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Environmental issues related to fracking

S. W. Carmalt* and Andrea Moscariello**

ABSTRACT

Hydraulic fracturing or 'fracking' overlays a major industrial operation on the land in areas where shale and tight hydrocarbon resources can be exploited. Every aspect of the fracking operation can cause environmental damage, although the damage from any individual well is both unlikely and usually fairly limited. Such damage has been extensively documented, giving the impression that fracking activity is bad for the environment. There is no yes or no answer to the question 'Is fracking harmful to the environment'; rather, it is an issue that must be resolved politically rather than scientifically.

1. INTRODUCTION

'Fracking', or as the oil and gas industry prefers, hydraulic fracturing, is the result of combining two petroleum exploitation technologies, both of which have been used and developed for decades. The first of these is horizontal drilling, which began as directional drilling to allow multiple wells from a single offshore platform to reach their completion depths with precise separations in the hydrocarbon-rich zones. This has progressed to drilling horizontally at depth, where the wellbore follows the productive interval for several kilometres. The second is hydraulic fracturing[1] using 'slick water' to increase the permeability of rocks previously considered too impermeable to economically produce hydrocarbons.

The use of the combined technologies was rapidly developed in the first decade of this century, with Mitchell Energy Corp.[2] developing the technologies in the Barnett Formation (a gas play) of northeast Texas.[3] This was followed in the Marcellus Formation (a gas play extending from Kentucky to New York, but developed primarily in Pennsylvania, Ohio, and West Virginia), the Bakken Formation (primarily light oil in North Dakota, extending into Montana and Saskatchewan), the Eagle Ford Formation (both oil and gas in Texas, extending into Mexico) and the Permian Basin (oil with associated gas in Texas and adjacent New Mexico). Many other plays have been exploited to a greater or lesser extent in the USA, and to some extent in Canada, Argentina and China with prospects in many additional countries. Each formation has posed

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1 Hydraulic in its meaning of any fluid; for example, as in hydraulic press.
2 Since acquired by Devon Energy.
3 R Gold, *The Boom* (New York, Simon & Schuster, 2014) 120–22.

its own operational problems, and industry has quickly developed effective technologies which it continues to improve upon.

The technologic challenge is to extract the fluid hydrocarbons, either oil or natural gas, from shales and tight siltstones, rocks of very low permeability. Many of these shales have been geologically known as containing hydrocarbons for decades, frequently because they are the source rocks for conventional oil or gas fields. But their very low permeability had made them uneconomic for traditional hydrocarbon exploitation. The combination of horizontal wells and hydraulic fracturing has made these strata economic for exploitation; the resulting production is shale oil[4] or shale gas.[5]

There has been a significant backlash to the widespread use of these new technologies on environmental grounds. In the past 20 years, there have been many thousands[6] of peer-reviewed scientific papers presenting data related to fracking operations, plus numerous government reports, professional technical presentations and other investigations. To this should be added a very large number of blog posts of varying quality. We note that many of the environmental issues discussed with respect to fracking are, in fact, common to all oil and gas operations. The debates about fracking are not entirely a scientific question; questions of social and economic impacts are part of the discussion.

We attempt in this paper to use 'fracking' to describe the entire suite of activities involved in the exploitation of tight or impermeable hydrocarbons, and 'fracturing' to refer to the specific breaking of the rock using fluid pressure. Table 1 is a brief glossary of technical terms used; Figure 1a illustrates the concept and context of fracking, and Figure 1b shows a well pad.

2. LIFE CYCLE OF A FRACKED WELL

The environmental issues that surround fracking change over the life cycle of a well. The basic stages are site selection and preparation, drilling the well, completing the well (which includes the fracturing operation itself), producing the well, and eventual abandonment and site restoration.

Site selection and preparation

Even with hydraulic fracturing technology, the very low permeability of the target strata requires that wells be located close together. This is most economically done by concentrating the surface installations for multiple wells in a single location—the well pad. This can be thought of as an on-shore platform. The number of wells that the pad can support will vary, but pad design generally supports a minimum of four wells and usually will support more. A total of 8, 12 or 16 wells is common, depending on the specifics of the target formation. As with an offshore platform, pads are constructed after the production potential of the play has been established.

Site selection for the pad starts with assessment of mineral rights ownership and seismic information. The specific site must provide a secure base for all of the equipment that will be involved; construction of a well pad thus requires civil engineering expertise to create a strong, level, and well-drained foundation for a 1–3

4 Shale oil should not be confused with oil shale, which is very different. Oil shale is shale rock that contains solid hydrocarbons not yet transformed into liquids by geologic heat and time; to obtain oil from an oil shale the rock must be heated; the technical challenges have not yet been solved to allow economic extraction from oil shales. By contrast, shale oil is liquid oil produced directly from a rock that is shale; the technical challenges of extraction from this very impermeable rock have been met by fracturing.

5 Also sometimes 'tight oil' or 'tight gas' when the rock is not strictly a shale.

6 See, for example, PSE, 'The ROGER Citation Database' (2020) <https://www.zotero.org/groups/248773/repository_for_oil_and_gas_energy_research_roger_-_pse_healthy_energy_collections/RWRMA2FU/items/9EMGA46W/collection> accessed 14 May 2020 or Concerned Health Professionals of NY and Physicians for Social Responsibility, *Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking* (6th edn, Unconventional Gas and Oil Extraction 2019) <http://concernedhealthny.org/wp-content/uploads/2019/06/Fracking-Science-Compendium_6.pdf> accessed 24 July 2019; GE King, Hydraulic Fracturing 101, Conference Presentation at SPE Hydraulic Fracturing Technology Converence (2012) <https://www.onepetro.org/conference-paper/SPE-152596-MS> accessed 25 February 2020.

Table 1. Technical terms used

Completion	The actions taken once a well has been drilled that will allow it to produce hydrocarbons
Connate water	Water, usually a brine, found to some extent in all rocks at depth
Continuous deposits	Hydrocarbon source rocks that only can be exploited by fracturing in contrast to conventional deposits (meaning 1)
Conventional	Two meanings: (1) situations where hydrocarbons have been concentrated over geologic time into relatively permeable strata, and (2) wells that are primarily vertical rather than having horizontal sections. Note that definition 2 oil and gas wells may be fractured in their pay zones
Cuttings	Bits of rock brought to the surface during drilling of the well
Flowback	Fluid used for fracturing that returns to the surface when the fracturing pressure is released
Fracking	All hydrocarbon extraction activities requiring the use of fracturing to increase permeability and thus make the exploitation economic
Fracturing	Using hydraulic pressure to break rocks at depth, thereby increasing their permeability
Horizontal well	The portion of a well which follows a specific geologic stratum or horizon
Hydraulic fracturing	See fracturing
Hydrocarbon	Oil or natural gas; chemically any chemical composed of hydrogen and oxygen
Lateral	See horizontal well
Operator	An oil or gas company that produces hydrocarbons for economic benefit
Pad	An area, generally about 1–3 hectares (2.5–7.5 acres) from which multiple wells are drilled and operated
Pay zone	The geologic strata that contain the hydrocarbons being exploited
Permeability	A measure of the ease with which fluids can flow through a solid; see also porosity
Play	A geological formation coupled with a set of ideas that support hydrocarbon production
Porosity	The space between constituents of a solid which may contain something else, usually a liquid or a gas; see also permeability
Produced water	Water produced along with exploited hydrocarbons
Production	The economic hydrocarbons coming from a well; depending on context production may or may not include associated water
Shale	Fine-grained sedimentary rock, almost always impermeable; shales are the sedimentary source deposits for hydrocarbons
Vertical well	A well drilled vertically down from the surface; this may be completed as an oil or gas well, or may then be 'turned' to become a horizontal well at depth
Wellhead	The surface location of the well

hectare (2.5–7.5 acre) work area. Construction of the well pad itself must consider preserving natural drainage, creating barriers to contain any accidental spills, and generally minimizing damage to existing ecosystems. Environmental considerations during pad construction will be similar to those for other civil engineering projects, with the addition of placing impermeable barriers and constructing drainage to ensure that spills and runoff do not contaminate surface or ground water. Erosion control due to disrupted land cover, modifications to drainage and the noise of heavy construction equipment will all be factors in pad design. Because the presumption is that a well pad is a temporary rather than permanent feature, although it may be in use for several decades, site construction normally includes provisions for restoration of the land surface and drainage to its original state, and will provide for preservation or replacement of topsoil and replanting. We again emphasize that the specific requirements at a site will vary somewhat with the specific

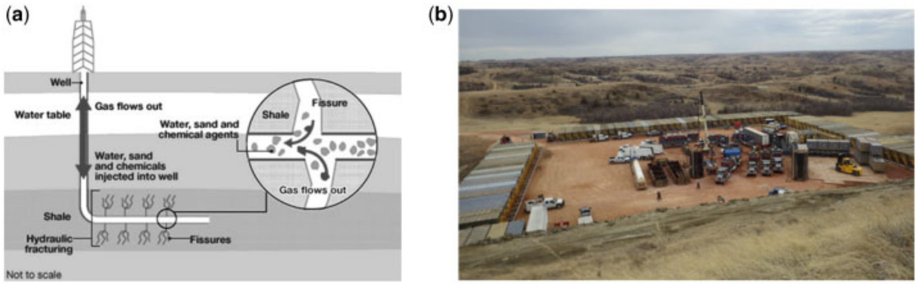

Figure 1. (a) Schematic diagram showing fracturing. (b) Aerial photo of a pad.

Notes: (a) Not to scale; in particular, in most plays, the distance from the water table to the stratum being fractured is many times the thickness shown; fissures preferentially form horizontally rather than vertically. (b) Note the significant excavation at the near side of the pad and fill at the near side to create a level work area.

Sources: (a) G Hammond and Á O'Grady, 'Indicative Energy Technology Assessment of UK Shale Gas Extraction' (2017) 185 Applied Energy 1908. (b) JL Butler and others, 'Biological Assessment of Oil and Gas Development on the Little Missouri National Grassland' (2018) General Technical Report RMRS-GTR-384, Fort Collins, CO, USA, Rocky Mountain Research Station, US Forest Service, 74.

jurisdictions; the permits needed in Pennsylvania are shown in Table 2. Each of the issues in Table 2 includes a long list of detailed subsidiary regulations which must be addressed in permit applications. Figure 2 illustrates the result in one case. The operator could not obtain a permit to have a temporary access road cross the wetlands, with the result that a much longer access route, with a weight limit of 25 tons, was required.

In other states, there may be other agencies involved. For example, US Indian tribes and/or the US Bureau of Indian Affairs may be involved; different US agencies may be involved in the case of federal lands, depending on how the land is classified; the US Army Corps of Engineers may be involved when there are impacts to navigable watercourses; in some states, local restrictions may be imposed in addition to state-level requirements. The operators complain about the overlay of these different levels of regulation. But oil and gas regulations exist almost everywhere,[7] many of which are either directly or indirectly designed to protect the environment. To date, fracking has not been economic in offshore environments, ie from offshore platforms.[8] Neither have continuous plays been developed extensively outside the USA.[9]

Drilling the well

The actual drilling of wells uses techniques that have been deployed for decades. There are two major differences in fracking operations: first, that the well will be deviated, 'turned', at depth so as to follow a specific geologic stratum for thousands of feet and second, a number of wells will be drilled from the same surface location. The drill pad is an active, heavy-industry operation during drilling and fracturing. It will operate around-the-clock, making issues of noise and traffic significant. The actual drilling will seldom take more than a month for an individual well; modern practice frequently is to use one rig to drill vertically down to the point where the well will be turned, which is often a matter of a few days, and then use a different drill rig to 'turn' the well and drill the horizontal section. This division of the drilling into two separate operations is only possible after the geology of the strata is reasonably well-known.

