- 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.[885]

- 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.[886] 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.[887] 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."[888]

- June 3, 2013 – A study by Duke University researchers linked fracking with elevated levels of methane, ethane, and propane in nearby groundwater.[889] 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

[885] 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.
[886] 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.
[887] 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.
[888] 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.
[889] 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.[890]

- 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.[891]

- 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.[892]

- 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.[893]

- 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."[894]

- 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

[890] 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/.
[891] 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.
[892] 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.
[893] 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.
[894] 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 fueled 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."[895]

- 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.[896]

- 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.[897]

- 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.[898]

- 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

[895] 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.
[896] 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.
[897] 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.
[898] 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…."[899]

- 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."[900] 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"[901] 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.[902] 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,[903] 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.[904] In subsequent years, studies have continued to link underground injection of drilling wastewater to pollution as well as earthquakes.[905]

- 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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[899] 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.
[900] 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.
[901] 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.
[902] 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.
[903] 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.
[904] 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.
[905] 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.[906]

- 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.[907, 908, 909]

- 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.[910]

- May 17, 2011 – A Duke University study documented "systematic evidence for methane contamination of drinking water associated with shale gas extraction."[911] 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.[912]

- 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.[913]

- 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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[906] 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.
[907] 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.
[908] 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.
[909] Dusty Horwitt, "Cracks in the Façade" (Environmental Working Group, August 3, 2011), https://static.ewg.org/reports/2011/Cracks-in-the-Facade.pdf.
[910] 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.
[911] 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.
[912] 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.
[913] 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."[914] These findings were reported in the *New York Times*.[915]

- 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."[916]

- 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.[917]

- 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

[914] 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.
[915] 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.
[916] 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.
[917] 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.[918]

- 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.[919]

- 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.[920]

- 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.[921]

- 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.[922, 923, 924]

[918] 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.
[919] 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.
[920] 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.
[921] 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.
[922] 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.
[923] 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.
[924] 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.[925]

- 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.[926]

- February 1, 2020 – Researchers studied possible interconnections between wells on adjacent and nearby pads to assess the potential for such wells to communicate through

[925] 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/.
[926] 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.[927]

- 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."[928]

- 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."[929]

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[927] 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.
[928] 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.
[929] 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.[930, 931]

- 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 microorganism 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."[932]

- 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.[933] 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."[934]

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[930] 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/.
[931] BC Oil and Gas Commission, "Gas Mitration Preliminary Investigation Report," December 2013, https://www.bcogc.ca/node/14620/download.
[932] 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.
[933] 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.
[934] 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.[935]

- 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."[936]

- 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.[937]

- 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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[935] 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.

[936] 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.

[937] 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.[938]

- 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.[939]

- 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.[940]

- 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.[941] 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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[938] 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.
[939] 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.
[940] 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.
[941] 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.[942, 943]

- 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."[944] 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

[942] 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.
[943] 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/.
[944] 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).[945] 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.[946]

- 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.[947]

- 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.[948] 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

[945] 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).
[946] 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.
[947] 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.
[948] 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."[949]

[949] 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 liquid and solid fracking waste, including sludge and drilling cuttings. These raising exposure risks for workers and the general public. Exemptions from federal hazardous waste laws mean that no national regulatory framework exists for handling the disposal of radioactive materials from oil and gas extraction activities. 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 imperil 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.

As confirmed in a 2023 study, the scaly mineral build-up that accumulates inside fracking equipment can also be a significant source of radiation because radium coprecipitates within calcium carbonate and barium sulfate.

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, although not all studies show consistent results. 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, 2023 – A study of radioactive fracking waste compared two different unpermitted landfills—one in Kentucky and one in Oregon—that had received such waste. Geological and hydrological characteristics varied between sites as did the type of radioactive materials deposited: more brine in Kentucky and more solid radioactive waste at the Oregon site. The materials accepted as waste also differed as did the used of liners and personal protective equipment for workers. Risk assessments compared three scenarios for current and future receptors: during disposal, a closure-in-place alternative, and an excavation alternative. The exposure pathway for potential receptors depended on method of removal, and included inhalation of radon or suspended particles blown offsite during removal operations, inadvertent soil ingestion, and external exposure. In both risk assessments, the preferred remediation alternative was to leave the materials in place as it was far more protective of on-site workers, the public, and the environment. Further, the authors advocated for a uniform Federal standard for disposal of naturally occurring radioactive materials whose radionuclide concentrations have been increased by human activity. [Note that the authors of this study were all employed by limited liability corporations that engage in environmental risk assessments.][950]

- February 25, 2023 – In Brazil, no repositories exist for the storage of radioactive wastes from oil and gas extraction activities. Instead, they are stored in drums at sites not intended for radioactive materials. A radiological assessment of oil and gas industry waste in Brazil asked whether the effective doses at these local facilities remain below the annual limit for public exposure. Using methods developed by the Argonne National Laboratory for the United States Department of Energy and the United States Nuclear Regulatory Commission, the research team evaluated the radiological dose and excess cancer risk for individuals exposed while within or outside the area of primary contamination. Several pathways of exposure were considered, and the scenario selected was a subsistence farm with crops and animals raised on top of the closed landfill with residents drinking water from a well located next to the site. The results showed that one factor mediating risk was the depth of soil covering the waste, with greater cover being more protective. "The main exposure pathway contributing the total effective dose and the cancer risk in all scenarios analyzed was direct radon exposure from the primary contamination and from atmospheric release."[951]

- February 9, 2023 – Particularly high concentrations of radioactivity are found on oil and gas extraction equipment where scaly mineral build-up accumulates, especially barium sulfate and calcium carbonate, within which radium coprecipitates. The pathway of exposure is via inhalation. For this study, researchers analyzed five samples of scale collected from oil and gas equipment in southern Algeria for the presence of radioactive isotopes (radium, thorium, and potassium) The findings indicated that gonadal doses of radioactivity were excessive. "All mean hazard parameters are greater than the

[950] Emily A. Caffrey et al., "Comparison of Doses from Disposals of Technologically Enhanced Naturally Occurring Radioactive Materials in Kentucky and Oregon," *Health Physics* 124, no. 6 (June 2023): 441–50, https://doi.org/10.1097/HP.0000000000001683.
[951] Amanda Gomes Lopes, Francisco Cesar Augusto Da Silva, and Ricardo Tadeu Lopes, "Radiological Assessment of the Disposal of Bulk Oil NORM Waste: Case Study from Brazil," *Journal of Environmental Radioactivity* 261 (May 2023): 107139, https://doi.org/10.1016/j.jenvrad.2023.107139.

recommended safety limit, and the estimated dose rates show that long-term accumulation of [radioactive] scale residues may lead to possible radiological hazards in the future." The authors recommend special methods during cleaning and maintenance, such as chemically treating scale residues, storing residues in underground bunkers, and reducing personal exposure and environmental contamination through regulatory controls.[952]

- October 3, 2022 – The Radiation Protection Bureau of Health Canada reviewed industrial activities, outside of the nuclear industry, that involve naturally occurring radioactive materials to clarify the variety of regulations governing different industries and consolidate that information into one source. The report identifies oil and gas extraction, as the industry with the largest number of exposed workers. Further, the oil and gas sector is the industry responsible for the largest air and land releases of radioactive materials and the second largest source of radioactive materials released to water. (Metal ore mining was number one.)[953]

- June 1, 2022 – A research team analyzed shale gas wastewater from several sites in the Sichuan Basin in China to determine the potential for recovering and monetizing valuable chemicals including salts, strontium, lithium, and gallium. The findings showed that current technology does not provide an economically feasible way to extract them. Further, while radioactivity was 95 percent removed, the radioactive residuals left behind still exceeded drinking water standards. Noting that residual radioactivity persisted in shale gas wastewater pretreated with sophisticated disc tube reverse osmosis, the authors raised concerns about levels of radioactivity in wastewater not treated with reverse osmosis.[954]

- 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

[952] El Hadji Mamadou Fall et al., "Assessment of Occupational Radiation Exposure of NORM Scales Residues from Oil and Gas Production," *Nuclear Engineering and Technology* 55, no. 5 (May 2023): 1757–62, https://doi.org/10.1016/j.net.2023.02.012.
[953] Jing Chen, "A Review of Current Inventory for Major Industries Involving Naturally Occurring Radioactive Materials in Canada," *Journal of Radiological Protection* 42, no. 3 (September 1, 2022): 031520, https://doi.org/10.1088/1361-6498/ac9396.
[954] Wancen Xie et al., "Shale Gas Wastewater Characterization: Comprehensive Detection, Evaluation of Valuable Metals, and Environmental Risks of Heavy Metals and Radionuclides," *Water Research* 220 (July 2022): 118703, https://doi.org/10.1016/j.watres.2022.118703.

air quality, safety, and health of the citizens of Scranton, as well as the water quality of Meadow Brook Creek and the Lackawanna River."[955]

- 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.[956]

- 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.[957]

- March 30, 2021 – Radon is a proven cause of lung cancer, and shale basins where fracking occurs typically have high radon concentrations due to the decay of naturally occurring uranium. In this study, the authors identified radon hotspots throughout the state of Pennsylvania, looked at radon trends from 1988 through 2018, and asked whether fracking activities—by breaking up rocks and allowing great flow of radon gas into soil—have increased radon levels inside residential homes. They also examined how factors such as seasonal changes in weather might influence indoor radon concentrations. The aim was to offer mitigation measures and thereby reduce lung cancer risk. The results showed that geology is the primary factor affecting radon levels in Pennsylvania,

[955] 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/.
[956] 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.
[957] 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/.

with shales, limestone, and granite all containing elevated levels of radon. Single family homes, tested at the basement level, in Northeast Pennsylvania had the highest radon concentrations. Higher levels were found in the winter, possibly due to less ventilation. Homes in rural areas where most fracking occurs, showed significant variability. More research is needed to make solid recommendations regarding mitigation.[958]

- 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 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."[959]

- 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.[960]

- 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

[958] Kyle R. Kellenbenz and Kabindra M. Shakya, "Spatial and Temporal Variations in Indoor Radon Concentrations in Pennsylvania, USA from 1988 to 2018," *Journal of Environmental Radioactivity* 233 (July 2021): 106594, https://doi.org/10.1016/j.jenvrad.2021.106594.
[959] 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/.
[960] 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/.

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.[961]

- 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.[962]

- 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.[963]

- 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

[961] 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/.
[962] 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.
[963] 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/.

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 the two entities: the landfill and the treatment plant."[964] New state legislation was drafted in 2019 that would prevent TENORM disposal in Pennsylvania public waters.[965]

- 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.[966] 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.[967]

- 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.[968] The team evaluated exposure to radionuclides from oil and gas waste by landfill worker job description: drivers, workers receiving the waste, and workers

[964] 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/.
[965] 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/.
[966] "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.
[967] 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.
[968] 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.

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 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.[969]

- 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*.[970] 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 under protected; 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

[969] 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/.
[970] 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.

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.[971]

- 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 in Krakow, Poland concluded that handling black powder presents radiological risk to employees.[972]

- 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.[973] 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.[974] 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

[971] 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/.
[972] 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.
[973] 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.
[974] 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.

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 leachate from the landfill at levels higher than allowed by EPA's drinking water standards. A *State Impact 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."[975]

- 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.[976] "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.[977] 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.[978]

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[975] 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, 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/.

[976] 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.

[977] 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.

[978] 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.

- 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."[979] 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 progressive, hydrologic enrichment of injected fluids during hydraulic fracturing.[980] 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."[981]

- 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."[982]

- 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."

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[979] 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.
[980] 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.
[981] 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.
[982] 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.

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.[983]

- January 4, 2018 – A research team from Duke and Pennsylvania State universities collected stream sediments upstream and downstream from three disposal sites in 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."[984]

- 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.[985]

- 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

[983] 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.
[984] 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.
[985] 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/.

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."[986]

- 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 accumulated in the soils of spill-affected areas.[987] 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.[988]

- 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.[989]

- 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.[990]

- 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

[986] 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.
[987] Lauer, Harkness, and Vengosh, "Brine Spills Associated with Unconventional Oil Development in North Dakota."
[988] 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.
[989] 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/.
[990] 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.

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.[991]

- 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 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.[992]

- 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.[993] Radon exposure is the second leading cause of lung cancer worldwide, after cigarette smoking.[994] 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.[995]

- 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.[996] "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

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[991] 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.
[992] 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.
[993] 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.
[994] 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.
[995] 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/.
[996] 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.

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 proximity to where people live and work, raise risks for human exposure. "The technology is vastly outpacing what we know about the health effects."[997]

- 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.[998]

- 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.[999] 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."[1000]

- 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

[997] 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/.
[998] 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/.
[999] 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.
[1000] 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.

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."[1001]

- 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."[1002, 1003]

- 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."[1004]

- 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

[1001] 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.
[1002] 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.
[1003] 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.
[1004] 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.

samples "is too small to … yield statistically valid results" and urged "collection and interpretation of additional data."[1005]

- 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 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."[1006]

- 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.[1007] (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

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[1005] 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.

[1006] 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.

[1007] 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.

accepting drilling waste with radium levels 12 or more times as high as the drinking water standard.[1008]

- 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 level limit for radium in drinking water. These figures later informed the 2011 study of radium in drilling wastewater conducted by the USGS.[1009]

- 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*.[1010] 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.

[1008] 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.
[1009] 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 (5-133, 5-141, 7-60, Appendix 12, Appendis 13, Rep.)," Technical Report, 2011.
[1010] 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 2021, the most recent year for which data are available, 58 oil and gas extraction workers died on the job, up from 44 deaths in 2020. These deaths represent over 60 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 motor vehicle accidents, head injuries, blunt trauma, burns, inhalation of hydrocarbon vapors, toxic chemical exposures, radiation exposure, heat exhaustion, dehydration, and sleep deprivation. Two-thirds of workers report reported workday shifts of 12 or more hours. 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.

