The Risks of Hydraulic Fracturing and the Responsibilities of Engineers

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1. Introduction

In the autumn of 2013, two of the faculty authors met informally to talk over matters of common interest. This is not so unusual, except that one is an engineer specializing in geomechanics and the other a philosopher specializing in practical ethics. The common interest, though, was in understanding the ethical responsibilities of scientists and engineers and, perhaps more importantly, in developing new approaches of integrating ethics instruction into engineering curricula.

That initial conversation led to a collaboration that drew in the other authors of this paper – another faculty member in engineering and two (then) undergraduate students – as well as a graduate student and a librarian. The aim of the collaboration was to grapple with the risks of hydraulic fracturing – and of unconventional oil and gas exploitation more generally – and the concomitant responsibilities of scientists and engineers.

Our broader goal has been to develop, implement and refine pedagogical techniques and teaching materials for integrating ethical imagination and professional responsibility into the engineering curriculum at our home institution and elsewhere.

The project team convened two workshops at the Georgia Institute of Technology (Georgia Tech). The first, in November 2014, brought together a number of experts in the geological, technological, industrial, legal and political aspects of hydraulic fracturing, most of them from elsewhere in the United States. The aim was to identify and specify areas of uncertainty and risk in the process of hydraulic fracturing and subsequent extraction.

The second workshop, in April 2015, drew in faculty and students from across the Georgia Tech campus. The aim in this case was to develop approaches and curricular materials for integrating ethics instruction into engineering courses and degree programs, using hydraulic fracturing as the primary example.

This paper – the first product of our collaboration – is a synthesis of what we learned in the first workshop, clarified and extended through subsequent research and discussion.

In preparing for the first workshop, the project team divided into two groups. One group worked to develop a more adequate model of the process of hydraulic fracturing at the scale of a single borehole, in terms of how shale responds to the injection of fluid under pressure. The other group developed an overview of the social and political responses to the perceived risks and benefits of hydraulic fracturing and subsequent extraction, taking a particular site in western Pennsylvania as a case study.

What became clear to us, by the time we convened the first workshop, was the tremendous perceived distance between the modeling work of a single lab and the wider social discussion of hydraulic fracturing. The two frames of reference – call them *the lab* and *the forum* – are so distinct, in terms of the scale and the terms of inquiry within each, that one might be forgiven for thinking there could be no connection between them at all.

Between the lab and the forum is *the field*, where engineers and others implement hydraulic fracturing within – and extract resources from – particular local environments. It is in the field, as the techniques of fracturing and extraction interact with local conditions, that *hazards* may arise, hazards that may then become the urgent focus of research in the lab and deliberation in the forum.

To cast our own project in terms of this *lab-field-forum* schema, our team's modeling effort (in the lab) aimed to fill in what should be a critical area of uncertainty that should be relevant to understanding the hazards of hydraulic fracturing (in the field), which should in principle inform public deliberation concerning acceptable risk (in the forum). However, researchers' work in the lab occurs in a context and at a scale that may obscure, for researchers themselves, the salience of their work to wider social questions of acceptable risk. From the other side, the modeling effort requires mastery of highly specialized tools of inquiry – a conceptual apparatus, refined jargon, mathematical formulae and so on – that make it all but incomprehensible to many in the forum who have a genuine stake in knowing what happens when shale fractures and oil and gas flow.

The apparent disconnection between the lab and the forum serves to frame the central question of this paper: What are the responsibilities of scientists and engineers in conducting research, communicating with the public, and contributing to deliberation regarding acceptable risks in relation to hydraulic fracturing and subsequent extraction?

We begin in the lab, setting out in considerable detail the scientific context within which a modeling project in geomechanics takes place, with special attention to uncertainties that persist even in the most basic understanding of how shale behaves. We then move to the field to set out some of the main hazards associated with hydraulic fracturing and subsequent extraction, as they are currently understood. From there, we go on to the forum, considering the important but delimited role of engineers and researchers in public deliberation concerning risk and acceptable risk.

A basic premise of our entire project is that scientific and engineering research does have a vital role in deliberation on public policy regarding hydraulic fracturing. Indeed, it is difficult to imagine a legitimate and informed policy process that somehow excludes the work and the voices of engineers and scientists! Theirs are not the only voices that matter, however, and in that fact lie a number of their responsibilities in the forum.

We should also briefly clarify the meanings of some basic terms we have already been using: uncertainty, hazard, harm and risk.

Hydraulic fracturing and the subsequent extraction of gas and oil involve *risk*. In empirical terms, risk is the product of two factors: *hazard* and *harm*. Hazard is variability in how the environment responds to a particular intervention expressed as the probability of some adverse occurrence. Harm is the degree to which individuals affected by the adverse occurrence are made worse off in some substantive way, whether in terms of personal wellbeing, security, or property, or as a decrease in net utility, sometimes expressed in monetary terms.

Uncertainty adds further complexity to understanding risk, in that the probability of a given hazard and the magnitude of the resulting harm often cannot be specified due to insufficient understanding of the underlying dynamics.

To restate the purpose of this paper, then, we consider how and to what extent engineers and scientists can address *uncertaint*y, specify *hazards* and respond to *risks* in the practice of hydraulic fracturing, and what might be their appropriate contributions to public deliberation concerning *acceptable risk* – a term about which we have more to say below.

2. In the Lab: Grappling with Uncertainty

Hydraulic fracturing is a process of injecting fluid at high pressure into rock formations in order to open fractures and allow fluids trapped in the rock – e.g., oil and gas – to flow out more easily. For purposes of this consideration, we limit our focus to hydraulic fracturing in oil- and gas-bearing shale formations.

Some of the possible hazards of the process are a function of how shale itself behaves under such conditions: How far do fractures propagate and in what pattern? Could the products of reactions between shale and the injected fluids potentially contaminate those fluids? Might such chemical reactions lead to contamination of groundwater or surface water? Is it possible that the process of hydraulic fracturing could induce seismic events, including earthquakes?