7 H Rabia, 'Engineered Well Design: From Spud to Abandonment', SPE Distinguished Lecture, Geneva, Switzerland, 11 December 2019. Everywhere with the exception of Saudi Arabia.

8 Fracturing is routinely used offshore in conventional wells; it is the unconventional, continuous deposits which require long lateral well segments that have not yet been economically exploited offshore.

9 There are exceptions, notably in Canada, Argentina and China, but to date the extent of fracking activity in these plays has not been extensive.

Table 2. Permits, regulations and other requirements for oil and gas operations in Pennsylvania; this table is indicative, not definitive

Description	*Regulation or permit*	*Government level*
Well drilling permit Complete location, depth, casing cementing plans Notification to all interested parties Posting of bond Approval of any waivers Emergency response plans On-site sewage facilities	Permit	State, with local and/or federal requirements for some aspects
Waste handling Onsite waste management Waste transfer facilities Haulage requirements	Regulation	State, with local and/or federal approvals required
Road occupancy and use Temporary access roads Pipeline crossings	Permit	State, sometimes local
Pits and impoundments Water or mud pit berms may be considered as dams Liners must meet standards	Permit and/or regulation	State, some federal and/or local requirements
Water use and discharge Water management plan required	Permit and/or regulation	State, federal and/or interstate compacts
Air emissions Applies to both well sites and pipeline operations	Permit	State, embodying federal standards; exemption from state requirements does not exempt from federal rules
Wetlands protections Required for modifications and/or crossings	Permit	State and federal
Erosion and sedimentation controls Applies to both pads and pipelines	Permit	State
Miscellaneous Endangered species protections Cultural resource protections	Regulation	State and federal
Water use permit	Permit	Varies with a specific site, multiple permits may be required[a]

Source: Modified from <https://pioga.org/education/oil-and-gas-regulations/> accessed 7 May 2020.
[a]For example, the multistate Susquehanna River Basin Commission in addition to local jurisdictions.

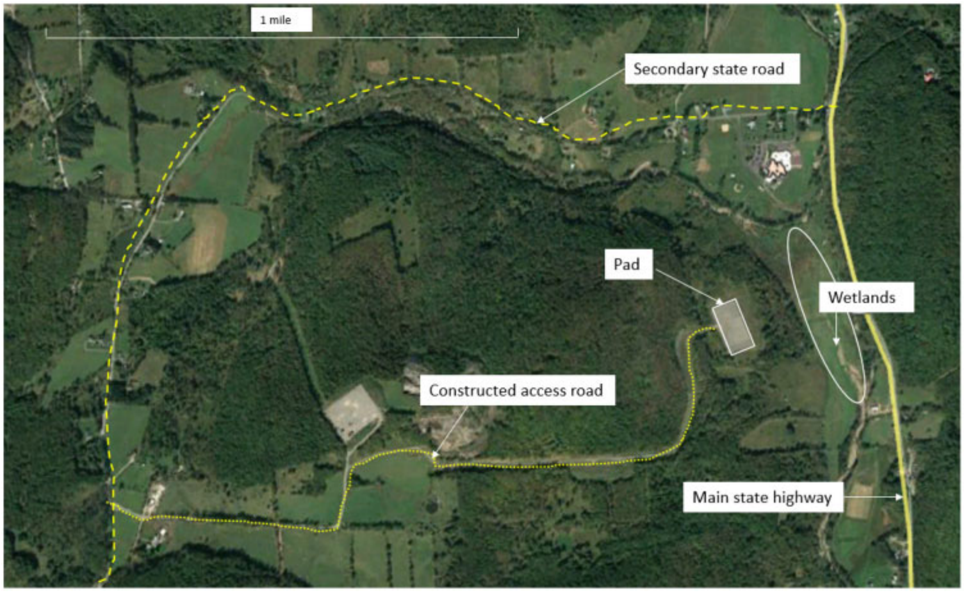

Figure 2. Environmental modifications required for a pad site.

Notes: Damage to wetlands was not allowed, requiring the use of a secondary road (25-ton weight limit) and long constructed road to reach the pad. Direct access would have required a route of ca 0.7 km while the final, permitted route is ca 6.3 km.

Source: Google Earth (2020) with annotations added by the author (SWC) based on personal conversations with the landowners involved.

During the actual drilling, a mud slurry, or simply 'mud', is pumped down the centre of the drilling pipe[10,11]; this both cools and lubricates the actual drill bit and is sufficiently thick to carry the bits of drilled rock, 'cuttings', back to the surface as it flows up around the outside of the drill stem. The mudflow may also be used to power the rotary bit itself. Periodically, the drilling stops, and casing is inserted into the drilled well. The annulus between the casing and the surrounding rock is filled with cement, and the drilling recommences at a smaller diameter. Figure 3 shows some idealized well constructions for vertical wells; horizontal wells follow the same principles. Important is that almost all jurisdictions require that surface casing extend to a depth below the deepest known aquifer.[12,13] Obvious from the figure is that the integrity of the cement is critical in preventing contamination of groundwater aquifers; cement is also critical when high pressures are encountered during drilling. Both the Macondo blow-out in the Gulf of Mexico in 2010[14] and the contaminated aquifer issues in Dimock, PA, popularized in the film *Gasland*, have been traced back to cement problems.[15]

10 This pipe is called the drill stem. When the initial vertical well is drilled separately, compressed air sometimes is be used instead of mud.

11 When the initial vertical well is drilled separately, compressed air sometimes is be used instead of mud.

12 Rabia, SPE Distinguished Lecture, Geneva, Switzerland, 11 December 2019.

13 It was not clear in the groundwater contamination case concerning the aquifer above the Barnett Formation in Texas whether the contamination was due to failure to case wells through the aquifer being used for drinking water. In that area, the aquifer has two zones, and the protective casing may only have been set to below the upper zone. Gold (n 3) 98.

14 US Chemical Safety and Hazard Investigation Board (2016) Report 2016-04-12 Executive Summary, 6 'Earlier, a critical cement barrier intended to keep the hydrocarbons below the seafloor had not been effectively installed at the bottom of the well.'

15 Pa DEP Consent Order and Decree 4 November 2009 <https://s3.amazonaws.com/propublica/assets/natural_gas/final_cabot_co-a.pdf?_ga=2.157896178.998274142.1589362599-1169587268.1589362599> accessed 13 May 2020. At page 3, the decree has '. . .

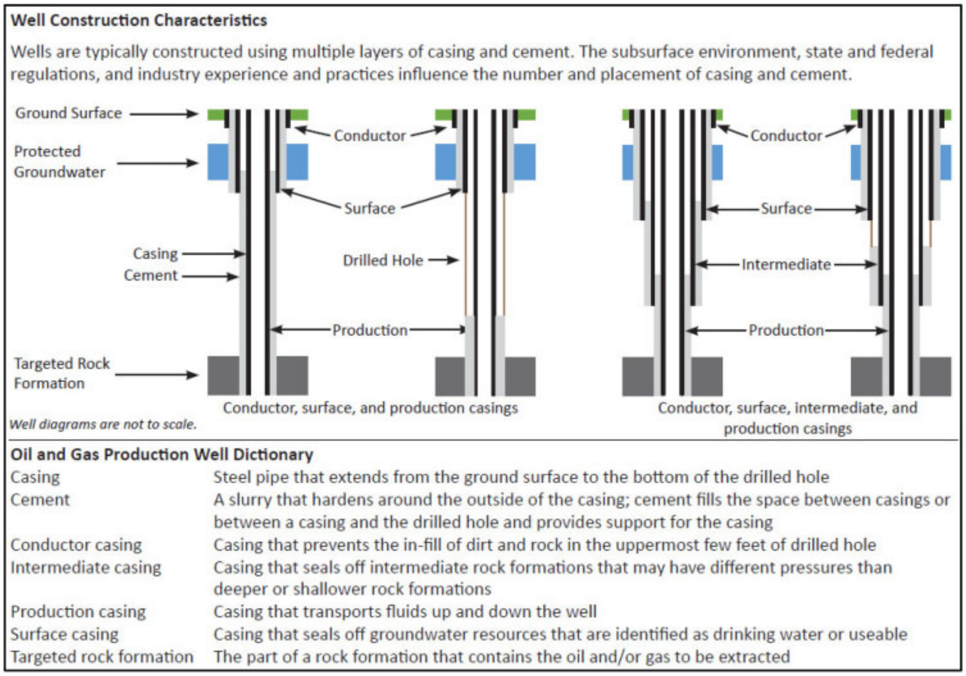

Figure 3. Well construction details.

Notes: At various levels, casing is set, with cement used to seal the surrounding rock from the interior of the well. As shown, this may be done repeatedly.

Source: US EPA (n 17) 5.

The mud slurry circulated during drilling is carefully engineered so that its properties will be a good match for the rocks through which the well is drilled. Different types of mud work best in different types of rock, and in addition to the basic constituents of water and dry clay powder, specific chemicals may be added to the mixture. The volume of mud needed to drill a well is significant, but seldom more than 2000 m^3; by comparison, an Olympic-sized swimming pool ($50 \times 2 \times 25$ metres) holds 2500 m^3 of water. As the mud circulates, the cuttings are separated out. Historically, the mud was created by mixing dry clay with water in an open pit. While still called the 'mud pit', modern practice always requires that this be lined with very heavy-duty plastic to prevent any seepage down into aquifers; frequently today's mud pits are not open but are large, enclosed containers or tanks. While the circulating mud is contained within a closed system, leaks and spills can and do occur, creating possible contamination issues. Eventually, both the cuttings and the mud require correct disposal; re-use of the mud itself in adjacent wells is possible, which minimizes the disposal problem.

The volume of cuttings will vary depending on the depth of the vertical portion of the well and the length of the lateral portion. Amounts vary, but a typical Marcellus well is likely to produce between 350 and 400 metric tons of cuttings.[16] Cuttings are generally dried and then used as landfill or for construction purposes and are frequently exempt from US Environmental rules governing hazardous wastes.[17] The organic-rich

Department issued Cabot a Notice of Violation for failing to properly cement casing at certain of the Cabot Wells, and for failing to prevent gas from entering groundwater from the Cabot Well . . .'.

16 MY Stuckman and others, 'Geochemical Solid Characterization of Drill Cuttings, Core and Drilling Mud from Marcellus Shale Energy Development' (2019) 68(102922) Journal of Natural Gas Science and Engineering 1.

