full-scale impact testing, tank fire testing, and worst-case scenarios protocols were developed. The second phase of the project, to be completed in mid-2022, will provide a more in-depth review and examination of the applicability of existing guidelines for emergency responses to LNG rail incidents, including "incidents caused by deliberate acts, human factors, or track component defects."[1920]

- June 3, 2021 – According to an engineering analysis, the force of a vapor cloud explosion (VCE) at LNG plants has likely been significantly and systematically underestimated by industry. VCEs occur when heavier hydrocarbons, which are used to cool natural gas, leak and ignite. LNG terminals, which typically hold 50 tons of these refrigerants, are usually designed with barriers at the perimeter to prevent vapor leaks from spreading off site, but, on rare occasions, as during windless conditions, such barriers can allow vapor

[1918] Rose Murphy, "Feds Haven't Received Funding Application for Goldboro LNG Project, Says MP," CBC.Ca, June 30, 2021, https://www.cbc.ca/news/canada/nova-scotia/lng-pipeline-goldboro-nova-scotia-1.6085957.
[1919] Sarah Collins, "US Backer Revives Its Plans for €650m Shannon LNG Project," June 22, 2021, https://www.independent.ie/business/irish/us-backer-revives-its-plans-for-650m-shannon-lng-project-40567970.html.
[1920] Policy Studies, Transportation Research Board, and National Academies of Sciences, Engineering, and Medicine, *Preparing for LNG by Rail Tank Car: A Review of a U.S. DOT Safety Research, Testing, and Analysis Initiative* (Washington, D.C.: Transportation Research Board, 2021), https://doi.org/10.17226/26221.

accumulation sufficient for explosions, which can be massive. In 2019, for example, a VCE in Philadelphia threw a 38,000-pound vessel across the Schuylkill River and led to the permanent closure of that oil refinery. Although federal standards are in place for risk calculations for other types of hazards, PHMSA had accepted industry's computer model indicating that the force of a VCE would be greatly diminished by the time it reached the edge of the facility. However, an expert study not associated with the industry showed that the force of that type of incident could be 15 to 20 times higher than projections from industry modeling. PMHSA intends to develop new rules on VCEs in the coming year and yet, meanwhile, approved safety plans for three proposed LNG terminals in Louisiana (although one of three was subsequently cancelled because of financial issues). Jerry Havens, the former director of the Chemical Hazards Research Center at the University of Arkansas said, "If something doesn't get corrected, there might be some terrible accidents."[1921]

- May 14, 2021 – The Irish government pledged in June 2020 to disallow the import of LNG derived from fracked gas, and Ireland's Department of the Environment, Climate and Communications (DECC) has said that no LNG projects should proceed until a review of the country's energy supply security is completed. DECC has also said that Ireland would withhold EU member state approval for EU funding for LNG import terminals in the country. A spokesperson for the agency commented, "as Ireland moves toward climate neutrality, it does not make sense to develop LNG projects importing fracked gas." This policy has led to the suspension of one planned project by a U.S. developer, but two others are still in progress: Shannon and Predator. The High Court in Ireland ruled against all development consents for the Shannon LNG project, but Shannon is preparing new applications and hopes to come online in late 2022. Predator, a UK project, plans a floating LNG import terminal and stated it would not use LNG sourced from fracking.[1922]

- April 30, 2021 – Plans for a €40 million LNG terminal at the port of Bratislava, Slovakia are backed by unsubstantiated claims from the state-owned investor that the facility will reduce pollution and greenhouse gas emissions on the Danube and make freight transport "greener." Part of an EU plan to build a Rhine-Danube transport corridor connecting different means of transport across Europe, the terminal will be located less than one kilometer away from a densely populated area, and, according to critics, would increase traffic and cause a reduction in air quality. Concerns about the project's potential to increase Slovakia's reliance on natural gas have prompted request for an analysis of its compatibility with EU climate policies.[1923]

[1921] Will Englund, "Engineers Raise Alarms Over the Risk of Major Explosions at LNG Plants," *The Washington Post*, May 3, 2021, https://www.washingtonpost.com/business/2021/06/03/lng-export-explosion-vce/.
[1922] Stuart Elliot, "Ireland Advises Against All LNG Project Developments During Energy Review," S&P Global, May 14, 2021, https://www.spglobal.com/platts/en/market-insights/latest-news/natural-gas/051421-ireland-advises-against-all-lng-project-developments-during-energy-review.
[1923] Irena Jenčová, "Bratislava Port to Get Its Own €40 Million LNG Terminal," Euractiv.com, April 30, 2021, https://www.euractiv.com/section/politics/short_news/bratislava-port-to-get-its-own-e40-million-lng-terminal/.

- April 26, 2021 – The United Kingdom approved $1 billion for a large LNG development in Mozambique that is now facing a court challenge on the grounds that the project is consistent with neither the United Kingdom's nor Mozambique's obligations under the Paris Climate Agreement. The construction phase of the project would increase Mozambique's GHG emissions by up to 10 percent and the burning of the fuel produced would cause emissions equivalent to those of the EU's total aviation sector.[1924]

- April 22, 2021 – Plans for three LNG import terminals in Germany have received strong state support, even though plans for a renewable energy transition would render over 70 percent of all gas distribution grids in that nation unnecessary. A research team examined the ways in which the continuing build-out of LNG infrastructure in Germany locks in a dependency on natural gas, allowing the industry to avoid stranded assets while also impeding the transition to renewables and substantially delaying the attainment of climate goals. They found that local and political forces work together to create momentum for LNG proposals and to keep federal opposition weak. The continued use of gas requires no change in equipment or consumer behavior while political pressure from the United States to reduce Russian gas imports and to import U.S. LNG keep climate and environment issues subordinate to short-term economic and energy security concerns. The authors recommend that policy and energy investment decisions include climate targets and the risks of locking in natural gas dependencies.[1925]

- April 15, 2021 – The Delaware River Basin Commission (DRBC), comprised of representatives of New York, New Jersey, Pennsylvania, and Delaware, as well as the commander of the U.S. Army Corp of Engineers' North Atlantic Division, has made paradoxical decisions regarding fracked gas. In February 2021 the DRBC banned fracking in the area that it oversees. However, only a few months earlier, the Commission approved a dock in Gibbstown, New Jersey to export LNG from a plant in Pennsylvania, potentially placing at risk over 1.5 million people in an area ranging over 200 miles from the plant to the export dock. The Pennsylvania Department of Environmental Protection estimated that the LNG plant would produce more than one million metric tons of greenhouse gases yearly and burning the gas after delivery would produce millions more. A special permit from the Trump administration for the use of rail to transport LNG from Pennsylvania to New Jersey for this project was followed by a complete lifting of the federal ban on LNG transport by rail in densely populated areas in 2020. When New Fortress Energy built a dock in Gibbstown in 2017, the company indicated the facility would not use it for LNG export. However, a subsidiary of New Fortress applied for a permit to build the Pennsylvania LNG plant intending to export the gas from a port on the Delaware River. The subsidiary, Delaware River Partners, subsequently applied for a permit to construct another dock attached to the Gibbstown facility, which would be used for LNG export. Not only adjacent to a low-income and largely non-white "overburdened community," the location itself is a Superfund site, and dredging needed for the dock

[1924] Brendan Montague, "Britain's $1 Billion Bet Against the Climate," *Ecologist*, April 26, 2021, https://theecologist.org/2021/apr/26/britains-1billion-bet-against-climate.
[1925] Hanna Brauers, Isabell Braunger, and Jessica Jewell, "Liquefied Natural Gas Expansion Plans in Germany: The Risk of Gas Lock-In under Energy Transitions," *Energy Research & Social Science* 76 (2021), https://doi.org/10.1016/j.erss.2021.102059.

could release carcinogenic PCBs into the river. When the DRBC approved "Dock 2," the agency stated that the climate and environmental issues would need to be addressed at the state, interstate, and federal level. New Fortress still needed permits from New Jersey's Department of Environmental Protection and an export permit from the federal Department of Energy. A motion for summary judgement was filed with the New Jersey district court asking that the Army Corps of Engineers' permit be nullified because a full environmental impact assessment had not been done prior to approval. Other roadblocks to the project include the possibility that President Biden could revoke the prior administration's executive order regarding LNG rail transport.[1926]

- March 30, 2021 – Bowing to public pressure and determining that its chemical discharges would harm local wetlands, the Australian government denied the LNG import terminal at Crib Point planned by AGL Energy. Australia's biggest climate polluter, AGL Energy had already spent about $130 million on the project. AGL also plans to split its business in two, in an attempt to improve its emissions profile and reputation, by separating out its continued coal-fired power generation.[1927]

- January 22, 2021 – The accidental release of LNG from a railroad tank car can result in fire and boiling liquid expanding vapor explosions. Because of these risks, transport of LNG by rail, which is regulated by the PHMSA and the Federal Railroad Administration, had been allowed only on a case-by-case basis. However, on July 24, 2020, PHMSA finalized the LNG by rail regulation allowing the practice. The decision has been challenged in court, but the Biden administration requested that the case be delayed until it reviews the LNG by rail rule.[1928]

- November 9, 2020 – LNG transport from Russia to Asia via the Northeast Passage has markedly increased due to climate change-induced ice melt. That sea route, from Russia past the North Pole and Alaska and south to China, historically was covered with ice for most of the year, but, when available for shipping, cuts about 2400 nautical miles off the trip. The route is now open for much longer periods each year, and there have been thousands of transits since 2015. China, expected to double its natural gas use in the next 15 years, had previously obtained most of its natural gas via pipelines from other Asian countries and southern Russia. In 2017, Russia opened an LNG export terminal on the Yamal Peninsula that offers easy access, via the Northeast Passage, to China. Traffic is expected to increase as ice melt continues. In contrast, a proposed US LNG export terminal in Oregon is on hold because of climate concerns.[1929]

[1926] Zoya Teirstein, "The Delaware River Basin Paradox: Why Fracking Is So Hard to Quit," *Grist*, April 15, 2021, https://grist.org/politics/the-delaware-river-basin-paradox-why-fracking-is-so-hard-to-quit/.
[1927] Australian Associated Press, "Victoria Blocks AGL's Gas Terminal on Environmental Grounds," *The Guardian*, March 30, 2021, https://www.theguardian.com/business/2021/mar/30/victoria-blocks-agl-energy-gas-terminal-crib-point-split-business.
[1928] Environmental & Energy Law Program, "LNG by Rail Rule," Regulatory Tracker (Harvard Law School, January 22, 2021), https://eelp.law.harvard.edu/2021/01/lng-by-rail-rule/.
[1929] Tim McDonnell, "A Brutal New Climate Feedback Loop Is Brewing in the Arctic," *Quartz*, November 9, 2020, https://qz.com/1928866/how-the-northeast-passage-is-helping-russia-sell-more-natural-gas/.

- July 6, 2020 – Investors concerned about falling demand, rising competition from renewable energy, and opposition due to climate concerns have delayed financing for at least 20 of 45 major LNG projects in preconstruction development around the world.[1930] "Investing in new fossil fuel infrastructure like liquefied natural gas (LNG) terminals is increasingly an economically unsound decision," commented Andrew McDowell, the vice president of European Investment Bank (EIB). EIB will stop financing fossil fuel projects after 2021. The pandemic has also slowed LNG terminal development. The industry and some nations, however, still plan to boost LNG exports over the next 10 years. Methane, the main component of LNG, is a potent greenhouse gas, and these plans raise concerns about the possibilities of achieving the goals of the Paris climate accord.

- June 23, 2020 – The US Energy Information Administration reported that LNG export capacity would be used at less than 50 percent during June, July, and August 2020.[1931] Seventy-four US cargoes were exported in January 2020, but over 70 were cancelled for June and July and more than 40 cancelled for August. According to the report, "A mild winter and COVID-19 mitigation efforts have led to declining global natural gas demand and high natural gas storage inventories in Europe and Asia, reducing the need for LNG imports. Historically low natural gas and LNG spot prices in Europe and Asia have affected the economic viability of U.S. LNG exports."

- June 23, 2020 – Royal Dutch Shell's "Prelude," a floating plant designed to produce LNG from remote offshore gas fields has not been operational since January 2020 because of safety problems, reported *Forbes*.[1932] Shell had not revealed the cost of the project, but estimates ranged from $12 billion to $17 billion. Operational costs were estimated to be high as well. Analysts at Goldman Sachs estimated that Prelude's costs are more than double those from other new LNG projects. Oil and gas prices have fallen dramatically since the project began about 10 years ago, and an analyst at Credit Suisse said that record low LNG prices make it difficult to cover operating costs. In contrast, Shell Australia's chairman said that Shell was pleased with Prelude's progress.

- June 19, 2020 – Following President Trump's executive order signed in Houston in April 2019 to reconsider the prohibition of LNG transport by rail, the U.S. Department of Transportation (USDOT) and the Pipeline and Hazardous Material Safety Administration (PHMSA) issued a final rule in June 2020 allowing the practice.[1933] The Congressional Research Service (CRS) published a report addressing the new rule, including criticism:

[1930] Matthew Green, "Global LNG Projects Jeopardized by Climate Concerns, Pandemic Delays - Report," *Reuters*, July 6, 2020, sec. Environment, https://www.reuters.com/article/us-climate-change-gas-idUKKBN247303.
[1931] U.S. Energy Information Administration, "U.S. Liquefied Natural Gas Exports Have Declined by More than Half so Far in 2020 - Today in Energy - U.S. Energy Information Administration (EIA)," June 23, 2020, https://www.eia.gov/todayinenergy/detail.php?id=44196.
[1932] Tim Treadgold, "Shell's $12 Billion LNG Experiment Becomes A Big Headache," *Forbes*, June 23, 2020, sec. Asia, https://www.forbes.com/sites/timtreadgold/2020/06/23/shells-12-billion-lng-experiment-becomes-a-big-headache/.
[1933] U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration, "U.S. Department of Transportation Issues Final Rule for the Safe Transportation of Liquefied Natural Gas by Rail Tank Car | PHMSA," Press Release, June 19, 2020, https://www.phmsa.dot.gov/news/us-department-transportation-issues-final-rule-safe-transportation-liquefied-natural-gas-rail.

"perceived public safety and security risks of LNG by rail have raised concerns among state officials, the National Transportation Safety Board, and other members of Congress."[1934] The rule includes new operational safeguards and monitoring requirements for the highly combustible product including increased outer tank thickness, new braking requirements, and remote monitoring of pressure and location of each LNG car. There are also requirements that attempt to reduce security risk. The CRS report reviewed the inherent risks of LNG by rail, safety and environmental record of the industries, and policy issues including legislation actions. Ongoing concerns included inadequacy of emergency responder training, manpower, and resources to deal with an LNG rail accident. LNG burns hotter and more rapidly than gas or oil. If LNG spills but does not ignite it can cause asphyxiation or can create a vapor cloud which can burn if it contacts an ignition source. A boiling liquid expanding vapor explosion (BLEVE) could occur if a tank car was heated until rupture, resulting in a blast wave. "Cascading failures," where an LNG release and fire from one tank car can trigger succeeding cars to fail in the same manner, have occurred in rail accidents involving rail shipments of crude oil and ethanol, according to the report. Proposed legislation includes an Act to carry out further evaluation of LNG-by-rail safety, containing specific requirements, and which "would rescind any special permit or approval for the LNG transportation by rail tank car issued prior to enactment and would prohibit any regulation, special permit, or approval prior to the conclusion of a specified study period."

- May 25, 2020 – Seven LNG projects are in various stages of construction in Canada's British Columbia, where the province is expecting a fracking boom to feed the projects while concomitantly trying to address methane emissions.[1935] The largest of the LNG projects under construction is expected to require double the existing fracking operations. The province must also consider significant emissions from inactive and orphan wells. As new wells are drilled to meet LNG demands, the number of unattended wells is expected to rise dramatically, which will undermine efforts to cut methane emissions. British Columbia's goal is a 45 percent reduction in methane emissions from 2014 levels, to be achieved by 2025. Controversy surrounds the province's methods of assessing methane emissions, with one evaluation indicating that emissions were 2.5 times the province's official report. British Columbia has formed a methane research group to better evaluate the problem, but, the "group's work is focused solely on upstream operations—companies that extract or produce oil and gas—meaning facilities like LNG Canada are off the hook as an end-use, downstream facility." One member of the group noted that LNG Canada receives significant government subsidies including carbon tax exemptions estimated in excess of $150 million a year: "If the government wants to reach its methane target it needs to stop subsidizing oil and gas."

- May 15, 2020 – Now recognized by the European Union (EU), the problem of high methane emissions from the oil and gas industry offsets any potential climate benefits of

[1934] P. W. Parfomak and J. Frittelli, "Rail Transportation of Liquefied Natural Gas: Safety and Regulation" (Congressional Research Service, 2020).
[1935] Natalia Balcerzak, "'I Don't Think We Will Ever Catch up': B.C. Methane Targets out of Reach amid Growing LNG, Fracking," *The Narwhal*, May 25, 2020, https://thenarwhal.ca/climate-change-b-c-methane-targets-out-of-reach-growing-lng-fracking/.

importing LNG over coal. The EU's goal of climate neutrality by 2050 and multi-pronged strategies to curb methane emissions of imported natural gas, considers measurement and reporting across fossil fuel sectors and supply chains, as reported by the Germany-based, cross-border focused energy journalism group, *Clean Energy Wire*.[1936] Such a strategy, codified as concrete legislation, could force U.S. LNG producers to take their methane leakage problem more seriously if they want continued access to EU markets. The United States has been a net exporter of LNG since 2016, with most of the gas coming from the Permian Basin in western Texas and southeastern New Mexico that is now the world's largest oil-producing region and the United States' second biggest gas-producing region. Recent studies have shown that flaring, venting, and leaking of natural gas are much worse in the Permian Basin than elsewhere in the United States. One recent study indicated that the amount of fugitive methane emissions from the Permian oil and gas operations nearly triples the climate impact of burning the produced gas. Natural gas production, liquefaction, and transport are all energy intensive and lead to carbon dioxide emissions as well.

- March 1, 2020 – In April 2019 Donald Trump signed an executive order instructing the US Department of Transportation to write rules allowing rail transport of LNG. A detailed piece in the National Fire Protection Association's *NFPA Journal* detailed the issues of concern to the safety community, in the period between the Trump order and the release of the final rule.[1937] Public safety organizations such as the International Association of Firefighters (IAFF), the National Association of Fire Marshalls, and the National Transportation Safety Board (NTSB) were "strongly opposed" to the proposed rule. "The IAFF, pointing out that LNG will quickly evaporate into an immense and potentially flammable vapor cloud when exposed to ambient air, wrote that 'it is nearly certain any accident involving a train consisting of multiple rail cars loaded with LNG will place vast numbers of the public at risk while fully depleting all local emergency response forces.'" Safety experts noted that communities and public agencies should be preparing for rail accidents and recommended the involvement of the nation's 3,000 local emergency planning committees, mandated by Congress in 1986 to develop comprehensive emergency response plans.

- January 28, 2020 – For use as a marine fuel, there was no climate benefit for 20-year global warming potential from using LNG, and the use of LNG appeared to actually worsen the climate impact of shipping, according to a working paper from the International Council on Clean Transportation.[1938] More ships are being built to use LNG, which emits 25 percent less CO_2 than usual fuel for the same amount of propulsion. The study evaluated climate impact by comparing lifecycle greenhouse gas emissions of LNG, marine gas oil, very low sulfur fuel, and heavy fuel oil when used for marine

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[1936] Julian Wettengel, "Unravelling the Climate Footprint of U.S. Liquefied Natural Gas," *Clean Energy Wire*, May 15, 2020, https://www.cleanenergywire.org/news/unravelling-climate-footprint-us-liquefied-natural-gas.
[1937] Jesse Roman, "NFPA Journal - LNG By Rail, March/April 2020," *NFPA Journal*, April 2020, https://www.nfpa.org/News-and-Research/Publications-and-media/NFPA-Journal/2020/March-April-2020/Features/LNG-Trains.
[1938] Nikita Pavlenko et al., "The Climate Implications of Using LNG as a Marine Fuel | International Council on Clean Transportation," Working Paper (The International Council on Clean Transportation, January 28, 2020), https://theicct.org/publications/climate-impacts-LNG-marine-fuel-2020.

shipping. The assessment included leakage during extraction, processing, and transport, as well as downstream emissions from combustion and unburned gas. The paper emphasized that the International Maritime Organization has developed climate goals, has "signaled" that it will regulate emissions, and that "continued investment in LNG infrastructure on ships and on shore risks making it harder to transition to zero-emission vessels in the future."

- January 14, 2020 – The NTSB warned of the risk of "catastrophic" fires and explosions in response to a Trump administration draft rule to allow LNG transport by rail. Other groups, including fire marshals, the union representing rail engineers, and 16 state attorneys general, also oppose the rule. The NTSB recommended that PHMSA should require stricter safety precautions, but some rail industry groups oppose this. The executive director of the National Association of State Fire Marshals said, "The combination of a lack of information with no increased safety measures…puts the public and our first responders at even greater risk."[1939]

- January 11, 2020 – Scientists from Greece's National Centre of Scientific Research identified "scientific and harmonization gaps" at ports storing and transferring LNG.[1940] The study examined 35 legislative documents and 23 articles in an extensive review of literature regarding safety and risk assessment, and summarized regulations addressing LNG storage tanks, bunker trucks, buffer ships, and LNG fueled ships. At the time of the study, there were 21 operating LNG ports worldwide, and ten more with "confirmed plans to operate by 2020," but, the authors stated, "the knowledge regarding safe storage, handling and supply of LNG is still insufficient." They identified gaps including harmonization of LNG safety regulations at sea and on land, for all LNG operations at ports and within various countries. Additionally, more work needs to be done using quantitative risk methods to better define safety and hazardous zones during LNG storage and bunkering at ports. The authors identified areas for further work by the academic community and industry organizations.

- October 10, 2019 – Authors of an overview of risk analysis in the LNG sector proposed a "comprehensive classification framework," a classification strategy for LNG risk studies covering "more aspects of risk analysis process compared with the existing review articles."[1941] The storage, transport, and use of LNG carries the potential for catastrophic accident, and the field of risk analysis has been used "to identify the potential hazards, calculate the probability of accidents, as well as assessing the severity of consequences." The authors reviewed and categorized 66 papers addressing risk analysis in the LNG sector. The literature was examined with regard to methods, tools, data sources, and the type of LNG facility. The various risk analysis tools were described, along with their

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[1939] Mike Lee, "Feds Warn of 'Catastrophic' Blasts from Trump LNG Rule," *E&E News*, January 14, 2020, https://web.archive.org/web/20200114194145/https://www.eenews.net/energywire/stories/1062074737.
[1940] Olga Aneziris, Ioanna Koromila, and Zoe Nivolianitou, "A Systematic Literature Review on LNG Safety at Ports," *Safety Science* 124 (2020): 104595, https://doi.org/10.1016/j.ssci.2019.104595.
[1941] Isaac Animah and Mahmood Shafiee, "Application of Risk Analysis in the Liquefied Natural Gas (LNG) Sector: An Overview," *Journal of Loss Prevention in the Process Industries* 63 (January 2020): 103980, https://doi.org/10.1016/j.jlp.2019.103980.

advantages and drawbacks. Authors said that in spite of progress in the application of LNG risk analysis in the LNG sector, further research is needed, for which they make specific recommendations. These included attention to improved data quality and the introduction of real-life electronic data, more use of dynamic versus conventional risk assessment, and the use of more powerful risk assessment tools and methods. The review of data sources revealed that "expert judgement" was the most common source, suggesting that there is a lack of good quality data for LNG risk analysis.

- September 5, 2019 – The Trump Administration has used multiple means to push Europe to buy more American LNG, according to the *Houston Chronicle*.[1942] Trump aggressively promoted the exports through speeches and meetings with heads of state, and eight federal agencies have been charged with getting overseas gas infrastructure built. US officials have acted as "go-betweens" with foreign counterparts regarding their own energy sectors, assisting US allies in developing their own gas exports. Some in Europe, however, question America's sincerity about the stated goal of helping them achieve energy security: "After the Senate passed sanctions in 2017 targeting Russia's Nord Stream 2 natural gas pipeline into Germany—a project the Trump administration has fought to block—Austria and Germany's foreign officials released a joint statement calling the vote a bid to aid American energy companies."

- July 22, 2019 – An upcoming rule from PHMSA is expected to concern "streamlining U.S. regulations and harmonizing them with those in other countries," rather than focusing on safety and prevention of catastrophic explosions, reported *E&E News*.[1943] A PHMSA working group indicated in September 2018 that there "… is no process in place to evaluate the suitability of the software models to calculate these hazards." Five new LNG export facilities were expected to be operational by the end of 2019, and six more had been fully permitted. It remained unclear what the PHMSA will do to address the risk of explosion. Jerry Havens, a professor emeritus of chemical engineering, expressed concern that the current LNG infrastructure fails to account for the risk of catastrophe. Current LNG computational safety models are proprietary so he could not determine their accuracy, and PHMSA had no protocol to evaluate the models. Havens said that the current system might dramatically underestimate the power of a worst-case accident by a factor of ten.

- July 1, 2019 – The climate impact of proposed LNG expansion would be twice that of the current base of coal in the United States, Global Energy Monitor told *CNN*, for their coverage of a new report by the network of researchers who track fossil fuel projects.[1944] This impact is primarily related to leaks of methane, the potent greenhouse gas, and the reason that the United Nations' Intergovernmental Panel on Climate Change has called

[1942] James Osborne, "Trump's Hard Sell of American LNG," *Houston Chronicle*, September 5, 2019, sec. Energy, https://www.houstonchronicle.com/business/energy/article/Trump-s-hard-sell-of-American-LNG-14414269.php.
[1943] Jenny Mandel, "Trump LNG Rule: Will It Address 'Catastrophic' Risks?," *E&E News*, July 22, 2019, https://web.archive.org/web/20190722172209/https://www.eenews.net/stories/1060771257.
[1944] Matt Egan, "America's Liquefied Natural Gas Boom May Be on a Collision Course with Climate Change," *CNN Business*, July 1, 2019, https://www.cnn.com/2019/07/01/business/lng-boom-environment-climate-change/index.html.

for reducing natural gas in the coming decades, *CNN* reported. Economic viability is also in doubt, according to the Global Energy Monitor report, with "plunging renewable energy costs" putting much of the $1.3 trillion of LNG investments at risk.

- July 13, 2018 – A retrospective look at the risk management and risk governance used to develop and construct three LNG facilities in Gladstone, Australia evaluated the process by which multiple stakeholders—including government, business, community, and environmental groups—contributed to decision-making and management. The framework developed by the International Risk Governance Council was used for comparison. Environmental, social, and economic impacts occurred during construction, including death of harbor marine life, increased housing prices, and increased cost of living. Several problems in risk assessment and management were identified, including lack of cooperation between organizations at the onset of construction; disagreement as to whether monitoring and compliance mechanisms were adequate; and concern that the government was reactive to problems, rather than attempting to prevent or mitigate risks. Several recommendations were made to improve the risk management process of future projects.[1945]

- February 12, 2018 – Two LNG storage tanks were shut down at Cheniere Energy's Sabine Pass export facility after leaking LNG was found in a containment ditch around one of the tanks and 14 separate natural gas leaks were discovered around the base of a second tank. The Sabine Pass facility is located on the U.S. Gulf Coast on the border between Texas and Louisiana. Emergency procedures were put into place to assure the safety of the 107 on-site workers, but the public was not notified about this incident until more than two weeks later. Inspection revealed four cracks up to six feet long in the outer shell of the tank that had leaked LNG. These tanks are double walled, but only the inner tank is designed to tolerate the super-chilled temperature of LNG. The outer tank, rated to only -25° F, became brittle upon contact with -260° F LNG. The resulting investigation uncovered a long history of safety issues at this plant, including 11 other incidents involving these tanks that had occurred as far back as 2008 (when Sabine Pass was operating as an LNG import facility) after the federal Pipeline and Hazardous Materials Safety Administration (PHMSA) ordered Cheniere to conduct a root cause analysis and turn over records of any prior leaks.[1946] The agency also issued an order stating, "continued operation of the affected tanks without corrective measures is or would be hazardous to life, property, and the environment." Sabine Pass facility was required to receive written authorization from the Federal Energy Regulatory Commission (FERC) before the tanks could be put back in service.[1947] As part of a later hearing, parts of which were closed to the press and to the public, an accident investigator with PHMSA said that

[1945] R. G. van der Vegt, "Risk Assessment and Risk Governance of Liquefied Natural Gas Development in Gladstone, Australia: Risk Assessment and Risk Governance of LNG Development," *Risk Analysis* 38, no. 9 (2018): 1830–46, https://doi.org/10.1111/risa.12977.
[1946] Jenny Mandel and Mike Soraghan, "Feds Order Partial Shutdown at Cheniere LNG Export Site," *E&E News*, February 12, 2018, https://web.archive.org/web/20180212171644/https://www.eenews.net/stories/1060073537.
[1947] Mark Schleifstein, "Sabine Pass LNG Ordered to Shut down Leaking Gas Storage Tanks," *The Times-Picayune*, February 10, 2018, https://www.nola.com/news/environment/article_e93f653c-18d3-5016-abc6-47cdd7370b90.html.

she had struggled with the company to get information "timely and in enough detail."[1948] In April 2018, the parties agreed to resolve the issue without administrative proceedings or litigation.[1949]

- November 20, 2017 – Using a hybrid lifecycle and energy strategy analysis, a team of energy researchers investigated the potential climate impacts of U.S. LNG exports to Asia. They found that gas emissions were widely variable, dependent on the specific destination and the ultimate purpose for which the gas is used. Despite this range, under a scenario in which U.S. LNG exports continue to rise, "emissions are not likely to decrease and may increase significantly" because of additional energy demand, higher U.S. emissions, and increased methane leakage. The study also predicted that increased LNG exports could actually prolong the lifespans of coal-fired plants within the United States. All together, these factors, "have the very real potential to undermine any prospective climate benefit in the long run." Going forward, policymakers must consider "the complete climate ramifications of LNG exports."[1950] *E&E News*, reporting on the study, quoted one of the authors as saying, "The implications of our paper are that the greenhouse gas impacts from exporting U.S. natural gas…here at home and abroad, can be very, very bad."[1951]

- November 16, 2017 – A legal analysis in the *Energy Law Journal* examined the contested decision by the Federal Energy Regulatory Commission to authorize the expansion of the Dominion Cove Point LNG facility to allow for export as well as import activity, by examining the multiple direct and indirect effects of the expansion. Direct effects included impacts on water quality, the North Atlantic right whale, and the public safety of local residents. Indirect effects included an increase in domestic fracking, increase in tanker traffic, and exacerbation of climate change as export markets increase demand for natural gas. Because this latter set of problems is not directly related to facility expansion but rather to increased LNG exports, two different federal agencies have jurisdiction. The responsibilities of FERC and the Department of Energy (DOE) were clarified regarding this distinction. FERC handles the environmental review, while the DOE regulates export of LNG. In the case of Cove Point, FERC had issued a finding of no significant impact and was therefore not legally required to investigate indirect effects such as climate change. The analysis therefore concluded that FERC followed proper procedures and that the DOE would be a more appropriate target of legal action because of its control over LNG exports. This analysis reveals the diffusion of responsibility among federal agencies

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[1948] Edward Klump and Mike Soraghan, "Cheniere Says No Public Danger from Sabine Pass Leaks," *E&E News*, March 22, 2018, https://web.archive.org/web/20180322180240/https://www.eenews.net/stories/1060077135.
[1949] "Cheniere Settles Sabine Pass LNG Tanks Issue with PHMSA," *LNG World News*, April 24, 2018, https://www.offshore-energy.biz/cheniere-settles-sabine-pass-lng-tanks-issue-with-phmsa/.
[1950] Alexander Q. Gilbert and Benjamin K. Sovacool, "US Liquefied Natural Gas (LNG) Exports: Boom or Bust for the Global Climate?," *Energy* 141 (December 2017): 1671–80, https://doi.org/10.1016/j.energy.2017.11.098.
[1951] Ellen M. Gilmer and Jenny Mandel, "Increased LNG Exports Would Spell Trouble for Climate – Study," *E&E News*, December 15, 2017, https://web.archive.org/web/20180730192553/https://www.eenews.net/stories/1060069129.

regulating LNG facilities and the legal difficulties of addressing far-removed, indirect harms.[1952]

- July 25, 2017 – Citing volatile market conditions, Malaysia's energy giant Petronas cancelled plans for a massive LNG export terminal at the mouth of the Skeena River on British Columbia's remote northwest coast in Canada. As reported extensively by *The Tyee,* the project was the target of intense protest by First Nations people and the subject of many lawsuits, as it threatened public health and would industrialize pristine salmon habitat. "At one time as many as twenty LNG projects were proposed for coastal communities, but not one has been built. The majority of largely Asian-backed proponents have now cancelled or deferred their projects. A 50 percent drop in global oil prices combined with a 70 percent drop in global LNG prices forced Petronas to…scuttle a number of projects over the last two years."[1953]

- July 10, 2017 – Using a lifecycle assessment and optimization analysis to forecast the environmental impacts of LNG, researchers modeled three usage scenarios: hydrogen production; electricity generation; and vehicle fuel. The model assumed LNG transport by pipeline only, and not by tanker. The highest environmental impact in each case was global warming potential (GWP), and the highest GWP occurred when LNG was used as vehicle fuel.[1954]

- April 11, 2017 – The World Bank Group, which makes loans to developing nations for capital projects like infrastructure, released environmental, health, and safety guidelines for LNG facilities. These guidelines address the risks of spills, fire, explosions, air quality impacts, venting, flaring, and fugitive emissions. Also addressed was the danger of "roll-over," a phenomenon that occurs when layers of LNG of different density in a storage tank mix inappropriately. The result can be a rapid release of vapors and rise in pressure, potentially leading to catastrophic structural damage of the tank.[1955]

- March 30, 2017 – Transportation researchers identified and assessed potential risks to public safety from LNG transport on inland waterways and as a fuel for vessels and ferries. The hazards included the possibility of collision with other ships or with stationary objects such as bridges, as well as the threats of vapor release, flash and jet fires, boiling liquid expanding vapor explosion, and rapid phase transition. Firefighting strategies for different scenarios were proposed.[1956]

[1952] K. Rhodes, "The Weakest Link: The Consistent Refusal to Consider Far-Removed Indirect Effects of the Expansion of LNG Terminals," *Energy Law Journal* 38, no. 2 (2017): 431–53.
[1953] Andrew Nikiforuk, "'Basic Economics' Kill $11-Billion LNG Project on BC's Coast," *The Tyee*, July 25, 2017, https://thetyee.ca/News/2017/07/25/LNG-Project-BC-Coast-Killed/.
[1954] Yun Zhang et al., "Life Cycle Assessment and Optimization Analysis of Different LNG Usage Scenarios," *The International Journal of Life Cycle Assessment* 23, no. 6 (2018): 1218–27, https://doi.org/10.1007/s11367-017-1347-2.
[1955] World Bank Group, "Environmental, Health, and Safety Guidelines for Liquefied Natural Gas," 2017, https://www.ifc.org/wps/wcm/connect/Topics_Ext_Content/IFC_External_Corporate_Site/Sustainability-At-IFC/Publications/Publications_Policy_EHS-LNG.
[1956] Andrea Galieriková, Tomáš Kalina, and Jarmila Sosedová, "Threats and Risks during Transportation of LNG on European Inland Waterways," *Transport Problems* 12, no. 1 (2017): 73–81, https://doi.org/10.20858/tp.2017.12.1.7.

- March 9, 2017 – Liquefaction, LNG transport, and LNG evaporation determined more than 50 percent of LNG's global warming potential (GWP) in a "cradle to gate" life cycle analysis of LNG imported to the UK from Qatar. The analysis confirmed the dangerous effect of fugitive methane emissions on the total GWP of the supply chain. Other important parameters affecting GWP included the shipping distance and the tank volume.[1957]

- December 22, 2016 – Methane emissions from the heavy-duty transportation sector have climate change implications, according to a "pump-to-wheels" evaluation of natural gas powered vehicles and the compressed natural gas and LNG stations that fuel them. While fueling stations themselves leak methane, tailpipe and crankcase emissions were the highest sources.[1958]

- May 2, 2016 –The potential economic and greenhouse gas (GHG) impacts of importing LNG to Hawaii for electricity generation was modeled. Methane is a potent GHG, and although the use of LNG would decrease the local GHG output of Hawaii's electrical sector, lifecycle (global) GHG emissions would likely increase. This study did not examine other potential environmental impacts of LNG. Currently, the majority of Hawaii's electricity is provided by oil-fired generation.[1959]

- November 12, 2015 – New York Governor Andrew Cuomo rejected a heavily contested proposal to construct an LNG terminal 19 miles off the coast of Long Island. From his letter to the Maritime Administration: "The security and economic risks far outweigh any potential benefits….The potential for disaster with this project during extreme weather or amid other security risks is simply unacceptable." The governor also noted the risks posed to scallop and squid fisheries as well as the project's conflict with a proposed large-scale, offshore wind farm.[1960]

- September 30, 2015 – Measurements of the gaseous and particulate emissions of a cruise ferry on the Baltic Sea using a dual-fuel engine showed that LNG is not a clean fuel for ships. Methane made up about 85 percent of the vessel's hydrocarbon emissions. Particulate emissions showed a huge amount of volatile and nonvolatile particles, both of which are hazardous to human health.[1961]

[1957] Carla Tagliaferri et al., "Liquefied Natural Gas for the UK: A Life Cycle Assessment," *The International Journal of Life Cycle Assessment* 22, no. 12 (2017): 1944–56, https://doi.org/10.1007/s11367-017-1285-z.
[1958] Nigel N. Clark et al., "Pump-to-Wheels Methane Emissions from the Heavy-Duty Transportation Sector," *Environmental Science & Technology* 51, no. 2 (2017): 968–76, https://doi.org/10.1021/acs.est.5b06059.
[1959] Makena Coffman et al., "Economic and GHG Impacts of Natural Gas for Hawaii," *Environmental Economics and Policy Studies* 19, no. 3 (2017): 519–36, https://doi.org/10.1007/s10018-016-0157-2.
[1960] Marc Santora, "Cuomo Rejects Natural Gas Port Proposed Off Long Island," *The New York Times*, November 12, 2015, sec. New York, https://www.nytimes.com/2015/11/13/nyregion/cuomo-rejects-natural-gas-port-proposed-off-long-island.html.
[1961] Maria Anderson, Kent Salo, and Erik Fridell, "Particle- and Gaseous Emissions from an LNG Powered Ship," *Environmental Science & Technology* 49, no. 20 (2015), https://doi.org/10.1021/acs.est.5b02678.

