Physicians Scientists & Engineers for Healthy Energy

FLUID MIGRATION MECHANISMS DUE TO FAULTY WELL DESIGN AND/OR CONSTRUCTION: AN OVERVIEW AND RECENT EXPERIENCES IN THE PENNSYLVANIA MARCELLUS PLAY

BY

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1.0 INTRODUCTION: LOSS OF WELL STRUCTURAL INTEGRITY

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-annulus sections along the casing, and with high gas pressures encountering curing cement or entering such open-hole sections. 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 1a, for the simplest case of bypass by disbonding along the surface casing. Figure 2 is a close-up schematic showing other possible fluid pathways. Additional layers of casing and attendant cement interfaces, present in the defective wells in question, do not eliminate these phenomenon; they may, in fact, increase its likelihood. Figure 3 is a snapshot of yet another situation in which an intermediate casing annulus is left un-cemented, but open to a shallow gas source.

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 4 from Brufatto *et al.* (2003), who state:

“Since the earliest gas wells, uncontrolled migration of hydrocarbons to the surface has challenged the oil and gas industry…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”.

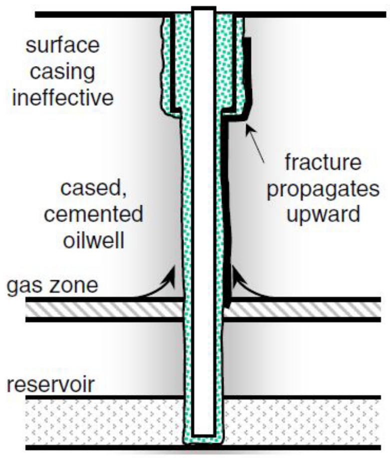


Figure 1. Simplified schematic showing phenomenon of upward gas migration along a casing string. From Dusseault *et al.*, 2000.

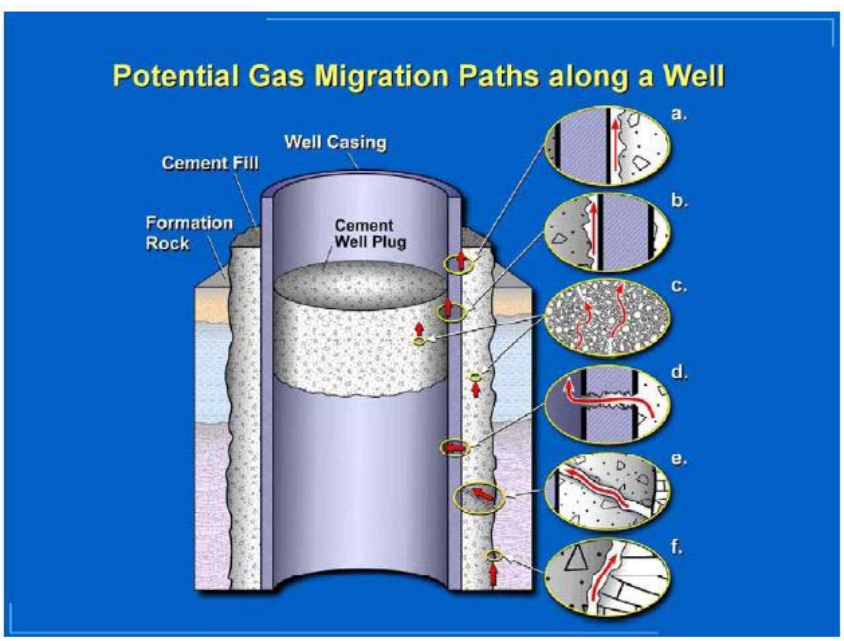


Figure 2. Schematic of details of possible fluid migration paths in and around a cased/cemented well.