17 EPA, 'Exemption of Oil and Gas Exploration and Production Wastes from Federal Hazardous Waste Regulations' (2002) <https://archive.epa.gov/epawaste/nonhaz/industrial/special/web/pdf/oil-gas.pdf> accessed 23 December 2019.

shales that are targets of fracking frequently contain toxic elements, notably arsenic, barium, and uranium; landfills sometimes reject loads of cuttings because radiation levels are too high.[18] When dried cuttings eventually are exposed to weathering, for example, when they are used as fill in construction projects, they may release these and other toxic elements—sometimes into runoff water and sometimes by seepage into aquifers used for drinking water.[19]

Completion activities

In conventional reservoirs, fracturing is simply an early step in the overall completion process; in wells that will be completed in shales, it is a major activity by itself. Prior to fracturing, the final design of the well will be completed; this may involve the final cementing job, installing the final set of casing, perforating the final casing where it is in contact with the hydrocarbon-rich strata, and installing at least sufficient surface equipment so that the well can be tested.

The fracturing operation

The basic technique of hydraulic fracturing is to pump fluid into a well until the pressure becomes sufficiently great that the rock breaks at the target level. A small amount of sand, frequently natural but sometimes a manufactured ceramic, is added so that when the pressure is removed the fractures remain open, hence the name 'proppants'. Added to the water are small amounts of chemicals: to reduce internal friction; to prevent any algae and bacteria in the water from growing; to prevent the water from causing rust or other corrosion to the metal casings; and sometimes as a treatment for the specific rock formation being fractured.[20]

One of the major technologic breakthroughs was the use of freshwater as the basic fracturing fluid, with an additive to reduce internal friction, hence 'slick water'.[21] The amounts of water needed vary considerably, from about 2000 m^3 to as much as 100,000 m^3.[22] While normally one per cent or less of the total fracturing fluid,[23] the additives used in the fracturing operation have been the subject of much controversy. Companies which conduct fracturing operations have exacerbated the controversy by responding to requests for information about the additives by refusing to identify the exact chemicals and proportions used on the grounds that these are competitive trade secrets.[24] Indeed, some of the chemical additives are toxic[25] and/or carcinogenic,[26] in particular, biocides needed to control algal and bacterial growth in the well are designed to be toxic.

18 TT Phan and others, 'Trace Metal Distribution and Mobility in Drill Cuttings and Produced Waters from Marcellus 89.

19 Concerned Health Professionals (2019); US Environmental Protection Agency, 'Hydraulic Fracturing for Oil and Gas' (2016) EPA-600-R-16-236ES <https://www.epa.gov/sites/production/files/2016-12/documents/hfdwa_executive_summary.pdf> accessed 16 November 2017; E Hill and L Ma, 'Shale Gas Development and Drinking Water Quality' (2017) 107 Am Econ Review 522; J Woda and others 'Detecting and explaining why aquifers occasionally become degraded near hydraulically fractured shale gas wells', (2018) 155 Proc Nat'l Acad Sciences 12349.

20 FracFocus, 'What Chemicals Are Used' (2020) <http://fracfocus.org/chemical-use/what-chemicals-are-used> accessed 18 May 2020. FracFocus is an industry database listing chemical additives to fracturing fluid for all wells in the USA, in some cases state regulations require posting information to the database.

21 The effect had been used elsewhere, for example, in firefighting. E Blum, 'Slippery Water: A Documented Advance in FireFighting Technology' (1969) Rand Corporation Report D-18684-NYC <https://www.rand.org/content/dam/rand/pubs/documents/2008/D18684.pdf> accessed 18 May 2020.

22 US Geological Survey, 'How Much Water Does the Typical Hydraulically Fractured Well Require?' (2019) <https://www.usgs.gov/faqs/how-much-water-does-typical-hydraulically-fractured-well-require?qt-news_science_products=0#qt-news_science_products> accessed 20 April 2020. Numbers are approximate. Petroleum Services Association of Canada, 'How Much Water Is Required to Frac a Well?' (2019) <https://oilandgasinfo.ca/know-fracking/how-much-water-is-required-to-frac-a-well/> accessed 20 April 2020.

23 S Zendehboudi and A Bahadori, *Shale Oil and Gas Handbook* (Gulf Prof Pub 2015) 102.

24 A Maule and others, 'Disclosure of Hydraulic Fracturing Fluid Chemical Additives' (2020) 23 New Solutions 167.

25 W Stringfellow and others, 'Identifying Chemicals of Concern in Hydraulic Fracturing Fluids Used for Oil Production' (2017) 220 Environmental Pollution 413

26 H Chen and KE Carter, 'Characterization of the Chemicals Used in Hydraulic Fracturing Fluids for Wells Located in the Marcellus Shale Play' (2017) 200 Journal of Environmental Management 312.

To help alleviate public concerns, the industry in the USA has established a public database showing the details of additives for each well.[27]

During a fracturing operation, the fluid pressure in the well is increased until the rock at depth physically breaks. One environmental concern is that these breaks will extend upwards into drinking water aquifers, or perhaps to the surface, thus providing a pathway for both the hydrocarbons and the fracking fluids to escape to shallow depths or even the surface. Whether this is likely to happen depends to a large extent on the vertical distance separating the bottom of the deepest aquifer and the top of the shallowest fractured stratum. As is expected, the greater this vertical separation, the less likely that such a break will extend across the entire vertical distance.[28] The actual propagation distance will depend on the specifics of the rocks involved. Davies[29] suggests less than 1 per cent of fractures will progress more than 300 m in the Marcellus formation; Flewelling and others[30] report that no seismic indications of fractures have been observed more than 600 m above the fractured formation, and Fisher and others found more than 750 metres separation between the top of fractures and the deepest aquifers in four plays.[31] The horizontal extent of fractures is much greater than their vertical extent,[32] which is expected due to the horizontal fabric of sedimentary rocks. When natural vertical fractures exist in the rock, there is a small chance that they extend into aquifers or to the surface, but most are found to be of approximately the same length as hydraulically induced fractures.[33]

Much more likely are problems created by the well itself or other nearby wells. When the hydraulic pressure is applied to fracture the hydrocarbon-bearing rock, it can also break the materials of the well. Ruptures of materials of the well itself are collectively called 'well integrity problems'. The most common is that the cement used to form a seal between each of the casing layers and the surrounding rock or next larger casing (Figure 3) has been improperly applied or has not been properly set. An example from a Marcellus well in Pennsylvania[34] found that cement had failed to set properly along an intermediate portion of the well with the result that gas was escaping up through the cement to the surface. Concerned that such gas leaks might also contaminate the aquifer used for drinking water in the area, the Pennsylvania regulators would not allow fracturing to take place until the leak issues had been resolved. The typical solution to such defects is to perforate the casing and 'squeeze' additional cement into the annulus. In this case, this was not required because the operator was able to demonstrate that the leakage remained isolated from both the shallower aquifer and the targeted gas layer at depth.[35] Cement takes time to set and form a barrier. Although not specifically a fracking issue, not taking the time to properly assess the quality of a cement job led to the Macondo blowout and criminal charges against the operator and some of the operator's employees.[36] King and Valencia[37] point out that despite the fact that no cement job is likely to be perfect, the multiple layers of cement in typical well construction mean that well integrity is almost always sufficient.

While poor cement in the well itself can cause problems, another route to the surface that the fracturing operation may create is to other wells, both presently operating wells and abandoned wells. When the fractures created by the fracturing operation intersect the fractures created in a neighboring well, the result is a 'frac hit'. When a play is developed by fracturing, the lateral portions of adjacent wells may be less than

27 FracFocus, 'Chemical Disclosure [Home Page], Industry Database' (2020) <https://fracfocusdata.org> accessed 19 May 2020.

28 R Davies and others, 'Hydraulic Fractures: How Far Can They Go?' (2012) 37 Marine and Petroleum Geology 1.

29 *Ibid.*

30 S Flewelling and others, 'Hydraulic Fracture Height Limits and Fault Interactions in Tight Oil and Gas Formations' (2013) 40 Geophysical Research Letters 3602.

31 MK Fisher and NR Warpinski, 'Hydraulic Fracture-Height Growth' (2011) SPE 145949.

32 ibid.

33 ibid.

34 LP Moore and others, 'Evaluation of Precompletion Annular Gas Leaks in a Marcellus Lateral' (2012) SPE 153142 <https://doi.org/10.2118/153142-MS> accessed 29 May 2020.

35 Ibid.

36 Gold (n 3) 275.

37 GE King and Valencia (2014), SPE 170949-MS <https://doi.org/10.2118/170949-MS> accessed 26 May 2020.

300 m (1000 ft) apart (Figure 4). This has been known to cause 'blowouts' in another well, which may have a surface location several miles away from the surface location of the well-being fractured.[38] Once wells have been put on production, some of the safety equipment available to contain high pressures frequently has been removed; several states now require an operator to notify all nearby well operators of fracturing operations.[39] But even without a blowout, both nearby wells and the new well undergoing fracturing may be damaged by the loss of pressure from a frac hit, thus diminishing the economic value of both wells.[40]

Similar to frac hits is the problem of having fractures created in the fracturing operation extend into abandoned wells, which then provide an easy path to the surface. King notes that well engineering practices, including abandonment practices, have changed over the years.[41] Particularly in the Pennsylvania and Ohio areas of the present Marcellus and Utica plays, where the industry has been drilling oil and gas wells for more than 150 years; some locations of old wells, along with pollution problems they could cause, may be unknown.[42]

At the end of the fracturing operation, when the pressure is released, some of the fluid pumped into the well to cause the fracturing will return to the surface. Not only will this fluid contain the additives mentioned above, but it will be mixed to a greater or lesser extent with fluid which has been in the rocks at depth. Because of the mixture with formation waters, this water is generally a brine with components that require that it be processed before it can be discharged to the environment.[43]

Other completion steps

Once the fracturing is completed, the well must be tested, in part to see how successful the fracturing operation has been. This will determine the flow rates the well can sustain. Then pipeline connections, storage tanks, separators, compressors and other equipment must be installed. The major environmental issues that arise during this phase are proper disposal of whatever comes up the well. This may include flowback of some of the fracturing fluid and initial amounts of hydrocarbons mixed with water present in the subsurface strata being exploited. Because the well is not entirely ready for production, gas typically is flared and fluids put in temporary storage tanks. The tests may last for several days. Flaring is environmentally problematic, particularly in more densely populated areas, with particulate soot, light and noise pollution[44] which are known to cause health risks.[45]

Producing the well

Once the testing of the well has been completed, the well will be shut until all of the production equipment is installed, perhaps waiting to include equipment for wells still being drilled on the same pad. If final production plans require the hydrocarbons to be delivered by pipeline, the pipeline will need to be constructed, otherwise necessary storage tanks will be constructed. When all the pieces are in place, the well will go into production. The major environmental concerns during production are leaks, the most important of which is

38 T Jacobs, 'Oil and Gas Well Producers Find Frac Hits in Shale Wells a Major Problem' (2017) <https://doi.org/10.2118/0417-0029-JPT> accessed 27 December 2017.

39 Distance requirements vary by state.

40 Jacobs (n 36).

41 G King, 'Are Well Construction Practices Safe for the Environment?' (2015) 67 Journal of Petroleum Technology 24.

42 King and Valencia (n 35).

43 YI Lester and others, 'Characterization of Hydraulic Fracturing Flowback Water in Colorado' (2015) 512–13 Sci Total Environment 637; N Abualfaraj and others, 'Characterization of Marcellus Shale Flowback Water' (2014) 31(9) Environmental Engineering Science 514.