Uncertainty about such hazards and the associated risks are due in part to uncertainty about shale itself. In truth, geophysicists are still puzzled about how shale rocks form, deform and break. What follows is a technical discussion, providing specialized scientific and engineering information on uncertainty. The technical discussion, while deliberately simplified where possible, may further demonstrate the disconnection between engineers' efforts to understand micro-scale processes that occur in hydraulic fracturing and the larger-scale concerns of policy makers.

Solid and Fluid Materials involved in Hydraulic Fracturing

One third of U.S. natural gas is extracted from shale. Shale is a structured rock, containing clay flakes (also called platelets) of less than one micron, which form porous aggregates (called floccules) of up to tens of micrometers (Slatt and O'Brien, 2011).

The pores in shale may be modeled at various scales, across several orders of magnitude from the nanoscale (very small) to the macroscale (very large): (1) so-called "organopores", within the platelets, are a few nanometers (one billionth of a meter) in size and can contain only a few molecules; (2) the space between platelets is of the order of the micrometer (one millionth of a meter); (3) pores between clay aggregates are of the order of a millimeter (one thousandth of a meter); and (4) natural planes of discontinuity and fractures between blocks of shale can be a meter long or more.

One major source of uncertainty in hydraulic fracturing is the variability of rock microstructure. Under the same conditions of applied loading, fluid pressure and temperature, pores at different scales may be subject to different physical and chemical processes modeled according to different equations. Although more and more laboratory experiments are being conducted to provide microscope images and macroscopic mechanical properties of shale, relationships between shale microstructure, deformability (ability to change shape) and permeability (ability for liquids to pass through) are mostly just a matter of observed correlations without a good mathematical model or theoretical explanation to back them up. Permeability within shale could be due to the existence of fractures parallel to the bedding planes (at a larger scale), or to the existence of flow paths within and between aggregates (at a smaller scale). Currently, no sound basis exists on which to choose one account over another.

As a consequence, the basic mechanism of hydraulic fracturing remains unexplained. Scientists and engineers do not yet know why creating large-scale fracture patterns enhances the flow of fluids like oil and gas.

Another area of uncertainty concerns the effect of the hydraulic fracturing process on fluids already in the shale and on the fluids injected into a borehole. The fluid injected during the process of hydraulic fracturing tends to acidify and cool the water that saturates the rock formation. Dissolution, where minerals dissolve as pressure is applied, creates zones of high chemical concentration, resulting in precipitation and clogging, which decreases the permeability of the shale and reduces well injectivity (Bachu, 2008). On the other hand, crystals may grow in pores and exert pressure on pores, causing local stress concentrations that can induce damage around pores in the rock matrix, which ultimately raises permeability.

The fracturing fluids are designed to avoid unstable chemical reactions at the interface between the fluid and the fractures, propagate the fracture tip during the injection, and keep the fractures open during withdrawal. High-precision video recordings of injection experiments in shale (Hayatdavoudi et al., 2015) indicate that the chemical imbalance between the rock and the fluid triggers the migration of ions within the lattice of the rock matrix. Chemical substitutions could explain why organic molecules eventually migrate towards fractures, with the implication that enhanced oil recovery is mostly driven by transport of molecules within the crystallographic micro-structure of shale.

However, the numerous processes that occur simultaneously at different scales are coupled (e.g. occur at same time and may affect each other), which raises fundamental questions about the micro-processes that control the rate of deformation (i.e. how fast a shape changes), the triggering mechanisms of fracture bifurcation (splitting), and crack coalescence (joining).

Uncertainty comes from the accuracy of thermodynamic models to predict microscopic processes at different scales, and from the couplings that exist between adsorption, suction, diffusion and fracture propagation. As a result, little is known about the waste fluids that flow from oil and gas boreholes (Elsner et al., 2015). Refer to the supplemental materials for detail on the state of the art in modeling.

Uncertainty

As seen in the lab, then, the process of hydraulic fracturing is rife with uncertainty, even about the most basic behaviors of fluid and rock. The mechanics and dynamics of hydraulic fracturing involve complex interactions across scales. To make sense of them, researchers develop models that are always simpler than the dynamics themselves, models that may be adequate for some purposes but not for others. Models always have the possibility of missing something, such as a physical or chemical interaction that might in practice give rise to a hazard.

3. In the Field: Identifying Hazards

The careful work of researchers outlined above can provide insight into just one piece of the larger puzzle. Hydraulic fracturing and the extraction of oil and gas also involve other systems at other scales, modeled by researchers in other fields. Accordingly, we turn now to an overview of some of the main hazards associated with hydraulic fracturing, drawing from various sources. The focus is not so much on the modeling of basic dynamics as on the probability of adverse outcomes as experienced by people and other living beings.

In terms of our schema, we are leaving the lab on the way to the forum, taking in the various ways in which the mechanics and dynamics of hydraulic fracturing and subsequent resource extraction may become matters of public concern in the field.

Induced Seismicity

One hazard often associated with hydraulic fracturing in the public imagination are earthquakes caused by the injection of fluid into shale beds. The magnitude (M) of an earthquake indicates the quantity of energy liberated by the seismic source. For an event to be felt, the magnitude needs to exceed 2 ($M > 2$). In the U.S., seismic events that are likely related to energy development have been documented in Alabama, Arkansas, California, Colorado, Illinois, Louisiana, Mississippi, Nebraska, Nevada, New Mexico, Ohio, Oklahoma and Texas.

Criteria used by the scientific community to establish correlations between seismic events and human activity include “the amplitude and direction of the state of stress in the Earth’s crust in the vicinity of the fluid injection or withdrawal area; the presence, orientation, and physical properties of nearby faults; pore fluid pressure (pressure of fluids in the pores of the rocks at depth, hereafter simply called pore pressure); pore pressure change; the rates and volumes of fluid being injected or withdrawn; and the rock properties in the subsurface” (National Research Council, 2013).