- September 26, 2014 – The U.S. Government Accountability Office (GAO) issued a report of the federal process for reviewing applications to export LNG. As part of the process, the DOE and FERC consider public comment. Numerous environmental concerns include the risk that exports will increase hydro-fracking for natural gas, along with its associated environmental effects and greenhouse gas emissions. Under the National Environmental Policy Act, the DOE must consider the environmental effects of its decisions.[1962]

- April 23, 2014 –The dynamics and hazards from a LNG spill are not well understood and require further research, according to a comprehensive review of research into the LNG production chain from Australia that examined vapor production, vapor dispersion, and mechanisms of combustion. Noting the "intrinsic process safety issues" of LNG as well as potential attraction as a terrorist target, authors described various threats to human safety, including pool fires, jet fires, and vapor cloud explosions.[1963]

- December 14, 2009 – Certain LNG hazards are not "understood well enough to support a terminal siting approval," according to a Congressional Research Service (CRS) report that summarizes LNG hazards in the context of federal rules related to where LNG terminals are located. Potential risks include pool fires and flammable vapor clouds, as well as the possibility of terrorist attacks. The analysis points out the need for additional LNG safety research.[1964]

- July 7, 2009 – Because LNG projects are among the most expensive energy projects, the reserves of gas to justify the investment need to be large enough to guarantee about 30 years of production, according to a report by the Joint Research Centre of the European Union.[1965]

- May 13, 2008 – LNG infrastructure is "inherently hazardous and it is potentially attractive to terrorists," according to a CRS study that was prepared at a time when the United States was a net importer of LNG. Security of tankers, import terminals, and inland storage plants were identified as issues of concern. Serious risks include pool fires with intense heat, which can occur when LNG spills near an ignition source; flammable vapor clouds that can drift until reaching an ignition source; and a rapid phase transition

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[1962] U.S. Government Accountability Office, "Federal Approval Process for Liquefied Natural Gas Exports," Congressional Report, September 2014, https://www.gao.gov/assets/gao-14-762.pdf.
[1963] Walter Chukwunonso Ikealumba and Hongwei Wu, "Some Recent Advances in Liquefied Natural Gas (LNG) Production, Spill, Dispersion, and Safety," *Energy & Fuels* 28, no. 6 (2014): 3556–86, https://doi.org/10.1021/ef500626u.
[1964] [Name Redacted], "Liquefied Natural Gas (LNG) Import Terminals: Siting, Safety, and Regulation," Congressional Research Report, December 2009.
[1965] Boyan Kavalov, Hrvoje Petric, and Aliki Georgakaki, "Liquefied Natural Gas for Europe: Some Important Issues for Consideration." (Publications Office, 2009), https://publications.jrc.ec.europa.eu/repository/handle/JRC47887.

that can generate a flameless explosion. As per this report, there have been 13 serious accidents at onshore LNG terminals since 1944.[1966]

- February 22, 2007 – The GAO examined the results of studies on the consequences of an LNG spill and discussed expert opinion about the consequences of a terrorist attack on an LNG tanker. The studies indicate that 30 seconds of exposure to the heat of an LNG fire could cause burns up to a distance of about one mile. The experts concluded that this would be the most likely public safety hazard, with the risk of explosion less likely. Recommendations were made for further studies, including evaluating the possibility of "cascading failure," where multiple LNG tanks on a ship might fail in sequence.[1967]

- September 9, 2003 – As part of a larger investigation of potential terrorist targets in wake of the 9/11 attacks, the CRS provided a background report to the U.S. Congress on the security of LNG terminals in the United States. At the time, the United States was a net importer of natural gas, and LNG was shipped from overseas to U.S. ports. CRS identified LNG tanker ships and storage infrastructure as "vulnerable to terrorism," noting that tankers could be turned as weapons against coastal cities and that inland LNG facilities are typically located near large population centers. The CRS further noted that the public cost of security for LNG shipments, via Coast Guard escorts of tankers through coastal shipping channels, was considerable ($40,000-$80,000 per tanker).[1968]

- August 1, 1995 – The U.S. Department of Transportation identified three important hazardous properties of LNG: flammability hazards (fire or explosion from ignition of leaks); toxicity hazards (asphyxiation from exposure to non-odorized fuel gas); cryogenic hazards (personal injury plus structural failure of equipment from prolonged exposure to extremely cold temperatures.)[1969]

Gas-fired power plants

In 2016, natural gas-fired power plants surpassed coal-burning plants as the leading source of electrical generation in the United States. In 2019 alone, U.S. gas-fired generation increased by 8 percent, according to the International Energy Agency. As of May 2021, at least eight large utilities in the United States were building new gas plants, and five were considering it.

[1966] Paul W. Parfomak, "Liquefied Natural Gas (LNG) Infrastructure Security: Issues for Congress," Congressional Research Report (Library of Congress, Congressional Research Service, May 2008), https://www.hsdl.org/?view&did=486464.
[1967] U.S. Government Accountability Office, "Public Safety Consequences of a Terrorist Attack on a Tanker Carrying Liquefied Natural Gas Need Clarification," February 2007, https://www.gao.gov/new.items/d07316.pdf.
[1968] Paul W. Parfomak, "Liquefied Natural Gas (LNG) Infrastructure Security: Background and Issues for Congress" (Library of Congress, Congressional Research Service, September 9, 2003), https://apps.dtic.mil/sti/pdfs/ADA426272.pdf.
[1969] Michael J. Murphy et al., "Clean Air Program: Summary Assessment of the Safety, Health, Environmental and System Risks of Alternative Fuel" (U.S. Department of Transportation, Federal Transit Administration, August 1, 1995), https://doi.org/10.21949/1403909.

There are two types of gas-fueled power plants: combined cycle plants and simple cycle plants. Both types are major emitters of carbon dioxide, uncombusted methane, and nitrogen oxides, which contribute to the formation of ground-level ozone (smog). Combined cycle gas plants reuse waste heat to generate additional electricity and are roughly equivalent in efficiency to an older coal plant. Simple cycle gas plants—also called peaker plants—can be turned on and off faster to meet fluctuating energy demands when electricity needs peak, but they are much less efficient and more polluting than combined cycle plants. Simple cycle peaker plants can often generate more nitrogen oxides and carbon monoxide than coal plants.

Gas-fired combined cycle plants were formerly promoted as a bridge to reduce emissions while renewables ramp up. However, renewable prices have fallen low enough to allow a transition directly from coal to solar and wind power, revealing that gas plants, with long returns on investment, are more barrier than bridge and serve to delay a speedy transition to renewable energy. At the same time, the lifecycle greenhouse gas emissions of both types of gas-fired power plants have been shown to be far higher than previously estimated. In Virginia, carbon dioxide emissions from electricity generation rose rather than fell after the state retired its fleet of coal plants and embarked on a massive build-out of gas-burning plants.

New natural gas plants, which have an operational lifespan of 40 years, lock in demand for gas for longer than current climate scenarios dictate, which call for net-zero carbon emissions by mid-century. Gas plants thus risk becoming stranded assets, as they would need to be decommissioned well before the end of their lifespan.

Gas-fired simple cycle plants that are used on demand as peakers have become obsolete as battery technology now allows for the storage of renewable energy, eliminating the need for gas plants to provide power in times of peak demand.

Emerging evidence shows a variety of health impacts to people living near gas-fired power plants. At this writing in New York State, several fracked gas power plant projects are facing stiff opposition on climate, public health, and economic grounds. These include a proposed expansion of the Danskammer peaker plant; three recently built gas plants (CPV Valley, Cricket Valley, and Bayonne Energy Center); and NRG's proposed peaker plant oil-to-gas conversion in Astoria.

- July 2, 2021 – In New York State, the proposed rebuilding of the Danskammer gas-fired power plant in the environmental justice community of Newburgh prompted day-long hearings on the part of two state agencies, the Public Service Commission, which oversees the state's power plant siting laws, and the New York Department of Environmental Conservation (DEC), which permits air pollutants and other discharges. The Danskammer plant is the first large-scale gas-fired power plant to be considered by New York state authorities since the 2019 passage of the Climate Leadership and Community Protection Act (CLCPA). This legislation calls for sharp, rapid reductions in the use of all fossil fuels, including natural gas, in New York State and therefore the

Danskammer plant would interfere with its attainment, according to both testimony and the DEC.[1970]

- June 18, 2021 – Energy stakeholders are split over California's inclusion of fossil fuel resources in a proposed procurement package. At issue is ensuring grid reliability due to the closure of a nuclear power plant and unreliable and aging power plants. Environmental groups maintained that modeling has not indicated a need for additional fossil fuel resources in the state.[1971]

- May 21, 2021 – President Biden set a 15-year deadline for a zero-emissions electric grid. A new gas plant has a projected lifespan of 40 years. This discrepancy places any new power plant into a timeslot which falls outside of that carbon neutral timeline. At least eight large utilities in the U.S. are currently building new gas plants right now, and another five are considering doing so.[1972]

- April 22, 2021 – The Danskammer power plant in Newburgh is testing New York's Climate Leadership and Community Protection Act (CLCPA), passed in 2019, and the state's commitment to reducing fossil fuel emissions, according to an investigation published jointly by *City & State New York* and *New York Focus*. An advisory panel to the Climate Action Council planned to recommend that New York declare a moratorium on new natural gas facilities.[1973]

- April 1, 2021 – Ocean water is customarily used to cool some machinery at older natural gas plants on the California coast, a practice resulting in releases of much warmer water back into the ocean, harming fish and the environment. Local politicians, including the mayor of Redondo Beach, have opposed this practice and have called for the closure of these archaic power plants. However, power shortages during the hottest summer on record in 2020 prompted the Statewide Advisory Committee on Cooling Water Intake Structures to vote to recommend a delay of the planned shutdown of the Redondo Beach gas plant until the end of 2023.[1974]

- February 2, 2021 – The federally owned electric utility corporation, Tennessee Valley Authority (TVA), is proposing to replace its aging coal plants with natural gas plants.

[1970] Rick Karlin, "Plan for Hudson Valley Power Plant Collides with State's New Green Law," *Albany Times Union*, July 2, 2021, https://www.timesunion.com/news/article/Public-comment-period-starts-reigniting-gas-16290500.php.
[1971] Kavya Balarman, "California Groups Clash Over Gas in 11.5 GW Procurement Proposal as CAISO Calls for Conservation," *Utility Dive*, June 18, 2021, https://www.utilitydive.com/news/california-clash-gas-11-5-gw-proposal-caiso/602039/.
[1972] Josh Saul, "New Gas Plants Threaten Carbon Hangover Long Past Biden Deadline," Bloomberg Green, 21 2021, https://www.bloomberg.com/news/features/2021-05-21/lifespan-of-new-u-s-gas-plants-exceeds-net-zero-climate-goals.
[1973] Lee Harris, "Gas Plant in Newburgh Tests Limits of NY's Landmark Climate Law," *City & State New York*, April 22, 2021, https://www.cityandstateny.com/articles/policy/energy-environment/gas-plant-newburgh-tests-limits-nys-landmark-climate-law.html.
[1974] Sammy Roth, "How a Beachfront Gas Plant Explains California's Energy Problems," *Los Angeles Times*, April 1, 2021, https://www.latimes.com/environment/newsletter/2021-04-01/how-a-beachfront-gas-plant-explains-californias-energy-problems-boiling-point.

Over the past decade and a half, the sources of TVA's electricity generation have shifted away from coal toward more natural gas and nuclear power. Among the 50 biggest U.S. utilities, TVA had the second biggest increase planned in new natural gas production, with more than 3 gigawatts of capacity in its long-range plans. TVA provides electricity to all of Tennessee as well as parts of Alabama, Georgia, Kentucky, Mississippi, North Carolina, and Virginia.[1975]

- January 21, 2021 – The largest gas-fired power plant in Europe, under development by Drax in North Yorkshire in the United Kingdom would, all by itself, account for 75 percent of emissions from the UK's power sector when it becomes fully operational. The Planning Inspectorate, a U.K. executive agency on land use planning, recommended that ministers refuse permission for the plant on the grounds that it would undermine the government's commitment, as codified in the Climate Change Act 2008, to cut greenhouse emissions. However, the Inspectorate was overruled.[1976]

- September 3, 2020 – Between 2000-2018, the proportion of U.S. electricity generated by coal fell by half (from 52 percent to 27 percent) and electricity from burning natural gas more than doubled (from 16 percent to 35 percent). Over the same time period, carbon dioxide emissions from the U.S. power sectors dropped by 24 percent. However, using a commitment accounting approach, an analysis of U.S. power plants found that coal-to-gas switching in the power sector has, in fact, failed to lower greenhouse gas emissions. Commitment accounting takes into account cumulative emissions across the entire assumed operating lifecycle of coal and gas plants. Because coal plants nearing the end of their operation lifespans tend to be replaced by new gas plants that have more future longevity, substituting gas plants for coal plants has not functioned to decreased committed emissions, even when a modest upstream methane leakage rate of 3 percent is assumed. "Thus, although annual emissions have fallen, cumulative future emissions will not be substantially lower unless existing coal and gas plants operate at significantly lower rates than they have historically. Moreover, our estimates of committed emissions for U.S. coal and gas plants finds steep reductions in plant use and/or early retirements are already needed for the country to meet its targets under the Paris climate agreement—even if no new fossil capacity is added."[1977]

- July 15, 2020 – The municipality of Cornwall, New York passed a resolution opposing the expansion of the Danskammer power plant, which is seeking to retool its gas-fired peaker plant in the Hudson River Valley into a continuously operating baseload facility.

[1975] Dave Flessner, "TVA Proposes to Build New Gas Plants at Shuttered Coal Sites," *Chatanooga Times Free Press*, February 2, 2021, https://www.timesfreepress.com/news/business/aroundregion/story/2021/feb/02/tvproposes-build-new-gplants-shuttered-coal-s/540871/.
[1976] Damian Carrington, "Legal Bid to Stop UK Building Europe's Biggest Gas Power Plant Fails," *The Guardian*, January 21, 2021, https://www.theguardian.com/environment/2021/jan/21/climate-crisis-uk-legal-bid-stop-biggest-gas-power-station-europe-fails?CMP=twt_a-environment_b-gdneco.
[1977] Christine Shearer et al., "Committed Emissions of the U.S. Power Sector, 2000–2018," *AGU Advances* 1 (2020): e2020AV000162, https://doi.org/10.1029/2020AV000162.

In so doing, Cornwall joined 20+ other towns and cities in opposing the project.[1978] The Danskammer plant would increase nitrogen oxides, ozone, and particulate matter in the area and increase greenhouse gas emissions. Permitted through 2053, its operation would also exceed the state's timeline to reach 100 percent clean energy by 2040. Further, the downwind city of Newburgh is an environmental justice community. As noted by the City of Hudson Common Council when it passed its own resolution, the proposal, if approved, "will continue the state's reliance upon fossil fuels and will not promote the state's climate change policy."[1979] The proposal is currently under review by the New York State Public Service Commission. A decision will be made by a State Siting Board.

- July 8, 2020 – Samples of water, sediments, soil, and biota were analyzed for concentration of potentially toxic trace metals—arsenic, cadmium, chromium, mercury, lead, zinc—in a lagoon next to a gas and oil power plant in Lagos, Nigeria.[1980] Rigorous sampling and analysis of crabs and shrimp, which are ingested by the local population as an important food source, showed bioaccumulation of cadmium, lead, mercury, and zinc. Another pathway of exposure was via air, as atmospheric deposition of pollutants was believed to be responsible for chromium measured in proximal soil samples. And since the concentration of arsenic, cadmium, chromium, and lead in the lagoon water decreased steadily with distance away from the plant, the authors concluded that their levels in the lagoon were influenced by operations of the power plant.

- May 22, 2020 – The approval of the largest power plant in Europe, which is being developed by Drax in North Yorkshire, could account for 75 percent of the UK's power sector emissions when fully operational. The UK's planning inspectorate recommended that ministers refuse permission for the 3.6GW gas plant because it "would undermine the government's commitment, as set out in the Climate Change Act 2008, to cut greenhouse emissions" by having "significant adverse effects."[1981] This was the first time this group had ever taken such an action. Despite this recommendation, the secretary of state for business, energy and industrial strategy rejected the advice and approved the project in October 2019.

- May 22, 2020 – A new set of data visualization tools from Physicians, Scientists, and Engineers for Healthy Energy (PSE) demonstrates that peaker generating natural gas plants causing the greatest health burdens can be retired and replaced with energy storage. For each state with storage-friendly policies—California, Nevada, Arizona, New

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[1978] Helu Wang, "Cornwall Joins the Force Opposing Danskammer Power Plant," *Times Herald-Record*, July 15, 2020, https://www.recordonline.com/story/news/2020/07/15/cornwall-joins-20-ny-municipalities-oppose-danskammer-power-plant/5427624002/.
[1979] Abby Hoover, "Hudson Joins Riverfront Cities in Opposing Power Plant Expansion," *HudsonValley360*, May 29, 2020, https://www.hudsonvalley360.com/news/columbiacounty/hudson-joins-riverfront-cities-in-opposing-power-plant-expansion/article_96be26b1-0302-56aa-8c0d-64d0036cdafb.html.
[1980] Gideon A. Idowu et al., "Impact of Gas and Oil-Fired Power Plants on Proximal Water and Soil Environments: Case Study of Egbin Power Plant, Ikorodu, Lagos State, Nigeria," *SN Applied Sciences* 2, no. 8 (2020): 1352, https://doi.org/10.1007/s42452-020-3150-0.
[1981] Damian Carrington, "UK Approval for Biggest Gas Power Station in Europe Ruled Legal," *The Guardian*, May 22, 2020, sec. Environment, https://www.theguardian.com/environment/2020/may/22/uk-approval-for-biggest-gas-power-station-europe-ruled-legal-high-court-climate-planning.

Mexico, Texas, Florida, New York, New Jersey, and Massachusetts—there is a report with data visualization. According to PSE's Director of Research Elena Krieger, "Regulators and policymakers can use our findings to inform decisions related to energy storage and clean energy targets, greenhouse gas and criteria pollutant emission reductions, and investments to improve clean energy access for under-served and vulnerable communities."[1982]

- May 20, 2020 – A review of EPA emissions data show that Virginia is an outlier for U.S. electricity emissions reductions, attributable to the state's massive build-out of natural gas plants.[1983] Although all but two of its six remaining coal plants have closed, the state's replacement with gas for electricity generation has led to soaring carbon dioxide emissions: about four million tons in 2009 to almost 25 million tons in 2019, accounting for 80 percent of all power sector emissions in Virginia. The low cost of fracked gas served as an incentive to the power plant boom as did state legislation that encouraged utilities to build more power plants.

- May 4, 2020 – Tens of billions of dollars of shareholder risk accompanies new natural gas infrastructure according to a report reviewed by Forbes.[1984] The report by the organization Energy Innovation and the shareholder advocacy group As You Sow argues that utility investment in new natural gas infrastructure only compounds risks for investors, consumers, and society. Due to incompatibilities with climate goals, as well as intense competition from renewables, the report advocates for a clean energy transition as the more affordable, less risky option. The article reinforced the report's findings, citing studies by the National Renewable Energy Laboratory, National Oceanic and Atmospheric Administration, Evolved Energy, and Vibrant Clean Energy, which found that at least 80 percent our electricity could be generated from renewable sources without reliability or affordability issues.

- April 26, 2020 – Air pollution is strongly associated with cardiovascular disease. In one of the first studies of its kind, a research team investigated the effects of air pollution exposure among workers in natural gas-fired power plants in Nigeria and matched them with healthy controls.[1985] They found increased systolic blood pressure, increased pulse rate, and higher levels of the inflammatory marker C-reactive protein in the workers compared to the controls. The longer the workers were employed there, the more abnormal their results.

[1982] William Driscoll, "Replacing Peakers with Storage to Achieve the Greatest Health Benefit," *PV Magazine*, May 22, 2020, https://pv-magazine-usa.com/2020/05/22/replacing-peakers-with-storage-to-achieve-the-greatest-health-benefit/.
[1983] Benjamin Storrow, "Coal Plants Disappear in Va. But CO2 Is Rising," *E&E News*, May 20, 2020, https://web.archive.org/web/20200527214244/https://www.eenews.net/stories/1063179963.
[1984] Michael O'Boyle, "Utility Investors Risk Billions In Rush To Natural Gas: Is It A Bridge To Climate Breakdown?," *Forbes*, March 4, 2020, sec. Energy, https://www.forbes.com/sites/energyinnovation/2020/03/04/utility-investors-risk-billions-in-rush-to-natural-gas-is-it-a-bridge-to-climate-breakdown/.
[1985] C. D. Ekpruke and V. I. Iyawe, "Cardiovascular System Response to Chronic Exposure to Emissions from Gas Turbines Power Plants," *World Journal of Cardiovascular Diseases* 10, no. 04 (2020): 208–24, https://doi.org/10.4236/wjcd.2020.104020.

- April 8, 2020 – New York State could have met the need for electricity with renewables, storage, and energy efficiency measures following the closure of the Indian Point nuclear power plant without constructing two major gas-fired power plants, according to an analysis by PSE Healthy Energy.[1986] The report concludes expanding gas infrastructure risks creating stranded assets and threatens to undermine New York's climate goals, and that employing clean resources instead of gas "could bring co-benefits like improved local air quality from the reduction of criteria air pollutants emitted by natural gas plants and enhanced grid resiliency in the case of natural disasters or other emergencies."

- March 12, 2020 – The Leviathan natural gas fields, discovered ten years earlier off the coast of Haifa in Israel, became operational in December 2019. Hundreds of billions of dollars in revenue were anticipated. However, the economic downturn, a European Union carbon tax imposed on imported fossil fuels, decreased demand, falling costs of renewables, and greater concern about climate change combined to reduce the expected windfall by a factor of ten, raising questions about further investments in gas infrastructure and in building gas-fired power plants that will be obsolete within 20 years.[1987]

- February 27, 2020 – The monthly report by an energy analyst from the Australian National University's Crawford School of Public Policy challenged the national government's investment in a program that proposes up to five new gas-powered power plants.[1988] The monthly National Energy Emissions Audit suggested instead that to increase supply, currently functioning power plants can operate at greater capacity. According to the Audit, combined-cycle gas plants in the national grid were operating at only 30 percent capacity. "In reality, gas is expensive, it's high-polluting and, as this research shows, it is under-performing… Given this, why would we underwrite new gas-fired plants?"[1989]

- January 6, 2020 – The Cayuga Power Plant in Lansing, New York ceased generating power on August 29, 2019 after plans to convert the facility from a coal plant to a natural gas peaker plant were scrapped in the face of massive public opposition and after electricity transmission upgrades made electricity generated from this plant unnecessary.

[1986] Annie Dillon, "Evaluating the Potential for Renewables, Storage, and Energy Efficiency to Offset Retiring Nuclear Power Generation in New York," *PSE Healthy Energy*, April 8, 2020, https://www.psehealthyenergy.org/our-work/publications/archive/research-brief-new-york-renewables-indian-point/.
[1987] Nir Hasson, "Israel Needs to Let Go of the Natural Gas Fantasy," *Haaretz*, March 12, 2020, https://www.haaretz.com/israel-news/.premium.MAGAZINE-israel-needs-to-let-go-of-the-natural-gas-fantasy-1.8669944?=&ts=_1584147526761.
[1988] Hugh Saddler, "No Case for More Gas: National Energy Emission Audit," *The Australia Institute*, February 27, 2020, https://australiainstitute.org.au/post/no-case-for-more-gas-national-energy-emission-audit/.
[1989] Adam Morton, "'Expensive and Underperforming': Energy Audit Finds Gas Power Running Well below Capacity," *The Guardian*, March 7, 2020, sec. Environment, https://www.theguardian.com/environment/2020/mar/08/expensive-and-underperforming-energy-audit-finds-gas-power-running-well-below-capacity.

An advisory committee to the Lansing Town Council will oversee the future of the site. Current plans are to convert the facility into a data center with energy storage.[1990]

- September 9, 2019 – Renewables and large storage batteries will put gas-fired powered plants out of business, according to an analysis by *Bloomberg*: "It will happen so quickly that gas plants now on the drawing boards will become uneconomical before their owners are finished paying for them."[1991]

- September 9, 2019 – An analysis by *USA Today* found as many as 177 natural gas power plants in the United States "planned, under construction or announced," with close to 2,000 currently in service. In addition to the potentially catastrophic climate implications of increased methane emissions from such plants, figures show that their cost "will be more expensive than renewable alternatives" and that incentives reward utility companies for building them instead of turning to renewable alternatives. That is, in most of the country "a combination of state-level rate-setting requirements and regional market rules" lead to compensation structures that favor coal and natural gas over renewable sources of energy.[1992]

- July 8, 2019 – *S&P Global* reported that economics are causing some utilities to consider renewable energy projects over gas-fired power plant investments.[1993] States that have placed moratoria or rejected plans for new gas-powered plants include Arizona, Colorado, California, and Virginia. Investments in new gas plants will become more risky if some form of carbon dioxide emissions price is enacted in the next few years.

- February 11, 2019 – The mayor of Los Angeles announced that the city will close rather than modernize three gas-fired power plants after the California legislature passed a bill requiring the state to get 100 percent of its electrical power from climate-friendly sources by 2045. Instead, the city will pursue clean energy technologies with battery storage. The Scattergood, Haynes, and Harbor natural gas plants will be phased out by 2029.[1994] In a press statement, Los Angeles mayor Eric Garcetti said, "This is the beginning of the end

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[1990] Andrew Sullivan, "What's next for the Cayuga Power Plant?," *Ithaca Times*, January 6, 2020, https://www.ithaca.com/news/lansing/what-s-next-for-the-cayuga-power-plant/article_171878da-2d96-11ea-b326-47a464efe599.html.

[1991] David R. Baker, "Gas Plants Will Get Crushed by Wind, Solar by 2035, Study Says," *Bloomberg*, September 9, 2019, https://www.bloomberg.com/news/articles/2019-09-09/gas-plants-will-get-crushed-by-wind-solar-by-2035-study-says.

[1992] Elizabeth Weise, "As Earth Faces Climate Catastrophe, US Set to Open Nearly 200 Power Plants," *USA Today*, September 9, 2019, https://www.usatoday.com/story/news/2019/09/09/climate-change-threatens-earth-us-open-nearly-200-power-plants/2155631001/.

[1993] Jared Anderson, "Climate Policy, Economics Give Renewables a Leg up on Natural Gas in the US: WRI," *S&P Global*, July 8, 2019, https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/070819-climate-policy-economics-give-renewables-a-leg-up-on-natural-gas-in-the-us-wri.

[1994] Associated Press, "Mayor: LA Will Ditch Plan to Rebuild Natural Gas Plants," *US News & World Report*, February 11, 2019, //www.usnews.com/news/best-states/california/articles/2019-02-11/mayor-la-will-ditch-plan-to-invest-billions-in-fossil-fuels.

of natural gas in Los Angeles. The climate crisis demands that we move more quickly to end dependence on fossil fuel, and that's what today is all about."[1995]

- February 8, 2019 – The Arizona Corporation Commission voted to extend the state moratorium on buying or building new gas-fired power plants and called for energy storage to provide peak power rather than additional natural gas plants.[1996]

- April 1, 2018 – Integrating environmental, economic, and social factors to evaluate overall sustainability, a British team compared shale gas with other electricity options in the United Kingdom. Fracking emerged as one of the least sustainable ways to produce electricity. Specifically, shale gas ranked seventh out of nine options for electrical generation, with wind and solar energy scoring the best and coal the worst. These results suggest that "a future electricity mix … would be more sustainable with a lower rather than a higher share of shale gas."[1997, 1998]

- July 14, 2017 – A European team evaluated the performance of coal- and gas-fired power plants that are used to back up renewable energy as the European Union transitions to greater reliance renewable sources for electrical generation. As renewables increasingly dominate, traditional fossil fuel plants will be required to ramp up and down and cycle on and off more frequently, However, these ramping and cycling events will negatively impact the operation of the fossil fuel power plants, as they will become fatigued, resulting in higher operational and maintenance costs, reduced lifetime, degraded performance, and higher emissions of air pollution over time. Gas plants are generally more efficient, faster, and less polluting than coal, but under certain conditions will produce more nitrogen oxides (a component of smog) and more carbon monoxide than coal-fired plants. Current fossil fuel technology will need significant and costly improvements in order to handle the increased gradients, number of starts, lower minimum load and emissions.[1999]

- February 1, 2017 – There is a high degree of uncertainty about the methane emissions from natural gas-fired power plants. As part of a study that also included oil refineries, a Purdue University team evaluated methane emissions from three gas-fired power plants in Utah, Indiana, and Illinois during hours of peak operation. Both fugitive methane leaks from the facility at large as well as uncombusted methane from the stacks were measured

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1995 Nichola Groom, "Los Angeles Abandons New Natural Gas Plants in Favor of Renewables," *Reuters*, February 12, 2019, sec. Commodities, https://www.reuters.com/article/us-usa-california-natgas-idUSKCN1Q12C9.
1996 David Wichner, "Regulators Extend Ban on New Gas Power Plants in Arizona," *Arizona Daily Star*, February 8, 2019, https://tucson.com/business/regulators-extend-ban-on-new-gas-power-plants-in-arizona/article_5d492ca0-5763-5fe5-8eac-29f63cbe2b72.html.
1997 Jasmin Cooper, Laurence Stamford, and Adisa Azapagic, "Sustainability of UK Shale Gas in Comparison with Other Electricity Options: Current Situation and Future Scenarios," *Science of The Total Environment* 619–620 (April 2018): 804–14, https://doi.org/10.1016/j.scitotenv.2017.11.140.
1998 Josh Gabbatiss, "Scientists Find Fracking Is One of the Least Sustainable Ways to Produce Electricity," *The Independent*, January 16, 2018, sec. Climate, https://www.independent.co.uk/climate-change/news/fracking-electricity-production-energy-shale-gas-extraction-sustainable-a8160661.html.
1999 Miguel Angel Gonzalez-Salazar, Trevor Kirsten, and Lubos Prchlik, "Review of the Operational Flexibility and Emissions of Gas- and Coal-Fired Power Plants in a Future with Growing Renewables," *Renewable and Sustainable Energy Reviews* 82 (2018): 1497–1513, https://doi.org/10.1016/j.rser.2017.05.278.

using aircraft. Results showed that average methane emission rates were larger than facility-reported estimates by factors of 21-120. The authors concluded that gas-fired power plants "may be significant contributors to annual methane emissions in the U.S. despite lack of facility emission reporting in U.S. inventories. Futhermore, results suggest that the primary source of methane emissions at these facilities may be from noncombustion sources."[2000]

- June 28, 2015 – Pregnant women living near gas-fired power plants were more likely to give birth prematurely, according to a study of more than 400,000 infants born in Florida between 2004 and 2005. This study investigated associations between adverse birth outcomes and residential proximity to several types of power plants, including those burning oil, gas, and solid waste.[2001]

- September 22, 2012 – An investigation of methane and nitrous oxide emissions at eight different gas-fired power plants in Korea found that emissions can vary depending on combustion technologies. Results from this study differed both from those used as default emission rates by the Intergovernmental Panel on Climate Change and from those measured in Japan. The authors concluded that technology-specific and country-specific emission factors for gas-fired power plants need to be established.[2002]

- February 27, 2012 – Using hospitalization data, a research team working in New York State examined whether living near a fuel-fired power plant increased the rate of hospitalization for asthma, acute respiratory infections, and chronic obstructive pulmonary disease, all of which have known links to air pollution exposure. Preliminary analyses of hospitalization rates associated with a residence in a zip code with a power plant stratified by type of fuel used (coal, gas, oil, or solid waste) did not show clear or consistent patterns. Therefore, patients were classified as exposed if they lived in a zip code with at least one power plant in it regardless of the type of fuel used. After adjusting for age, sex, race, median household income, and rural/urban residence, the research team found significantly elevated rates of hospitalization for asthma (11 percent increase), acute respiratory infection (15 percent increase), and chronic obstructive pulmonary disease (17 percent increase) among New Yorkers living near at least one fuel-fired power plant.[2003]

- October 20, 2011 – Emergency room visits and hospital admissions in elderly people living close to a new gas-fired power plant in Italy were counted and related to levels of

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[2000] Tegan N. Lavoie et al., "Assessing the Methane Emissions from Natural Gas-Fired Power Plants and Oil Refineries," *Environmental Science & Technology* 51, no. 6 (2017): 3373–81, https://doi.org/10.1021/acs.est.6b05531.

[2001] Sandie Ha et al., "Associations Between Residential Proximity to Power Plants and Adverse Birth Outcomes," *American Journal of Epidemiology* 182, no. 3 (2015): 215–24, https://doi.org/10.1093/aje/kwv042.

[2002] Seehyung Lee et al., "A Study on the Evaluations of Emission Factors and Uncertainty Ranges for Methane and Nitrous Oxide from Combined-Cycle Power Plant in Korea," *Environmental Science and Pollution Research* 20, no. 1 (2013): 461–68, https://doi.org/10.1007/s11356-012-1144-1.

[2003] Xiaopeng Liu, Lawrence Lessner, and David O. Carpenter, "Association between Residential Proximity to Fuel-Fired Power Plants and Hospitalization Rate for Respiratory Diseases," *Environmental Health Perspectives* 120, no. 6 (2012): 807–10, https://doi.org/10.1289/ehp.1104146.

air pollution both before and after the plants became operational. The results showed that ambient levels of nitrogen oxides and particulate matter rose after the plant started operations. Further, despite the fact that pollutants were below the limits set by the European legislation, there was a positive correlation between number of emergency room visits and daily concentrations of these air pollutants among nearby residents aged 70 or older.[2004]

- April 5, 2010 – Most new fossil fuel power plants are gas-powered. In this study, a research team estimated the number of premature deaths from fine particulate matter that would result from bringing 29 proposed fossil-fuel power plants in Virginia on line. Their modelling predicted that, were all 29 plants made operational, concentrations of fine particulate air pollution would rise in 271 counties across 19 states. Over a six-year period, 104 cumulative excess deaths would occur due to operations of these proposed plants.[2005]

[2004] Agostino Di Ciaula, "Emergency Visits and Hospital Admissions in Aged People Living Close to a Gas-Fired Power Plant," *European Journal of Internal Medicine* 23, no. 2 (2012): e53–58, https://doi.org/10.1016/j.ejim.2011.09.013.
[2005] Richard P. Hermann, Frank Divita, and Jack O. Lanier, "Predicting Premature Mortality from New Power Plant Development in Virginia," *Archives of Environmental Health: An International Journal* 59, no. 10 (2004): 529–35, https://doi.org/10.1080/00039890409605170.

Inaccurate jobs claims, increased crime rates, threats to property values and mortgages, and local government burden

According to multiple studies in multiple states, the oil and gas industry's promises of job creation from drilling for natural gas have been greatly exaggerated. Many of the jobs are short-lived, have gone to out-of-area workers, and, increasingly, are lost to automation. The contraction of the industry in 2019 and 2020, accelerated by the coronavirus pandemic, has led to mass lay-offs, lost jobs and high unemployment among fracking crews and associated workers. These jobs showed no sign of rebounding. Of the 100,000 jobs shed within the oil and gas industry in 2020, 70 percent of those may never return, according to a 2021 analysis. In April 2021, the economic sector within which oil and gas jobs are tracked, the mining sector, had the highest US unemployment rate.

With the arrival of drilling and fracking operations, rural communities have consistently experienced steep increases in rates of crime, variously including murder, assault, rape, sex trafficking, larceny, robbery, burglary, embezzlement and auto theft. Indigenous women are disproportionately victimized by violent crimes associated with oil and gas activities. In the Marcellus Shale region, violent crime increased 30 percent in counties that experienced a fracking boom compared to those without fracking. Aggravated and sexual assaults were the crimes primarily responsible for this increase. Crime rates have increased even with additional allocation of funds for public safety.

Financial and other strains on municipal services include those on law enforcement, road maintenance, emergency services, and public school district administration. In shale boom areas, school districts suffer lower test scores, lower attendance, higher teacher turnover, and exacerbated education inequities. Economists are increasingly quantifying community quality of life impacts and the unequal distribution of costs and benefits associated with drilling and fracking.

Drilling and fracking pose an inherent conflict with mortgages and property insurance due to the hazardous materials used and the associated risks. With the departure of drilling and fracking operations from these communities, some of the challenges are eased. However, such departures can also lead to additional economic harms, such as by sharp upticks in foreclosures, late car and mortgage payments, empty housing units, and failed or diminished local businesses. In Oklahoma and in England, fracking-induced earthquakes have negatively affected property values.

- July 8, 2021 – Citing a "transition towards a more renewable future" and an all-time low of only ten registered students over the previous two years, the University of Calgary in Canada suspended admission to its oil and gas engineering bachelor program.[2006]

[2006] Mark Villani, "University of Calgary Suspends Admission for Oil and Gas Engineering Program," *CTV News*, July 8, 2021, https://calgary.ctvnews.ca/mobile/university-of-calgary-suspends-admission-for-oil-and-gas-engineering-program-1.5502133.