44 OG Fawole and others, 'Gas Flaring and Resultant Air Pollution' (2016) 216 Environmental Pollution 182; M Troutman and JB Pribanic (eds), 'Focus on Flaring, Public Herald' (2011) <https://publicherald.org/video-investigation-gas-well-flaring-in-the-marcellus-shale/> accessed 15 June 2020.

45 W Babisch and others, 'Traffic Noise and Risk of Myocardial Infarction' (2005) 16(1) Epidemiology 33.

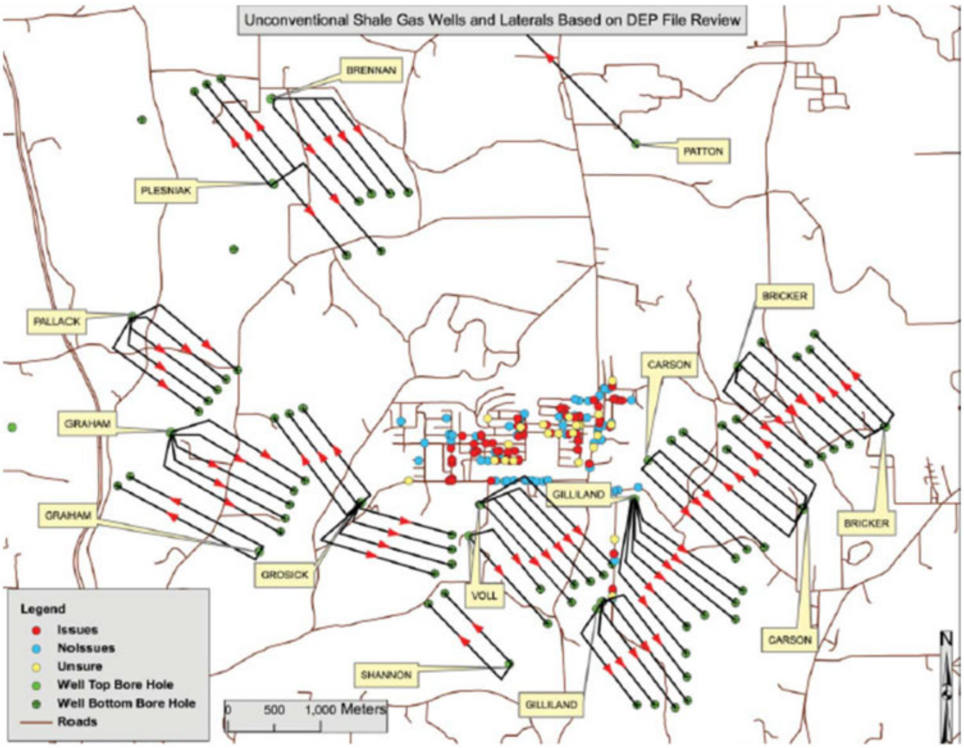

Figure 4. Pads and traces of horizontal wells in a portion of Lancaster and Connoquenessing townships, Butler County, Pennsylvania as of 2012.

Notes: Illustration of multiple, closely spaced wells drilled from a single pad. See also G Aisch, 'What North Dakota Would Look Like If Its Oil Drilling Lines Were Aboveground' (2014) <https://www.nytimes.com/interactive/2014/11/24/upshot/nd-oil-well-illustration.html> accessed 20 May 2020 which provides an interesting visual perspective of the closely spaced lateral wells in an area of the Bakken play.

Sources: SK Alawattegama and others, 'Well Water Contamination in a Rural Community in Southwestern Pennsylvania Near Unconventional Shale Gas Extraction' (2015) 50A(5) Journal of Environmental Science and Health 516.

escaping methane because of its large greenhouse gas contribution. Another environmental worry during production is noise associated with gas, either from flaring associated gas or for compressors when the gas is being sold.

Fracked wells are notorious for their rapid decline rates. Nevertheless, any specific well can be expected to produce for at least a decade, and probably several, although at very low rates going into the future. Provided there is good maintenance, these decades of production are the least environmentally problematic in the life cycle of the well. But there will come a time when the revenue being generated is insufficient to continue production, and the well will be shut in awaiting price recovery, or abandoned.

Abandonment and site restoration

There are well-established procedures for abandonment of wells with regulations governing the process, again mostly at the state level in the USA. But there is a problem. At this point, the well is not producing any revenue, and the abandonment procedures carry a cost. The problem is exacerbated in the USA where the structure of the industry allows the well to be sold to a different operator. Such sales will frequently happen, and when the well is abandoned it can be owned by a small company that has nothing except that single well as an asset, so it can simply declare bankruptcy and walks away, leaving an environmental problem.[46]

Technically, abandonment usually requires recovering as much of the casing as is practicable, and then filling some or all of the well with concrete. Just as in the drilling of the well, the integrity of the cement is critical, and for the same reasons.

3. DISCUSSION

As the fracturing technology began to be widely used in the first decade of this century, there were many debates about whether this was an environmentally hazardous technology. Much of the discussion, particularly in the first years, has been about water, both with respect to quantities of water needed, and to water quality due to additives. Additional environmental issues include air pollution, noise and light. Table 3 lists areas of environmental concern, with Table 4 showing activities which raise environmental concerns. Part of the environmental awareness was probably due in part to the fact that the initial fracking plays, the Bartlett Shale in the Dallas-Ft. Worth area of northeast Texas and the Marcellus area around Pittsburgh in Pennsylvania, are more densely populated than much of the USA, as can be seen in Figure 5. As noted above, fracking requires many closely spaced wells so public awareness and impact were higher than in many more traditional hydrocarbon areas.

Also, many who were concerned about CO_2 emissions and global warming were pinning their hopes on 'peak oil' forcing a decrease of these emissions,[47] particularly because there was no political will, especially in the USA, to address the CO_2 and related climate issues.

In the discussion that follows, it must always be remembered that the earth is heterogeneous; actual samples of the subsurface are obtained through a narrow well opening [frequently 8-inches (20 cm) in diameter] at a distance of 1–5 km (3000–15,000 feet) from the wellhead. The models of the strata and the detailed nature of the hydrocarbon-bearing rocks are generally correct and useful, but the reality is more complex in detail.

Water

Water gets the most attention in environmental concerns about fracking. There has been some concern about the amount of water needed for drilling and fracturing, but by far the greatest concern has been about possible contamination of drinking water supplies, from surface water sources and especially from groundwater sources.

The initial geologic exploitation using widespread fracking took place in areas with adequate water supplies.[48] As noted above, the amount needed to drill and fracture a well can range from 2000 m^3 to over 100,000 m^3 (0.5–26 million gallons or 1.6–80 acre-feet). Initially, water is needed to drill the well, and even more is needed in fracturing. But even where amounts of water are generally adequate, other water users need to be considered, often requiring permits.[49] In more arid areas, notably the Bakken play and Permian basin play, costs increase, and water becomes part of the economic calculation that determines whether a well is worth drilling.[50] In the Bakken play in North Dakota, water for all mining activities (of which

46 Confirmed in personal conversations with small operators for Northeastern Pennsylvania.

47 PA Kharecha and JE Hansen, 'Implications of "Peak Oil" for Atmospheric CO2 and Climate' (2008) 22 Global Biogeochemical Cycles 10; CAS Hall and JW Day, 'Revisiting the Limits to Growth after Peak Oil' (2009) 97(3) American Scientist 230; MK Hubbert, 'The World's Evolving Energy System' (1981) 49(11) American Journal of Physics 1007.

48 The Barnnet play in northeast Texas, the Marcellus play in Pennsylvania.

49 J Hoffman, 'Water Use and the Shale Gas Industry' (2011) Susquehanna River Basin Commission <https://tompkinscountyny.gov/files2/tccog/Other_Presentations/Susquehanna%20River%20Basin%20Commission-2.pdf> accessed 24 June 2020. One of the other uses is to ensure adequate flow for all other uses, including ecological services.

50 B Walton, 'Permian Oil Boom Uncorks Multibillion-Dollar Water Play' (2019) <https://www.circleofblue.org/2019/world/permian-oil-boom-uncorks-multibillion-dollar-water-play/> accessed 27 June 2020.

Table 3. Major environmental concerns and concerning fracking activities relative to the shale and tight gas industry; list of major environmental concern in fracking activity

Environmental concerns	*Activities and comment*
Sufficient water quantity	Siting; is there sufficient water for fracturing?
Water contamination	From pad construction through abandonment, contaminated surface runoff and/or aquifer damage are possible
Management of fracking and flowback fluid storage and disposal	Fracturing additives cause concerns
Solid waste disposal	Cuttings from drilling require proper disposal
Nuisances (noise, trucking, light)	Actual drilling is noisy, and 24/7 operations require well-lit working areas; compressors running throughout the production phase may also create a noise problem
Atmospheric emissions/air quality	Throughout well life, dust from truck traffic and stray gasses from production operations; during drilling and fracturing, emissions from large diesel motors
Habitat destruction	Pad siting; roads and pipeline rights-of-way
Induced seismicity	Possible from fracturing operation, but primarily a problem associated with wastewater disposal during production

Source: Modified from C Rivard and others, 'An Overview of Canadian Shale Gas production and Environmental Concerns' (2014) 126 International Journal of Coal Geology 64.

Table 4. Major environmental concerns and concerning fracking activities relative to the shale and tight gas industry; fracking activities which raise environmental concerns

Primary activities	*Environmental concerns and comment*
Pad construction	Habitat destruction; modifications to natural drainage
Drilling	Noise, light, disposal of cuttings
Fracturing	Toxic additives: both handling and disposal; noise
Completion (except fracturing)	Proper disposal of tested hydrocarbons and drilling fluids; noise
Production	Noise; disposal of produced water; disposal of unsold gases
Pipelines	Habitat destruction; noise of pumps and compressors
Abandonment	Maintaining isolation of toxic sub-surface products from surface and near-surface environments

hydraulic fracturing is one) is less than 20 per cent that of water used for agriculture (irrigation plus livestock).[51] All of these factors mean that the water has a cost; because water is always produced along with oil and gas,[52] recycling of this produced water may be more economic than acquiring new water for

51 CA Dieter and others, 'Estimated Use of Water in the United States in 2015' (2018) 1441 US Geological Survey Circular 65.
52 Termed 'produced water' in the industry.

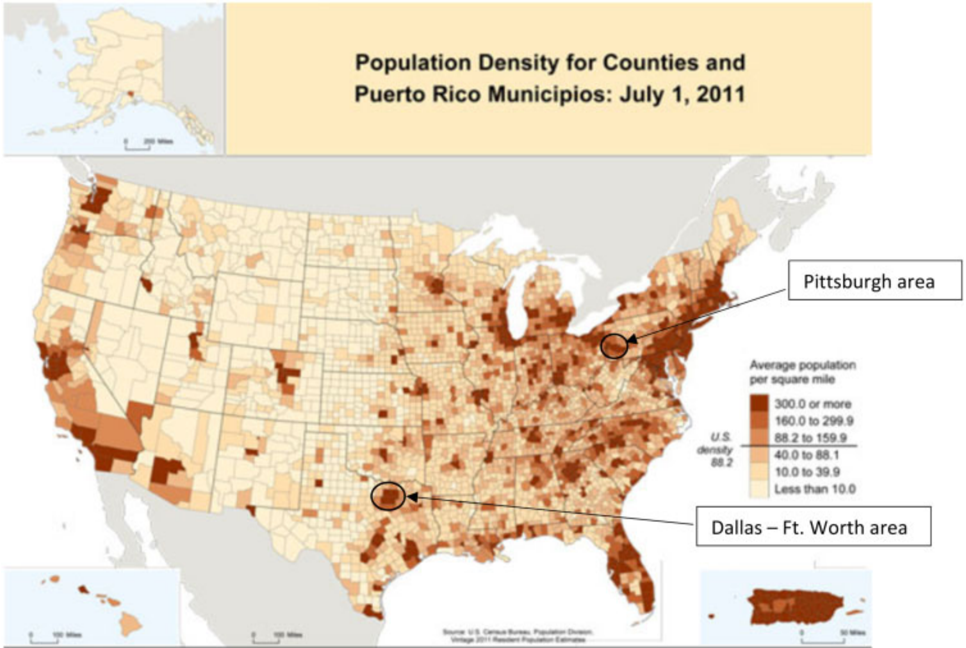

Figure 5. Population density of the USA highlighting areas of early fracking activity.

