Some Scientific Failings with the
Draft Supplemental Generic Environmental Statement
And Proposed Regulations:
Comments and Recommendations

Comments Submitted to the NYS Dept. of Environmental Conservation

by

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and

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1.0 INTRODUCTION

Governor Cuomo has stressed the importance of using science to inform the decision by New York on the future of shale gas development in our State. Unfortunately, the draft supplemental generic environmental impact statement (dSGEIS) released on September 7, 2011 fails to use the best available science. As a result, the document is inadequate as one to inform the Governor and Commissioner Martens in their decision making, and some proposed new regulations give a false sense of safety.

My comments and recommendations focus on three sections of the dSGEIS, and a provision of the Proposed Express Terms. Under potential environmental impacts,

6.1.4 Groundwater Impacts Associated With Well Drilling and Construction
6.1.6 Hydraulic Fracturing Procedure

and under proposed mitigation measures,

7.1.4 Potential Ground Water Impacts Associated With Well Drilling and Construction

and within the proposed regulations,

Proposed Express Terms 6 NYCRR Part 560

I have extensive professional expertise and experience associated with these topics. I attach as an Appendix to this document an excerpt from my resume supporting this assertion. In all three sections, the dSGEIS has completely ignored or misinterpreted critically important science. As a result, the dSGEIS severely underestimates the potential environmental harm from shale gas development in NYS, and fails to provide an adequate basis for the development of appropriate regulation for high-volume hydraulic fracturing (HVHF) for such development.

Please note that all cited references are attached to this comment document. These references do not constitute an exhaustive search on any topic, yet additional literature on each topic, much of it peer-reviewed, is readily available, for example, through OnePetro at

(http://www.onepetro.org/mslib/app/search.do)

DEC and its contractors are strongly encouraged to do a more thorough search and analysis of the literature on these topics.

This document concludes with a summary of my comments and a corresponding set of recommendations for improvement of the SGEIS and related regulations.

2.0 dSGEIS SECTIONS 6.1.4.2 AND 6.1.6.1

The relevant sections are:

"*6.1.4.2 Fluids Pumped Into the Well*
Fluids for hydraulic fracturing are pumped into the wellbore for a short period of time per fracturing stage, until the rock fractures and the proppant has been placed. For each horizontal well the total pumping time is generally between 40 and 100 hours. ICF International, under its contract with NYSERDA to conduct research in support of SGEIS preparation, provided the following discussion and analysis with respect to the likelihood of groundwater contamination by fluids pumped into a wellbore for hydraulic fracturing (emphasis added):[29]

> "In the 1980s, the American Petroleum Institute (API) analyzed the risk of contamination from properly constructed Class II injection wells to an Underground Source of Drinking Water (USDW) due to corrosion of the casing and failure of the casing cement seal. Although the API did not address the risks for production wells, production wells would be expected to have a lower risk of groundwater contamination due to casing leakage. Unlike Class II injection wells which operate under sustained or frequent positive pressure, a hydraulically fractured production well experiences pressures below the formation pressure except for the short time when fracturing occurs. During production, the wellbore pressure would be less than the formation pressure in order for formation fluids or gas to flow to the well. Using the API analysis as an upper bound for the risk associated with the injection of hydraulic fracturing fluids, the probability of fracture fluids reaching a USDW due to failures in the casing or casing cement is estimated at less than 2×10^{-8} (fewer than 1 in 50 million wells)."

More recently, regulatory officials from 15 states have testified that groundwater contamination as a result of hydraulic fracturing, which includes this pumping process, has not occurred (Appendix 15)."

and

"*6.1.6.1 Wellbore Failure:*

As described in Section 6.1.4.2, the probability of fracture fluids reaching an underground source of drinking water (USDW) from properly constructed wells due to subsequent failures in the casing or casing cement due to corrosion is estimated at less than 2×10^{-8} (fewer than 1 in 50 million wells). Hydraulic fracturing is not known to cause wellbore failure in properly constructed wells."

2.1 Comments on dSGEIS SECTIONS 6.1.4.2 and 6.1.6.1

These sections confuse different integrity issues, and are based on absence of, or inapplicable, evidence, rather than a true analysis of the available scientific literature.

2.1.1 Confusion of Issues

First, Section 6.1.4 is supposed to address "Groundwater Impacts Associated with *Well Drilling and Construction",* while, apparently, Section 6.1.6 is supposed to address groundwater impacts due to the *"Hydraulic Fracturing Procedure".* It is therefore questionable why material concerning the injection of fracing fluids is contained in the former, rather than the latter. Therefore, the statement,

> "More recently, regulatory officials from 15 states have testified that groundwater contamination as a result of hydraulic fracturing, which includes this pumping process, has not occurred (Appendix 15)."

is out of place in section 6.1.4.2 and will be addressed below in section 2.2.