- July 2, 2021 – Federal Reserve Bank of Dallas researchers found that the region's oil and gas industry employed fewer people by 2020 than at the beginning of the fracking boom eleven years ago, even as production quadrupled. Due to technological "efficiencies," Texas and New Mexico production rose 14 percent from December 2014 and December 2017 while industry employment dropped 29 percent during that time. The pandemic led to further job cuts and though recovery may add jobs, companies will "require fewer employees for more output."[2007]

- July 1, 2021 – Writing in the *MIT Technology Review*, environmental sociologist Colin Jerolmack reviewed the shaky financial ground on which the Appalachian fracking boom was based and provided a realistic view of actual fracking employment trends. He wrote, "Fracking has always been expensive; extraordinarily generous fossil-fuel subsidies helped hide the true cost." The oil and gas industry eliminated more than 100,000 jobs in 2020, and 70 percent of those may not ever return. In April 2021, the economic sector within which oil and gas jobs are tracked, the mining sector, had the highest US unemployment rate.[2008]

- June 17, 2021 – Economists determined that fracking booms in Arkansas, North Dakota, and West Virginia were associated with more crime than comparison states, and these crimes carried an estimated $15.68 million (in 2008 dollars) "annual victimization cost" per state. The methods used to estimate these costs was based on an established methodology on the cost of crimes to society. The comparison states had similar crime rates to the fracking states before the boom. The data from multiples sources used in the study covered the years 2000 to 2015. Crimes linked with fracking in the study were murder, forcible rape, robbery, aggravated assault, burglary, and embezzlement. Breaking these down by the instances and costs of specific crimes, this research showed that the 1.3 more murders per 100,000 residents led to a cost of $11.63 million, and the three additional forcible rapes per 100,000 averaged $7.45 million. The fracking boom states had 27.53 more aggravated assaults, costing about an extra $2.94 million. Researchers said their "consistent and robust results… support the hypothesis that the shale boom increases crime for relatively rural American states, especially violent crime."[2009]

- June 4, 2021 – The Enbridge Line 3 pipeline project brought an influx of thousands of workers to Minnesota "who are staying in hotels, campgrounds and rental housing along the pipeline route, often in small towns like Thief River Falls, and on or near Native reservations." The Violence Intervention Project in Thief River Falls received "more than 40 reports about Line 3 workers harassing and assaulting women and girls who live in north-western Minnesota." In addition, two workers charged in a sex trafficking sting operation were Line 3 workers from Missouri and Texas, employed by the Enbridge

[2007] Carolyn Davis, "Permian Oil Patch Faces Economic Conundrum as Efficiencies Reduce Workforce," Natural Gas Intelligence, July 2, 2021, https://www.naturalgasintel.com/permian-oil-patch-faces-economic-conundrum-as-efficiencies-reduce-workforce/.
[2008] Colin Jerolmack, "The Fracking Boom Is Over. Where Did All the Jobs Go?," *MIT Technology Review*, July 1, 2021, https://www.technologyreview.com/2021/07/01/1027822/fracking-boom-jobs-industry/.
[2009] Shishir Shakya and Kazi Sohag, "The Fracking Boom and Crime Rates in Rural American States: Some Critical Insights," *The Extractive Industries and Society* 8, no. 3 (2021), https://doi.org/10.1016/j.exis.2021.100948.

subcontractor Precision Pipeline. Violence prevention advocates had warned state officials in advance of the project "of the proven link between employees working in extractive industries and increased sexual violence." Indeed, Minnesota's Public Utilities Commission acknowledged in its environmental impact statement that the likelihood of sex trafficking or sexual abuse would increase if Line 3 were permitted and that the affected regions do not have the resources to track and prevent this violence.[2010]

- June 4, 2021 – Economists found that lower-income census tracts in Oklahoma experienced disproportionately greater negative impacts on property values from "induced" earthquakes compared to higher-income areas. Scientists attribute the dramatic increase in earthquakes in Oklahoma after 2009 to the disposal of fracking wastewater into deep injection wells. Most of these range in magnitude from 3 to 4—strong enough to be felt, though rarely causing property damage—but 30 of the 850 earthquakes in 2015 were magnitude 4 or greater. These induced earthquakes may negatively impact property values through the physical damage they cause. This study added to the literature on fracking and property values by using a unique dataset, US Geological Survey's Did You Feel It? system, by extending into the years following implementation of Oklahoma's wastewater injection rules that decreased induced earthquakes, and by addressing the environmental justice dimension, motivated by the body of research indicating lower-income groups suffer disproportionate harm from natural disasters. This study confirmed that earthquakes negatively impact the pricing of housing, including negative impacts linked with each additional earthquake in 2012, 2013, and 2014. Not only did the researchers find that lower-income households saw disproportionate impacts, but these impacts also lasted longer. The researchers "posit that poorer households incur greater proportional damage for any relative seismic event due to lower quality construction of their properties," and that these households may not be able to repair their properties in a timely way following an earthquake. Overall, the pricing impacts began to lessen in 2016 coinciding with the law mandating a reduction in induced seismic activity.[2011]

- April 26, 2021 – Pennsylvania "has an opportunity to manage the decline of its polluting energy industry while investing in sustainable, high-paying green union jobs as a replacement," according to the *Philadelphia Inquirer* Editorial Board. The Board criticized the state's continued investment in natural gas infrastructure in light of climate concerns and the failure of the industry to provide a remedy for the previous, unmanaged decline of coal and steel jobs. Citing statistics on increasing employment for solar installers and wind power technicians, the Board recommended that Pennsylvania transition fossil fuel subsidies into green jobs and called for investment in communities now shedding fracking jobs as well as in black communities that have suffered the most harm from oil and gas pollution.[2012]

[2010] Hilary Beaumont, "Sexual Violence Along Pipeline Route Follows Indigenous Women's Warnings," *The Guardian*, June 4, 2021, https://www.theguardian.com/us-news/2021/jun/04/minnesota-pipeline-line-3-sexual-women-violence.
[2011] Chris Mothorpe and David Wyman, "What the Frack? The Impact of Seismic Activity on Residential Property Values," *Journal of Housing Research* 30, no. 1 (2021): 34–58, https://doi.org/10.1080/10527001.2020.1827579.
[2012] Editorial Board, "Fracking Jobs Will Disappear. Pennsylvania Has to Manage the Decline.," *Philadelphia Inquirer*, April 26, 2021, https://www.inquirer.com/opinion/editorials/fracking-biden-climate-greenhouse-gas-methane-pennsylvania-20210426.html.

- March 31, 2021 –Colorado regulations now require a minimum 2,000-foot setback between oil and gas sites and homes. However, residents living near proposed fracking sites that were approved before the law went into effect are not protected by this rule. New homeowners in Colliers Hill, a suburban development in Erie, found themselves just 940 feet from a well pad. As reported by the *Colorado Sun,* this Occidental Petroleum Corporation fracking operation is exempt from the setback rule, as are 200 drilled but uncompleted wells and nearly 1,600 drilling permits that had been approved in the state in the twelve months before new rules went into effect. Colliers Hill residents began demanding action from the Erie Board of Trustees and filing complaints with the state. Erie Mayor Jennifer Carroll "told them that there was little the town could do, even though it had adopted its own stringent oil and gas rules, because the road separating Colliers Hills from the wells was also the boundary between Erie and unincorporated and pro-oil development Weld County."[2013]

- March 29, 2021 – At least 20 percent of jobs in oil and gas drilling, operational support, and maintenance may be automated in the next 10 years, reported the *Houston Chronicle*. Robotics and automation will replace hundreds of thousands of oil and gas industry jobs, in addition to those lost in the pandemic. In addition to inspection, maintenance, and repairs, the industry expects robotics to "reduce the number of roughnecks required on a drilling rig by 20 to 30 percent."[2014]

- March 8, 2021 – Greene County, a Pennsylvania fracking boom region with 1,257 gas wells, may not be able to cover its costs by 2023, despite receiving $37.2 million in gas development-related impact fees over ten years as part of a state program. Newly elected Green County commissioners criticized previous impact fee expenditures as "shortsighted and wasteful" and resolved to stop using these funds to balance the budget each year, according to an investigation by *Spotlight PA*. The new commissioners said that the county never planned appropriately for the transition from the coal bust and is now paying the price as the fracking bust arrives. The county's hospitality and rental markets had expanded dramatically to accommodate temporary, out-of-town gas company workers. Now many fewer such workers are spending money on rent, hotels, and elsewhere in the local economy. Public records showed that the county spent no income from the impact fees on planning initiatives, tax reductions, water preservation, or career and technical centers.[2015]

- March 8, 2021 – The Violence Intervention Project in Thief River Falls, Minnesota experienced an increase in calls for their services since the Enbridge Line 3 pipeline

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[2013] Mark Jaffe, "This Erie Neighborhood Is Ground Zero for Colorado's Collision of Fracking and Housing," *The Colorado Sun*, March 31, 2021, https://coloradosun.com/2021/03/31/colliers-hill-erie-colorado-oxy-fracking-conflict/.
[2014] Marcy de Luna, "Robots Could Replace Hundreds of Thousands of Oil and Gas Jobs by 2030," *Houston Chronicle*, March 29, 2021, https://www.houstonchronicle.com/business/energy/article/Robots-could-replace-hundreds-of-thousands-of-oil-16061352.php.
[2015] Jamie Martines, "A Pennsylvania County Went from Bust to Boom Times with Natural Gas. Now, It's Nearly Broke.," *Spotlight PA*, March 8, 2021, https://www.spotlightpa.org/news/2021/03/pa-greene-county-broke-tax-increase-gas-payouts-businesses/.

construction began in December 2020. The Violence Intervention Project described the assaults experienced by their callers, as well as other instances of harassment at local businesses, in a request for reimbursement from Enbridge's public safety fund, obtained through a public records request by the *Minnesota Reformer.* State permits for Enbridge Line 3 pipeline construction had required that the company create this fund to cover expected additional law enforcement costs as well as the human trafficking prevention plan linked with the project. The Violence Intervention Project's request—seeking reimbursement for hotel room costs for victims when its emergency shelter was full—said that finding hotel rooms has been increasingly difficult as pipeline workers occupy them, and that the cost of hotel rooms had doubled in recent months.[2016]

- February 24, 2021 – Contractors on Enbridge's Line 3 pipeline were arrested and charged in a human trafficking sting in Itasca County, Minnesota. The two men, out-of-state workers, were among seven arrested. One was charged with carrying a pistol without a permit and one count of solicitation to engage in prostitution and the other with one count of solicitation of a person believed to be a minor.[2017]

- February 18, 2021 – A policy researcher identified 23 locations in the US that have the highest rates of Missing and Murdered Indigenous Women (MMIW) cases. Within these, the researcher pinpointed 16 "hot spots," and of these, six were within 25 miles of drilling and fracking sites, and three more within 25 to 50 miles. The researcher wrote that this "analysis of the locations of fracking and other resource extraction sites in relation to the MMIW 'hot spots' highlights a need for additional research into the possible correlation of these two factors." The paper reviews the evidence showing that "man camps" change the demographics of communities near fracking "and have been connected to increased rates of violence, sexual assault, sexually transmitted diseases, prostitution, sex trafficking, and an increased presence of illicit drugs."[2018]

- February 12, 2021 – A study published by the Ohio River Valley Institute, a non-profit research center, found that jobs, personal income, and population all declined between 2008 and 2019 in the 22 Ohio, Pennsylvania, and West Virginia counties that produce 90 percent of Appalachia's natural gas. The seven eastern Ohio counties that suffered the worst impacts experienced a net job loss of more than eight percent. In addition, money that had been expected to stay in communities was spent outside the region, and, because

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[2016] Rilyn Eischens, "Shelter Reports Assaults, Harassment Linked to Line 3 Pipeline Workers," *Minnesota Reformer*, March 8, 2021, https://minnesotareformer.com/2021/03/08/shelter-reports-assaults-harassment-linked-to-line-3-pipeline-workers/.

[2017] Kevin Jacobsen, "2 Arrested in Itasca Co. Human Trafficking Bust Were Line 3 Workers," cbs3duluth.com, February 24, 2021, https://cbs3duluth.com/2021/02/24/2-arrested-in-itasca-co-human-trafficking-bust-were-line-3-workers/.

[2018] A. Skylar Joseph, "A Modern Trail of Tears: The Missing and Murdered Indigenous Women (MMIW) Crisis in the US," *Journal of Forensic and Legal Medicine* 79 (2021), https://doi.org/10.1016/j.jflm.2021.102136.

counties were counting on job creation by oil and gas companies, they had given tax breaks and other incentives that reduced the amount of revenue they received.[2019, 2020]

- January 29, 2021 – An investigation by the Pittsburgh *Post-Gazette* predicted that Pennsylvania counties, municipalities, state agencies, and conservation initiatives will have a difficult time making up for the expected record low impact fees to be collected. Based on natural gas prices and wells drilled, total impact fees assessed on the state's shale gas wells were predicted to fall by $56 million, to a record low of $145 million. Lower gas prices also mean lower royalties for landowners who lease land for fracking, including the state itself. The state doubled fracking permit prices in August 2020 but was receiving far fewer applications than anticipated in the fiscal year of this investigation. Because the Department of Environmental Conservation's Office of Oil and Gas Management is funded largely by well-drilling application fees, the Office was struggling to maintain its level of staffing and inspection responsibilities and could be short $17.5 million for the year.[2021]

- December 22, 2020 – UK researchers determined that earthquakes caused by fracking a first exploratory well in the Lancashire area of England led to a 3.9 to 4.7 percent housing price decrease in the region where the earthquakes occurred. Notably, no commercial fracking had yet taken place. This study specifically focused on the effects of issuing licenses that served as an official signal of potential fracking development. The results showed that the licensing itself did not affect housing prices, but when the exploratory fracking triggered small earthquakes, although they did not cause property damage, housing prices fell.[2022]

- July 30, 2020 – Oil and gas production employment in the state was expected to fall to its lowest since 2005, according to Texas Alliance of Energy Producers, which represents 2,600 independent oil and gas producers.[2023] Texas had already lost 46,100 jobs in production and oil-field services from February to June 2020, related to dropped demand during the coronavirus pandemic. The alliance noted that the oil and gas industry was contracting well before the pandemic.

[2019] Sean O'Leary, "Appalachia's Natural Gas Counties: Contributing More to the U.S. Economy and Getting Less in Return" (Ohio River Valley Institute, February 2021), https://ohiorivervalleyinstitute.org/wp-content/uploads/2021/02/Frackalachia-Report-update-2_12_01.pdf.
[2020] Beth Harvilla, "Report: Ohio Fracking Counties Saw Declines in Jobs, Population and Income," *The Columbus Dispatch*, February 10, 2021, https://www.thisweeknews.com/story/business/2021/02/10/ohio-fracking-boom-never-translated-more-jobs-and-growth-report-says/4450698001/.
[2021] Laura Legere, "Pain of Natural Gas Price Drop Spreads to Pa. Agencies, Communities," January 29, 2021, https://www.post-gazette.com/business/powersource/2021/01/29/natural-gas-price-royalties-shale-permits-impact-fees-Pennsylvania-DEP-DCNR/stories/202101280165.
[2022] Stephen Gibbons, Stephan Heblich, and Christopher Timmins, "Market Tremors: Shale Gas Exploration, Earthquakes, and Their Impact on House Prices," *Journal of Urban Economics* 122 (2021), https://doi.org/10.1016/j.jue.2020.103313.
[2023] Paul Takahashi, "Oil and Gas Production Jobs in Texas Could Hit Bottom This Fall," *Houston Chronicle*, July 30, 2020, sec. Energy, https://www.houstonchronicle.com/business/energy/article/Oil-and-gas-employment-forecast-to-bottom-out-15446433.php.

- July 8, 2020 – When considered in aggregate, 25 relevant, quantitative studies all published between 2005 and 2019 provide clear evidence that U.S. drilling and fracking is linked to an increase in crime, according to a systematic review by a social scientist and legal scholar.[2024] A majority of studies found "that shale gas development increases total crime, violent crime, property crime, social disorganization crimes and violence against women." Of seventeen studies that addressed violent crime, none showed that shale gas development led to less violent crime. Of the seven studies addressing shale gas development and crime against women, five of them showed a positive link, one suggested mixed results, and one suggested there no relationship. Of those studies that included data on pre- and post- increases in shale gas production, the review found drilling and fracking leads to a 28 to 46 percent increase in crime in surrounding communities. Only one study addressed shale gas development and crime outside of the United States. Noting the "considerable consistency" in these findings, the researchers recommended that, in addition to environmental impacts, the shale gas-crime considerations "should be considered by policymakers and planners when determining whether and how shale development should be allowed."

- May 26, 2020 – In April 2020, the oil and gas industry cut a record-breaking 26,300 jobs, according to the Texas Workforce Commission. Most of the jobs lost were drilling rig operators, hydraulic fracturing crews and equipment manufacturers.[2025]

- May 11, 2020 – Oil and gas industry journalist Irina Slav examined why young professionals view employment in the oil and gas industry as a poor career choice.[2026] The average age of Society of Petroleum Engineers' members is growing older while the number of students choosing engineering majors linked to careers in oil and gas are dropping. The current industry crisis is triggering layoffs among fracking crews as well as cancelling internships among young professionals. In addition, Slav argues, the contribution of the industry to the ongoing climate crisis is a disincentive to youth. Just as laid-off oil and gas workers find work in other industries, university graduates will likewise gravitate to internships and consequent recruitment in companies "that are not victims of the whims of the most volatile commodity market in the world."

- April 7, 2020 – A survey conducted by the Louisiana Oil and Gas Association of its 450 member companies found more than 23,000 jobs in the industry to be at immediate risk due to the coronavirus pandemic and the oil glut.[2027] This would constitute 70 percent of their workforce. "To boost the oil industry, LOGA put forth several measures, which include things it has long supported: suspending severance tax collections for one year,

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[2024] Paul Stretesky and Philipp Grimmer, "Shale Gas Development and Crime: A Review of the Literature," *The Extractive Industries and Society* 7, no. 3 (2020): 1147–57, https://doi.org/10.1016/j.exis.2020.06.008.
[2025] Sergio Chapa, "Texas Oil and Gas Industry Cut Record 26,300 Jobs in April," *Houston Chronicle*, May 26, 2020, sec. Energy, https://www.houstonchronicle.com/business/energy/article/Texas-oil-gas-industry-shed-record-number-of-15294860.php.
[2026] Irina Slav, "Why Young Professionals Are Steering Clear Of Oil & Gas," *OilPrice.Com*, May 11, 2020, https://oilprice.com/Energy/Energy-General/Why-Young-Professionals-Are-Steering-Clear-Of-Oil-Gas.html.
[2027] Timothy Boone, "Half of Louisiana Oil, Gas Wells Could Be Shut in, 70% of Industry Jobs Lost within 90 Days, Trade Group Survey Shows," *The Advocate*, April 7, 2020, https://www.theadvocate.com/baton_rouge/news/coronavirus/article_431c2ea0-78f9-11ea-ae04-677757648aaa.html.

ending government-led coastal restoration lawsuits, easing regulations at the Office of Conservation and identifying ways to expedite oil storage capacity."

- February 20, 2020 – Penn State education policy scholars found that fracking economically harms school districts and exacerbates educational inequalities.[2028] Using data from 2007-2015, they found that public school districts in Pennsylvania with fracking had "lower per pupil revenues, locally-raised per pupil funding for schools, per pupil income, and per pupil property wealth," than otherwise similar districts without fracking. School districts with fracking had $1,550.50 less per pupil compared to the otherwise similar districts. They concluded that fracking "may help to maintain and entrench spatial inequality across school districts."

- December 18, 2019 – A research team quantified various aspects of equity within the populations affected by the shale gas boom in Appalachia. Their findings revealed a disproportionate burden on the poor that included higher mortality risks induced by fracking-related air pollution. Poorer residents also derived fewer economic benefits from the industry.[2029] In addition to documenting that mortality risk from natural gas pollution increased as income decreased, the team also documented inequities in employment. In states where fracking takes place, 80 percent of natural gas-related employment was concentrated in just 10 percent of counties. Though authors discussed options for incorporating equity in planning and policy related to shale gas systems, their recommendations pointed to the need for fundamental socio- technical change in energy systems, in order to reduce or relieve "disproportionate costs to the poor and to future generations." A companion study to this one is described below (November 18, 2019).

- November 18, 2019 – A Carnegie Mellon, Stanford, and Princeton University study examined both the human health and climate impacts of fracking in Appalachia and was the first to put dollar values on some of the external and cumulative costs. The team found that premature deaths caused by the industry's pollution had an economic cost of $23 billion, while climate impacts cost an additional $34 billion, from 2004-2016. Their findings showed that one year of life is lost for every three job years created by the industry. These premature deaths extend beyond the communities where the gas wells—and attendant employment benefits—are located, with almost half occurring downwind of the fracking areas in urban regions of the Northeast. While these health harms from air pollution effects follow the boom-and-bust cycles of the industry, the climate harms will persist for generations well beyond the end of fracking. The study's lead author, Erin Mayfield, a postdoctoral research associate at the Princeton Environmental Institute, said, "Private firms across the supply chain have not faced the full costs of natural gas development… and the public has effectively subsidized greenhouse gas and air pollution

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[2028] Matthew Gardner Kelly and Kai A. Schafft, "A 'Resource Curse' for Education?: Deepening Education Disparities in Pennsylvania's Shale Gas Boomtowns," *Society & Natural Resources* 34, no. 1 (2021): 23–39, https://doi.org/10.1080/08941920.2020.1728000.
[2029] Erin N. Mayfield et al., "Quantifying the Social Equity State of an Energy System: Environmental and Labor Market Equity of the Shale Gas Boom in Appalachia," *Environmental Research Letters* 14, no. 12 (2019): 124072, https://doi.org/10.1088/1748-9326/ab59cd.

emissions that result in climate change and health impacts."[2030, 2031] See also the companion study above (December 8, 2019).

- October 9, 2019 – In a nationwide study, an Ohio State team examined social changes linked to fracking from 2009 to 2014. They anticipated that oil and gas employment growth during the shale boom would increase marriage rates. However, they found just the opposite. Marriage rates decreased and divorce rates increased. Specifically, fracking was linked to a decline in the share of the population who were married, an increase in the proportion of divorced people, and had little effect on those who never married or cohabited.[2032] Authors discuss the range of potential negative and positive consequences of this demographic restructuring in rural communities along with the possible role that inevitable fracking busts may play in altering marriage behaviors as compared to boom-phase fracking.

- October 1, 2019 – Fracking booms can bring gains in income, employment, and salaries, and increases in housing prices and rent. An economic analysis of nine U.S. shale regions found that, despite improvements in certain economic indicators such as these, fracking was also linked to "deterioration in local amenities, which may include increases in crime, noise, and traffic and declines in health.[2033] The researchers developed a measure called "willingness to pay" for allowing fracking, which was about $2,500 per household annually. They emphasized that they found "evidence of important heterogeneity in the local net benefits," and understanding these differences "is a first-order question for researchers and policymakers interested in assessing the impacts of allowing fracking in their community."

- August 29, 2019 – Economists found reduced student test scores and reduced student attendance in Texas school shale oil districts, compared to non-shale districts.[2034] Despite tripling of the local tax base in these districts in the study period from 2001 to 2014, schools did not spend money on teacher and other school staff wages. "As the gap between teacher wages and private sector wages grew, so did teacher turnover and the percentage of inexperienced teachers, which helps explain the decline in student achievement." Researchers noted that per capita student spending did increase in other needed areas such as renovations and debt service, but this type of spending did not

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2030 Erin N. Mayfield et al., "Cumulative Environmental and Employment Impacts of the Shale Gas Boom," *Nature Sustainability* 2, no. 12 (December 2019): 1122–31, https://doi.org/10.1038/s41893-019-0420-1.

2031 "Is Shale Development Worth the Costs? A CMU Study Says No.," *Pittsburgh Post-Gazette*, August 2019, https://www.post-gazette.com/news/health/2019/12/08/shale-development-natural-gas-drilling-fracking-costs-health-study-pennsylvania-cmu/stories/201912060038.

2032 Michael Shepard, Michael Betz, and Anastasia Snyder, "The Shale Boom and Family Structure: Oil and Gas Employment Growth Relationship to Marriage, Divorce, and Cohabitation," *Rural Sociology* 85, no. 3 (2020): 623–57, https://doi.org/10.1111/ruso.12306.

2033 Alexander W. Bartik et al., "The Local Economic and Welfare Consequences of Hydraulic Fracturing," *American Economic Journal: Applied Economics* 11, no. 4 (2019): 105–55, https://doi.org/10.1257/app.20170487.

2034 Joseph Marchand and Jeremy G. Weber, "How Local Economic Conditions Affect School Finances, Teacher Quality, and Student Achievement: Evidence from the Texas Shale Boom," *Journal of Policy Analysis and Management* 39, no. 1 (2020): 36–63, https://doi.org/10.1002/pam.22171.

prevent the declines in student achievement. They noted that oil and gas revenue has entirely bypassed the education section in other fracking states.

- August 7, 2019 – The *Houston Chronicle* reported on data from two research firms that compared differences between mid-2018 and mid-2019 in numbers of wells fracked and numbers of workers in the Permian Basin. The data showed that the wells were being fracked and completed at record numbers, but with the number of crews down almost 20 percent. The article stated, "the work is being done with far fewer people as energy companies scale back costs to appease Wall Street investors concerned about overspending."[2035]

- July 6, 2019 – Substantial evidence shows that that vulnerable women face increased violence in boomtowns full of transient laborers building big resource projects, according to a report by the Canadian National Inquiry into Missing and Murdered Indigenous Women and Girls. Pertinent to the impending approval of the Trans Mountain pipeline, the report is based on the testimony of thousands of survivors and family members of murdered and missing women, and it links "man camps" with higher rates of violence against Indigenous women. The report also raises concern about vulnerable women entering the sex trade near activity such as pipeline projects. "Women are made vulnerable by the combination of exclusion from high-paying resource jobs and having to make ends meet in a town where the cost of living is rising," according to Indigenous advocate Connie Greyeyes.[2036]

- July 5, 2019 – A statewide survey of 2,240 Pennsylvanians found that 23.4 percent of respondents had encountered fracking-related activities, including well sites, related truck traffic, pipelines, or fracking workers, during outdoor recreation. Over 12 percent reported being substantially impacted by fracking activities in their recreation, and almost 14 percent changed their plans, avoided a certain area, or no longer traveled to the Pennsylvania for outdoor activities due to these encounters. Outdoor recreation impacts were highest in the North Central and Southwest Pennsylvania, where fracking is most prominent.[2037] As noted in coverage of the study by *Consumer Affairs,* "outdoor activities provide a huge influx of income to the U.S. government, and interfering with such activities will start to interfere with those profits."[2038]

[2035] Jordan Blum, "Permian Fracking Activity Sets New Records with Fewer People," *Houston Chronicle*, August 7, 2019, https://www.chron.com/business/energy/article/Permian-fracking-activity-breaks-new-records-with-14286709.php.
[2036] Lori Culbert, "Indigenous Women Vulnerable to 'Man Camps': MMIWG Report. So, What's at Stake with the Pipeline Approval?," *Vancouver Sun*, July 6, 2019, https://vancouversun.com/business/energy/mmiwg-report-says-indigenous-women-vulnerable-in-resource-towns-whats-at-stake-with-the-pipeline-approval.
[2037] Michael D. Ferguson et al., "The Impacts of Shale Natural Gas Energy Development on Outdoor Recreation: A Statewide Assessment of Pennsylvanians," *Journal of Outdoor Recreation and Tourism* 27 (2019): 100230, https://doi.org/10.1016/j.jort.2019.100230.
[2038] Kristen Dalli, "Shale Natural Gas Development Hampers Consumer Outdoor Activities, Study Finds," *Consumer Affairs*, August 1, 2019, https://web.archive.org/web/20210302210635/https://www.consumeraffairs.com/news/shale-natural-gas-development-hampers-consumer-outdoor-activities-study-finds-080119.html.

- March 16, 2019 – University of Rochester environmental and health economists found that the public announcement of the proposed Constitution pipeline led to a led to a 9.29 percent (about $12,000) decrease in sale price for New York State homes located within three kilometers of its main route, compared to houses between 3-20 kilometers away.[2039] "Our results suggest that homebuyer expectations of the environmental externalities of natural gas pipeline construction and operations are large and negative." (The Constitution pipeline was cancelled in February 2020 after years of public opposition and failure to obtain a state water permit.)

- March 14, 2019 – A Canadian team reviewed the research published between 2009–2018 on the impacts on communities of "the whole suite of technologies that aid in the exploration, extraction, and transportation" of natural gas. This first review of impacts across the supply chain found most of the studies addressed upstream communities (those adjacent to the gas extraction), and that midstream and downstream communities were understudied. Midstream communities were those located in transportation corridors, such as near pipelines, and downstream communities were those near processing and shipping facilities. The study identified 28 community impacts across four broad categories: environmental impacts; impacts to infrastructure and service delivery; impacts on policy, regulation, and participation in decision-making; and socioeconomic impacts. In each area, the reviewers identified common findings, mixed results across studies, and research gaps. For social service delivery, for example, the review found significant effects from the boom and bust cycles. In the boom cycle these included "increased pressure on limited infrastructure, affordable housing and daycare, recreational and child/youth programs, and social services to address alcohol and drug addictions, domestic violence, and crime." In the bust cycle there is a continued need for social services, especially as created by unemployment, economic hardship, local business closures, dropping property values, and out-migration. In this period though, there may be cuts to social services, and "peer-reviewed articles rarely focused on the capacity of local governments to address impacts before, during, and after they happen."[2040]

- December 10, 2018 – Although Pennsylvania has been able to realize modest short-term economic growth from fracking, policy researchers found that the state has also allowed costs to be externalized to public health, the environment, and community integrity. Despite emerging evidence on adverse public health effects, there remain significant uncertainties about these externalized costs, especially with regard to the long term. Research done in the state has shown "significant remaining uncertainties in detecting and attributing responsibility for groundwater contamination" associated with fracking. Intensive gas extraction in Pennsylvania can strain communities by several pathways: increased demand for emergency medical and mental health services; loss of housing for low income residents displaced by temporary, out-of-state workers; and increased traffic violations and arrests for driving under the influence. Emergencies at fracking sites can

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[2039] Andrew Boslett and Elaine Hill, "Shale Gas Transmission and Housing Prices," *Resource and Energy Economics* 57 (2019): 36–50, https://doi.org/10.1016/j.reseneeco.2019.02.001.
[2040] Chris G. Buse et al., "Locating Community Impacts of Unconventional Natural Gas across the Supply Chain: A Scoping Review," *The Extractive Industries and Society* 6, no. 2 (2019): 620–29, https://doi.org/10.1016/j.exis.2019.03.002.

also strain or exceed the capabilities of local emergency response organizations. At the state level, policy weaknesses include failure to mandate the disclosure of fracking chemicals, failure to exercise adequate inspection and enforcement, and failure to institutionalize "stewardship of rents extracted from a nonrenewable resource for future generations."[2041]

- November 21, 2018 – The presence of drilling and fracking operations is linked with fewer visits to overnight recreation sites in National Forests in western states. As part of a USDA Forest Service study that analyzed visitor use data from 27 National Forests with 722 overnight use areas, researchers found that, on average, each additional oil or gas well within a five-kilometer radius of a site was linked to six fewer visits annually. Within a five-kilometer radius, the distance between the well and the campground was not a significant factor. The researchers did not speculate on the overall user experience but wrote that their results do "suggest that the presence of oil and gas development may have a significant enough effect on the user experience to motivate users to recreate elsewhere."[2042]

- October 28, 2018 – In 15 states between 2000 and 2013, intensive shale oil and gas drilling activity was linked with 41,760 fewer students enrolled in school per year in grades 11 and 12. This phenomenon was greatest in states with a younger compulsory schooling age (16 years of age instead of 17 or 18), in states with a lower effective tax rate on oil and gas production, and in rural counties with traditional mining or persistent poverty.[2043] The results of the study, conducted by a team of economists, aligned with historical evidence from the 1970s energy boom as well as complementary research from the 2000s, both showing that oil and gas booms "can discourage educational attainment by increasing the opportunity cost for students to stay in school." (See entry below for July 2015.)

- September 24, 2018 – An *E&E* investigation examined cities in North Dakota, Pennsylvania, and Oklahoma that are experiencing lingering financial and social disruptions following oil and gas booms. In Oklahoma, "the state Legislature is trying to fix what some viewed as a string of bad fiscal decisions that led to cuts in education and other services." In Pennsylvania, communities are still roiled by "a series of bitter disputes about whether local landowners were getting their fair share of royalties from gas drilling." In North Dakota, the debt held by the city of Williston was high for a town its size, with its manageability dependent on continuing oil tax income from the state.[2044]

[2041] Brian Alexander Chalfant and Caitlin C. Corrigan, "Governing Unconventional Oil and Gas Extraction: The Case of Pennsylvania," *Review of Policy Research*, 2018, e0001, https://doi.org/10.1111/ropr.12319.
[2042] Rebecca Rasch, Matt Reeves, and Colin Sorenson, "Does Oil and Gas Development Impact Recreation Visits to Public Lands? A Cross-Sectional Analysis of Overnight Recreation Site Use at 27 National Forests with Oil and Gas Development," *Journal of Outdoor Recreation and Tourism* 24 (2018): 45–51, https://doi.org/10.1016/j.jort.2018.11.001.
[2043] Na Zuo, Jack Schieffer, and Steven Buck, "The Effect of the Oil and Gas Boom on Schooling Decisions in the U.S," *Resource and Energy Economics* 55 (2019): 1–23, https://doi.org/10.1016/j.reseneeco.2018.10.002.
[2044] Mike Lee and Pamela King, "These Places Rode out the Boom and Bust. Now What?," *E&E News*, September 24, 2018, https://web.archive.org/web/20180924163148/https://www.eenews.net/stories/1060099341.

- August 22, 2018 – Marking a decade since Marcellus Shale fracking began in earnest, a five-university research team presented a review of impacts to people, policy, and culture in the greater mid-Atlantic region of the United States. The review's geographic and thematic sections address a range of impacts on Pennsylvania communities and a discussion of the less-studied communities in West Virginia and Ohio undergoing fracking. Economic impacts in Pennsylvania, contrary to what political and business interests typically tout, are mixed. Employment data showed that positive effects for local residents "are relatively small and temporary, in large part because much of the employment benefits from the activity goes to workers living outside the host communities." Further, among local residents, economic benefits were unequally distributed based on land ownership. In Pennsylvania, about half of lease and royalty dollars accrue to the top 10 percent of local landowners who owned the most acreage, while the bottom 70 percent of landowners collectively receive only 2.8 percent of all such dollars. "The vast majority of local residents were not rural landowners and thus were unable to take advantage of gas leasing for revenue." For poorer residents in fracking areas, "radically tightening housing markets, coupled with skyrocketing housing costs," presented fundamental economic hardships.[2045]

- June 6, 2018 – Uneven distribution of economic/service-related benefits and social/environmental costs characterize the Barnett and the Eagle Ford shale plays in Texas, according to an analysis of shale energy development in the southern United States that included both objective and perceived effects. Transportation-related hazards, deemed "the big one," were seen as the primary concern to community leaders and residents. Multiple sources and study types corroborated the objective transportation trends and harms. For example, a survey of county and city public officials in the 15-county Eagle Ford Shale region concluded that increasing transportation demands resulting from fracking "have not been met with needed state resources to maintain and/or upgrade transportation facilities to meet the increased volume and weight of vehicles using the transportation system in local communities." An Academy of Medicine, Engineering and Science of Texas Task Force on Environmental and Community Impacts of Shale Development in Texas likewise concluded, "the level of funding to address the impacts to the transportation infrastructure and traffic safety in the oil and gas industry area is low relative to the magnitude of the impact." This analysis also described uneven distribution of benefits. For example, individuals and energy companies located outside of the region held 96 percent of Eagle Ford mineral wealth.[2046]

- May 21, 2018 – Public administration scholars at Binghamton University interviewed 43 local government officials in 26 municipalities in high-density drilling areas of the Marcellus Shale regions of Pennsylvania.[2047] They considered these officials to be "on

[2045] Jeffrey B. Jacquet et al., "A Decade of Marcellus Shale: Impacts to People, Policy, and Culture from 2008 to 2018 in the Greater Mid-Atlantic Region of the United States," *The Extractive Industries and Society* 5, no. 4 (2018): 596–609, https://doi.org/10.1016/j.exis.2018.06.006.
[2046] Gene L. Theodori, "Shale Energy Development in the Southern United States: A Review of Perceived and Objective Social Impacts," *The Extractive Industries and Society* 5, no. 4 (2018): 610–18, https://doi.org/10.1016/j.exis.2018.05.006.
[2047] Pamela A. Mischen and Stephanie Swim, "Social Equity and 'Fracking': Local Awareness and Responses," *Administration & Society* 52, no. 1 (2020): 138–65, https://doi.org/10.1177/0095399718774032.

the frontlines" of social equity issues linked to the geographic distribution of environmental costs versus economic benefits of fracking. They found that most municipal officials "explicitly recognized that there were distributional benefits-sharing problems associated with shale gas drilling," while most also believed shale gas drilling was a net positive for their communities. Still, "there were mixed feelings regarding whether the financial gains of drilling compensated for the environmental impacts," with some expressing "incredulity" at the idea that money compensated for impact. Researchers demonstrate that local officials are aware of equity issues, with some taking action to reduce inequities, but that action in their communities often conflicts with convictions about property rights.

- March 4, 2018 – Local governments in highly rural regions experiencing large-scale growth in oil and gas activity faced the greatest fiscal challenges, according to a study evaluating the effects of this development in 21 U.S. regions during boom and bust periods. "Increased crime, vehicle accidents, and other public safety issues were major challenges," and "the scale of these challenges tended to track the scale of population growth and a region's rurality." Though revenues from property and sales taxes and other sources resulted in a net gain for many local governments, the volatility of industry activity and population growth created especially difficult challenges for some municipalities. In a rural western Colorado city, for example, residents were faced with increased taxes, as well as increased water and wastewater fees to service the debt incurred by needed upgrades.[2048]

- February 13, 2018 – Economists found that Oklahoma home prices in 2006 to 2014 declined by three to four percent after experiencing a moderate earthquake. Further, sale prices for the properties affected by the most intense earthquakes were estimated to have declined from 3.5-10.3 percent. The study also found that houses were on the market significantly longer following earthquake exposure. The intensity of a quake for each property was determined by linking earthquake magnitude to the distance of the home from its epicenter. The researchers wrote, "Oklahoma provides an exceptional case study as the state most affected by sudden changes in seismic frequency and intensity," and that although the exact proportion of earthquakes induced by oil and gas activity is not certain, "the Oklahoma Geological Survey has recognized that the majority of earthquakes are likely to be induced." They concluded that the rise in earthquake activity "has inflicted substantial costs on homeowners in Oklahoma."[2049]

- January 25, 2018 – In the Marcellus Shale region, counties experiencing a fracking boom suffered a 30 percent increase in violent crime, compared to those with no gas boom. Aggravated and sexual assaults were the crimes primarily responsible for this increase. This research took advantage of "natural experiment" conditions in the region, with a prohibition on fracking in New York State and a fracking boom across the border in

[2048] Richard G. Newell and Daniel Raimi, "The Fiscal Impacts of Increased U.S. Oil and Gas Development on Local Governments," *Energy Policy* 117 (2018): 14–24, https://doi.org/10.1016/j.enpol.2018.02.042.
[2049] Ron Cheung, Daniel Wetherell, and Stephan Whitaker, "Induced Earthquakes and Housing Markets: Evidence from Oklahoma," *Regional Science and Urban Economics* 69 (2018): 153–66, https://doi.org/10.1016/j.regsciurbeco.2018.01.004.