The lack of data (pre- and post-event, near and far from the energy exploitation site) often impedes the establishment of a causal link between a particular seismic event and human activity. The National Research Council (2013) reported that earthquakes attributed to energy geotechnologies are caused by a change in pore pressure and/or stress in the presence of faults (with specific properties and orientation) and critical states of stress in situ. Statistical analysis found that the closer to zero the net fluid balance (total balance of fluid injected into or removed from the subsurface), the less seismicity is induced.

As of 2013, only one case of felt seismicity (M ~ 2.8) in the U.S. was linked with high probability to hydraulic fracturing for shale gas development, out of 35,000 hydraulically fractured shale gas wells. The National Research Council (2013) explained this low number was caused by the short time of injection and small volume of liquid injected in the process of hydraulic fracturing in shale reservoirs. In general, the seismic events are too small, the regional networks are too sparse, and the data quality is often too poor to confirm a causal link to fluid injection for energy development.

That said, causal links have been established between the injection wells used for wastewater from hydraulic fracturing operations (over 150,000 wells in the U.S) and previously unrecognized faults in the subsurface. Although most disposal wells involve injection of wastewater at low pressure into aquifers of high porosity and permeability, the long-term effects of the increasing number of injection wells remain unknown.

In 2014, researchers at the U.S. Geological Survey studied a human-induced M5.0 earthquake near Prague, Oklahoma, which occurred in November 2011. The M5.0 foreshock occurred in close proximity to active fluid injection wells. The fluid injection caused a buildup of pore fluid pressure, and a decrease in the fault strength causing rupture (Sumy et al., 2014). The research, which analyzes the role of coseismic stress transfer along the fault, also suggests that the foreshock may have triggered the M5.7 mainshock, which in turn triggered thousands of aftershocks along separate portions of the Wilzetta fault system, including a M5.0 aftershock. If this hypothesis is correct, the M5.7 earthquake in Prague, Oklahoma would be the largest and most powerful earthquake ever associated with wastewater injection to date.

More current research has developed various techniques to demonstrate the probable connections between hydraulic fracturing and the various seismic events around the country. For example, in a study published in 2015, an optimized multi-station cross-correlation template-matching routine identified 77 events in Poland Township, Ohio, which coincided with nearby hydraulic fracturing operations and had local magnitudes (M_L) of up to 3. These earthquakes were some of the largest induced by hydraulic fracturing in the United States (Skoumal et al., 2015).

In summary, the mechanisms that cause earthquakes are known and the relationships among hydraulic fracturing, wastewater injection wells, and seismic activity have been determined and refined through ongoing research, but scientists cannot predict their occurrence, because (1) there is insufficient data on fault locations and properties, in situ stresses, fluid pressures, and rock properties; and (2) current modeling tools do not account for all the thermo-hydro-chemo-mechanical processes that take place in fractured rock systems.

Fresh Water Consumption

Another matter of public concern is that hydraulic fracturing may draw from local supplies of fresh water as a base for fracturing fluid. In some regions, this may raise the possibility of shortages of fresh water for other uses.

In fact, the volume of water injected for hydraulic fracturing is highly dependent on the type of geologic formation, the depth of the formation and the length of well exploited (including the horizontal part of the well). So-called low-volume hydraulic fracturing, typically conducted in vertical wells, requires between 20,000 and 80,000 gallons of water or other fluid. By contrast, high-volume hydraulic fracturing in low permeability formations such as shales often include long horizontal well segments and require millions of gallons of water: 3 to more than 5 million gallons per well in Marcellus shale and up to 7.8 million gallons for a multi-stage fracturing operation in a horizontal well (Environmental Protection Agency, 2015). Greater demand for fresh water in some shale gas producing counties raises concerns about the impact on the local ecosystem, particularly from short term, high volume withdrawals. Moreover, the overall assessment of the exploitation of water resources is complicated by some vocabulary inconsistencies, illustrated by the following excerpt: “It is not known whether any of [the disclosures reported in FracFocus 1.0] used the term ‘fresh’ to refer to recycled fluids that was [sic.] treated to achieve the quality of fresh water. […] Differences observed among disclosures from different states are likely due, in part, to variations in the rate of overall reporting of water sources and inconsistencies in terminology used” (Environmental Protection Agency, 2015).

The newest hydraulic fracturing technologies are based on the injection of gels instead of freshwater-based fluids. Still, there is increasing concern about potential local or regional water shortages that could occur if the number of injection wells continues to grow. The volumetric recovery of injected water depends on the mineral composition and microstructure of shale, and varies over the life span of a well. Reported recovery rates range between 5% and 85%. As of 2012, companies were recycling 14% of hydraulic fracturing wastewater (i.e., using it again for further hydraulic fracturing), up from 1% in 2010. In 2014, representative recovery rates were estimated to lie between 30% and 50% (Stringfellow et al., 2014). Further, recent changes at the state government level have shown the potential to reduce regulation and encourage wastewater recycling. For example, in March 2015, the New Mexico Oil Conservation Commission published a rule to encourage oil and gas producers to recycle wastewater by reducing wastewater storage requirements in recycling facilities (Small, 2015).

Water Pollution

Regulatory agencies have established requirements for reporting the composition of fluids injected during unconventional oil and gas production, but not all the reporting is mandatory (e.g., Rahm et al., 2013). In response to concerns about potential environmental and health impacts of hydraulic fracturing, the Ground Water Protection Council (GWPC) and the Interstate Oil and Gas Compact Commission (IOGCC) developed a national hydraulic fracturing chemical registry in the late 2000s, called ‘FracFocus’ (Groundwater Protection Council and Interstate Oil and Gas Compact Commission, 2016). Oil and gas producers started uploading information on the composition of hydraulic fracturing fluids used at individual production wells to FracFocus 1.0 in April 2011, on a voluntary basis (Environmental Protection Agency, 2015). Participation in the FracFocus registry is now “required by 12 state regulatory agencies to meet chemical disclosure requirements in order to receive environmental permits"(Stringfellow et al., 2014).