Source: Modified from US Census Bureau, 'Population Density by County' (2011) <https://www.census.gov/history/www/reference/maps/> accessed 18 June 2020.

operations.[53] Moving all this water around requires either many trips of large tanker trucks or pipelines. Either method can result in accidental spills.

Particularly as it was being introduced, the hydraulic fracturing technology was widely referred to as 'slick water' fracking, making it clear this was not the same as the water coming out of the tap at the kitchen sink. Operating companies have not been successful in allaying the perceptions of risk. The US Clean Water Act partially removes EPA jurisdiction for waters used in fracking; this 'Halliburton loophole', which exempts most chemicals in fracturing fluids from US Federal regulation under the Safe Water Drinking Act, is an illustration of how perception of risk can become more important than actual data-based determinations of risk.[54] In Texas, questions related to drinking water quality are normally under the purview of the Texas Commission on Environmental Quality, but if an oil or gas well is involved, the water quality issues are under the jurisdiction of the Texas Railroad Commission, which is the state's oil and gas regulator.[55]

A primary concern has been the safety of drinking water supplies. The World Health Organization publishes guidelines for drinking water[56]; in the USA, the Environmental Protection Agency sets legally enforce-

53 Walton (n 48).

54 R Sidortsov, 'Reinventing Rules for Environmental Risk Governance in the Energy Sector' (2014) 1 Energy Research & Social Science 171.

55 Meadows Center for Water and the Environment, *Water Policy in Texas: A Comprehensive Overview* (2015) 241 <https://gato-docs.its.txstate.edu/jcr:d175e07f-0d03-40bb-b151-4e90b536843a/Water_Policy_in_Texas_A_Comprehensive_Overview_2013.pdf> accessed 29 June 2020.

56 World Health Organization, *Guidelines for Drinking Water Quality*: *Incorporating the First Addendum* (4th edn, World Health Organization 2017) 631 <https://www.who.int/water_sanitation_health/publications/drinking-water-quality-guidelines-4-including-1st-addendum/en/> accessed 17 June 2020.

able limits for 90 possible contaminants[57] but some of the chemical additives and subsurface constituents may not have an assessment for a safe level.[58] While the EPA standards are legally enforceable in the USA, there are numerous legal issues surrounding enforcement because regulatory monitoring is done at the state level.

Many states incorporate reporting to the FracFocus database, mentioned earlier (<https://fracfocusdata.org/>), as part of their regulatory requirements. But on its own, this industry database has limitations from a regulatory viewpoint.[59] Shortly after FracFocus was set up, a study at the Harvard Law School[60] outlined a number of these problems. Some of the criticisms raised in the Harvard study have been addressed by FracFocus since 2013, but there remain problems. For example, the number of chemicals not identified because they are 'proprietary' has actually increased recently.[61] There is a danger that when states require companies to report the composition of fracturing fluids to FracFocus, states may feel that this is sufficient regulatory oversight, but an industry database can only support government regulation and enforcement—it cannot supplant government functions.[62] The substances added to drilling mud are not generally controversial, but those added to fracturing fluid are, despite being a small percentage of the total volume. The largest single additive to fracturing fluid is proppant—either sand or ceramics which will hold the fractures open after the pressure is released. These proppants are chemically benign. But the final additives, a mixture of organic and inorganic chemicals, while seldom more than 1% of the total fluid, are frequently toxic. And despite the low percentage, they still amount to thousands of gallons for each well. The specific chemicals used will depend on the chemistry of the rock being fractured; as noted above, chemicals are added to reduce friction in the water itself,[63] as well as chemicals to prevent algal and bacterial growth in the well and inhibit corrosion.[64]

The hazardous chemicals have several routes by which they may enter the environment. There can be accidents in which concentrated chemicals are released directly prior to being mixed and diluted for final use. When the well is fracked, the mixture containing chemicals is pumped into the well under very high pressure. As discussed above, where contamination has been observed it is almost always the result of some problem with the well construction. A significant problem is that there have been water pollution problems in the USA for centuries, and when contaminants are found in analysis, it can be difficult to determine whether fracturing fluids are the specific cause.[65] Today, many operators, if only to protect themselves against potential legal actions, routinely test all water sources prior to drilling in an area.

Initial concerns were that the pressure of fracturing would force some of the fracturing fluid up through the rock column and into aquifers. But the most likely aquifer contamination problems come in the other direction; they arise from surface contamination, followed by 'well integrity' problems, usually a problem with the cement. Spills at the surface of either additive to the fracturing fluids or from flowback and/or produced

57 US Environmental Protection Agency, 'National Primary Drinking Water Regulations, Overviews and Factsheets' (2015) <https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations> accessed 17 June 2020 referencing 40 CFR 141.

58 US Environmental Protection Agency (n 17) 41.

59 Maule and others (n 22).

60 Environmental Law Program, Harvard Law School, *Legal Fractures in Chemical Disclosure Laws* (2013) 16 <http://eelp.law.harvard.edu/wp-content/uploads/legal-fractures-voluntary-chemical-disclosure-regsitry-fails-regulatory-compliance-tool.pdf> accessed 17 June 2020. Some of the problems described in the report have since been at least partially resolved; for example, it is now possible for researchers to download the database in order to do regional studies.

61 KN Trickey and others, 'Public Reporting of Hydraulic Fracturing Chemicals in the USA, 2011-2018' (2020) 4 The Lancet Planetary Health e178-3185.

62 ibid; CT Holley and others, 'Shaping Unconvention Gas Regulation' (2019) 36(5) Environmental and Planning Law Journal 510.

63 Hence 'slick water frack' as the initial description of the fracking technology was frequently termed.

64 JN Meegoda and others, 'Can Fracking Be Environmental Acceptable?' (2017) 21(2) Journal of Hazardous, Toxic, and Radioactive Waste 04016013-1 to 04016013-11. This article lists as common constituents of fracturing fluid: Hydrochloric acid, glutaraldehyde, ammonium persulfate, tetramethyl ammonium chloride, acetaldehyde, potassium metaborate, petroleum distillate, ethylene glycol, thioglycolic acid, lauryl sulfate, sodium hydroxide, copolymer of acrylamide and sodium acrylate and 2-butoxyethanol.

65 HAB Lambert, 'Whose Water Is It?' (2016) 75(3) The American Journal of Economics and Sociology 681.

waters constitute the bulk of aquifer contamination. Unless tightly contained, such spills can seep down into aquifers and disperse over significant areas.[66] But the populations in areas of fracking are frequently dependent on relatively shallow aquifers for domestic water.[67] If an aquifer becomes contaminated, it is extremely difficult to de-contaminate it.[68] These concerns were exacerbated by a faulty cement job in an early Marcellus well near Dimock, PA, which the film *Gasland* used as evidence of generic problems.[69]

The critical book *Amity and Prosperity*[70] documents other problems with chemical contaminants in fracturing fluids. One of these is that when a company is sued, the resolution is frequently an out-of-court settlement that includes non-disclosure clauses, preventing important data from public scrutiny. *Amity and Prosperity* documents the many difficulties in unambiguously tracing contaminants. These include background levels which may be high due to either natural or non-fracking causes.[71] In a specific instance from *Amity and Prosperity* book, contaminants may have been transferred from water to the atmosphere when aeration was routinely used to prevent algae growth in holding ponds, thus contaminating the air in the vicinity with a toxic mist.[72] Changing the problem from water pollution to air pollution complicates jurisdiction and regulatory issues.

The result of these concerns has been numerous, rigorous studies of water quality in areas of fracking.[73] Critical to interpreting the results of analyses with respect to fracking is having comparable analyses from the time prior to fracking operations. Initial complaints frequently did not have such comparative analyses; more recently, it has become standard practice in most areas to do pre- and post-water quality analyses to determine whether fracking is the cause of water quality problems.

Disposal

A major water quality issue in fracking is what to do with the water that returns to the surface. Initially, this will be flowback of the water used in fracturing, containing many of the chemical additives used. Compounding environmental issues is that additives to the fracturing fluid may react with the subsurface strata, thus changing its chemical composition.[74] Inorganic constituents of the fracturing fluid may react with clay minerals causing the characterization of the dissolved salts to change. As hydrocarbons are produced, the composition of the water coming from the well changes to that of the water that is virtually always present at depth. Whether in flowback water or produced water, some of the chemicals are harmful to health.

Proper treatment of this flowback and/or produced water (FPW) is critical. Removing dissolved constituents from water is always difficult (as every cook who has over-salted a dish knows), although the cost of doing so may be offset if the water can be re-used for further fracturing or irrigation.[75] Although no longer permitted, operators in Pennsylvania used to send FPW to municipal wastewater treatment plants; now they

66 This is not unique to spills from fracking; there are many large and very many small groundwater contaminations going back for more than a century due to leakage down from the surface.

67 J Grönwall and K Danert, 'Regarding Groundwater and Drinking Water Access Through a Human Rights Lens: Self-Supply as a Norm' (2020) 12(2) Water 419.

68 JA MacDonald and MC Kavanaugh, 'Restoring Contaminated Groundwater' (1994) 28(8) Environmental Science & Technology 362a.

69 As cited in n 12, there was an initial finding of a faulty cement job with the operator initially being ordered to provide imported potable water, and eventually deciding to purchase the properties worst affected. The final judicial determinations were inconclusive see MC Carlson (Magistrate Judge) (2017) *Ely et al v Cabot Oil & Gas et al*, Civil No 3:09-CV-2284 <http://media.philly.com/documents/Memorandum-Opinion0331.pdf> accessed 9 April 2020.

70 E Griswold, *Amity and Prosperity* (Farrar, Straus and Giroux 2018) 336. This well-written book was awarded the 2019 Pulitzer prize for General Non-Fiction.

71 JT Engelder, *Frackademic in Appalachia*, preprint of ch 44—Arsenic (2020).

72 Griswold (n 68) 80.

73 See Prof A Vengosh's research group at Duke University (A Vengosh and many others, 'Duke Study on Shale Gas and Fracking and Impact on Water Resources' (*Avner Vengosh Research Group*, 2020) <https://sites.nicholas.duke.edu/avnervengosh/duke-study-on-shale-gas-and-fracking/> accessed 30 June 2020) and the Concerned Health Professionals of NY of n 4.