Pennsylvania. The study used 2004 to 2012 county-level data from New York and Pennsylvania Marcellus Shale regions, on unconventional gas wells drilled, and on seven "FBI Index I" offenses. The offenses were violent crimes (aggravated assault, rape, robbery, and murder) and property crimes (larceny, burglary, and auto theft). While violent crimes increased in fracking boom areas, property crimes did not. The research featured many controls to isolate the effects of the fracking economy on crime rates. In addition, "victimization costs" were estimated to be $8.1 million per year in high fracking counties. "Policymakers along with oil and natural gas proponents often cite the benefits in terms of jobs and income that are created in a community. However, the welfare costs of victims of crimes, among other issues, should also be considered to make optimal policy decisions."[2050]

- January 24, 2018 – The nearest full-time fire department to a deadly Quinton, Oklahoma natural gas rig explosion was nearly 30 miles away, according to an *E&E* investigation focusing on emergency response. "The deaths highlight a crucial fact of the drilling boom—much of it has occurred in rural areas where small-town police officers, sheriff's deputies and volunteer firefighters are often the first responders."[2051]

- January 13, 2018 – Sex trafficking in oil boomtowns remains a huge problem, according to interviews with 185 health and social service professionals, criminal justice personnel, industry and community representatives, and victims of violence in the Bakken oil field region. These results are reflective of the growing literature on the topic. Interviewees shared information on increases in domestic violence, dating violence, sexual assault, stalking, and sex trafficking, Findings demonstrated that sex trafficking was linked to "a confluence of underlying forces including big oil money, an increase in drug cartels and drug use, degradation of women in a male-dominated workforce, increased access to weapons, and a rise in transient populations." A noteworthy contribution of this study was the documentation that participants felt unprepared to address the needs of victims of sex trafficking, having very few resources, and limited background and experience with these problems.[2052]

- December 12, 2017 – Fracking is unlikely to be a panacea for economically marginalized rural, suburban, or urban areas, and economic optimism regarding fracking tends to be overgeneralized, according to a study analyzing national data on socioeconomic wellbeing for the years 2000 to 2011. Researchers noted that large profits for industry and economic development "may not trickle down to residents living in high-production counties," but instead often benefit a relative few, over a temporary time period. The study measured percentage of families below the poverty line in each county, average earnings, median household income, and employment status, to understand these socioeconomic impacts of oil and gas booms. Their literature review also uncovered a

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[2050] Timothy M. Komarek, "Crime and Natural Resource Booms: Evidence from Unconventional Natural Gas Production," *The Annals of Regional Science* 61, no. 1 (2018): 113–37, https://doi.org/10.1007/s00168-018-0861-x.
[2051] Mike Lee and Mike Soraghan, "Rig Wreckage Probed for Cause of Deadly Okla. Blast," *E&E News*, January 24, 2018, https://web.archive.org/web/20180124201230/https://www.eenews.net/stories/1060071777.
[2052] Thomasine Heitkamp, "Sex Trafficking in the Bakken Oil Fields" (Society for Social Work and Research, Washington, DC, 2018), https://sswr.confex.com/sswr/2018/webprogram/Paper32717.html.

disparity in findings: "industry-funded studies have found substantial economic windfalls related to extraction… but the peer-reviewed literature suggests mixed or modest effects."[2053]

- September 26, 2017 – The partial abandonment of the Eagle Ford Shale dramatically hurt small business owners, according to a report by *Bloomberg.* "As the shale drillers moved on to richer fields, the South Texas landscape became pockmarked with abandoned structures. This nimbleness—the ability to just pack up and leave at a moment's notice—may give U.S. oil companies a competitive advantage against their more rigid state-run OPEC rivals, but there is a human cost to it all." Concerning one tool and supply company in the region, the investigation found: "During the height of the Eagle Ford boom, R. Katz was supplying as many as 52 rigs and employing as many as 18 people in its office outside Cuero's main strip. Today, it's got 11 rig clients and three employees."[2054]

- August 10, 2017 – Researchers from the independent, nonpartisan economic research group Resources for the Future studied the impacts of unconventional oil and gas booms on public school districts in the oil- and gas-producing states Pennsylvania, Ohio, West Virginia, North Dakota, Montana, and Colorado between 2000 and 2013. Using quantitative data analysis as well as extensive interviewing with parents and students in the districts, the study addressed the effects of recent oil and gas booms on student enrollment, teachers, public education finances, and student achievement metrics. Though divergent trends were found between school districts in the eastern versus western U.S., "nearly all boom districts reported heightened stress from financial volatility." Though some districts had a statistically positive increase in per student funding while others had a decline, "the study found that greater revenues do not always translate into increased educational outcomes…. One western Colorado school district had to operate on a four-day-a week schedule and cut academic programs because of increased economic volatility."[2055] As reported in *U.S. News and World Report*, "the boom-and-bust cycle of the industry was found to create overwhelming stress on local districts as students and teachers were moving in and out of a region to meet the economic demands of drilling."[2056]

- June 18, 2017 – A Shale Task Force of the Academy of Medicine, Engineering and Science of Texas (TAMEST) developed the report, *Environmental and Community*

[2053] Adam Mayer, Shawn K. Olson-Hazboun, and Stephanie Malin, "Fracking Fortunes: Economic Well-Being and Oil and Gas Development along the Urban-Rural Continuum: Fracking Fortunes," *Rural Sociology* 83, no. 3 (2018): 532–67, https://doi.org/10.1111/ruso.12198.
[2054] Dan Murtaugh, "Life in the Oil Ghost Towns of Texas," *Bloomberg*, September 26, 2017, https://www.bloomberg.com/news/features/2017-09-26/the-oil-ghost-towns-of-texas.
[2055] Nathan Ratledge and Laura Zachary, "Impacts of Unconventional Oil and Gas Booms on Public Education: A Mixed-Methods Analysis of Six Producing States" (Resources for the Future, 2017), https://www.rff.org/publications/reports/impacts-of-unconventional-oil-and-gas-booms-on-public-education-a-mixed-methods-analysis-of-six-producing-states/.
[2056] Eric Englert, "Fracking Brings Challenges to Local School Systems," *US News & World Report*, August 10, 2017, //www.usnews.com/news/national-news/articles/2017-08-10/fracking-brings-challenges-to-local-school-systems.

Impacts of Shale Development in Texas, a "first-of-its-kind, comprehensive review of scientific research and related findings regarding impacts of shale oil and gas production in Texas." Transportation impacts included road damage costing Texas an estimated $1.5 to $2 billion a year, and rural crashes involving commercial vehicles increasing over 75 percent in some drilling regions. The number of fatal collisions in the Permian Basin doubled from 94 during 2006 to 2009, to 183 from 2010 to 2013. The report also noted that Texas is the only major oil and gas producing state without a "surface damage act" to protect landowners, who do not own the mineral rights on their land and have little control over oil and gas operations. The report, which also addressed topics such as seismicity, air, and water, noted that the various impacts of oil and gas development "can't be studied or addressed in isolation." Authors continued, "[t]hese connections are important and pervasive, but are not well-studied yet." TAMEST includes all of the state's Nobel Laureates, plus Texas-based members of the National Academies of Sciences, Engineering, and Medicine.[2057]

- April 6, 2017 – The economic impacts of fracking at the advent of the Marcellus Shale boom is an understudied topic. The onset of fracking was so rapid that academics were challenged to provide accurate and timely information to policymakers, and the one major paper that did appear in 2011 did not clearly disclose its industry sponsorship. A Pennsylvania Department of Community & Economic Development-funded study set out to investigate those early years. In addition to scrutinizing available data, the authors conducted a survey of 1,000 landowners in Bradford and Tioga counties, the two counties with the most fracked wells in Pennsylvania at the start of the boom. From the 501 returned surveys, they determined residents saved more than half of their earliest royalty and lease income, which "may or may not ultimately be spent within Pennsylvania." Hence, the windfalls from mineral rights created "little economic impact during the year received." Further, the study's overall "lower-bound" estimate of economic impacts for 2009 found that fully 15.4 percent of these mineral rights were owned by non-residents. At the same time, survey results showed that 37 percent of the workforce consisted of non-residents with only half of their income staying in the state. This study's upper-bound jobs count for 2009 was substantially lower than the estimates that made at the time. In addition, the study urged caution regarding future jobs predictions, as the sharp decline between 2011 and 2013 "was totally unexpected" and was not captured in a 2010 forecast for jobs in 2020.[2058]

- April 5, 2017 – Economists at Colorado State University quantified the "substantial environmental costs associated with hydraulic fracturing," as part of an analysis of the market and non-market costs and benefits of fracking in 14 U.S. states. These costs were "dominated by $27.2 billion ($12.5–$41.95 billion) health damages from air pollution." They also found costs including "$3.8 billion ($1.15–$5.89 billion) in greenhouse gas emissions, $4 billion ($3.5–$4.45 billion) in wildlife habitat fragmentation, and $1 billion

[2057] The Academy of Medicine, Engineering and Science of Texas, *Environmental and Community Impacts of Shale Development in Texas* (TAMEST, 2017), https://doi.org/10.25238/TAMESTstf.6.2017.
[2058] Kyle A. Hoy, Timothy W. Kelsey, and Martin Shields, "An Economic Impact Report of Shale Gas Extraction in Pennsylvania with Stricter Assumptions," *Ecological Economics* 138 (2017): 178–85, https://doi.org/10.1016/j.ecolecon.2017.03.037.

($0.5–$1.6 billion) in pollution of private drinking water wells." Results also showed a disconnect between those reaping economic rewards from fracking and those paying the price: the "benefits" (mostly in the form of lower natural gas prices to residential, commercial, and industrial consumers) were geographically dispersed while the costs tended to concentrate in localized areas where drilling took place. Although the most comprehensive economic study to date, this analysis was not able to fully quantify all costs, including those related to water contamination (beyond surface-spill related costs for damage to private wells); diminishment of open spaces and aesthetics for community members; and seismic activity. The authors concluded that costs might well outweigh the benefits for suburban dwellers near fracking operations, as exemplified by Denton, Texas, where "nearly all the royalty money was flowing to mineral owners living elsewhere…rather than to adjacent homeowners."[2059]

- February 19, 2017 – The *New York Times* reported on the oil and gas industry's embrace of automation and its threat to preserving and bringing back jobs. Executives interviewed as part of the investigation were straightforward in their intentions to shrink their work forces. "'We want to transform our work force to the point where we need to hire fewer people,' said Joey Hall, Pioneer's executive vice president for Permian Operations." In 2016 Pioneer Natural Resources added 240 wells in West Texas without adding any new employees. A vice president at a Pennsylvania manufacturer of drilling rigs stated, "If it's a repetitive task, it can be automated, and I don't need someone to do that. I can get a computer to do that."[2060]

- February 1, 2017 – Stanford University earth science professor Robert Jackson and two professors of law assessed how a new type of "conservation easement," an established kind of legal agreement, could enable landowners to restrict fracking on their properties. A mineral estate conservation easement (MECE) can serve as a private landowner response to the demonstrable threats of fracking to property and community: "Accompanying the rise of high-volume hydraulic fracturing has been a suite of environmental and social concerns, including potential water and air contamination, greenhouse gas emissions, health effects, and community disruptions." "We support the exploration of MECEs as an additional tool for landowners to exercise their rights and responsibilities," the team concluded.[2061]

- January 26, 2017 – Automation is reducing the size of drilling crews and will lessen the number of jobs added nationally with any upturn in oil and gas operations, according to a piece on OilPrice.com. The author described predictions, including:

[2059] John Loomis and Michelle Haefele, "Quantifying Market and Non-Market Benefits and Costs of Hydraulic Fracturing in the United States: A Summary of the Literature," *Ecological Economics* 138 (2017): 160–67, https://doi.org/10.1016/j.ecolecon.2017.03.036.
[2060] Clifford Krauss, "Texas Oil Fields Rebound From Price Lull, but Jobs Are Left Behind," *The New York Times*, February 19, 2017, sec. Business, https://www.nytimes.com/2017/02/19/business/energy-environment/oil-jobs-technology.html.
[2061] Robert B. Jackson, Jessica Owley, and James Salzman, "Mineral Estate Conservation Easements: A New Policy Instrument to Address Hydraulic Fracturing and Resource Extraction," *The Environmental Law Reporter*, January 31, 2017, https://elr.info/news-analysis/47/10112/mineral-estate-conservation-easements-new-policy-instrument-address-hydraulic-fracturing-and-resource-ext.

Automated drilling rigs may be able in the future to reduce the number of persons in a drilling crew by almost 40 percent, from 25 workers to 15 workers, *Houston Chronicle*'s Jordan Blum writes, quoting industry analysts.

Drilling company Nabors Industries expects that it may be able to reduce the size of the crew at each well site to around 5 people from 20 workers now if more automated drilling rigs are used, Bloomberg's David Wethe says.[2062]

- December 22, 2016 – Researchers with the Energy Policy Institute at the University of Chicago measured the costs and benefits of fracking in local communities across nine U.S. shale basins. They found that, despite contributions to local economies with the arrival of fracking, residents experienced decreases in local quality of life. Spikes in crime were the most directly measurable of these effects. "Despite local governments' efforts to improve public safety—allocating 20 percent more funding—the crime rates still marginally increased." The study also found unequal distribution of benefits. Students, the elderly, and those who don't own mineral rights did not benefit at all. Their analysis found an average gain of about $1,300 to $1,900 per household per year, but these gains were offset by a reduction in the typical household's quality of life, which the authors computed at about $1,000 to $1,600 per year.[2063]

- December 21, 2016 – Economists from the University of Anchorage and Montana State University studied the impact of regional shale energy booms on crime rates across U.S. counties from 2000 to 2013, documenting increased rates of many types of crime, including assault, rape, larceny, and auto theft. In 2013, they pegged the average monetary cost of these additional crimes at $2 million per county. Researchers emphasized these results represented short-term costs only, as they could not predict how crimes rates and attendant costs will accrue over longer periods of time, as, for example, if criminal behavior and labor migration facilitate a slow drain of human and physical capital from the region and propagate "a long-term resource curse." The study also found "that registered sex offenders moved in disproportionate numbers to boom towns in North Dakota," and "that income inequality increased as the shale boom progressed."[2064]

- May 24, 2016 – In 327 U.S. counties previously at the center of the fracking boom, overdue car loans approached their highest level in five years, and late mortgage payments also rose, according to a report by the *Financial Times* that examined data from the Federal Reserve Bank of New York. These trends stood in stark contrast to lowered overdue debt rates in the rest of the U.S. This surge in late car payments in intensely fracked areas of the United States has "exposed the damage done by the collapse in

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[2062] Tsvetana Paraskova, "Robots Over Roughnecks: Next Drilling Boom Might Not Add Many Jobs," *OilPrice.Com*, January 26, 2017, https://oilprice.com/Energy/Energy-General/Robots-Over-Roughnecks-Next-Drilling-Boom-Might-Not-Add-Many-Jobs.html.
[2063] Bartik et al., "The Local Economic and Welfare Consequences of Hydraulic Fracturing."
[2064] Alexander James and Brock Smith, "There Will Be Blood: Crime Rates in Shale-Rich U.S. Counties," *Journal of Environmental Economics and Management* 84 (2017): 125–52, https://doi.org/10.1016/j.jeem.2016.12.004.

drilling activity and marred broadly positive trends for late debt payments by American consumers."[2065]

- May 8, 2016 – With the downturn in the fracking industry, Wisconsin's sand mining sector, which provides silica sand for fracking operations, has also slumped and prompted significant layoffs and job losses in both 2015 and 2016, according to a report by Eau Claire's *Leader-Telegram*. "This is what the bust part of the boom-and-bust cycle of the energy sector looks like, and it's something west-central Wisconsin residents, who are mostly new to the industry, aren't used to seeing." Other companies that supply goods and services to sand mining operations in the region have also experienced a downturn.[2066]

- March 8, 2016 – A DeWitt County, Texas judge estimated it will cost his county $432 million to rebuild its roads, noting that if a road "leads to a rig site, it's bound to be a broken road." The judge stated that ultimately the companies would pay a large share.[2067]

- February 22, 2016 – *Inside Energy* investigated oil-industry related wage theft claims in the West, finding "a growing number of oil workers are turning to the courts, saying they weren't paid fairly even when times were good." Between 2010 and 2015, wage theft suits against oil and gas companies in Colorado increased by a factor of nine, and in Texas nearly ten times. The investigation found that oil and gas companies were consistently among the top violators of wage laws—especially in failure to pay overtime. A federal investigation of the industry led to the recovery of $40 million dollars in unpaid wages. One of the officers involved in the investigations is quoted saying, "We have found cases where workers were not even paid the minimum wage, because they're working so many hours…. So the idea that they're being highly compensated, in some cases, they're not."[2068]

- January 13, 2016 – A fire on a fracking site in Grady County, Oklahoma that consumed 22 oil tankers required the response of six regional fire departments.[2069]

- December 15, 2015 – The value of homes that rely on well water in Pennsylvania dropped an average of $30,167 when fracking took place within 1.5 kilometers, according to a study by Duke University researchers published in the *American Economic Review*. For these groundwater-dependent homes, a fracking well located within one kilometer was linked to a 13.9 percent average decrease in values; homes with wells at

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[2065] Sam Fleming, "US Fracking Bust Sparks Surge in Car Debt," *Financial Times*, May 24, 2016, https://www.ft.com/content/a4cb1270-21c2-11e6-aa98-db1e01fabc0c.
[2066] Eric Lindquist, "Silent Sandbox: Once Booming Frac Sand Industry Continues Major Downturn," *Leader-Telegram*, May 8, 2016, https://www.leadertelegram.com/news/front-page/silent-sandbox-once-booming-frac-sand-industry-continues-major-downturn/article_b6c1877b-3586-588f-a2b6-5cb2fe9b49ce.html.
[2067] Concetta Callahan, "Fracking Fall-off Leaves South Texas Roads a Mess," *KSAT*, March 8, 2016, sec. News, https://www.ksat.com/news/2016/03/08/fracking-fall-off-leaves-south-texas-roads-a-mess/.
[2068] Dan Boyce, "Wage Theft Claims Surge As Oil Prices Fall," *Inside Energy*, February 22, 2016, http://insideenergy.org/2016/02/22/wage-theft-claims-surge-as-oil-prices-fall/.
[2069] K. Querry and Lorne Fultonberg, "Firefighters Extinguish Damaging Grady Co. Fracking Fire," *KFOR.Com Oklahoma City*, January 13, 2016, https://kfor.com/news/all-lanes-of-traffic-shut-down-due-to-large-oil-rig-fire/.

least two kilometers away maintained their value. The study was based on home sales between 1995 and 2012 in 36 counties. Researchers stated that their figures may not fully reflect the total costs associated with groundwater contamination risk, as, for example, when homeowners purchase expensive home water filtration systems. Though their study does not incorporate data on actual contamination, concerns about contamination can significantly affect property values. Researchers found "strong evidence of localized costs borne particularly by groundwater-dependent homes."[2070]

- December 8, 2015 – Even as housing prices in shale gas-areas of Pennsylvania have dropped along with fracking activity, many seniors and people living on low incomes are still being priced out of the market, *StateImpact* reported. Pennsylvania still lacks a quarter million affordable rental homes for people in poverty despite a 2012 law requiring gas companies to pay well fees intended to offset the costs of affordable housing programs in communities where drilling is occurring.[2071]

- December 2, 2015 – "The local economy is feeling the pinch" of the downturn of activity in Pennsylvania's gas fields, according to a Reuters report. The late 2015 slump marked a turning point in Marcellus Shale fracking. Regional economic effects reported include empty hotel rooms and foreclosure notices in Lycoming County at their highest since data were first collected.[2072]

- October 7, 2015 – Vehicular collisions and Texas fracking activity are closely linked, according to a report by the Texas A&M University Transportation Institute. Researchers analyzed the number of crashes and injuries across Texas during the period from 2006 to 2009, when drilling and fracking operations were intensive over the Barnett Shale, as well as from 2010 to 2013, when activity increased in the Permian Basin in West Texas and the Eagle Ford Shale in South Texas, and decreased in the Barnett. Collisions increased where shale gas activity increased and decreased where it slowed down.[2073] Quoted in the *Texas Tribune*, report co-author Cesar Quiroga said, "The two trends correlated so well, and they were perfectly aligned ….We could use this as a predictive model."[2074] Further, the increase was greater in South Texas, the region that relies most heavily on horizontal, hydraulic fracking requiring millions of gallons of water and sand to be trucked in, compared to West Texas which does use fracking but also more simple, vertical wells. The comprehensive cost of these collisions was estimated to be about $2

[2070] Lucija Muehlenbachs, Elisheba Spiller, and Christopher Timmins, "The Housing Market Impacts of Shale Gas Development," *American Economic Review* 105, no. 12 (2015): 3633–59, https://doi.org/10.1257/aer.20140079.
[2071] Marie Cusick, "Despite Drilling Slowdown, Rents Still High in Fracking Boomtowns," *State Impact Pennsylvania*, December 8, 2015, https://stateimpact.npr.org/pennsylvania/2015/12/08/despite-drilling-slowdown-rents-still-high-in-fracking-boomtowns/.
[2072] Edward McAllister, "America's Biggest Gas Field Finally Succumbs to Downturn," *Reuters*, December 2, 2015, https://www.reuters.com/article/us-usa-marcellus-decline-insight-idUSKBN0TL0CY20151202#W0DRBI8eM4MKscSV.97.
[2073] Cesar Quiroga and Ioannis Tsapakis, "Oil and Gas Energy Developments and Changes in Crash Trends in Texas," Final Report (Transportation Policy Research Center, October 2015), http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/PRC-15-35-F.pdf.
[2074] Jim Malewitz, "Report: Traffic Crashes Related to Energy Boom Cost Billions," *The Texas Tribune*, October 7, 2015, https://www.texastribune.org/2015/10/07/report-shows-huge-toll-energy-boom-traffic-crashes/.

billion more from 2010 to 2013—in both the Eagle Ford and Permian Basin—compared to the previous period.

- September 30, 2015 – The North Dakota Bureau of Criminal Investigation was set to hire nine new agents, reported the *Billings Gazette*, "…allowing for more attention to cases of human trafficking and organized crime in western North Dakota … as increased oil production resulted in growing populations."[2075]

- September 29, 2015 – "New residential units sit empty as gas production falls," *HousingWire Magazine* wrote, following up on their earlier reporting describing the link between the drilling boom and the real estate boom in the Bakken shale region of North Dakota. Economic data indicate that Bakken drilling is not lasting long enough to sustain the building explosion.[2076]

- September 9, 2015 – Most local governments in Western North Dakota and Eastern Montana's Bakken region have experienced net negative fiscal effects, according to a Duke University analysis published by the National Bureau of Economic Research. These trends were also seen in municipalities in rural Colorado and Wyoming, which also struggled to manage fiscal impacts during recent oil and gas booms, but in these two states the fiscal impact eased as drilling activity slowed.[2077] Referencing the report, *McClatchyDC* wrote, "North Dakota cities and counties have been slammed." Municipal challenges have included providing water and sewer infrastructure, substantial damage to roads, soaring housing prices, and strained emergency services.[2078]

- August 27, 2015 – Fracking in or near public parks could cause tourists to stay away and lead to a decline in park use, according to a report published by a team of tourism, recreation, and sport management researchers from the University of Florida, North Carolina State University, and Florida State University. Using data collected from 225 self-identified park users from Pennsylvania, Ohio, West Virginia, Kentucky, and Tennessee, researchers reported that only one-third of participants were willing to participate in recreational activities near fracking operations, compared to 38 percent unwilling, and 29 percent neutral. Forty-six percent of respondents supported a ban on fracking on public lands, while 20 percent agreed with promoting fracking on public lands.[2079]

[2075] Nick Smith, "North Dakota to Hire 9 More Criminal Investigation Agents," *Billings Gazette*, September 30, 2015, https://billingsgazette.com/news/state-and-regional/montana/north-dakota-to-hire-9-more-criminal-investigation-agents/article_a4192344-c9b0-51cc-9693-5a4335f5be05.html.

[2076] Ben Lane, "Is Fracking about to Bust Housing in North Dakota?," *HousingWire*, September 29, 2015, sec. Mortgage, Real Estate, https://www.housingwire.com/articles/35196-is-fracking-about-to-bust-housing-in-north-dakota/.

[2077] Richard Newell and Daniel Raimi, "Shale Public Finance: Local Government Revenues and Costs Associated with Oil and Gas Development" (Cambridge, MA: National Bureau of Economic Research, September 2015), https://doi.org/10.3386/w21542.

[2078] Sean Cockerham, "Oil Boom a Loser for North Dakota Cities, Counties, Study Finds," *McClatchy Washington Bureau*, September 9, 2015, https://www.mcclatchydc.com/news/nation-world/national/economy/article34552824.html.

[2079] Tim Kellison et al., "Fracking & Parkland – Research Report," Research Report, 2015, http://plaza.ufl.edu/tkellison/_/Fracking.html.

- July 1, 2015 – Britain's Department for Environment, Food & Rural Affairs released previously redacted sections of a report on the impacts of drilling and fracking. The report found that housing prices near fracking wells would likely fall up to seven percent for houses within a mile of wells. Furthermore, properties within one to five miles of fracking sites could incur additional insurance costs. The report warned of environmental damages, including from leakage of fracking waste fluids, and found that public health could be affected indirectly through consumption of contaminated wildlife, livestock, or agricultural products. The report also found potential for some benefits, such as job growth.[2080]

- July 2015 – A working paper by researchers with the National Bureau of Economic Research found that fracking resulted in an increase in male teen high school dropout rates. "Our estimates imply that, absent fracking, the male-female gap in high school dropout rates among 17- 18-year olds would have narrowed by about 11 percent between 2000 and 2013 instead of remaining unchanged." The authors explained that by increasing the demand for low-skilled labor, fracking could slow growth in educational attainment. They noted that the relative wage boost from fracking may be only temporary. Indeed, by the end of the sample period, the benefits had started to wane as the labor demand from fracking appeared to no longer favor dropouts. Thus, the fracking boom may be inhibiting educational achievement among young men who "would already be near the bottom of the skill distribution, with possible implications for future productivity and the social safety net."[2081, 2082]

- March 20, 2015 – The U.S. Attorney for Western New York linked a rise in production of methamphetamine to use among workers in the fracking fields of northern and western Pennsylvania. Surging demand for the drug, which allows users to stay awake for 48 to 72 hours, may be related to the extremely long working hours that employees in the gas industry must endure.[2083]

- January 4, 2015 – A documentary by Forum News Service, "Trafficked Report," revealed that sex trafficking, including of children, in the Bakken oil fields of North Dakota was a significant problem.[2084] The dynamics of the oil boom, with an influx of out-of-state and

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[2080] Adam Vaughan and Rowena Mason, "Fracking Could Hurt House Prices, Health and Environment, Official Report Says," *The Guardian*, July 1, 2015, sec. Environment, https://www.theguardian.com/environment/2015/jul/01/fracking-could-hurt-house-prices-health-and-environment-official-report-says.
[2081] Elizabeth U. Cascio and Ayushi Narayan, "Who Needs a Fracking Education? The Educational Response to Low-Skill Biased Technological Change," Working Paper, Working Paper Series (National Bureau of Economic Research, July 2015), https://doi.org/10.3386/w21359.
[2082] Sho Chandra, "Fracking Jobs Encouraged American Teens to Become High School Dropouts," *Bloomberg*, July 14, 2015, https://www.bloomberg.com/news/articles/2015-07-14/fracking-jobs-encouraged-american-teens-to-become-high-school-dropouts.
[2083] Rich Newberg, "Meth Use Tied to Fracking Workers in Pennsylvania," *News 4 Buffalo*, March 20, 2015, https://www.wivb.com/news/crime/meth-use-tied-to-fracking-workers-in-pennsylvania/.
[2084] Amy Dalrymple and Katherine Lymn, "Trafficked: Sex for Sale in the Bakken," *Human Trafficking Search*, January 4, 2015, https://humantraffickingsearch.org/resource/trafficked-sex-sale-bakken/.

primarily male workers far from their families, created an increase in demand for prostitution.[2085]

- December 28, 2014 – The *New York Times* profiled the impacts of oil drilling and fracking on the Fort Berthold Indian Reservation in North Dakota, finding corruption, crime, and negative environmental impacts. Aside from a significant rise in jobs, which often go to transient workers, many residents "see deterioration rather than improvement in their standard of living. They endure intense truck traffic, degraded roads, increased crime, strained services and the pollution from spills, flares and illegal dumping." According to the *Times*' calculation, the reservation had seen 850 oil-related environmental incidents from 2007 through mid-October 2014, which generally went unpunished.[2086]

- December 26, 2014 – Examining Pennsylvania Department of Transportation data, Ohio's *Star Beacon* newspaper found that fracking poses a safety threat on rural roads. The paper found that Pennsylvania's five busiest drilling counties recorded 123 more heavy truck crashes in 2011 than before the gas boom began—a 107 percent increase. The paper noted the burden drilling and fracking placed on local communities and governments, including the strain on local emergency responders.[2087]

- December 17, 2014 – Heavy drilling and fracking (defined as 400 or more wells drilled within a county over 5-8 years) was positively correlated with increased crime, sexually transmitted diseases, and traffic fatalities, according to a report by the Multi-State Shale Research Collaborative.[2088] The report looked at the impacts in Pennsylvania, Ohio, and West Virginia, primarily finding statistically significant impacts in six heavily drilled counties in Pennsylvania. In those six counties, violent crime increased 17.7 percent—corresponding to about 130 more violent crimes in those counties in 2012—compared to a decrease in violent crime rates in both urban and rural non-drilling communities. Property crime increased 10.8 percent in those six counties, drug abuse rates rose 48 percent, and drunk-driving offenses rose 65 percent compared to 42 percent in rural areas with no drilling. The report found a statistically significant increase of 24 percent to 27 percent in rates of sexually transmitted diseases across drilling counties in all three states. Motor vehicle fatalities increased 27.8 percent in Pennsylvania's six high-drilling

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[2085] Jason Gaines, "The Oil Boom in North Dakota Now Has a Serious Sex-Trafficking Problem," *Business Insider*, March 9, 2015, https://www.businessinsider.com/north-dakota-sex-trafficking-prostitution-oil-boom-police-raid-2015-3.
[2086] Deborah Sontag and Brent McDonald, "In North Dakota, a Tale of Oil, Corruption and Death," *The New York Times*, December 29, 2014, sec. U.S., https://www.nytimes.com/2014/12/29/us/in-north-dakota-where-oil-corruption-and-bodies-surface.html.
[2087] John Finnerty, "Fracking's Biggest Safety Threat Is on Rural Roads," *Star Beacon*, December 26, 2014, https://www.starbeacon.com/news/fracking-s-biggest-safety-threat-is-on-rural-roads/article_bc48687a-8caf-11e4-b4d9-6382c924a6f9.html.
[2088] Mark Price et al., "The Shale Tipping Point - Multi-State Shale Research Collaborative" (Multi-State Shale Research Collaborative, December 2014), http://www.multistateshale.org/shale-tipping-point.

counties. The report found a modest increase in jobs, but noted that an influx of out-of-state workers at least partially explained the increases in traffic and crime.[2089]

- December 15, 2014 – A report written in French by Quebec's Advisory Office of Environmental Hearings concluded that the environmental costs of fracking in the St. Lawrence Lowlands would outweigh the potential economic benefits. In a press release, the Advisory Office of Environmental Hearings concluded that fracking "would not be advantageous for Quebec because of the magnitude of the potential costs and externalities, compared to royalties that would be collected by Quebec. Other concerns also remain, including plans of social acceptability, legislation, and a lack of knowledge, particularly with respect to water resources."[2090]

- October 30, 2014 – The *New York Times* profiled the profound impact heavy drilling has had on Glasscock County, Texas, including its farming community. Farmers described increases in trash, traffic accidents, clashes around farmers selling groundwater to drillers, and economic detriment. In many cases, acres of farmland around a drill site "will probably never be suitable for fertile farming again," and farmers are "at the mercy" of what drillers want to pay for damages. The county itself receives revenue, but most of that additional money "is being used to repair roads damaged by oil field truck activity. Overall, the gains from drilling are not viewed as worth the drawbacks in a county long dominated by cotton farming."[2091]

- September 28, 2014 – A *Washington Post* investigation reported on heroin and methamphetamine addiction—and associated violent crime—among Native American communities located within the Bakken Shale oil fields. According to a chief judge for the Mandan, Hidatsa, and Arikara Nation, "The drug problem that the oil boom has brought is destroying our reservation."[2092]

- September 11, 2014 – An editor for the *Washington Post* examined jobs and manufacturing data in Youngstown, Ohio, to demonstrate that drilling and fracking are not resulting in a revitalization of the Rust Belt as some proponents and a prominent *New York Times* story asserted. The *Post* determined that in Youngstown, Ohio, the manufacturing sector has lost jobs by the tens of thousands in the last twenty years and the oil and gas industry has created approximately two thousand jobs since the recession

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[2089] Wallace McKelvey, "Fracking Brought Spikes in Crime, Road Deaths and STDs to Pa.: Report," *Pennlive*, December 18, 2014, https://www.pennlive.com/midstate/2014/12/fracking_brought_spikes_in_vio.html.
[2090] Sean McCarthy, "Fracking Dealt Another Setback by Quebec Report," *The Globe and Mail*, December 15, 2014, https://www.theglobeandmail.com/report-on-business/industry-news/energy-and-resources/bape-says-shale-gas-production-not-advantageous-for-quebec/article22096203/.
[2091] Aman Batheja, "A County Resents Oil Drilling, Despite the Money It Brings In," *The New York Times*, October 30, 2014, sec. U.S., https://www.nytimes.com/2014/10/31/us/a-county-resents-oil-drilling-despite-the-money-it-brings-in.html.
[2092] Sarah Horwitz, "Dark Side of the Boom," *The Washington Post*, September 28, 2014, http://www.washingtonpost.com/sf/national/2014/09/28/dark-side-of-the-boom/.

ended. Six years prior, there were 13,000 more jobs in the Youngstown metro area than there were in summer 2014.[2093]

- September 9, 2014 – A study by researchers at Colorado State University examined the political economy of harm and crime associated with the oil and gas industry in rural Colorado, particularly around the rise of fracking. The researchers looked at complaints that citizens filed with the state, and also conducted interviews and examined other data. They found 2,444 complaints between November 2001 and June 2013 covering a range of issues including water, environment, noise, air quality, land use, and more. They characterized citizen complaints as "extensive and complex" and concluded that, regardless of the nature of the harm, most were "persistent and omnipresent" rather than short-lived, isolated problems.[2094]

- September 6, 2014 – In Williams County, North Dakota, in the Bakken Shale, increases in crime have corresponded with the flow of oil. The infusion of cash has attracted career criminals who deal in drugs, violence, and human sex trafficking. The *Williston Herald* portrayed, in a "reader's discretion advised" article, the rapid rise of "index crimes"—"violent crimes that result in the immediate loss of an individual's property, health or safety, such as murder, larceny and rape." With fewer than 100 law enforcement personnel, crime in Williams County "has risen in kind with the county's population, but funding, staffing and support training for law enforcement has not."[2095]

- September 2014 – Reporting on the social, environmental, health and safety, and economic burdens endured by localities from fracking, the magazine *Governing: The States and Localities* found that "fracking, in many cases, negatively impacts property values, which in turn depresses property tax revenue. For property owners who own the rights to the oil and gas on their land, the effects of drilling can be offset by royalty payments. But localities have no revenue offset if properties lose value."[2096]

- August 26, 2014 – The U.S. Justice Department Office on Violence Against Women awarded three million dollars to five rural and tribal communities to prosecute crimes of violence against women and provide services to victims of sexual assault, domestic violence, and stalking in the Bakken Region of North Dakota and Montana.[2097] Rationale documented by tribal leaders, law enforcement, and the FBI included, "rapid

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[2093] Jim Tankersley, "Fracking Hasn't Restored the Rust Belt's Lost Jobs," *The Washington Post*, September 11, 2014, https://www.washingtonpost.com/news/storyline/wp/2014/09/11/fracking-hasnt-restored-the-rust-belts-lost-jobs/.
[2094] Tara Opsal and Tara O'Connor Shelley, "Energy Crime, Harm, and Problematic State Response in Colorado: A Case of the Fox Guarding the Hen House?," *Critical Criminology* 22, no. 4 (2014): 561–77, https://doi.org/10.1007/s10612-014-9255-2.
[2095] Tyler Bell Williston, "Modernized Slavery," *Williston Herald*, September 6, 2014, https://www.willistonherald.com/news/modernized-slavery/article_84e257d8-3615-11e4-a4f8-001a4bcf887a.html.
[2096] Frank Shafroth, "Fracking's Financial Losers: Local Governments," *Governing: The States and Localities*, August 25, 2014, sec. Archive, https://www.governing.com/archive/gov-frackings-financial-losers.html.
[2097] U.S. Department of Justice, "Associate Attorney General West Announces $3 Million in Grants to Address Violence Against Women in Rural and Tribal Communities in the Bakken Region," Press Release (U.S. Department of Justice, August 28, 2014), https://www.justice.gov/opa/pr/associate-attorney-general-west-announces-3-million-grants-address-violence-against-women.

development of trailer parks and modular housing developments often referred to as 'man camps;' abrupt increase in cost of living, especially housing; rapid influx of people, including transients, in a previously rural and stable community; constant fear and perception of danger; and a lost way of life. Local and tribal officials and service providers reported that these changes have been accompanied by a rise in crime, including domestic and sexual violence."[2098]

- May 27, 2014 – A *Bloomberg News* analysis of 61 shale-drilling companies found that the economic picture of shale oil and gas is unstable. Shale debt has almost doubled over the last four years while revenue has gained just 5.6 percent. For the 61 companies in their analysis, *Bloomberg News* reported: "In a measure of the shale industry's financial burden, debt hit $163.6 billion in the first quarter." Further, *Bloomberg* noted that drillers are caught in a bind because they must keep borrowing to pay for exploration needed to "offset steep production declines typical of shale wells…. For companies that can't afford to keep drilling, less oil coming out means less money coming in, accelerating the financial tailspin."[2099]

- May 5, 2014 – An Associated Press analysis found that traffic fatalities have spiked in heavily drilled areas of six states, whereas most other roads in the nation have become safer even as population has grown. In North Dakota drilling counties, for instance, traffic fatalities have increased 350 percent.[2100]

- April 16, 2014 – A comprehensive article in the *Albany Law Review* concluded that the risks inherent with fracking are not covered by homeowner's insurance, not fully insured by the oil and gas industry, and threaten mortgages and property value.[2101]

- April 2014 – A report by the Multi-State Shale Research Collaborative, "Assessing the Impacts of Shale Drilling: Four Community Case Studies," documented economic, community, government, and human services impact of fracking on four rural communities. The study found that fracking led to a rapid influx of out-of-state workers and, although some new jobs were created, these were accompanied by additional costs for police, emergency services, road damage, and social services. In addition, increased rents, and a shortage of affordable housing accompanied the fracking boom. Unemployment rose after one county's boom ended; in another county, unemployment stayed above the state average throughout.[2102]

[2098] U.S. Department of Justice, "OVW Fiscal Year 2014 Violence Against Women Bakken Region Initiative: Enhanced Response to Victims Application Guidelines," 2014.
[2099] Asjylyn Loder, "Shakeout Threatens Shale Patch as Frackers Go for Broke," *Bloomberg*, May 27, 2014, https://www.bloomberg.com/news/articles/2014-05-26/shakeout-threatens-shale-patch-as-frackers-go-for-broke.
[2100] Jonathan Fahey, "AP IMPACT: Deadly Side Effect to Fracking Boom," *Associated Press*, May 5, 2014, sec. Archive, https://apnews.com/article/ac54bee4225241729f360adbbcf394dd.
[2101] Elisabeth N. Radow, "At the Intersection of Wall Street and Main: Impacts of Hydraulic Fracturing on Residential Property Interests, Risk Allocation, and Implications for the Secondary Mortgage Market," *Albany Law Review* 77, no. 2 (2014): 673–704.
[2102] Multi-State Shale Research Collaborative, "Assessing the Impacts of Shale Drilling County Case Studies," April 10, 2014,

- March 27, 2014 – A report by researchers at Rand Corporation determined that each shale gas well in Pennsylvania causes between $5,400 and $10,000 in damage to state roads. The report did not calculate damage to local roads, which is also significant. Researchers used estimates of truck trips that are significantly below the number estimated for New York by the New York State Department of Environmental Conservation (NYS DEC).[2103, 2104]

- February 15, 2014 – The *Los Angeles Times* detailed steep increases in crime that have accompanied fracking in parts of the Eagle Ford Shale in Texas, including sexual assaults and thefts.[2105]

- February 14, 2014 – Pennsylvania landowners with fracking leases rallied in Bradford County against gas companies for precipitous drops in royalty payments.[2106]

- December 20, 2013 – The National Association of Realtors' *RealtorMag* summarized a growing body of research, including a University of Denver survey and a *Reuters* analysis, that shows threats property values from fracking and gas drilling.[2107]

- December 12, 2013 – A *Reuters* analysis discussed how oil and gas drilling has made making some properties "unsellable" and researched the link between drilling and property value declines. The analysis highlighted a Duke University working paper that finds shale gas drilling near homes can decrease property values by an average of 16.7 percent if the house depends on well water.[2108]

- December 10, 2013 – Pennsylvania's *Daily Review* reported that more gas companies are shifting costs to leaseholders and that royalty payments are drastically shrinking. The story quoted Bradford County Commissioner Doug McLinko saying that some gas companies "are robbing our landowners" and that the problem of royalty payments being

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https://docs.google.com/viewer?a=v&pid=sites&srcid=ZGVmYXVsdGRvbWFpbnxtdWx0aXN0YXRlc2hhbGV8Z3g6NGU4MjIyNWU5ZjFhZjM4Yg.

