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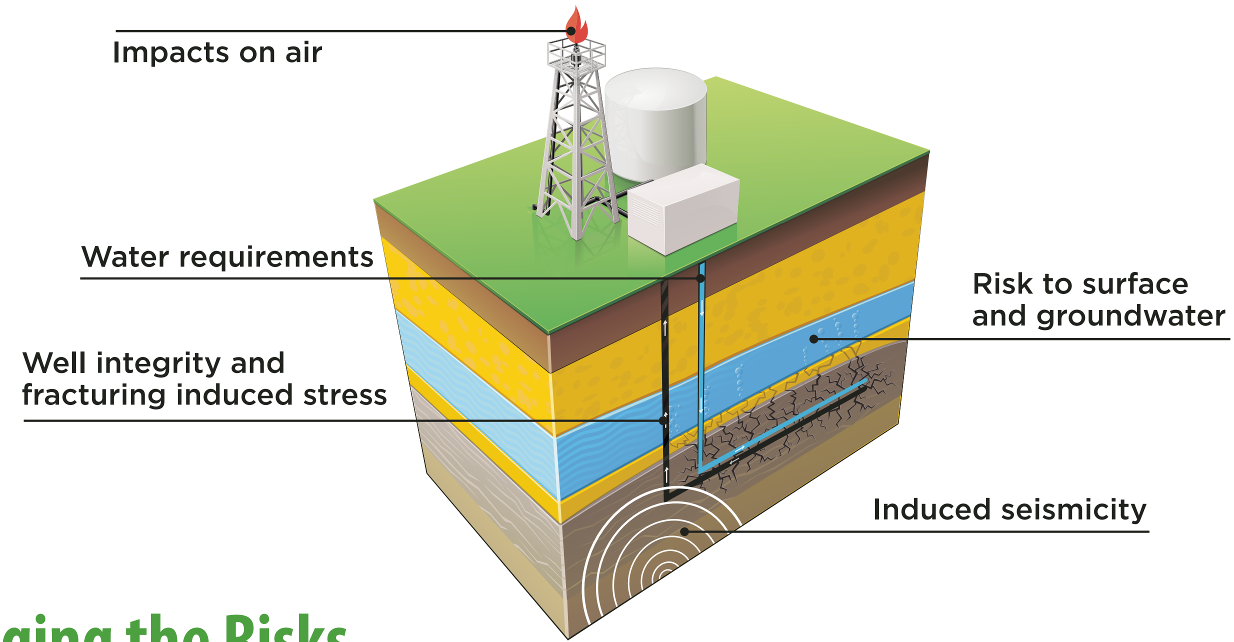


Managing the Risks of Hydraulic Fracturing: An Update

by Kenneth P. Green and Taylor Jackson

Summary

- Activist groups continue to oppose hydraulic fracturing, a new application of old technologies that is unlocking vast supplies of oil and natural gas in the United States and Canada. This opposition has resulted in the establishment of moratoria in several Canadian provinces, preventing the extraction of resources that could provide Canadians with significant benefits.

- Research on the safety of hydraulic fracturing confirms that while there are indeed risks with it, they are for the most part readily manageable with available technologies and best practices.

- Ground water contamination is one of the greatest concerns voiced by opponents of hydraulic fracturing. But as a recent US Environmental Protection Agency multi-year study found, hydraulic fracturing has not led to systemic impacts on drinking water. Research has also found that risks from well integrity failure are minimal when best practice procedures are implemented.

- Risks from exposure to the various air emissions generated by hydraulic fracturing are found to be minimal and manageable. Hydraulic fracturing and the natural gas it produces could also lead to fewer CO_2 emissions if natural gas displaces coal in electricity generation.

- While hydraulic fracturing can cause increased seismic activity, the tremors generated by the process are often very small—undetectable at the earth's surface. When compared with other industries such as mining and conventional oil and gas extraction, the magnitudes and incidences of earthquakes caused by hydraulic fracturing are quite minimal.

Introduction

Canada has tremendous potential to produce oil and gas from shale using hydraulic fracturing. The US Energy Information Agency (EIA) places Canada in the top 10 countries based on technically recoverable shale oil and gas resources (EIA, 2013).[1] Also, natural gas consumption, particularly for electricity generation, is expected to grow considerably in the future (EIA, 2015). In the face of such trends, development of Canada's shale gas could generate significant wealth, employment, and prosperity for Canadians.