Groundwater impacts associated with *well drilling and construction* would include such phenomena as contamination of groundwater with drilling fluids during the drilling process, and migration of hydrocarbon gases and liquids due to faulty casing and/or faulty or absent cement during and after the construction process. Neither of these potential impacts is evaluated in 6.1.4 in the light of available scientific literature.

2.1.2 Absence of Evidence

Section 6.1.4 offers no literature review and analysis concerning migration of hydrocarbon gases and liquids due to faulty casing and/or faulty or absent cement during and after the drilling and construction process. As a minimum, the dSGEIS should address and evaluate this phenomenon in light of the following materials.

An overall description of mechanisms by which oil and gas wells can develop gas and other fluid leaks can be found in Dusseault et al. (2000). These mechanisms can be exacerbated with repeated pressurization of the casing, with open-hole sections along the casing, and with high gas pressures entering such open-hole sections. Note that effectively open-hole situations can occur in "cemented" non-vertical wells, since it is well known that cement effectiveness is substantially reduced in such wells, e.g. Sabins, 1990; Deenadayalu, 2010. This factor is overlooked in the dSGEIS's attempt to quantify the probability of fluid migration. All of these exacerbating factors lead to more rapid occurrence and upward growth of circumferential fractures, essentially disbonding, in the rock-cement and /or the cement-casing interface.

A schematic depiction of the phenomenon of gas, or additional fluid, migration upwards along a wellbore is presented in Figure 1, for the simplest case of bypass by disbonding of surface casing. Figure 2 is a close-up schematic showing other possible fluid pathways. *Additional layers of casing and attendant cement interfaces, as are proposed in the dSGEIS and attendant proposed regulations do not eliminate these phenomenon; they may, in fact, increase its likelihood*.

These phenomena are not rare in the oil and gas industry. Data on failure rates for cement jobs leading to sustained casing pressure and possible fluid migration into USDW can be found, for example, in Figure 3 from Brufatto et al. (2003), who evaluated over 15,500 wells. The authors state:

> "...many of today's wells are at risk. Failure to isolate sources of hydrocarbon either early in the well-construction process or long after production begins has resulted in abnormally pressurized casing strings and leaks of gas into zones that would otherwise not be gas bearing".

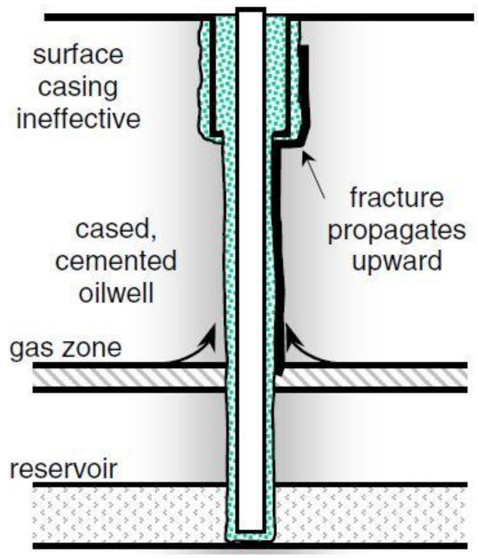


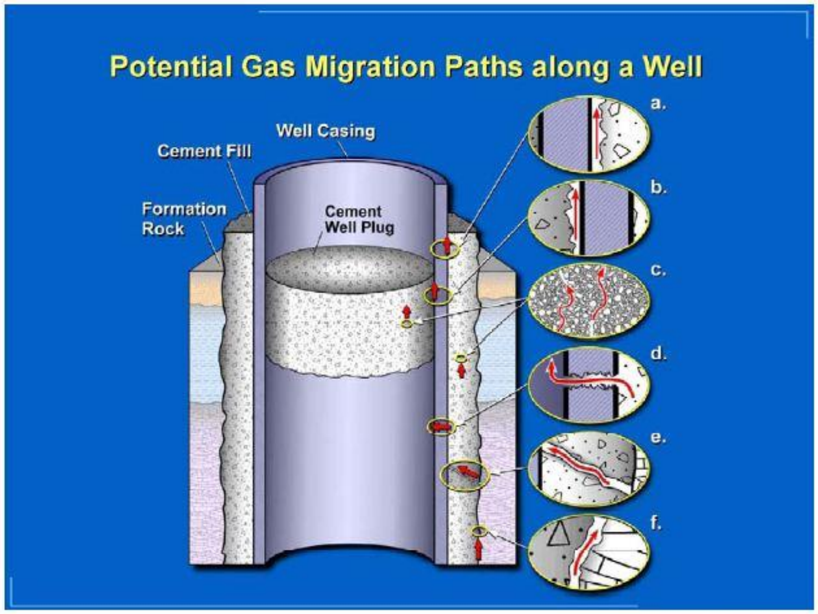
Figure 1. Simplified schematic showing phenomenon of upward gas migration along a casing string. From Dusseault *et al*., 2000.