2103 Marie Cusick, "Report Finds Each Marcellus Gas Well Costs Thousands in Road Damage," *State Impact Pennsylvania*, March 27, 2014, https://stateimpact.npr.org/pennsylvania/2014/03/27/report-finds-each-marcellus-gas-well-costs-thousands-in-road-damage/.

2104 Shmuel Abramzon et al., "Estimating the Consumptive Use Costs of Shale Natural Gas Extraction on Pennsylvania Roadways," *Journal of Infrastructure Systems* 20, no. 3 (2014): 06014001, https://doi.org/10.1061/(ASCE)IS.1943-555X.0000203.

2105 Molly Hennessy-Fiske, "Fracking Brings Oil Boom to South Texas Town, for a Price," *Los Angeles Times*, February 15, 2014, sec. World & Nation, https://www.latimes.com/nation/la-na-texas-oil-boom-20140216-story.html.

2106 J. Marshall, "Landowners Rally for Royalties from Gas Companies," *WBNG*, February 14, 2014, http://www.wbng.com/news/local/Landowners-rally-for-245596511.html.

2107 Daily Real Estate News, "'Fracking' Sparks Concern over Nearby Home Values," December 20, 2013, https://web.archive.org/web/20201105141321/https://magazine.realtor/daily-news/2013/12/20/fracking-sparks-concern-over-nearby-home-values.

2108 Michelle Conlin, "Gas Drilling Is Killing Property Values For Some Americans," *Business Insider*, December 12, 2013, https://www.businessinsider.com/drilling-can-make-some-properties-unsellable-2013-12.

significantly reduced by deductions for post-production costs "is widespread throughout our county."[2109]

- November 30, 2013 – The *New York Times* reported striking increases in crime in Montana and North Dakota where the oil and gas boom is prevalent, as well as challenges faced by local residents from the influx of out-of-area workers and the accompanying costs. The *New York Times* reported, "'It just feels like the modern-day Wild West,' said Sgt. Kylan Klauzer, an investigator in Dickinson, in western North Dakota. The Dickinson police handled 41 violent crimes last year, up from seven only five years ago."[2110]

- November 21, 2013 – The Multi-State Shale Research Collaborative released a six-state collaborative report demonstrating that the oil and gas industry has greatly exaggerated the number of jobs created by drilling and fracking in shale formations. The report found that far from the industry's claims of 31 direct jobs created per well, only four jobs are created for each well. It also demonstrated that almost all of the hundreds of thousands of 'ancillary' jobs that the drilling industry claims are related to shale drilling existed before such drilling occurred. As Frank Mauro, Executive Director Emeritus of the Fiscal Policy Institute put it, "Industry supporters have exaggerated the jobs impact in order to minimize or avoid altogether taxation, regulation, and even careful examination of shale drilling."[2111]

- November 12, 2013 – *The American Banker* reported that the "Fracking Boom Gives Banks Mortgage Headaches," with a number of financial institutions refusing to make mortgages on land where oil and gas rights have been sold to an energy company. The article stated that the uniform New York state mortgage agreement used by Fannie Mae and Freddie Mac requires that homeowners not permit any hazardous materials to be used or located on their property. Fracking is therefore a problem because it is just such a hazardous activity with use of hazardous materials.[2112]

- September 25, 2013 – A report found that fracking is linked to significant road damage, increased truck traffic, crime, and strain on municipal and social services. Data from the past ten years on the social costs of fracking including truck accidents, arrests, and higher rates of sexually transmitted diseases are all causes for alarm.[2113]

[2109] J. Loewenstein, "Shrinking Royalty Checks," *The Daily Review*, December 10, 2013, http://thedailyreview.com/news/shrinking-royalty-checks-1.1598195.
[2110] Jack Healy, "As Oil Floods Plains Towns, Crime Pours In," *The New York Times*, November 30, 2013, https://www.nytimes.com/2013/12/01/us/as-oil-floods-plains-towns-crime-pours-in.html?smid=tw-share&_r=0.
[2111] Jon Campbell, "Report: Industry-Backed Studies Exaggerate Fracking Job Estimates," *Democrat and Chronicle*, November 21, 2013, https://www.democratandchronicle.com/story/news/local/2013/11/21/report-industry-backed-studies-exaggerate-fracking-job-estimates/3671199/.
[2112] Andy Peters, "Fracking Boom Gives Banks Mortgage Headaches," *American Banker*, November 12, 2013, https://www.americanbanker.com/news/fracking-boom-gives-banks-mortgage-headaches.
[2113] Brendan S. Gibbons, "Environmental Groups Calculate Social Cost of Natural Gas Boom," *The Times-Tribune*, September 25, 2013, https://www.thetimes-tribune.com/archive/environmental-groups-calculate-social-cost-of-natural-gas-boom/article_a6f11ae0-77d7-5fe1-ac25-a4ec8dd6cd06.html.

- September 12, 2013 – In a feature titled "Pa. fracking boom goes bust," *The Philadelphia Inquirer* presented data from the independent Keystone Research Center detailing "flat at best" job growth and declines in production and royalty payments.[2114]

- August 22, 2013 – A University of Denver study in the *Journal of Real Estate Literature* found a 5-15 percent reduction in bid value for homes near gas drilling sites.[2115]

- August 21, 2013 – *The Atlantic Cities* and *MSN Money* reported that fracking operations may be damaging property values and may impair mortgages or the ability to obtain property insurance.[2116, 2117]

- August 13, 2013 – A *ProPublica* investigative analysis found that Chesapeake Energy is coping with its financial difficulties in Pennsylvania by shifting costs to landowners who are now receiving drastically reduced royalty payments.[2118]

- August 4, 2013 – In a survey of West Virginia landowners with shale wells on their property, more than half reported problems including damage to the land, decline in property values, truck traffic, and lack of compensation by the oil and gas company.[2119]

- May 24, 2013 – Pennsylvania Department of Transportation Secretary Allen D. Biuhler and Pennsylvania State Police Commissioner Frank Pawlowski said that gas drilling has led to increases in truck traffic, traffic violations, crime, demand for social services, and the number of miles of roads that are in need of repairs. They noted that drilling companies that committed to repairing roads have not kept pace with the roads they damage. Commissioner Pawlowski reported that 56 percent of 194 trucks checked were over the legal weight limit and 50 percent were also cited for safety violations.[2120]

- May 4, 2013 – Pennsylvania's *Beaver County Times* asked, "What boom?" in pointing to Keystone Research Center data showing that the number of jobs numbers created by shale gas extraction do not add up to what the gas industry claims, noting that

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[2114] Will Bunch, "Pa. Fracking Boom Goes Bust," *The Philadelphia Inquirer*, November 12, 2013, https://www.inquirer.com/philly/hp/news_update/20130911_Pa__fracking_boom_goes_bust.html.
[2115] Bob Downing, "Survey Says Home Values Hurt by Fracking at Drill Sites," *Akron Beacon Journal*, April 22, 2013, https://web.archive.org/web/20140326041052/http://www.ohio.com/blogs/drilling/ohio-utica-shale-1.291290/survey-says-home-values-hurt-by-fracking-at-drill-sites-1.422838.
[2116] Roger Drouin, "How the Fracking Boom Could Lead to a Housing Bust," *CityLab*, August 19, 2013, https://www.bloomberg.com/news/articles/2013-08-19/how-the-fracking-boom-could-lead-to-a-housing-bust.
[2117] Jason Notte, "Fracking Leaves Property Values Tapped Out," *Concerned Burlington Neighbors* (blog), August 21, 2013, http://concernedburlingtonneighbors.blogspot.com/2013/08/.
[2118] Abrahm Lustgarten, "Unfair Share: How Oil and Gas Drillers Avoid Paying Royalties," *ProPublica*, August 13, 2013, https://www.propublica.org/article/unfair-share-how-oil-and-gas-drillers-avoid-paying-royalties.
[2119] Alan R. Collins and Kofi Nkansah, "Divided Rights, Expanded Conflict: The Impact of Split Estates in Natural Gas Production," Scholarly Project (Natural Resource Economics, West Virginia University, August 4, 2013), https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.734.6591&rep=rep1&type=pdf.
[2120] PR News Wire, "Increased Gas Drilling Activities Bringing New Challenges to Local Governments in Pennsylvania," *PR Newswire*, May 24, 2010, https://www.prnewswire.com/news-releases/increased-gas-drilling-activities-bringing-new-challenges-to-local-governments-in-pennsylvania-94774764.html.

unemployment has increased and the state actually fell to 49th in the nation for job creation.[2121]

- April 2, 2013 – The *New York Times* reported that manufacturing jobs resulting from an abundance of shale gas have not appeared. "The promised job gains, other than in the petrochemical industry, have been slow to materialize," The *New York Times* reported. The article suggested that increased automation has made it unlikely that manufacturers will add many jobs.[2122]

- March 19, 2013 – The *Wall Street Journal* reported that the shale gas boom has not had a big impact on U.S. manufacturing because lower energy prices are only one factor in a company's decision on where to locate factories, and not always the most important factor. "Cheap energy flowing from the U.S. shale-gas boom is often touted as a 'game changer' for manufacturing," the *Journal* reported. "Despite the benefits of lower energy costs, however, the game hasn't changed for most American manufacturers."[2123]

- February 2013 – A peer-reviewed analysis of industry-funded and independent studies on the economics of fracking found that it is unlikely that fracking will lead to long-term economic prosperity for communities. The analysis noted that shale gas development brings a number of negative externalities including the potential for water, air, and land contamination; negative impacts on public health; wear and tear on roads and other infrastructure; and costs to communities due to increased demand for services such as police, fire departments, emergency responders, and hospitals.[2124]

- November 16, 2012 – A Duke University study showed a drop in home values near fracking for properties that rely on groundwater.[2125]

- September 27, 2012 – The *New York Times* reported that the prospect of fracking has hindered home sales in the Catskills and raised concerns about drops in property values, according to real estate agents and would-be buyers.[2126]

[2121] Rachel Morgan, "Beaver County Times: What Boom? Industry Pundits Claim Thousands of Jobs Will Be Created, but Numbers Don't Quite Add up," *Keystone Research Center*, May 4, 2013, https://web.archive.org/web/20131010021511/http://keystoneresearch.org/media-center/media-coverage/beaver-county-times-what-boom-industry-pundits-claim-thousands-jobs-will.

[2122] Nelson D. Schwartz, "Rumors of a Cheap-Energy Jobs Boom Remain Just That," *The New York Times*, April 1, 2013, sec. Business, https://www.nytimes.com/2013/04/02/business/economy/rumors-of-a-cheap-energy-jobs-boom-remain-just-that.html.

[2123] James R. Hagerty, "Shale-Gas Boom Alone Won't Propel U.S. Industry," *Wall Street Journal*, March 19, 2013, sec. Business, https://online.wsj.com/article/SB10001424127887324392804578362781776519720.html.

[2124] Jannette M. Barth, "The Economic Impact of Shale Gas Development on State and Local Economies: Benefits, Costs, and Uncertainties," *New Solutions* 23, no. 1 (2013): 85–101, https://doi.org/10.2190/NS.23.1.f.

[2125] Danielle Muoio, "Duke Researchers Show Dip in Home Value Caused by Nearby Fracking," *The Chronicle*, November 16, 2012, https://www.dukechronicle.com/article/2012/11/duke-researchers-show-dip-home-value-caused-nearby-fracking.

[2126] Mireya Navarro, "Gas Drilling Jitters Unsettle Catskills Sales," *The New York Times*, September 27, 2012, sec. Real Estate, https://www.nytimes.com/2012/09/30/realestate/fracking-fears-hurt-second-home-sales-in-catskills.html.

- August 17, 2012 – A study by the state agencies, the Montana All Threat Intelligence Center and the North Dakota State and Local Intelligence Center, found that crime rose by 32 percent since 2005 in communities at the center of the oil and gas boom.[2127]

- October 30, 2011 – A comprehensive article in the *New York State Bar Association Journal* concluded that the risks inherent with fracking threaten mortgages.[2128]

- October 26, 2011 – The Associated Press reported that areas with significant fracking activity, including Pennsylvania, Wyoming North Dakota and Texas, are "seeing a sharp increase in drunken driving, bar fights and other hell-raising."[2129]

- October 20, 2011 – A *New York Times* investigation found that fracking can create conflicts with mortgages, and that "bankers are concerned because many leases allow drillers to operate in ways that violate rules in landowners' mortgages," and further that "[f]earful of just such a possibility, some banks have become reluctant to grant mortgages on properties leased for gas drilling. At least eight local or national banks do not typically issue mortgages on such properties, lenders say."[2130]

- September 7, 2011 – The NYS DEC estimated that 77 percent of the workforce on initial shale gas drilling projects would consist of transient workers from out of state. Not until the thirtieth year of shale gas development would 90 percent of the workforce be comprised of New York residents.[2131]

- August 15, 2011 – The *Pittsburgh Post-Gazette* reported that increases in crime followed the Pennsylvania gas drilling boom, noting, for instance, that drunken driving arrests in Bradford County were up 60 percent, DUI arrests were up 50 percent in Towanda, and criminal sentencing was up 35 percent in 2010.[2132]

2127 "Impact of Population Growth on Law Enforcement in the Williston Basin Region" (Montana All Threat Intelligence Center & North Dakota State and Local Intelligence enter, August 17, 2012).

2128 Elisabeth N. Radow, "Homeowners and Gas Drilling Leases: Boon or Bust?," *New York State Bar Association* 83, no. 9 (2011), https://planetwaves.net/pdf/fracking.pdf.

2129 Mark Levy, "Towns See Crime, Carousing Surge amid Gas Boom," *The San Diego Union-Tribune*, October 26, 2011, https://www.sandiegouniontribune.com/sdut-towns-see-crime-carousing-surge-amid-gas-boom-2011oct26-story.html.

2130 Ian Urbina, "Rush to Drill for Natural Gas Creates Conflicts With Mortgages," *The New York Times*, October 20, 2011, sec. U.S., https://www.nytimes.com/2011/10/20/us/rush-to-drill-for-gas-creates-mortgage-conflicts.html.

2131 New York State Department of Environmental Conservation, "Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program, Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs," 2011.

2132 Zack Needles, "Must Crime Follow Pennsylvania's Gas Drilling Boom?," *Pittsburgh Post-Gazette*, August 15, 2011, https://www.post-gazette.com/business/legal/2011/08/15/Must-crime-follow-Pennsylvania-s-gas-drilling-boom/stories/201108150204.

- July 26, 2011 – A New York State Department of Transportation document estimated that fracking in New York could result in the need for road repairs and reconstruction costing $211 million to $378 million each year.[2133]

- June 20, 2011 – A Keystone Research Center study found that the gas industry's claim of 48,000 jobs created between 2007 and 2010 as a result of natural gas drilling in Pennsylvania is a far cry from the actual number of only 5,669 jobs—many of which were out-of-state hires.[2134]

- May 9, 2011 – A study in the *Journal of Town & City Management* found that shale gas development can impose "significant short- and long-term costs" to local communities. The study noted that shale gas development creates a wide range of potential environmental hazards and stressors, all of which can adversely impact regional economies, including tourism and agriculture sectors.[2135]

- November 30, 2010 – The *Dallas Morning News* featured a story, "Drilling Can Dig into Land Value," reporting that the Wise County Central Appraisal District Appraisal Review Board found that a drilling company had caused an "extraordinary reduction" in property value, by 75 percent.[2136]

- November 28, 2010 – The Texas *Wise County Messenger* reported that some landowners near fracking operations experience excessive noise, exposure to diesel fumes, and problems with trespassing by workers.[2137]

[2133] S. Reilly, "Document Estimates Fracking's Toll on N.Y. Roads," *Pressconnects.Com*, July 26, 2011, http://www.pressconnects.com/article/20110726/NEWS01/107260384/Document-estimates-fracking-s-toll-N-Y-roads.
[2134] Stephen Herzenberg, "Drilling Deeper into Job Claims" (Keystone Research Center, 2011), http://keystoneresearch.org/sites/keystoneresearch.org/files/Drilling-Deeper-into-Jobs-Claims-6-20-2011_0.pdf.
[2135] Susan Christopherson and Ned Rightor, "How Shale Gas Extraction Affects Drilling Localities: Lessons for Regional and City Policy Makers," *Journal of Town & City Management* 2, no. 4 (2012), http://greenchoices.cornell.edu/resources/publications/drilling/Effects_on_Drilling_Localities.pdf.
[2136] Peggy Heinkel-Wolfe, "Drilling Can Dig into Land Value," *Dallas News*, September 18, 2010, https://web.archive.org/web/20120323152358/http://www.dallasnews.com/incoming/20100918-Drilling-can-dig-into-land-value-9345.ece.
[2137] Brandon Evans, "Rising Volume: 'Fracking' Has Bolstered Economies, but Noise Still Echoes around Drilling," *WC Messenger*, November 28, 2010, https://web.archive.org/web/20110603152315/http://www.wcmessenger.com/2010/news/rising-volume-fracking-has-bolstered-economies-but-noise-still-echoes-around-drilling/.

Inflated estimates of oil and gas reserves, profitability problems, and risk disclosure to investors

Industry projections of shale-based oil and gas reserves have proven undependable, and unable to forecast how much oil or gas can be extracted from a given basin based on the production of existing wells. Further, unlike conventional oil or gas fields, which can provide steady yields for decades, fracked wells typically deplete 70-90 percent within three years, requiring more drilling and continuous capital investment. Low yields and heavy extraction costs have led companies drilling shale to reduce the value of their assets by billions of dollars, creating shortfalls that are largely filled through asset sales and mounting debt load. Throughout the fracking boom, the industry as a whole has spent more money drilling wells than selling oil and gas, remaining dependent on cheap credit made possible by historically low interest rates. Fracking has never been consistently profitable, despite being heavily subsidized through tax incentives that have functioned to encourage continuing investments even when gas and oil prices are low.

In 2014, a fall in oil and gas prices led to a two-year downturn in fracking operations and a wave of bankruptcies. When companies abandoned operations, they also abandoned the wells they drilled, raising questions about who serves as the custodian of inactive wells and their associated infrastructure, now and hereafter. Bonding requirements proved—and still are—notoriously inadequate. In New Mexico alone, the gap between the posted bonds for remediating abandoned and depleted wells and the actual clean-up cost should companies go bankrupt is, as of April 2021, $8.18 billion.

A modest upswing in prices in 2017 brought renewed industry enthusiasm for fracking. However, because of the rapid depletion of individual shale wells and the falling output of major shale basins, operators invested in drilling new wells at an increasingly rapid pace to maintain the same level of extraction. More than half of all U.S. oil was extracted from wells that were two years old or younger, and they pumped less oil than forecast. Despite rising oil prices, fracking-focused companies continued to lose cash. Thus, by 2018, the need to stabilize economic fundamentals by increasing production and lowering costs contributed to the shift toward mega-fracking—with ever-longer laterals and higher volumes of water, sand, and chemicals per well—and also toward the practice of clustering many secondary wells near a productive parent well. The act of fracking these so-called child wells, however, often permanently damages the primary wells they surround, undermining production in the whole area.

In 2020, oil and gas prices collapsed under suddenly constricted demand during the COVID-19 pandemic, oversupply in the global markets, and a price war between Russia and Saudi Arabia. By April 2020, oil futures had fallen to levels below the break-even point for fracking operations, triggering a wave of bankruptcies. Decisions by major investors to divest from fossil fuel projects and rising competition from renewable energy sources abroad have further constrained profitability of fracking and liquefied natural gas (LNG) exports. In 2020 renewables surpassed fossil fuels in their share of European electricity generation.

By 2021, under investor pressure to turn profits and slash carbon emissions, oil and gas majors began selling off fracking assets to smaller, independent companies. As a group, however, these

companies are among the biggest methane emitters in the industry. Commitments by nation states to deep decarbonization under the Paris Agreement, if enacted, will render many new investments in drilling and fracking unprofitable, especially in the Appalachian basin.

Recognition is rapidly consolidating that carbon emissions and related policy and litigation pose material risks to oil and gas investments. First publicly acknowledged by a major oil company in 2016, these risks have since been disclosed in an increasing number of drilling company annual reports. An international shift toward compulsory corporate climate risk reporting is accelerating. Credit risks are rising for natural gas infrastructure projects, while major oil company credit ratings have been downgraded. In May 2021, climate activist investors claimed three of Exxon's board seats, and a Dutch court ordered Shell to cut carbon emissions. While banks around the world are increasingly limiting exposure to, and raising borrowing rates for, oil and gas investments, the European Investment Bank is scheduled to terminate fossil fuel industry lending altogether by the end of 2021. Goldman Sachs forecasts renewable power investment overtaking oil and gas within the year.

- June 23, 2021 – A study from the Stockholm Environment Institute, a nonprofit research center, examined how U.S. federal policy in the form of powerful tax incentives has created an indirect subsidy to the fracking industry throughout the past two decades. These tax breaks reduce the risks of investing and amplify the expected financial returns of investing in fracking operations, thereby aiding and sustaining the U.S. shale boom. The expensing of intangible drilling costs and percentage depletion provisions, for example, work to reduce tax payments and increase the expected value of new oil and gas wells by up to $20 billion in a single year. Among other specific findings: between 2007 and 2014, when oil prices were high (above $60/barrel), subsidies had relatively little effect on decisions to drill. But in low-price years, "subsidies increased expected returns enough to push more than 30 percent of new oil projects into profitability, greenlighting their investment decisions." Further, subsidies likely played a substantial role in abetting the fracking boom in Appalachia, "making new gas projects viable, beginning in 2010, when more than 30 percent of new gas projects may have been subsidy-dependent." This study illustrates that tax code is a powerful policy tool, able to influence what energy projects get developed.[2138]

- June 14, 2021 – Small, independent drilling and fracking companies backed by private equity are disproportionately represented among the highest emitters of methane, according to a report based on industry data submitted to the U.S. Environmental Protection Agency. These 195 small producers together account for 9 percent of production but contribute 22 percent of total reported emissions. "The study also reinforces concerns that oil firms 'greening up' by selling assets does little to help the

[2138] Peter Erickson and Ploy Achakulwisut, "How Subsidies Aided the US Shale Oil and Gas Boom" (Stockholm Environment Institute, June 23, 2021), https://www.sei.org/publications/subsidies-shale-oil-and-gas/.

climate when the emissions are just transferred to another operator that may be less environmentally minded."[2139]

- May 26, 2021 – A group of investors, backed by three large pension funds, installed new board members at ExxonMobil over the objection of the company's management. The new investors want ExxonMobil to pledge to reduce its emissions to net zero by 2050, warning that an emissions reduction strategy was a fundamental investor issue given the immense risk to ExxonMobil's current business model and flagging financial performance. "Investors are no longer standing on the sidelines."[2140]

- May 26, 2021 – The Hague District Court ordered Royal Dutch Shell to cut carbon emissions by 45 percent by 2030, in line with United Nations guidance for member states to limit global warming to 1.5° Celsius above pre-industrial levels. This is the first ruling in the Netherlands of a non-State entity being ordered to reduce carbon dioxide emissions, a ruling which can potentially pave the way for further litigation against other emitters in and outside of the Netherlands.[2141]

- May 18, 2021 – The International Energy Agency, an intergovernmental energy policy advisor to 30 different member nations and other emerging economies, called in a major report for no new investments in fossil fuels as part of a plan to achieve to net-zero emissions by 2050. The plan also calls for retiring coal plants by 2030 and banning sales of new internal combustion engine cars by 2035.[2142]

- April 30, 2021 – The first study to fully assess the inadequacies of New Mexico's oil and gas bonding requirements on both state and private lands found a $8.18 billion gap between the bonds posted for in the state ($201.42 million) and the projected costs of cleaning up the sites should companies declare bankruptcy ($8.38 billion). The study also found that no bonding requirements exist for many of the ancillary pieces of drilling-related infrastructure, including compressor station sites, fracking waste pits, storage facilities, and warehouses.[2143] This study was based on publicly available data as well as data provided to researchers by the New Mexico State Land Office. However, the authors emphasize that their analysis was limited by lack of transparency. "For instance, we did not have access to a full report on the financial assurance carried by operators permitted

[2139] Stephen Cunningham, "Private Equity-Backed Drillers Under Emissions Scrutiny," Argus, June 14, 2021, https://www.argusmedia.com/en/news/2224429-private-equitybacked-drillers-under-emissions-scrutiny?backToResults=true.
[2140] Stephen Cunningham, "Exxon Humbled by Shareholder Revolt: Update," Argus, May 26, 2021, https://www.argusmedia.com/en/news/2218876-exxon-humbled-by-shareholder-revolt-update.
[2141] "Climate Change Litigation Bombshell: Dutch Lower Court Orders Royal Dutch Shell to Reduce CO2 Emissions," Jonesday.com, May 26, 2021, https://www.jonesday.com/en/insights/2021/06/climate-change-litigation-bombshell-dutch-lower-court-orders-royal-dutch-shell-to-reduce-co2-emissions.
[2142] International Energy Agency, "Net Zero by 2050: A Roadmap for the Global Energy Sector, 3rd Revision," May 2021, https://www.iea.org/reports/net-zero-by-2050.
[2143] The Center for Applied Research, Inc., "An Analysis of the Adequacy of Financial Assurance Requirements for Oil and Gas Infrastructure Located on State Trust and Private Lands In New Mexico" (The Center for Applied Research, Inc., April 30, 2021), https://www.nmstatelands.org/wp-content/uploads/2021/05/NM-Assurance-Assessment-May-FINAL.pdf.

by the New Mexico Oil Conservation Division, and therefore we had to use sampling techniques to build a reasonable estimate."[2144]

- March 9, 2021 – A joint analysis by the Stockholm Environment Institute and the Ohio River Valley Institute looked at the major drivers of demand for natural gas and found financial risks for expanding natural gas extraction in Appalachia, including for new gas wells, pipelines, and export terminals. Analysts predicted that decreased global demand and robust competition from renewables will ultimately render new fracking operations in the region, which includes Ohio, West Virginia, and Pennsylvania, unprofitable.[2145]

- February 9, 2021 – Chesapeake Energy, once the United States' second-largest natural gas producer, emerged from bankruptcy with a business plan that signals a shift back to fracking for natural gas—with a focus on Louisiana and Appalachia—and away from oil extraction. Chesapeake filed for court protection in June 2020 and won approval, six months later, for a plan that allowed it to shed about $7.7 billion in debt. Chesapeake was unable to turn a profit while simultaneously paying down $9 billion in debt. To complete its exit from bankruptcy, Chesapeake took on $1 billion in new debt and dismissed 15 percent of its workforce. "We were never able to invest in our assets to the benefit of our shareholders," said Chief Executive Doug Lawler in an interview with Reuters.[2146]

- February 1, 2021 – S&P Global Ratings downgraded the credit ratings of Exxon Mobil Corp, Chevron Corp and ConocoPhillips, citing poor financial performance and pressure to act on climate change. Weeks earlier, the agency had warned it was considering downgrades for 13 of the world's largest oil companies due to rising risk from energy transition and price volatility.[2147]

- January 21, 2021 – The president of the European Investment Bank, Werner Hoyer, announced that the bank is phasing out funding for fossil fuel projects and intends to pursue a decarbonization policy that aligns with the goals of the Paris Climate Agreement. "To put it mildly, gas is over. This is a serious departure from the past, but

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[2144] Hannah Grover, "Analysis Finds $8.1 Billion Gap in New Mexico Bonding Requirements, Clean Up Costs for Oil and Gas," *NM Political Report*, May 20, 2021, https://nmpoliticalreport.com/2021/05/20/analysis-finds-8-1-billion-gap-in-new-mexico-bonding-requirements-clean-up-costs-for-oil-and-gas/.
[2145] Peter Erickson and Ploy Achakulwisut, "Risks for New Natural Gas Developments in Appalachia" (Stockholm Environment Institute U.S. and Ohio River Valley Institute, March 2021), https://cdn.sei.org/wp-content/uploads/2021/03/risks-of-new-natural-gas-developments-in-appalachia-march-2021-final-3.9.21.pdf.
[2146] Jennifer Hiller, "Chesapeake Energy Emerges from Bankruptcy and Shifts Back to Natural Gas," February 2, 2021, https://www.reuters.com/article/us-chesapeake-energy-bankruptcy/chesapeake-energy-emerges-from-bankruptcy-and-shifts-back-to-natural-gas-idUSKBN2A92Z7?feedType=mktg&feedName=&WT.mc_id=Newsletter-US&utm_source=Sailthru&utm_medium=email&utm_campaign=IBM+SEC+Q1+2021+US+Business+News+-+2%2F9&utm_term=2018+-+US+Business+1700.
[2147] Reuters Staff, "S&P Downgrades Exxon and Chevron on Climate Risk, Dour Earnings," Reuters, February 12, 2021, https://www.reuters.com/article/us-usa-oil-credit/sp-downgrades-exxon-and-chevron-on-climate-risk-dour-earnings-idUSKBN2AC29C.

without the end to the use of unabated fossil fuels, we will not be able to reach the climate targets."[2148]

- January, 2021 – Providing 38.2 percent of Europe's electricity, renewable energy surpassed fossil fuels in the European power sector in 2020, jumping by four percent over its 2019 contribution. The use of fossil fuels for power generation declined in the years 2010-2020 from 49 percent to 37 percent, with coal falling fastest.[2149]

- October 2, 2020 – Credit rating agency Moody's announced that long-term credit risks for natural gas infrastructure projects are rising, as the increasing public focus on decarbonization threatens to reduce demand for natural gas. Moody's cited obstacles to pipeline permitting and construction, rising capital costs, and climate goals, in addition to methane emissions and rising safety concerns.[2150]

- July 22, 2020 – An analysis of energy return on investment showed that the fracking industry has consumed an ever-larger portion of the energy it extracts as the shale basins become exhausted and the energy infrastructure is forced to expand and absorb more GDP. Further, because fracked wells typically deplete 70-90 percent within three years, fracking incurs heavy extraction costs and continuous capital investment. The advent of the fracking boom itself, which corresponds to the economic downturn in 2008, was made possible by historically low interest rates and continues to depend on cheap credit. Driven by fracking, the fossil fuel economy suffers from an inability to sustain economic growth as the energy return on investment is lower with fracking than it was for conventional fossil fuels. This article concludes that the United States' increasing reliance on fracking to obtain energy is not sustainable. "On the one hand, this will lead to 'energy sprawl'—the growth of the energy sector, as this sector consumes a much larger portion of the energy it extracts—leaving less energy surplus for other sectors. On the other hand, we will see an unsustainable imbalance between the fuel prices that fossil-fuel companies will need to meet their costs and the fuel prices that the larger economy can afford to pay."[2151]

- July 7, 2020 – The energy media outlet *Energy Review* reported that the collapse in the global gas market has jeopardized the future of capital-intense LNG export projects, which were driven by the U.S. fracking boom. Even as spending on new gas terminals to ship LNG abroad has doubled since 2019, these projects are at risk of being abandoned because of a global glut of fossil fuels. At least two dozen such projects are already cancelled or facing serious financial difficulties. These problems have been made worse

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[2148] "'Gas Is over', EU Bank Chief Says," *Euractiv*, January 21, 2021, https://www.euractiv.com/section/energy-environment/news/gas-is-over-eu-bank-chief-says//.
[2149] Agora Energiewende and Ember, "The European Power Sector in 2020: Up-to-Date Analysis on the Electricity Transition," January 2021, https://ember-climate.org/wp-content/uploads/2021/01/Report-European-Power-Sector-in-2020.pdf.
[2150] Tom DiChristopher, "Moody's: Long-Term Credit Risks Are Rising for Natural Gas Infrastructure Projects," IEEFA.org, October 2, 2020, https://ieefa.org/moodys-long-term-credit-risks-are-rising-for-natural-gas-infrastructure-projects/.
[2151] Bart Hawkins Kreps, "The Rising Costs of Fossil-Fuel Extraction: An Energy Crisis That Will Not Go Away," *American Journal of Economics and Sociology* 79, no. 3 (2020): 695–717, https://doi.org/10.1111/ajes.12336.

by the pandemic but are not expected to resolve when the pandemic ends due to other underlying trends. Other nations have adopted renewable energy technology sooner than expected, and some large investors, including the European Investment Bank, have stopped funding fossil fuel projects altogether as it becomes clear that any new gas infrastructure places the goals of the Paris Climate Accord out of reach.[2152]

- June 28, 2020 – Fracking giant Chesapeake Energy said that it had filed for bankruptcy protection. Once the nation's second-largest gas producer, Chesapeake was beset by debt and deeply harmed by the downturn in oil and gas prices in the wake of the coronavirus pandemic. Owing $9 billion to lenders, Chesapeake entered an agreement to cut $7 billion of its debt.[2153, 2154]

- June 17, 2020 – Goldman Sachs Group reports that investment in renewable energy is expected to overtake oil and gas investment in 2021, representing a $16 trillion investment opportunity in the coming decade. This trend is driven in part by a diverging cost of capital, as borrowing rates have risen as high as 20 percent for hydrocarbon projects compared with as little as 3 percent for clean energy.[2155]

- April 24, 2020 – The largest oil producer in North Dakota, Continental Resources, stopped all drilling in the state and shut in most of its wells as another major player the Bakken Shale, Whiting Petroleum, filed for bankruptcy.[2156]

- April 19, 2020 – U.S. oil prices fell into negative numbers as demand for crude oil plummeted and created a supply glut that filled storage facilities, including tanker vessels anchored at sea. U.S. crude futures fell to levels well below the break-even costs for fracking operations, leading to a wave of drilling halts. Fracking service company Halliburton reported a $1 billion loss during its first quarter.[2157]

- April 10, 2020 – In a financial analysis of U.S. fracking operations, journalist Bethany McLean argued that the willingness of investors to continue buying debt at super-low interest rates has served as a financial lifeline to the fracking industry for the past decade.

[2152] "Gas Projects in Jeopardy as Global Market Collapses," *Energy Review*, July 7, 2020, https://energyreviewmena.com/index.php/article/oil-gas/item/813-gas-projects-in-jeopardy-as-global-market-collapses.
[2153] Cathy Bussewitz and Tali Arbel, "Fracking Pioneer Chesapeake Energy Files for Bankruptcy Protection," *USA Today*, June 28, 2020, https://www.usatoday.com/story/money/2020/06/28/plunging-oil-prices-send-chesapeake-into-bankruptcy/3275712001/.
[2154] Clifford Krauss, "Chesapeake Energy, a Fracking Pioneer, Is Reeling," *The New York Times*, June 9, 2020, sec. Business, https://www.nytimes.com/2020/06/09/business/energy-environment/chesapeake-energy-bankruptcy-protection.html.
[2155] Dan Murtaugh, "Goldman Sachs Sees $16 Trillion Investment Opportunity in Renewable Energy Through 2030," IEEFA.org, June 17, 2020, https://ieefa.org/goldman-sachs-sees-16-trillion-investment-opportunity-in-renewable-energy-through-2030/.
[2156] Devika Krishna Kumar and Liz Hampton, "U.S. Oil Firm Continental Resources Halts Shale Output, Seeks to Cancel Sales," *Reuters*, April 24, 2020, sec. Commodities, https://www.reuters.com/article/us-continental-resources-shale-north-dak-idUSKCN2260PX.
[2157] Stephanie Kelly, "Oil Price Crashes into Negative Territory for the First Time in History amid Pandemic," *Reuters*, April 19, 2020, sec. Commodities, https://www.reuters.com/article/us-global-oil-idUSKBN2210V9.