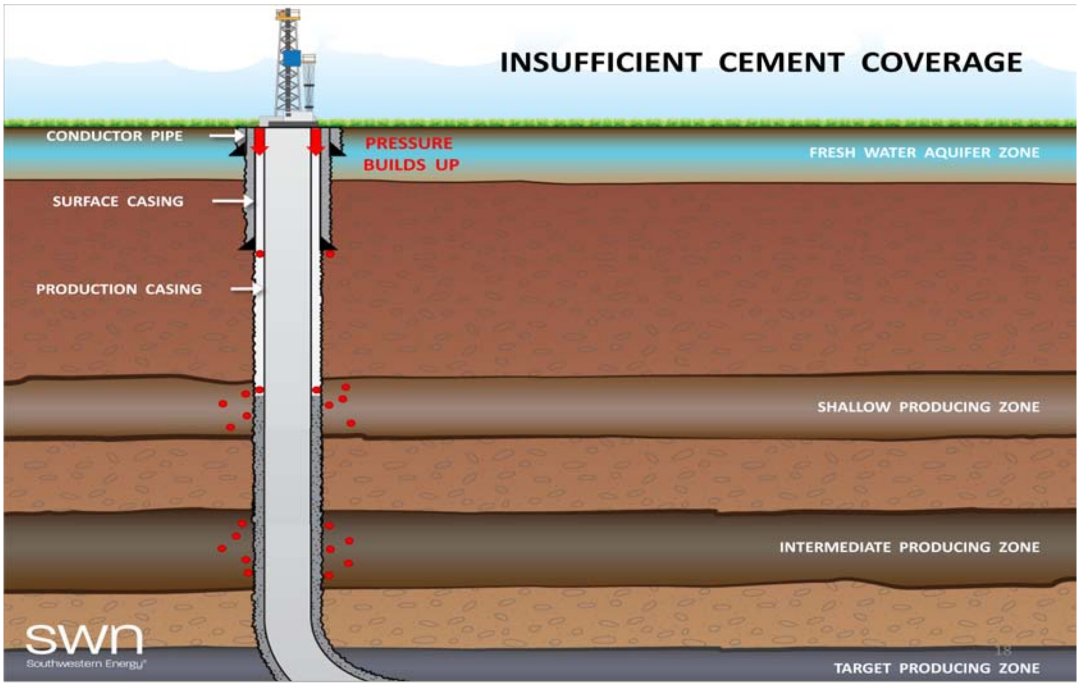
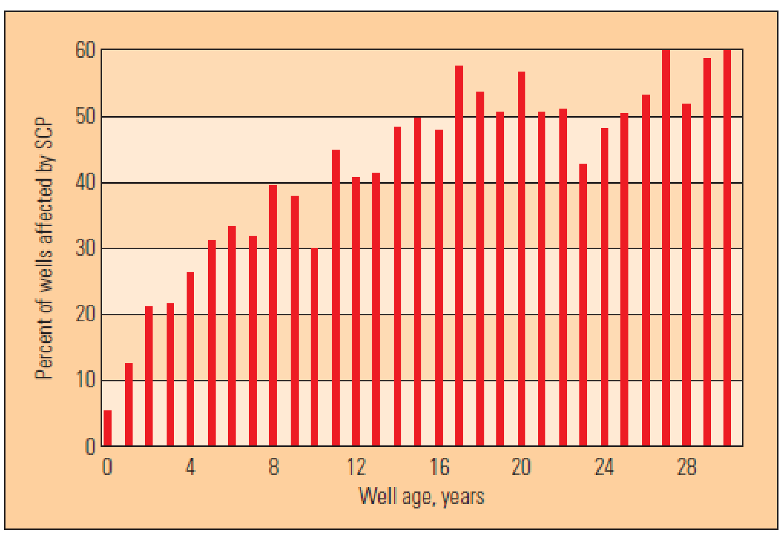


Figure 3. Depiction of entry of gas from a shallow source into an un-cemented annulus, leading to sustained casing pressure and migration of fluids into an USDW. From Boling (2011).



^ 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 4. Data on frequency of occurrence of sustained casing pressure (SCP) in offshore wells. From Brufatto *et al.* (2003).

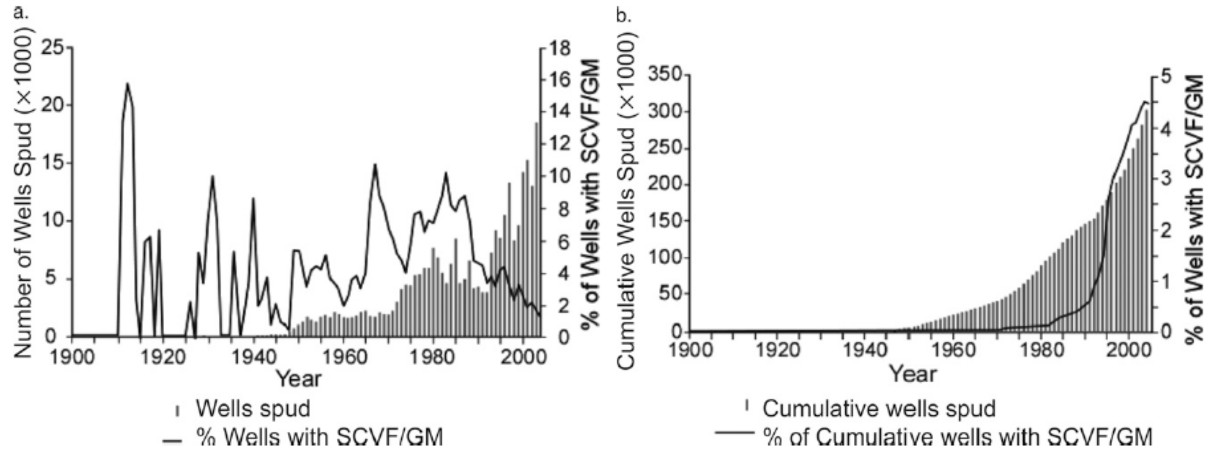


Fig. 8—Historical levels of drilling activity and SCVF/GM occurrence in Alberta: (a) by year of well spud and (b) by cumulative wells drilled.