As with other methods of hydrocarbon extraction (or any extractive activity for that matter), hydraulic fracturing is not without risks. Late in 2014, we published a study that summarized what was then known about the risks of hydraulic fracturing, and examined what additional measures might help to further mitigate those risks (Green, 2014). To avoid charges of cherry-picking individual studies that might be non-representative of the broader literature on hydraulic fracturing, we focused on the findings of large, government empaneled review organizations, and review articles published in top ranking journals such as Science. Further, as hydraulic fracturing practices in Canada are somewhat different than those employed in the United States and elsewhere, where possible, we gave preference to Canadian sources, particularly an assessment published by the Canadian Council of Academies in 2014. The documents we reviewed in 2014 included:

- Australian Council of Learned Academies (2013). *Engineering Energy: Unconventional Gas Production—A Study of Shale Gas in Australia.*
- Canadian Council of Academies [CCA] (2014). *Environmental Impacts of Shale Gas Extraction in Canada: The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction.*
- Clark, C., A. Burnham, C. Harto, and R. Horner (2013). *Hydraulic Fracturing and Shale Gas Production: Technology, Impacts, and Regulations*. Argonne National Laboratory.
- National Research Council of the National Academies (2013). *Induced Seismicity Potential in Energy Technologies.*
- NY State Health Department (2011). *Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs.*
- Quebec, Government of (2014). *Strategic Environmental Assessment on Shale Gas: Knowledge Gained and Principal Findings.*
- United States Environmental Protection Agency [EPA] (2014). *Natural Gas Extraction—Hydraulic Fracturing.*
- Vidic, R.D., S.L. Brantley, J.M. Vandenbossche, D. Yoxtheimer and J.D. Abad (2013). Impact of Shale Gas Development on Regional Water Quality. *Science* 340 (May): 1-9.
- Wheeler, David, *et al.* (2014). *Report of the Nova Scotia Independent Review Panel on Hydraulic Fracturing.*

Subsequent to the publication of the Green (2014) paper, several additional analyses have been published, including some in Canada, and importantly, a long-awaited analysis by the United States Environmental Protection Agency (EPA) on the risks posed to drinking water resources by hydraulic fracturing.

[1] Canada has the 10th largest shale oil reserves and the 5th largest shale gas reserves according to EIA (2013).

These new comprehensive analyses include:

- C.S. Long, Jens T. Birkholzer, and Laura C. Feinstein (2015). An Independent Scientific Assessment of Well Stimulation in California: Summary Report. An Examination of Hydraulic Fracturing and Acid Stimulations in the Oil and Gas Industry.
- Robert Mair, Michael Bickle, Dougal Goodman, John Roberts, Richard Selley, and Zoe Shipton (2012). Shale Gas Extraction in the UK: A Review of Hydraulic Fracturing.
- Robert B. Jackson, Avner Vengosh, J. William Carey, Richard J. Davies, Thomas H. Darrah, Francis O'Sullivan, and Gabrielle Pétron (2014). The Environmental Costs and Benefits of Fracking. Annual Review of Environment and Resources 39: 327-62.
- Intrinsik Environmental Sciences (2014). Phase 2: Recommendations Report.
- Environmental Protection Agency [EPA] (2015). Assessment of the Potential Impacts of Hydraulic Fracturing for Oil and Gas on Drinking Water Resources: Executive Summary.

This bulletin will recap the results of the Green 2014 study on hydraulic fracturing and summarize the findings of the additional reports published subsequently.

The major risks of hydraulic fracturing

Most discussions of the risk of hydraulic fracturing center on five areas:

- risk to surface and ground water
- well integrity and fracturing induced stress
- water requirements
- impacts on air, and
- induced seismicity

The below reviews new research regarding the risks of hydraulic fracturing for these five areas.[2]

Water risks

Risks involving water are at the center of the debate over hydraulic fracturing. Hydraulic fracturing can affect water supplies in several ways: first, hydraulic fracturing consumes a considerable amount of fresh water even net of recycling or reinjection; second, it injects considerable quantities of chemicals into the ground that have the potential to migrate into groundwater; and third, it produces considerable amounts of wastewater contaminated with a range of substances that includes toxic substances and radioactive materials.

Water pollution

The US Environmental Protection Agency (EPA) (2015) recently conducted a multi-year analysis of the potential for the contamination of ground water from hydraulic fracturing activities. Specifically, the EPA assessment "reviews, analyzes, and synthesizes information relevant to the potential impacts of hydraulic fracturing on drinking water resources at each stage of the hydraulic fracturing water cycle. Impacts are defined as any change in the quality or quantity of drinking water resources" (p. ES-3).[3]

[2] For longer analysis of many of the studies cited in this bulletin, see Green (2014).

[3] Note that the EPA cast its net very widely when assessing risks to drinking water resources. EPA (2015) states that, "[d]rinking water resources are defined within this report as any body of ground water or surface water that now serves, or in the future could serve, as a source of drinking water for public or private use. This definition is *broader* than most federal and state regulatory definitions of drinking water and encompasses both fresh and non-fresh bodies of water" (p. ES-3, emphasis added).

We acknowledge that the EPA report is marked as a draft, but nonetheless, it was released onto the Internet and was covered extensively by the media. Should the EPA's report be revised in a way that changes what we cite here, we will address such changes at that time.

