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Clean Unconventional Gas Production: Myth or Reality? – The Role of Well Integrity and Methane Emissions

Peter Reichetseder[1]

«Das Antifragile steht Zufälligkeit und Ungewissheit positiv gegenüber, und das beinhaltet auch – was entscheidend ist – die Vorliebe für eine bestimmte Art von Irrtümern. Antifragilität hat die einzigartige Eigenschaft, uns in die Lage zu versetzen, mit dem Unbekannten umzugehen, etwas anzupacken – und zwar erfolgreich –, ohne es zu verstehen. Um es noch schärfer zu formulieren: Wir sind im Grossen und Ganzen besser, wenn wir handeln, als zu denken, und das verdanken wir der Antifragilität.»

[aus: Nassim Nicholas Taleb, «Antifragiltät – Anleitung für eine Welt, die wir nicht verstehen», btb, Juli 2014].

Key words: Unconventional gas, methane emissions, well integrity, failure mechanism, barriers, best practice, casing design, well construction, cementing, stray gas

Abstract

This paper is focusing on Well Integrity, because it is an important subsurface element, which is the foundation for reliable and sustainable oil and gas production. Shale gas production in the US, predominantly from the Marcellus shale, has been accused of methane emissions into the atmosphere or contaminating drinking water under the suspicion that this is caused by hydraulic fracturing in combination with compromised leaking wells. Several scientific studies seemed to prove this hypothesis mainly by geochemical and statistical analysis over the last 4 years.

A multiple line-of-evidence approach (isotope analysis in combination with complex analysis of geology and broad inventory of gas and water well data) has helped to distinguish different possible sources and identify shallow gas formations («stray gas») below the groundwater formations as main methane source, whereas the studies did not find any link between hydraulic fracturing and water contamination! Too slim well design and compromised well integrity (cement, casing) are more likely the enabler for possible gas migration behind casing.

This paper is attempting a critical review and reinterpretation of the wealth of available information and opinions. If a best practice approach based on recent experience and standards is applied for proper well design, construction and operations, methane emissions into groundwater or atmosphere can be avoided. The main barriers against any leakage are proper casing design and cementing. Baseline studies and monitoring of groundwater quality need to be an integral part of shale gas developments.

1 Methane Emissions – the «Achilles' heel» of Unconventionals?

Shale gas has been in the focus of discussion in recent years and months because of many economical and also technical concerns. While this business has dramatically changed and pushed both domestic gas and oil production in North America, and in the US alone 30.000 wells are drilled every year, most of them multi-fracked, Europe is torn between negative opinions (ban/moratorium in e.g. France, Germany) and early activities towards unlocking the potential for unconventional gas production (Poland, UK). In the media mainly negative cases from US are reported and dominate, while the huge benefits do not get much attention. Very slowly a more rational approach is growing.

One of the main concerns is the question, if shale gas production can be considered as favorable as conventional gas with respect to Greenhouse Gas (GHG) Emissions.

Shale gas production in US has grown enormously and the Marcellus Shale in Pennsylvania (Fig. 1) presently contributes 40% of US shale gas production (EIA 2014).

However, the Marcellus region, because of special geological and historic reasons, has also become a hotspot for problems with contaminated drinking water. McKay & Sali-

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ta (2011) are referring to legal claims of 13 families in Lenox township having filed a lawsuit in Susquehanna County Court (in the NE of Pennsylvania) in which «they allege that fracking contaminated their drinking water supply and made them ill». Like the lawsuits, some media reports imply that Marcellus Shale drilling and production operations have caused widespread problems.

In a study from Duke University, Osborn et al (2011) argue quite firmly «In aquifers overlying the Marcellus and Utica shale formations of northeastern Pennsylvania and upstate New York, we document systematic evidence for methane contamination of drinking water associated with shale gas extraction.» The authors are considering three possible mechanisms for fluid migration in the shallow drinking-water aquifers:

a. Displacement of gas-rich deep solutions from deep target formation.
b. Casing leaks from production wells, in combination with lateral and vertical fracture systems – which the authors consider the most likely case.
c. Enhanced migration of gas via newly created fractures.

Groundwater contamination in water wells from natural gas sources was not considered.

Molofsky et al. (2011) published the results of a comprehensive investigation of more than 1.700 water wells sampled and tested prior to proposed gas drilling in the Susquehanna County, PA; this study concludes methane to be ubiquitous in shallow groundwater with a clear correlation of methane concentrations with surface topography. Specifically, water wells located in lowland valley areas seem to exhibit significantly higher dissolved methane levels than water wells in upland areas, with no relation to proximity of existing gas wells. The correlation of methane concentrations with elevation would indicate that, on a regional level, elevated methane concentrations in groundwater are a function of geologic features, rather than shale gas development.

