COMMENTARY

The integrity of oil and gas wells

Robert B. Jackson[a,b,1]

[a]*Department of Environmental Earth System Science, School of Earth Sciences, Woods Institute for the Environment, and Precourt Institute for Energy, Stanford University, Stanford, CA 94305; and* [b]*Division of Earth and Ocean Sciences and Center on Global Change, Nicholas School of the Environment, Duke University, Durham, NC 27708*

Public concerns about oil and natural gas extraction these days inevitably turn to hydraulic fracturing, where millions of gallons of water, sand, and chemicals are pumped underground at high pressures to crack open rocks. Hydraulic fracturing often occurs a mile or more down, far from the water we drink or the air we breathe. The focus for safety and environmental stewardship should often be somewhere else—nearer the surface—emphasizing risks from spills, wastewater disposal, and the integrity of oil and natural gas wells passing through drinking-water aquifers (1–4). In PNAS, Ingraffea et al. (5) examine one of these factors, well integrity, across the Marcellus region of Pennsylvania, using inspection records from the state Department of Environmental Protection (DEP).

In a technical sense, "well integrity" refers to the zonal isolation of liquids and gases from the target formation or from intermediate layers through which the well passes. In a practical sense, it means that a well doesn't leak. Drilling companies emphasize well integrity because a faulty well is expensive to repair and, in the rarest of cases, costs lives, as in the *Deepwater Horizon* disaster in the Gulf of Mexico. Drillers use steel casing (pipes), cement between nested casings and between the outside casing and rock wall, and mechanical devices to keep fluids inside the well.

Faulty casing and cementing cause most well integrity problems. Steel casing can leak at the connections or corrode from acids. Cement can deteriorate with time too, but leaks also happen when cement shrinks, develops cracks or channels, or is lost into the surrounding rock when applied. If integrity fails, gases and liquids can leak out of the casing or, just as importantly, move into, up, and out of the well through faulty cement between the casing and the rock wall.

Rates of Well Failure

Much is known and unknown about well integrity. Historical rates of well "failure" in oil and gas fields vary from a few percent of wells with barrier failures to >40% (4). Analyses of 8,000 offshore wells in the Gulf of Mexico show that 11–12% of wells developed pressure in the outer strings (called "sustained casing pressure") (6), as did 3.9% of 316,000 wells in Alberta (7). However, not all wells with a single barrier failure leak now or later (8); there can be multiple safety barriers and there must be a pressure or buoyancy gradient for fluids to migrate.

Well integrity is the key to minimizing many of the risks associated with hydraulic fracturing and unconventional resource extraction.

Previous analyses of well integrity in the Marcellus region, where Ingraffea et al. (5) worked, found various results. Considine et al. (9) used state violation records to estimate that 2.6% of 3,533 gas wells drilled between 2008 and 2011 had barrier or integrity failure. Vidic et al. (3) extended the timeline (2008–2013) and number of wells studied (6,466) and found that 3.4% had well-barrier leakage, primarily from casing and cementing problems. Davies et al. (4) estimated that 6.3% of wells drilled between 2005 and 2013 had a well-barrier or integrity failure, consistent with Ingraffea et al.'s number of 6.2% for unconventional wells (5). The latter two studies had slightly higher estimates because they included comments from the DEP database in their analyses, including cases where remedial action was taken but notices of violation were not issued.

The new analysis by Ingraffea et al. (5) covers more time (2000–2012) and digs more deeply into the data for >41,000 oil and gas wells. There are some surprises. The percentage of wells showing a "loss of structural integrity" (Ingraffea et al.'s term) is 1.9% across the period, with the lowest rate for conventional wells drilled from 2000 to 2008. However, unconventional shale gas wells were six times more likely to show problems than conventional wells drilled during the same period: 6.2% compared with 1.0%, respectively. The most common violations assessed were for "defective, insufficient or improperly installed" cement or casing and for pressure build-up, apparent as surface bubbling or sustained casing pressure (5). In 24 cases the Pennsylvania DEP concluded that there had been a "failure to prevent migrations to fresh groundwater" (5). Since 2005, the state has confirmed more than 100 cases of water-well contamination from oil and gas activities (10).

Are Newer Wells Safer?

Ingraffea et al. (5) also applied hazard analysis to compare different well cohorts at the same age. By definition, a well drilled later (2009–2012) can't be more than 4 y old, whereas wells in the earlier interval can be as old as 12 y, having more time to develop leaks and for those leaks to be detected.

