November 15, 2013

Attention Docket ID No. EPA-HQ-ORD-2010-0674
U.S. Environmental Protection Agency
EPA Docket Center
Mail code: 28221T
1200 Constitution Avenue, N.W.
Washington, D.C. 20460

Re: Docket ID No. EPA-HQ-ORD-2010-0674
EPA's Hydraulic Fracturing Research Related to Drinking Water Resources

The Natural Resources Defense Council (NRDC) appreciates the Environmental Protection Agency's (EPA's) scientific research work to examine the relationship between hydraulic fracturing and the risks and impacts to drinking water resources. NRDC also appreciated the opportunity to send representatives to the April and June 2013 Workshops on this topic.

This letter responds to EPA's request for additional information to be considered in the research efforts. Below we have provided a specific list of recommendations based on the scientific research work presented by EPA and its contractors at the April and June 2013 Workshops.

1. Hydraulic Fracture Model Type, Calibration, and Access.

NRDC supports EPA's efforts to independently model hydraulic fracturing (HF) scenarios and examine the risks and impacts to drinking water resources. EPA hired Lawrence Berkley National Laboratory (LBNL) to develop a three dimensional numerical, deterministic, multi-phase computer simulation model, based on first principles, using open source data. LBNL's model uses the TOUGH model code. The LBNL model will not be a usable long-term product for industry, EPA, or the public because it requires access to proprietary software, must be run on a super computer, and will not have a user-friendly front-end built.

NRDC believes that it is very important for EPA to develop a national HF modeling tool that can be used by EPA, industry, and the public to examine the risks and impacts to drinking water resources, using computer codes and systems that are available to a broad range of scientists and engineers. A standardized HF modeling tool would provide a platform to predict and prevent adverse impacts.

In addition to creating a standardized HF model, EPA should also investigate the HF models currently used by industry to design, implement, and evaluate HF impacts. It will be very important for EPA to thoroughly investigate the accuracy, reliability and predictive capability of industry's current modeling tools since government approvals to proceed with HF jobs both at a federal and state level are based on the use of these tools. EPA should determine whether industry's tools are accurate and reliable or should identify any limitations or improvements needed.

At the April and June 2013 Workshops LBNL reported that it had not yet examined existing oil/gas industry HF models. LBNL expressed a willingness to review industry model data and model runs that examine the same scenarios it is investigating. However, at the time of the workshops, industry had not provided model data or model runs for LBNL to evaluate.

NRDC recommends that EPA request industry to provide access to their models and request industry to model the same scenarios that LBNL is modeling so that EPA can verify if the two models are providing consistent and accurate results. This way EPA will be able to examine HF models used by industry and LBNL to compare and contrast the accuracy, reliability, and predictive capabilities of those models. If industry has not provided EPA the data needed to calibrate the models or access to its models, EPA should document where industry has not provided field data or access to the models.

LBNL reported that it has not used actual field data to calibrate the model. EPA and LBNL made repeated requests during the workshop for industry model and field data. NRDC requests that EPA's models be calibrated with actual field data, including data where groundwater contamination has actually occurred. EPA must validate that LBNL's theoretical simulation models used field data and that the model can accurately replicate past performance ("history match") and can accurately predict future performance. History matching a model (field data validation and calibration) is a key step in the model building process that can't be skipped.

Industry has provided some data on actual HF propagation data for HF treatments at 5,000 feet and deeper; however, industry has not provided data on the actual HF propagation height for HF treatments shallower than 5,000' which are of greatest concern to drinking water resources. This is critical scientific data needed for EPA's analysis. NRDC recommends that EPA ask industry to provide this data.

Without these revisions to the model, it will not be a comprehensive analysis of how hydraulic fracturing can contaminate drinking water and will not answer all of the public's questions.

2. Hydraulic Fracture Modeling of Shale, Coal Bed Methane and Tight Sandstones

EPA's research plan includes an examination of shale, coal bed methane, and tight sandstone hydrocarbon HF impacts; however, LBNL was not tasked by EPA to model coal bed methane and tight sandstone impacts. LBNL's work only investigates HF propagation scenarios for the Marcellus Shale.