- April 25, 2023 – In 2021, the year on which the 32nd edition of the AFL-CIO's "Death on the Job: The Toll of Neglect" reports, the category that includes oil and gas extraction workers ("mining, quarrying, and oil and gas extraction") again had the third highest fatality rate of all industry groupings. This rate was 14.2 deaths per 100,000 workers, up from 10.5 in 2020. Oil and gas extraction workers specifically comprised 61 percent of the on-the-job fatalities (58 of the 95 deaths) in this category. Oil and gas extraction workers suffered fourteen more deaths in 2021 than in 2020. 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.[1011]

[1011] AFL-CIO, "Death on the Job: The Toll of Neglect, 32nd Edition," A National and State-by-State Profile of Worker Safety and Health in the United States (AFL-CIO, April 25, 2023), https://aflcio.org/reports/death-job-toll-neglect-2023.

- March 15, 2023 – In this report on working conditions in the oil and gas industry, "The Future of Energy & Work in the United States: The American Oil & Gas Worker Survey," worker safety emerged as a top concern. The report analyzes results of a cross sectional survey of 1,635 oil and gas workers. A section of the report on safety and liability describes the findings. These include that "45 percent of survey respondents believe that their company's safety program was explicitly or implicitly designed to shift liability of an accident onto the worker." Further, more than 25 percent of workers in the survey said they would hesitate to raise safety concerns with management. Thirty-five percent of respondents "indicated that they had been ordered to engage in unsafe working practices that were in direct violation of established safety practices." Seventeen percent said "they had been threatened to have their employment terminated if they did not engage in unsafe working practice." The authors also provide an analysis of raw data from OSHA's "Severe Injury Report" of 2015-2022. They parsed out incidents related to upstream, midstream and downstream oil and gas jobs, finding 2,484 reported severe injuries and 2,031 hospitalizations. "The leading types of injuries included fractures (722), amputations (692), soreness from injury (163), heat, thermal burns (111), and lacerations (94)."[1012]

- October 19, 2022 – On June 28, 2021, a gas explosion killed two workers and injured two others during routine maintenance using an in-line inspection tool ("pigging") at an Atmos Energy Corporation worksite near Farmersville, Texas. The National Transportation Safety Board (NTSB) Pipeline Investigation Report into the explosion found the probable cause to be "a leaking mainline valve that allowed natural gas to enter the launcher where it mixed with air, creating a flammable gas–air mixture that was ignited by an undetermined source." The Board said that Atmos Energy Corporation's procedures and training practices "did not prepare workers to recognize and safely respond to abnormal operating conditions," and that this contributed to the explosion and its severity.[1013]

- June 23, 2022 – Long daily commutes, nonstandard work schedules, less sleep on workdays, and lack of employer policies were linked to risky driving behaviors by oil and gas extraction (OGE) workers, according to a study by National Institute of Occupational Safety and Health (NIOSH) researchers published in the *American Journal of Industrial Medicine*. Because U.S. oil and gas workers have consistently high fatality rates—with motor vehicle crashes being the leading cause of those deaths—researchers sought understanding of the underlying causes. Of the 500 OGE workers studied, nearly two-thirds reported workdays of 12 or more hours and nearly half reported less than seven hours of sleep per workday. About one quarter of those surveyed reported having fallen

[1012] Megan Milliken Biven and Leo Lindner, "The Future of Energy & Work in the United States: The American Oil & Gas Workers Survey" (True Transition, March 2023), https://www.truetransition.org/_files/ugd/0ad80c_069ea867b3f044afba4dae2a1da8d737.pdf?index=true.
[1013] National Transportation Safety Board, "Atmos Energy Corporation Natural Gas–Fueled Explosion During Routine Maintenance," Pipeline Investigation Report, October 19, 2022, https://www.ntsb.gov/investigations/AccidentReports/Reports/PIR2203.pdf.

asleep while driving a work vehicle or feeling extremely drowsy more than once a month while driving at work. Researchers called for policies and programs to address these risk factors.[1014]

- April 28, 2022 – Chemical and physical hazards are the "most dangerous occupational factors" according to a scoping review aiming to identify influences on sexual and reproductive outcomes among women employed worldwide in the oil, gas, and mining (OGM) industry. Though the authors report a scarcity of global research (their review incorporated 15 studies), the studies they identified and analyzed suggest that menstrual cycle disorders may be due to occupational hazards such as exposure to heavy metals, toxic gases, and dust. The researchers cite the importance of this review and the need for continued research, given that the majority of women working in OGM are of childbearing age. They call for high-quality research that addresses "all potential biological, chemical, and environmental health hazards, particularly air and water pollutants, which are often found in OGM industry."[1015]

- April 26, 2022 – In 2020, the year about which the 31st edition of the AFL-CIO's "Death on the Job: The Toll of Neglect" reports, the category that includes oil and gas extraction workers ("mining, quarrying, and oil and gas extraction") had the third highest fatality rate of all industry groupings. This rate was 10.5 deaths per 100,000 workers. Oil and gas extraction workers specifically comprised over 56 percent of the on-the-job fatalities (44 of the 78 deaths) in this category. 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.[1016]

- November 14, 2021 – A NIOSH-led scoping review provided summaries of existing research on the health and safety consequences of shift work, fatigue, and sleepiness in the oil and gas extraction (OGE) workforce and outlined unmet research needs. The researchers found that only a minority of the 78 papers located addressed onshore OGE workers, even though 85 percent of U.S. oil and over 96 percent of U.S. natural gas is produced onshore. This detailed call for filling research gaps relating to shift work and fatigue includes: building knowledge on the impacts of fatigue in OGE; exploring interactions between on- and off-the-job risk factors and behaviors; and identifying and evaluating interventions to address fatigue in OGE. They call for improved methodologies in studies and conclude that "research is needed to assess the effects of

[1014] Kyla Hagan-Haynes et al., "On the Road Again: A Cross-sectional Survey Examining Work Schedules, Commuting Time, and Driving-related Outcomes among U.S. Oil and Gas Extraction Workers," *American Journal of Industrial Medicine* 65, no. 9 (September 2022): 749–61, https://doi.org/10.1002/ajim.23405.
[1015] Rina Hariniaina Razafimahefa, Jerico Franciscus Pardosi, and Adem Sav, "Occupational Factors Affecting Women Workers' Sexual and Reproductive Health Outcomes in Oil, Gas, and Mining Industry: A Scoping Review," *Public Health Reviews* 43 (April 28, 2022): 1604653, https://doi.org/10.3389/phrs.2022.1604653.
[1016] AFL-CIO, "Death on the Job: The Toll of Neglect, 31st Edition," A National and State-by-State Profile of Worker Safety and Health in the United States (AFL-CIO, April 26, 2022), https://aflcio.org/reports/death-job-toll-neglect-2022.

shiftwork, unpredictable work schedules, overtime, on-call, and fatigue on the onshore OGE workforce and in other parts of the world."[1017]

- 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.[1018]

- 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 Railroad Commission. The release killed an Aghorn employee and his spouse. (See July 21, 2020 entry.)[1019]

- 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.[1020]

- 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.[1021]

[1017] Kyla Hagan-Haynes et al., "US Research Needs Related to Fatigue, Sleep, and Working Hours among Oil and Gas Extraction Workers," *American Journal of Industrial Medicine* 65, no. 11 (November 2022): 840–56, https://doi.org/10.1002/ajim.23310.
[1018] 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/.
[1019] 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-/.
[1020] 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.
[1021] 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.

- 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 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 reductions in workplace exposures to prevalent hazards such as noise, silica, and diesel exhaust.[1022]

- 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."[1023]

- 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.[1024] 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."

[1022] 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.
[1023] 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.
[1024] 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.

- 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."[1025]

- April 30, 2020 –NIOSH released its 2017 data set from the Fatalities from the Oil and Gas Extraction Industry (FOG) database.[1026] 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.[1027] 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.)

[1025] 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.
[1026] 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.
[1027] A. Ramirez-Cardenas, Personal Communication re: Data Set Release Dates and Report Delay Information, July 24, 2020.

- 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."[1028]

- 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," where researchers found over 76 percent were exposed to silica.[1029] 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.[1030] 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."[1031] They find that replacement with a less harmful, more expensive alternative would be economical if these health-related "externalities" were taken into account.

[1028] 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.
[1029] 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.
[1030] 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.
[1031] 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.

- 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.[1032]

- 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 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."[1033]

- 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."[1034, 1035] This accident remains one of the worst oil field incidents in U.S. history.

[1032] 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.

[1033] 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.

[1034] 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.

[1035] U.S. Chemical Safety and Hazard Investigation Board.

- 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."[1036] 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.

- 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.[1037] There were 18 more fatal occupational injuries in oil and gas extraction industries than the previous year.[1038] (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."[1039] 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, 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

[1036] 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.
[1037] 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.
[1038] U.S. Bureau of Labor Statistics, "Injuries, Illnesses, and Fatalities," 2018, https://www.bls.gov/iif/oshwc/cfoi/cfoi-chart-data-2017.htm.
[1039] 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.

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 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."[1040]

- 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.[1041]

- 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

[1040] 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.
[1041] 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/.

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."[1042]

- 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 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.[1043] The operating company blamed contractors.[1044] (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."[1045] 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."[1046]

[1042] 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.
[1043] 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.
[1044] 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.
[1045] Antonia Juhasz, "Death on the Dakota Access," *Pacific Standard*, September 12, 2018, https://psmag.com/magazine/death-on-the-dakota-access.
[1046] Antonia Juhasz, "Methodology for Calculating Fatality Rates," *Pacific Standard*, September 12, 2018, https://psmag.com/magazine/methodology-for-calculating-fatality-rates.

- 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.[1047]

- 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 fluids from the well was unable to fully close on the day of the accident and that other safety corners had been cut.[1048]

- 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."[1049]

- 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.[1050]

- 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.

[1047] 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.
[1048] 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-/.
[1049] 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.
[1050] 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.

- 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.[1051]

- 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 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.[1052]

- 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

[1051] 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.
[1052] 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/.

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.'"[1053]

- 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 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).[1054]

- 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.[1055] (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

[1053] 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.
[1054] 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.
[1055] 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.

report, such as the lack of information on self-employed workers and lack of detail in some fatality reports.[1056]

- 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 about the regulatory gaps in controlling a range of potentially fatal hazards in the industry.[1057]

- 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."[1058]

- 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

[1056] 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.
[1057] AFL-CIO, "Death on the Job: The Toll of Neglect, 26th Edition," 2017, https://aflcio.org/reports/death-job-toll-neglect-2017.
[1058] 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.

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."[1059]

- 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 patients are not described, presumably they were oil and gas industry workers with easy access to fracking fluid.[1060]

- 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."[1061]

- 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

[1059] 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.
[1060] 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.
[1061] R. J. Sangosti and John Ingold, "Drilling Through Danger," *The Denver Post*, September 25, 2016, http://extras.denverpost.com/oil-gas-deaths/index.html.

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.[1062]

- 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.[1063]

- 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 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."[1064]

- 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."[1065]

- 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

[1062] AFL-CIO, "Death on the Job: The Toll of Neglect, 2016," 2016, http://www.aflcio.org/Issues/Job-Safety/Death-on-the-Job-Report.
[1063] 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.
[1064] 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/.
[1065] 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/.

[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.[1066] 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."[1067]

- 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 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.[1068]

- 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.'"[1069] (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

[1066] 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.
[1067] 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.
[1068] 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.
[1069] 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/.

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.[1070]

- 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.[1071]

- 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 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."[1072] (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."[1073]

- 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

[1070] 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.
[1071] 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.
[1072] 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.
[1073] 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/.

noted that nearly 80 percent of the air samples on the well pads were above the recommended exposure limit for silica dust.[1074]

- 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.[1075]

- 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.[1076]

- 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.[1077]

- 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

[1074] 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/.
[1075] 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.
[1076] 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/.
[1077] 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/.

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.[1078]

- 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 12.4 per 100,000 in this industry.[1079, 1080]

- 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."[1081] 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.[1082] 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

[1078] 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.
[1079] AFL-CIO, "Death on the Job: The Toll of Neglect, 25th Edition," April 22, 2015, https://aflcio.org/reports/death-job-2016.
[1080] 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.
[1081] 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.
[1082] 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/.

obstacles to proper training in tank handling techniques.[1083] NIOSH issued recommendations for worker protections, including respiratory protection training and engineering controls for remote gauging and venting.[1084]

- 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.[1085]

- 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.[1086]

- 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]."[1087]

- 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

[1083] 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/.
[1084] 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/.
[1085] 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/.
[1086] 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.
[1087] 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.

gas was firefighting, the report stated. These statistics are inclusive of deaths related to fracking operations but are not specific to them.[1088]

- 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.[1089]

- 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 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."[1090]

- 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."[1091]

- 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

[1088] 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.
[1089] 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.
[1090] 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/.
[1091] 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.

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*.[1092] (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.[1093]

- 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 or protective gear was provided."[1094] 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."[1095]

- 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,

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[1092] 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.
[1093] 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/.
[1094] 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.
[1095] "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.

New York, North Carolina, South Carolina, Pennsylvania, Tennessee, Vermont, and Virginia. The *International Business Times* published a summary of the findings.[1096, 1097]

- 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 Conference of Governmental Industrial Hygienists' Threshold Limit Value, "when workers performed work tasks near a point source for benzene emissions."[1098]

- 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."[1099]

- 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

[1096] 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.
[1097] 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.
[1098] 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.
[1099] 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.

prevalence of occupational illness; industry/academic collaboration to conduct occupational epidemiologic studies; and assessment of the effectiveness of industry interventions to reduce exposures.[1100]

- 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."[1101]

- 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.[1102, 1103]

- 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."[1104, 1105]

- 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

[1100] 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.
[1101] 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.
[1102] Jennifer Smith Richards, "Glitch Sparks Smoky Fire at Gas Well," *The Columbus Dispatch*, June 29, 2014, https://www.dispatch.com/article/20140629/NEWS/306299873.
[1103] Laura Arenschield, "Fracking Fire Points out Failings," *The Columbus Dispatch*, August 31, 2014, https://www.dispatch.com/article/20140831/NEWS/308319916.
[1104] 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/.
[1105] Robert Iafolla, "Four Fatalities Linked to Used Fracking Fluid Exposure During 'Flowback,' NIOSH Reports," *Bloomberg BNA*, May 20, 2014, https://perma.cc/M5RY-QPZA.

disease and autoimmune diseases.[1106] Although community exposures distant from mines are possible, there are no federal or state standards for silica in ambient air.[1107]

- 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."[1108]

- 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.[1109]

- 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.[1110]

- 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

[1106] 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.
[1107] 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.
[1108] 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/.
[1109] 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.
[1110] "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/.

suffered burns and 675 broke bones. From 2007 to 2012, at least 664 U.S. workers were killed in oil and gas fields.[1111, 1112]

- 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.[1113]

- 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 also noted that the public health perspective has been inadequately represented in policy processes related to HVHF.[1114] 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."[1115]

- 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

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[1111] 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.
[1112] 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/.
[1113] 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.
[1114] 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.
[1115] 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.