The major findings of the EPA's draft water report were that:

> [f]rom our assessment, we conclude there are above and below ground mechanisms by which hydraulic fracturing activities have the potential to impact drinking water resources. These mechanisms include water withdrawals in times of, or in areas with, low water availability; spills of hydraulic fracturing fluids and produced water; fracturing directly into underground drinking water resources; below ground migration of liquids and gases; and inadequate treatment and discharge of wastewater.
>
> *We did not find evidence that these mechanisms have led to widespread, systemic impacts on drinking water resources in the United States.* Of the potential mechanisms identified in this report, we found specific instances where one or more mechanisms led to impacts on drinking water resources, including contamination of drinking water wells. The number of identified cases, however, was small compared to the number of hydraulically fractured wells (p. ES-6, emphasis added).

Jackson et al. (2014) come to similar conclusions about the risks hydraulic fracturing pose to surface and ground water. Jackson et al. found that:

> In principle, hydraulic fracturing could open incipient fractures (cracks) thousands of meters underground, connecting shallow drinking-water aquifers to deeper layers and providing a conduit for fracturing chemicals and formational brines to migrate upward. In practice, this occurrence is unlikely because of the depths of most target shale and tight-sand formations (1,000–3,000 m) and because microseismic data show that man-made hydro-fractures rarely propagate >600 m. A somewhat more plausible scenario would be for man-made fractures to connect to a natural fault or fracture, an abandoned well, or some other underground pathway, allowing fluids to migrate upward.
>
> A simpler pathway for groundwater contamination, though, is through poor well integrity. In the first study to test for potential drinking-water contamination associated with unconventional energy extraction, Osborn et al. analyzed groundwater wells for 68 homes overlying the Marcellus Shale in Pennsylvania. They found no evidence for increased salts, metals, or radioactivity in drinking water of homes within 1 km of shale-gas wells.[4]

Additionally, Jackson et al. (2014) state that:

> Kell compiled groundwater contamination incidents from oil and gas operations in Ohio and Texas. For a 25-year period, the state of Ohio acknowledged 185 cases of groundwater contamination caused primarily by failures of wastewater pits or well integrity. Ohio had about 60,000 producing wells, for an incident rate of about 0.1% (~5 in 100,000 producing well-years). The rate for Texas was lower, with 211 total incidents (~0.02%, or 1 in 100,000

[4] Internal citations deleted for clarity.

> producing well-years). Interestingly, Kell's study also included 16,000 horizontal shale-gas wells in Texas, none associated with reported groundwater contamination. (p. 339)

There has been some evidence of higher methane and ethane concentrations in water close to hydraulically fractured wells. That being said, Hammack et al. (2014), studied gas and fluid migration in the Marcellus formation for the US Department of Energy, finding that "there has been no detectable migration of gas or aqueous fluids to the Upper Devonian/Lower Mississippian gas field during the monitored period after hydraulic fracturing" (p. 2).

Mair et al. (2012) in the UK also investigated whether fractures would pose major risks to surrounding aquifers, finding that:

> The available evidence indicates that this risk is very low provided that shale gas extraction takes place at depths of many hundreds of metres or several kilometres. Geological mechanisms constrain the distances that fractures may propagate vertically. Even if communication with overlying aquifers were possible, suitable pressure conditions would still be necessary for contaminants to flow through fractures. More likely causes of possible environmental contamination include faulty wells, and leaks and spills associated with surface operations. Neither cause is unique to shale gas. Both are common to all oil and gas wells and extractive activities. (p. 4)

The conclusions of Mair et al. (2012) found low risk for underground water contamination at greater depths. But not all fracturing takes place at great depths: in California, wells tend to be rather shallow, potentially posing a greater risk for ground water. Even here, Long et al. (2015) found "no documented instances of hydraulic fracturing or acid stimulations directly causing ground water contamination in California" (p. 52). The authors do, however, go on to say that more research and monitoring is needed to better evaluate any potential effects hydraulic fracturing could be having on ground water in California.

The Canadian Council of Academies (CCA) (2014), on the issue of potential contamination of ground water, found that "[t] he risks due to surface activities will likely be minimal if proper precautionary management practices are followed" (p. xiii).