NRDC supports EPA's work to evaluate HF propagation scenarios for the Marcellus Shale. However, the Marcellus Shale is only one type of shale formation. EPA should examine the full range of shale types planned for development in the United States, or explain why it opted to only examine the Marcellus Shale.

EPA should also complete modeling of coal bed methane and tight sandstone hydrocarbon HF impacts. Coal bed methane resources are often located within Underground Source of Drinking Water (USDW) where HF treatments are directly injected into the drinking water resource, or where hydraulic fracturing fluids are injected just below the base of the drinking water resource with little or no vertical separation. For example, LBNL's proposed modeling scenarios assume that the USDW is always separated by an intervening zone of at least 330'; this is not true in the case where a HF treatment occurs directly into a USDW.

Citizens are concerned about groundwater contamination linked to HF that has occurred in coal bed methane or tight sandstone formations. These concerns are significant and should not be ignored. Coal bed methane HF scenario modeling is an important and easy scenario for EPA to model, given that in many cases coal bed methane reservoirs are located within an Underground Source of Drinking Water (USDW) and LBNL's current model could be readily adapted to examine these scenarios.

Without expanding the model, the public will not accept that the EPA has fully examined the risks to drinking water from hydraulic fracturing.

Additionally, NRDC supports all of the recommendations in the comments that Dr. Tom Myers submitted to EPA on June 21, 2013, titled "Comments on Subsurface Modeling of Hydraulic Fracturing." We have attached a copy to our comments for EPA's ease of reference.

3. Hydraulic Fracture Modeling Scenarios

EPA proposes to examine five (5) potential failure scenarios in wells targeting the Marcellus Shale Formation.

1. Scenario A: Migration Along Wellbore;
2. Scenario B: Hydraulically Induced Fracture;
3. Scenario C: Hydraulically Induced Fracture Through Oil/Gas (located in an intervening zone);
4. Scenario D: Natural Pathway (Fault or Fracture); and
5. Scenario E: Artificial Pathway.

NRDC supports these proposed scenarios; however, this list is incomplete. It is essential that EPA evaluate the full range of well types, formation types, well construction hazards, and design flaws that may be encountered in order to fulfill the goal of the research study. EPA must evaluate the following additional scenarios to ensure adequate scientific inquiry into the risks to drinking water:

- **Wells with insufficient casing or cement barriers**. For example, open hole completions used in tight sandstone reservoirs or coal bed methane wells where the production zone is not cased or cemented. LBNL's model assumes that all wells will be completed with casing and cement across the entire wellbore; this is not true for all wells types under EPA study.

- **Wells that were improperly constructed, leaving a portion of the USDW zone exposed**. LBNL's model assumes that wells will have casing and cement set across the entire USDW zone; yet, this may not be true for all wells. Some operators may not have correctly identified the USDW depth and set casing and cement across the entire USDW zone. Some operators may have installed poor water protection string cement jobs that do not isolate the USDW zone from HF fluid and hydrocarbon contamination. This situation could also occur if the intermediate casing is just "tacked" with cement at the intermediate casing shoe (bottom 500-600'), leaving the rest of the intermediate casing annulus open. If the annulus is un-cemented, the USDW zone could be exposed hydrocarbons that migrate into the annulus.
- **Wells where HF treatments are injected directly into a USDW**. LBNL's model assumes that all HF jobs are injected at a depth of at least 330' below the USDW; this is not the case for a coal bed methane well where the HF fluid is injected directly into a USDW.

  EPA's work should examine the impacts to USDW including all United States subsurface waters included in EPA's definition of a USDW. Most coal bed methane wells are typically designed and installed as vertical wells with an open-hole (un-cemented) completion in the production zone. Some coal bed methane wells are cased and cemented through the hydrocarbon interval, using horizontal drain-holes but this is less common. Therefore, proposed shale gas Scenarios A-E showing a cased, cemented horizontal well through the hydrocarbon interval separated from the USDW by an intervening zone does not represent the typical CBM well.
- **Wells where HF treatments are injected into tight sandstones that are located in close vertical proximity to USDW.** LBNL's model does not examine HF into sandstones at all.
- **Wells where the operator didn't verify if the water protection string was deep enough or casing/cement condition was adequate before conducting a HF**. Not every well will be constructed to a best practice standard. In particular, EPA should examine existing wells that have been subject to corrosion and erosion or where outdated construction practices and materials were used. LBNL's model does not examine casing integrity failures due to corrosion or erosion.