In their statistical analysis of information about nearly 315,000 oil and gas wells, Watson and Bachu (2009) state:

> "The majority of leakage occurrence is because of time-independent mechanical factors controlled during wellbore drilling, construction, or abandonment— mainly cementing. Several of these factors may be inferred from readily available information such as spud date relating to regulation, oil price and technology."

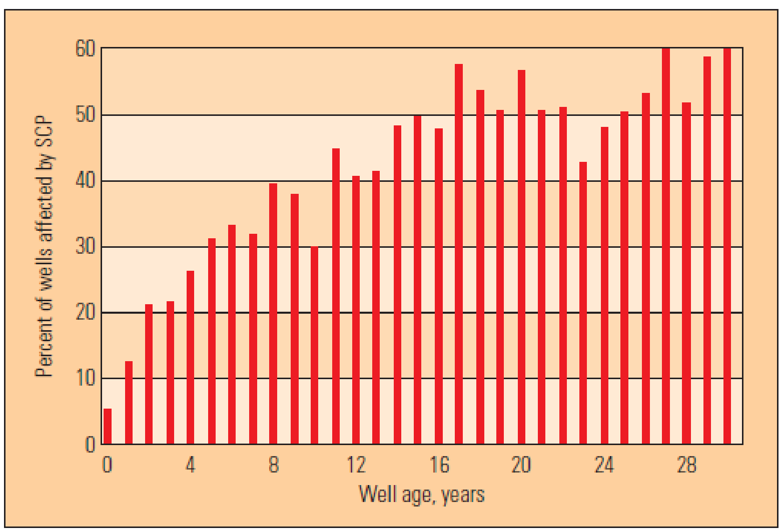
Figure 4 shows data gathered by Watson and Bachu that is consistent for young wells with that shown in Figure 3.

Together, this extensive, industry-produced data show that the expected rate of failure of containment of migration by cement is on the order of 5% (1 well in 20) initially. They also show that failure rate increases, as expected with age of a well. *The dSGEIS does not contain any reference to this well-known data, nor does it offer any form of quantification of expected probability of failure of shale gas wells in New York state. As a minimum, DEC should perform*



Source: Alberta Energy Utilities Board

Figure 2. Schematic of details of possible fluid migration paths.



^ Wells with SCP by age. Statistics from the United States Mineral Management Service (MMS) show the percentage of wells with SCP for wells in the outer continental shelf (OCS) area of the Gulf of Mexico, grouped by age of the wells. These data do not include wells in state waters or land locations.

Figure 3. Data on frequency of occurrence of sustained casing pressure (SCP). From Brufatto *et al*. (2003).

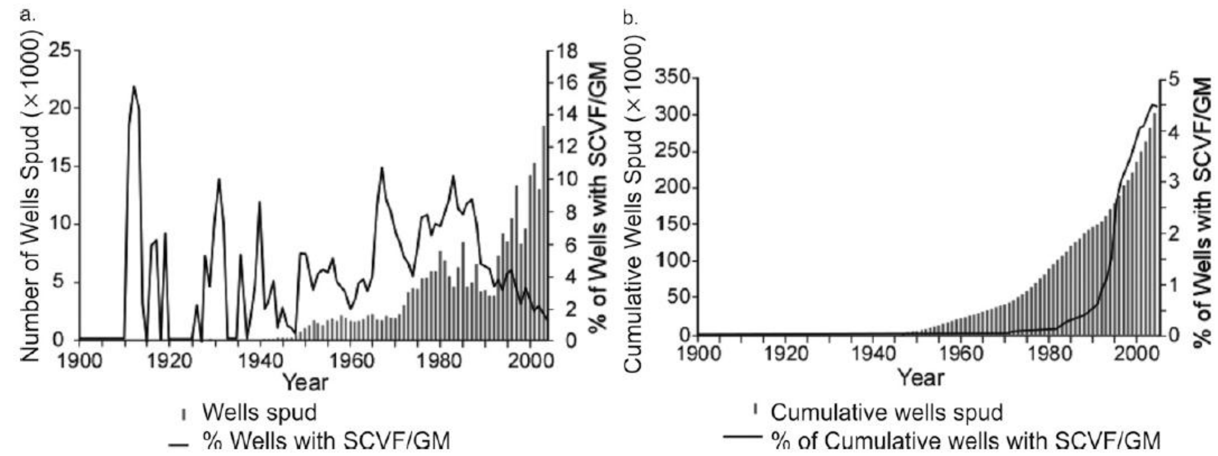


Fig. 8—Historical levels of drilling activity and SCVF/GM occurrence in Alberta: (a) by year of well spud and (b) by cumulative wells drilled.

Figure 4. Data on frequency of occurrence of sustained casing vent flow (SCVF) and groundwater migration. From Watson *et al*. (2009).

a statistical analysis of documented incidents of hydrocarbon migration into USDW in the Marcellus play in Pennsylvania, and develop its own prediction of immediate and long-term rate of cement failures for shale gas development in New York.