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.[1116]

[1116] 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, Colorado, and Ohio, birth defects were elevated among infants whose mothers lived near drilling and fracking sites while pregnant. A 2023 study documented elevated rates of neural tube defects, spina bifida, and limb reduction defects in Ohio infants born to mothers living near drilling and fracking sites. 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 developmental toxicants, including 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. In Pennsylvania, children living within 1.2 miles of a fracking well were 2-3 times more likely to be diagnosed with leukemia. In Pennsylvania elevated rates of bladder and thyroid cancers were found 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; elevated motor vehicle fatalities; symptoms of depression and anxiety; ambulance runs and emergency room visits; and incidence of sexually transmitted diseases. An emerging body of evidence from multiple states links fracking to increased risk of death and increased rates of heart attack, ischemic heart disease, and heart failure among older residents living nearby.

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.

- May 8, 2023 – Using air quality data from six government monitors, a study in northeastern British Columbia examined the relationship between particulate air pollution levels (PM10 and PM2.5) at or near the homes of 92 pregnant women and proximity to conventional oil and gas wells and wells that were fracked. The results showed that higher density and activity of nearby oil and gas wells increased gestational exposure to particulate matter among participants. Higher conventional well metrics (proximity, density, and activity) were more strongly correlated with higher PM10 estimations whereas the metrics for fracked wells were correlated with higher levels of inhalable PM2.5 but not with PM10.[1117]

- May 8, 2023 – An analysis of health impacts from air pollution due to oil and gas production in the United States in 2016 1) used information from a US EPA emissions database; 2) simulated the resulting PM2.5, NO2, and ozone air pollution as it dispersed; and 3) estimated asthma and premature mortality and related economic impacts of exposure to those pollutants at the census tract level. The research team found that air pollution from the oil and gas sector in the United States resulted in 410,000 asthma exacerbations, 2,200 new cases of childhood asthma, and 7,500 excess deaths, with a mid-point estimate of $77 billion in total health impacts. Nitrogen dioxide was the highest contributor to health impacts (37 percent) followed by ozone (35 percent) and fine particulate matter (28 percent). The impacts were highest in, but not limited to, areas with concentrated oil and gas production as they also extended to areas downwind, even into states that do not have oil and gas activity themselves.[1118]

- April 24, 2023 – Compared to other dog breeds, boxers and golden retrievers are at elevated risk for developing multicentric lymphoma, a malignancy similar to non-Hodgkin's lymphoma in humans. A recent study sought to determine whether residential radon and proximity to fracking operations are, in addition to breed, risk factors for the development of pet dog lymphoma. Fifty-six boxers and 54 golden retrievers with multicentric lymphoma were used in a case-control study. Controls without lymphoma were matched for age, breed, and sex. Counties of residence were matched to radon zones and percentage of home radon tests that exceeded the actionable radiation level of 4

[1117] Élyse Caron-Beaudoin et al., "Estimation of Exposure to Particulate Matter in Pregnant Individuals Living in an Area of Unconventional Oil and Gas Operations: Findings from the EXPERIVA Study," *Journal of Toxicology and Environmental Health, Part A* 86, no. 12 (June 18, 2023): 383–96, https://doi.org/10.1080/15287394.2023.2208594.
[1118] Buonocore et al., "Air Pollution and Health Impacts of Oil & Gas Production in the United States."

pCi/L from 2008-2017. Locations of horizontal oil and gas wells were obtained from the Enverus Database. Distances from dog homes to the closest well and well density by county were calculated for each case and control. The analysis found no significant differences in radon zones, county level radon measurements, or residential proximity to active fracking wells between dogs with and without lymphoma in either breed of dog.[1119]

- April 17, 2023 – A registry-based cohort study of 965,236 live births in Ohio from 2010-2017 examined structural birth defect risks associated with proximity of maternal residence to drilling and fracking operations. Birth defects were identified in 4653 individuals. Exposure to fracking activity was based on maternal residential proximity to active wells within 10 kilometers (6.2 miles) the density of wells, and whether or not there was a well upgradient of groundwater flow toward the maternal residence as a potential pathway of exposure to pollutants. The authors accounted for a variety of potential individual- and neighborhood-level confounders and effect modifiers. They found that children born to women who lived within 10 kilometers of fracking sites were 13 percent more likely to have any birth defect although this difference did not quite reach statistical significance. However, the risk of certain individual birth defects was significantly increased. The odds of neural tube defects were 57 percent higher, limb reduction defects 99 percent higher, and spina bifida 93 percent higher. The highest risk was associated with potential drinking water exposure from an upstream source within 10 km. The odds of hypospadias in boys was reduced by 38 percent in those whose birth home was within 10 km of a fracking site. The authors speculate that this latter finding could be due to exposure to androgenic chemicals previously identified in fracking waste water. The results corroborate some findings in other studies.[1120]

- March 6, 2023 – A study in the Marcellus Shale region of northern Pennsylvania and southern New York examined trends in hospitalizations for illnesses plausibly related to air pollution from drilling and fracking operations among older people as fracking activity rapidly increased in Pennsylvania after 2009. Using 2002-2015 Medicare claims, the authors took advantage of the stark difference in fracking activity between Pennsylvania, where the practice became widespread beginning in 2008, and New York, where the practice was and remains banned. The team selected three northern Pennsylvania counties to serve as the exposed areas and two unexposed neighboring regions in New York as controls. For each region, from 2002 to 2015, they identified the numbers and trends for hospitalization with acute myocardial infarction (heart attack), chronic obstructive pulmonary disease, bronchiectasis, heart failure, ischemic heart disease, and stroke among adults aged ≥65 years. The authors examined the differences in hospitalization rates for these conditions among the three regions before fracking began in Pennsylvania and then followed the numbers and trends in the following years with increasing exposure to fracking activities. They found that from 2002-2008 the rates

[1119] Ashleigh Tindle and Lauren Trepanier, "Radon and Fracking Exposures and Lymphoma Risk in a Canine Model of Non-Hodgkin Lymphoma," *Journal of Clinical and Translational Science* 7, no. s1 (April 2023): 142–142, https://doi.org/10.1017/cts.2023.502.
[1120] Casey Gaughan et al., "Residential Proximity to Unconventional Oil and Gas Development and Birth Defects in Ohio," *Environmental Research*, April 2023, 115937, https://doi.org/10.1016/j.envres.2023.115937.

of hospitalizations for these illnesses and their trends were similar in the Pennsylvania and New York regions. But soon after 2009, the trends began to diverge. In New York, the trends for heart attack and heart failure continued downward, while they began to increase in Pennsylvania where fracking intensity increased. For heart attacks, the association between hospitalization rates and fracking grew consistently larger between 2012 and 2015 in Pennsylvania. In 2015 alone, Pennsylvania counties had an additional 11.8, 21.6, and 20.4 hospitalizations for acute myocardial infarction, heart failure, and ischemic heart disease, respectively, per 1000 Medicare beneficiaries than would have been expected without fracking. The team did not find an association between fracking and chronic obstructive pulmonary disease or stroke.[1121]

- February 1, 2023 – Researchers in Broomfield, Colorado studied health symptoms in residents where oil and gas fracking operations had rapidly developed close to residential neighborhoods. A survey of 3,993 randomly selected households investigated any association between living near wells and frequency of a variety of health-related symptoms. Homes were within 1 mile of well pads, within 1–2 miles, or more than 2 miles away. Response rates to the survey for the three distance bands were similar. During the survey, 30 wells were in the production phase, 21 in the pre-production phase, and 33 had no activity. The research team found no differences in unadjusted analysis of self-reported health symptoms by setback distance. However, after adjusting for a number of individual and family-related variables, symptoms trended higher as the distance to the wells decreased. This association was particularly apparent for upper respiratory, lower respiratory, and gastrointestinal symptoms. There were no differences in reports of mental health or neurological symptoms.[1122]

- December 23, 2022 – A study of exposure to trace elements, many of which are known to be released in fracking wastewater, was undertaken in 85 pregnant women living in northeastern British Columbia where fracking development has rapidly increased in the past 15 years. The researchers found elevated urinary levels of barium, cobalt, copper, manganese, selenium, strontium, and vanadium when compared to reference populations in Canada or the United States. These findings suggest that people living near fracking wells could be exposed to elevated levels of contaminants, conceivably introduced into ground- or surface-water by hydraulic fracturing, and raise concerns about potential impacts in the developing fetus.[1123]

- December 2, 2022 – A Texas statewide population-based cohort study of birth defects, identified through two different birth defect registries, examined associations between

[1121] Kevin S Trickey, Zihan Chen, and Prachi Sanghavi, "Hospitalisations for Cardiovascular and Respiratory Disease among Older Adults Living near Unconventional Natural Gas Development: A Difference-in-Differences Analysis," *The Lancet Planetary Health* 7, no. 3 (March 2023): e187–96, https://doi.org/10.1016/S2542-5196(23)00009-8.
[1122] Meagan L. Weisner et al., "Health Symptoms and Proximity to Active Multi-Well Unconventional Oil and Gas Development Sites in the City and County of Broomfield, Colorado," *International Journal of Environmental Research and Public Health* 20, no. 3 (February 1, 2023): 2634, https://doi.org/10.3390/ijerph20032634.
[1123] Lucie Claustre et al., "Assessing Gestational Exposure to Trace Elements in an Area of Unconventional Oil and Gas Activity: Comparison with Reference Populations and Evaluation of Variability," *Journal of Exposure Science & Environmental Epidemiology*, December 23, 2022, https://doi.org/10.1038/s41370-022-00508-8.

multiple exposure measures of oil and gas extraction and odds of congenital anomalies. Birth outcomes of mothers who lived within 5 kilometers (3.1 miles) of an oil or gas well, combined with intensity of activity at the well(s), were compared to birth outcomes in an otherwise similar group. The study found a 25 percent increased risk of having a child with any birth defect, when using proximity to well site, well site count, gas production, and produced water as exposure measures. For cardiac and circulatory anomalies, the association was particularly robust and consistent for all measures of exposure. Associations were smaller and less consistent for oil production. The authors hypothesized that the agents responsible for this association may include hazardous fluids associated with various steps in the production process; pollutants from diesel truck traffic; flaring; and naturally occurring radioactive material that is pumped from the ground.[1124]

- October 17, 2022 – A population-based, case control study in Germany examined the relationship between residential proximity to an oil or gas well and the likelihood of being diagnosed with a hematologic malignancy in adulthood. The study included 3,978 cases and 15,912 similar controls without malignancy. Residential proximity to oil or gas wells at the time of diagnosis was used as the exposure measure. Proximity to main roadways and agricultural land were considered potential confounders. Cases were not contacted so individual smoking history, occupation, and nutrition were unknown. The study found no association between residential proximity to oil or gas wells for all hematologic malignancies. When stratified by subtype, the odds of acute myelogenous leukemia was 34 percent higher, although this difference was not statistically significant. When stratifying by gender, the odds of malignancy was 50 percent higher in women living near wells than in controls. When the analysis was limited to gas production sites only, the odds of hematologic malignancy were 50 percent higher in people living within one kilometer (.62 miles) of a well.[1125]

- October 3, 2022 – Most of the evidence of negative impacts of natural gas development on infant health comes from high-producing states in the United States. To expand the generalizability of the findings, a cross-sectional study examined associations between proximity to natural gas development and county-level birth outcomes, overall and by race/ethnicity, in all states where gas drilling takes place. The study included 33,849,409 births from the 28 states with any natural gas extraction—conventional and/or unconventional—from 2005 to 2018. The analysis examined birth outcomes associated with the distance between the population-weighted center in each county and the nearest well, combined with its production levels. Overall, prenatal proximity to natural gas extraction activity was associated with increased adverse birth outcomes. A 10 percent increase in gas production in a county was associated with a small decrease in mean birth weight (1.48 grams). The association was larger in women of color—a 10 percent

[1124] Mary D. Willis, Susan E. Carozza, and Perry Hystad, "Congenital Anomalies Associated with Oil and Gas Development and Resource Extraction: A Population-Based Retrospective Cohort Study in Texas," *Journal of Exposure Science & Environmental Epidemiology* 33, no. 1 (January 2023): 84–93, https://doi.org/10.1038/s41370-022-00505-x.