LBNL should proceed with modeling Scenario D but must ensure that the model parameters reflect geologically realistic conditions in order to alleviate the geo-mechanical implausibility concerns raised at the June 2013 workshop. Some participants were concerned that the proposed scenario was geomechanically implausible because gas would not have been trapped in a reservoir if a naturally conductive fault or fracture directly connected the gas zone to a shallower USDW. While this concern is valid, it is also an oversimplification to assume that gas could not be stored in a reservoir cut by a naturally conductive fault or fracture. A perfect seal is not necessary to trap hydrocarbons. It is geologically possible to have a hydrocarbon reservoir seal that includes faults or fractures that may have low or partial transmissibility, such that gas or other fluids may be able to migrate slowly over time without completely depleting a hydrocarbon accumulation. In fact, many oil and gas fields were discovered due to the presence of surface seeps, demonstrating that subsurface pathways between oil- and gas-bearing reservoirs and the surface (or USDWs) can exist without completely compromising the ability of a formation to retain hydrocarbons. In some cases, fault and fracture systems have been identified as the source of surface seeps at producing oil and gas fields, for example this occurred at the Pineview Field in Utah and the Lost Hills field in California.[1] More recently, researchers found that a low pressure anomaly in the Eagle Ford shale play is the result of fractures in the overlying Austin Chalk, which consequently forms only a partial seal at the study location.[2] Although wells at this location are less productive, gas is nonetheless still present.

Consequently, NRDC recommends that LBNL proceed with modeling Scenario D, but ensure that the model reflects plausible scenarios under which faults and fractures act as partial seals, allowing some leakage while not compromising the ability of a reservoir to retain commercial quantities of hydrocarbons. Additionally, we also recommend that a second, related scenario (Scenario D2) be modeled to include a hydrocarbon reservoir cap that would have initially trapped the hydrocarbons and prevented upward migration prior to installation of a well into that hydrocarbon zone.

The second scenario ("D2") should examine how the installation of a well or implementation of a HF treatment penetrating the hydrocarbon reservoir cap could allow hydrocarbons to escape the reservoir and vertically migrate to a drinking water resource. For example, a poorly designed HF treatment that propagates out "out-of zone" could create a pathway from the hydrocarbon reservoir through the cap into an overlying natural fracture system or conductive fault. This scenario should examine the likelihood of hydrocarbons entering an overlying natural fracture system or conductive fault reaching drinking water resources.

4. Well Files Under Review

NRDC is concerned that well files reviewed may not include wells with cement evaluation logs that were run on the water protection casing strings (surface casing and intermediate casing when used as part of the water protection casing string). It is very important that EPA's study examine the quality of the water protection casing string. Cement evaluation log data only provided by industry on production casing is insufficient to verify the quality of cement used to protect USDWs. EPA's research should document whether operators are running cement evaluation logs on the water protection casing strings to verify cement quality, and if so what the logs show. If operators are not running cement evaluation logs, EPA's research should examine the accuracy and reliability of any other methods that the operators are using to confirm cement integrity and make recommendations for best practices to verify cement integrity.

NRDC requests that for each well examined by EPA, that EPA determine the depth of protected water using EPA's definition of USDW and compare that depth to the water protection casing and cement barrier set in that well. This analysis will allow EPA to determine what portion of the USDW has been protected. As discussed further below, NRDC is concerned that because some

[1] Jones, V. T., and R. J. Drozd. "Predictions of oil or gas potential by near-surface geochemistry." AAPG Bulletin 67.6 (1983): 932-952.

[2] Bello, Hector, Gervasio Barzola, and Kit Clemons. "Seismic Attributes: Leveraging Seismic Data for Reservoir Characterization: Fracture Identification and Prediction To Understand Seal Integrity in the Unconventional Eagle Ford Shale Reservoir, South Texas, USA." Unconventional Resources Technology Conference. 2013.

states do not use the same definition of protected water as EPA that wells have been and continue to be constructed without protecting the entire USDW.