For example, my review of the Pennsylvania DEP database on violations (http://www.dep.state.pa.us/dep/deputate/minres/oilgas/OGInspectionsViolations/OGInspviol.htm)
shows that, during the first 8 months of 2011, 65 Marcellus wells were cited for faulty casing and cementing practices. During this same period, about 1300 Marcellus wells were drilled, yielding a normalized citation rate of about 5%. Sixty-four such citations were issued in 2010, when a total of 1386 Marcellus wells were drilled, yielding a similar citation rate. Granted, citations for such violations are not proof of migration and contamination of USDW; however, they are an indication that, despite ultra-modern cementing technologies operating in a supposed exacting regulatory environment, cementing failures are still occurring at rates similar to those cited in Figures 3 and 4.

I do not think it is possible to perform a rational cost-benefit analysis of shale gas development in New York without a science-based, probabilistic estimate of the number of expected well contamination incidents due to faulty well construction and inevitable break-downs in cement.

2.1.2 Inapplicable Evidence

The quoted text in section 6.1.4.2, which ends with,

> "Using the API analysis as an upper bound for the risk associated with the injection of hydraulic fracturing fluids, the probability of fracture fluids reaching a USDW due to failures in the casing or casing cement is estimated at less than 2 x 10^{-8} (fewer than 1 in 50 million wells)."

is not applicable to shale gas development. The study cited therein was performed on Class II waste injection wells, in entirely different geological settings from New York, and a decade before shale gas development. The statement,

> "Although the API did not address the risks for production wells, production wells would be expected to have a lower risk of groundwater contamination due to casing leakage."

is offered without any type of scientific support. The complete quoted text does not account for the actual practice of shale gas development in which multiple wells are drilled and fraced from a single pad, and pads are clustered. For example, the assertion that,

> "For each horizontal well the total pumping time is generally between 40 and 100 hours."

implies that there is no interaction among multiple adjacent laterals, or among wells on adjacent pads. Current practice in some shale gas developments involve 16 or more closely spaced (on the order of only 10 feet) verticals, and 8 or more sub-parallel laterals; pad spacing can be less that length of laterals. It is reasonable to expect that such multi-well, clustered pad technology will be employed in New York. It is well-known that communication among laterals on the same pad, and also among laterals on adjacent pads can occur. (BC Oil and Gas Commission, 2010; Handren, 2011). This means that total injection time during which migration through a faulty casing or cement job must include all fracing stages not on a single well, but on all wells on a pad, and, with horizontal communication known to be possible, also on all wells within communication distance.

Another reason why the cited probability of **2 x 10^{-8}** for Class II injection wells is totally inapplicable to shale gas production is that under Proposed Express Terms 6 NYCRR Parts 750.1 and 750.3, and in particular in "750-3.4 Requirement to obtain a permit":

> "(6) Unless an alternative plan is approved by the Department, certification that HVHF operations will be conducted only where the top of the fracture zone at all points along the proposed length of the wellbore is greater than both 2,000 feet below the surface and 1,000 feet below the base of fresh groundwater;"

there can be as few as 1000 feet between the top of the target shale layer and the base of fresh groundwater. The Class II injection wells included in this study had much larger separations between base of fresh water and injection zone, typically at least 5000 feet.

In summary, the dSGEIS offers no scientific evidence that the probability of contamination of USDW from migration due to casing/cement failure of frac or native fluids from many-well, clustered pads has been quantified.

2.2 Comments on Section 6.1.6.2 Subsurface Pathways

As noted above, the dSGEIS statement,

> "More recently, regulatory officials from 15 states have testified that groundwater contamination as a result of hydraulic fracturing, which includes this pumping process, has not occurred (Appendix 15)."

is out of place in section 6.1.4.2, and refers to phenomena addressed in section 6.1.6.2. *Moreover, this statement is not a result of scientific analysis of the practice addressed by this dSGEIS: high-volume fracing of shale formations using many-well, clustered pads and long laterals*. *Such a scientific analysis has never been done*.

The ICF analysis cited in this section,

> "Reference is made in Section 5.9 to ICF International's calculations of the rate at which fracturing fluids could move away from the wellbore through fractures and the rock matrix during pumping operations under hypothetical assumptions of a hydraulic connection. Appendix 11 provides ICF's full discussion of the principles governing potential fracture fluid flow under this hypothetical condition. ICF's conclusion is that ―hydraulic fracturing does not present a reasonably foreseeable risk of significant adverse environmental impacts to potential fresh water aquifers."

is based on a single well scenario, not at all representative of expected practice, and does not employ any state-of-the-art simulation technologies in arriving at its conclusions. Among its many technical faults, this report says, in dSGEIS Appendix 11:

> ***"1.2.5 Flow through fractures, faults, or unplugged borings***
> It is theoretically possible but extremely unlikely that a flow path such as a network of open fractures, an open fault, or an undetected and unplugged wellbore could exist that directly connects the hydraulically fractured zone to an aquifer."