And even though New York has banned the practice of hydraulic fracturing, on the issue of water contamination, the New York State Health Department (2011) found:

> analyses… demonstrate that no significant adverse impact to water resources is likely to occur due to underground vertical migration of fracturing fluids through the shale formations… there is no likelihood of significant adverse impacts from the underground migration of fracturing fluids.
>
> No significant adverse impacts are identified with regard to the disposal of liquid wastes. (pp. 11-12)

Finally, according to a recent review in the journal *Science*:

> Since the advent of hydraulic fracturing, more than 1 million hydraulic fracturing treatments have been conducted, with perhaps only one documented case of direct groundwater pollution resulting from injection of hydraulic fracturing chemicals used for shale gas extraction. Impacts from casing leakage, well

Table 1: Water Intensity for Extraction, Processing, and Electricity Generation, by Energy Source

Energy Source	Water for extraction (l/GJ)	Water for extraction and processing (l/GJ)	Water consumption intensity of electricity generation (l/MWh)
Natural gas, conventional	0.7	6.7	See below
Natural gas, unconventional	8.6	15	See below
Natural gas combined cycle (once through)	See above	See above	520
Natural gas combined cycle (closed loop)	See above	See above	850
Pulverized coal (once through)	9	27	1,400
Pulverized coal (closed loop)	9	27	1,900
Saudi Arabian crude	79	110	NA
Oil shale	200	240	NA
Oil sands	NA	110	NA
Nuclear (once through)	14	47	1,700
Corn ethanol (unirrigated)	300	430	2,100
Corn ethanol (irrigated)	14,000	14,000	16,000
Solar photovoltaic	0	0	10
Concentrated solar power	NA	NA	3,100
Wind	0	0	4

Source: Jackson, Vengosh, Carey, Davies, Darrah, O'Sullivan, and Pétron (2014).

> blowouts, and spills of contaminated fluids are more prevalent but have generally been quickly mitigated. (Vidic et al., 2013: 6).

Vidic et al. (2013) also noted that when spills of contaminated fluid do occur, potentially posing a threat to ground water, they are usually quickly mitigated.

Water requirements

Concerns have also been raised about the potentially large volumes of water used in the fracturing process. For example, a single fractured well in the Barnett, Marcellus, and Fayetteville shale formations typical requires between 8,000 to 80,000 m^3 (8 to 80 million litres) of water (Jackson et al., 2014). While these numbers seem large, comparisons to the huge amount of water required for agriculture and thermoelectric uses helps put these figures in context. Consider that the city of Fort Worth, Texas, uses over 55 million litres of water just to water their lawns every day (Levant, 2014). Also, as pointed out in the review of hydraulic fracturing in California, the water requirements for hydraulic fracturing in the areas where this activity is taking place in the drought-stricken state represent less than 0.2 percent of human water use (Long et al., 2015).

That being said, Jackson et al. (2014), did find that during early development in the Marcellus formation, too much water was being withdrawn, and lower water levels were starting to have adverse consequences, which were identified by the state and rectified.

Recycling is also reducing water use. Prior to 2011 only 13 percent of wastewater was recycled in the Marcellus, but by 2011 that number had risen to 56 percent, and more recently recycling is approaching 90 percent (Jackson et al., 2014).

Water use for hydraulic fracturing also needs to be considered in the context of other ways we use water, for extraction, processing, and electricity generation for other energy sources (see table 1).

As Jackson et al. (2014) state:

> … given all the attention that hydraulic fracturing receives for its water requirements, shale-gas extraction and processing are less water intensive than most other forms of energy extraction except conventional natural gas and, especially, renewables such as wind and solar photovoltaics that consume almost no water…. The water intensities for coal, nuclear, and oil extraction are ~2 times, 3 times, and 10 times greater than shale gas, respectively. (p. 336)

Although water use for natural gas shale fracturing sounds large in isolation, when compared to other industrial processes or other forms of energy extraction it does not seem so extreme. Also, when problems have arisen, current oversight measures have been able to detect and rectify them.

Well integrity

One of the major concerns about hydraulic fracturing is well integrity and failure in this area likely presents the greatest risk to the contamination of water resources. In general, but especially during the fracturing process, liquids or gases can escape through “holes or defects in the steel casing, through joints between casing, and through defective mechanical seals or cements inside or outside the well” (Jackson et al., 2014: 337). With the nature of some of the chemicals used in the fracturing process being toxic, such seepage can pose risks to the environment.

When there is a buildup of pressure inside the well that might force fluids into the environment this is called Sustained Casing Pressure (SCP), and it can be used as a measure of well performance. Jackson et al. (2014) reviewed the SCP literature and found significant differences between regions.

> Results from surveys of wells offshore and onshore show distinct differences in rates of SCP, reflecting the importance of geology and well construction. In the Gulf of Mexico, 11–12% of wells in an 8,000-well survey showed SCP on outer casing strings, with results ranging from 2% to 29% across fields. In Alberta, companies reported that 3.9% of 316,000 wells showed evidence of SCP, with one region east of Edmonton having 15.3% SCP. Davies et al. recently reviewed well integrity and SCP globally. For studies with >100 wells, SCP was found to range from 3% to 43% of wells in Bahrain, Canada, China, Indonesia, the United Kingdom, the United States, and offshore Norway and the Gulf of Mexico; 12 of 19 studies showed SCP values for ≥10% of wells. Publicly available data for well failure rates are still relatively scarce. (p. 338)

These results are similar to those by Mair et al. (2012), who found in their review of the safety of hydraulic fracturing for the United Kingdom (UK) that “[t]he probability of well failure is low for a single well if it is designed, constructed, and abandoned according to best practice" (p. 4).