5. Federal vs. State Definition of Protected Water

EPA must clarify whether its study will examine protection of USDWs as defined by EPA or only protection of water resources as defined by the state. Federal and state definitions for USDW are inconsistent in some cases, resulting in some aquifers lacking protection.

Some states have adopted the EPA's definition of a USDW; other states have not. The states that have not adopted the USDW do not protect drinking water to the same depth as would be protected by EPA; these states only protect to a shallower depth set by the state's protected water definition. For example, several states do not use EPA's 10,000 mg/l Total Dissolved Solids (TDS) definition of USDW - using instead - 1,000 mg/l or 3,000 mg/l in some cases.[3]

According to EPA, some states only require casing to be set below the depth of current drinking water wells without consideration that future drinking water supplies may need to tap deeper aquifers, or even tap more saline or higher TDS waters and provide treatment.

Installation of surface casing and cement is not always sufficient to protect USDWs and in some cases multiple strings of cemented casing is required.

Therefore, in those states that only protect a portion of the USDW, and not the entire USDW as defined by EPA, there will be a portion of the USDW that is exposed to a higher risk of contamination.

EPA's research should identify which states do not protect the entire USDW, and provide an assessment of the amount of U.S. drinking water that is at risk where state regulations do require water protection casing string (surface and intermediate casing and cement across the entire USDW.

6. Best Practice Implementation

EPA should not assume that all operators are implementing "best practices" reported by some operators at the workshops. Some members of industry many be implementing best practices and some may not, and those that do may not be implementing them in all of their operations. EPA should instead identify which best practices are used, and then survey all the operators to find out how many operators (large and small) are actually using these practices and on how many wells in their inventory.

NRDC requests that EPA list each best practice used to reduce the risk of USDW contamination and provide a statistical analysis showing how many companies routinely use these best practices and where gaps exists.

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[3] For example, New York State defines drinking water as groundwater having a total dissolved solids (TDS) concentration equal to or less than 1,000 mg/l (see 6 NYCRR § 750-3.2(b)(21), and the Texas Railroad Commission defines freshwater as less than 1,000 mg/l TDS and useable water quality as less than 3,000 mg/l TDS. (see Title 16, Part 1, Chapter 3, Rule § 3.30).

7. Risks Poses by HF into Existing Wells

EPA should consider the risks of hydraulically fracturing existing wells, not only new wells, and verify the condition and construction of existing wells prior to HF. Some existing wells would not meet new well construction or integrity standards, or may have met those standards when originally constructed but have been subject to corrosion or mechanical wear since that time.

EPA should consider long term risks, such as well integrity failure due to sustained casing pressure. EPA should examine additional well failures including HF's in existing wells.

Conclusion

In conclusion, NRDC is very concerned about several fundamental aspects of the current study approach. The current scope of the study is too narrow to assess the full range of potential impacts to drinking water from HF into shales, coal bed methane, and tight sandstones and doesn't assess the full range of risks and impacts that could result from existing wells that were built to earlier standards or improperly constructed wells.

It is essential that EPA fulfill its own stated intent "to better understand **any** potential impacts of hydraulic fracturing on drinking water and ground water." (emphasis added). Fulfilling this goal of creating a comprehensive study is crucial to ensuring the public that all risks have been examined.

NRDC appreciates the opportunity to comment on this important research project. If EPA has any questions about our comments, please contact Briana Mordick, 415.875.8270, bmordick@nrdc.org.

Sincerely,

Briana Mordick
Staff Scientist
Natural Resources Defense Council

Attachment: June 21, 2013 Comments on Subsurface Modeling of Hydraulic Fracturing submitted to EPA by Dr. Tom Myers.

Technical Memorandum
Comments on Subsurface Modeling of Hydraulic Fracturing
Docket ID No. EPA-HQ-ORD-2010-0674

June 21, 2013

Prepared by: Tom Myers, Ph.D., Hydrologic Consultant

Prepared For: Natural Resources Defense Council

This memorandum outlines concerns about the scope of the subsurface modeling work being performed by Lawrence Berkley National Laboratory (LBNL), under contract to the EPA as presented at the EPA Hydraulic Fracturing Workshop at Research Triangle Park (April 16-17, 2013) and discussion session at Arlington, VA (June 3, 2013).