The issue of well age addresses a critical question: Are recently drilled wells safer than older wells? Intuitively, the answer should be "yes." Materials are often better, regulations are often stricter (as they are over this interval in Pennsylvania), and people learn as they go, tailoring practices to local geology (8).

The data of Ingraffea et al. (5) suggest otherwise. For unconventional wells, the violation rate in the northeast was 9.8% for wells drilled from 2000 to 2008 compared with 9.1% for 2009 to 2012. Elsewhere in the state it was 1.5% for the older cohort of unconventional wells and 1.9% for the younger cohort. In both comparisons, though, the younger cohort had fewer years of inspections. When compared at the same age, both conventional and unconventional wells had more violations if drilled between 2009 and 2012 than between 2000 and 2008.

Greater regulatory scrutiny may explain some of this effect, as could the physics of hydraulic fracturing. A higher percentage of new wells were inspected in their first year from 2009 to 2012 (89%) than from 2000 to 2008 (76%), suggesting greater oversight. The intensity of hydraulic fracturing also likely increased during this period. For the Barnett

---

Author contributions: R.B.J. wrote the paper.

The author declares no conflict of interest.

See companion article on page 10955.

[1] Email: rob.jackson@stanford.edu.

10902–10903 | PNAS | July 29, 2014 | vol. 111 | no. 30 www.pnas.org/cgi/doi/10.1073/pnas.1410786111

Shale in Texas, a typical horizontal drilling length in 2005 was 600 m (2,000 feet); by 2011 it was 75% longer (11). The average volume of water used to fracture a well doubled during the period as well, from 9.9 to 17.4 million L (2.6–4.6 million gallons) (11, 12). Wells today are longer, must curve laterally, often access substantially overpressured reservoirs, and must withstand more intense hydraulic fracturing pressures and larger water volumes. All of these factors influence well integrity.

Perhaps the most striking result in Ingraffea et al. (5) was how much geography mattered. The cumulative risk of violations was 8.5-times (850%!) higher for wells drilled in northeastern Pennsylvania than for the rest of the state. What caused this surprising difference? Ingraffea et al. (5) make no attempt to explain the finding and probably didn't have enough information to do so. There are many possibilities. The local geology in northeastern Pennsylvania is fractured and complex. The region also has less of a history of oil and gas drilling than in western Pennsylvania, and the drilling came quickly. Starting in 2007, the state issued ∼1,550 drilling permits over 3 y for Bradford, Susquehanna, and Tioga counties.

Differences in people and best practices probably mattered as well. People in the northeast may have been in a hurry. Different companies may have had different best practices and cultures of safety; some of the most contentious cases of water contamination, including Dimock, Franklin Forks, Towanda, and Granville Summit, Pennsylvania, are all found in this part of the state. A host of other physical, statistical, and sociological explanations are also possible. One possibility that only the state can answer is whether the inspectors in the northeast were tougher or newer or different in some other way.

Older Wells See Few Inspections

Another important finding is that older wells are apparently rarely inspected. More than 8,000 wells drilled between 2000 and 2012 have no inspection records at all, at least publicly available. Moreover, for most vintages (wells and wines are both identified by year), the majority of wells appear to have no inspections after their first year, as assessed in table S2 of Ingraffea et al.'s report (5). If oil and gas wells aren't being inspected much after the first year or two, then we have very little data on long-term well integrity in the region.

Contrast the actual rate of inspections with instructions from the state guidelines (www.pacode.com/secure/data/025/chapter78/subchapXtoc.html). Pennsylvania Code § 78.903 (13) states that inspections are to occur "at least once a year to determine whether compliance with the statutes administered by the Department has been achieved." Inspections are also supposed to happen "at least once during each of the phases of siting, drilling, casing, cementing, completing, altering and stimulating a well." Keeping up with the >40,000 wells drilled in Pennsylvania since the year 2000 has apparently made this code unachievable, at least at current staffing rates.

Priorities and economics affect these factors. In 2013, Pennsylvania produced 3.1 trillion cubic feet (∼88 billion cubic meters) of natural gas from shale and other unconventional sources, valued at about US$15 billion. During the same period Pennsylvania collected ∼$225 million in impact fees. What Pennsylvania did not do that most other states do is levy a severance tax on production. In West Virginia and Texas, for example, the rates are 5% and 7.5% of produced value, respectively. Those rates would have generated $750 million and $1.1 billion in income in Pennsylvania.