As Jackson et al. (2014) describe, many of the causes of well failure are well known, making it easier to address the associated risks. Different shale formations can have different effects on well integrity and failure rates. The local nature of issues suggests that regulation should likely be carried out at the state or provincial level, where specific differences can better be addressed.

As Green (2014) points out, jurisdictions might pursue additional policies to reduce the risk of well failures further. Among them is the creation of for-profit or non-profit third party verification entities that would have to certify that a well was properly drilled and cased before production could commence.

Conventional air pollution and greenhouse gas emissions

Air quality

Like most industrial processes that consume energy, hydraulic fracturing releases pollutants into the atmosphere. In addition to the power-generation emissions used in the hydraulic fracturing process, the process itself first injects, then brings a variety of volatile chemicals to the surface that could, if not trapped and safely handled, escape into the atmosphere.

Intrinsik (2014) Environmental Sciences recently conducted a human health risk assessment focusing on the potential impacts of oil and gas activities, which includes hydraulic fracturing, on human health. The study was commissioned by the BC Ministry of Health, after concerns were raised by residents in northeastern BC. The conclusions of the general human health risk assessment, which centered mostly on the health effects from airborne Chemicals Of Potential Concern (COPC)[5], were that:

> [o]n a short-term basis, the predicted air concentrations of the COPC generally were less than their health based exposure limits. The potential combined effects of these COPC were also not predicted to result in adverse health effects in people living or visiting the study area…
>
> Long-term inhalation exposures to the COPC were generally predicted to be associated with a low potential for adverse health effects…
>
> In the assessment of potential exposures to the COPC that people in the area might receive over the long term through the consumption of local foods, drinking water, contact with soils and water, it was determined that the potential for adverse human health effects is low. (p. 8)

Intrinsik (2014) went on to conclude that BC's existing regulatory framework is quite extensive and protective of human health. However, the report did have some specific recommendations regarding hydraulic fracturing, after noting that "the probability of adverse human health impacts occurring in relation to fracturing-related water emissions was determined to be low" (p. 12).

Intrinsik (2014) recommended that companies disclose the small proportion of chemicals used in the fracturing fluid to government and health officials. The disclosed chemical information would be kept confidential in order to protect trade secrets. The Canadian Association of Pe-

[5] I.e., NO_2, SO_2, $PM_{2.5}$, formaldehyde, etc.

troleum Producers (CAPP) and the American Petroleum Institute (API) both support chemical disclosure.

It should come as no surprise that the hydraulic fracturing process results in some air pollutant emissions and as CCA (2014) notes, many of these emissions are the same as those generated by conventional oil and gas production, mining, and other industrial activities.[6] But there is a distinction to be made between emissions, exposures, and risk.

Emissions that do not reach a vulnerable population do not turn into exposures, and those non-exposures do not turn into risks. What matters is whether or not hydraulic fracturing processes are producing enough additional emissions to pose additional risk to susceptible populations and ecosystems. On this front, the evidence is limited and in line with the recent findings of Intrinsik (2014), at least in Canada.

An environmental assessment of shale gas conducted for the government of Quebec (2014) found that the risk of widespread pollution from hydraulic fracturing is small, and can be remedied by the use of existing technologies.

Finally, a study by the Argonne National Laboratory (Clark et al., 2013) in the US suggests that more evidence is needed, but at present, the estimated pollutant levels are below the level of health concern.

Greenhouse gas emissions

Hydraulic fracturing locations are generally remote, meaning that the energy used to engage in the activity has to be generated on-site. For the most part, conventional power generators fueled by diesel fuel, natural gas, or other fossil fuels, the combustion of which leads to the emission of greenhouse gases (GHG), are used to generate the necessary energy. Other ways by which hydraulic fracturing can emit GHGs are leakage of methane and other greenhouse gases, particularly if a well has been drilled improperly, and when burned, the fuels produced by hydraulic fracturing also lead to the emission of greenhouse gases. The latter issue is really a matter of relative comparisons between hydrocarbons produced via hydraulic fracturing and hydrocarbons produced in other ways.

On the matter of fuel displacement, the CCA (2014) is mixed, finding that the relative benefits of hydraulic fracturing depend on whether natural gas displaces coal and oil or nuclear and renewables.[7] Although there is disagreement among experts on this point, there does appear to be evidence that natural gas is displacing significant amounts of coal fired electricity generation. A Joint Institute for Strategic Energy Analysis (Logan et al., 2012) report found that:

> [l]ow-priced natural gas has led to more than 300 terawatt-hours of fuel switching from coal to gas in the US power sector between 2008 and 2012. This switching, in combination with rapid growth in certain renewable energy generation sources, has led to a reduction in power-sector carbon dioxide emissions of about 300 million tons—about 13% of the sector's total. (p. 120)

[6] One of the largest sources of emissions during the process of hydraulic fracturing comes from the use of diesel generators. Considine et al. (2011) estimated that a typical hydraulic fracturing job uses about 15,000 gallons (approx.. 57,000 litres) of diesel fuel.