To summarize, I am concerned about the small spatial scale of the modeling, as well as its failure to consider overlapping or cumulative effects. The proposed modeling scenarios will not provide much insight regarding the potential for long-term contaminant transport or larger-scale or cumulative impacts of multiple and widespread hydraulic fracturing (HF) operations within a region. The proposed modeling scenarios are designed to only identify pathways related to one HF operation in a single wellbore. This memorandum recommends that LBNL expand its modeling work to examine the potential for long-term contaminant transport in the aftermath of widespread HF operations within a region.

Additionally, LBNL is not proposing to model impacts of HF into coal bed methane (CBM) reservoirs or tight sandstone reservoirs. LBNL's proposed modeling scenarios are limited to shale gas, while EPA's proposed study purports to include CBM and tight sandstones. Many reports of citizen concerns about groundwater contamination linked to HF have occurred in coalbed methane or tight sandstone formations. This memorandum recommends that LBNL expand its modeling work to examine potential contamination that could occur to an Underground Source of Drinking Water (USDW) by direct injection into a USDW or by a failure pathway that could cause contaminant migration from a CBM or tight sandstone well to a USDW.

LBNL's Modeling of Single HF Injection into a Single Wellbore

HF is designed to change the properties of the targeted hydrocarbon formation[1] by making it more permeable; a target formation is any geologic formation containing hydrocarbons, but in the context of HF the formation is considered unconventional and requires HF to release the oil

[1] Throughout this memorandum, I refer to the targeted hydrocarbon formation, which could include CBM, tight sandstone or shale, as a more generic "hydrocarbon formation" because EPA's study scope committed to study HF impacts to CBM, tight sandstones and shales.

or gas since it is tightly bound in a tight matrix. The EPA study will investigate the effects of HF using deterministic numerical models of fracture development and fluid transport. Although not described as such, the modeling is essentially interpretative because it is designed to determine whether the geophysics can allow an occurrence of fracture development or fluid transport, including slickwater or gas, to shallow groundwater without having substantial data with which to calibrate the model or verify its predictions. The modeling did not apparently consider the potential movement of natural brine or the movement of other naturally-occurring contaminants as a result of HF.

LBNL's model as presented at the workshops simulates one HF injection into a single wellbore to test through numerical simulations whether certain failure scenarios are possible. The five failure scenarios under study include: two scenarios that examine HF fractures extending from the hydrocarbon reservoir to shallow groundwater through the overburden via HF-induced fractures; HF-activated faults; groundwater contamination via failed casing or cement during a HF treatment; or contamination during a HF treatment that connects with an improperly constructed or improperly abandoned offset wells. These scenarios consider whether it is physically possible for HF-induced fractures to reach groundwater or whether the fluid migration induced by HF to groundwater is possible. Model runs are designed to determine what combination of model parameters will allow the contaminants to reach groundwater but will not determine the actual contamination probability.

LBNL is not planning to model long-term contaminant transport in the aftermath of widespread and concurrent HF operations within a region, or impacts of HF into CBM reservoirs or tight sandstone reservoirs. All of LBNL's scenarios assume that the hydrocarbon formation to undergo HF is located at some distance below (at least 330') the USDW. LBNL work has not, and apparently will not, examine any case where HF are conducted directly into the USDW, where contamination is immediate and direct, such as occurs in most CBM wells.

LBNL's modeling tracks the development of fractures and the movement of fluids through those fractures toward existing faults caused by HF operations in a single wellbore. Faults may be reactivated by fluid pressure lubricating the fault faces or by induced seismicity (see the presentations by Steve Kraemer and George Moridas)[2]or faults may be naturally conductive serving as HF pathways. The temporal scale appears to be on the order of a few months representing the time for one injection followed by the time for the pressure to reach a new equilibrium or for contaminants to flow up through failure pathways. EPA describes the scenarios as potential failure scenarios and implies they are the only ones possible. However, the five scenarios that EPA requested LBNL to model represent just a limited set of potential failures and only one potential *scale of failure*. LBNL's models do not consider the potential for a large-

[2] Presentations noted herein are those from the Hydraulic Fracturing Workshop held in Research Triangle Park on April 16 and 17, 2013.

scale failure caused by multiple hydraulic fracturing operations over a large area or examine the highest risk impact of direct HF injection into a USDW.