Figure 5. Data on frequency of occurrence of sustained casing vent flow (SCVF) or gas migration (GM). From Watson *et al*. (2009).

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

> "Low cement top or exposed casing was found to be the most important indicator for SCVF/GM. The effect of low or poor cement was evaluated on the basis of the location of the SCVF/GM compared to the cement top... the vast majority of SCVF/GM originates from formations not isolated by cement."

Figure 5 shows data gathered by Watson and Bachu that is consistent for young wells with that shown in Figure 4. Note that all these citations are from industry sources. It should be noted that, even with ongoing technological and chemistry improvements in cement and in cementing, loss of wellbore integrity is still common. For example, during 2011, Cabot drilled 68 new Marcellus wells in Pennsylvania, and was cited by PA DEP seven times for "Failure to report defective, insufficient, or improperly cemented casing w/in 24 hrs or submit plan to correct w/in 30 days". Chesapeake Appalachia drilled 279 wells and was cited 24 times for the same violation. A summary of the incidence of well failure in the PA Marcellus since 2010 is presented in Section 3, below.

2.0 PREVALENCE OF FLUID MIGRATION FROM FAULTY WELLS

The science on contamination of drinking water from shale gas drilling, fracing, and production, is recent, ongoing, and incomplete. A peer-reviewed, archival journal study from Duke University (Osborne, *et al*., 2011) found apparent migration of substantial amounts of methane from gas wells to private water wells as far out as 1000m in the Marcellus play in Pennsylvania. A more recent paper from the Duke University team (Warner *et al.*, 2012) documented geochemical evidence for possible natural migration of Marcellus formation brine to shallow aquifers in Pennsylvania. Also, the U.S. Environmental Protection Agency (EPA, 2011) recently released a preliminary report from an on-going study in Pavilion, WY, that suggests that substances used in fracing might migrate into adjacent water-bearing strata. The study also found clear evidence that there had been migration of methane from gas wells to nearby drinking water wells - likely caused by deficient cement jobs. Inadequate well construction and, of course, spills have been implicated in many states in a large number of cases of migration of drilling related substances into nearby drinking water.

Along with these fairly direct evaluations of the migration of methane and other substances, industry sources have asserted that private water wells are often contaminated by "naturally occurring" methane. This is often presented in an apparently analytical but confusing way, suggesting that the appearance of methane in drinking water wells is sort of "common" and thus unlikely related to any gas well drilling. Such presentation fails nearly entirely to, first, distinguish between dangerous/hazardous levels of methane in water (7 mg/L or more in PA), and much lower levels that are not generally taken to be of concern. Second, it ignores the prevalence or likelihood of having a dangerous "natural" level of methane in drinking water. Third, it ignores any time line: has there been any significant change in the concentration of methane concurrent with the beginning of nearby gas field development?

The New York DEC's data (NYS rdSGEIS, pg. 4-39) make crystal clear that for a 2010 sample of water wells (n=46) in the "Delaware, Genesee, and St. Lawrence River Basins," presumably not near gas wells, just 2% of the wells had a dangerous level over 10 mg/L. One well had a level of 22 mg/L; the remaining wells then had an average level of 0.31 mg/L. This low percentage of "normal" risk has been confirmed repeatedly in studies in PA, Figure 6, in the Southern Tier of NY (1450 water wells, USGS, 2010), in Alberta, Canada (360,000 wells, Griffiths, 2007) and by both independent investigations and by testing by gas drillers (e.g., Boyer, *et al*., 2011). None of these findings suggest, in any way, that dangerous levels of methane are at all common in rural private water wells. Thus, a fairly strong implication is that, if and when methane does occur at high levels in water wells near gas drilling, it is likely due to some aspects of gas drilling, fracing and/or production operations themselves. This is consistent with both the Osborn, *et al.* (2011) study and the EPA Pavilion (2011) preliminary report. Exact migration mechanisms are not yet completely clear in each case, but the potential well failure mechanisms described in the previous section are often implicated.