74 GA Kahrilas and others, 'Biocides in Hydraulic Fracturing Fluids' (2015) 49(1) Environmental Science & Technology 16.

75 Walton (n 48).

must use industrial wastewater treatment plants which can better handle these waters.[76] Reuse of water is frequently cost-effective. As a result, operators now reuse this water when possible in new wells they are drilling in the area.[77] The other option is to use waste disposal wells to bury the waters at great depth. Use of waste disposal wells is discussed below in conjunction with seismic activity.

Treatment of FPW has significantly improved as fracking has become a widespread activity. Nevertheless, environmental monitoring of treated effluents has shown the presence of amounts of non-natural water constituents. Some of these may be toxic, others radiogenic, and some may be problematic simply because they are not natural. An example of the benign but non-natural constituents are dissolved bromine salts because they react with a standard treatment used for municipal water supplies downstream to create toxic chemicals in the treated water[78]; this can force downstream communities to switch to more expensive treatment methods.

The Marcellus play in particular is noted for having high concentrations of radioactive salts in its FPW. In treated effluent, dissolved radium may be well below a danger threshold, but because the dissolved radium will tend to sorb onto clay minerals in the stream bed, the stream bed may become a low-level hazardous waste.[79] Another natural process that can concentrate the low levels of dissolved toxic material in wastewater is organic metabolism. Organisms can become toxic simply because they live in low-level toxicity. The classic example is swordfish, which have become contaminated with mercury[80]; a recent study has shown that fish living in streams of treated FPW have abnormalities.[81]

During production, FPW is separated from the commercially valuable hydrocarbons. But some hydrocarbons always remain dissolved in the water. Depending on the hydrocarbon chemistry of the geologic formation being exploited, these dissolved hydrocarbons may be more or less problematic. Most studies have shown the majority of the dissolved hydrocarbons in FPW are saturated, which carry lower health risks than aromatic hydrocarbons.[82]

While waiting to be reused or transported for disposal, FPW will be stored either in tanks or open pits. Either way, unless it is used on the same pad, it will need to be transported. If the transport is to a nearby pad, this may be done by temporary, above-ground pipeline. Otherwise tanker trucks will be used. Either way, there is a chance of spills, either from the storage tanks or during transport. A North Dakota spill was of 3 million gallons (ca 11,000 m^3). The news report stated that 'this flowed into the Missouri River, where it was quickly diluted to well below harmful levels'.[83]

When storage is in open pits, they are lined with heavy-duty plastic to prevent any seepage into groundwater. An obvious concern is that the plastic lining may develop a leak either through tears or normal wear. The water in an open pit must be kept free of algae in order to make it re-useable. One common method is to use sprinklers to aerate the water.

76 J Hurdle, 'EPA Bans Disposal of Fracking Waste Water at Public Treatment Plants' (2016) <https://stateimpact.npr.org/pennsylvania/2016/06/14/epa-bans-disposal-of-fracking-waste-water-at-public-treatment-plants/> accessed 10 June 2020.

77 The nature of fracking is that wells have a rapid decline in hydrocarbons produced, so additional wells are frequently being drilled.

78 KM Parker and others, 'Enhanced Formation of Disinfection Byproducts in Shale Gas Wastewater-Impacted Drinking Water Supplies' (2014) 48(19) Environmental Science & Technology 11161; NR Warner and others, ' Impacts of Shale Gas Wastewater Disposal on Water Quality in Western Pennsylvania' (2013) 47(20) Environmental Science & Technology 11849.

79 ibid.

80 S Torres-Escribano and others, 'Mercury and Methylmercury Bioaccessibility in Swordfish, Part A' (2010) 27(3) Food Additives & Contaminants 327.

81 DM Papoulias and AL Velasco, 'Histopathological Analysis of Fish from Acorn Fork Creek, Kentucky, Exposed to Hydraulic Fracturing Fluid Releasess' (2013) 12(sp4) Southeastern Naturalist 92.

82 SJ Maguire-Boyle and AR Barron, 'Organic Compounds in Produced Waters from Shale Gas Wells' (2014) 16(10) Environmental Science: Processes & Impacts 2237. This is unlike dissolved hydrocarbons from coal bed methane, which tend to be rich in cancer-inducing aromatic hydrocarbons.

83 CH Arnaud, 'Figuring Out Fracking Wastewater' (2015) 93(11) Chemical and Engineering News 8.

Cement

Cement is used during the construction of a well to isolate the final wellbore from the surrounding rock. This isolates the hydrocarbons flowing to the surface from the surrounding rock layers. As illustrated in Figure 2, this may be done in multiple stages. Well integrity is defined as preventing any uncontrolled release of fluids during the life of the well.[84] As petroleum engineer Claude E Cooke, Jr has commented 'if there is a problem, the issue is well integrity', going on to explain that the most likely cause is faulty cement.[85]

Cement is a complex substance, and books have been written on its use in oil wells.[86] Two aspects of cement are critical with respect to wells: it shrinks slightly as it sets and the setting reaction is exothermic. The slight shrinking can result in microscopic cracks between the cement and the casing, between the cement and the surrounding rock, or within the cement itself. The temperature changes as the cement sets can be another cause of microscopic cracks forming, either due to thermal expansion and contraction, or because the adjacent casing will expand and contract differently. Finally, the chemical reaction when cement sets is never really complete and can continue so long as there are water molecules available.[87] Gas is more likely to seep through the resulting microcracks than liquids, but any fluid flow has the possibility to degrade the cement. The greatest concern with such microscopic flows is that the fluid, especially gases, from the hydrocarbon horizon will reach the surface outside of the equipment designed to process and control them.[88] Other concerns are that fluids may not reach the surface, but instead contaminate aquifers used for drinking water.[89] Bad cement can also provide a channel for gas or liquid to migrate from one intermediate stratum to another.[90] Figure 6 illustrates this problem. The long lateral well segments typical of fracked wells mean that when cement is used around these sections, gravity may cause the fluid cement to distribute unevenly. This can result in a weak zone along the top of the anulus.[91]

Cement also is critical when a well is abandoned. What is usually done is to fill at least both the bottom and topmost portions of the well with cement. But as mentioned above, the chemical reaction for cement is never totally complete. Although in the abandonment process, the cement is presumed to last eons, if not forever, there will always be some risk that the abandoned well provides a vertical pathway through the rock strata. Thus, abandoned wells continue to present at least some risk to the environment.[92]

Air

During the drilling process, the well pad is a major industrial site.[93] The largest environmental issue during this stage of operations is exhaust from the large diesel engines used to power the drilling and fracturing activities.[94] Dust can also be a problem. At the well pad, any dry chemical, including cement and proppant, can pose problems as they are mixed into mud or fracturing fluids.[95] More often, dust is a problem along roads

84 Standards Norway, *D-010 Well Integrity in Drilling and Well Operations* (Rev 4, *Standards Norway*, June 2013) Standard D-010, 224.

85 Quoted in Gold (n 3) 271.

86 Amongst many, see A Lavrov and M Torsaeter, *Physics and Mechanics of Well Cementing* (Springer International Publishing 2016) 111 or EB Nelson (ed), *Well Cementing* (Elsevier 1990) Developments in Petroleum Science No 28, 1515.

87 JA Lewis, 'Concrete: Scientific Principles' (1992) <http://matse1.matse.illinois.edu/concrete/prin.html> accessed 8 April 2020.

88 GE King and DE King, 'Environmental Risk Arising from Well-Construction Failure' (2013) 28 SPE Production & Operations 323.

89 ibid.

90 US Environmental Protection Agency (n 17) 26 <https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=530285&Lab=NCEA> accessed 3 July 2020.

91 HJ Skadsem and others, 'Annular Displacement in Highly Inclined Irregular Wellbore: Experimental and Three-dimensional Numerical Simulations' (2019) 172 Journal of Petroleum Science and Engineering 998.

92 Rabia (n 7).

93 WB Allshouse and others, 'Community Noise and Air Pollution Exposure During the Development of a Multi-Well Oil and Gas Pad' (2019) 53(12) Environmental Science & Technology 7126.

94 K Vafi and A Brandt, 'GHGfrack: An Open-Source Model for Estimating Greenhouse Gas Emissions from Combustion of Fuel during Drilling and Hydraulic Fracturing' (2016) 50(14) Environmental Science & Technology 7913.

95 EJ Esswein and others, 'Occupational Exposures to Respirable Crystalline Silica During Hydraulic Fracturing' (2013) 10(7) Journal of Occupational and Environmental Hygiene 347.

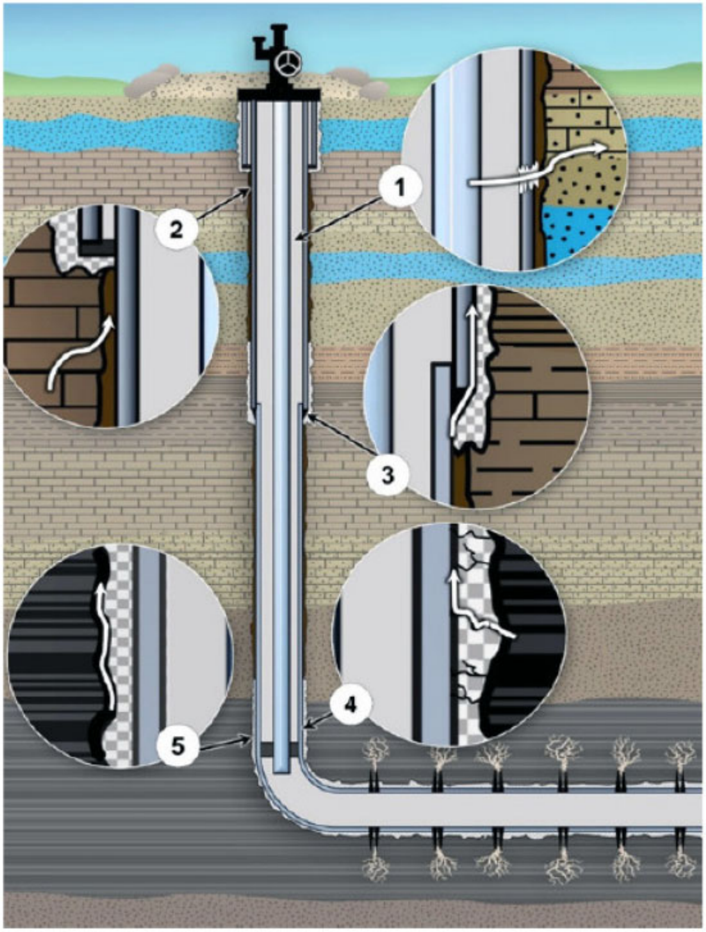

Figure 6. Possible contamination paths from well integrity (primarily cement) problems.

Note: Escape from the well environment can be into any overlying stratum, including shallow drinking-water aquifers.

Sources: US Environmental Protection Agency (n 17) 26 <https://cfpub.epa.gov/si/si_public_file_download.cfm? p_download_id=530285&Lab=NCEA> accessed 3 July 2020.

due to the increased traffic needed to support drilling operations than at the actual well pad.[96] Other air pollution problems include aromatic hydrocarbons used as additives in the fracturing process, with at least some evaporation occurring during transfers from tankers to storage tanks and during mixing with the fracturing fluid. Aromatic hydrocarbons are frequently carcinogenic.[97] Evaporation can also occur from flowback fracturing fluid.[98]

96 K Graber and others, 'Is Oil-well Produced Water Effective in Abating Road Dust?' (2017) 228(11) Water, Air & Soil Pollution 449.