"Fracking fluids" consist of water mixed with polymers and nitrogen bubbles, which are used to promote fracture propagation during the injection phase. After injection, proppants such as sand, quartz, or silica are introduced to maintain the fractures open upon fluid withdrawal. The permeability of proppants is higher than that of the rock matrix, which is favorable to natural gas extraction. The "slurry" that is injected to maintain fractures open is composed of base fluids and sand at 98% to 99.5% by volume. "Base fluids are the fluids into which additives and proppants are mixed to create the fracturing fluid." In more than 93% of the disclosures reported in FracFocus 1.0, water was listed as the base fluid: "The median maximum reported concentration of water in hydraulic fracturing fluid was 88% by mass, with a range of 68% to 99% (5th and 95th percentile), suggesting its primary use as a base fluid." (Environmental Protection Agency, 2015).

Liquid nitrogen and carbon dioxide are the most frequently used non-aqueous ingredients that are mixed with water to form the base fluid. Gases are used to generate a foam, which not only reduces the use of water, but also avoids contact between water and reactive rock formations. Nitrogen and carbon dioxide are also known to expand during the production phase, which promotes flowback and facilitates natural gas extraction. The most common types of chemicals added to the base fluid and the propping agents are listed in Table 1 (based on information about chemical constituents and their toxicology in Stringfellow et al., 2014).

Table 1. Range of concentrations of chemical compounds mixed with the base fluid and the proppant (compiled from data in Stringfellow et al. 2014)

Constituent	Contents	Purpose
Gelling agents	10–1000 mg/L	Increase fracturing fluid viscosity, increase proppant suspension and promote transport into developed fractures
Friction reducers ("slickwater")	30–1200 mg/L	Reduce fluid surface tension and facilitate fracturing fluid withdrawal (alternative to gelling agents)
Crosslinkers	0.5 - 250 mg/L	Bind gel polymer molecules together to form larger molecules, increase fracturing fluid viscosity and facilitate proppant transport
Breakers	1 - 400 mg/L	Reverse crosslinking and reduce fluid viscosity after fracturing, to facilitate the removal of residual polymers from newly created fractures (usually encapsulated or with time-release)
pH adjusters	100 - 300 mg/L	Adjust pH and improve effectiveness of certain chemical additives
Biocides	10 – 800 mg/L	Control bacteria that degrade fracturing chemicals and/or corrode well tubing, casings, and equipment.
Corrosion inhibitors	10 – 7000 mg/L	Form a protective layer on metal well components and prevent corrosion by acids, salts, and corrosive gasses
Scale inhibitors	75 – 400 mg/L	Prevent formation plugging, ensure rock permeability and allow proper fluid flow in piping and tubing
Iron controllers	50 – 200 mg/L	Control iron precipitates that block flow paths within the formation
Clay stabilizers	50 – 2000 mg/L	Prevent clay swelling, which can cause borehole instability and reduce reservoir rock permeability

Surfactants	50 – 1800 mg/L	Optimize fracturing fluid viscosity, reduce surface tension between the fluid and shale, and assist natural gas extraction after fracturing

After the injection of fluids to fracture the shale, there is the possibility that groundwater may be contaminated by salts, dissolved constituents and stray gases, and that surface water may be contaminated from spills and leaks around drilling pads, disposal of untreated wastewater, fracturing fluids and backflow fluids. Wells in Northeastern Pennsylvania (NE PA) are almost exclusively used for shale gas extraction, which makes it possible to distinguish contamination from hydraulic fracturing from that of older legacy wells. The composition of salinized groundwater in NE PA is deduced from that of the pore fluids in the natural formation or in the upper geological layers, which were proven to be similar (Gregory and Dzombak, 2011). More direct assessments of water contamination in Pennsylvania have recently been published (e.g., Llewellyn et al., 2015; Muehlenbachs et al., 2012; Vidic et al., 2013; Warner et al., 2013).

Spills and leaks of this fluid can pollute soil, surface water and shallow groundwater with toxic organic chemicals, salts, metals and other constituents. For example, elevated levels of benzene, toluene and xylene were found in the groundwater of Weld County, Colorado (Vengosh et al., 2014). Similarly, hypersaline flowback fluids are expected to bring high concentrations of salts, alkaline and metallic compounds and radionuclides into surface water (Gregory and Dzombak, 2011). Flowback fluids (including Marcellus brines) contain high levels of radium because fracking fluids react with shale, which is naturally rich in uranium. Therefore, the disposal of hydraulic fracturing waste fluids into freshwater streams or ponds can result in radium adsorption onto stream sediments in disposal and spill sites.

Given the depth of shale formations typically developed for oil and gas extraction, percolation of fracking fluids from shale fractures to surface aquifers is unlikely. However, there are instances (Vengosh et al., 2014) in which leaks were detected at the interface between the borehole and the rockmass, allowing fluid flow along the well into the groundwater. For example, a joint U.S. Geological Survey and U.S. Fish and Wildlife Service study showed that widespread deaths of aquatic species were likely caused by the unauthorized disposal of hydraulic fracturing fluids to Acorn Fork Creek in southeastern Kentucky (Gregory and Dzombak, 2011).

Greenhouse Gas Emissions

When power plants switch from coal to natural gas, greenhouse gas emissions are reduced by half. Thus a possible benefit of hydraulic fracturing is an increase in the available supply of natural gas, facilitating the transition of more power plants to lower emission fuels. On the other hand, increased exploitation of shale gas raises concerns over possible releases of natural gas, particularly methane, into the atmosphere during extraction.

Carbon dioxide has been typically regarded as the worst greenhouse gas due to its prevalence, accounting for approximately 81% of all greenhouse gas emissions (Environmental Protection Agency, 2016b). Despite its potency, methane is typically ignored because it accounts for a much smaller percentage (11 percent) of total emissions (Environmental Protection Agency, 2016b). But methane has a warming potential that is significantly higher than carbon dioxide. It is far more effective at trapping heat in the atmosphere than carbon dioxide, so even small amounts of methane emissions can have a large influence on the greenhouse gas footprint of natural gas use (Howarth, 2014).