Most of the impact fees that Pennsylvania did collect in 2013 funded county and state operations, with only ∼$10 million allocated to current environmental initiatives, such as habitat restoration, flood protection, and abandoned well plugging. Compared with other states, Pennsylvania is underinvesting in environmental protection from its oil and gas operations. Moreover, very little money will be available in the future when Marcellus wells age. Appalachian states (and countries such as Canada) are still paying the legacy of past coal mining, where acid mine drainage has cost taxpayers billions of dollars and still turns streams blaze orange decades after mining stops.

We need much more information on the structural integrity of older producing wells and abandoned wells (11, 14). A new analysis suggests there are between 280,000 and 970,000 abandoned wells in Pennsylvania alone, most of them unaccounted for in the state database (15). How many of these wells leak fluids into groundwater or the atmosphere? A random survey of 19 (a small sample) showed that all of these older wells leaked methane to the air, mostly at low rates, but could be responsible for 4–13% of methane emissions from human activities in the state (15).

Well integrity is the key to minimizing many of the risks associated with hydraulic fracturing and unconventional resource extraction. It is also central to successful operations for wastewater injection, CO_2 sequestration, underground gas storage, and even geothermal energy (16–20). We have a lot to learn about how often wells fail, when and why they fail, and the extent to which increased well-integrity standards will bear fruit in the future. Expect a lot more research on this topic to come.

1 Royal Society and Royal Academy of Engineering (2012) *Shale Gas Extraction in the UK: A Review of Hydraulic Fracturing* (Tech. Rep, London).

2 Jackson RB, et al. (2013) Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. *Proc Natl Acad Sci USA* 110(28):11250–11255.

3 Vidic RD, Brantley SL, Vandenbossche JM, Yoxtheimer D, Abad JD (2013) Impact of shale gas development on regional water quality. *Science* 340(6134):1235009.

4 Davies RJ, et al. (2014) Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. *Mar Pet Geol*, 10.1016/j.marpetgeo.2014.03.001.

5 Ingraffea AR, Wells MT, Santoro RL, Shonkoff SBC (2014) Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. *Proc Natl Acad Sci USA* 111:10955–10960.

6 Brufatto C, et al. (2003) From mud to cement—Building gas wells. *Oilfield Review* 15:62–76.

7 Watson TL, Bachu S (2009) Evaluation of the potential for gas and CO_2 leakage along wellbores. *SPE Drill & Compl* 24:115–126.

8 King GE, King DE (2013) Environmental risk arising from well construction failure—Differences between barrier failure and well failure, and estimates of failure frequency across common well types, locations and well age. *SPE Production and Operations* 28:323–344.

9 Considine TJ, Watson RW, Considine NB, Martin JP (2013) Environmental regulation and compliance of Marcellus Shale gas drilling. *Environ Geosci* 20-1:16.

10 Begos K (2014) Some states confirm water pollution from drilling. Associated Press. Available at http://bigstory.ap.org/article/some-states-confirm-water-pollution-drilling. Accessed June 19, 2014.

11 Jackson RB, et al. (2014) The environmental costs and benefits of fracking. *Annu Rev Environ Resour*, in press.

12 Nicot JP, Scanlon BR (2012) Water use for Shale-gas production in Texas, U.S. *Environ Sci Technol* 46(6):3580–3586.

13 Frequency of inspections, The Pennsylvania Code, Chapter 78, Subchapter X, Sect. 78.903 (2001).

14 Erno B, Schmitz R (1996) Measurements of soil gas migration around oil and gas wells in the Lloydminster area. *J Canadian Petroleum Technol* 35:37–45.

15 Kang M (2014) CO_2, methane, and brine leakage through subsurface pathways: Exploring modeling, measurement, and policy options. PhD dissertation (Princeton Univ, Princeton).

16 Government Accountability Office (1989) Drinking Water: Safeguards Are Not Preventing Contamination From Injected Oil and Gas Wastes, GAO-RCED-89-97. Available at www.gao.gov/products/RCED-89-97. Accessed June 19, 2014.

17 Bachu S, Watson TL (2009) Review of failures for wells used for CO_2 and acid gas injection in Alberta, Canada. *Energy Procedia* 1:3531–3537.

18 Miyazaki B (2009) Well integrity: An overlooked source of risk and liability for underground natural gas storage: Lessons learned from incidents in the USA. *Geol Soc Lond Spec Publ* 313:163–172.

19 Carey JW (2013) Geochemistry of wellbore integrity in CO_2 sequestration: Portland cement-steel-brine-CO_2 interactions. *Rev Mineral Geochem* 77:505–539.

20 Vengosh A, et al. (2014) A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environ Sci Technol*, 10.1021/es405118y.