Potential sources of this naturally occurring methane include thermogenic gas-charged (from underlying Devonian layers) sandstones in the Catskill formation, which are tapped by most water wells in this region. These sandstones exhibit an extensive net-

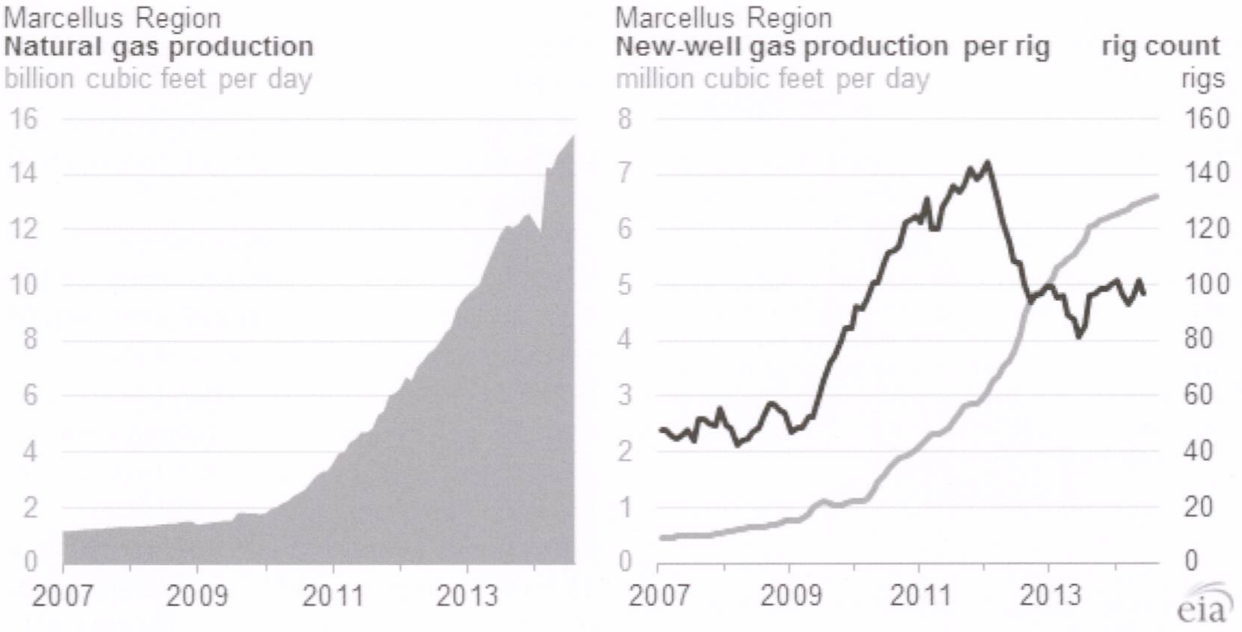


Fig. 1: Marcellus Gas Production and Drilling per 8/2014 (EIA 2014).

work of fractures, joints and faults that serve as principle conduits of groundwater flow and potential pathways for the movement of shallow-sourced dissolved methane (Fig. 2).

Biogenic methane, which is produced by the natural decomposition of organic material within thick valley alluvium and glacial drift deposits in the area, may also be found in water wells that draw water from shallower sediment deposits. The source of this dissolved methane is important with regard to understanding the potential effects of ongoing shale gas development and appropriate measures for protection of water resources. Fig. 3 depicts a possible situation where methane from different sources may be found in contaminated water wells. Forensics using isotopes and noble gases give the ability to unambiguously distinguish between biogenic and also different thermogenic gases (Sueker et al. 2014).

This has important implications with regards to the findings of the recent study from Duke University (Osborn et al. 2011), which suggested that the thermogenic signature of elevated methane concentrations in water wells in Susquehanna County was consistent with an origin in deep shale gas deposits, such as the Marcellus and Utica formations.

Molofsky et al (2011), however, show that the isotope signatures of the Duke study's thermogenic methane samples were more consistent with those of shallower Upper and Middle Devonian deposits overlying the Marcellus shale. These findings indicate that the methane could have originated entirely from shallower sources above the Marcellus that are *not related to hydraulic fracturing activities*.

The apparent misinterpretation of the origin of the observed thermogenic methane underscores the need of the multiple lines-of-evidence approach for proper characterization of methane gas sources, with careful integration of the relevant geologic, historical, *well construction*, and isotopic data.