According to the 2013 Intergovernmental Panel on Climate Change Synthesis Report (Stocker et al., 2014), methane is 34 times stronger as a heat-trapping gas than CO2 over a 100-year time scale, so its global-warming potential (GWP) is 34. This is an approximately 40% increase from the IPCC's previous GWP estimate of 25. These findings have motivated the Environmental Protection Agency to release the first-ever standards to reduce methane, volatile organic compounds (VOCs) and toxic air emissions in the oil and natural gas industry. The standards are expected to reduce 510,000 short tons of methane in 2025, the equivalent of reducing 11 million metric tons of carbon dioxide (Environmental Protection Agency, 2016a).

Ongoing research is also being conducted to both better understand and quantify the release of methane gas from hydraulic fracturing as to reduce such releases. For example, researchers are using new top down estimates to more accurately quantify the amount of methane and non-methane hydrocarbon emissions from hydraulic fracturing in order to better determine their impact on climate change and air quality (Pétron et al., 2014). Recent technological advances to reduce methane emissions include the utilization of "Green Completion" methods, sealed systems for plunger lift replacement, and replacement of high-bleed pneumatic controllers, among others (Fernandez, 2013). Well operators may also use methane released by the well to power the exploitation site, though often they simply burn off the methane, as can be seen from flares at the well site. (Green, personal communication, 2015).

Explosion Hazards

There have been explosive events associated with hydraulic fracturing, but the hazard seems easily overstated and misunderstood. While public portrayals of such events may imply that explosions originate deep underground, stemming from the rupturing of shale, investigations show the explosive hazard is most often related to storage of hydraulic fracturing fluids in pressure vessels and to flaws in the design, construction and maintenance of the machinery on the surface, including the wellhead itself.

For example, on the morning of February 11, 2014, a large gas well explosion and fire in Dunkard Township, Pennsylvania, was reported to the Pennsylvania Emergency Management Agency (PEMA). The explosion killed one worker and injured another, and the subsequent fire spread to an adjacent well, which in turn triggered the explosion of a propane tanker truck on the site. In all, it took emergency personnel over 12 hours to extinguish the flames (Department of Environmental Protection (PA), 2014).

After the event, the Pennsylvania Department of Environmental Protection (DEP) conducted a thorough investigation, which concluded that the explosion originated from natural gas leaking from the wellhead under high pressure. The gland nut and lockscrews, used in wellhead equipment to mechanically energize or retain internal wellhead components, were ejected from the machinery, suggesting a possible cause. Apparently, the assembly on the wellhead was loosened several days before this incident and was not properly re-secured. The DEP provided a set of recommendations to the well owner to prevent future incidents. These recommendations include inspection and quality control issues for the gland nut and lockscrew mechanisms. The recommendations put the responsibility to prevent future explosions on the well owners, inspectors, contractors and engineers associated with the well (Colaneri, 2014).

4. In the Forum: Deliberating about Acceptable Risk

And so we arrive in the forum, where important decisions are to be made about hydraulic fracturing and subsequent extraction, somehow taking into account the risks and uncertainties in the lab and in the field.

For any matter of public policy concerning possible hazards, the question is not only, “what are the risks?” but, “which risks are acceptable?” The former is a factual question, while the latter is a normative or ethical question. In other words, what level of risk *ought* people put up with, relative to what level of expected benefit?

It would seem that scientific and engineering research into hazards and harms is necessary for gauging whether and under what conditions the risks of hydraulic fracturing are acceptable, but is such research, on its own, sufficient? If scientists and engineers in the lab or in the field could answer every question about hazard and harm, this alone would not resolve the policy question of whether the risks are acceptable.

The issue is the role of engineers and scientists as experts in an ongoing public deliberation on the question of whether and under what conditions the risks of hydraulic fracturing are acceptable. Engineers and scientists, because of their salient expertise, may seek to or be asked to inform the deliberation (see Dewey, 1991). But which special responsibilities fall on engineers and scientists in their role as experts, given the character and limitations of the knowledge that they can provide?

Specialization

A necessary feature of discipline-bound scientific and engineering research is a narrow focus. In order to achieve a desired level of precision and control in the lab or in the field, a researcher often has to attend only to a particular phenomenon or type of phenomenon within a narrow range of spatiotemporal scales. Other phenomena and scales must be controlled in order to avoid confounding complications.

In the example of geomechanics discussed above in section 2, developing an adequate account of the behavior of shale itself under conditions introduced by hydraulic fracturing requires a focus on particular interactions across a particular range of scales, from nanometers to micrometers, up to a few meters. However, many of the hazards of hydraulic fracturing that are of public concern may involve phenomena across larger scales. The risk of pollution of ground water, for example, might arise at the scale of meters or kilometers and take into account dynamics beyond the scope of studies in the field of geomechanics.

Nevertheless, research in geomechanics at the scale of nanometers to micrometers can contribute to an understanding of larger-scale hazards. For example, fractures in shale take the form of meter-scale flat planes, not jagged scars. Combining this knowledge with how the layers of rock formed over eons, the behavior of groundwater, and the depth at which the oil and gas deposits of economic interest may be found, could lead to ruling out one hazard as follows. The probability that fractures which opened up around a well bore 1.5 km below the surface would extend up into groundwater less than 300 m below the surface, allowing for direct migration of gas or oil into supplies of drinking water, would be near zero. This example shows that research at a very small scale contributes to the understanding of how fractures in shale form and propagate, and that such understanding can rule out certain hazards at larger scales.

Any one study in any one laboratory provides only one piece of the puzzle relevant to a risk assessment because laboratory research is so carefully delimited. Scientific and engineering research is thus partial, in the sense that it tends to study one carefully delimited part of the world at a time (see Peirce, 1955). The entire research enterprise of the contemporary world is to some degree a patchwork of such partial studies in need of a broader synthesis.