3.0 RECENT EXPERIENCES IN THE PA MARCELLUS PLAY

A previous review of the PA DEP Marcellus Violations Database at

http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/OG_Compliance

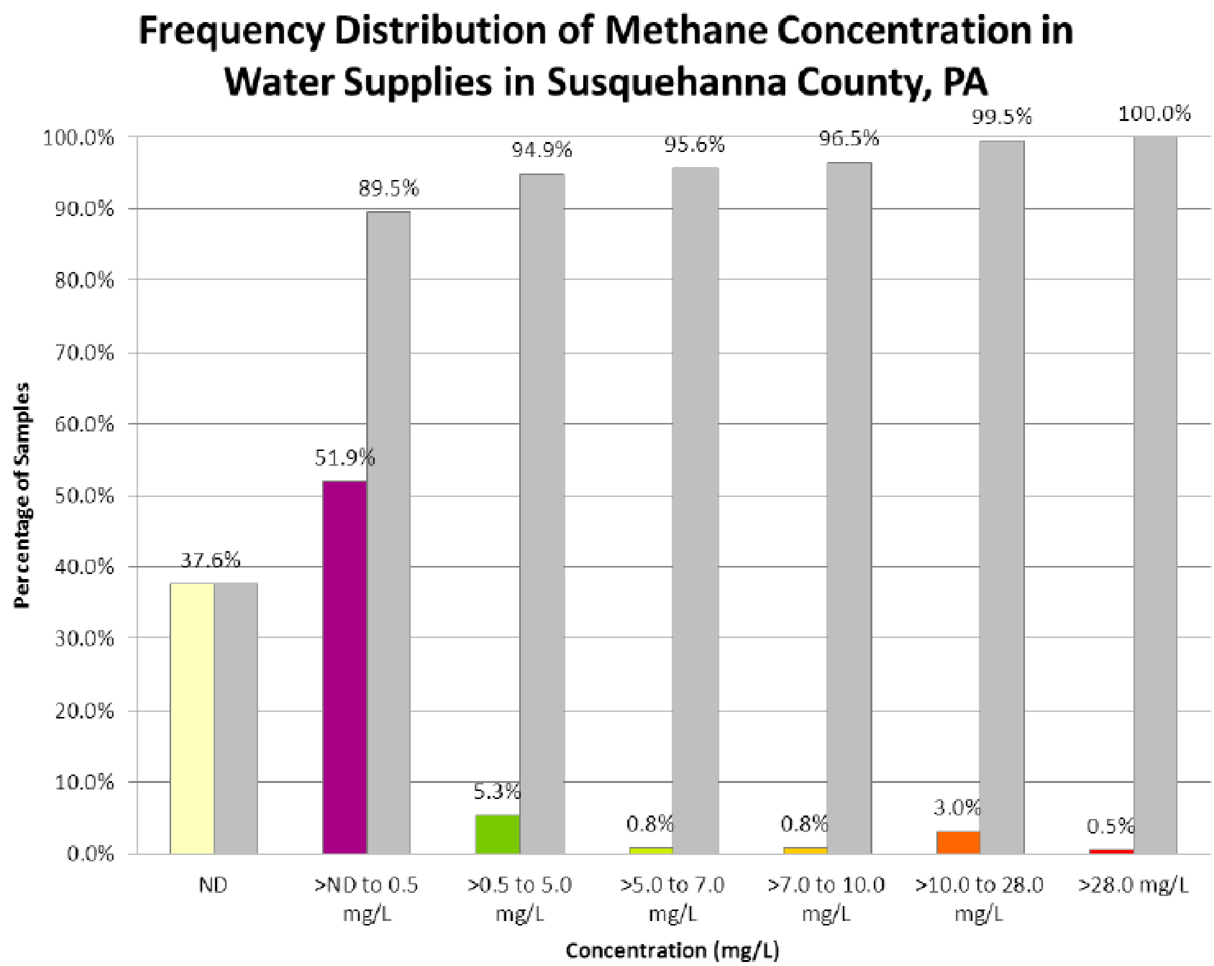


Figure 6. Data collected by PA DEP on methane concentration in private water wells in Susquehanna County, PA. 2433 water supplies were tested: 89.5% had concentrations of methane < 0.5 mg/L, 95.6% had concentrations of methane < 7.0 mg/L. Courtesy of Seth Pelepko, PA DEP.

resulted in the data shown in Figure 7. However, a recent re-review of this database revealed that the data shown in Figure 7 are inaccurate. That data was obtained by searching the violations database for all violations indicating that a well was leaking outside its production casing. Table 1 shows all the violation codes used by PA DEP to indicate that a well is leaking outside its production casing, why it might have occurred, and the consequences of such failure. These were the codes used to filter the entire violations database to identify wells with compromised structural integrity presented in Figure 7.