Use of the phrase "extremely unlikely" without probabilistic quantification is unacceptable in a scientific analysis. The dSGEIS should report the probability of such an event based on scientific principles. For example, Figure 5 (Fisher, 2010) shows data relevant to this probability. *It shows many unexpected vertical excursions of the stimulated zone hundreds of, and in some cases more than a thousand, feet above the top of perforation, well above the top of the stimulated formation*. Data of this type could be used to quantify the probability only asserted in Appendix 11. Note, however, that this data provides no insight into the probability of unexpected vertical excursion for laterals shallower than 5000 feet. Such data would be necessary to quantify probability for most Marcellus wells in New York. *In the absence of such data, state-of-the-art simulation of the fracing process as actually practiced and in a realistic geological setting should be done.*

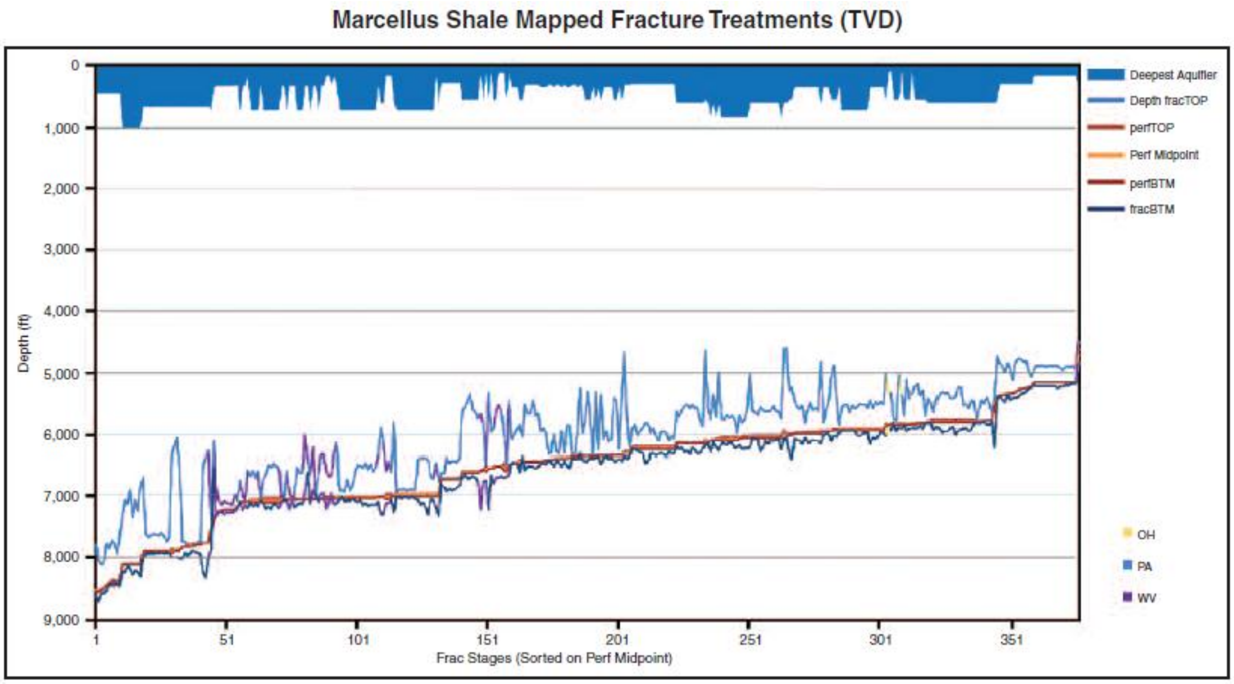


Figure 5. Results from microseismic evaluation of hydraulic fracture stimulation vertical extent in the Marcellus in three states. From Fisher, 2010.

Results from two ongoing scientific analyses by the U.S. EPA should be the bases for deciding whether fracing itself, in HVHF or otherwise, has contaminated, or might contaminate USDW. These studies are:

1. EPA's Study of Hydraulic Fracturing and Its Potential Impact on Drinking Water Resources, hereafter called the "EPA Fracing Study", (http://www.epa.gov/hfstudy/)
2. EPA's Pavillion, Wyoming, Groundwater Study, hereafter called the "EPA Pavillion Study" (http://www.epa.gov/region8/superfund/wy/pavillion/).

Contrary to the out-of-place statement cited above, the EPA Pavillion Study has tentatively concluded that groundwater contamination as a result of hydraulic fracturing has occurred. This study is currently open for public comment, and will undergo an extensive review process early in 2012. The DEC should wait for the results of that review process and then, if necessary, re-evaluate its position on this important question.