The analytic-deliberative approach to risk characterization developed by the National Research Council (1996) suggests that such a synthesis can only take place in the forum. Analysis and deliberation are "two complementary approaches to gaining knowledge of the world," each shaping the other in significant ways. Notably, it is the context of public deliberation that establishes whether a particular analytic technique – including, one might suppose, the laboratory techniques of geomechanical modeling – are appropriate in characterizing and managing risks.

As researchers attempt to act as experts in public deliberation, communication becomes an issue. Much of the evidence that supports scientific argumentation uses mathematic symbols and may not easily be communicated to the public without misunderstanding. The core symbols involved in reading skills are the letters of the alphabet. By contrast, mathematics "has many types and levels of representations [...] which build on one another as the mathematical ideas become more abstract. [...] Communicating about mathematical ideas, therefore, requires that one choose representations" that balance transparency, efficiency, generality and clarity (National Research Council, 2001).

The use of formal mathematical symbols is a comfort zone for engineers, but not the appropriate communication medium to reach a broad audience. For example, how can a given group of scientists explain the mechanical, physical and chemical processes that govern rock deformation and fluid flow during hydraulic fracturing? The exercise first requires unfolding scientific problems in English sentences, which means translating mathematical formalism into words. Then, the abstract modeling framework has to be reconstructed in this new symbolic representation. Engineers must both explain physical process in lay terms and adapt the level of representation to the audience.

Funding Sources

Knowledge produced by research may be partial from the necessary specialization of specific studies, but it may be partial in another sense, as well. Put simply, scientific and engineering research is expensive, so researchers are perpetually in need of sources of funding, whether from industry, philanthropy or public funds. Lack of funding may move work to answer questions about hazards out of reach, regardless of technical or conceptual challenges of modeling and testing.

Each of the entities offering funding does so for its own purposes, including profit, political or humanitarian aims, or the broader interests of public well-being and economic growth. The criteria by which they decide to award funding are likely to be shaped by aims other than pure scientific interest or concern to understand hazards and mitigate risks. If a researcher seeks to address some key area of uncertainty regarding the behavior of shale under conditions created by hydraulic fracturing but cannot secure funding for that research, the question may go unanswered, leaving one area of uncertainty unresolved. Researchers may not personally be corrupted by the sources of their funding, but their attention and effort are directed this way or that by others.

Even if researchers remain uncorrupted by the pursuit of funding, a problem of public perception and trust remains. Engineers and scientists may present themselves as impartial experts seeking to inform public deliberation, and yet the funding that contributes to the foundation of their expertise may be provided by those who have some particular stake in the direction and outcome of that same deliberative process, particularly when that funding comes from the private sector. In this, researchers risk being perceived as “stealth issue advocates” rather than as honest brokers (see Pielke, 2007). At the very least, this can present an apparent conflict of interest (Harris et al., 2005), one that could undermine public trust not only in particular researchers but also in the entire research enterprise. This is arguably a bad thing for serious public deliberation about matters that clearly require sophisticated understanding of physical systems’ behavior.

Value Language

The engineering and scientific research considered so far addresses the hazards and risks of hydraulic fracturing, where risk is understood in empirical terms as the product of the probability of a hazard and the magnitude of the resulting harm. In the context of public deliberation, engineers and scientists may be called upon or take it upon themselves to draw from their empirical research conclusions about whether a particular risk is acceptable.

To do so, however, is to smuggle in ethical discussions; in other words, to make claims about what is good and bad. While *risk* is an empirical concept, *acceptable risk* is an ethical concept; to claim a risk is acceptable is to say it is one people *ought to* accept or cope with in light of other values that are at stake (Harris et al., 2005).

The shift from empirical claims about risk to ethical claims about acceptable risk is often difficult to see. The language of utility, an ethical value system, seems to lend itself to the language of empirical research. Whether people are better or worse off in the aggregate *seems* like a scientific question – a matter of causal connections and the measurement of magnitude – but it is still a value question, indexed to what states of affairs are worth having for their own sake. The question of what states of affairs are worth having seems to be outside the scope of scientific and engineering research, whatever that research may contribute to understanding the underlying hazards and their causal consequences. More than this, utility is not the only variety of value at stake in public deliberation about acceptable risks. Equally important are values that focus on respect for the inherent worth of persons as beings capable of choosing and acting on their own behalf, what are called autonomy values.

Attention to autonomy values implies that, in public deliberation regarding the risks of hydraulic fracturing, the question of whether a risk is acceptable must be decided not only in terms of benefits and harms, but also in terms of consent, dignity, equity and the openness and robustness of the deliberative process itself (Hansson, 2005; Sagoff, 2003). It may well be reasonable to say that, all else being equal, a risk is acceptable to the degree the magnitude of the expected benefit outweighs the magnitude of the risk. It is also reasonable to say at the same time that, all else being equal, a risk to which individuals or communities give their free and informed consent are more acceptable than those imposed against their will or without their knowledge.

The Responsibilities of Engineers

Having examined some of the particular uncertainties, hazards and risks of hydraulic fracturing, and briefly addressed some of the values involved in acceptable risk, we return to our initial question: What are the responsibilities of engineers and scientists in addressing risk and uncertainty, and participating in public deliberation regarding hydraulic fracturing?

We said at the outset that the two frames of reference – the lab and the forum – are so distinct from one another as to seem unconnected, especially in regards to the scales and terms of inquiry that predominate in each. The example of hydraulic fracturing suggests, however, that the lab and the forum are connected at least in one direction: the work of the forum in deliberating about the risks associated with engineered systems requires the direct contributions of researchers and engineers whose main work is in the lab or in the field.

There is also a connection in the other direction, to the extent researchers and engineers are *professionals*. To be a professional is to hold a particular status and prestige, granted by the public and held in trust to the public. So, to be a researcher or an engineer, in the lab or in the field, is already to play a defined social role, one sanctioned and supported by the forum.

We emphasize this is a delimited role, including bounds to the scope of professional authority: in general, professionals are prohibited from offering professional judgment on matters beyond their particular expertise. A doctor offering an expert opinion on a matter of law, or a civil engineer on a matter of chemical engineering, would be overstepping that limit and so breaking the public trust. This leads us to suggest three, relatively modest obligations on scientists and engineers in their relationship to the public forum.