[1125] Felix Forster et al., "Residential Proximity to Oil and Gas Production Sites and Hematologic Malignancies: A Case-control Study," *American Journal of Industrial Medicine* 65, no. 12 (December 2022): 985–93, https://doi.org/10.1002/ajim.23434.

increase in gas production decreased birth weight for infants born to Black women by 10.19 grams and Asian women by 2.76 grams. Increases in gas production were associated with slightly increased gestational age, particularly for infants born to Black women, a finding inconsistent with prior literature showing gas production associated with an increased risk of preterm birth. This study used county-level data for both birth outcomes and distance from each well and is, therefore, not as granular as others that are able to examine the association between individual birth outcomes and residential distance from the nearest well.[1126]

- August 17, 2022 – A well-designed study in Pennsylvania found that children whose birth residence was within 2 kilometers (1.2 miles) of a fracking site were 2-3 times more likely to be diagnosed with acute lymphoblastic leukemia between ages 2-7 years than otherwise similar children who were not living near fracking sites. While those living within two kilometers faced the highest risk, leukemia levels among children were elevated as much as 10 kilometers (6.2 miles) from a well, raising questions about safe setback distances. The study included 405 children with leukemia identified through the state cancer registry and considered prenatal, perinatal, and postnatal time periods as potential windows of susceptibility to fracking-related exposures. Similarly, increased odds of acute lymphoblastic leukemia were also seen when fracking wells were located upstream and groundwater flow toward the residence was considered as a potential pathway of exposure. These findings suggest that contaminated drinking water could be an important risk factor.[1127]

- April 4, 2022 – A 2022 Canadian study in rural Alberta found that babies born to mothers living within 6.2 miles (10 kilometers) of one or more fracking wells had increased incidence of low birth weight, premature birth, and major congenital abnormalities. This study included nearly 35,000 pregnancies over a six-year period, 2013-2018.[1128]

- January 30, 2022 – A research team working in Pennsylvania found "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 team showed that shale gas operations near mothers' homes raised levels of contaminants in drinking water and raised the risk for preterm birth and low birthweight.[1129]

[1126] Hailee Schuele et al., "Associations between Proximity to Gas Production Activity in Counties and Birth Outcomes across the US," *Preventive Medicine Reports*, October 2022, 102007, https://doi.org/10.1016/j.pmedr.2022.102007.
[1127] Cassandra J. Clark et al., "Unconventional Oil and Gas Development Exposure and Risk of Childhood Acute Lymphoblastic Leukemia: A Case–Control Study in Pennsylvania, 2009–2017," *Environmental Health Perspectives* 130, no. 8 (August 2022): 087001, https://doi.org/10.1289/EHP11092.
[1128] 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.
[1129] 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.

- January 22, 2022 – Using data gathered from more than 15 million Medicare recipients and records from more than 2.5 million gas and oil wells, a Harvard University 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. Furthermore, those living downwind from fracking wells were more likely to suffer premature death than those upwind.[1130]

- January 20, 2022 – A research team that included First Nations investigators 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.[1131]

- January 6, 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 fracking activity and during a period of time in which gas extraction through fracking was increasing. Previous research demonstrates that environmental exposure is implicated in the pathophysiology of this disease.[1132]

- December 13, 2021 – A study led by Oregon State University researchers of more than 3 million pregnant women in Texas showed that living near an active oil or gas well increased the risks for both gestation hypertension (high blood pressure) and eclampsia (onset of seizures or coma during pregnancy or childbirth). "Among pregnant women who reside within 1 km of at least one oil or gas drilling site, we find 5% increased odds of gestational hypertension and 26% increased odds of eclampsia."[1133]

- 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-

[1130] 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.
[1131] 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): 150242, https://doi.org/10.1016/j.scitotenv.2021.150242.
[1132] 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.
[1133] 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.

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.[1134]

- 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."[1135]

- 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 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

[1134] 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.
[1135] 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.

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."[1136] 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."[1137]

- 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.[1138] 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.)[1139] 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 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

[1136] 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.
[1137] 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/.
[1138] 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.
[1139] Charles Minshew, "EHN- A Family's Chemical Exposure," January 4, 2021, https://public.tableau.com/app/profile/charles.minshew2414/viz/EHN-AFamilysChemicalExposure/FamilyDashboard.

requesting that the Pennsylvania governor "direct adequate funding to thoroughly study the full and complete health impacts of fracking."[1140]

- 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."[1141]

- 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 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.[1142] "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,

[1140] 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.
[1141] 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.
[1142] 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.

prothrombotic pathways, and epigenomic changes, all of which are known to contribute to heart failure.[1143]

- 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.[1144]

- 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 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,

[1143] 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.
[1144] 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.

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.[1145]

- 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."[1146]

- 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 should examine how the aggregation of exposures from fracking wells and potency of exposures at the residence levels affects health.[1147]

- 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

[1145] 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.
[1146] 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.
[1147] 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.

records from 2012 to 2015 in the Eagle Ford Shale of south Texas.[1148] 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."[1149] 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 studies of fracking and birth outcomes, "which can decrease precision in our effect estimates."[1150]

- 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

[1148] 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.
[1149] 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.
[1150] 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.

weeks' gestation, according to Stanford University research.[1151] 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.[1152] 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 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

[1151] 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.
[1152] 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.

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."[1153]

- 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.[1154] 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.[1155] 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.

- 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.[1156] (See also July 25, 2019 and May 22, 2019 entries below.) These studies, conducted in laboratory animals and human tissue culture cells, used four

[1153] 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.
[1154] 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.
[1155] 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.
[1156] 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.

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.[1157] 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 literature on general health harms of fracking. The second will investigate whether young cancer patients had higher exposures to fracking than the general population.[1158] 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-

[1157] 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.
[1158] Chaffin, "Pennsylvania Governor Funds Research Examining Potential Fracking Health Impacts."

2005, a period prior to the arrival of drilling and fracking activities in the area.[1159] (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.[1160] 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.[1161] 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 well pad, concluded Colorado's state-funded human health risk assessment.[1162, 1163]The

[1159] 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.
[1160] 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.
[1161] 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.
[1162] 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.
[1163] 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.

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*.[1164] *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."[1165] 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.[1166] 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 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

[1164] 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.
[1165] 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/.
[1166] 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.

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."[1167] 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.[1168] 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."

- 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.[1169] The study included 7,715 mothers without anxiety or depression at the time of conception, who delivered their

[1167] 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.
[1168] 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.
[1169] 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.

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.[1170] 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 several highways experiencing increased crashes in "the busiest oil and gas region in the United States.[1171] 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

[1170] 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.
[1171] 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.

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."[1172] 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.[1173] 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 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."[1174]

[1172] April Reese, "Death Highway," *Searchlight New Mexico*, June 27, 2019, https://searchlightnm.org/death-highway/.
[1173] 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.
[1174] 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.

- 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.[1175] 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.[1176] Subsequently, additional cases came to light, and public calls for more comprehensive investigations continued.[1177, 1178, 1179, 1180]

- 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.[1181] Taken as a whole, oil and gas production slightly 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.

[1175] 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/.

[1176] 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.

[1177] 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/.

[1178] 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/.

[1179] 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/.

[1180] 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.

[1181] 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.

- 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.[1182] 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.[1183] 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.[1184] 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 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.

[1182] 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.
[1183] 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.
[1184] 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.

- 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.[1185]

- 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.[1186] 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.[1187] Authors found no evidence that confounding 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

[1185] 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.
[1186] 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.
[1187] 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.

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.[1188] 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.[1189]

- 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.[1190] 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 asthma hospitalizations across age groups, as well as links for younger children to additional pollutants.

[1188] 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.

[1189] 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.

[1190] 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.

- 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.[1191] (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.[1192] 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.[1193] 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 had 21 percent increased rates of chlamydia and 19 percent increased rates of

[1191] 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.
[1192] 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.
[1193] 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.

gonorrhea.[1194] 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."[1195]

- 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.[1196, 1197] 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 infections) in counties containing unconventional natural gas wells than in those without

[1194] 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.
[1195] 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.
[1196] 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.
[1197] 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.

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."[1198]

- 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."[1199] (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."[1200]

- 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.[1201] 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 site during pregnancy." For mothers living within one kilometer (.6 miles), they found a

[1198] 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.
[1199] 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.
[1200] 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.
[1201] 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.

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.[1202] 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."[1203]

- 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.[1204]

- 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."[1205]

[1202] 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.
[1203] 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.
[1204] 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.
[1205] 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.[1206]

- 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.[1207]

- 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.[1208]

- 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

[1206] 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.
[1207] 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.
[1208] 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."[1209]

- 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.[1210] 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.[1211] 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."[1212]

- 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.[1213] 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

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[1209] 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.
[1210] 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.
[1211] 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.
[1212] 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/.
[1213] 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.[1214]

- 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."[1215]

- 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.[1216]

- 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

[1214] 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/.
[1215] 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.
[1216] 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.[1217] 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."[1218]

- 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.[1219, 1220]

- 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."[1221]

- 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

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[1217] 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.
[1218] Endocrine Society, "Fracking Chemicals Tied to Reduced Sperm Count in Mice," *ScienceDaily*, October 14, 2015, https://www.sciencedaily.com/releases/2015/10/151014134533.htm.
[1219] 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.
[1220] 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.
[1221] 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."[1222] 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."[1223]

- 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.[1224] 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*.[1225]

- 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.[1226]

- 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

[1222] 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.
[1223] 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.
[1224] Shonkoff et al., "Chapter 6: Potential Impacts of Well Stimulation on Human Health in California."
[1225] 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.
[1226] 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.[1227, 1228] 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."[1229]

- 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.[1230]

- 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

[1227] 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.
[1228] 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.
[1229] 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.
[1230] 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.[1231]

- 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

[1231] 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.[1232]

- 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.[1233] 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.[1234] 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.[1235]

- 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

[1232] 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.
[1233] 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.
[1234] 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.
[1235] 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."[1236, 1237]

- 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.[1238]

- 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."[1239] 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.[1240]

- 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).[1241]

- 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.[1242]

[1236] 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.
[1237] 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.
[1238] 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/.
[1239] 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.
[1240] American Lung Association, "American Lung Association State of the Air 2013," 2013.
[1241] 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.
[1242] 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.[1243, 1244]

- 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.[1245] 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.[1246]

[1243] 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/.
[1244] 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/.
[1245] 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.
[1246] 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."[1247]

- 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.[1248]

- March 14, 2020 – Living in a community with extensive fracking was linked with lower self-rated health, according to an interdisciplinary research team.[1249] 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

[1247] 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.
[1248] 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.
[1249] 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.[1250] 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.[1251] 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."[1252] 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

[1250] 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.
[1251] 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.
[1252] 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/.

residents in the press release.[1253] The City received over 35 official noise complaints and 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."[1254] 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.[1255] 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.[1256] 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

[1253] 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), https://docs.google.com/document/d/1R2qrVSwPls5bI8dKhZ4GG5OrFia76TwGlC09P_JMD1o/mobilebasic?urp=gmail_link.
[1254] 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.
[1255] 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.
[1256] 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.

complying with notification requirements, the company was allowed to move forward with the estimated four to six weeks of exploration.

- 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.[1257]

- 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.[1258]

- 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."[1259]

- 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

[1257] 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.
[1258] 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.
[1259] 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.

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 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."[1260]

- 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.[1261]

- 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."[1262] 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

[1260] 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.
[1261] 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.
[1262] 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.

the contamination experienced by the interviewees reflected a "new normal of non-conventional fossil fuel industries."

- 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.[1263]

- 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."[1264]

- 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

[1263] 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.
[1264] 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.

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 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.[1265]

- 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.[1266]

- 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.[1267]

- 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."[1268]

- 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

[1265] 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.
[1266] Shonkoff et al., "Chapter 6: Potential Impacts of Well Stimulation on Human Health in California."
[1267] New York State Department of Health, "A Public Health Review of High Volume Hydraulic Fracturing for Shale Gas Development."
[1268] 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.

and anxiety from uncertainty that could lead to "poor mental wellbeing," and noise-related health effects due to continuous drilling. The HIA also noted a lack of public trust and confidence.[1269, 1270]

- 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.[1271]

- 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."[1272] 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.[1273]

- 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

[1269] 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.
[1270] 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.
[1271] 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.
[1272] 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.
[1273] 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.

heavy equipment, compressors, and diesel powered generators. Loud continuous noise 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.[1274]

- 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.[1275]

- 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.[1276]

- 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.[1277] 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.[1278]

- 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

[1274] 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.
[1275] 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.
[1276] 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.
[1277] Roland Dechesne, "Limiting Oil Field Light Pollution for Safety and the Environment," in *Sustainable Environment and Energy CPANS 2013 Conference*, 2013.
[1278] 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.

specific stressors, including: being taken advantage of; health concerns; 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.[1279] Notably, mounting evidence indicates that chronic stress magnifies individuals' susceptibility to effects of pollution; for children, this interactive effect can begin during prenatal life.[1280]

- 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.[1281]

[1279] 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.
[1280] 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.
[1281] 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

Increasing numbers of studies from the United States, Canada, China, and the United Kingdom show that both fracking and the underground disposal of fracking wastewater is definitively linked to earthquakes. In 2019, the United Kingdom 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 in ways that could prevent them from occurring. This moratorium is still in place.

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. Between 2017 and 2020, the number of earthquakes linked to fracking wastewater injection more than tripled in Oklahoma, Texas, Louisiana, and New Mexico.

Recent research has clarified the mechanisms by which fracking and the injection of fracking waste may trigger earthquakes. Fracking wastewater injection into shallow geological zones increases pressures within the pore spaces of rock layers and may lead to the unclamping of stressed geological faults, including within deeper faults located several miles below the surface. The act of fracking itself takes place in deeper geological formations than injection of fracking waste. Recent research shows that fracking activities can trigger earthquakes both near and far from the well pad by increasing fault zone permeability. Fracking can also cause long-dormant faults to slip in ways that can damage wells through shearing forces. Even small fault slips and imperceptible microquakes caused by fracking can deform well casings, according to the results of a 2022 study. The impact of induced earthquakes on well leakage is not well understood. The question of what to do with fracking wastewater remains a problem with no viable, safe solution.

Emerging evidence suggests that the frequency of fracking-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. In Canada, elevated earthquake activity in heavily fracked regions continued during a period of industry quiescence brought on by the COVID-19 pandemic.

Emerging evidence suggests that the injection of supercritical carbon dioxide in fracking operations may also be linked to earthquake risk.