97 Hydrocarbons are divided into two major categories: aliphatic and aromatic. Natural gas (entirely) and crude oil (primarily) consist of aliphatic hydrocarbons; solvents and many manufactured organic chemicals are aromatic. PN Boffetta and others , 'Cancer Risk from Occupational and Environmental Exposure to Polycyclic Aromatic Hydrocargons' (1997) 8(3) Cancer Causes & Control 444.

98 LM McKenzie and others, 'Ambient Nonmethane Hydrocarbon Levels along Colorado's Northern Front Range' (2018) 52(8) Environmental Science & Technology 4514.

Once a fracked well is in production, the mixture of volatile hydrocarbons will need to be separated from fluids and either sold separately or discarded. When the economic justification for a well is oil, then all the gases are extra. Traditionally they have been flared; this reduces the risk of pollution by various hydrocarbon constituents while increasing CO_2 emissions. Natural gas flaring can be avoided by selling the gas as an additional hydrocarbon product, by using it in oil extraction operations, or disposing of it through injection into non-productive geologic strata. But selling the gas requires a pipeline, which may not be available in the area; unlike oil, gases are difficult to transport by tanker.

One of the issues in oil-producing plays is that the economics of the well demand that it produces and sell the liquids it produces as quickly as possible. All of the operators in the Bakken and Permian Basin, which are two of the largest oil-producing frack plays, would like to also sell gas, but they cannot due to lack of pipeline capacity; delaying production until pipelines are available threatens the economic viability of the well. After a delay and some public outcry, North Dakota (the bulk of the Bakken play) has introduced more stringent regulation for flaring.[99] Texas and New Mexico (the Permian basin play) are rushing to build needed gas pipelines.[100]

Flaring is not a perfect solution for disposing of unwanted gas. The bulk of the flared gas is methane, which can be explosive when the concentration in air is correct.[101] But released unburnt, the methane is quickly diluted by air to being only a trace constituent, so flaring for safety is required only near the source of release. Another safety reason for flaring is that hydrogen sulfide (H_2S) is frequently found in both oil and gas accumulations, and this gas is extremely toxic. H_2S safety is a concern in all petroleum operations, and flaring is often required to control it.[102]

The products of any flaring operation are complex, with many of them being toxic, corrosive or both.[103] Notable is some incompletely oxidized carbon, resulting in CO rather than CO_2. Any H_2S burns to create H_2O (water) plus SO_2 (sulphur dioxide, a gas), which together are sulfuric acid. The burning reactions can also produce various nitrogen compounds, NO_x, which cause smog and have other problematic issues.

The fracking boom has been responsible for a significant decrease in the USA's CO_2 emissions. This is due to a switch from coal to natural gas in many applications, notably electricity generation. Burning natural gas releases more energy per unit of CO_2 emitted than burning coal.[104] The basic reason is that coal is essentially pure carbon, so the chemical energy is obtained by combining the carbon with atmospheric oxygen; when natural gas (close to pure methane) burns, the energy comes not only from carbon but also from hydrogen.

Methane

While using methane as a fuel has CO_2 emission benefits, methane itself, i.e., unburned, is a much more potent greenhouse gas than is CO_2.[105] For the fracking plays that are exploiting gas, there are concerns that much of the benefit of switching from coal to natural gas is offset by methane leakage throughout the path

99 MU Ehrman, 'Lights Out in the Bakken' (2014) 117 West Virginia Law Review 549.

100 B Dix and others, 'Nitrogen Oxide Emissions from U.S. Oil and Gas Production: Recent Trends and Source Attribution' (2019) 47 Geophysical Research Letters 10, doi:10.1029/2019gl085866.

101 T Engelder and JF Zevenbergen, 'Analysis of a Gas Explosion in Dimock PA (USA) During Fracking Operations in the Marcellus Gas Shale' (2018) 117 Process Safety and Environmental Protection 61.

102 L Skrtic, 'Hydrogen Sulfide, Oil and Gas, and People's Health' (Energy and Resources Group, University of California, Berkeley 2006) <https://fwcando.org/sites/default/files/lanamasters.pdf> accessed 4 July 2020.

103 OS Ismail and GE Umukoro, 'Modelling Combustion Reactions for Gas Flaring and Its Resulting Emissions' (2016) 28(2) Journal of King Saud University - Engineering Sciences 130.

104 US Energy Information Agency, 'How Much Carbon Dioxide Is Produced per Kilowatt Hour of US Electricity Generation' <https://www.eia.gov/tools/faqs/faq.php> accessed 4 July 2020; RW Howarth and others, 'Should Fracking Stop?' (2011) 477 Nature 271.

105 G Yvon-Durocher and others, 'Methane Fluxes Show Consistent Temperature Dependence across Microbial to Ecosystem Scales' (2014) 507 Nature 488.

Table 5. Heavy truck trips per well

Well stage	*No. of truck trips*
Pad preparation	45
Drilling	235
Fracking	258–698
Completion	70
Production	45 to hundreds
Abandonment	(Not estimated)

Source: Summarized from Abramzon and others 'Estimating the Consumptinve Use Costs of Shale Natural Gas Extraction on Pennsylvania Roadways', (2014) 20(3) Journal of Infrastructure Systems 11.

from producing well to final user.[106] Some of these leaks date back to infrastructure originally put in place for 'town gas' more than a century ago,[107] but some can be directly attributed to natural gas production from fracking plays.

Atmospheric methane concentrations have been increasing recently with the result that its sources have been the subject of recent research.[108] The increases in atmospheric methane data can be traced to increased oil and gas production over the past decades, despite the fact that methane released per unit of production has decreased.[109]

Traffic

One of the major environmental issues during well pad construction and continuing through the drilling and fracturing operations is the amount of heavy truck traffic required to support the operations. As illustrated in Figure 2, secondary and specially constructed roads are often used; frequently these are unpaved. Even when load and speed limits are strictly observed, the amount of traffic and weight of trucks may require frequent maintenance of roads across the area of a play compared to pre-fracking maintenance schedules.

Table 5, drawing on data from an environmental impact statement, gives the estimated number of heavy truck trips needed to support a single well. In 2012, the deputy director of the Texas Department of Transportation was quoted 'We need $2 billion, and the shortfall is $2 billiion'[110] when discussing the road maintenance needed to support fracking. Several factors compound the problem of road maintenance. When an operating company makes a road improvement, the costs are capital expenses which can be financed against projected revenue, whereas for governments these are maintenance costs which must be currently financed. In addition to a timing mismatch, there is frequently a jurisdictional mismatch between the jurisdiction responsible for the costs and the jurisdiction that, eventually, may collect tax revenue. 'Road Use and Maintenance' agreements may help, but seldom cover all of the costs involved.[111]

Road use is an issue during pad construction, but as Table 1 shows, the major road use issues are during drilling and fracturing. In addition to road maintenance, environmental issues of noise and air pollution from exhaust and dust arise along all the roads used from wellhead to final destinations. Dust can be a major issue

106 RW Howarth and others, 'Methane and the Greenhouse-Gas Footprint of Natural Gas from Shale Formations' (2011) 106(4) Climatic Change 679.

107 JC von Fischer and others, 'Rapid, Vehicle-Based Identification of Location and Magnitude of Urban Natural Gas Pipeline Leaks' (2017) 51(7) Environmental Science & Technology 4091.

108 EG Nisbet and others, 'Rising Atmospheric Methane' (2016) 30(9) Global Biogeochemical Cycles 1356.

109 S Schwietzke and others, 'Upward Revision of Global Fossil Fuel Methane Emissions Based on Isotope Database' (2016) 538(7623) Nature 88.

110 B Shlachter, *Ft. Worth Star-Telegram*, 3 July 2012.

111 S Abramzon and others, 'Estimating the Consumptive Use Costs of Shale Natural Gas Extraction on Pennsylvania Roadways' (2014) 20(3) Journal of Infrastructure Systems 11.

on unpaved roads . On all road surfaces, traffic creates fine particle pollution, with microscopic tire wear and exhaust soot being major components.[112] Furthermore, cars and trucks create noise. There is the noise of the engine plus the noise created by the tires on the road surface.[113] And because drilling and fracking is a round-the-clock operation seven days per week, whatever traffic noise there is will be unceasing. This has led to particular problems where a quiet home has been purchased for retirement on a small country road that suddenly becomes a busy highway.[114]

Land use

The fracturing process enhances permeability next to the wellbore. But unlike exploitation of conventional, more permeable accumulations, fracking plays require a very large number of wells to collect the hydrocarbons stored in the rocks. Figure 4 shows the density of wells in North Dakota. Although drilling clusters of wells from a single pad reduces the land surface footprint, the number of wells required still means that pads in a play will dot the landscape.

In addition to the pads, access is needed for each pad, including roads, utilities and eventually pipelines. For the environment, roads and pipelines are a major break in habitat. For example, some species of woodland birds are not found within 300 feet of the woodland edge; while a road or pipeline right-of-way may use very little of the land surface, say 5 per cent, they may destroy an ecology by creating paths, and therefore edges, within large tracts of woodland.[115] Similar issues can impact wetlands.

Fragmentation of rights

Specific to the situation in the USA, private ownership of mineral rights makes the siting of pads more difficult. The fact that surface ownership and mineral rights can be severed compounds these difficulties. Operators spend many hours researching ownership, sometimes having to trace intestate ownership through several generations, which can be costly. Furthermore, the mineral rights carry, with some restrictions, the right to access the subsurface; this may give rise to additional issues.[116]

Social changes

The economic activity of developing a play with fracking can lead to social changes. Some of these can be for the better. As one local landowner observed "ten years ago it was obviously an impoverished county; today the houses are painted".[117] Operating companies have funded improvements to local hospitals,[118] and other local projects.

But the economic benefits have come with 'boom town' problems. Formerly, one could transit Towanda, PA, having to wait at most for one cycle of the traffic light; now the wait to get through the intersection can take 45 minutes.[119] More significantly, the uneven distribution of these benefits can lead to animosities. Neighbors no longer speak to neighbors; families can be torn apart.[120]

112 A Wik and G Dave, 'Occurrence and Effects of Tire Wear Particles in the Environment' (2009) 157(1) Environmental Pollution 1.

113 Y Wei and others, 'Analysis of Coast-by Noise of Heavy Truck Tires' (2016) 3(2) Journal of Traffic and Transportation Engineering [English edition] 172.

114 JT Engelder, 'The Environmental Realities of Hydraulic Fracturing (Fracking): Fact vs. Fiction' AAPG Distinguished Lecture, Univ. de Genève, 16 October 2013.

115 LM Porensky and TP Young, 'Edge-Effect Interactions in Fragmented and Patchy Landscapes' (2013) 27(3) Conservation Biology 509.

116 For example, see *EQT Prod. Co. v Crowder*, 241 W Va 738. See write-up at <https://www.propublica.org/article/when-fracking-companies-own-the-gas-beneath-your-land> accessed 15 July 2019.

117 P Flaherty, Personal communication (2015).

118 R Hiduk, 'Looking Back, Moving Forward' (2018) <https://wellsaidcabot.com/looking-back-moving-forward-loren-stone/> accessed 4 July 2020.