The EPA Fracing Study will, for the first time, use state-of-the-art computer modeling, like that currently used to design a single frac job, to evaluate the risk of groundwater contamination under realistic HVHF conditions, including fully 3D, multi-well, clustered pad scenarios. The DEC should link its quantification of risk of such events to the EPA Hydraulic Fracturing Study Plan, November 2011, pages 36 and 37 (http://www.epa.gov/hfstudy/#status) scenario evaluation component:

> "Scenario evaluation.
> EPA will use computer modeling to investigate the role of mechanical integrity in creating pathways for contaminant migration to ground and surface water resources. The models will include engineering and geological aspects, which will be informed by existing data. Models of the engineering systems will include the design and geometry of the vertical and horizontal wells in addition to information on the casing and cementing materials. Models of the geology will include the expected geometry of aquifers and aquitards/aquicludes, the permeability of the formations, and the geometry and nature of boundary conditions (e.g., closed and open basins, recharge/discharge).
>
> Once built, the models will be used to explore scenarios in which well integrity is compromised before or during hydraulic fracturing due to inadequate or inappropriate well design and construction. In these cases, the construction of the well is considered inadequate due to improper casing and/or cement or improper well construction. It is suspected that breakdowns in the well casing or cement may provide a high permeability pathway between the well casing and the borehole wall, which may lead to contamination of a drinking water aquifer. It will be informative to assess how different types of well construction and testing practices perform during these model scenarios and whether drinking water resources could be affected.
>
> EPA expects the research outlined above to produce the following:
> • Assessment of well failure scenarios during and after well injection that may lead to drinking water contamination. "

This study far exceeds the scope, and will employ much more rigorous modeling science, than the ICF study on which the dSGEIS now rests. *The dSGEIS offers no scientific evidence that the probability of contamination of USDW from migration of frac or native fluids from many-well, clustered pads over shale formations has been quantified*.

3.0 dSGEIS SECTION 7.1.4

The relevant text is part of section 7.1.4.2 Sufficiency of As-Built Wellbore Construction

"Current casing and cementing practices attached as conditions to all oil and gas well drilling permits state that intermediate casing string(s) and cementing requirements will be reviewed and approved by the Department on an individual well basis. The Department proposes to require, via permit condition and/or regulation, that for high-volume hydraulic fracturing the installation of intermediate casing in all wells covered under the SGEIS would be required. However, the Department may grant an exception to the intermediate casing requirement when technically justified. A request to waive the intermediate casing requirement would need to be made inwriting with supporting documentation showing that environmental protection and public safety would not be compromised by omission of the intermediate string. An example of circumstances that may warrant consideration of the omission of the intermediate string and granting of the waiver could include: 1) deep set surface casing, 2) relatively shallow total depth of well and 3) absence of fluid and gas in the section between the surface casing and target interval. Such intermediate casing waiver request may also be supported by the inclusion of information on the subsurface and geologic conditions from offsetting wells, if available."

3.1 Comments on dSGEIS Section 7.1.4.2

Figure 6, taken from the DEC website, is misleading and offers a false sense of safety to the public. It is misleading because it, and the Proposed Express Terms 6 NYCRR Part 560, which derives directly from dSGEIS section 7.1.4.2:

"§560.6 Well Construction and Operation.

(13) Intermediate casing must be installed in the well. The setting depth and design of the casing must be determined by taking into account all applicable drilling, geologic and well control factors. Additionally, the setting depth must consider the cementing requirements for the intermediate casing and the production casing as noted below. Any request to waive the intermediate casing requirement must be made in writing with supporting documentation and is subject to the department's approval. Information gathered from operations conducted on any single well or the first well drilled on a multi-well pad may be considered by the department upon a request for a waiver of the intermediate casing requirement on subsequent wells in the vicinity of the single well or subsequent wells on the same multi-well pad."

suggest that the proposed required additional, intermediate casing is a *new* technology: it is definitely not, not in New York and not in Pennsylvania. A check of DEC's database of well records will surely show that many existing gas wells in New York state, especially those accessing such deep formations as Trenton Black River, have been drilled with at least 4 levels

NEWS

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New York State Department of Environmental Conservation

Andrew M. Cuomo, Governor — Joe Martens, Commissioner

FACT SHEET: 2011 RECOMMENDATIONS FOR PERMITTING HIGH-VOLUME HYDRAULIC FRACTURING IN NEW YORK STATE

Additional Well Casing to Prevent Gas Migration: In most cases, an additional third, cemented well casing is required around each well to prevent the migration of gas. The three required casings are the surface casing, the new intermediate casing and the production casing. The depths of both surface and intermediate casings will be determined by site-specific conditions.

Figure 6. Reproduction of portion of DEC's online Fact Sheet.

of casing: conductor, surface, intermediate, and production. Figure 7 contains casing schematics for two vertical Pennsylvania Marcellus wells that clearly show this same casing design. Both of these wells were declared out of regulatory compliance by the Pennsylvania DEP (Consent order, 2009).

Neither additional well casing, nor any other technology or practice currently known, can "prevent" gas migration. Even an initially perfect cement job in all annuli can, over time, fail in one of the manners previously described herein. Some technologies, like certain additives to the cement, can decrease the rate of occurrence and/or the intensity of leakage, but the word "prevent" implies "no possibility", and that is "impossible".