Each well pad may have dozens of wells and in areas with densely spaced well pads, HF injection over a short time period will cause changes beneath a large surface area. This would affect a much larger stimulated volume of rock than is being simulated by LBNL's current models. Over the long-term, overburden pressure and proppant compression may cause the HF-induced fractures to partially close, but to the extent that HF reaches existing natural fractures, or existing conductive faults, natural conductivity may be enhanced. The cumulative effect of hundreds of HF injections in a region larger than that affected by a single HF operation should be considered. Formation volumes much larger than those affected by a single HF operation would be affected by changes in pressure and brine displacement. This is not dissimilar to the changes caused by large-scale injection, such as waterflooding or gas flooding, which are common methods used to mobilize hydrocarbons by the oil and gas operators. It was this broad change that I hypothesized about in a simple fashion (Myers 2012). The proposed scenarios being examined by the LBNL models do not consider long-term transport, or any of the hydrogeologic changes in the hydrocarbon formation or overburden at a large scale created by modern, clustered, multi-well pad development.

Industry strives to keep the HF-induced fractures within the hydrocarbon formation, and when this is successful most of the HF fluid remains within the hydrocarbon formation where it may eventually imbibe. A failed HF job results in HF fluid leaving the hydrocarbon formation; fractures leaving the hydrocarbon formation will transport HF fluid along with mobilized hydrocarbons into formations above it. Additionally, HF may displace natural brine from the hydrocarbon formation to areas from which transport through any of the potential pathways to shallow groundwater could occur.

The required detail for LBNL's small-scale modeling may increase the likelihood that natural or HF-induced transport pathways will be missed or ignored. For example, small-scale modeling will miss the potential overlapping hydrogeologic effects of multiple HF operations from adjacent well bores or even different segments of the same well bore. For example, subsequent HF could extend the fractures caused by earlier HF operations either from different stages of the same wellbore or from adjacent wellbores.

Additionally, small-scale models will treat overburden as more impermeable than it actually is due to the inherent shortcomings associated with detailed modeling of thin layers where heterogeneities are not included. With LBNL's models having up to 1000 layers, there will be as many as 1000 lithologic changes, which means that properties such as permeability, conductivity, and porosity, will change 1000 times. Considering such detail in the layering without considering the heterogeneities of individual layers will result, for example, in an average vertical conductivity (Kv) that is controlled by the layers with the lowest value, which may be unrealistic because of the heterogeneities. Geologic formations that extend for miles are actually assemblages of heterogeneous lithologic layers which thicken, thin, and crop out such that layers within well cores from nearby wells rarely match. The calculation of average vertical conductivity with such layering implicitly assumes that flow is perpendicular to the layering when flow would actually follow the more permeable pathways around the less permeable formations. The effective vertical conductivity is substantially decreased by considering so many continuous lithologic layers unless fracture/fault zone or zones of higher conductivity are considered as passing through the layers.

Induced fracture modeling as a function of HF injection requires small discretization in all directions to accurately simulate the growth and development of a HF fracture. Parameters are set model cell by model cell, probably based on an average value for the given cell size, or scale. The smallest elements will be the size of actual fractures. Based on the property values for modeling presented at the Arlington meeting, all elements in large portions of the model have the same parameter values which indicates that the parameters for large volumes are based on the parameter as chosen for the very small scale of the element. Models that have larger element sizes usually have parameters with larger magnitudes due to scale effects (Schulze-Makuch et al., 1999). This is due to the small scale not including the natural fractures which are included at larger sizes (although the smallest elements are the size of an individual HF fracture). The effective vertical conductivity will depend on the assumed conductivity for each layer, set element by element, but, because of the small-scale and discretization, will not include natural fractures; for example, as the volume of a model element increases, the number of fractures that would naturally occur within the volume likely increases to a point and the conductivity also increases (Schulze-Makuch et al. 1999; Bear 1979). In addition, small-scale modeling may not include the fractures that affect flow only at larger scales, such as faults and fractures with spacing greater than the size of the model cell or element.