[7] CCA (2014) also noted that the extent to which hydraulic fracturing is a benefit towards reducing GHGs vis-à-vis displacing higher carbon fuel sources will depend on the volume of methane leakage that occurs.

And natural gas produced via hydraulic fracturing does not seem to be particularly dissimilar from conventionally produced gas in terms of GHG emissions. Natural Resources Canada (2012) found that most shale gas development has similar GHG emissions per unit as conventional gas. Long et al. (2015) in their review for California actually found that:

> [o]il and gas production from hydraulically fractured reservoirs emits less greenhouse gas per barrel of oil than production using steam injection. Oil produced in California using hydraulic fracturing also emits less greenhouse gas per barrel than the average barrel imported to California. If the oil and gas derived from stimulated reservoirs were no longer available, and demand for oil remained constant, the replacement fuel could have larger greenhouse emissions. (p. 58)

The Australian Council of Learned Academies (2013) also examined the question of relative emissions. They found:[8]

> [o]n average, a shale gas-fuelled, baseload combined cycle gas turbine (CCGT) plant will produce 23% more life cycle GHG emissions per MWh, when compared with a conventional gas-fuelled CCGT, and will produce life cycle GHG emissions per MWh that are 53%, 66%, and 69% of the emissions produced from coal combusted in a subcritical, supercritical, or ultra-supercritical pulverised coal plants respectively.
>
> On average a shale gas-fuelled open cycle gas turbine (OCGT) plant will produce 12% more life cycle GHG emissions per MWh, when compared with a conventional gas fuelled OCGT, and will produce life cycle GHG emissions per MWh that are 71%, 88%, and 93% of the emissions produced from coal combusted in a subcritical, supercritical or ultra- supercritical pulverized coal plant, respectively. (p. 146)

Then there is the issue of methane leakage. Several authors have claimed that hydraulic fracturing would increase natural gas emissions to the atmosphere due to leakage during the hydraulic fracturing process, and at the beginning of gas recovery. Methane is considered to be one of the more potent of the greenhouse gases.

The Argonne National Laboratory (Clark et al., 2013) considered the question of leakage and found that the risk can largely be solved by existing, cost-effective technologies. And the assessment report for the government of Quebec (2014) found that the leakage rate for fracked gas production would only be about 3 percent, considerably lower than estimates cited by environmental groups.

Earthquakes (induced seismicity)

Opponents of hydraulic fracturing often cite the potential for earthquakes as reasons for stopping the activity. These critiques, however, are often devoid of context and frequently ignore the literature that has analyzed the link between earthquakes and hydraulic fracturing. For reference, table 2 provides an example of the effects that can occur within a range of magnitudes.[9]

[8] The report adds that gas fired electricity generation will likely first replace the less efficient subcritical coal fired facilities and that for this reason, this is the most relevant comparison between natural gas and coal.

[9] Earthquakes can be measured in many different ways. The one people are most likely familiar with is the Richter scale (M_L), which determines the magni-

Table 2: Effects of Earthquakes

Magnitude	Effects as measured by Modified Mercalli Intensity Scale
1.0-3.0	Not felt except by a very few under especially favorable conditions.
3.0-3.9	Felt only by a few persons at rest, especially on upper floors of buildings. Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
4.0-4.9	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably. Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
5.0-5.9	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
6.0-6.9	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
7.0 and higher	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent. Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly. Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Source: United States Geological Survey [USGS] (2014).

The CCA (2014) found that hydraulic fracturing can cause minor earthquakes. However, most cannot be felt by the public and are not necessarily directly caused by the fracturing but rather by the wastewater injection that occurs after the hydraulic fracturing has taken place. The study goes on to find that "[m]ost experts judge the risk of hydraulic fracturing causing earthquakes to be low" and "[t]he risk by injection of waste fluids is greater but still low, and can be minimized through careful site selection, monitoring and management" (p. xvi).

The National Research Council of the National Academies (2013) came to similar conclusions as CCA (2014), finding that hydraulic fracturing "does not pose a high risk for inducing felt seismic events" (p. 1).