- May 29, 2023 – Combining a wide variety of imaging and analytic approaches, researchers in China investigated the cause of four recent moderately large earthquakes in an area that had been previously seismically quiescent and was recently and intensively fracked. Their proposed model, which employs readily available and increasingly common technological tools, encourages prospective evaluations of proposed industrial sites for "geological susceptibility" and explicitly calls for operators to be "more conservative" near susceptible regions: "The conservativeness in operations may include reducing injection volumes, lowering the injection pressures, shortening horizontal wells,

restricting the thresholds for the traffic light protocol [guidelines for interrupting or ceasing hydraulic fracturing or wastewater disposal activities], or their combinations." This structure-based susceptibility evaluation approach, the authors contend, can be used to avoid inducing damaging earthquakes from fracking operations.[1282]

- March 23, 2023 – On November 30, 2022, the town of Peace River experienced the largest (ML5.6) earthquakes ever recorded in the Canadian province of Alberta. Although the Alberta Energy Regulator initially judged this a natural tectonic event, researchers employing a broad range of imaging and analytic methods concluded that the earthquake occurred due to underground wastewater disposal from nearby fracking operations. By resampling seismic data to improve accuracy, determining subsurface fault planes and origins of seismic activity, and using InSAR geodetic modeling to depict surface deformations temporally related to industrial activities, the researchers showed human activities were the most plausible explanation of the earthquake. The new study argues that the injected wastewater, by being forced into a deep geological fault, reduced the friction holding the two sides together in ways that allowed them to slip past each other and trigger an earthquake. This study highlights the need for rigorous assessments of causality and raises concerns also about subsurface injections of carbon dioxide, which has been proposed as a potential climate mitigation strategy. The authors note that the industrial-scale injection of carbon dioxide into deep sedimentary formations carries similar risks of inducing earthquakes as wastewater disposal. Earthquakes of these magnitudes can be deadly, if they occur in populated areas.[1283]

- December 14, 2022 – A research team investigated a possible link between induced earthquakes from fracking operations and healthcare visits for anxiety disorders in Oklahoma between 2010 and 2019. By correlating earthquake activity in Oklahoma with anxiety-related health care visits recorded in a large de-identified database of Medicare Advantage claims, researchers identified a statistically significant increase in health care visits coded as stress disorders for every five felt earthquakes (defined as earthquakes of Moment Magnitude greater than or equal to 4) in the preceding six months. The psychiatric diagnosis of stress disorder relates to traumatic events and includes features such as anxiety, intense fear, or helplessness, dissociative symptoms, and avoidant behaviors. Because the vast majority of mental health needs go unmet, this study likely underestimates the number of people experiencing trauma secondary to experiencing earthquakes induced by hydraulic fracturing activities, including wastewater injection. The researchers note that related studies with Oklahoma residents indicate "an overall sense of resentment towards induced earthquakes [and their costs]." The results of this study are supported by prior studies in Oklahoma that have documented an increase in motor vehicle crashes and in online searches related to anxiety that were both correlated

[1282] Junlun Li et al., "High Seismic Velocity Structures Control Moderate to Strong Induced Earthquake Behaviors by Shale Gas Development," *Communications Earth & Environment* 4, no. 1 (May 29, 2023): 188, https://doi.org/10.1038/s43247-023-00854-x.
[1283] Ryan Schultz et al., "Disposal From In Situ Bitumen Recovery Induced the ML Peace River Earthquake," *Geophysical Research Letters* 50, no. 6 (March 28, 2023): e2023GL102940, https://doi.org/10.1029/2023GL102940.

with felt earthquakes. These represent indirect indicators of harms to human populations from fracking-related induced earthquake activity.[1284]

- November 10, 2022 – An assessment of ground deformation and seismicity in two areas of intense fracking activity in the Argentinian Patagonian Plateau correlated ground movements, as measured with Satellite Synthetic Aperture Radar Interferometry and records of hydraulic fracturing, fluid extraction, and fluid injection, along with historic and current seismic records. The researchers concluded that correlations exist between the onset of hydraulic fracturing activities and large magnitude earthquakes, as well as surface deformations (and inferred subsurface fault planes). Available data do not allow a determination as to whether water extractions or injections of fluids during hydraulic fracturing play a more dominant role in triggering induced earthquakes in the region.[1285]

- April 25, 2022 – Employing a dense array of seismic stations in an intensely fracked area marked by recent large earthquakes, researchers in Weiyuan, China used a variety of new computerized analytic methods to characterize complex subsurface fault systems that they conclude "are reactivated by hydraulic fracturing." They also found that, by increasing fault zone permeability, fracking can trigger earthquakes far from the well pad, "hence increasing the potential seismic hazard associated with injection-induced earthquakes in this and other regions around the world." Because Chinese regulations require that all wastewater from hydraulic fracturing is collected, purified, and then reused, underground wastewater injection could be ruled out as a cause of the earthquake activity documented in the study.[1286]

- February 7, 2022 – Slippage on subsurface faults occurs at rates ranging along a continuum from "creep to supershear earthquakes." Slow slip events are known to be important in releasing stress, delaying or preventing abrupt radiations of damaging seismic energy. However, these kinds of aseismic shifts can sometimes increase stress in unstable zones, leading to dynamic rupture. To clarify the role of slow-slip events in fault activation and earthquake generation related to hydraulic fracturing, a team of researchers in Canada used Interferometric synthetic-aperture radar to study an area near Calgary that is well-monitored by seismic networks. Despite an absence of detected seismicity, radar imagery revealed "consistent patterns of paired uplift and subsidence," indicative of shear dislocations on faults (i.e., aseismic slow slip events) at shallow depths near the underground injection interval targeted by fracking. In other words, the data revealed that the largest fracking-induced earthquake in Canada, to date, is the result of a slow-slip event. Researchers documented that these events also correlated with concurrent reports of deformations in the steel casings of fracked wells in the areas that were of sufficient magnitude to lodge equipment in the wellbore and interrupt fracking activities. Noting

[1284] Holly Elser et al., "Manmade Earthquakes and Healthcare Visits for Anxiety Disorders in Oklahoma, 2010–2019," *Environmental Epidemiology* 7, no. 1 (February 2023), https://doi.org/10.1097/EE9.0000000000000232.
[1285] Guillermo Tamburini-Beliveau et al., "Assessment of Ground Deformation and Seismicity in Two Areas of Intense Hydrocarbon Production in the Argentinian Patagonia," *Scientific Reports* 12, no. 1 (November 10, 2022): 19198, https://doi.org/10.1038/s41598-022-23160-6.
[1286] Minhan Sheng et al., "Earthquakes Triggered by Fluid Diffusion and Boosted by Fault Reactivation in Weiyuan, China Due to Hydraulic Fracturing," *Journal of Geophysical Research: Solid Earth* 127, no. 5 (May 2022), https://doi.org/10.1029/2021JB022963.

that casing deformation is not uncommon during hydraulic fracturing, the researchers conclude that "'thrust belts activated by fluid injection [during hydraulic fracturing] can exhibit a range of slip behavior…, ranging from slow slip events to dynamic rupture." They recommend using radar technology to monitor deformation processes in areas of fluid injection to more accurately characterize earthquake hazards and illuminate links between slow-slip events, casing deformations, and earthquake activity related to hydraulic fracturing.[1287]

- February 1, 2022 – To elucidate the mechanisms driving earthquake activity and surface deformation in the intensely fracked Delaware Basin in Texas, researchers used satellite-based interferometric Synthetic Aperture Radar images coupled with sophisticated modeling and analysis of subsurface data. Building on prior studies that identified local instances of sinking caused by oil, gas, and groundwater extraction and instances of uplift caused by the injection of fracking wastewater, this study provides a detailed model to explain how swaths of land can rise and fall along long, narrow strips as movement-prone, shallow underground faults slip in response to increased fluid pressure. When the fault is activated by fluid injection, the upper block of the fault slides downward along the lower block under the force of gravity. While some fault slippage results in measurable earthquake activity, slippage can sometimes continue in an aseismic fashion for years to decades.[1288] The findings suggest the observed motion on the surface is caused by slip on shallow faults where two blocks of Earth's crust meet along an inclined plane, "like a loaf of bread sliced diagonally."[1289]

- January 27, 2022 – While earthquake induction by fracking-related activities is proven, the responsible mechanisms are still debated as the geological depths from where the earthquakes arise have varied widely. This study sought to resolve the uncertainty around the question of depth. Accurate depth determination can differentiate between earthquakes triggered by fracking wastewater injection, which takes place at comparatively shallow levels, from earthquakes triggered by fracking itself, which takes place in deeper geological zones. A Stanford-led research team studied a small, intensively fracked area within the Delaware Basin in Texas, where 21 perceptible earthquakes had struck within the previous few years. Using two seismic monitoring stations and an "attentive, deep-learning model" (a specialized form of artificial intelligence), researchers were able detect and analyze subtle seismic activity, including hundreds of microquakes centered within the study area as well as thousands of other small quakes that originated from zones farther away. Using three independent but complementary characterizations of subsurface seismicity—seismic velocities; precise location of the depths of origin of identified earthquakes; and modeling of low-frequency body and surface waves in relation to subsurface faults—the researchers determined that fracking wastewater injection, rather than fracking per se, was the cause of the quakes in

[1287] Thomas S. Eyre et al., "InSAR Data Reveal That the Largest Hydraulic Fracturing-Induced Earthquake in Canada, to Date, Is a Slow-Slip Event," *Scientific Reports* 12, no. 1 (February 7, 2022): 2043, https://doi.org/10.1038/s41598-022-06129-3.
[1288] K. S. Pepin et al., "Shallow Aseismic Slip in the Delaware Basin Determined by Sentinel-1 InSAR," *Journal of Geophysical Research: Solid Earth* 127, no. 2 (February 2022), https://doi.org/10.1029/2021JB023157.
[1289] Josie Garthwaite, "Earthquakes from Oil Field Wastewater," *Stanford Earth Matters*, May 19, 2022, https://earth.stanford.edu/news/earthquakes-oil-field-wastewater#gs.3pyoiu.

this particular swath of the Delaware Basin. All three forms of analysis showed that the earthquake activity originated from the shallow geological zone that is used for the disposal of fracking wastewater. Combined with emerging satellite evidence of surface deformation in the same area of the Delaware Basin, these results provide support for the hypothesis that preexisting faults are activated when pore pressures are elevated by wastewater injections. Fracking wastewater disposal is an unavoidable cause of fault slippage.[1290]

- January 7, 2022 – By analyzing the evolution over time of induced seismicity caused by hydraulic fracturing activities, researchers in Alberta discovered two distinct geologic regions and calculated the annual likelihood of large earthquakes (magnitude $M > 4$) in each region for the period from 2014 to 2020. Despite increasing intensity of hydraulic fracturing activities, the seismic hazard in the Duvernay Play region has declined, possibly due to regulatory restraints and changes in operational practices, including a relative avoidance of earthquake prone areas.[1291]

- October 28, 2021 – To better detect and characterize fracking-induced earthquakes in the Blackpool region of the United Kingdom, researchers used historical data combined with digital template matching (TM) techniques, which extract waveform images of past events and use them as templates to find similar new events. These methods make possible the detection of smaller magnitude earthquakes, the modeling of faults and seismic sources, and better correlation of subsurface events with various stages of hydraulic fracturing activities. This novel application of template matching techniques allows for the study of induced earthquakes in places that lack well-distributed arrays of surface monitoring stations.[1292]

- 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

[1290] Yixiao Sheng, Karissa S. Pepin, and William L. Ellsworth, "On the Depth of Earthquakes in the Delaware Basin: A Case Study along the Reeves–Pecos County Line," *The Seismic Record* 2, no. 1 (January 1, 2022): 29–37, https://doi.org/10.1785/0320210048.
[1291] Mauricio Reyes Canales et al., "The Rise, Peak and Decline of the Seismic Hazard Related to Hydraulic Fracturing Activities in the Duvernay Play, Fox Creek Area, Alberta," *Journal of Geophysical Research: Solid Earth* 127, no. 1 (January 2022), https://doi.org/10.1029/2021JB023060.
[1292] Nasim Karamzadeh et al., "Induced Seismicity Due to Hydraulic Fracturing near Blackpool, UK: Source Modeling and Event Detection," *Journal of Seismology* 25, no. 6 (December 2021): 1385–1406, https://doi.org/10.1007/s10950-021-10054-9.

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."[1293]

- 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 occur in the future if current fracking activities in the region continue unabated. In a 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."[1294]

- May 21, 2021 – A study led by a U.S. Geological Survey (USGS) team determined that the dramatic proliferation of seismic activity near the Permian Basin city of Pecos, Texas since 2000 is likely caused by fracking wastewater disposal practices. This includes a magnitude 5.0 earthquake in March 2020. The team identified more than 45,000 seismic events in the area and compared spatial and temporal data in the earthquake inventory with industrial records. "We identify several cases of hydraulic fracturing induced seismicity…but the vast majority of earthquakes are likely induced by wastewater disposal…in particular injecting at depths greater than 1.5 kilometers."[1295]

- 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.[1296]

- 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

[1293] 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/.
[1294] 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.
[1295] 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.
[1296] 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.

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." 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."[1297]

- 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.[1298]

- 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.[1299]

- March 21, 2021 – Citing research from 2018 demonstrating that injected wastewater can cause sufficient pressure to trigger earthquakes more than 55 miles away [see entry for February 15, 2018 below], 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

[1297] 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.
[1298] 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.
[1299] 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.

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.[1300]

- 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.[1301] Separately, a co-author of this study argued that California's natural earthquake activity may have been masking industry-induced quakes.[1302] 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.[1303]

[1300] 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.
[1301] 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.
[1302] 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.
[1303] 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.

- 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 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.[1304]

- 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.[1305]

- 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.[1306]

- 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 &*

[1304] 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.
[1305] 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.
[1306] 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.

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.[1307] Referring to this work, a Canadian investigative report outlined the deficits of 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.[1308] 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."[1309]

- 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

[1307] 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.
[1308] 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/.
[1309] 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.

earthquakes of magnitude 3.5 or greater within approximately 5 kilometers (3 miles) of vulnerable structures.[1310]

- 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.[1311] The largest event ascribed directly 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."[1312]

- 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.[1313]

- November 13, 2019 – Fracking induced 94 earthquakes with a magnitude greater than 2.0 from 2014 through 2018 in the Eagle Ford Shale.[1314] This included what may have been

[1310] 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.
[1311] 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.
[1312] 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/.
[1313] 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.
[1314] 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.