LBNL's current HF modeling will help to identify the cause of out-of-formation fractures. However, it could be very difficult to establish a range of parameters for which failure is more likely because the modeling is deterministic and extremely complex, and there is a need to establish realistic probability distributions to many parameters. Also, due to the massive model run time, the multiple runs necessary to estimate the range in properties that could cause this failure may not be feasible to complete. LBNL should use their complex modeling to determine whether the base geophysics actually allow a failure under reasonable conditions. Then, they should simplify the model, perhaps by combining layers, to analyze the probability that such a failure will occur because simple knowledge that a given failure scenario is possible is not very useful if the frequency of such a failure is not assessed.

A second useful purpose of fracture-development modeling could be to estimate the after-HF properties of the hydrocarbon formation. How will the permeability and conductivity of fractured hydrocarbon formation vary from what it was prior to HF? It is through these changes that HF can affect the hydrogeology of the region. A potential difficulty of assigning permeability parameters to the post-HF hydrocarbon formation is that there is no way to verify either the modeled fracture apertures or fracture densities or to calibrate the resulting permeability. The modeler should estimate intrinsic permeability (in L^2 units) (Bear 1979, p 67) using the average aperture radius or other suitable parameter for pore size for the calculation

This section has described my critiques associated with LBNL's modeling of that aspect of HF operations that is of primary concern to me. That is the potential for HF-induced fractures to propagate vertically out of the hydrocarbon zone into a formation above it -- or otherwise cause fluid to leak from the hydrocarbon formation to formations above it – where that formation has an upward natural hydrological gradient, resulting in potential USDW contamination via long-term hydrological transport (Myers, 2012). My second primary concern, one that LBNL has not considered at all, is that an upward gradient from below the hydrocarbon formation will combine with the increased permeability of the formation due to widespread HF as described above to drive contaminants, either HF fluid or natural brine, into formations above the hydrocarbon formation that have a long-term upward driving force that does not depend on the pressure imparted by the HF operation. In my experience as a hydrogeologist, it is common to find upward natural hydrological transportation in subsurface geologic formations. As explained in more detail later in this memorandum, there are scientific data that show that there is also an upward natural hydrological gradient that transports brine from below the Marcellus Shale to formations above the Marcellus Shale that could also transport HF contaminants and hydrocarbons into a USDW. LBNL's models do not appear to examine the potential for a natural upward hydrological gradient continuing to mobilize contaminants upward over a longer period of time, once mobilized by the initial HF. The next section discusses recommendations for expanding the modeling to better include large-scale factors.

Large-Scale Modeling of HF Impacts

The movement of brine from the Marcellus Shale to shallow aquifers has potentially been documented (Warner et al. 2012), although the exact pathway had not been determined and timescale for the transport was not estimated. Simple large-scale modeling suggested that natural advective transport from the Marcellus Shale to shallow aquifers could require from hundreds to up to 100,000 years depending on the properties of the formations between the shale and aquifers (Myers 2012). HF could shorten that natural timeframe by a couple orders of magnitude with potential transport with ideal conditions occurring in as little as 10 years (Myers 2012). Other studies have indicated that the concentration of methane gas in groundwater is higher near HF gas wells (Osborn et al. 2011). These studies all represent transport that would occur over a scale much larger than that associated with the simulation of one well bore with one HF operation.

EPA should therefore model the changes caused by HF over a large area and how those changes may affect the flow of water, brine, gases, and other contaminants. The spatial scale could range from a few square kilometers, to a cluster of well pads, to entire regions similar to those evaluated for carbon sequestration (Celia and Nordbotten 2009) or other large injection proposals. The primary difference between the large-scale HF modeling that I am proposing and carbon sequestration modeling that has been completed by others is that the modeling of HF would be of a large-scale change in formation properties with the injection of a relatively small amount of fluid, whereas sequestration modeling is of the long-term injection of a large volume of fluid without the formation properties changing. The actual amount of fluid injected with large-scale HF modeling depends on the total volume used for an HF operation, the amount of flowback, and the amount imbibed in the very small pores as oil or gas is released from the media. Large-scale HF modeling could utilize various assumptions to simplify the modeling that are not available for small-scale modeling, as listed below, adapted from Celia and Nordbotten (2009):