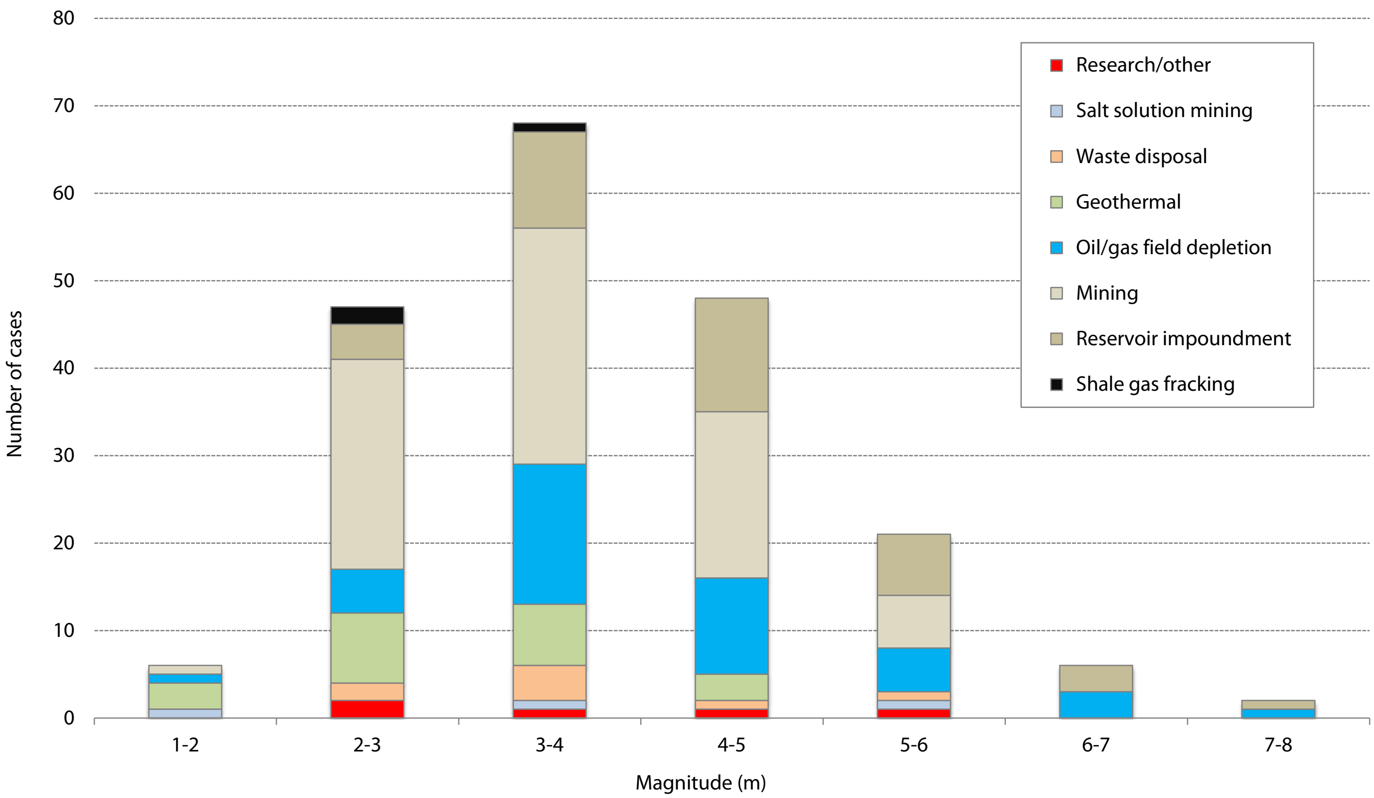
In addition, Ellsworth (2013) reviewed the impact of fracking on earthquakes. He found that both the act of fracking and the later injection of wastewater can induce seismic events. That being said, the magnitudes of the earthquakes (usually micro-earthquakes) from the fracturing process are quite small, with "the vast majority [being] $M_W < 1$" (p. 3). Ellsworth went on to find that although there had been recent reports of earthquakes linked to hydraulic fracturing that were large enough to be felt, they were ultimately "too small to cause structural damage" (p. 3). The greater issue regarding fracking and earthquakes is the potential for wastewater injection to cause somewhat larger seismic events. Although Ellsworth (2013) notes that while "[l]ong-term and high-volume injection in deep wells clearly carries some risk… most wells are apparently aseismic" (p. 6).

Davies et al. (2013), in a review of hydraulic fracturing and induced seismicity, found that "[h]ydraulic fracturing of sedimentary rocks, for recovery of gas from shale, usually generates very small magnitude earthquakes only…. It should be noted, however, that after hundreds of thousands of fracturing operations, only three examples of felt seismicity have been documented" (p. 183). Davies et al. (2013) also compared induced seismicity from fracking with other industrial and resource industries, finding that, as seen in figure 1, hydraulic fracturing features far fewer cases of induced seismicity than other industries, significantly reducing the legitimacy of arguments that induced seismicity from fracturing poses systemic threats.