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 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.[1315]

- 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.[1316] 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."[1317]

- 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

[1315] 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.
[1316] 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.
[1317] 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.

accuracy."[1318] 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.[1319]

- 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.[1320]

- 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.[1321]

- 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.[1322] 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

[1318] 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.
[1319] 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.
[1320] 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.
[1321] 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/.
[1322] 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.

very sensitive factor."[1323] 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 than a decade and increase with depth.[1324] 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.[1325] 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.[1326, 1327]

- 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.[1328] In 1997, a series of earthquakes, including the second

[1323] Arizona State University, "Predicting Earthquake Hazards From Wastewater Injection," *Phys.Org*, July 29, 2019, https://phys.org/news/2019-07-earthquake-hazards-wastewater.html.
[1324] 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.
[1325] 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/.
[1326] Bhattacharya and Viesca, "Fluid-Induced Aseismic Fault Slip Outpaces Pore-Fluid Migration."
[1327] 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.
[1328] 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.

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.[1329]

- 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.[1330]

- 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. "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.[1331]

- 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.[1332] 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."[1333] 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.[1334] Further,

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[1329] 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.
[1330] Myers, "China Experiences a Fracking Boom, and All the Problems That Go with It."
[1331] 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.
[1332] 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/.
[1333] 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.
[1334] 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/.

companies are allowed to continue their activities despite predictions that considerable seismic activity may result, including earthquakes of much greater magnitude than predicted.[1335]

- 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 research provides far greater detail and accuracy than data and notifications voluntarily released by drilling operators.[1336]

- 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.[1337]

- 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.[1338]

[1335] 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/.
[1336] 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.
[1337] 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.
[1338] 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.

- 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.[1339] 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."[1340]

- 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.[1341]

- 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."[1342, 1343] 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.[1344] 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."

[1339] 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.
[1340] 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.
[1341] 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.
[1342] 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.
[1343] 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/.
[1344] 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/.

- 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.[1345] 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."[1346] 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.[1347]

- 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.[1348]

- 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.[1349] 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.[1350]

- 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

[1345] 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.
[1346] 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/.
[1347] Wethe, "Oklahoma Toughens Oil Fracking Rules after Shale Earthquakes."
[1348] 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.
[1349] 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.
[1350] 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.

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.[1351, 1352]

- 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. 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.[1353]

- 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.[1354] 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."[1355] 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.[1356]

[1351] 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.
[1352] 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/.
[1353] 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.
[1354] 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.
[1355] 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/.
[1356] 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/.

- 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.[1357] Altogether, 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."[1358]

- 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 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."[1359] (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."[1360]

- 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

[1357] 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.
[1358] 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.
[1359] 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.
[1360] 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.

carefully tapering injection rates."[1361] Geophysicist Andrew Barbour, lead author of the study, said that fluctuating injection rates likely have a "profound effect" on earthquake risk.[1362] 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.[1363]

- 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 high-failure consequences under one per ten thousand per year.[1364] 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.[1365]

- 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."[1366] 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."[1367]

- 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

[1361] 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.
[1362] 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.
[1363] 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/.
[1364] 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.
[1365] 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/.
[1366] 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.
[1367] 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/.

fracturing of wells in the Utica Shale.[1368] 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.[1369]

- December 20, 2016 – In an attempt to reduce 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."[1370]

- 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 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 rock mass to hydraulic fracturing," as well as "pore-pressure changes due to fluid diffusion along a permeable fault zone."[1371] 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.[1372]

- 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.[1373]

- 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

[1368] 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.
[1369] 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.
[1370] 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.
[1371] 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.
[1372] 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.
[1373] 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.

injured one, damaged more than 40 buildings, closed a school, and triggered evacuations. Oil infrastructure was not damaged.[1374] (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.[1375] 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.[1376, 1377]

- 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 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.[1378]

- 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.[1379]

- 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.[1380]

[1374] 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.
[1375] Mike Soraghan, "EPA Suggests Partial Disposal Moratorium in Okla," *E&E EnergyWire*, October 7, 2016, https://subscriber.politicopro.com/article/eenews/1060043991.
[1376] 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.
[1377] 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.
[1378] 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.
[1379] 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.
[1380] 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.

- 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."[1381]

- 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 very difficult for operators to avoid areas with faults because their locations are very often unknown.[1382]

- 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.[1383]

- 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."[1384]

[1381] 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.
[1382] 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.
[1383] Anna Kuchment, "Drilling for Earthquakes," *Scientific American*, March 28, 2016, https://doi.org/10.1038/scientificamerican0716-46.
[1384] 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.

- 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.[1385]

- 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.[1386]

- 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.[1387]

- 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.[1388] 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."[1389]

- 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

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[1385] 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.
[1386] 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.
[1387] 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.
[1388] 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.
[1389] 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.

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."[1390] 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.[1391]

- 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 of several surrounding states.[1392] In response, gas and oil operators voluntarily shut down two nearby wastewater injection wells and reduced operations by half at a third well.[1393] 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.[1394] 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.[1395] 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.[1396]

- 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

[1390] 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.
[1391] 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.
[1392] 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.
[1393] Oklahoma Corporation Commission, "New Actions Taken in Response to Earthquake Activity in Crescent Area," Media Advisory, July 28, 2015.
[1394] 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/.
[1395] Oklahoma Corporation Commission, "OCC Announces Next Step in Continuing Response to Earthquake Concerns," Press Release, July 17, 2015.
[1396] 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.

constrained, making it "difficult to determine the wells that will induce earthquakes and those that will not."[1397]

- 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 planned.[1398]

- 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.[1399, 1400]

- 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

[1397] 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.
[1398] 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.
[1399] 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.
[1400] Julia Rosen, "Pumped up to Rumble," *Science* 348, no. 6241 (2015): 1299–1299, https://doi.org/10.1126/science.348.6241.1299.

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."[1401]

- 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 primary gradual slippage of fault planes leading to secondary sudden seismic activity.[1402, 1403]

- 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.[1404]

- 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.[1405]

- 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

[1401] 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.
[1402] 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.
[1403] 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/.
[1404] Andrew Nikiforuk, "More Industry Linked Earthquakes Recorded in Alberta," *The Tyee*, June 11, 2015, http://thetyee.ca/News/2015/06/11/More-Fracking-Earthquakes/.
[1405] 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.

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.[1406, 1407]

- 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-predict hazards of induced earthquakes.[1408] 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.[1409] 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.[1410] 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.[1411, 1412]

- 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.[1413]

[1406] 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.
[1407] Oklahoma Corporation Commission.
[1408] 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.
[1409] U.S. Geological Survey, "New Insight on Ground Shaking from Man-Made Earthquakes," Open-File Report, Open-File Report (USGS Newisroom, April 23, 2015).
[1410] 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.
[1411] 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.
[1412] 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.
[1413] Richard D. Andrews and Austin Holland, "Statement on Oklahoma Seismicity" (Oklahoma Geological Survey, April 21, 2015).

- 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.[1414]

- 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.[1415] In addition, noted lead author Dan McNamara, such information can "aid in adapting building codes to ensure that structures can withstand more damaging earthquakes.[1416]

- 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.[1417]

- 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

[1414] 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.
[1415] 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.
[1416] 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.
[1417] 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.

operations of thousands of fracking wells, reported the *Vancouver Observer*.[1418]

- 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 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."[1419]

- 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.[1420, 1421]

- 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.[1422, 1423]

- 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

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[1418] 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.
[1419] 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/.
[1420] 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.
[1421] 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.
[1422] 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.
[1423] 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/.

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.[1424] Lead author Bill Barnhart, a USGS geophysicist, told *Reuters*, "We saw a big increase in seismicity starting in 2001, including magnitude 5 earthquakes, in many locations in the basin, and that coincided with a surge in gas production and injection of wastewater."[1425]

- 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.[1426]

- 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[1427], 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.[1428]

- 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

[1424] 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.
[1425] 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.
[1426] 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/.
[1427] 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/.
[1428] 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).

Colorado in 2011—the second largest earthquake to date for which there is clear evidence that the earthquake sequence was induced by fluid injection.[1429]

- 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 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.[1430]

- 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.[1431]

- 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.[1432]

- 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

[1429] 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.
[1430] 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.
[1431] 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.
[1432] 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/.

earthquake activity has been noted over the past decade, are showing an increased interest in obtaining earthquake insurance.[1433]

- 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 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.[1434] 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.[1435]

- 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.[1436]

- 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.[1437]

[1433] 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.
[1434] 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.
[1435] 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.
[1436] 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
[1437] 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/.

- 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 well.[1438] 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.[1439]

- 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."[1440] 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."[1441]

- 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.[1442]

- 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

[1438] 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.
[1439] 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.
[1440] Bryan Walsh, "The Seismic Link Between Fracking and Earthquakes," *Time*, May 1, 2014, https://time.com/84225/fracking-and-earthquake-link/.
[1441] 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.
[1442] 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.

state of Nuevo Leon, which registered at least 31 quakes between magnitude 3.1 and 4.3.[1443]

- 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 2006 and March 2012.[1444] On November 13, 2014, *CBC News* reported on a more recent increase in earthquakes, which may also be linked to injection wells.[1445]

- 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.[1446] 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."[1447]

- 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.[1448]

- 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."[1449]

[1443] 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/.
[1444] 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.
[1445] 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.
[1446] 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.
[1447] Becky Oskin, "Wastewater Injection Triggered Oklahoma's Earthquake Cascade," *Live Science*, March 7, 2014, https://www.livescience.com/43953-wastewater-injection-earthquake-triggering.html.
[1448] 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/.
[1449] 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.

- 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."[1450]

- July 19, 2013 – A study from the Lamont-Doherty Earth Observatory linked 109 earthquakes in Youngstown, Ohio to fracking wastewater disposal.[1451, 1452]

- 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."[1453]

- 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.[1454]

- 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.[1455] 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.[1456] The research team concluded in a paper in the journal *Geology*

[1450] 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.
[1451] 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.
[1452] 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/.
[1453] 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.
[1454] 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.
[1455] 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.
[1456] 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/.

that their data called into question the previously predicted maximum size of injection-induced earthquakes.[1457, 1458]

- December 14, 2012 – At a 2012 American Geophysical Union meeting, scientists presented data and concluded that some U.S. states, including Oklahoma, Texas and 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."[1459]

- 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.[1460, 1461, 1462]

- 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

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[1457] 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.
[1458] 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/.
[1459] 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/.
[1460] 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.
[1461] New York City Department of Environmental Protection, "Comments on the Revised Draft Supplemental Generic Environmental Impact Statement," January 11, 2012.
[1462] New York City Department of Environmental Protection, "Comments on the Revised High-Volume Hydraulic Fracturing Regulations," November 30, 2012.

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.[1463]

- 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 "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.[1464, 1465]

- 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.[1466]

- March 10, 2010 – In Texas, a 2008-2009 swarm of earthquakes in the Dallas-Fort Worth area was linked to produced water disposal wells.[1467]

- 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.[1468]

[1463] 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.
[1464] 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.
[1465] 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.
[1466] 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/.
[1467] 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.
[1468] 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. A 2022 study of methane leaks from more than 2,500 wells in northern Colorado found widespread well casing failures throughout the region.

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, 24,619 wells are documented as abandoned with an additional estimated 200,000 wells orphaned and unaccounted for in state records. 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. 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.

- May 29, 2023 – A University of California, Santa Barbara team undertook a critical analysis of the world's estimated 29 million abandoned oil and gas wells, focusing on the challenges for decommissioning them. The issue has both global and local consequences. Globally, abandoned wells emit over 2.5 million tons of methane annually, while the toxic chemicals associated with them contaminate local air and water. In the United States, 14 million people live within one mile of an abandoned or orphaned well and these wells are often located near marginalized communities. No national database of well locations exists in the United States, and historical records of old wells are incomplete. As more abandoned wells continue to be discovered and as new wells continue to be drilled, the number of wells requiring decommissioning continues to rise. The process of decommissioning is expensive. In California, for example, the average cost to plug an orphan well is $68,000. The research team found that the surety bonds required of corporations to cover these costs are typically inadequate and that corporations often use evasion tactics such as offloading liabilities, shell companies, and bankruptcy to avoid responsibility. The costs of decommissioning thus often falls to taxpayers. The authors recommend the development of long-term plans for decommissioning fossil fuel infrastructure as an important facet of a transition to clean energy. These plans should include addressing corporate responsibility, funding, ongoing monitoring of decommissioned wells, and improving the database of orphaned and abandoned wells.[1469]

- May 19, 2023 – A chemical analysis of the gaseous emissions from 48 abandoned wells (8 plugged and 40 unplugged) in western Pennsylvania found frequent detections of benzene and other volatile organic compounds (VOCs), including hexane, cyclohexane, and heptane. Benzene, toluene, and xylene levels were significantly higher than the California Chronic Reference Exposure levels, with the health risk dominated by benzene (a known carcinogen). The rate of emission of VOCs depended on the flow rate of the gas stream and the concentration of VOCs in the gas. Carbon monoxide was detected in 19 percent of wells, and hydrogen sulfide was detected at some, suggesting that abandoned wells should be routinely screened for those gases. Gas was detectable at the ground surface for 11 percent of tested wells, indicating that measurements should be made both before and after remediation. According to a proximity analysis, almost 41 percent of abandoned wells in Allegheny County, Pennsylvania were located within 100 meters of a residence, with some much closer. The authors recommend further studies to

[1469] Tristan Partridge et al., "Decommissioning: Another Critical Challenge for Energy Transitions," *Global Social Challenges Journal*, May 29, 2023, 1–15, https://doi.org/10.1332/NNBM7966.