"They have subprimed the American energy ecosystem." As debt markets grew more cautious, fracking was propped up by private equity investors. "In the Haynesville and the Utica Shales, two major natural gas plays, over half of the drilling is being done by private equity-backed companies; in the oil-rich Permian Basin, it's about a quarter of the drilling. From 2015 through 2019, private equity firms raised almost $80 billion in funds focused mostly on shale production…. Energy independence was a fever dream, fed by cheap debt and frothy capital markets."[2158]

- April 1, 2020 – U.S. fracking company Whiting Petroleum announced it had filed for bankruptcy protection.[2159]

- March 11, 2020 – U.S. fracking company Occidental Petroleum announced it had cut dividends to investors for the first time in 30 years due to a sharp decline in prices.[2160]

- December 23, 2019 – Banks that have helped fund the fracking boom have begun to tighten revolving lines of credit as they revise estimates on the value of shale reserves held as collateral.[2161]

- December 11, 2019 – Chevron announced that it would write down at least $10 billion in assets, mostly shale gas holdings in the Marcellus Shale and a planned LNG export facility in Canada, while EQT, also a major player in the Marcellus Shale, cut a quarter of its work force.[2162]

- August 20, 2019 – Using new methods involving water pyrolysis, a team of researchers at University of Nottingham estimated the amount of gas inside the Bowland Shale in the United Kingdom. Their findings showed dramatically less gas available for extraction by fracking than previous supposed. According to their results, the amount of gas available is the equivalent of five to seven years of gas, based on current rates of consumption in the United Kingdom. Previous estimates by the British Geological Survey had pegged the likely amount of gas as a 50-year supply.[2163, 2164]

[2158] Bethany McLean, "Opinion | Coronavirus May Kill Our Fracking Fever Dream," *The New York Times*, April 10, 2020, sec. Opinion, https://www.nytimes.com/2020/04/10/opinion/sunday/coronavirus-texas-fracking-layoffs.html.
[2159] Collin Eaton and Andrew Scurria, "Whiting Petroleum Becomes First Major Shale Bankruptcy as Oil Prices Drop," *Wall Street Journal*, April 1, 2020, sec. Business, https://www.wsj.com/articles/u-s-shale-driller-whiting-petroleum-to-file-for-bankruptcy-11585746800.
[2160] "US Fracking Giant Feels Pain of Price Crash," *Energy Reporters*, March 11, 2020, https://www.energy-reporters.com/production/us-fracking-giant-feels-pain-of-price-crash/.
[2161] Christopher M. Matthews, Bradley Olson, and Allison Prang, "Banks Get Tough on Shale Loans as Fracking Forecasts Flop," *Wall Street Journal*, December 23, 2019, sec. Business, https://www.wsj.com/articles/banks-get-tough-on-shale-loans-as-fracking-forecasts-founder-11577010600.
[2162] Clifford Krauss, "Natural Gas Boom Fizzles as a U.S. Glut Sinks Profits," *The New York Times*, December 11, 2019, sec. Business, https://www.nytimes.com/2019/12/11/business/energy-environment/natural-gas-shale-chevron.html.
[2163] Patrick Whitelaw et al., "Shale Gas Reserve Evaluation by Laboratory Pyrolysis and Gas Holding Capacity Consistent with Field Data," *Nature Communications* 10, no. 1 (2019): 3659, https://doi.org/10.1038/s41467-019-11653-4.
[2164] Matt McGrath, "Fracking: UK Shale Reserves May Be Smaller than Previously Estimated - BBC News," *BBC News*, August 20, 2019, https://www.bbc.com/news/science-environment-49395658.

- January 2, 2019 – An analysis by the *Wall Street Journal* comparing productivity estimates provided to investors with third-party projections revealed that thousands of shale wells are pumping considerably less oil and gas than owners were forecasting. Two-thirds of projections made by fracking companies between 2014-2017 in Texas and North Dakota oil basins were overly optimistic. All together, these companies are on track to extract 10 percent less oil and gas than they predicted. "The Journal's findings suggest current production levels may be hard to sustain without greater spending because operators will have to drill more wells to meet growth targets."[2165]

- October 17, 2018 – A research brief jointly published by the Institute for Energy Economics and Financial Analysis and the Sightline Institute tracked cash flow for 33 leading fracking companies. It found that fracking-focused companies continued to lose cash through the first half of 2018. Specifically, between January and June 2018, in spite of rising oil prices, fracking companies spent $3.9 billion more on drilling than they generated by selling oil and gas.[2166]

- September 20, 2018 – Confronted with falling prices and mounting debt, Southwest Energy sold off its assets in Arkansas' Fayetteville Shale, placing fracking on hold.[2167]

- June 4, 2018 – A macroeconomic study using a simulation model found that economies that depend on fossil fuel extraction could be gravely harmed if global demand for fossil fuels declines in the face of innovations in energy efficiency and renewable technologies and public policy that promotes them. "Russia, the United States or Canada…could see their fossil fuel industries nearly shut down. ... The United States is worse off if it continues to promote fossil fuel production and consumption than if it moves away from them. This is due to the way global fossil fuel prices are formed. If the rest of the world reduces fossil fuel consumption and there is a sell-out, then lower fuel prices will make much US production non-viable, regardless of its own policy, meaning that its assets become stranded."[2168]

- December 12, 2017 – Under pressure from investors, Exxon agreed to disclose more details about climate risks by filing with the SEC, in a Form 8-K, a statement that said the company would no longer resist motions from shareholders seeking this information.[2169]

[2165] Bradley Olson, Rebecca Elliott, and Christopher M. Matthews, "Fracking's Secret Problem—Oil Wells Aren't Producing as Much as Forecast," *Wall Street Journal*, January 2, 2019, sec. Markets, https://www.wsj.com/articles/frackings-secret-problemoil-wells-arent-producing-as-much-as-forecast-11546450162.
[2166] Institute for Energy Economics and Financial Analysis, & Sightline Institute. (2018, October 17). *Energy market update: Red flags on U.S. fracking, disappointing financial performance continues.* Retrieved from http://ieefa.org/wp-content/uploads/2018/10/Red-Flags-on-U.S.-Fracking_October-2018.pdf
[2167] Daniel Breen, "Fayetteville Shale Assets Sold Off, Fracking Still On Hold," *Arkansas Public Media*, September 20, 2018, https://www.arkansaspublicmedia.org/post/fayetteville-shale-assets-sold-fracking-still-hold.
[2168] J.-F. Mercure et al., "Macroeconomic Impact of Stranded Fossil Fuel Assets," *Nature Climate Change* 8, no. 7 (2018): 588–93, https://doi.org/10.1038/s41558-018-0182-1.
[2169] David Hasemyer and John H. Cushman Jr., "Exxon Agrees to Disclose Climate Risks Under Pressure from Investors," *Inside Climate News*, December 12, 2017, https://insideclimatenews.org/news/12122017/exxon- climate-risk-disclosure-sec-shareholder-investigation-pressure.

- June 16, 2017 – Because of a persistent slump in gas prices and the declining productivity of many of its Marcellus Shale wells, the revenue from gas drilling fees fell for a third straight year in Pennsylvania. The annual fee revenue goes to county and municipal governments, roadway repairs, and infrastructure upgrades, among other things.[2170]

- April 3, 2017 – A British team of researchers assessed the physical footprint of well pads in Europe and the United Kingdom if shale gas development goes forward. When they included proposed setbacks for the UK—the minimal distance well pads have to be away from existing homes and other infrastructure—they found that recoverable oil and gas would be limited by 74 percent.[2171]

- March 25, 2017 – The *Economist* took shale fracking to task for its unstable finances and inability to turn a profit. "Shale firms are on an unparalleled money-losing streak. About $11bn was torched in the last quarter, as capital expenditures exceeded cashflows. The cash-burn rate may well rise again this year. . . . The oil bulls of Houston have yet to prove that they can pump oil and create value at the same time."[2172]

- March 21, 2017 – An MIT study questioned the U.S. Energy Information Administration's rosy projections on the abundance and availability of shale gas and oil. Analyzing field data on oil wells in North Dakota's Williston Basin, the authors found that advances in fracking technology, such as the shift to longer laterals per well, have had a more modest impact on boosting oil and gas production than the agency had estimated. At the same time, the attraction of operators to the most productive areas of basins has had a greater impact. As time goes by, the prime drilling spots with the easy-to-extract oil or gas will get used up, the authors argued, and technology may not be able to compensate.[2173, 2174]

- March 2, 2017 – In 2016, Chevron became the first major oil company to warn investors in its Form 10-K, which oil and natural gas companies are required to file with the U.S. Securities and Exchange Commission, about the risk of climate change lawsuits. "Increasing attention to climate change risks has resulted in an increased possibility of governmental investigations and, potentially, private litigation against the company."[2175]

[2170] C. Carlson, "Pennsylvania Gas Drilling Fee Revenue Falls for Third Year," *WENY News*, June 16, 2017, https://www.weny.com/story/35680098/pennsylvania-gas-drilling-fee-revenue-falls-for-third-year.
[2171] S.A. Clancy et al., "An Assessment of the Footprint and Carrying Capacity of Oil and Gas Well Sites: The Implications for Limiting Hydrocarbon Reserves," *Science of The Total Environment* 618 (2018): 586–94, https://doi.org/10.1016/j.scitotenv.2017.02.160.
[2172] "America's Shale Firms Don't Give a Frack about Financial Returns," *The Economist*, March 25, 2017, https://www.economist.com/business/2017/03/25/americas-shale-firms-dont-give-a-frack-about-financial-returns.
[2173] J.B. Montgomery and F.M. O'Sullivan, "Spatial Variability of Tight Oil Well Productivity and the Impact of Technology," *Applied Energy* 195 (2017): 344–55, https://doi.org/10.1016/j.apenergy.2017.03.038.
[2174] Christa Marshall, "Studies Attack Conventional Wisdom on Natural Gas," *E&E News*, October 6, 2017, https://web.archive.org/web/20171006225015/https://www.eenews.net/stories/1060062933.
[2175] Joe Romm, "Chevron Is First Oil Major to Warn Investors of Risks from Climate Change Lawsuits," *Think Progress*, March 2, 2017, https://thinkprogress.org/chevron-admits-climate-lawsuits-threaten-profits-33937dd562fd/#.56j1qq4h3.

- July 7, 2016 – "Oil-field-services companies are depleted after slashing prices and laying off workers, and their slow recovery could crimp the energy industry's overall ability to bounce back from the oil bust," according to the *Wall Street Journal*. Almost 70 percent of fracking equipment in the United States has been idled, and 60 percent of field workers involved in fracking have been laid off. Halliburton alone has laid off over 28,500 workers, which is one third of its workforce. More than 70 oilfield services companies have filed for bankruptcy since the beginning of 2015.[2176]

- June 15, 2016 – Billions of dollars of proven reserves have become unproven this year, as "59 U.S. oil and gas companies deleted the equivalent of 9.2 billion barrels, more than 20 percent of their inventories," according to *Bloomberg*. In 2009, the Securities and Exchange Commission (SEC) made it easier for the companies to include in their proven reserves undeveloped acreage and wells that wouldn't be drilled for years on the grounds that "shale prospects are predictable across wide expanses." Since then, the SEC has become more strict about inflated reserves estimates.[2177]

- May 16, 2016 – *CNN Money* reported on the two latest U.S. oil and gas bankruptcies: SandRidge Energy's Chapter 11 filing was based on roughly $4 billion of debt and came the week after the biggest such bankruptcy to date—that of Linn Energy with more than $10 billion in debt. There had been at least 29 U.S. oil and gas bankruptcies in 2016 at the date of the article's publication, bringing the 2015-2016 total to at least 64. "The industry has historically been full of wildcatters and speculators. It's not surprising we're going through this boom-and-bust cycle," the article quoted the managing director at oil restructuring firm SOLIC Capital, George Koutsonicolis, as saying.[2178]

- May 9, 2016 – "The pace of oil patch bankruptcies is picking up," a *Forbes* piece read, listing the 15 biggest such bankruptcies to date. "All told, 69 oil and gas producers with $34.3 billion in cumulative secured and unsecured debt have gone under."[2179]

- March 25, 2016 – Oil and gas borrowers "feasted on what Bloomberg estimates was $237 billion of easy money without scrutinizing whether the loans could endure a drastic downturn," according to a *Washington Post* piece focusing on one company, Swift Energy, which itself was $1.349 billion in debt and had entered bankruptcy. Despite having been cautious prior to the Texas fracking boom, "[a]s the company began to frack more often, the amount it spent on exploration and drilling skyrocketed by hundreds of millions of dollars." Those expenses combined with global developments led to its

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[2176] Alison Sider, "Revving Up Oil Fields Won't Be So Easily Done," *Wall Street Journal*, July 7, 2016, sec. Business, https://www.wsj.com/articles/revving-up-oil-fields-wont-be-so-easily-done-1467883807.
[2177] Asjylyn Loder, "Why Billions in Proven Shale Oil Reserves Suddenly Became Unproven," *Bloomberg*, June 15, 2016, https://www.bloomberg.com/news/articles/2016-06-15/shale-drillers-paper-wells-draw-sec-scrutiny-before-vanishing.
[2178] Matt Egan, "Oil Bankruptcies Mount despite Crude Rebound," *CNNMoney*, May 16, 2016, https://money.cnn.com/2016/05/16/investing/sandridge-energy-oil-bankruptcy/index.html.
[2179] Christopher Helman, "The 15 Biggest Oil Bankruptcies (So Far)," *Forbes*, May 9, 2016, sec. Energy, https://www.forbes.com/sites/christopherhelman/2016/05/09/the-15-biggest-oil-bankruptcies-so-far/.

failure, along with over 40 other oil and gas companies in 2015. "The consequences are far-reaching. The U.S. oil industry, having grown into a giant on par with Saudi Arabia's, is shrinking, with the biggest collapse in investment in energy in 25 years. More than 140,000 have lost energy jobs. Banks are bracing for tens of billions of dollars of defaults, and economists and lawyers predict the financial wreckage will accelerate this year."[2180]

- March 10, 2016 – Crude oil production is not falling as quickly as predicted, given the sharp decline in prices and the drop-off in new drilling and fracking operations. As reported by Reuters, this disconnect is due to refracking of older wells, along with other unconventional techniques such as "choking" and "lifting," which can extend the productive lives of wells or otherwise capture more product from them.[2181]

- March 1, 2016 – An analysis of fracking trends in the journal *Nature* concluded that a European shale gas boom was unlikely due to disappointing early yields (Poland, Lithuania and Denmark), links to earthquakes (United Kingdom), and intense public opposition in densely populated areas throughout the continent.[2182]

- June 19, 2015 – A *Bloomberg Business* analysis of the 62 drilling companies in the Bloomberg Intelligence North America Independent Exploration and Production Index found that the companies' debt continued to be a major problem. For 27 of the 62 companies, interest payments were consuming more than 10 percent of revenue. Drillers' debt rose to $235 billion at the end of the first quarter, a 16 percent increase over the year prior. *Bloomberg Business* expressed concern that shale drillers have "consistently spent money faster than they've made it, even when oil was $100 a barrel." S&P assigned speculative, or junk, ratings to 45 of the 62 companies in Bloomberg's index.[2183]

- April 7, 2015 – A Moody's Investors Service analysis of liquefied natural gas (LNG) prospects found that lower oil prices were causing suppliers to defer or cancel most proposed LNG projects. Moody's found that this was due in part to the drop in international oil prices relative to U.S. natural gas prices, thus removing the economic advantage of U.S. LNG projects. Moody's stated, "LNG is a capital-intensive infrastructure business prone to periodic construction cycles that lead to overcapacity, which we expect will continue for the rest of the decade."[2184]

[2180] Chico Harlan, "The Big Bust in the Oil Fields," *The Washington Post*, March 25, 2016, https://www.washingtonpost.com/news/wonk/wp/2016/03/25/the-big-bust-in-the-oil-fields/.
[2181] Swetha Gopinath and Amrutha Gayathri, "Forget Fracking. Choking and Lifting Are Latest Efforts to Stem U.S. Shale Bust," *Reuters*, March 9, 2016, sec. Commodities News, https://www.reuters.com/article/us-usa-shale-analysis-idUSKCN0WB1AI.
[2182] Mason Inman, "Can Fracking Power Europe?," *Nature* 531, no. 7592 (2016): 22–24, https://doi.org/10.1038/531022a.
[2183] Asjylyn Loder, "The Shale Industry Could Be Swallowed By Its Own Debt," *Bloomberg*, June 18, 2015, https://www.bloomberg.com/news/articles/2015-06-18/next-threat-to-u-s-shale-rising-interest-payments.
[2184] Moody's Investors Service, "Lower Oil Prices Cause Suppliers of Liquefied Natural Gas to Nix Projects," *Moodys.Com*, April 7, 2015, sec. Ratings & Assessments News, http://www.moodys.com:18000/research/Moodys-Liquefied-natural-gas-projects-nixed-amid-lower-oil-prices--PR_322439.

- March 20, 2015 – A study by the Energy Watch Group in Germany found that the costs of allowing fracking in Germany would outweigh the benefits, noting in part that natural gas trading in the United States has been declining since 2009. The study also noted the costs of infrastructure, environmental and health risks and pointed to the need to expand renewable energy.[2185]

- December 19, 2014 – An International Energy Agency (IEA) report projected that U.S. domestic oil supplies, dominated by fracking, face challenges, and oil output from shale formations output, will level off and decline in the early 2020s.[2186] IEA Chief Economist Fatih Birol said, "A well-supplied oil market in the short-term should not disguise the challenges that lie ahead."[2187]

- August 29, 2014 – Andrew Nikiforuk, a Canadian energy analyst, reported on diminishing returns and the higher-cost, higher-risk nature of fossil fuel extraction by fracking. Nikiforuk wrote, "Most of the world's oil and gas firms are now pursuing extreme hydrocarbons because the cheap and easy stuff is gone…. That means industry will spend more good money chasing poor quality resources. They will inefficiently mine and frack ever larger land bases at higher environmental costs for lower energy returns."[2188]

- July 29, 2014 – According to the U.S. Energy Information Administration, energy companies are incurring increasing debt and selling assets to continue drilling in shale. "Based on data compiled from quarterly reports, for the year ending March 31, 2014, cash from operations for 127 major oil and natural gas companies totaled $568 billion, and major uses of cash totaled $677 billion, a difference of almost $110 billion. This shortfall was filled through a $106 billion net increase in debt and $73 billion from sales of assets . . ."[2189]

- July 2014 – Researchers at the Washington, DC-based Environmental Law Institute and Washington & Jefferson College in Pennsylvania collaborated to produce a report designed in part to help communities avoid the "boom and bust" cycles of extractive industries. Authors warned, "While resource extraction has long been regarded as an economic benefit, a body of academic literature suggests that long term growth based chiefly on resource extraction is rare." Confounding factors include transience of the

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2185 Nicole Sagener, "Fracking Costs Outweigh Benefits for Germany and Europe, Study Says," *EurActiv*, March 20, 2015, sec. Energy, https://www.euractiv.com/section/energy/news/fracking-costs-outweigh-benefits-for-germany-and-europe-study-says/.
2186 International Energy Agency, "World Energy Outlook 2014 – Executive Summary," December 2014, https://iea.blob.core.windows.net/assets/e6f58562-203e-474c-97a3-486f409aa7ff/WEO2014.pdf.
2187 Dennis Dimick, "How Long Can the U.S. Oil Boom Last?," *National Geographic*, December 19, 2014, sec. Science, https://www.nationalgeographic.com/science/article/141219-fracking-oil-supply-price-reserves-profits-environment.
2188 Andrew Nikiforuk, "A Big Summer Story You Missed: Soaring Oil Debt," *The Tyee*, August 29, 2014, http://thetyee.ca/Opinion/2014/08/29/Soaring-Oil-Debt-Summer/.
2189 U.S. Energy Information Administration, "As Cash Flow Flattens, Major Energy Companies Increase Debt, Sell Assets," *Today in Energy*, July 29, 2014, https://www.eia.gov/todayinenergy/detail.php?id=17311.

workforce, localized inflation, widening disparities in royalties and impact fee disbursement, commodity price volatility, and communities overspending on infrastructure.[2190]

- June 19, 2014 – Energy analyst Deborah Lawrence Rogers outlined the spiraling debt and severe deterioration of the assets of five major shale gas drillers over the last five years. She concluded, “This is not sustainable. It could be argued that it is not even moral. It is a failed business model of epic proportion. While companies could make the argument at one time that this was a short term downtrend, that no longer holds water because this pattern is long term.”[2191]

- April 10, 2014 – A report by a petroleum geologist and petroleum engineer concluded the 100-year supply of shale gas is a myth, distinguished between what is technically recoverable and economically recoverable shale gas, and asserted that at current prices, New York State has no economically recoverable shale gas.[2192]

- February 28, 2014 – Maria van der Hoeven, Executive Director of the IEA, said in an interview with *The Christian Science Monitor* that there is only a decade left in the U.S. shale oil and gas boom, noting that her agency’s analysis predicts that production will soon flatten out and, by 2025, begin to decline.[2193]

- December 18, 2013 – A University of Texas study in *Proceedings of the National Academy of Sciences* found that fracking well production drops sharply with time, which undercuts the oil and gas industry’s economic projections.[2194] In an interview about the study with *StateImpact NPR* in Texas, Tad Patzek, Chair of the Department of Petroleum and Geosystems Engineering at University of Texas at Austin, noted that fracking “also interferes now more and more with daily lives of people. Drilling is coming to your neighborhood, and most people abhor the thought of having somebody drilling a well in their neighborhood.”[2195]

[2190] Environmental Law Institute & Washington & Jefferson College, “Getting the Boom without the Bust: Guiding Southwestern Pennsylvania through Shale Gas Development,” 2014, https://www.eli.org/sites/default/files/eli-pubs/getting-boom-final-paper-exec-summary-2014-07-28.pdf.
[2191] Deborah Lawrence Rogers, “Huge CAPEX = Free Cash Flow? Not in Shales,” *Energy Policy Forum*, June 19, 2014, https://web.archive.org/web/20130630100230/http://energypolicyforum.org/2013/06/19/huge-capex-free-cash-flow-not-in-shales/.
[2192] Labyrinth Consulting Services, Inc., A. Berman, and L. Pittinger, “Resource Assessment of Potentially Producible Natural Gas Volumes From the Marcellus Shale, State of New York,” https://www.slideshare.net/MarcellusDN/resource-assessment-of-potentially-producible-natural-gas-volumes-from-the-marcellus-shale-state-of-new-york.
[2193] D. J. Unger, “IEA Chief: Only a Decade Left in US Shale Oil Boom,” *Christian Science Monitor*, February 28, 2014, https://www.csmonitor.com/Environment/Energy-Voices/2014/0228/IEA-chief-Only-a-decade-left-in-US-shale-oil-boom.
[2194] Tad W. Patzek, Frank Male, and Michael P. Marder, “Gas Production in the Barnett Shale Obeys a Simple Scaling Theory,” *Proceedings of the National Academy of Sciences* 110, no. 49 (2013): 19731–36, https://doi.org/10.1073/pnas.1313380110.
[2195] Mose Buchele, “New Study Shows How Gas Production From ‘Fracked’ Wells Slows Over Time,” *State Impact Texas*, December 18, 2013, https://stateimpact.npr.org/texas/2013/12/18/new-study-shows-how-gas-production-from-fracked-wells-slows-over-time/.

- August 18, 2013 – *Bloomberg News* reported that low gas prices and disappointing wells have led major companies to devalue oil and gas shale assets by billions of dollars.[2196]

- October 21, 2012 – The *New York Times* reported that many gas drilling companies overproduced natural gas backed by creative financing and now "are committed to spending far more to produce gas than they can earn selling it." "We are all losing our shirts today," said Exxon CEO Rex Tillerson in the summer of 2012.[2197]

- July 13, 2012 – *The Wall Street Journal* reported that ITG Investment Research, at the request of institutional investors, evaluated the reserves of Chesapeake Energy Corporation's shale gas reserves in the Barnett and Haynesville formations and found them to be only 70 percent of estimates by Chesapeake's engineering consultant for the company's 2011 annual report. Chesapeake and its consultant defended their figures.[2198]

- August 23, 2011 – The U.S. Geological Survey (USGS) cut the government's estimates of natural gas in the Marcellus Shale from 410 trillion cubic feet to 84 trillion cubic feet, equivalent to a reduction from approximately 16 years of U.S. consumption at current levels of natural gas use, to approximately 3.3 years of consumption. The USGS's updated estimate was for natural gas that is technically recoverable, irrespective of economic considerations such as the price of natural gas or the cost of extracting it.[2199]

- June 26-27, 2011 – As reported in two *New York Times* stories, hundreds of emails, internal documents, and analyses of data from thousands of wells from drilling industry employees, combined with documents from federal energy officials, raised concerns that shale gas companies were overstating the amount of gas in their reserves and the profitability of their operations.[2200, 2201, 2202] The *New York Times*' public editor criticized the stories, but offered no evidence that the major findings were wrong.[2203] The *New York*

[2196] Matthew Monks, Rebecca Penty, and Gerrit de Vynck, "Shale Grab in U.S. Stalls as Falling Values Repel Buyers: Energy," *Bloomberg*, August 18, 2013, https://www.bloomberg.com/news/articles/2013-08-18/shale-grab-in-u-s-stalls-as-falling-values-repel-buyers.
[2197] Clifford Krauss and Eric Lipton, "After the Boom in Natural Gas," *The New York Times*, October 20, 2012, https://www.nytimes.com/2012/10/21/business/energy-environment/in-a-natural-gas-glut-big-winners-and-losers.html?pagewanted=all.
[2198] Matt Wirz, "Chesapeake Reserve Doubted," *Wall Street Journal*, July 13, 2012, sec. Business, https://online.wsj.com/article/SB10001424052702303644004577523411723501548.html.
[2199] U.S. Geological Survey, "USGS Releases New Assessment of Gas Resources in the Marcellus Shale, Appalachian Basin," August 23, 2011, https://www.usgs.gov/science-explorer-results?es=USGS+releases+new+assessment+of+gas+resources+in+the+Marcellus+shale%2C+Appalachian+Basin.
[2200] Ian Urbina, "Insiders Sound an Alarm Amid a Natural Gas Rush," *The New York Times*, June 26, 2011, sec. U.S., https://www.nytimes.com/2011/06/26/us/26gas.html.
[2201] U.S. Energy Information Administration, "U.S. Natural Gas Summary," May 30, 2014, https://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_nus_a.htm.
[2202] Ian Urbina, "Geologists Sharply Cut Estimate of Shale Gas," *The New York Times*, August 25, 2011, sec. U.S., https://www.nytimes.com/2011/08/25/us/25gas.html.
[2203] Arthur S. Brisbane, "Opinion | Clashing Views on the Future of Natural Gas," *The New York Times*, July 16, 2011, sec. Opinion, https://www.nytimes.com/2011/07/17/opinion/sunday/17pubed.html.

Times' news editors publicly defended both stories against the public editor's criticism.[2204, 2205]

[2204] Arthur S. Brisbane, "Times Editors Respond to My Shale Gas Column," *The New York Times*, July 17, 2011, sec. Opinion, https://publiceditor.blogs.nytimes.com/2011/07/17/times-editors-respond-to-my-shale-gas-column/.
[2205] Arthur S. Brisbane, "Times Editors Respond to Column on Redactions," *The New York Times*, July 30, 2011, http://publiceditor.blogs.nytimes.com/2011/07/30/times-editors-respond-to-column-on-redactions/.

Medical and scientific calls for more study, reviews confirming evidence of harm, and calls for increased transparency and science-based policy

As published reviews and international governmental reports underscore the mounting evidence of health risks—including developmental, neurological, carcinogenic, respiratory, reproductive, and psychological—medical professionals and scientists in the United States and around the world increasingly call for the suspension of fracking in order to prevent its adverse public health harms, including health threats from climate change. Organizations of medical professionals and scientists are also issuing calls for comprehensive, long-term study of the full range of potential health and ecosystem effects of fracking. These appeals underscore the accumulating evidence of harm, point to the knowledge gaps that remain, and decry the atmosphere of secrecy and intimidation that continues to impede the progress of scientific inquiry.

- June 26, 2021 – The president and CEO of Mental Health Colorado called for a systemic shift away from the "harmful and short-sighted cycle of boom and bust" energy policies, noting that the oil and gas industry's activities in the state have led to chronic stress, depression, and anxiety among Colorado residents. Impacts threatening mental health include light pollution, noise pollution, safety concerns, landscape changes, and feelings of powerless in local decision-making. "Coloradans who have called these communities home for generations find that they often have little to say about the transformation of their world by an invasion of powerful industry." The author also urged "true representation in the decision-making process."[2206]

- June 8, 2021 – A sweeping review of the research on the environmental, economic, and anthropogenic impacts of fracking called for greater focus on the inevitable bust periods that follow fracking booms, noting that most research findings have been solely based on investigations of boom-time activities. In their analysis on costs and benefits of fracking, this team of economists and public health scientists examined the literature on local air pollution, global air pollution, water pollution, noise, light, seismic activity, direct and indirect measures of health, migration, education, labor, income, agriculture, and environmental justice. Their analysis showed mixed results and revealed data gaps. The authors emphasized that an understanding of all these impacts is critical for policy makers, who now must also pay attention to changes affecting communities while the industry contracts due to factors such as the COVID pandemic.[2207]

- June 4, 2021 – Following the fourth "near-miss" in nine months at the Enbridge North Weymouth gas compressor (a release of over 11,000 cubic feet of highly pressurized gas, following large leaks on September 11, September 30, and April 6), two prominent Boston-area physician-researchers appealed for the facility to be shut down. Dr. Caren Solomon, a deputy editor at the *New England Journal of Medicine,* an associate professor

[2206] Vincent Atchity, "Opinion: Another Factor to Keep in Mind in Colorado's Oil and Gas Communities — Healthy Minds," *The Colorado Sun*, June 26, 2021, https://coloradosun.com/2021/06/26/mental-health-oil-gas-opinion/.
[2207] Katie Jo Black et al., "Economic, Environmental, and Health Impacts of the Fracking Boom," *Annual Review of Resource Economics* 13 (2021), https://doi.org/10.1146/annurev-resource-110320-092648.

of medicine at Harvard Medical School, and a physician at the Brigham and Women's Hospital, and Dr. Philip J. Landrigan, Professor at Boston College (BC) and Director of BC's Program for Global Public Health and the Common Good, wrote, "Enbridge's cavalier reaction is typical of the arrogance, dishonesty, lack of regulatory oversight, and lack of concern for public safety that has characterized the North Weymouth compressor project from its beginning." They welcomed the retraction of the state's own flawed Health Impact Assessment but noted that state support of the project should have been withdrawn much sooner.[2208]

- May 17, 2021 – Fracking was named as an emerging concern by the American Pediatric Society in its statement on ambient air pollution harming children. The authors of "Policy Statement on Organizational Principles to Guide and Define the Child Health Care System and/or Improve the Health of all Children" identified fracking wells, flare stacks, water storage pits, tanks, sand operations, and diesel-powered equipment and trucks as contributors of multiple air pollutants, including toxic vapors, and criteria air pollutants, such as nitrogen oxides and fine particles. They also noted that fracking pollutants are among those named that originate outdoors but that may enter buildings and vehicles through open doors and windows, ventilation systems, and cracks in structures. By these pathways, fracking can exacerbate the burden of indoor-derived air pollutants on children.[2209]

- April 26, 2021 – Three faculty members at the Columbia University Mailman School of Public Health called for a rapid phaseout of fracking. Noting exemptions from "an astonishing list" of key federal regulations, the authors outlined the many significant risks research has documented for pregnant people, including congenital heart defects, elevated maternal stress from noise and light pollution, and endocrine disruption. They also noted environmental injustices from disproportionate impacts on low-income communities. "For the millions of Americans directly affected by fracking, it's time to put their health, and the health of future generations health, first and stop these injustices."[2210]

- January 25, 2021 – Dr. Philip J. Landrigan, a leading pediatrician, epidemiologist, and public health physician, wrote to the Federal Energy Regulatory Commission to request reexamination of the agency's decision to permit the operation of a natural gas compressor station in North Weymouth, Massachusetts. Dr. Landrigan critiqued the limited scope of the state's Health Impact Assessment, citing deficiencies in its review of fire and explosion hazards, toxic emissions, existing chronic disease burden in the community, economic and racial justice concerns, and climate impacts.[2211]

[2208] Caren Solomon and Philip Landrigan, "Enough Is Enough. It's Time To Shut Down The Weymouth Compressor," WBUR, June 4, 2021, https://www.wbur.org/cognoscenti/2021/06/04/weymouth-compressor-leak-shutdown-caren-solomon-philip-landrigan.
[2209] Heather L. Brumberg and Catherine J. Karr, "Ambient Air Pollution: Health Hazards to Children," *Pediatrics* 147, no. 6 (2021), https://doi.org/10.1542/peds.2021-051484.
[2210] Chelsea Clinton, Terry McGovern, and Micaela Martinez, "End Fracking Exemptions, a Threat to Maternal and Public Health," *Stat*, April 26, 2021, https://www.statnews.com/2021/04/26/end-fracking-exemptions-a-threat-to-maternal-and-public-health/.
[2211] Philip J. Landrigan, "Re: Natural Gas Compressor Station in North Weymouth, Massachusetts," Letter to the Federal Energy Regulatory Commission, January 25, 2021.

- June 1, 2020 – Writing in the *Lancet*, biologist and endocrinologist Barbara A. Demeneix called for recognition of, and action on, the interlinked threats to life brought by fossil fuels, specifically highlighting fracking. She described a web of threats originating with fossil fuel extraction and highlighted the dangers of endocrine-disrupting chemicals, writing that, "Gas derived from fracking is rapidly driving the development of new petrochemical and plastics plants worldwide," and those stark increases harm health, biodiversity, and the climate. Urgent attention, political support, and investment in alternative energies will reduce these harms and help attain the United Nations sustainable development goals.[2212]

- May 9, 2020 – The Advisory Committee of the German Society of Toxicology, the largest scientific toxicological organization in Europe, published a "Critical evaluation of human health risks due to hydraulic fracturing in natural gas and petroleum production."[2213] Among their conclusions: strong evidence links fracking fluids to local environmental contamination; fracking fluids that contain known human carcinogens cannot be confirmed as safe; and the health risks from fracking can include long-lasting contamination of soil and water. Reviewers noted that the "… most critical part of risk assessment in this context is the exposure assessment which is hampered by the unavailability of data from qualified baseline monitoring" before the start of fracking operations.

- February 24, 2020 – An open letter signed by over 50 health care professionals cited health risks related to fracking and climate change in their expressed opposition to the continued construction of the Coastal GasLink fracked gas pipeline in in northern British Columbia.[2214] They wrote, "the health risks from fracking are well known, including release of carcinogenic toxins such as benzene. Pregnant women in northeastern B.C. have serum benzene levels three times the normal level and studies have shown this has an association with increased childhood leukemia rates. U.S. studies have shown increases in congenital heart disease, chronic pulmonary disorders and small birth-weight babies in populations living in proximity to fracking operations. And as we all know, every pipeline leaks." Their letter expressed solidarity with Indigenous rights of Wet'suwet'en, whose land is being annexed for this pipeline without their consent.

- January 29, 2020 – A new report outlining the serious health and environmental dangers of fracking by Canadian Association of Physicians for the Environment called for a moratorium on the development of new fracked natural gas wells in each province and territory across Canada; plans to phase out existing fracking wells to meet Canada's commitments under the Paris Agreement; Health and Equity Impact Assessments to

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[2212] Barbara A Demeneix, "How Fossil Fuel-Derived Pesticides and Plastics Harm Health, Biodiversity, and the Climate," *The Lancet Diabetes & Endocrinology* 8, no. 6 (2020): 462–64, https://doi.org/10.1016/S2213-8587(20)30116-9.

[2213] Klaus-Michael Wollin et al., "Critical Evaluation of Human Health Risks Due to Hydraulic Fracturing in Natural Gas and Petroleum Production," *Archives of Toxicology* 94, no. 4 (2020): 967–1016, https://doi.org/10.1007/s00204-020-02758-7.

[2214] Various Authors, "Health Professionals Call for a Moratorium on Coastal GasLink Construction Permits," *Ricochet*, February 24, 2020, https://ricochet.media/en/2952.

prioritize wells for early closure; and "Just Transition" plans to help workers and their 14communities prepare for the new low-carbon economy.[2215] In a press release, Dr. Éric Notebaert, member of the Association and advisor to the report, outlined findings of urgent concern and strong evidence including low birth weight, "an indicator for a number of serious health impacts including developmental deficits in children and increased rates of cardiovascular disease in later life."[2216]

- January 9, 2020 – "Gas is associated with health and environmental hazards and reduced social welfare at every stage of its life cycle," wrote three medical doctors in the *New England Journal of Medicine.*[2217] The piece briefly highlighted those hazards from the well to transport and storage, from routine exposures to explosions, as well as providing an up-to-date summary of the threat to the climate by continued extraction and use of fracked gas. The authors stated, "As physicians deeply concerned about climate change and pollution and their consequences, we consider expansion of the natural-gas infrastructure to be a grave hazard to human health," calling for "courageous political leadership" to enact the appropriate policies.