The dSGEIS does not offer any scientific evidence that such an "additional" casing will decrease the likelihood of migration.

4.0 SUMMARY: COMMENTS AND RECOMMENDATIONS

Comment 1: *Groundwater impacts associated with well drilling and construction include such phenomena as contamination of groundwater with drilling fluids during the drilling process, and migration of hydrocarbon gases and liquids due to faulty casing and/or faulty or absent cement during the construction process. Neither of these potential impacts is evaluated in 6.1.4 in the light of available scientific literature.*

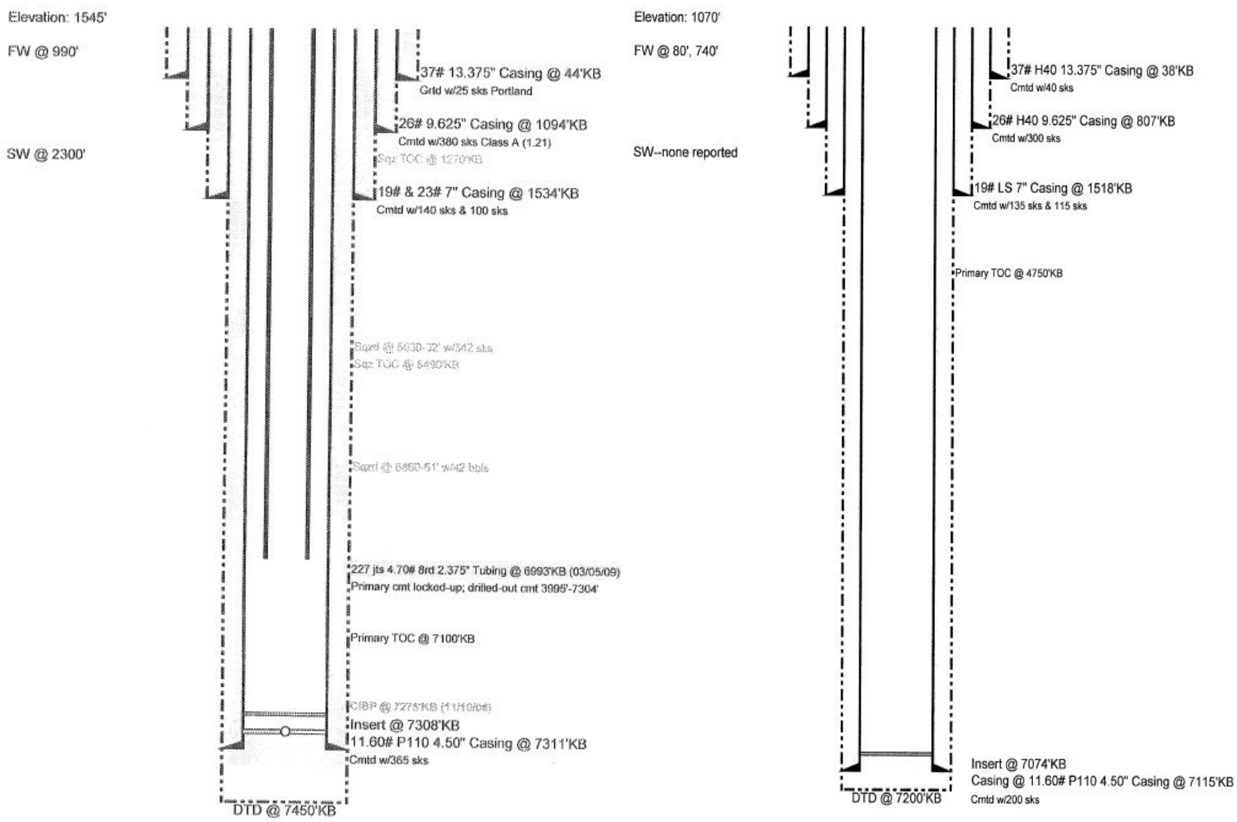

Figure 7. Casing designs for two vertical Pennsylvania Marcellus wells showing 4 strings of casing, including an intermediate casing. Both of these wells were declared out of regulatory compliance because of gas migration by the Pennsylvania DEP.

Recommendation: Rewrite section 6.1.4 to include scientific analysis of the probability of contamination of groundwater with drilling fluids during the drilling process, and migration of hydrocarbon gases and liquids due to faulty casing and/or faulty or absent cement during the well construction process. Eliminate from this section discussion of probability of groundwater contamination as a result of hydraulic fracturing, and include this discussion in section 6.1.6.2 where it belongs.

Comment 2: *Extensive industry-produced data show that the expected rate of failure of containment of migration by cement is on the order of 5% (1 well in 20) initially. They also show that failure rate increases, as expected with age of a well. The dSGEIS does not contain any reference to this well-known data, nor does it offer any form of quantification of expected probability of failure of shale gas wells in New York state.*

Recommendation: As a minimum, DEC should include this data in the SGEIS, and perform a statistical analysis of documented incidents of hydrocarbon migration into USDW in the Marcellus play in Pennsylvania, and develop its own prediction of immediate and long-term rate of cement failures for shale gas development in New York.