determine whether emissions from abandoned oil and gas wells pose a health risk to people living near them. According to Pennsylvania Department of Environmental Protection records, 24,619 abandoned oil and gas wells are scattered across the state; another estimated 200,000 abandoned and orphaned wells are undocumented and unrecorded.[1470]

- March 9, 2023 – As part of the NASA Arctic-Boreal Vulnerability Experiment (ABoVE), which examines the vulnerability and resilience of ecosystems in Alaska and Western Canada, a team of researchers examined the impacts of the region's 242,007 documented oil and gas wells. Database analysis indicates that 63 percent of wells are abandoned and 19 percent remain unplugged. The permafrost, present in most of that area, is thawing. The resulting changes in landform may further compromise well integrity. Methane emissions in the ABoVE domain were estimated to be more than 200 percent higher than Canadian Greenhouse Gas Reporting Program estimates and collectively represented about 30 percent of total Canadian anthropogenic methane emissions. Oil and gas activities may also be contributing to loss of evergreen forest. The wide range of estimates of methane emissions in this study indicate a need for better evaluation of abandoned oil and gas wells in this region, including verification of site locations and improvement of well databases.[1471]

- March 6, 2023 – A critical review of the available literature on emissions from both abandoned and active oil and gas wells sought to evaluate factors that can affect leakage and consider options for remediation. Conventional and fracked wells were not separately considered. Variables that consistently affect leakage included production type (conventional vs. unconventional), well location, plugging status, reservoir pressure, and deviation of the wellbore. Regulations regarding monitoring and plugging of inactive and abandoned wells varied across Canada and the United States, and these are often not enforced. The authors recommend strictly enforced regulations regarding monitoring and repair of leakage and stricter timelines for plugging abandoned wells. Studies across wider geographic areas were also recommended.[1472]

- January 24, 2023 – In Pennsylvania, a state law directs how federal funds for oil and gas well plugging should be used, but the same law disallows the Environmental Quality Board from setting bonding requirements for conventional wells. As part of an investigation prompted by this law, the Pennsylvania Department of Environmental Protection found that conventional well operators frequently ignore state laws requiring them to report information about the status of their wells without consequence and that 3,000 newly abandoned wells over the past five years remain unplugged. Other

[1470] Dominic C. DiGiulio et al., "Chemical Characterization of Natural Gas Leaking from Abandoned Oil and Gas Wells in Western Pennsylvania," *ACS Omega*, May 19, 2023, acsomega.3c00676, https://doi.org/10.1021/acsomega.3c00676.
[1471] Louise A Klotz et al., "Oil and Natural Gas Wells across the NASA ABoVE Domain: Fugitive Methane Emissions and Broader Environmental Impacts," *Environmental Research Letters* 18, no. 3 (March 1, 2023): 035008, https://doi.org/10.1088/1748-9326/acbe52.
[1472] Khalil El Hachem and Mary Kang, "Reducing Oil and Gas Well Leakage: A Review of Leakage Drivers, Methane Detection and Repair Options," *Environmental Research: Infrastructure and Sustainability* 3, no. 1 (March 1, 2023): 012002, https://doi.org/10.1088/2634-4505/acbced.

unreported violations included drilling fluid spills. The cost to decommission and plug one well in Pennsylvania is $30,000. The state has an estimated 200,000 wells to decommission, indicating a massive financial risk not compensated by the current bonding requirements.[1473, 1474]

- November 15, 2022 – The surface casing of an oil or gas well is a steel pipe around the well forming a barrier to fluid migration and extending below the lowest level of potable groundwater. Measurements of casing pressure and casing vent flow at the surface are indicators of well casing integrity and can help assess the potential for environmental contamination. A research team led by the U.S. Department of Energy's National Energy Technology Laboratory analyzed geochemical samples collected from the surface casings of 2,573 wells in northern Colorado as part of a publicly available dataset. Available carbon isotope analysis enabled the research team to assess whether the surface gas originated from microbes (biogenic origin) or from deep geological strata (thermogenic origin). The results showed that the methane leaking from the surface casing was thermogenic, indicating that its origin was a subsurface reservoir. Furthermore, benzene, toluene, ethylbenzene, and xylenes (BTEX) exceeding the EPA maximum contaminant level were found in almost all samples tested for those compounds. Assessment of possible gas migration pathways indicated that "gas migration into the surface casing annulus predominantly occurs through compromised barriers (e.g., steel casings or cement seals), indicative of extensive integrity issues in the region." The authors recommend monitoring and correcting elevated surface casing pressures to avoid release of subsurface gas and fluids.[1475]

- August 22, 2022 – The United States Geological Survey created a publicly available database of 117,672 unplugged, orphan oil and gas wells across 27 different states. This database includes location coordinates and well type (i.e. oil, gas, or both). The definition of "inactive" varies by state, ranging from 6 to 24 months of lack of production. Orphaned, in this context, signifies that a party responsible for management of the well cannot be located. There is no distinction between conventional and fracked wells in this dataset.[1476]

- February 3, 2022 – A McGill University research team evaluated methane and hydrogen sulfide emissions from 63 oil and gas wells in Ontario, Canada. The wells were classified according to their production status as abandoned, marginally producing, or active. A wetland area over a possible undocumented well was also tested. The results showed that

[1473] Rachel McDevitt, "Pa. Drillers Abandoned Thousands of Natural Gas Wells in 5 Years, Ignored State Law, Report Says," *State Impact Pennsylvania*, January 24, 2023, https://stateimpact.npr.org/pennsylvania/2023/01/24/pa-drillers-abandoned-thousands-of-natural-gas-wells-in-5-years-ignored-state-law-report-says/.
[1474] Pennsylvania Department of Environmental Protection, "Executive Summary," n.d., https://files.dep.state.pa.us/OilGas/BOGM/BOGMPortalFiles/Governor's_Lapsing_Statement_Report_2022-12-29.pdf.
[1475] Greg Lackey et al., "Composition and Origin of Surface Casing Fluids in a Major US Oil- and Gas-Producing Region," *Environmental Science & Technology* 56, no. 23 (December 6, 2022): 17227–35, https://doi.org/10.1021/acs.est.2c05239.
[1476] Claire A Grove and Matthew D Merrill, "United States Documented Unplugged Orphaned Oil and Gas Well Dataset" (U.S. Geological Survey, 2022), https://doi.org/10.5066/P91PJETI.

wells emitting hydrogen sulfide also emitted methane at the highest rates. Hydrogen sulfide is highly corrosive and has the potential to deteriorate wellbore cement and steel. The next highest methane emitters were marginal and unplugged, abandoned wells. Abandoned plugged wells were the lowest emitters, but the team noted that the average methane emission from those wells nevertheless markedly exceeded that reported in the Canadian National Inventory Report. That report also appeared to underestimate active and marginal well emissions. Recommendations include further studies to determine the true number of undocumented wells in Canada and more regulatory oversight to ensure well monitoring , licensing, and plugging.[1477]

- October 16, 2021 – Working in British Columbia, an international research team simulated a well integrity failure in order to characterize surface methane emissions from gas migration in a structurally compromised well. Researchers synthesized a gas that matched the composition of the gas in the underlying shale basin and injected it at a constant rate 26 meters below the surface at the base of an aquifer, to simulate a well casing integrity failure. Gas migration at the surface was measured in 12 chambers as well as by eddy-covariance flux of atmospheric methane. Soil gas was collected at 22 monitoring wells. As an incidental finding, one of the monitoring wells provided an unexpected pathway for gas migration. Approximately 25 percent of the injected gas was detected as surface emissions even though the immediate subsurface soil had low permeability. The research team documented that subsurface gas was able to migrate against the direction of groundwater flow. Most of the injected gas remained confined underground, suggesting the possibility of risk to groundwater.[1478]

- July 14, 2021 – An economic analysis by the U.S. non-profit organization Resources for the Future provided cost estimates for decommissioning the nation's more than 2.1 million non-producing but unplugged oil and gas wells. The authors note that decommissioning is an expensive, multi-step process that involves not only plugging the wellbore but also removing equipment and restoring the well pad. Factors affecting the full cost of plugging and reclamation included well depth, well age, and the surrounding topography. Bonding requirements prior to drilling are inadequate to cover the full costs of decommissioning. Hence, well operators often declare bankruptcy or cannot be located, leaving taxpayers to foot the bill. Analyzing data from over 19,500 oil and gas wells, the study found that the median costs for plugging only was $20,000 but the full decommissioning cost, including surface reclamation, was $75,000 per well. "Each additional 1,000 feet of well depth increases costs by 20%, older wells are more costly than newer ones, natural gas wells are 9% more expensive than wells that produce oil, and costs vary widely by state. Surface characteristics also matter: each additional 10 feet of elevation change in the 5-acre area surrounding the well raises costs by 3%." The authors suggest that bonding requirements could be improved by accounting for these

[1477] Khalil El Hachem and Mary Kang, "Methane and Hydrogen Sulfide Emissions from Abandoned, Active, and Marginally Producing Oil and Gas Wells in Ontario, Canada," *Science of The Total Environment* 823 (June 2022): 153491, https://doi.org/10.1016/j.scitotenv.2022.153491.
[1478] Julia V. Soares et al., "Towards Quantifying Subsurface Methane Emissions from Energy Wells with Integrity Failure," *Atmospheric Pollution Research* 12, no. 12 (December 2021): 101223, https://doi.org/10.1016/j.apr.2021.101223.

factors and that decommissioning costs could be improved somewhat by "contracting in bulk." Site surface restoration adds considerably to cost, but is estimated to add ecosystem service benefits of approximately $49,000 per well.[1479]

- 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."[1480]

- 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 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.[1481]

- 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

[1479] Daniel Raimi et al., "Decommissioning Orphaned and Abandoned Oil and Gas Wells: New Estimates and Cost Drivers," *Environmental Science & Technology* 55, no. 15 (August 3, 2021): 10224–30, https://doi.org/10.1021/acs.est.1c02234.
[1480] 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.
[1481] 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/.

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.[1482]

- 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.[1483]

- 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

[1482] 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/.
[1483] 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/.

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.[1484]

- 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.[1485]

- 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

[1484] 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.
[1485] 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.

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.[1486]

- 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.[1487]

- 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. Proposals are under consideration to add stricter financial requirements for oil and gas producers that would limit the likelihood of well abandonment.[1488]

- 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

[1486] 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.
[1487] 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/.
[1488] 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/.

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.[1489]

- 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.[1490]

- 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 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

[1489] 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.
[1490] 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/.

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.[1491]

- 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.[1492]

- 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. 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.[1493]

[1491] 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.
[1492] 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/.
[1493] 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.

- 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."[1494, 1495] 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."[1496]

- 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 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

[1494] 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.
[1495] 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.
[1496] 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.

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.[1497]

- 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."[1498]

- 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.[1499] 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 (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

[1497] 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.
[1498] Deighton et al., "Measurements Show That Marginal Wells Are a Disproportionate Source of Methane Relative to Production."
[1499] 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.

abandoned oil and gas wells, leaking about 2.5 million tons of methane yearly.[1500] 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.*[1501] 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 structural weakness of the shale industry already create a "'perfect storm' for a cleanup crisis."[1502]

- 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

[1500] 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.
[1501] 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.
[1502] 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.

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.[1503]

- 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.[1504] 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-its-kind analysis of state records" by the *Los Angeles Times* and the Center for Public Integrity.[1505] 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

[1503] 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.
[1504] 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/.
[1505] 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.

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.[1506] 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.[1507] 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 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.

[1506] 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.
[1507] 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.

- 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.[1508] 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*.[1509] 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 through present activity of the oil and gas industry in the region, was the focus of an *E&E* piece.[1510] 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

[1508] 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.
[1509] 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/.
[1510] 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.

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.[1511] 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."[1512] 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 University of British Columbia.[1513] 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

[1511] 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.
[1512] 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.
[1513] 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.

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.[1514] 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.[1515] 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 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.[1516] 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

[1514] 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.
[1515] 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.
[1516] 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.

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).[1517] 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*.[1518] 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*.[1519] Those wells are estimated to cause between five and eight percent of the state's human-caused methane emissions, in 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

[1517] 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.
[1518] 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.
[1519] Lee, "Millions of Abandoned Wells Spark Climate, Safety Fears."

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.[1520]

- 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.[1521]

- 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."[1522]

- 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 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.[1523]

[1520] 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.

[1521] 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/.

[1522] 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.

[1523] 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/.

- 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."[1524]

- 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.[1525]

- 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."[1526]

- 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.[1527]

[1524] 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.
[1525] 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.
[1526] 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/.
[1527] 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.

- 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.[1528]

- 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.[1529]

- 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."[1530, 1531]

- 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

[1528] 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/.
[1529] 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.
[1530] 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.
[1531] 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.

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."[1532, 1533]

- 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."[1534, 1535]

- 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.[1536]

- 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 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

[1532] 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/.
[1533] 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/.
[1534] 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.
[1535] 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/.
[1536] 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-/.

together, Pennsylvania's abandoned wells contribute 5-8 percent of the state's annual greenhouse gas emissions.[1537, 1538]

- 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.[1539]

- 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.[1540]

- 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 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.[1541]

[1537] 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.
[1538] 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/.
[1539] 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.
[1540] 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.
[1541] 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.

- 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.[1542] 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."[1543]

- 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.[1544]

- 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, deconstructing the inventory of wells abandoned just in the past year alone will be a 20-year task.[1545]

- 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-

[1542] 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.
[1543] 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.
[1544] Stringfellow et al., "Chapter Two: Impacts of Well Stimulation on Water Resources."
[1545] 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.

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.[1546]

- 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.[1547]

- 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 scattered across the United States and likely represent "the second largest potential contribution to total US methane emissions above US Environmental Protection Agency

[1546] 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.
[1547] 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.

estimates." In the United States, no regulatory requirements for monitoring methane leaks from abandoned wells exist.[1548, 1549]

- 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.[1550]

- 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.[1551]

- 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.[1552]

- 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 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."

[1548] 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.
[1549] 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.
[1550] 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.
[1551] Urbina, "A Tainted Water Well, and Concern There May Be More."
[1552] 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.