First, engineers and scientists in their role as experts seeking to inform public deliberation ought to remain within the limitations of that role. They may have authority on the answers to particular empirical questions, but not over every question of policy. In other words, researchers ought to keep in mind that sound empirical research in the lab and sound technical judgment in the field may be necessary for good policy, but they are not sufficient as a basis for good policy in the forum.

Second, engineers and scientists ought to exercise due modesty in reporting the results of empirical research, making the scope and limits of each finding and model as clear as possible. This includes acknowledging and describing remaining areas of uncertainty, especially those that may be most relevant to questions of public interest.

Third, engineers and scientists in their role as experts seeking to inform public deliberation should be careful of apparent, potential and actual conflict of interest, and they should beware of the risk of capture by parties with vested interests in particular policy outcomes. They ought to avoid even apparent conflicts of interest whenever possible, and they ought to disclose those conflicts where they are unavoidable.

5. The Formation of Responsible Engineers

At last, we come back around to the main question that has motivated our work on this project: How might the lab-field-forum schema and the insights it has yielded inform our work as educators? The faculty authors are all directly engaged, in one way and another, in the formation of young engineers and scientists.

We use the term *formation* in contrast with *training* or *instruction*. Training aims at the development of technical competence in the lab and in the field: formation encompasses not only a concern for technical proficiency, but the development of engineers and scientists as professionals capable of taking up the particular social roles implied in being designated a professional. In the initial conversations that led to this project, two of us spoke of *visionary* engineering, which fuses technical expertise in the lab and in the field with a clear and critical vision of what work in those domains means in its wider context, and how it fits with the needs and reasonable expectations of others (following Weston, 2012).

Likewise, training suggests classroom instruction and hands-on demonstration and practice of particular technical skills, while formation encompasses that as well as well as other forms of direction, instruction, advising and mentorship.

What we aspire to is an integrated approach to the formation of engineers and scientists. As it is, the standard approach at our own institution is simply to require engineering students to take one or another courses in the humanities and social sciences, courses that may or may not have much ethical salience, and may or may not prompt students to reflect on the connection between ethical perspectives and their own technical training.

What we envision instead is to provide structured learning experiences focused on the social context of and the ethical values at stake in the work of scientists and engineers. Ideally, these experiences may be woven into the engineering curriculum, perhaps mainly in design-based courses and/or capstone courses. The result may be a redesigned, team-taught course or modules that may be integrated into existing courses. One of the faculty authors has already undertaken a team-taught, design-based course in engineering ethics, in which groups of students worked on a design project for a client with opportunities for a rigorous consideration of the ethical values implicated in decisions they made along the way.

What we can offer here is some suggestions, based on what we have learned in our exploration of the risks of hydraulic fracturing and the responsibilities of engineers, as to the desired learning outcomes of the kinds of experiences we have in mind.

The broad frame for our suggested learning outcomes is the idea of *moral imagination.* Based on the notion that human beings make sense of our experience through mental models or conceptual schemas, moral imagination is the capacity to make sense of the ethical aspects of experience, grounded in the particularities of events and circumstances (Werhane, 1999). This encompasses 1) the capacity to see a particular event or circumstance as involving ethical values, 2) the capacity to see a particular event or circumstance from others' points of view, through other conceptual schemas, and 3) the capacity to reframe a problem situation in order to open up new possibilities for responding to it (adapted from Werhane, 1999).

In this light, our hope for the lab-field-forum schema is that it can help to foster moral imagination, that engineers in the lab or in the field have the capacity to notice and respond to the values implicated in their work, and to imagine how their work, its circumstances, and possible hazards look from the points of view of others with whom they share the forum.

The specific outcomes of the learning experiences we aim to develop and implement may be stated as follows:

1. Students should be better able to identify and describe ethical values at stake in particular problem situations in the lab or in the field.

   For example: If students are presented with a problem situation in a laboratory setting in which they are called on to determine an appropriate scale at which to model the fracturing of shale, they should be able to articulate the possible ethical weight of that choice in terms of how the model might inform (or misinform, or distort) later discussions of hazards, risks and acceptable risk in the field and the forum.

2. Students should be better able to describe the problem situation as it would be seen by others who may bring to bear other schemas as well as their particular needs and expectations.

For example: If students are presented with a problem situation in the field involving a possible hazard from hydraulic fracturing and subsequent extraction, they should be able to articulate how others who may be affected by that hazard would see the situation, and how the concerns expressed by some might be grounded in reasonable expectations of safety and mutual respect rather than a simple fear-reaction.

3. Students should be better able to develop and assess a diverse and nuanced array of options for responding to a problem situation.

   For example: If students are presented with a problem situation in the forum involving a determination of whether the risks of a particular oil-field development project are acceptable, students should be able to set out an array of nuanced options for responding to the situation, looking beyond a simple yes-or-no decision; they should seek out ways of framing a response that can attend to and honor a wide range of perspectives and value considerations.

To this initial list of outcomes we might also add entries concerning role responsibility, intellectual modesty, and proficiency in the language of the forum, but each of those would still be tied to the central aim of fostering the development of moral imagination as a set of tools or capacities that should be available to engineers and scientists, in whatever context they may be working.

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Supplemental Materials

Models for Solid Deformation and Fluid Flow

Understanding the mechanics of hydraulic fracturing requires more than an understanding of the behavior of the materials involved, considered separately. It is also necessary to consider models developed for describing and predicting the behavior of shale and of fluids in relation to one another, both how rock deforms and fractures in response to fluids, and how fluids flow in response to the structure of rock.