- January 8, 2020 – An interdisciplinary team headed by Yale environmental health epidemiologist Nicole Deziel together with Israeli colleagues conducted a scoping review to assess what is known about the human health outcomes associated with fracking. Of the 29 studies that met their criteria for inclusion, 25 reported at least one statistically significant adverse health outcome linked to a fracking-related exposure. The authors concluded that a growing body of evidence shows health problems in communities near drilling and fracking sites. They also emphasized that many health outcomes may take years to emerge, partly because of latency periods for diseases such as cancer. They stated that while it is important that these data be replicated in other populations, "the need for more research need not be used as a barrier to implementing policies."[2218]

- November 19, 2019 – A letter signed by over 100 leading Israeli scientists, including Nobel laureate Robert Aumann, called for the reversal of the government's decision to build a new network of 16 gas-fired power plants.[2219] In their appeal to transition to renewable energy rather than to gas, they cite the powerful short-term climate warming impact of methane as well as carcinogenic emissions. "During the production, refining and delivery of the gas, much greater quantities of methane are released than were

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[2215] Ronald Macfarlane and Kim Perrotta, "Fractures in the Bridge: Unconventional (Fracked) Gas, Climate Change and Human Health" (Canadian Association of Physicians for the Environment, 2020), https://cape.ca/wp-content/uploads/2020/01/CAPE-Fracking-Report-EN.pdf.
[2216] Milissa Hughes, "Doctors Release New Report Calling for Moratorium on Fracking in Canada" (Canadian Association of Physicians for the Environment, January 29, 2020), https://cape.ca/wp-content/uploads/2020/01/Fracking-press-release-EN-Jan-29.pdf.
[2217] Philip J. Landrigan, Howard Frumkin, and Brita E. Lundberg, "The False Promise of Natural Gas," *New England Journal of Medicine* 382, no. 2 (2020): 104–7, https://doi.org/10.1056/NEJMp1913663.
[2218] Nicole C. Deziel et al., "Unconventional Oil and Gas Development and Health Outcomes: A Scoping Review of the Epidemiological Research," *Environmental Research* 182 (2020): 109124, https://doi.org/10.1016/j.envres.2020.109124.
[2219] Sue Surkes, "112 Top Scientists Call on Government to Abort Plan for Gas-Fired Power Stations," *The Times of Israel*, November 19, 2019, https://www.timesofisrael.com/leading-scientists-call-on-government-to-abort-plan-for-gas-fired-power-stations/.

previously recognized. These emissions contain volatile organic compounds that are recognized as carcinogenic." The letter also warned of negative economic and social impacts of building out a gas infrastructure instead of investing in renewables.

- November 19, 2019 – Brian Schwartz, a professor of environmental health and engineering at Johns Hopkins Bloomberg School of Public Health, called for a ban on fracking while addressing a public health conference in Pittsburgh.[2220] "Schwartz, who has presented his research at the conference in the past, but had never before called for a ban on fracking, said he'd recently become convinced the time had come to make a public statement." Dr. Schwartz cited years of studies indicating that proximity to fracking increases the risk of asthma, premature birth, headaches, and maternal stress levels, concluding that "the evidence that fracking is bad for your health is clear enough."

- June 15, 2019 – A Colorado and Pennsylvania team of epidemiologists summarized the literature to date on the health effects of populations living near fracking operations, with a focus on methodological rigor. They adapted systematic review frameworks from the medical and environmental health field, analyzing 20 epidemiologic studies, with 32 different health outcomes, ranging from self-reported symptoms to confirmed disease diagnoses. The review's highest rated studies primarily focused on birth outcomes, and in general they found that study quality has improved over time. They found that studies of populations living near fracking operations provide "modest scientific findings" of "harmful health effects including asthma exacerbations and various self-reported symptoms."[2221] The review includes an important discussion of the limitations inherent to observational epidemiologic studies and the necessity of combining them with exposure and risk assessments to inform public health and policies. Differences in observational epidemiologic study types make comparing results across studies a difficult task. The authors recommend researchers "integrate community members and concepts of health equity and environmental justice into their research approaches."

- March 29, 2019 – Doctors for the Environment Australia announced the reinforcement of its position that no new gas extraction of any kind should occur in Australia. Its position was largely informed by the wealth of literature from the United States documenting adverse health findings.[2222] The organization's review found growing evidence of direct health impacts as well as a clear potential for indirect impacts of gas and oil mining on essential environmental determinants of health. "These concerns include risks to a stable climate, air quality, water quality, water security, food security, community cohesion and,

[2220] Reid Frazier, "Johns Hopkins Researcher: Pa. Should Ban Fracking," *State Impact Pennsylvania*, November 20, 2019, https://stateimpact.npr.org/pennsylvania/2019/11/20/johns-hopkins-researcher-pa-should-ban-fracking/.
[2221] Alison M. Bamber et al., "A Systematic Review of the Epidemiologic Literature Assessing Health Outcomes in Populations Living near Oil and Natural Gas Operations: Study Quality and Future Recommendations," *International Journal of Environmental Research and Public Health* 16, no. 12 (2019): 2123, https://doi.org/10.3390/ijerph16122123.
[2222] Melissa Haswell and David Shearman, "Expanding Gas Mining Threatens Our Climate, Water and Health," *The Conversation*, March 29, 2019, http://theconversation.com/expanding-gas-mining-threatens-our-climate-water-and-health-113047.

in some locations, geological stability. The cumulative impacts of these industries on the wider requirements for good health and wellbeing are extremely concerning."[2223]

- February 1, 2019 – Natural gas extraction via fracking is associated with "preterm birth, high-risk pregnancy, and possibly low birth weight; three types of asthma exacerbations; and nasal and sinus, migraine headache, fatigue, dermatologic, and other symptoms," according to a review covering research through mid-2017.[2224] The Johns Hopkins Bloomberg School of Public Health scientists cited the methodological robustness of these studies and the biological plausibility of the links found. Further, they included in their review the contribution of fracking to climate change and its further health impacts. Authors expressed serious doubt that the risks of fracking can be managed. "Some have suggested that regulations will prevent health impacts, but no health studies provide guidance on what regulations, if any, will get the health effects to go away." The authors further noted that the fracking boom has, in many regions, outpaced the ability of science to document health impacts with long latencies, such as cancer and neurodegenerative diseases. The review concluded that the results of early health studies "should give pause" about whether and how shale gas fracking should proceed and referenced the several U.S. states and nations that have disallowed fracking, citing health concerns.

- December 12, 2018 – "The healthcare community has a professional mandate to protect society from harm to human health. We have a responsibility to help society move away from fossil fuels and accelerate the transition to renewable energy," wrote a team of medical professionals in an editorial for the *British Medical Journal*. Citing the "overwhelming" evidence that fossil fuels pose serious threats to public and planetary health, the group identified divestment from fossil fuel corporations as a strategy that increasing numbers of medical professional groups are taking, as part of fulfilling that professional mandate.[2225]

- December 4, 2018 – In a review of 63 studies in 20 countries, a University of Southern California medical research team concluded that the potential public health effects of "upstream oil extraction" include cancer, liver damage, immunodeficiency, and neurological damage. Collectively, onshore operations that bring crude oil to the surface affect nearly six million people that live or work nearby. Community health, worker health, and animal health in oil-drilling regions were addressed in this review, as well as effects on soil, air, surface water, and drinking water quality. In their analysis, the authors included both conventional or unconventional extraction techniques but noted that, in the

[2223] Melissa Haswell and David Shearman, "The Implications for Human Health and Wellbeing of Expanding Gas Mining in Australia: Onshore Oil and Gas Policy," Background Report (Doctors for the Environment Australia, 2019), https://apo.org.au/sites/default/files/resource-files/2019-03/apo-nid208281.pdf.
[2224] Irena Gorski and Brian S. Schwartz, "Environmental Health Concerns From Unconventional Natural Gas Development," in *Oxford Research Encyclopedia of Global Public Health*, by Irena Gorski and Brian S. Schwartz (Oxford University Press, 2019), https://doi.org/10.1093/acrefore/9780190632366.013.44.
[2225] Adam Law et al., "Medical Organisations Must Divest from Fossil Fuels," *BMJ*, 2018, k5163, https://doi.org/10.1136/bmj.k5163.

United States, hydraulic fracturing accounted for 50 percent of total oil production in 2015—up from less than two percent in 2000.[2226]

- August 16, 2018 – The closer one lives to fracking sites, the more likely one is to experience toxic exposures and a related number of health impacts. Setbacks less than one quarter mile (1,320 feet) from drilling and fracking operations are not sufficient to protect public health, and additional setbacks are needed to protect vulnerable groups and settings, according to an expert panel assembled in Pennsylvania. "Vulnerable groups were defined by the panelists as children, neonates, fetuses, embryos, pregnant women, elderly individuals, those with pre-existing medical or psychological conditions, and those with pre-existing respiratory conditions. Vulnerable settings were defined as schools, day care centers, hospitals, and long-term care facilities. The panel, which consisted of 18 health care providers, public health practitioners, environmental advocates, and researchers/scientists, was brought together to compare existing minimum setback requirements against research about the health impacts of living near fracking activity. The panel was unable to come to agreement on a minimum safe setback distance between one quarter and two miles. It also noted that the failure to achieve consensus on this issue reflects uncertainties based on limited data of real-time toxic emissions from drilling and fracking operations, the limited number of scientific studies available, and the potential for episodically recurrent periods of high exposures.[2227]

- June 5, 2018 – The exacerbation of climate change caused by shale gas development is sufficient grounds to confirm that "the risks clearly and considerably outweigh any possible benefits," according to two public health scholars who published their editorial in the *British Medical Journal*.[2228]

- May 9, 2018 – With the objective of making practical recommendations for primary care providers, researchers sought to identify all published peer-reviewed studies examining evidence of direct relationships between high-volume hydraulic fracturing and human health harms. As a scoping review, the study purpose was to examine the extent and breadth of research and identify research gaps. Their criteria for inclusion were "narrow" and included peer-reviewed journal articles from the United States, in English, published between 2000 and September 2017. Among the 18 studies selected, 10 showed a positive correlation to the negative health outcome, six showed a mixed relationship, and two found no relationship. The authors wrote, "The health impacts found in the limited studies in this scoping review should encourage health care providers to maintain a high

[2226] Jill E. Johnston, Esther Lim, and Hannah Roh, "Impact of Upstream Oil Extraction and Environmental Public Health: A Review of the Evidence," *Science of The Total Environment* 657 (2019): 187–99, https://doi.org/10.1016/j.scitotenv.2018.11.483.
[2227] Celia Lewis, Lydia H. Greiner, and David R. Brown, "Setback Distances for Unconventional Oil and Gas Development: Delphi Study Results," ed. Carla A. Ng, *PLOS ONE* 13, no. 8 (2018): e0202462, https://doi.org/10.1371/journal.pone.0202462.
[2228] David McCoy and Patrick Saunders, "Fracking and Health," *BMJ*, 2018, k2397, https://doi.org/10.1136/bmj.k2397.

index of suspicion with patients who live or have lived near [drilling and fracking] activity or who have worked in oil and gas fields."[2229]

- April 4, 2018 – Two scholars critiqued the wide-ranging consultation on unconventional gas extraction, including fracking, which was commissioned by the Scottish government and published in November 2016.[2230] Noting that the Scottish assessment is more comprehensive than assessments conducted in the United States and elsewhere, the authors wrote, "The public health impact assessment in particular is underpinned by what appears to be a rigorous and transparent examination of existing scientific literature drawing on external peer review at some stages." However, they also went on to say that some of the conclusions drawn "appear to be optimistic readings of data and experience. For example, assessments of the ability of industry and regulators to control fracking effects on public health do not stand up to scrutiny." They identified several other ways in which the health impact assessment's conclusions were not always supported by the evidence it reviewed and if the assessment had overlooked areas of concern. For example, the literature on social impact assessments, as well as health research addressing questions of well-being and mental health, were neglected. Nevertheless, these scholars recommended the Scottish consultation as a research and policy tool.

- February 12, 2018 – The Los Angeles County Department of Public Health reviewed the public health and safety risks of oil and gas facilities and identified "next steps." These included an increase in setback distances, continuous air monitoring systems around oil and gas operations, increased local oversight, a comprehensive Community Safety Plan, and Emergency Preparedness Plans. For this report, authors reviewed epidemiological literature, environmental and health impact assessments, neighborhood health investigations, and consultations with various jurisdictions regarding oil and gas ordinances.[2231] At the time of the report preparation, there were 3,468 active and 1,850 inactive oil and gas wells countywide. Conditions varied widely. Among the most egregious was an active well that was located 60 feet from a multi-unit housing complex and that shared borders with a local high school and a college dormitory. "The potential public health impacts of oil and gas sites located in densely populated areas are concerning, particularly to those who experience disproportionate economic and health inequities." Recommendations for some individual neighborhoods included offering temporary relocation assistance. "The report was ordered by the city of Los Angeles after complaints of headaches, eye and throat irritation, nausea and vomiting were received

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[2229] Rosemary Wright and Richard D. Muma, "High-Volume Hydraulic Fracturing and Human Health Outcomes: A Scoping Review," *Journal of Occupational & Environmental Medicine* 60, no. 5 (2018): 424–29, https://doi.org/10.1097/JOM.0000000000001278.
[2230] Andrew Watterson and William Dinan, "Public Health and Unconventional Oil and Gas Extraction Including Fracking: Global Lessons from a Scottish Government Review," *International Journal of Environmental Research and Public Health* 15, no. 4 (2018): 675, https://doi.org/10.3390/ijerph15040675.
[2231] Katherine Butler et al., "Public Health and Safety Risks of Oil and Gas Facilities in Los Angeles County" (Los Angeles County Department of Public Health, 2018), http://publichealth.lacounty.gov/eh/docs/PH_OilGasFacilitiesPHSafetyRisks.pdf.

from residents of South Los Angeles, Wilmington and unincorporated county areas in the past several years."[2232]

- December 12, 2017 – Commissioned by the Australian government, the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory released its Draft Final Report. Tasked with identifying and assessing the risks of shale gas fracking for Australia's remote Northern Territory—and with making recommendations to mitigate those risks where possible—the Inquiry describes a multiplicity of risks, including many that are ill-defined and understudied.[2233] Most notably, it recommends a halt on all fracking production licenses until a two-to-three-year study can be launched to further understand the nature of the risks for the particular ecology and culture of the region."[2234] Fracking is currently prohibited in the Northern Territory, which is estimated to hold over one-third of Australia's shale gas.

- November 7, 2017 – In a commentary published in *JAMA*, two South Dakota physicians reviewed the data on the potential public health implications of fracking, including asthma, water contamination, exposures to fracking fluid, and exposure of workers to silica dust. They voiced specific concerns about parkinsonism, neuropathy, and kidney disease, and called for prospective toxicity studies.[2235]

- October 25, 2017 – Scientists and physicians (including two co-authors of this *Compendium*) reviewed the body of evidence on the potential of unconventional oil and natural gas (UOG) development and operations to contribute to neurological and developmental harm via increased air and water pollution in the surrounding communities where it takes place. Highlighting data gaps and research limitations (such as the nondisclosure by industry of chemical mixtures), they nevertheless pinpointed evidence in the existing literature showing that "the chemicals that are used in or are byproducts of UOG operations have been linked to serious neurodevelopmental health problems in infants."[2236] Interviewed by the *Guardian,* a co-author said, "Given the profound sensitivity of the developing brain and the central nervous system, it is very reasonable to conclude that young children who experience frequent exposure to these pollutants are at particularly high risk for chronic neurological problems and disease."[2237]

[2232] Steve Scauzillo, "Living near Oil Wells Can Cause Health Problems, LA County Believes It Has Solutions," *Los Angeles Daily News*, February 28, 2018, https://www.dailynews.com/2018/02/27/living-near-oil-wells-can-cause-health-problems-la-county-believes-it-has-solutions/.
[2233] Northern Territory of Australia, "Draft Final Report of the Scientific Inquiry Into Hydraulic Fracturing in the Northern Territory," Draft Final Report (Government of Australia, January 30, 2018), https://frackinginquiry.nt.gov.au/inquiry-reports?a=479268.
[2234] Reuters Staff, "Study Seen Needed before Lifting Fracking Ban in Remote Australia," *Reuters*, December 12, 2017, sec. Environment, https://www.reuters.com/article/us-australia-fracking-idUSKBN1E60TL.
[2235] Russell A. Wilke and Jerome W. Freeman, "Potential Health Implications Related to Fracking," *JAMA* 318, no. 17 (2017): 1645, https://doi.org/10.1001/jama.2017.14239.
[2236] Ellen Webb et al., "Neurodevelopmental and Neurological Effects of Chemicals Associated with Unconventional Oil and Natural Gas Operations and Their Potential Effects on Infants and Children," *Reviews on Environmental Health* 33, no. 1 (2018): 3–29, https://doi.org/10.1515/reveh-2017-0008.
[2237] Nicola Davis, "Pollutants from Fracking Could Pose Health Risk to Children, Warn Researchers," *The Guardian*, October 25, 2017, sec. Environment, https://www.theguardian.com/environment/2017/oct/25/pollutants-from-fracking-could-pose-health-risk-to-children-warn-researchers.

The research team concluded that there is "a need for public health prevention techniques, well-designed studies, and stronger state and national regulatory standards."

- October 23, 2017 – A Yale University research team reported that carcinogens involved in fracking operations have the potential to contaminate both air and water in nearby communities in ways that may increase the risk of childhood leukemia. The team identified 55 known or possible carcinogens that may be released into air and water from fracking operations. Of these, 20 are linked to leukemia or lymphoma.[2238] "This analysis creates a priority list of carcinogens to target for future exposure and health studies."[2239]

- July 31, 2017 – A review by a team of medical, psychological, occupational, and environmental health professionals concluded, "there appears to be an array of levels of psychosocial functioning that are deleteriously affected by the fracking process and industries and their aftermath." Though much of the research they identified linking fracking to psychological functioning was preliminary, documented impacts included: individual-level impacts, such as feelings of stress and powerlessness; community-level impacts, such as disrupted social fabric and new gender/sex imbalances in the community; collective trauma such as caused by a boom-and-bust cycle; and worker impacts, such as psychosocial impacts of being a transient worker. The review provided "an important first step in understanding the psychological toll that this energy development strategy has on fracking communities and sets the stage for advancements in research, clinical and policy, that will help us to better understand, assist, and advocate for those affected by fracking."[2240]

- May 1, 2017 – The Southwest Pennsylvania Environmental Health Project established a voluntary public health registry "aimed at tracking and eventually analyzing the impacts of shale gas development on people living near wells, impoundments, compressor stations and pipelines." According to a spokesperson, "The point is that the vast majority of independent science is looking at [shale gas development] and saying something's not good there. We need to know more… The findings of this registry will allow the health care community to be more informed about what problems people are experiencing when they walk into their offices. It will give the doctors some idea of what they should be looking for."[2241]

- April 28, 2017 – Portuguese and Brazilian reviewers identified the issue of water resources "as one of the most sensitive to negative impacts by shale gas exploration and

[2238] Elise G. Elliott et al., "Unconventional Oil and Gas Development and Risk of Childhood Leukemia: Assessing the Evidence," *Science of The Total Environment* 576 (2017): 138–47, https://doi.org/10.1016/j.scitotenv.2016.10.072.
[2239] Denise Meyer, "Fracking Linked to Cancer-Causing Chemicals, New YSPH Study Finds," *Yale News*, October 24, 2016, https://ysph.yale.edu/news-article/fracking-linked-to-cancer-causing-chemicals-new-ysph-study-finds/.
[2240] Jameson K. Hirsch et al., "Psychosocial Impact of Fracking: A Review of the Literature on the Mental Health Consequences of Hydraulic Fracturing," *International Journal of Mental Health and Addiction* 16, no. 1 (2018): 1–15, https://doi.org/10.1007/s11469-017-9792-5.
[2241] Don Hopey, "Registry Will Study Health Impact from Living near Shale Gas Wells," *Pittsburgh Post-Gazette*, May 1, 2017, https://www.post-gazette.com/business/powersource/2017/05/01/Registry-will-study-health-impact-from-living-near-shale-gas-wells/stories/201705010018.

exploitation," in their examination of scientific articles published between 2010 and 2015. They pointed to "expected" new legislation and industry practices for impact reductions but continued on to say that there are "no indications of a solution in the near future" for the problems of wastewater and greenhouse gas emissions.[2242]

- February 8, 2017 – Addressing the community health and safety harms linked with camps that house temporary workers in extractive industries, the British Columbia Ministry of Aboriginal Relations and Reconciliation funded a research project carried out in consultation with Indigenous nations. The premise, that "Indigenous women and youth can experience negative impacts of resource extraction at every phase of resource development," was borne out by the project's community dialogues and literature review. "Increased domestic violence, sexual assault, substance abuse, and an increased incidence of sexually transmitted infections (STIs) and HIV/AIDS due to rape, prostitution, and sex trafficking are some of the recorded negative impacts of resource extraction projects, specifically as a result of the presence of industrial camps and transient work forces." The objectives of the project were to stimulate dialogue and to develop detailed protective steps for Nations, government, and industry in advance of the initiation of planned extraction projects in the region, such as the TransCanada and Spectra Energy pipelines, in order to prevent violence against women and other life changing negative effects linked to the industrial camps.[2243]

- February 8, 2017 – Los Angeles County health officials criticized as insufficient the allocation of only one million dollars by the Southern California Gas Company to fund an independent health study in the aftermath of the massive methane leak at Aliso Canyon that lasted from October 2015 until February 2016. "'It's a study, but not a health study,' said Angelo Bellomo, the Los Angeles County deputy director for health protection. 'It is not responsive to addressing the health needs and concerns to this community. More importantly, it's inconsistent with advice given to [South Coast Air Quality Management District] by health officials.'" Health experts from across the state had suggested a design "that was comprehensive and larger in scope as well as consistent with a state Senate bill introduced last year that estimated such a design would cost $13 million in the first three years, and up to $40 million to complete."[2244]

- January 19, 2017 – An epidemiologist at Brown University reviewed studies to date on health outcomes in communities living close to unconventional natural gas development, and identified areas requiring further study. "Future epidemiologic studies should implement personal exposure assessments to examine associations between individual

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[2242] Daniele Costa et al., "Extensive Review of Shale Gas Environmental Impacts from Scientific Literature (2010–2015)," *Environmental Science and Pollution Research* 24, no. 17 (2017): 14579–94, https://doi.org/10.1007/s11356-017-8970-0.

[2243] G. Gibson et al., "Indigenous Communities and Industrial Camps: Promoting Healthy Communities in Settings of Industrial Change" (The Firelight Group with Lake Babine Nation and Nak'azdli Whut'en, 2017), https://firelight.ca/wp-content/uploads/2016/03/Firelight-work-camps-Feb-8-2017_FINAL.pdf.

[2244] Brenda Gazzar and Susan Abram, "$1 Million Health Study 'Shortchanges' Porter Ranch Gas Leak Victims, Critics Say," *Daily News*, February 8, 2017, https://www.dailynews.com/business/20170208/1-million-health-study-shortchanges-porter-ranch-gas-leak-victims-critics-say.

contaminants and relevant health outcomes, particularly to explain associations seen with respiratory and birth outcomes," the author concluded."[2245]

- December 5, 2016 – A team of British scientists wrote a 156-paper review on the risks and harms of fracking that attempts to "capture, review and interpret the published literature across all the accepted domains of public health in a systematic way and consider specific implications for the UK." They concluded that shale gas fracking "unequivocally presents an exposure hazard," and that further studies were needed to address exposure and health outcome data, noting the lack of before, during, and after exposure data for both air and water around drilling and fracking sites. Authors also noted that the claims that shale gas is less harmful to the climate than coal are not backed by lifecycle analyses. This team called for more research and a delay on any proposed drilling and fracking activity in the United Kingdom.[2246]

- November 1, 2016 – The government of Scotland released a health impact assessment that reconfirmed the evidence for potential contamination of air and water, threats to worker health from silica dust exposure, and risks to the health of nearby residents.[2247]

- October 23, 2016 – In a unanimous vote of the society's 300-member House of Delegates, the Pennsylvania Medical Society called for a moratorium on new shale gas drilling and fracking in Pennsylvania and an initiation of a health registry in communities with pre-existing operations.[2248, 2249]

- October 11, 2016 – A group of health care professionals in Massachusetts called for an immediate moratorium on major new natural gas infrastructure until the impact of these projects on the health of the communities affected can be adequately determined through a Comprehensive Health Impact Assessment.[2250] The group noted that the operation of natural gas facilities risks human exposures to toxic, cancer-causing, and radioactive pollution due to the presence of naturally co-occurring contaminants, toxic additives to the hydraulic fracturing process, and through the operation of transmission pipelines.[2251]

[2245] Shaina L. Stacy, "A Review of the Human Health Impacts of Unconventional Natural Gas Development," *Current Epidemiology Reports* 4, no. 1 (2017): 38–45, https://doi.org/10.1007/s40471-017-0097-9.
[2246] Patrick J. Saunders et al., "A Review of the Public Health Impacts of Unconventional Natural Gas Development," *Environmental Geochemistry and Health* 40, no. 1 (2018): 1–57, https://doi.org/10.1007/s10653-016-9898-x.
[2247] Health Protection Scotland, "A Health Impact Assessment of Unconventional Oil and Gas in Scotland: Volume 1 – Full Report," 2016, https://www.hps.scot.nhs.uk/web-resources-container/a-health-impact-assessment-of-unconventional-oil-and-gas-in-scotland-volume-1-full-report/.
[2248] Pennsylvania Medical Society, "Resolution 16-206: Pennsylvania Medical Society Support for a Moratorium on Fracking," October 23, 2016, https://www.pamedsoc.org/docs/librariesprovider2/pamed-documents/pamed-downloads/HODAEC/16-206.pdf.
[2249] Don Hopey, "Doctors Call for State Ban on Drilling and Fracking," *Pittsburgh Post-Gazette*, October 27, 2016, https://www.post-gazette.com/local/region/2016/10/27/Doctors-group-calls-for-moratorium-on-fracking-in-Pennsylvania/stories/201610270226.
[2250] Massachusetts Health Care Professionals Against Fracked Gas, "Call for a Moratorium on Natural Gas Projects Undergoing Construction or Review in the Commonwealth of Massachusetts," October 2016.
[2251] Massachusetts Health Care Professionals Against Fracked Gas, "The Role of Comprehensive Health Impact Assessment in Evaluating Natural Gas Infrastructure Proposals in Massachusetts," February 20, 2016.

- September 15, 2016 – A systematic review of 45 studies, primarily but not exclusively addressing conventional oil and gas activities, showed an emerging body of evidence documenting harm to reproductive health from residential and occupational exposure to these operations. The strongest evidence existed for increased risk of miscarriage, prostate cancer, birth defects, and decreased semen quality. Authors state that there is "ample evidence for disruption of the estrogen, androgen, and progesterone receptors with individual chemicals and waste products related to oil and gas extraction," and "impacts from unconventional oil and gas activities will likely be greater, given that unconventional activities have many similarities to conventional ones and employ dozens of endocrine-disrupting chemicals in the process of hydraulic fracturing."[2252]

- September 14, 2016 – In a commentary about fracking in the *American Journal of Public Health*, Weill Cornell Medicine physicians wrote, "mounting empirical evidence shows harm to the environment and to human health . . . and we have no idea what the long-term effects might be. . . . Ignoring the body of evidence, to us, is not a viable option anymore."[2253]

- July 7, 2016 –The UK health professional organization Medact released an updated assessment of the potential health impacts of shale fracking in England that confirm the findings of its 2015 report, *Health and Fracking*. The new report, *Shale Gas Production in England,* concluded, "Our view that the UK should abandon its policy to encourage [shale gas production] remains unchanged." The new report included hundreds of new academic papers addressing impacts on air and water quality, health, climate change, social wellbeing, economics, noise and light pollution, and seismic events. Still, authors wrote, "the absence of an independent social, health and economic impact assessment of [shale gas production] at scale is a glaring omission. Given the availability of alternative sources of energy, these are grounds for placing an indefinite moratorium on SGP (a position adopted by many jurisdictions across the world) until such time that there is greater clarity and certainty about the relative harms and benefits of shale gas."[2254]

- May 31, 2016 – "There are too many science, technology and risk-assessment gaps to green-light fracking in western Newfoundland," according to a panel that studied the question. In an interview with Canada's *Globe and Mail*, panel leader and engineering professor Ray Gosine said, "The science, the studies that have been done, have been somewhat limited – certainly limited compared to what we'd expect to have done in order

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[2252] Victoria D. Balise et al., "Systematic Review of the Association between Oil and Natural Gas Extraction Processes and Human Reproduction," *Fertility and Sterility* 106, no. 4 (2016): 795–819, https://doi.org/10.1016/j.fertnstert.2016.07.1099.
[2253] Madelon L. Finkel and Adam Law, "The Rush to Drill for Natural Gas: A Five-Year Update," *American Journal of Public Health* 106, no. 10 (2016): 1728–30, https://doi.org/10.2105/AJPH.2016.303398.
[2254] David McCoy and Alice Munro, "Shale Gas Production in England - an Updated Public Health Assessment" (MedAct Health Professionals for a Safer, Fairer, & Better World, July 7, 2016), https://www.medact.org/2016/resources/reports/shale-gas-production-in-england/.

to plan this kind of operation…. There are a number of gaps and deficiencies that are significant."[2255]

- May 13, 2016 – Physicians for Social Responsibility called for a ban on hydraulic fracturing, pointing both to the irremediable climate harm caused by methane emissions as well to the multiple health risks from industrial-scale water consumption, air pollution, seismic effects, the generation of large quantities of toxic liquid waste, and long-term impacts on drinking water aquifers. "We cannot stay healthy in an unhealthy environment. Nor can we survive indefinitely on a planet growing hotter and more prone to extreme, unpredictable and destructive weather. These factors impel PSR to call for a ban on fracking and for a rapid transition to cleaner, healthier, carbon-free sources of energy."[2256]

- March 27, 2016 – Noting that many chemicals used in fracking fluids are known or suspected endocrine disruptors, a group of public health researchers called for an endocrine-centric component for health assessments in areas impacted by oil and gas operations. The team outlined a series of recommendations to assess the "potential endocrine-related risks from chemical exposures associated with oil and natural gas operations. We present these recommendations in light of the growing body of information regarding both chemical concentrations in the environment and adverse health outcomes reported in humans and wildlife."[2257]

- November 24, 2015 – A Harvard University team identified a trend toward increasing chemical secrecy and less transparency by examining 96,000 chemical disclosure forms filed by fracking companies between March 2011 and April 2015. These forms were submitted to the Fracfocus website, a chemical disclosure portal for the fracking industry that operates on a voluntary basis but for which reporting in mandated in more than 20 states. Fracfocus is the largest public database on chemicals used in U.S. fracking operations.[2258] Companies involved in fracking withheld chemical data at significantly higher rates in 2015 (16.5 percent) as compared to 2011-2013 (11 percent). The research team also found that withholding drops by a factor of four when companies report aggregate data without attribution to the specific products in the fracking fluid. The authors called for state governments to retain authority in requiring disclosure of "product-specific ingredient lists."[2259]

[2255] Sue Bailey, "Too Many Gaps to Recommend Fracking in Newfoundland: Panel," *The Globe and Mail*, May 31, 2016, https://www.theglobeandmail.com/report-on-business/industry-news/energy-and-resources/too-many-unknowns-to-recommend-fracking-in-western-newfoundland-panel/article30216746/.

[2256] Physicians for Social Responsibility, "PSR Position Statement on Hydraulic Fracturing," Physicians for Social Responsibility, May 13, 2016, https://www.psr.org/blog/resource/psr-position-statement-on-hydraulic-fracturing/.

[2257] Christopher D. Kassotis et al., "Endocrine-Disrupting Chemicals and Oil and Natural Gas Operations: Potential Environmental Contamination and Recommendations to Assess Complex Environmental Mixtures," *Environmental Health Perspectives* 124, no. 3 (2016): 256–64, https://doi.org/10.1289/ehp.1409535.

[2258] Lisa Song, "What Chemicals Are Used in Fracking? Industry Discloses Less and Less," *Inside Climate News*, November 24, 2015, https://insideclimatenews.org/news/24112015/fracking-natural-gas-drilling-chemicals-frac-focus-study/.

[2259] Katherine Konschnik and Archana Dayalu, "Hydraulic Fracturing Chemicals Reporting: Analysis of Available Data and Recommendations for Policymakers," *Energy Policy* 88 (2016): 504–14, https://doi.org/10.1016/j.enpol.2015.11.002.

- August 7, 2015 – While acknowledging the "dramatic increase in the number of peer-reviewed published studies" on environmental and health impacts of fracking, Weill Cornell Medical College's Dr. Madelon Finkel and co-author PSE Healthy Energy's Jake Hays called for more well-designed longer-term epidemiologic studies to quantify the connections between fracking-related risk factors and health outcomes. Without such studies it is challenging to capture, for example, outcomes such as cancer that take many years to present. The authors described several important studies that are currently underway that will add to the body of knowledge in the future.[2260]

- June 9, 2015 – Information on individual exposures and local environmental conditions prior to the commencement of fracking in a given area is often "unavailable or hard to obtain. These and other data gaps have hindered the kind of large-scale epidemiological studies that can link exposures to actual health outcomes, with valid comparison groups," wrote public health journalist David Tuller in the journal *Health Affairs*.[2261] In an interview with *Michigan Radio*, Tuller noted that, because well development happens quickly, there was generally a lack of pre-drilling baseline studies.[2262]

- April 17, 2015 – Using sophisticated Geographic Information Systems (GIS) tools to examine distribution of fracking wells compared to distribution of vulnerable populations, Clark University researchers found consistent evidence that, in the Pennsylvania Marcellus Shale region, census tracts with potential exposure to pollution from fracking wells contained "significantly higher" percentages of poor people. They also found clusters of vulnerable populations concentrated near drilling and fracking in all three states they studied: Pennsylvania (for poverty and elderly population), West Virginia (for poverty, elderly population, and education level) and Ohio (for children). Researchers also reported difficulty in accessing high quality and consistent unconventional well data in all three states, demonstrating an "urgent need" for common data collection and reporting.[2263] Another GIS-based study sought to begin to fill this gap in data on spatially distributed risks of fracking, identifying Pennsylvania populations at "very high" and "high" risk in over a dozen counties. The author called for more focus on those areas to understand the impacts of fracking.[2264]

[2260] Madelon L. Finkel and Jake Hays, "Environmental and Health Impacts of 'Fracking': Why Epidemiological Studies Are Necessary," *Journal of Epidemiology and Community Health* 70, no. 3 (2016): 221–22, https://doi.org/10.1136/jech-2015-205487.
[2261] David Tuller, "As Fracking Booms, Dearth Of Health Risk Data Remains," *Health Affairs (Project Hope)* 34, no. 6 (June 2015): 903–6, https://doi.org/10.1377/hlthaff.2015.0484.
[2262] Rebecca Williams, "Why There Are Gaps in Public Health Studies on Fracking," Michigan Radio, June 9, 2015, https://www.michiganradio.org/environment-science/2015-06-09/why-there-are-gaps-in-public-health-studies-on-fracking.
[2263] Ogneva-Himmelberger and Huang, "Spatial Distribution of Unconventional Gas Wells and Human Populations in the Marcellus Shale in the United States: Vulnerability Analysis."
[2264] Qingmin Meng, "Spatial Analysis of Environment and Population at Risk of Natural Gas Fracking in the State of Pennsylvania, USA," *The Science of the Total Environment* 515–516 (2015): 198–206, https://doi.org/10.1016/j.scitotenv.2015.02.030.

- March 30, 2015 – The UK medical organization Medact published a report, *Health & Fracking: The Impacts and Opportunity Costs*, which concluded that fracking poses significant risks to public health and called for an immediate moratorium to allow time for a full and comprehensive health and environmental impact assessment to be completed.[2265] The report was supported by a letter published in the *British Medical Journal* calling for shale gas development to be put on hold, signed by the Climate and Health Council and over a dozen senior health professionals. The letter stated, "The arguments against fracking on public health and ecological grounds are overwhelming. There are clear grounds for adopting the precautionary principle and prohibiting fracking."[2266]

- February 17, 2015 – Writing in the *Canadian Medical Association Journal*, a public health scientist and medical doctor briefly reviewed the human health risks of fracking documented to date and made the case for a health care worker role in insisting on improved understanding. They cited worker and community safety issues as the biggest short-term risks, but emphasized that more needs to be known "before health care providers can definitively respond to their patients' and communities' concerns.… Physicians may wish to advocate delaying new development activities until the potential health effects are better understood."[2267]

- January 22, 2015 –The acting head of research at the Cancer Association of South Africa, Carl Albrecht, said that known carcinogenic chemicals used in fracking could lead to an epidemic of cancer in South Africa's Karoo desert. As South Africa was poised to publish draft regulations, Albrecht said that the effect of fracking on human health was ignored.[2268]

- January 19, 2015 – In an article that reviewed research and research gaps, a team of British and U.S. medical and scientific professionals urged the United Kingdom and other nations to engage in science before engaging in fracking. They warned that even strong regulations may not effectively address air pollution from fracking, and that "permanent, adverse environmental, climatic, and population health impacts" may exist in some cases.[2269]

[2265] David McCoy and Patrick Saunders, "Health & Fracking: The Impacts and Opportunity Costs" (MedAct Health Professionals for a Safer, Fairer, & Better World, 2015), https://www.medact.org/2015/resources/reports/health-and-fracking/.
[2266] Robin Stott et al., "Public Health England's Draft Report on Shale Gas Extraction," *BMJ* 348 (2014): g2728, https://doi.org/10.1136/bmj.g2728.
[2267] Lalita Bharadwaj and Bernard D. Goldstein, "Shale Gas Development in Canada: What Are the Potential Health Effects?," *CMAJ : Canadian Medical Association Journal* 187, no. 3 (2015): E99–100, https://doi.org/10.1503/cmaj.140599.
[2268] Paul Vecchiatto, "Chemicals Used in Fracking 'Could Cause Cancer'," *Business Day BDLive*, January 22, 2015, https://web.archive.org/web/20150124035808/http://www.bdlive.co.za/business/energy/2015/01/22/chemicals-used-in-fracking-could-cause-cancer.
[2269] Jake Hays et al., "Considerations for the Development of Shale Gas in the United Kingdom," *Science of The Total Environment* 512–513 (2015): 36–42, https://doi.org/10.1016/j.scitotenv.2015.01.004.