Such communication between active wells raises the potential that similar communication can occur between active wells and abandoned wells.[1553]

- 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."[1554] 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.[1555]

- 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."[1556] 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 2.5 million abandoned oil and gas wells in the U.S.[1557]

[1553] British Columbia Oil & Gas Commission, "Safety Advisory: Communication during Fracture Stimulation," Safety Advisory, May 20, 2010, https://www.bcogc.ca/node/5806/download.
[1554] New York State Department of Environmental Conservation, "New York Oil, Gas and Mineral Resources 2010," 2010.
[1555] 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.
[1556] 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.
[1557] 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.

- 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.[1558]

- 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."[1559]

- 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.[1560] 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 cases in which pollutants had migrated up abandoned wells and contaminated

[1558] 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.
[1559] U.S. Government Accountability Office, "Drinking Water: Safeguards Are Not Preventing Contamination From Injected Oil and Gas Wastes."
[1560] 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.

groundwater. In one case, drilling wastewater migrated up an abandoned well a half mile away from where the wastewater was injected underground for disposal.[1561]

- 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."[1562]

[1561] 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).
[1562] 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 are disproportionately higher in impoverished communities. A 2023 study found that coastal California residents living closest to flood-prone oil and gas wells are disproportionately low-income people of color.

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.

- May 2, 2023 – A mapping study identified 129 hazardous industrial facilities at high risk for flooding in coastal California by 2050 due to rapidly rising sea levels. Oil and gas wells—along with ancillary fossil fuel infrastructure—made up a large fraction of these sites. The study also found that residents living nearest to flood-prone hazardous sites were disproportionately low-income, elderly, unemployed, and non-white. By the end of the century, the number of at-risk hazardous sites could rise to 423, imperiling even more socially vulnerable communities from flood-induced contaminant releases. "Because we did not include pipelines in our analysis, we underestimated the extent of oil and gas infrastructure that may threaten communities with contaminant releases due to sea level rise. Prior analyses suggest about 90 to 290 km of natural gas pipelines are projected to be flooded by century's end due to sea level rise in the San Francisco Bay Area alone."[1563]

[1563] Cushing et al., "Toxic Tides and Environmental Injustice."

- July 20, 2022 – An analysis of permits and other public records revealed that at least 20 new major oil and gas plants have been proposed in flood zones. These include seven LNG export terminals and six natural gas compressor stations. Five of the proposed projects are located on the Texas Gulf coast where industrial malfunctions and toxic chemical releases to air and water followed Hurricane Harvey's wake in 2017.[1564]

- May 2, 2023 – Spring flooding in April 2023 worsened erosion near the 70-year-old Enbridge Line 5 oil and gas pipeline in northern Wisconsin, heightening fears of exposure among the Bad River Band of Lake Superior Chippewa whose reservation is nearby. Line 5 carries crude oil and natural gas liquids across northern Wisconsin and Michigan to Sarnia, Ontario. Enbridge is planning to relocate the Line 5 pipeline around the Bad River reservation by constructing 41 miles of new pipeline.[1565, 1566]

- 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.[1567]

- 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

[1564] Brendan Gibbons, "At Least 20 Major Oil and Gas Plants Proposed in Flood Zones," *Oil and Gas Watch Newsletter*, July 20, 2022, 20, https://news.oilandgaswatch.org/post/dozens-of-major-new-oil-and-gas-plants-proposed-in-flood-zones.
[1565] Danielle Kaeding, "Spring Flooding Worsens Erosion near Enbridge Pipeline, Heightening Fears of Exposure," WPR.org, May 2, 2023, https://www.wpr.org/wisconsin-spring-flooding-erosion-enbridge-pipeline-bad-river-tribe.
[1566] Wisconsin Department of Natural Resources, "Draft Environmental Impact Statement: Proposed Enbridge Line 5 Relocation Project" (Wisconsin Department of Natural Resources, December 2021), https://widnr.widen.net/s/pmjdl6pbpd/el5_drafteis_dec2021_vol1-deis.
[1567] 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.

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.[1568]

- 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.[1569] *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 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.[1570]

- 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

[1568] 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.
[1569] 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.
[1570] 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.

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.[1571]

- 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*.[1572] "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 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.[1573] 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.

[1571] 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.

[1572] 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.

[1573] 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.

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.'"[1574]

- 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?"[1575]

- 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 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."[1576]

- 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

[1574] 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.
[1575] 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.
[1576] 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/.

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.[1577]

- 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.[1578]

- 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.[1579]

- 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 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."[1580] 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

[1577] 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.
[1578] 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.
[1579] 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.
[1580] 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.

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.[1581]

- 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.[1582] 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.[1583] 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 site will all take more time given the likely nasty condition of many Eagle Ford access roads," according to an energy analyst.[1584]

- 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.[1585] 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."[1586]

[1581] 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.
[1582] 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.
[1583] 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.
[1584] 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.
[1585] 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/.
[1586] Schladen, "Flooding Sweeps Oil, Chemicals Into Rivers."

- 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."[1587]

- 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.[1588]

- 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 tank to drop and break a valve.[1589]

- 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

[1587] 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/.
[1588] 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.
[1589] 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/.

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.[1590]

- 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.[1591, 1592, 1593, 1594, 1595, 1596, 1597]

- February 7, 2013 – In its 2012 annual report to investors, oil and gas drilling company 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."[1598]

- 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.[1599] 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.

[1590] 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.
[1591] 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.
[1592] 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/.
[1593] 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.
[1594] 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).
[1595] L. Szabo, "REMOVE THIS" (United States Geological Survey, 2011).
[1596] 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.
[1597] 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).
[1598] Noble Energy, "Annual Report (Form 10-K)," February 7, 2013.
[1599] 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).

- 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.[1600] 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.[1601] 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.[1602]

[1600] 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).
[1601] 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.
[1602] 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. Pipeline construction compacts and damages agricultural soils in ways that can persist for decades. On average in the United States, each fracking well is associated with a 3.3 acre reduction in crop acreage. This loss of farmland is exacerbated by potentially permanent soil contamination from fracking wastewater spills. Additionally, studies find soil degradation, lower crop yields, and loss of microbial diversity on farmland intentionally irrigated with oil and gas wastewater. 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. In California, fracking wastewater illegally injected into aquifers threatens crucial irrigation supplies to farmers in a time of severe drought.

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.

Drilling and fracking operations have led to documented harm to forests and natural areas. In forested areas of Pennsylvania, fracking activities have greatly reduced canopy covers and thereby diminished the carbon storage capacity of photosynthesizing forest trees. Throughout Appalachia, as forests and grasslands are fragmented by fracking operations, their surfaces become more impervious, regional biodiversity declines, and sediment and runoff into nearby streams increases. Soil compaction in cleared areas is detrimental to new plant growth and encourages the growth of invasive species. In Ohio, water withdrawals to service fracking operations episodically reduce the flow of small streams in ways that can disrupt downstream aquatic ecosystems and threaten regionally endangered 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. In Wyoming, fracking operations are disrupting the migratory movements of mule deer in ways that may lead to lower survival and reproductive success.

- May 29, 2023 – Researchers investigating how the construction of three oil and gas pipelines had affected agricultural soils on the western Canadian prairie found persistent signs of damage more than half a century later, as measured by organic carbon levels, soil compaction, pH, salinity, and calcium carbonate abundance. "Residual effects remained.

Neither soil conservation and reclamation practices, nor natural recovery had yet achieved equivalent capability for the target soil group."[1603]

- May 1, 2023 – Using county-level data on active fracking sites and acreage of crops, a research team investigated the impact of drilling and fracking well pads on agricultural land use across multiple shale basins in the United States during 1997-2018. The team found that, on average, each active well was associated with a 3.3 acre reduction in crop acreage, but with large regional differences. In the Great Plains and in Appalachia, fracking operations negatively affected agricultural land use. In the Southwest, where windfall income from mineral rights may have encouraged farmers to expand crop production rather than take retirement, researchers found a positive relationship between the number of active fracking wells and crop acreage.[1604]

- December 7, 2022 – A systematic literature review evaluated the effects of pipeline installation on soils and plants in agricultural and natural ecosystems. Altogether, the studies showed that pipeline installation degrades soil and inhibits plant productivity in ways that persist for many years. A quantitative analysis found that, compared to non-disturbed adjacent areas, the water infiltration and aggregate stability of soils near pipelines decreased while soil compaction increased. Fifteen out of 25 studies documented declines in crop yields (6.2-45.6 percent), and six out of nine studies reported decreased biomass from natural ecosystems.[1605]

- November 8, 2022 – A systematic quantitative review of the social sciences literature regarding the perceived impacts of fracking on natural resources looked at 96 different papers that used survey research techniques. In more than two-thirds of papers, respondents identified perceived risks associated with land use.[1606]

- October 6, 2022 – Using remote sensing data, a research team in Wyoming investigated how well pads disrupted the movements of mule deer within migratory corridors during the spring. They found that deer did not acclimate to the ecological disturbances that accompanied oil and gas development. Even when only a small portion of their migration corridor was industrialized, herds of mule deer altered their movements and lost their ability to freely move across the landscape to forage on the flush of nutritious spring growth within sagebrush communities. The research team predicted that the decoupling

[1603] Ivan Richard Whitson, "Residual Effects of Pipeline Construction on Agricultural Soils of the Canadian Prairie," *Land Degradation & Development*, May 29, 2023, ldr.4767, https://doi.org/10.1002/ldr.4767.
[1604] Yuelu Xu, Levan Elbakidze, and Xiaoli Etienne, "Unconventional Oil and Gas Development and Agricultural Land Use in the United States," *Journal of Agricultural and Resource Economics* 48, no. 2 (2023): 219–36, https://doi.org/10.22004/AG.ECON.320672.
[1605] Theresa Brehm and Steve Culman, "Pipeline Installation Effects on Soils and Plants: A Review and Quantitative Synthesis," *Agrosystems, Geosciences & Environment* 5, no. 4 (January 2022), https://doi.org/10.1002/agg2.20312.
[1606] Gene L. Theodori et al., "A Systematic Quantitative Review of the Perceived Environmental and Natural Resource-Related Impacts of Unconventional Oil and Gas Development," *The Extractive Industries and Society* 12 (December 2022): 101176, https://doi.org/10.1016/j.exis.2022.101176.

of deer migration from the annual spring "green wave" would result in less body fat for the winter, lower survival, and fewer offspring.[1607]

- September 28, 2022 – An Ohio Northern University study found that water withdrawals from fracking operations episodically reduced the flow of smaller streams in the eastern Ohio River basin in ways that could significantly disrupt downstream aquatic ecosystems and threaten regionally endangered species. Using modelled estimates of historic stream flow, the team found that half of all streams had significant flow reductions (10-20 percent) during fracking operations.[1608]

- August 29, 2022 – In the ten-year period between 2007-2017, permits were granted to 21,000 shale gas wells located on 4,240 well pads in the Marcellus Shale region of Pennsylvania, West Virginia, and Ohio. Researchers investigating ecological changes associated with these sites mapped land use and land cover disturbances with a 25-hectare buffer zone (= 61.8 acres) around well pads in this region. Researchers found that forests and grasslands were the most damaged cover types. On average, disturbances caused by fracking operations damaged 6.2 hectares(15.3 acres) in Pennsylvania, 4.7 hectares (11.6 acres) in Ohio, 4.4 hectares (10.9 acres) in West Virginia, and 5.6 hectares (13.8 acres) over the region. As forests and grasslands are fragmented and their surfaces become more impervious, regional biodiversity declines and sediment and runoff into nearby streams increases.[1609]

- April 28, 2023 – A fourth sinkhole developed in Daisetta, Texas above land used for oil and gas wastewater injection. Daisetta sits above a salt dome, which may have dissolved and caused the cave-in.[1610] [See also entry below for March 16, 2018.]

- March 30, 2022 – A Colorado State University-led study 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 and into forested areas, simply shift the burden of harm from human to wildlife populations. The researchers recommend an energy justice framework to mitigate the effects of oil and gas extraction, which includes the element of responsibility, whereby humans recognize the intrinsic value of nonhuman life and acknowledge their obligation

[1607] Ellen O. Aikens et al., "Industrial Energy Development Decouples Ungulate Migration from the Green Wave," *Nature Ecology & Evolution*, October 6, 2022, https://doi.org/10.1038/s41559-022-01887-9.
[1608] Brady Harmon et al., "Flow Alterations in Rivers Due to Unconventional Oil and Gas Development in the Ohio River Basin," *Science of The Total Environment* 856 (January 2023): 159126, https://doi.org/10.1016/j.scitotenv.2022.159126.
[1609] Shawn T. Grushecky et al., "Land Cover Change Associated with Unconventional Oil and Gas Development in the Appalachian Region," *Environmental Management*, August 29, 2022, https://doi.org/10.1007/s00267-022-01702-y.
[1610] Shelby Webb, "Sinkholes Are Emerging in Texas. Is Oil and Gas to Blame?," *E&E EnergyWire*, April 28, 2023, https://www.eenews.net/articles/sinkholes-are-emerging-in-texas-is-oil-and-gas-to-blame/.

to minimize environmental degradation."[1611]

- 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."[1612]

- 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.[1613]

- 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

[1611] 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.
[1612] 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.
[1613] 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.

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.[1614]

- 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. Cheniere cited an economic downturn, cost overruns, and the pandemic as reasons for the lack of reconstruction of the farmers' lands.[1615]

- 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.[1616]

- 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.[1617]

- 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

[1614] 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.
[1615] 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.
[1616] 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/.
[1617] 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.

fracking waste creates surface salt formation. These secondary impacts are more difficult to determine and take more time to assess.[1618]

- 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 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."[1619]

- 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.[1620]

- 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.[1621]

- 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

[1618] 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.
[1619] 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/.
[1620] 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.
[1621] 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.

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 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.[1622]

- 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.[1623] 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

[1622] 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.
[1623] 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.

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.[1624]

- 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.[1625] 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.[1626] 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,

[1624] 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.
[1625] 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.
[1626] 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.