In addition, Skoumal et al. (2015) in a review of induced seismic activity in Poland Township, Ohio, found that "[t]he temporal and spatial proximity of the Poland Township earthquakes to active hydraulic fracturing operations strongly suggested that the stimulation process triggered the seismic events" (p. 194). This article generated quite a bit of publicity from anti-fracturing activists who argued that hydraulic fracturing should be banned based on the results of the survey. The authors of the study felt that calls for bans were unfounded, stating that "millions of people saw this [study], and the

tude of an earthquake by using the logarithm of the amplitude waves (USGS, 2012). Another more recent scale is called the moment magnitude scale (M_W). The M_W scale differs little with the Richter scale at magnitudes below 8, but only the M_W scale is capable of measuring larger events accurately. The M_W scale is based on the total amount of "moment" releases, moment being defined as "a product of the distance a fault moved and the force required to move it" (Michigan Tech, 2007). Earthquake intensity is different than their magnitudes. According to the US Geological Survey (2013), an earthquake's intensity is the effect that it has, ranging from minor feelings to catastrophic destructions. Scientists use the Modified Mercalli Intensity Scale to help understand the effects that earthquakes can have and the scale is based on observed effects (USGS, 2013).

Figure 1: Induced Earthquakes and their Source



Note: Most of the magnitudes in the figure are measured on the Richter scale (M_L).
Source: Davies, Foulger, Bindley, and Styles, 2013.

comment section was just a train wreck. People didn't really see what we see what we were doing, what we were arguing…These are pretty small events, so an outright ban [on fracking] wouldn't be appropriate" (Melchior, 2015, January 21). Indeed all of the earthquakes in the study ranged from M_L ~1 to 3, magnitudes which would be barely felt at the upper end, as seen in table 2 (Skoumal et al., 2015).

While it is true that hydraulic fracturing can cause earthquakes per se, the resulting induced seismicity is often a magnitude that cannot be felt by humans, and the number of earthquakes is quite small considering the scope of the industry and the amount of earthquakes induced by other industrial processes.

Conclusion

The additional research on the safety of hydraulic fracturing reviewed since the publication of Green (2014) results in many of the same conclusions. Additional research on the safety of hydraulic fracturing confirms that while there are indeed risks from this process as there are with all industrial activities, they are for the most part readily managed with available technologies and best practices. Some of the latest research, such as EPA (2015), which found that hydraulic fracturing does not pose widespread or systemic effects to drinking water, cleared up much of the uncertainty which was present in the earlier comprehensive reviews.

Green (2014) also analyzed the regulatory environment in Canada, finding that Canada has a robust regulatory process that covers the entire range of hydraulic fracturing processes at both federal and provincial levels. In addition, the industry, through its trade association, has stringent self-regulation that exceeds regulatory requirements. More research is needed into the potential environmental impacts of hydraulic fracturing as well as the risks it may pose to human and ecological health—and of course that research is continuing both in Canada and around the world.

Calls for bans and moratoria are passionate, and no doubt heartfelt by those who fear the technology or oppose the product of that technology (hydrocarbons), but policymakers should ignore the siren song of the simplistic solution. Bans and moratoria may make it seem like one is taking action against risk, but they are not—they simply defer those risks to a later date, if and when activity resumes, which, given the vast economic potential of shale gas and oil, it most likely will.

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Kenneth P. Green is Senior Director of the Centre for Natural Resources at the Fraser Institute. He has studied environmental, energy, and natural resource policy for more than 20 years at think-tanks across North America including the Reason Foundation in Los Angeles; the American Enterprise Institute in Washington, DC; and previously at the Fraser Institute, where he ran the Centre for Risk, Regulation and the Environment. A frequent commentator in North American print and broadcast media, he has testified before several state and federal legislative bodies in the United States. He twice reviewed reports for the United Nations Intergovernmental Panel on Climate Change and is also the author of two textbooks: ***Global Warming: Understanding the Debate****, for middle-school students studying climate change, and* ***Abundant Energy: The Fuel of Human Flourishing****, for post-secondary studies in energy policy. Kenneth holds a Bachelor's Degree in Biology from UCLA, a Master's in Molecular Genetics from San Diego State University, and a Doctorate in Environmental Science and Engineering, also from UCLA.*

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Taylor Jackson *is a Policy Analyst in the Centre for Natural Resource Studies at the Fraser Institute. He holds a BA and an MA in Political Science from Simon Fraser University. Mr. Jackson is the co-author of a number of Fraser Institute studies, including* ***Safety in the Transportation of Oil and Gas: Pipelines or Rail?****, and the Fraser Institute's annual* ***Global Petroleum Survey****, and* ***Survey of Mining Companies****. He is also the coauthor of a book chapter on the past, present, and future of Canadian-American relations with Professor Alexander Moens. Mr Jackson's work has been covered in the media around the world and his commentaries have appeared in the* ***National Post****,* ***Financial Post****, and* ***Washington Times****, among other newspapers.*

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