Hydro-mechanical models, which deal with both the fluid and solid bodies, are needed to account for shale deformation and changes in crack patterns. Analytical penny-shaped crack models were proposed to describe idealized fracture propagation, but hydraulic fracturing can be modeled more realistically with Finite Element Methods (FEM) at the reservoir scale (e.g., Adachi et al., 2007). FEM are numerical techniques that find approximate solutions to problems of this type. Extended Finite Element Methods (XFEM) use complex mathematical equations to update the position of the fracture tip (e.g., Mohammadi, 2008). In contrast, cohesive surface models assume a predefined fracture propagation path, and elasto-plastic models represent discrete fractures by irreversible deformation induced by differential stress (e.g., Schrefler et al., 2006). Current models fail at predicting the feedback effects between hydraulic fracture propagation and dissipative phenomena (i.e., irreversible deformation and micro-crack propagation) ahead of the fracture tip.

Note that micromechanics and upscaling were successfully used to determine the mechanical properties of porous solids subject to deformation and damage (Deudé et al., 2002; Lu and Elsworth, 2012; Lubarda and Krajcinovic, 1993). In those models, damage represents micro-cracks, considered as inclusions, with postulated shape and space distributions. Governing equations depend on the scale of observation: micromechanical models are formulated at the scale of pores and micro-cracks, which makes the approach questionable for attempting to capture the growth of micro-cracks into larger-scale fractures (Lacy et al., 1999). Moving to larger scales, the equations that govern the deformability of rock may still be valid, while those that govern regimes of fluid flow may not (Schubnel et al., 2006).

One way to account for crack connectivity is to introduce percolation thresholds (i.e., the transition from no- or low-flow to higher flow), which was done in a few upscaling schemes (Kondo and Dormieux, 2004). However, these upscaling schemes do not capture the three dimensional effects of micro-crack connectivity and pore shape on flow path. Moreover, micro-crack coalescence requires increasing the scale of observation, or modeling the transition from a distribution of micro-cracks (represented as continuum damage) to a discrete fracture. Transition between smeared micro-crack propagation and discrete fracture propagation was modeled based on the assumption that the characteristic dimension of the microstructure was known (Mazars and Pijaudier-Cabot, 1996), which is impractical for the prediction of damage and fractures in rocks that have discontinuities at multiple scales (such as shale).

Some other models were proposed, but were limited to periodic microstructures (e.g., Pruess et al., 1990; Zimmermann et al., 1996) or flat debonded micro-cracks (Suzuki, 2012).

In contrast with micromechanics models just discussed, continuum mechanics approaches capture the average geometrical changes (e.g., size, aspect ratio, orientation) undergone by elements of the microstructure (e.g. pores, cracks, capillaries) under variable far field boundary conditions (e.g. stress, pore pressure, temperature, chemical concentrations). Biot's theory of poromechanics couples macroscopic deformation to porosity changes. Thermodynamic models of in-pore crystallization relate variations of macroscopic stress to changes of pore orientation (Lecampion, 2010; Scherer, 2004).

However, nanometer-scale pores can contain only a few molecules of carbon dioxide or hydrocarbon, which cannot be represented as a fluid continuum in a classical fluid flow model. Adsorption, adhesion of atoms, ions, or molecules from a gas, liquid, or dissolved solid to a surface, at this scale is controlled by chemical potentials; and the energy dissipated by the resulting fabric changes cannot be expressed by means of porosity changes and pore pressures, which are the variables used in continuum poromechanics. In meso-pores (less than a micron in size), adsorption is controlled by the energy of interfaces, which can be expressed in function of a surface stress. Stress/strain relationships are similar to the ones obtained in Biot's theory of elasticity, but encompass an adsorption stress and an adsorption strain (Vandamme et al., 2010). In micro-pores and micro-cracks (a micron in size and larger), porosity controls rock poromechanical behavior. Therefore, in nano-porous rocks, constitutive laws at different scales are governed by independent thermodynamic variables, which cannot be related by space averaging techniques employed in classical up-scaling schemes and poromechanics.

Turning from models of rock deformation to models of fluid flow in relation to rock structure, a large number of rock permeability models are based on the Kozeny-Carman relation (Carman, 1937; Kozeny, 1925), which assumes that fluid flows in a bundle of parallel pipes contained in a representative volume of rock. The mental picture of parallel pipes has some appeal; not only does it make the structure of shale easy to visualize, but it is mathematically tractable. However, it is an inadequate model of shale behavior.

Several approaches have been proposed to relate permeability to microstructure in a way that is less tidy but more adequate than the image of parallel pipes. These include: (1) modified Kozeny-Carman permeability formulas (Berryman and Blair, 1986; Brace et al., 1968; Mavko and Nur, 1997) that relate flow properties to other physical properties that indirectly account for tortuosity (e.g., electrical conductivity); (2) statistical flow networks models (Arson and Pereira, 2013; Dienes, 1982; Schubnel et al., 2006), characterized by the probability density functions of the dimensions, aspect ratios and orientations of geometric elements of the network (e.g., tubes, penny-shaped cracks, ellipsoids); (3) fractal network models (e.g., Tyler and Wheatcraft, 1990); and (4) mechanical homogenization schemes adapted to fluid flow (Kondo and Dormieux, 2004).

Fluid flow does not only depend on microstructure, but also on other coupled processes that include suction, diffusion (molecular intermingling) and dissolution. Most models that relate capillary pressure to pore size (e.g., Van Genuchten, 1980) assume that the pore network is a bundle of pipes of constant cross section, which are entirely filled with the same fluid (e.g., liquid or gas). Infiltration models capture the positive feedback effect of the dissolution front propagation on reactive fluid flow (e.g., Chadam et al., 1988). The dissolution front is assumed to be planar (e.g., Zhao et al., 2008), which is insufficient to model reactive flow in two or three dimensions.

By contrast, the percolation theory (Stauffer and Aharony, 1994) can be used to predict the space organization of connected fluid segments in a network with a pre-defined topology. The probability law of network site occupancy is assumed to be known for each invading fluid. When used for fractal flow networks, this binary modeling approach explains why population dynamics obey power laws. However, because the probability of site occupancy is assumed *a priori*, the percolation theory does not link the evolution of fluid fronts to macroscopic flow constraints.

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