Comment 3: *The ICF analysis used in the dSGEIS to assert that the probability of migration of frac fluids into USDW is "extremely unlikely" is based on a single well scenario, not at all representative of the expected practice of multiple-well clustered pads, and does not employ any state-of-the-art simulation technologies in arriving at its conclusions*.

Recommendation: The DEC should perform, or have performed for it, a more realistic and stochastic analysis of this phenomenon. Alternatively, DEC should await the results of the two EPA studies on this phenomenon, as recommended next.

Comment 4: *The dSGEIS offers no scientific evidence that the probability of contamination of USDW from migration of frac or native fluids from many-well, clustered pads over shale formations has been quantified*.

Recommendations: The EPA Pavillion Study has tentatively concluded that groundwater contamination as a result of hydraulic fracturing has occurred. This study is currently open for public comment, and will undergo an extensive review process early in 2012. The DEC should wait for the results of that review process and then, if necessary, re-evaluate its position on this important question.

The EPA Fracing Study far exceeds the scope, and will employ much more rigorous modeling science, than the ICF study on which the dSGEIS now rests. The DEC should wait for the results of this study and then, if necessary, re-evaluate its position on this important question.

Comment 5: *The dSGEIS does not offer any scientific evidence that an "additional", intermediate string of casing will decrease the likelihood of migration of hydrocarbons into USDW*.

Recommendation: The DEC should acknowledge that the inclusion of an intermediate casing string is not a new technology in New York state oil and gas wells, and in Marcellus wells in other states. DEC should also perform a statistical study of the 4500 plus Marcellus wells already drilled in Pennsylvania to determine:

1. What percentage of this wells included an intermediate casing; and

2. Whether there exists any statistically meaningful difference in loss of well integrity between wells that do, and do not, have such casing.

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APPENDIX

Dr. A. R. Ingraffea: Background, Publications, and Projects Related to Hydraulic Fracturing and Gas Pipeline Safety

Note: ***Bold Italics*** indicates student or post-doctoral fellow of Dr. Ingraffea
Bold indicates O&G industry scientist/engineer

PROFESSIONAL SOCIETIES

American Rock Mechanics Association/Foundation

- Founding Member
- Member of the Board, 1999-2003

International Society for Rock Mechanics
Society of Petroleum Engineers

AWARDS IN ROCK MECHANICS

National Research Council/U.S. National Committee for Rock Mechanics 1978 Award for Outstanding Research in Rock Mechanics at the Doctoral Level

National Research Council/U. S. National Committee for Rock Mechanics 1991 Award for Applied Research for the paper, "Simulation of Hydraulic Fracture Propagation in Poroelastic Rock with Application to Stress Measurement Techniques", co-authored by ***TJ Boone***, *Int. J. Rock Mech. Min. Sci. & Geomech. Abst*r., **28**, 1, 1-14, 1991.

International Association for Computer Methods and Advances in Geomechanics 1994 Significant Paper Award: One of Five Significant Papers in the category of Computational/Analytical Applications in the past 20 years, "A Numerical Procedure for Simulation of Hydraulically-driven Fracture Propagation in Poroelastic Media", co-authored with ***TJ Boone***, *Int. J. Num. Analyt. Meth. in Geomech.*, **14**, 1, 1990.

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EXTERNALLY FUNDED RESEARCH PROJECTS

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2. "Laboratory Testing of the Crack - at - an - Interface Problem," Sandia National Laboratories Contract No. 13 - 5038, 5/79 - 5/80, $42,000, Principal Investigator.
3. "Research in Fracture Mechanics", Exxon Education Foundation, 9/89-9/92, $30,000, Principal Investigator.
4. "Numerical Investigations into Crack Propagation in Rock," National Science Foundation Grant CEE - 8316730, 6/1/84 - 5/30/86, $150,000. Principal Investigator
5. "Influence of Perforations Upon Subsequent Hydraulic Fracturing," Digital Equipment Corp. and Dowell Schlumberger, 1/88 - 12/96, $448,000. Principal Investigator.
6. "Computational Simulation of Hydrofracturing", NSF CISE Postdoctoral Associate Award for Dr. K. Shah. 11/95-10/97, $46,200. Principal Investigator.
7. "Evaluation of Cased and Uncased Gas Distribution and Transmission Piping Under Railroads and Highways", Gas Research Institute, 11/86 - 1/94, $ 3,602,035. Co-Principal Investigator. T. D. O'Rourke and H. Stewart, Co-Principal Investigators.
8. "An IGERT Training Program In Sustainable Energy Recovery From The Earth-Education At The Intersection Of Geosciences And Engineering". July 2010-June 2015, National Science Foundation, $1,137,047. Co-Principal Investigator. Prof. Jeff Tester, Principal Investigator, Profs. Terry Jordan, Paulette Clancy, Co-PI's.