- Large-scale modeling can utilize an assumption that there is a sharp interface between fluids with substantially different properties, probably including the differences between HF fluid and brine (which has a density as high as 1200 kg/m^3 as compared to 1000 kg/m^3 for freshwater), which would allow simple two-phase flow modeling rather than multiphase modeling. Cihan et al. (2011) found that it is not even necessary to simulate multiphase flow for the injection of CO_2; they found that volumes of brine could be simulated as being injected into the model domain to represent the change in fluid volume and pressure caused by the injection.
- Geochemical reactions, dissolution, and geo-mechanical responses due to fluid movement away from the fracturing can be ignored. The details of small-scale HF operations, as they are occurring, would not be included, but the changes to the formations including the HF-induced fractures would be included.
- Fluid properties, primarily density, may be considered constant without considering the changes in temperature. The primary driving force in the system therefore would be the imposed vertical and horizontal gradients and residual pressure from the HF.
- The dominant spatial features of large scale modeling would be the large-scale geologic layers of the sedimentary basins and the small-scale faults or wells as leakage pathways. It is unnecessary to consider or model small-scale heterogeneities, which are factors that are very poorly known. Additionally, geologic formations are continuous through a region but lithologic layers that make up a formation are heterogeneous and likely discontinuous when considered at a small scale. Parameter values would be based on the representative elemental volume concept which includes matrix and fracture properties. The location and properties of potential faults are the exception in that they should be modeled as transport pathways.
- Probabilistic analysis can be used to determine the effect of uncertainty in the parameter values. These include the parameters that describe the fractured shale and those that describe the vertical pathways such as faults or wells.

A further simplification suggested by Celia and Nordbotten (2009) was that formations may be assumed to be horizontal and homogeneous. This may not be appropriate and with the other assumptions may not be necessary for simple large-scale modeling. The natural dip of the geologic formations in many sedimentary basins targeted for HF development of hydrocarbons may provide a pathway for a contaminant to bypass some of the horizontal confining layers. Also, the homogeneous conditions will not exist all around a formation layer because HF may have change the properties in some areas or because the formations may have naturally more conductive regions that will allow differing rates of vertical transport.

Large-scale transport from the hydrocarbon formation to shallow aquifers requires that there be a vertical gradient to drive the flow once the formation properties change (Myers 2012; Warner et al. 2012). Evidently there is a vertical gradient at some locations in the Marcellus Shale (Dresel and Rose 2010; Williams 2010; TAL 1981), though the source is not obvious. The upward movement of brine to encounter downward moving freshwater, as discussed by John Williams at the April workshop, demonstrates there is an upward gradient in the brine at least between some formations above the Marcellus Shale; the rise in water from wells perforated in formations below the Marcellus Shale to near the ground surface also demonstrates an upward gradient across the Marcellus Shale (Williams, 2010). A significant change in the hydrogeology affecting the flow of the brine would likely change the mixing point (i.e., depth) where brine and freshwater meet; this would be caused by a change in the upward flow rate of brine brought on by a change in conductivity or gradient. The EPA should test the sensitivity of contaminant transport to changes in the vertical gradient to explore whether the transport is even possible at time frames of interest to water managers. The EPA might also consider the potential sources of upward vertical gradients, such as glacial unloading or topography coupled with broad, steady-state circulation through the sedimentary basins (Garven, 1995).

Conclusion

In summary, current modeling being undertaken as part of the ongoing EPA HF study will not provide much insight on the potential for contaminant transport in the aftermath of widespread HF operations within a region, nor does it examine HF injection directly into a USDW such as occurs routinely in CBM wells. The potential for large-scale transport over long timescales has already been demonstrated, and as such it should be included among the scenarios EPA is considering, as well as model scenarios that examine contamination by CBM wells. Indeed, it was our understanding that this would be the case when the final study plan was published in December of 2011. Therefore, I urge the EPA to expand its modeling approach to include coarser-grained models to evaluate the potential for long-term (e.g., decadal) transport beneath large surface areas and include CBM model scenarios. I also urge the EPA to consider whether natural upward vertical gradients operative on a regional scale could promote this vertical transport. Such modeling would allow the EPA to address the risk of contamination probabilistically, relative to a broad range of parameters and vertical gradients relevant to contaminant transport and fate.

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