119 A resident's personal communication.

120 S McGraw, *The End of Country* (Random House 2011) 256 (about fracking in NE Pennsylvania); see also U Sinclair, *Oil!* (Penguin Books 1926) 506 (about oil development in southern California).

In particular, those who benefit from fracking operations: workers, the support economy, operators, mineral rights holders, will tend to be supportive; those who bear the costs: local property owners (through higher taxes), and users of public health facilities and other common facilities such as parks and a clean environment will skew towards opposition. And as noted specifically for roads, the tax structure is not designed to channel any monetary benefit of fracking to the government sectors and entities which are directly impacted.[121]

Health effects

An area of great concern is the health impact of fracking. A number of studies have directly addressed this issue.[122] One study has detailed the changes in health parameters before and after fracking activity in an area.[123] Another study has shown that there are adverse effects of fracking in direct proportion to the distance from the pad.[124] This peer-reviewed article has valid statistics but is not able to specify a cause. It could be noise pollution, air pollution, or possibly that increased royalties resulted in more economic ability to address medical issues. While difficult to assess, the noise of a drill pad may cause health problems.[125]

Economic interests

All extractive industries are subject to a boom and bust cycle. The earth is finite, and extraction has limits, almost by definition. The economic benefits and problems accrue at different time scales, and frequently in different locations.

The land itself is changed by the extraction. Whether it is simply changing the topography slightly to construct a pad or a right-of-way cut through a forest, the changes to the land will be long-lasting. Abandoned wells are for fracking what abandoned open-pit mines are to mining—changes to the landscape that will only be fully erased in eons to come.

On the positive side, the global economy requires energy. As many have pointed out, GDP is directly correlated with energy 'consumption'.[126] At present, over 80 per cent of global energy comes from fossil fuels: 27 per cent coal, 33 per cent oil; 24 per cent natural gas.[127] This means that 57 per cent of the global economy is dependent on supplies of natural gas and oil.

Fracking is expensive and has never been profitable across all operators.[128] At present, several non-fossil-fuel energy sources are competitive for new supplies on a cost basis.[129] But two things make rapid change difficult. First, the economic system, particularly transportation, is designed around fossil fuels. Changing requires capital investment in different equipment, which may either require some write-off of existing

121 A Samuels, 'Texas Is Making Billions from Oil and Gas Drillling', but counties say rural roads are being destroyed, Austin, TX, *The Texas Tribune* (online) <https://www.texastribune.org/2018/04/12/texas-oil-gas-drilling-rural-roads-damages/> accessed 5 July 2020.

122 J Hays and SBC Shonkoff, 'Toward an Understanding of the Environmental and Public Health Impacts of Unconventional Natural Gas Development' (2016) 11(4) PLOS One e0154164; JK Hirsch and others, 'Psychosocial Impact of Fracking' (2018) 16(1) International Journal of Mental Health and Addiction 1.

123 B Jacobson, 'Epigenetic and Phenotypic Effects of Fracking Exposure in Children from the Fragile Families and Child Wellbeing Study' (2019) <http://dataspace.princeton.edu/jspui/handle/88435/dsp012n49t451m> accessed 5 June 2020.

124 J Currie and others, 'Hydraulic Fracturing and Infant Health' (2017) 3(12) Science Advances e1603021.

125 J Hayes and others, 'Public Health Implications of Environmental Noise Associated with Unconventional Oil and Gas Development' (2017) 580 Science of the Total Environment 448.

126 We may have learned in secondary school the 'energy is neither created nor destroyed'. This is true; but 'consumed' feels the correct word—gasoline does not unburn, so we have to keep filling up our tank. The reason is that energy goes from a concentrated to a diffused state; energy from gasoline to dissipated heat. See S Carmalt, *The Economics of Oil* (Springer 2017) 105.

127 BP, 'Statistical Review of World Energy' (2020) <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf> accessed 19 June 2020.

128 MM Foss, 'U.S. Shale Goes Viral' (*Forbes*, 2020) <https://www.forbes.com/sites/thebakersinstitute/2020/03/19/us-shale-goes-viral/#2465f7e3165a> accessed 8 June 2020.

129 RW Bentley and others, 'The Resource-Limited Plateau in Global Conventional Oil Production' (2020) 5(2) Biophysical Economics and Responsibilitiy, doi: 10.1007/s41247-020-00076-1.

Table 6. Depths to major shale oil and shale gas plays in the USA

Shale play	*US state(s)*	*Geologic age*	*Depths (m)*	*Reserves*	*O/G*
Bakken	Montana, North Dakota	Devonian/ Carboniferous	1000–3750	2 Bbbls + 3.5 TCF	Oil + Gas
Barnett	Texas	Mississippian	600–1800	7 TCF	Gas
Eagle Ford	Texas	Cretaceous	600–4250	0.5 Bbbls + 6 TCF	Oil + Gas
Fayetteville	Arkansas	Carboniferous	450–2000	1 TCF	Gas
Haynesville-Bossier	Texas, Louisiana	Jurassic	3200–4000	15 TCF	Gas
Marcellus	Maryland, New York, Ohio, Pennsylvania, Virginia, West Virginia	Devonian	900–1800	>70 TCF	Gas
Permian Basin	Texas, New Mexico	Permian	900–3600	7 Bbbls + ca 40 TCF	Oil
Utica	Maryland, New York, Ohio, Pennsylvania, West Virginia	Ordovician	1500–3650	6 TCF	Gas
Woodford	Oklahoma	Devonian/ Carboniferous	1500– 6000	12 TCF	Gas

Sources: 1) J Laharrère 'Forecasts for US oil and gas production' (2018) a paper prepared for presentation at the American Chemical Society general meeting in New Orleans, LA on 2018-03-21; (2) Multiple publications of the US Geological Survey (if a location is needed it is Reston, Va., USA): a) Timothy C Hester and others, 'Log-Derived Regional Source-Rock Characteristics of the Woodford Shale, Anadarko Basin, Oklahoma' (1990) US Geological Survey Bulletin 1866-D. b) [from the USGS suggested citation] U.S. Geological Survey Williston Basin Province Assessment Team 'Assessment of undiscovered oil and gas resources of the Williston Basin Province of North Dakota, Montana, and South Dakota' (2011), (2010 (ver. 1.1, November 2013)) U.S. Geological Survey Digital Data Series 69–W, 7 chaps., 1 CD-ROM, https://pubs.usgs.gov/dds/dds-069/dds-069-w/ (accessed 2018-05-09). c) [from the USGS suggested citation] R F Dubiel and others 'Assessment of Unidiscovered Oil and Gas Resources in Convential and Continuous Petroleum Systems in the Upper Cretaceous Eagle Ford Group, U.S. Gulf Coast Region, 2011' (2012) U.S. Geological Survey Fact Sheet 2012–3003, 2p., https://pubs.usgs.gov/fs/2012/3003/FS12-3003.pdf (accessed 2018-08-02). d) Barnett Shale Assessment Team 'Assessment of Undiscovered Shale Gas and Shale Oil Resources in the Mississippian Barnett Shale, Bend Arch-Vort Worth Basin Province, North-Central Texas' (2015) U.S. Geological Survey Fact Sheet 2015-3078 2p., https://pubs.usgs.gov/fs/2015/3078/fs20153078.pdf (accessed 2018-02-23). e) S T Paxton and others 'Assessment of Undiscovered Oil and Gas Resources in the Haynesville Formation, U.S. Gulf Coast, 2016' (2017) U.S. Geological Survey Fact Sheet2017-3016 2p., http://pubs.er.usgs.gov/publication/fs20173016 (accessed 2018-03-15). f) K Robinson 'Petroleum Geology and Hydrocarbon Plays of the Permian Basin Petroleum Province, West Texas and Southeast New Mexico' (1988) U.S. Geological Survey Open File Report 88-450Z, 56p., https://pubs.usgs.gov/of/1988/0450z/report.pdf (accessed 2018-03-23). (3) Multiple publications and information documents from the US Energy Information Agency (if a location is needed, it is Washington, D.C., USA). a) Olga Popova and others 'EIA produces new maps of the Utica Shale play' (2016) U.S. Energy Information Agency, https://www.eia.gov/todayinenergy/detail.php?id=26052# (accessed 2018-03-21). b) Olga Popova 'Marcellus Shale Play: Geology review' (2017) U.S. Energy Information Agency, https://www.eia.gov/maps/pdf/MarcellusPlayUpdate_Jan2017.pdf (accessed 2018-03-21). c) U.S. Department of Energy 'Shale Gas Glossary' (2013) U.S. Dept. of Energy, Washington, D.C., USA, https://energy.gov/sites/prod/files/2013/04/f0/shale_gas_glossary.pdf (accessed 2018-02-09). d) Peggy Wells 'Assumptions to the Annual Energy Outlook 2015' (2015) U.S. Energy Information Agency, 233p., https://www.eia.gov/outlooks/aeo/assumptions/pdf/0554(2015).pdf (accessed 2016-07-15). (4) Richard M Pollastro and others 'Geologic framework of the Mississippian Barnett Shale, Barnett-Paleozoic total petroleum system, Bend arch-Fort Worth Basin, Texas' (2007) 91(4) AAPG Bulletin pp 405-436, http://archives.datapages.com/data/bulletns/2007/04apr/BLTN06008/BLTN06008.HTM (accessed2018-02-23).

(un-depreciated) equipment or incompatibilities with respect to operations; this is an inertia which works against change. Secondly, the remaining reserves of conventional oil in Russia and the Arabian/Persian Gulf are not well known, but for a number of years can, on a technical basis, continue to undercut supplies produced by fracking.[130] Because these resources can be provided at a lower cost, they undercut the expansion of fracking to supply hydrocarbon energy.

130 M Auzanneau, 'The EU Can Expect to Suffer Oil Depletion by 2030' (2020) Paris, The Shift Project, 66 <https://theshiftproject.org/en/article/eu-oil-depletion-2030-study/> accessed 26 June 2020.

4. CONCLUSIONS

A single well is unlikely to cause problems

A single fracked well, or even a cluster of wells on a single pad, is unlikely to be a major environmental problem. There is some surface impact and a small chance of technical problems creating a large impact.

What all of the above documents, and what is more problematic, is that wells on a single pad will not exploit the resource, and many more pads and wells will be needed. Combined, this certainly increases the 'footprint' on the land, and statistically, a few of the wells will have significant environmental problems or accidents during the course of their productive lives which have a significant impact on the environment. Furthermore, while any single well or pad may be within regulatory tolerances, the thousands of wells drilled to exploit a play will have a cumulative impact, which the regulations do not address.

In considering the environmental risks, operators tend to cite the studies showing that there is a low environmental risk from fracturing a single well, whereas campaigns against fracking tend to cite the cumulative effects in developing the resources over an area.[131] The result is a 'dialogue of the deaf' because the two positions are talking about different things.

The resolution of the question 'is fracking environmentally detrimental' is therefore not one that can be addressed solely as a matter of science. There is no yes or no answer. Rather, it requires a political discussion in which the benefits of fracking are weighed against risks and severity of the detrimental impacts. At present, particularly in the USA, such political discussions rely heavily on economic metrics rather than metrics derived from pure science.

131 See King (n 6) 4.