However, recently it has come to our attention that this filtering process results in a *lower-bound on the number of wells with compromised structural integrity.* That is, more wells have failed cement jobs than have been reported through the violations shown in Figure 7. All inspection

1,454 wells drilled in 2010.
90 well failures.
6.2% rate of failure.

1,937 wells drilled in 2011.
121 well failures.
6.2% rate of failure.

262 wells drilled in Jan/Feb 2012
19 well failures
7.2% rate of failure

Consistent with previous industry data, and not improving.

Figure 7. Preliminary results of survey of leaking wells in the Pennsylvania Marcellus play based on violations issued by the DEP. Violations data from http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/OG_Compliance

Table 1. Violation Codes Used to Identify Wells with Violations for Figure 7.

78.73A - Operator shall prevent gas and other fluids from lower formations from entering fresh groundwater.
78.81D2 - Failure to case and cement properly through storage reservoir or storage horizon
78.83A - Diameter of bore hole not 1 inch greater than casing/casing collar diameter
78.73B - Excessive casing seat pressure
78.83GRNDWTR - Improper casing to protect fresh groundwater
78.83COALCSG - Improper coal protective casing and cementing procedures
78.85 - Inadequate, insufficient, and/or improperly installed cement
78.86 - Failure to report defective, insufficient, or improperly cemented casing
207B - Failure to case and cement to prevent migrations into fresh groundwater

reports for the more than 6000 wells drilled to-date in the Marcellus in PA were reviewed; this is a more complete and revealing search than just filtering on certain violations. The inspection reports indicate that many failed wells were not issued violations. Rather, they received "Violation Pending" comments; or comments indicating that "squeezing", a cement repair procedure which would only be done if a well was leaking outside its production casing, had been done or was to be done; or comments that repairs were underway for a perforated casing; or comments that gas was detected at the wellhead at or above the LEL (lower explosive limit).

Table 2 shows the comparison for each of 2010, 2011, and 2012 between the numbers of wells that had actually received violations, and those that were noted in inspection comments to be leaking but had not received violations.

Table 2. Additional Counts of Wells with Loss of Integrity Included in Figure 8.

2010	64 wells with violations, 47 additional wells with loss of integrity noted in Inspection Comments
2011	97 wells with violations, 45 additional wells with loss of integrity noted in Inspection Comments
2012 (Jan-Aug)	31 wells with violations, 36 additional wells with loss of integrity noted in Inspection Comments

Figure 8 contains the revised well failure rates, using both actual violations and inspection comments to identify leaking wells. The complete database supporting the results shown in Figure 8 is available on request to http://www.psehealthyenergy.org/CONTACT.

Finally, it should be noted that a well that appears, at its wellhead, not to be leaking is not necessarily a sound well. It is well known that fluid migration can occur a significant distance away from the wellhead of a well that appears on inspection of only the wellhead to be of sound structural integrity.

4.0 SUMMARY

The most recent experience with shale gas wells in the Pennsylvania Marcellus play reflects long term, world-wide industry data with respect to new wells with compromised structural integrity. Operator-wide statistics in Pennsylvania show that about 6-7% of new wells drilled in each of the past three years have compromised structural integrity. This apparently low failure rate should be seen in the context of a full buildout in the Pennsylvania Marcellus of at least 100,000 wells, and in the entire Marcellus, including New York, of twice that number. Therefore, based on recent statistical evidence, one could expect at least 10,000 new wells with compromised structural integrity. It is too early to discern whether the other industry experience with this technical problem, an increase in loss of integrity with well age, will also be reflected. However, at play in modern shale gas development are many of the key factors identified by industry researchers as having a negative influence on well structural integrity: the need for deviated wells, rapid development of a field, presence of "shallow" high-pressure gas horizons, and disturbance of young cement due to adjacent drilling activities on the same pad.

1,609 wells drilled in 2010.
111 well failures.
6.9% rate of failure.

1,979 wells drilled in 2011.
142 well failures.
7.2% rate of failure.

1014 wells drilled in Jan/Aug 2012
67 well failures
6.6% rate of failure

Consistent with previous industry data,
and not improving.

Figure 8. Revised results of survey of leaking wells in the Pennsylvania Marcellus play based on violations issued by the DEP and well inspector comments. Violations and comments data from http://www.depreportingservices.state.pa.us/ReportServer/Pages/ReportViewer.aspx?/Oil_Gas/OG_Compliance

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