- December 17, 2014 – In an editorial, Rutgers University environmental exposure expert Paul J. Lioy (now deceased) highlighted fracking as an area in which accurate exposure monitoring and risk assessment did not yet exist. Lioy emphasized that the relevant research was compartmentalized and fragmented and that exposures and health outcomes around unconventional natural gas development need to be systematically addressed through "well-defined exposure studies in communities and workplaces."[2270]

- December 5, 2014 – A team of medical and scientific researchers, including from the Institute for Health and Environment at the State University of New York (SUNY) at Albany, reviewed the scientific evidence that both adult and early life—including prenatal—exposure to chemicals from fracking operations can result in adverse reproductive health and developmental effects. These include: endocrine-disrupting chemicals potentially increasing risk for reproductive problems, breast cancer, abnormal growth and developmental delays, and changes in immune function; benzene, toluene and xylene (BTX chemicals) increasing risk for impaired sperm quantity and quality in men and menstrual and fertility problems in women; and heavy metals increasing the risk of miscarriage and/or stillbirths. Potential exposures occur through both air and water. Based on their review, the authors concluded, "Taken together, there is an urgent need for the following: 1) biomonitoring of human, domestic and wild animals for these chemicals; and 2) systematic and comprehensive epidemiological studies to examine the potential for human harm."[2271] Lead author Susan Nagel said in an accompanying interview, "We desperately need biomonitoring data from these people. What are people actually exposed to? What are the blood levels of people living in these areas? What are the levels in the workers?"[2272]

- November 12, 2014 – A team of Australian researchers reviewed the strength of evidence for environmental health impacts of fracking based on publications from 1995 to 2014. They noted that the rapid expansion of fracking had outstripped the pace of science and that most studies focused on short-term, rather than long-term, health. Hence, "very few studies examined health outcomes with longer latencies such as cancer or developmental outcomes." Noting that no evidence exists to rule out health impacts, the team called for direct and clear public health assessments before projects are approved, longitudinal studies that include baseline data, and government and industry transparency.[2273]

[2270] Paul J. Lioy, "Exposure Science and Its Places in Environmental Health Sciences and Risk Assessment: Why Is Its Application Still an Ongoing Struggle in 2014?," *Journal of Exposure Science & Environmental Epidemiology* 25, no. 1 (2015): 1–3, https://doi.org/10.1038/jes.2014.59.
[2271] Ellen Webb et al., "Developmental and Reproductive Effects of Chemicals Associated with Unconventional Oil and Natural Gas Operations," *Reviews on Environmental Health* 29, no. 4 (2014), https://doi.org/10.1515/reveh-2014-0057.
[2272] Ian Sample, "Fracking Chemicals Could Pose Risks to Reproductive Health, Say Researchers," *The Guardian*, December 5, 2014, sec. Environment, https://www.theguardian.com/environment/2014/dec/05/fracking-chemicals-could-pose-risks-to-reproductive-health-say-researchers.
[2273] Angela K. Werner et al., "Environmental Health Impacts of Unconventional Natural Gas Development: A Review of the Current Strength of Evidence," *Science of The Total Environment* 505 (2015): 1127–41, https://doi.org/10.1016/j.scitotenv.2014.10.084.

- September 15, 2014 – Researchers led by University of Rochester's Environmental Health Sciences Center conducted interviews in New York, North Carolina, and Ohio to evaluate community health concerns about unconventional natural gas development. They identified many areas where more study is needed, including baseline measures of air quality, ongoing environmental monitoring, and health impact assessments. They noted that other areas where data are lacking involve the assessment of drilling and fracking impacts on vulnerable populations such as very young children, and the potential consequences of interactions between exposures resulting from shale gas extraction operations. Researchers suggested incorporating the input of potentially affected community members into the development of the research agenda.[2274]

- July 21, 2014 – An independent assessment report by Scientists for Global Responsibility and the Chartered Institute of Environmental Health reviewed current evidence across a number of issues associated with shale gas extraction by hydraulic fracturing, including environmental and public health risks, drawing on academic research. Among the report's conclusions: there are major shortcomings in regulatory oversight regarding local environmental and public health risks; there is a large potential for UK shale gas exploitation to undermine national and international efforts to tackle climate change; the water-intensive nature of the fracking process which could cause water shortages in many areas; the complete lack of evidence behind claims that shale gas exploitation will bring down UK energy bills; and concerns that it will impact negatively on UK energy security. Despite claims to the contrary, the report noted that evidence of local environmental contamination from shale gas exploitation is well reported in the scientific literature. It emphasizes that, "[t]here are widespread concerns over the lack of evidence on fracking-related health impacts," and that there is a lack of "substantive epidemiological study for populations exposed to shale gas extraction."[2275]

- July 18, 2014 – A working group of the Environmental Health Sciences Core Centers, supported by the National Institute of Environmental Health Sciences, reviewed the available literature on the potential health impacts of fracking for natural gas. They concluded that further research is urgently needed. Needs identified included: monitoring of air and water quality over the entire lifetime of wells; further epidemiologic research addressing health outcomes and water quality; and research addressing whether air pollution associated with fracking increases the risk of pulmonary and cardiovascular disease. The working group advocated for the participation of potentially affected communities in all areas of research.[2276]

[2274] Katrina Smith Korfmacher, Kathleen M. Gray, and Erin Haynes, "Health Impacts of Unconventional Natural Gas Development: A Comparative Assessment of Community Information Needs in New York, North Carolina, and Ohio," Final Project Report, September 15, 2014.
[2275] Gwen Harrison and Stuart Parkinson, "Shale Gas and Fracking: Examining the Evidence" (Scientists for Global Responsibility & the Chartered Institute of Environmental Health, July 2014), https://www.sgr.org.uk/sites/sgr.org.uk/files/SGR-CIEH-Shale-gas-bfg.pdf.
[2276] Trevor M. Penning et al., "Environmental Health Research Recommendations from the Inter-Environmental Health Sciences Core Center Working Group on Unconventional Natural Gas Drilling Operations," *Environmental Health Perspectives* 122, no. 11 (2014): 1155–59, https://doi.org/10.1289/ehp.1408207.

- July 12, 2014 – Eli Avila, Pennsylvania's former Secretary of Health, said that health officials need to be proactive in protecting the public from the health effects of unconventional shale gas extraction. In 2011, funding was approved for a Pennsylvania public health registry to track drilling related complaints and address concerns, but was cut at the last minute. Speaking to the problem posed by the dearth of information, Avila asked, "How can you keep the public safe if you're not collecting data?"[2277]

- June 30, 2014 – The immediate past chair of the Executive Committee of the Council on Environmental Health for the American Academy of Pediatrics, Jerome A. Paulson, MD, called for industry disclosure of all ingredients of fracking fluid; thorough study of all air contaminants released from drilling and fracking operations and their protected dispersal patterns; and study and disclosure of fracking-related water contamination and its mechanisms. In a letter to the Pennsylvania Department of Environmental Protection (PA DEP), Paulson said:

  > In summary, neither the industry, nor government agencies, nor other researchers have ever documented that [unconventional gas extraction] can be performed in a manner that minimizes risks to human health. There is now some evidence that these risks that many have been concerned about for a number of years are real risks. There is also much data to indicate that there are a number of toxic chemicals used or derived from the process, known or plausible routes of exposure of those chemicals to humans; and therefore, reason to place extreme limits on [unconventional gas extraction].[2278]

- June 20, 2014 – Highlighting preliminary studies in the United States that suggest an increased risk of adverse health problems among individuals living within ten miles of shale gas operations, a commentary in the British medical journal *The Lancet* called for a precautionary approach to gas drilling in the United Kingdom. According the commentary, "It may be irresponsible to consider any further fracking in the UK (exploratory or otherwise) until these prospective studies have been completed and the health impacts of fracking have been determined."[2279]

- June 20, 2014 – Led by an occupational and environmental medicine physician, a Pennsylvania-based medical and environmental science research team documented "… the substantial concern about adverse health effects of [unconventional natural gas development] among Pennsylvania Marcellus Shale residents, and that these concerns may not be adequately represented in medical records." The teams identified the continued need to pursue environmental, clinical, and epidemiological studies to better

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[2277] Kevin Begos, "Expert: Pa. Didn't Address Fracking Health Impacts," *Observer-Reporter*, July 12, 2014, https://observer-reporter.com/news/regional/expert-pa-didn-t-address-fracking-health-impacts/article_88d539c7-cb17-56a5-95df-b19887246e60.html.
[2278] Jerome A. Paulson, "Letter to the Pennsylvania Department of Environmental Protection," June 30, 2014, https://concernedhealthny.org/2014/06/letter-from-dr-jerome-a-paulson-to-the-pennsylvania-department-of-environmental-protection/.
[2279] Michael Hill, "Shale Gas Regulation in the UK and Health Implications of Fracking," *The Lancet* 383, no. 9936 (2014): 2211–12, https://doi.org/10.1016/S0140-6736(14)60888-6.

understand associations between fracking, medical outcomes, and residents' ongoing concerns.[2280]

- June 17, 2014 – A discussion paper by the Nova Scotia Deputy Chief Medical Officer and a panel of experts identified potential economic benefits as well as public health concerns from unconventional oil and gas development. On the health impacts, they wrote, "uncertainties around long term environmental effects, particularly those related to climate change and its impact on the health of both current and future generations, are considerable and should inform government decision making…" The report noted potential dangers including contamination of groundwater, air pollution, surface spills, increased truck traffic, noise pollution, occupational health hazards, and the generation of greenhouse gases. It also noted that proximity of potential fracking sites to human habitation should give regulators pause and called for a health impact assessment and study of long-term impacts.[2281] Responding to the report, the Environmental Health Association of Nova Scotia applauded the go-slow approach and called for a 10-year moratorium on fracking.[2282]

- May 29, 2014 – In New York State, more than 250 medical organizations and health professionals released a letter detailing emerging trends in the data on fracking that show significant risk to public health, air quality, and water, as well as other impacts. With signatories including the American Academy of Pediatrics, District II, the American Lung Association in New York, Physicians for Social Responsibility, and many leading researchers examining the impacts of fracking, they wrote, "The totality of the science — which now encompasses hundreds of peer-reviewed studies and hundreds of additional reports and case examples—shows that permitting fracking in New York would pose significant threats to the air, water, health and safety of New Yorkers."[2283, 2284]

- May 9, 2014 – In a peer-reviewed analysis, leading toxicologists outlined some of the potential harm and uncertainty relating to the toxicity of the chemical and physical agents associated with fracking, individually and in combination. While acknowledging the need for more research and greater involvement of toxicologists, they noted the potential for surface and groundwater contamination from fracking, growing concerns about air

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[2280] Pouné Saberi et al., "Field Survey of Health Perception and Complaints of Pennsylvania Residents in the Marcellus Shale Region," *International Journal of Environmental Research and Public Health* 11, no. 6 (2014): 6517–27, https://doi.org/10.3390/ijerph110606517.
[2281] Frank Atherton et al., "Report of the Nova Scotia Independent Review Panel on Hydraulic Fracturing" (Cape Breton University, 2014).
[2282] Michael MacDonald, "N.S. Expert Calls for Go-Slow Approach for Fracking," *CTV News*, June 17, 2014, https://atlantic.ctvnews.ca/n-s-expert-calls-for-go-slow-approach-for-fracking-1.1872529.
[2283] Concerned Health Professionals of NY, "Letter to Governor Cuomo and Acting Health Commissioner Howard A. Zucker," Concerned Health Professionals of NY, May 29, 2014, https://concernedhealthny.org/letters-to-governor-cuomo/.
[2284] Kyle Hughes, "NY Fracking Opponents Call for Moratorium of 3 to 5 Years," *Daily Freeman*, May 29, 2014, https://www.dailyfreeman.com/news/ny-fracking-opponents-call-for-moratorium-of-3-to-5-years/article_f1383150-da0d-5291-973f-461498241056.html.

pollution particularly in the aggregate, and occupational exposures that pose a series of potential hazards to worker health.[2285, 2286]

- May 1, 2014 – A 292-page report from a panel of top Canadian scientists urged caution on fracking, noting that it poses "the possibility of major adverse impacts on people and ecosystems" and that significantly more study is necessary to understand the full extent of the risks and impacts.[2287] The *Financial Post* reported that the panel of experts "found significant uncertainty on the risks to the environment and human health, which include possible contamination of ground water as well as exposure to poorly understood combinations of chemicals."[2288]

- April 30, 2014 – Medical professionals spoke out on the dearth of public health information collected and lack of long-term study five years into Pennsylvania's fracking boom. Walter Tsou, MD, MPH, past president of the American Public Health Association and former Health Commissioner of Philadelphia commented, "That kind of study from a rigorous scientific perspective has never been done." Other experts added, "There has been more health research involving fracking in recent years, but every study seems to consider a different aspect, and … there is no coordination."[2289]

- April 17, 2014 – In the preeminent *British Medical Journal*, authors of a commentary, including an endocrinologist and a professor of clinical public health, wrote, "Rigorous, quantitative epidemiological research is needed to assess the risks to public health, and data are just starting to emerge. As investigations of shale gas extraction in the US have continually suggested, assurances of safety are no proxy for adequate protection."[2290]

- April 15, 2014 – The *Canadian Medical Association Journal* reported on the increasing legitimacy of concerns about fracking on health: "While scientists and area residents have been sounding the alarm about the health impacts of shale gas drilling for years, recent studies, a legal decision and public health advocates are bringing greater legitimacy to concerns."[2291]

[2285] Society of Toxicology, "Toxicologists Outline Key Health and Environmental Concerns Associated with Hydraulic Fracturing," *ScienceDaily*, May 9, 2014, https://www.sciencedaily.com/releases/2014/05/140509172545.htm.

[2286] Bernard D. Goldstein et al., "The Role of Toxicological Science in Meeting the Challenges and Opportunities of Hydraulic Fracturing," *Toxicological Sciences* 139, no. 2 (2014): 271–83, https://doi.org/10.1093/toxsci/kfu061.

[2287] Council of Canadian Academies, "Environmental Impacts of Shale Gas Extraction in Canada: The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction."

[2288] The Canadian Press, "Top Canadian Scientists Urge Cautious Approach to Fracking until More Known of Impact," *Financial Post*, May 1, 2014, https://financialpost.com/commodities/energy/top-canadian-scientists-urge-cautious-approach-to-fracking-until-more-known-of-impact.

[2289] Natasha Khan, "Health Impact of Gas Fracking Left in the Dark," *Pocono Record*, April 30, 2014, https://www.poconorecord.com/article/20140430/NEWS90/404300301.

[2290] Adam Law et al., "Public Health England's Draft Report on Shale Gas Extraction," *BMJ* 348, no. apr17 6 (2014): g2728–g2728, https://doi.org/10.1136/bmj.g2728.

[2291] Wendy Glauser, "New Legitimacy to Concerns about Fracking and Health," *Canadian Medical Association Journal* 186, no. 8 (2014): E245–46, https://doi.org/10.1503/cmaj.109-4725.

- March 3, 2014 – In the *Medical Journal of Australia*, researchers and a physician published a strongly worded statement, "Harms unknown: health uncertainties cast doubt on the role of unconventional gas in Australia's energy future." They cited knowledge to date on air, water, and soil pollution, and expressed concern about "environmental, social and psychological factors that have more indirect effects on health, and important social justice implications" yet to be understood. They wrote in summary:

  > The uncertainties surrounding the health implications of unconventional gas, when considered together with doubts surrounding its greenhouse gas profile and cost, weigh heavily against proceeding with proposed future developments. While the health effects associated with fracturing chemicals have attracted considerable public attention, risks posed by wastewater, community disruption and the interaction between exposures are of also of concern.[2292]

- March 1, 2014 – In the prestigious British medical journal *The Lancet*, researchers summarized workshops and research about the health impacts of fracking, noting that the scientific study on the health impacts of fracking is "in its infancy." Nevertheless, the existing evidence suggests, said these researchers, that health risks posed by fracking exceed those posed by conventional oil and gas wells due to the sheer number and density of well pads being developed, their proximity to densely populated areas, and the need to transport and store large volumes of materials.[2293]

- February 24, 2014 – In a review of the health effects of unconventional natural gas extraction published in the journal *Environmental Science & Technology*, leading researchers identified a range of impacts and exposure pathways that can be detrimental to human health. Noting how fracking disrupts communities, the review states, "For communities near development and production sites the major stressors are air pollutants, ground and surface water contamination, truck traffic and noise pollution, accidents and malfunctions, and psychosocial stress associated with community change." They concluded, "Overall, the current scientific literature suggests that there are both substantial public concerns and major uncertainties to address."[2294]

- August 30, 2013 – A summary of a 2012 workshop by the Institute of Medicine Roundtable on Environmental Health Sciences, Research, and Medicine featured various experts who discussed health and environmental concerns about fracking and the need for more research. The report in summary of the workshop stated, "The governmental public health system, which retains primary responsibility for health, was not an early participant in discussions about shale gas extraction; thus public health is lacking critical information about environmental health impacts of these technologies and is limited in its

[2292] Alicia Coram, Jeremy Moss, and Grant Blashki, "Harms Unknown: Health Uncertainties Cast Doubt on the Role of Unconventional Gas in Australia's Energy Future," *Medical Journal of Australia* 200, no. 4 (2014): 210–13, https://doi.org/10.5694/mja13.11023.
[2293] Sari Kovats et al., "The Health Implications of Fracking," *The Lancet* 383, no. 9919 (2014): 757–58, https://doi.org/10.1016/S0140-6736(13)62700-2.
[2294] Adgate, Goldstein, and McKenzie, "Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development."

ability to address concerns raised by regulators at the federal and state levels, communities, and workers employed in the shale gas extraction industry."[2295]

- June 2013 – A group of three nursing professors published a cautionary review questioning the rollout of new shale-based energy practices at a time when, "anecdotal reports make clear that the removal of fossil fuels from the earth directly affects human health." Although the results of longterm studies are not yet available, the authors point to emerging evidence for negative human and ecologic health effects of fracking. Furthermore, they continue, "sufficient evidence has been presented to the [American Nurses Association], the American Public Health Association, and the American Medical Association's Resident and Fellow Section to result in a call for a moratorium on the issuance of new fracking permits nationally." They urge nurses to contribute to keeping health issues "front and center as we address national energy needs and policies."[2296]

- April 22, 2013 – In one of the first peer-reviewed nursing articles summarizing the known health and community risks of fracking, Professor Margaret Rafferty, Chair of the Department of Nursing at New York City College of Technology wrote, "Any initiation or further expansion of unconventional gas drilling must be preceded by a comprehensive Health Impact Assessment (HIA)."[2297]

- May 10, 2011 – In the *American Journal of Public Health*, two medical experts cautioned that fracking "poses a threat to the environment and to the public's health. There is evidence that many of the chemicals used in fracking can damage the lungs, liver, kidneys, blood, and brain." The authors urged that it would be prudent to invoke the precautionary principle in order to protect public health and the environment.[2298]

[2295] Christine Coussens and Rose Marie Martinez, "Health Impact Assessment of Shale Gas Extraction: Workshop Summary," in *Roundtable on Environmental Health Sciences, Research, and Medicine* (Institute of Medicine and the Board on Population Health and Public Health Practice, Washington, D.C., 2013), https://www.ncbi.nlm.nih.gov/books/NBK201904/.
[2296] Ruth McDermott-Levy, Nina Kaktins, and Barbara Sattler, "Fracking, the Environment, and Health: New Energy Practices May Threaten Public Health," *American Journal of Nursing* 113, no. 6 (2013): 45–51, https://doi.org/10.1097/01.NAJ.0000431272.83277.f4.
[2297] Margaret A. Rafferty and Elena Limonik, "Is Shale Gas Drilling an Energy Solution or Public Health Crisis?," *Public Health Nursing* 30, no. 5 (2013): 454–62, https://doi.org/10.1111/phn.12036.
[2298] Madelon L. Finkel and Adam Law, "The Rush to Drill for Natural Gas: A Public Health Cautionary Tale," *American Journal of Public Health* 101, no. 5 (2011): 784–85, https://doi.org/10.2105/AJPH.2010.300089.

"Fracking"

Dr. Robert Leonard

Is "fracking" the term most commonly used by the general public? Yes

Is "fracking" a slang term? No

“Fracking” is the common term and is not slang.

This conclusion is supported by analyses of:

- Data from **dictionaries**
- Large **databases** that reflect how language is used
- Data from **Colorado newspapers**

Dictionaries

“Fracking” and
“Hydraulic Fracturing”

Dictionaries

Source	"fracking" entry?	...labeled informal/slang?	"hydraulic fracturing" entry?
Collins English Dictionary	yes	no	yes
Dictionary.com	yes	no	yes
Encyclopedia Britannica	yes	no	no
Macmillan English Dictionary	yes	no	no
Merriam-Webster	yes	no	yes
Oxford English Dictionary	yes	no	yes (but listed under "hydraulic")

Examples of slang/informal entries: Merriam-Webster Dictionary

buck 1 of 6 *noun (1)*

ˈbək

plural **bucks**

Synonyms of *buck* ›

1 a informal

(1) : DOLLAR sense 3b

I only had a *buck* in my pocket.

Dinner cost twenty *bucks*.

(2) : a sum of money especially to be gained

make a quick *buck*

also : MONEY → usually used in plural

making the big *bucks*

b US slang → used in place of "hundred" in combination with other numbers

... as much at ease going 40 in First as it is doing a *buck*-twenty [=120 miles an hour] down the freeway ...

– Hot Rod

chillax *verb*

chil·lax chi-ˈlaks

chillaxed; chillaxing; chillaxes

intransitive verb

slang

: to calm down : RELAX

Examples: Merriam-Webster Dictionary

fracking noun

frack·ing ˈfra-kiŋ

: the injection of fluid into shale beds at high pressure in order to free up petroleum resources (such as oil or natural gas)

frack ˈfrak verb

Examples: Merriam-Webster Dictionary

hydraulic fracturing noun

: FRACKING

The gas-fired plants come courtesy of the revolution in *hydraulic fracturing* ("fracking"), which has delivered a vast supply of low-cost natural gas to an electricity market that has struggled with steadily rising coal prices since 2001.

– Jerry Taylor and Peter Van Doren

Recent Examples on the Web

The news adds to concerns about natural gas companies' *hydraulic fracturing*, commonly called fracking.

– Joseph Calamia, *Discover Magazine*, 3 Sep. 2010

Corpus Analysis

Which term is more commonly used?

Reference Corpora

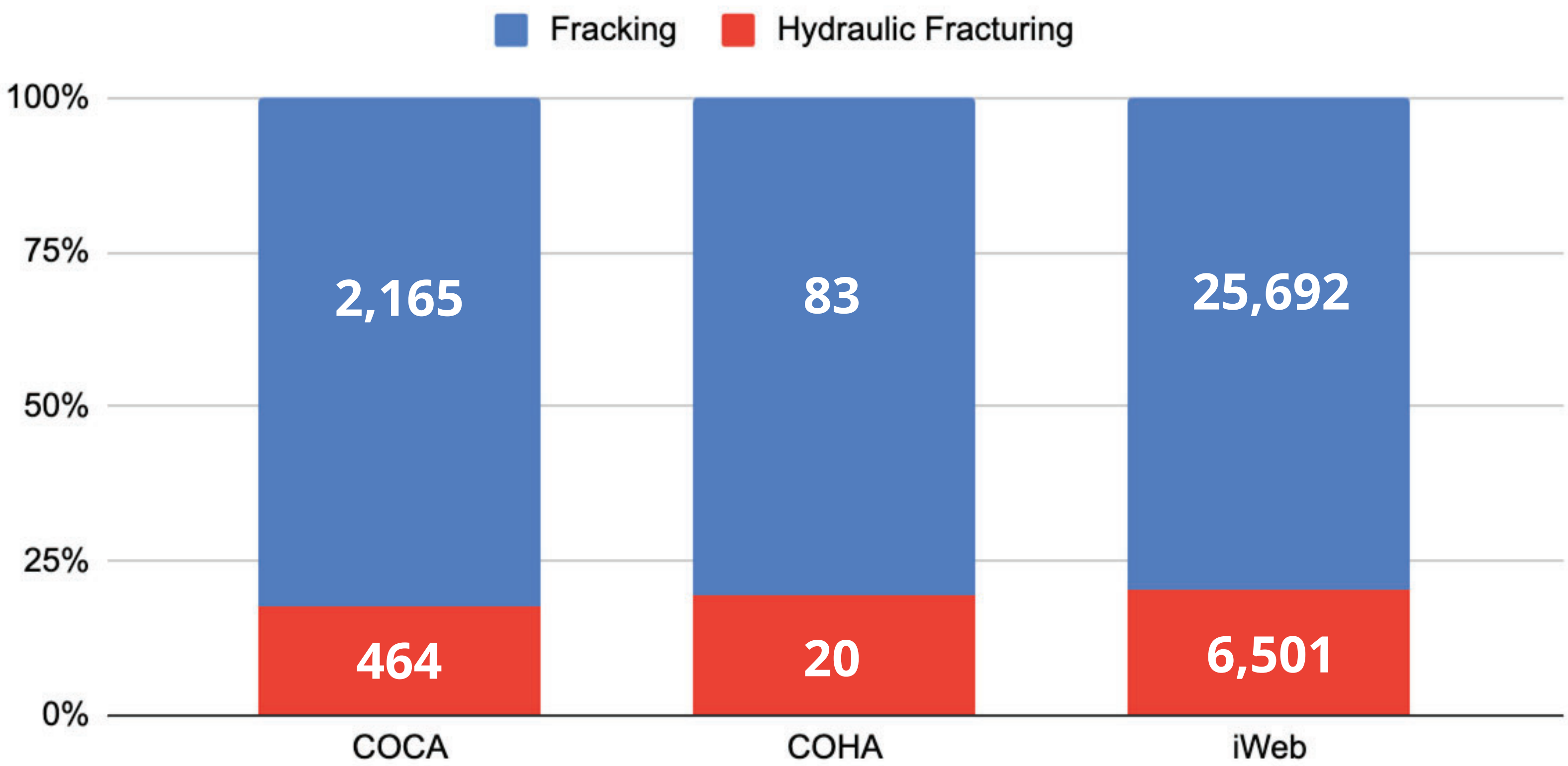
1. Corpus of Contemporary American English (COCA) (1 billion words)
2. Corpus of Historical American English (COHA) (475 million words)
3. iWeb (international corpus of websites) (14 billion words)

Reference Corpora: Analysis

Corpus	fracking	hydraulic fracturing
Corpus of Contemporary American English (COCA)	2,165	464
Corpus of Historical American English (COHA)	83	20
iWeb	25,692	6,501
"commonly known as …"	35*	0
"better known as …"	11	0
"best known as …"	1	0

*includes 7 occurrences of "more commonly known as fracking"

Reference Corpora: “fracking” and “hydraulic fracturing” frequencies



Reference Corpora: Analysis Examples (COCA)

Under the law, companies that use a drilling technique called hydraulic fracturing -- **commonly known as fracking** -- to tap gas deposits in shale would have been free to drill even in areas where local officials had voted against wells. - *publicintegrity.org*

On Sept. 24, President Skorton and Glenn Altschuler, Vice President of University Relations co-authored *Forbes* article entitled, "**Fracking**: A Role for Universities." - *The Cornell Daily Sun*

Engineers in areas without much water, such as Basel, sometimes create boreholes by way of **hydraulic fracturing, or "fracking,"** which involves forcefully injecting water to create fissures. - *Popular Science*

Reference Corpora: Analysis Examples (COHA)

"Thanks to **hydraulic fracturing -- or fracking, as it's often called** -- America's shale fields are now capable of yielding massive quantities of previously inaccessible natural gas." - *Popular Mechanics*

"The industry is also reaping massive benefits from the federal money that set off the explosion of **hydraulic fracturing, or fracking**, the controversial technology used to squeeze gas and oil from shale deposits." - *Mother Jones*

"**Formally called hydraulic fracturing, fracking** has allowed drillers to make money off sandstones and shales that had been considered too 'tight' for the gas and oil to flow freely into wells." - *Science News*

Reference Corpora: Analysis Examples (iWeb)

“Hydraulic fracturing, **commonly known as fracking**, is a method used to extract underground natural gas using high-pressure injections of fluid...” - *chem.info*

“Hydraulic fracturing -- **better known as fracking** -- is a technique that uses high-pressure fluids to " fracture " and extract gas...” - *tomdispatch.com*

“... in exporting American-style hydraulic fracturing the controversial, environmentally damaging technique **best known as fracking** to countries all over the world.” - *theintercept.com*

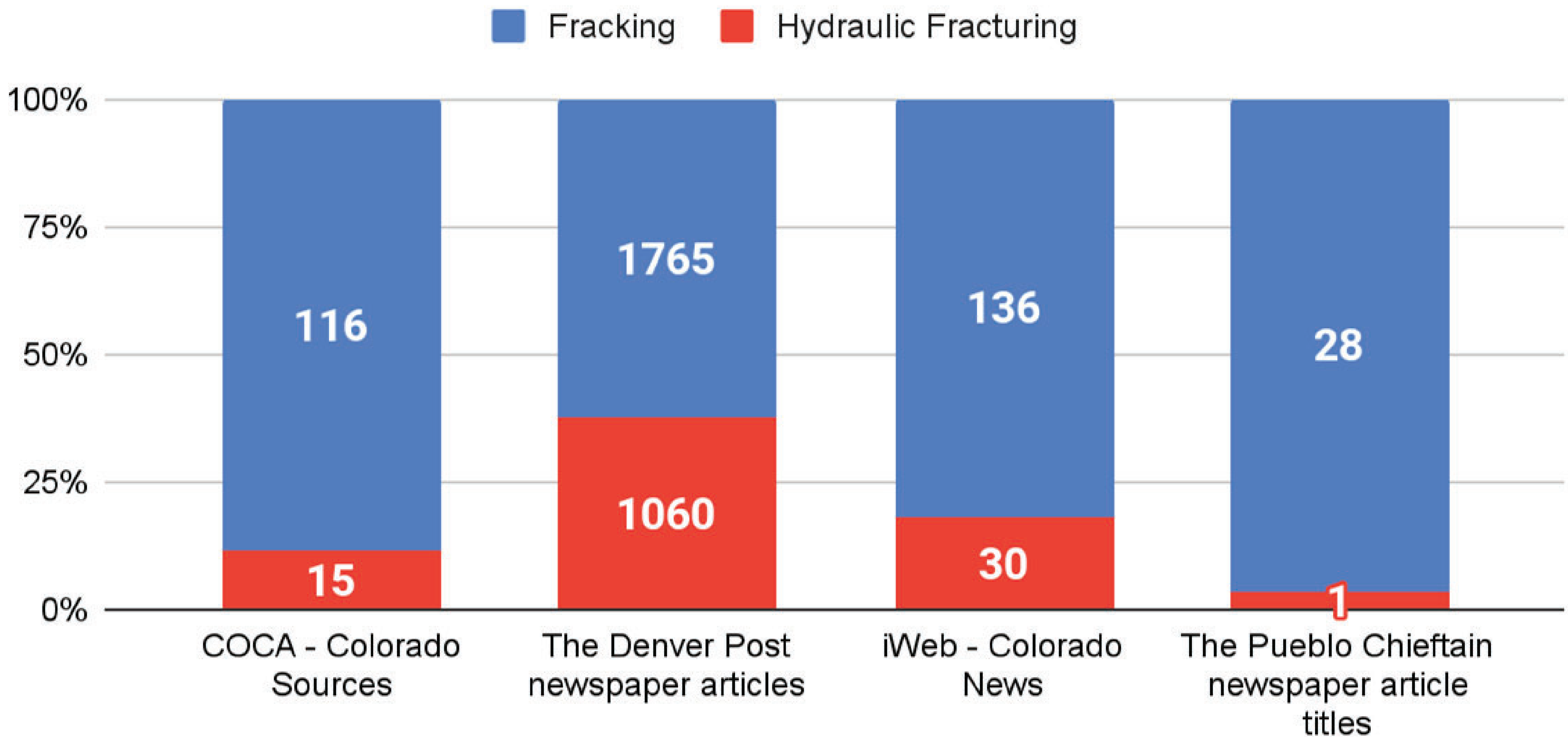
Specialized Colorado Corpora

- The **COCA - Colorado Sources** corpus includes hits on all sources from the COCA reference corpus with either “Colorado” or “Denver” in the name (e.g. CBS News Colorado; *The Colorado Independent*).
- ***The Denver Post* newspaper articles** corpus includes all article results on *The Denver Post*’s website that appear under searches for “fracking” and/or “hydraulic fracturing.”
- The **iWeb - Colorado News** corpus includes hits on nine widely circulated Colorado daily newspapers that are included in the iWeb reference corpus.
- ***The Pueblo Chieftain* newspaper articles titles** corpus includes all titles of articles on the *Pueblo Chieftain*’s website that appear under searches for “fracking” and/or “hydraulic fracturing”. This corpus dates back to the year 2000.

Specialized Colorado Corpora

Corpus	fracking	hydraulic fracturing
COCA - Colorado Sources	116	15
The Denver Post newspaper articles	1765	1060
iWeb - Colorado News	136	30
The Pueblo Chieftain newspaper article titles	28	1

Specialized Colorado Corpora: “fracking” and “hydraulic fracturing” frequencies



Specialized Colorado Corpora: Analysis Examples (COCA - Colorado Sources)

"As Pew project Stateline reported last week, each instance of **hydraulic fracturing, or fracking**, includes anywhere from 2 million to 12 million gallons of water." - *The Colorado Independent*

"Most operators hire oil field service companies, such as Baker Hughes and Halliburton, for drilling and **hydrofracturing, or fracking**, which pumps pressurized fluids into wells to crack rock and release oil." - *The Denver Post*

"The team will review **hydraulic-fracturing, or fracking**, practices, and the effort includes a citizen-science component." - *The Denver Post*

A note on “fracking” in article titles…

The first written use of the term “fracking” was in the **title** of an article in *The Oil and Gas Journal* in 1953 ➤

EXPLORATION

"Fracking"—a New Exploratory Tool

by Philip C. Ingalls

THE use of hydraulic fracturing to stimulate the productivity of oil and gas wells completed in formations of low permeability has proved so successful that the process is affecting exploratory thinking.

Sands and limestones known to contain gas or live oil in place but which exhibit permeabilities too low (0.1 to 5 md.) for satisfactory producing rates and efficient recoveries by shooting or acidizing, have been made profitable objectives by "fracking."

At the American Association of Petroleum Geologists' regional meeting in Wichita, George Roberts, Jr., manager of Stanolind Oil & Gas Co.'s research department, Tulsa, presented that thought in these words: ". . . formation fracturing can be planned to overcome various types of unfavorable conditions. It is indicated that many oil-bearing strata previously considered to have inadequate permeability for commercial production might now be made commercial by creating deep penetrating fractures. Geologists should therefore become familiar with these possibilities in order to better plan exploration programs."

Stanolind research engineers have made calculations of recoveries for several hypothetical reservoirs with low permeability. These calculations, verified by field results, indicate that substantial recovery may be obtained from extremely low permeability formations provided a deep fracture is created—

Reasons for hydraulic fracturing success. (1) Exposes larger areas. (2) Bypasses zones of reduced permeability. (3) Alters flow pattern.

area enlargement are relatively small. (2) Zones of reduced permeability resulting from drilling and completion techniques are breached to provide a low-resistance path for formation fluids into the well. Most of the spectacular results from fracturing are due to this mechanism. (3) The increasing distances that fluid must creep through low-permeability rock to reach the well bore are shortened. Large increases in productivity for uniform but very tight formations can be credited to this result of fracturing.

Initial fracturing work was performed using only 20 bbl. of treating fluid carrying about 400 lb. of sand. Today the technique has advanced to 2,400 bbl. of fluid containing more than 50 tons of propping agent. To answer the question of the relation of the volume of fluid to the length of the fracture radius in tight formations, Roberts gave the following estimates based on 1 lb. of sand per gallon of fluid: 100 ft., 10 to 25 bbl.; 200 ft., 50 to 100 bbl.; 400 ft., 250 to 500 bbl.; and 600 ft., 1,000 to 2,000 bbl.

Today, fracturing operations, which were put on a commercial basis in 1949, are being performed at the rate of nearly 2,000 per month. They are found to be successful in increasing production rates and estimated ultimate recoveries in more than 75 per cent of the wells treated.

Measured in barrels of oil, formation fracturing is comparable to the opening of a large sedimentary basin to production. And, in some of the old shallow producing areas, especially where water is not a problem, it is causing as much excitement.

HIGHLIGHTS OF WEEK'S DEVELOPMENTS

Is "fracking" the term most commonly used by the general public? Yes
Is "fracking" a slang term? No

- "Fracking" is far **more commonly used** than the term "hydraulic fracturing" as attested to by large **reference corpora** of spoken and written American English and **Colorado news sources**

- "Fracking" appears in dictionaries and **it is not labelled as slang**.

Initiative 46

Legislative
Council Staff
Nonpartisan Services for Colorado's Legislature

Fiscal Summary

Date:	May 15, 2023	**Fiscal Analyst:**	Bill Zepernick (303-866-4777)

LCS TITLE: CONCERNING OIL AND GAS PERMITS THAT INCORPORATE THE USE OF FRACKING

Fiscal Summary of Initiative 46

This fiscal summary, prepared by the nonpartisan Director of Research of the Legislative Council, contains a preliminary assessment of the measure's fiscal impact. A full fiscal impact statement for this initiative is or will be available at **www.colorado.gov/bluebook**. This fiscal summary identifies the following impact.

State expenditures and revenue. The measure requires that the Colorado Oil and Gas Conservation Commission adopt rules by January 1, 2026, to discontinue the issuance of new oil and gas permits that involve hydraulic fracturing (commonly referred to as fracking) after December 31, 2030, and transition to a primary mission of monitoring, plugging, and remediating existing oil and gas facilities permitted before this date. On net, the measure is not anticipated to immediately change the workload or costs of the department related to permitting. Once issuance of new permits involving hydraulic fracturing ends, revenue from permitting fees and associated expenditures will decrease. Any fixed costs that are no longer supported with permitting fees will require an appropriation of state funds.

The Department of Natural Resources will also have increased costs to create a program to explore transition strategies for displaced oil and gas workers. This cost is estimated to be at least $300,000 per year to administer the program. To implement any identified strategies, additional funding may be required in the future for grants, training, and other services.

The measure is expected to reduce state revenue from severance taxes as a result of reduced oil and gas production in the future. Severance taxes will continue to be collected on existing wells, however at a diminishing rate. The state aid requirement for total program funding for school finance will increase because the local share, which is dependent on property taxes, including from oil and gas producing property, will decline.

Local government impact. Once all state permitting of oil and gas operations involving hydraulic fracturing is discontinued, any local government with regulatory programs related to siting oil and gas development will have reduced expenditures and fee revenue. Local property tax revenue on oil and gas producing property will decrease as existing wells cease production. In addition, local governments receiving a distribution of severance tax revenue will have less revenue as this funding source diminishes over time.

Economic impacts. Ending oil and gas production involving hydraulic fracturing removes a significant sector of the economy from commercial activity. As industry activity winds down, the measure is likely to reduce capital investment, employment, investment income, and business profits attributable to the oil and gas industry and related upstream and downstream industries. Economic impacts will be distributed unevenly across the state, with the greatest impacts in areas with significant oil and gas production, including the northern Front Range, the western slope, southwest Colorado, and portions of the eastern plains. The measure may also promote additional activity in other energy production industries beyond what would arise under current law, partially mitigating its other economic effects.