Duke University conducted a follow-up study (Jackson et al. 2013) of their 2010/2011 study based on a more extensive dataset for

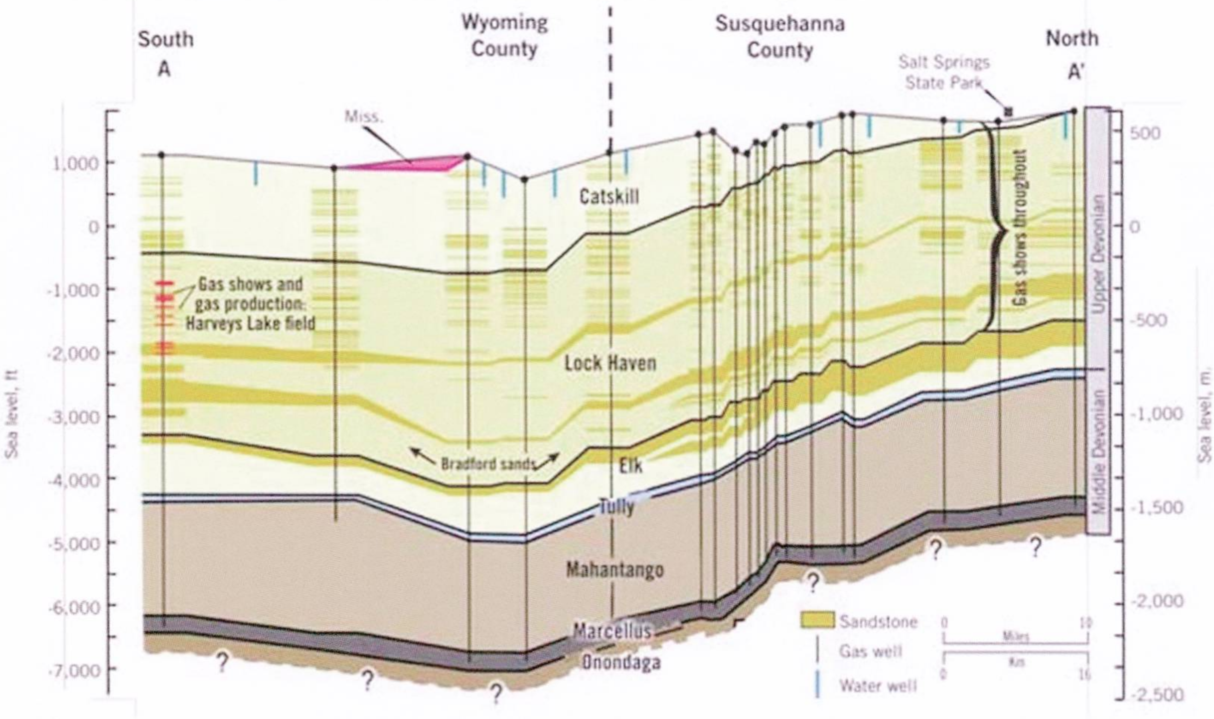


Fig. 2: Generalized Cross Section of Upper Devonian and Marcellus Formations (Molofsky et al. 2011).

natural gas in shallow water wells in NE Pennsylvania, comparing sources of thermogenic methane, biogenically derived methane, and methane found in natural seeps. The team expanded the analysis by investigating also ethane and propane concentrations to distinguish thermogenic from biogenic sources and using isotopic data for methane, ethane and inorganic carbon, and helium analysis to reach better differentiation between different sources.

Among the different parameters investigated: distance to gas wells, proximity to both valley bottom streams (potential discharge areas), and the Appalachian Structural Front (ASF; an index for the trend in increasing thermal maturity and degree of tectonic deformation), *distance to gas wells* (Fig. 5) was the *dominant* statistical factor for both methane and ethane. The authors did not investigate naturally occurring contaminations in water wells.

If hydraulic fracturing was not related to methane contamination of drinking water wells, what could be a plausible mechanism?

The authors were immediately pointing towards well integrity problems (casing leaks or imperfections of cement) also triggered by the fact that in 2010 PADEP (Pennsylvania Department of Environmental Protection) had already issued 90 violations for faulty casing and cementing on 64 Marcellus shale gas wells, 119 similar violations were issued in 2011. Are these only symptoms or do they prove the cause?

Of course, the NE sector of Pennsylvania – different to many other sedimentary basins where conventional and unconventional gas is produced – is characterized by many shallow gas layers located between the deep Marcellus (> 2.000 m) and the groundwater formations (< 300 m). Duke researchers, not being very positive towards shale gas production in general, continued to follow this track with more research - and heavy statistics.

Driven by strong suspicion that integrity of cement must be the weak link of the system the Duke researcher Ingraffea et al (2014) published a paper in May 2014 based on the

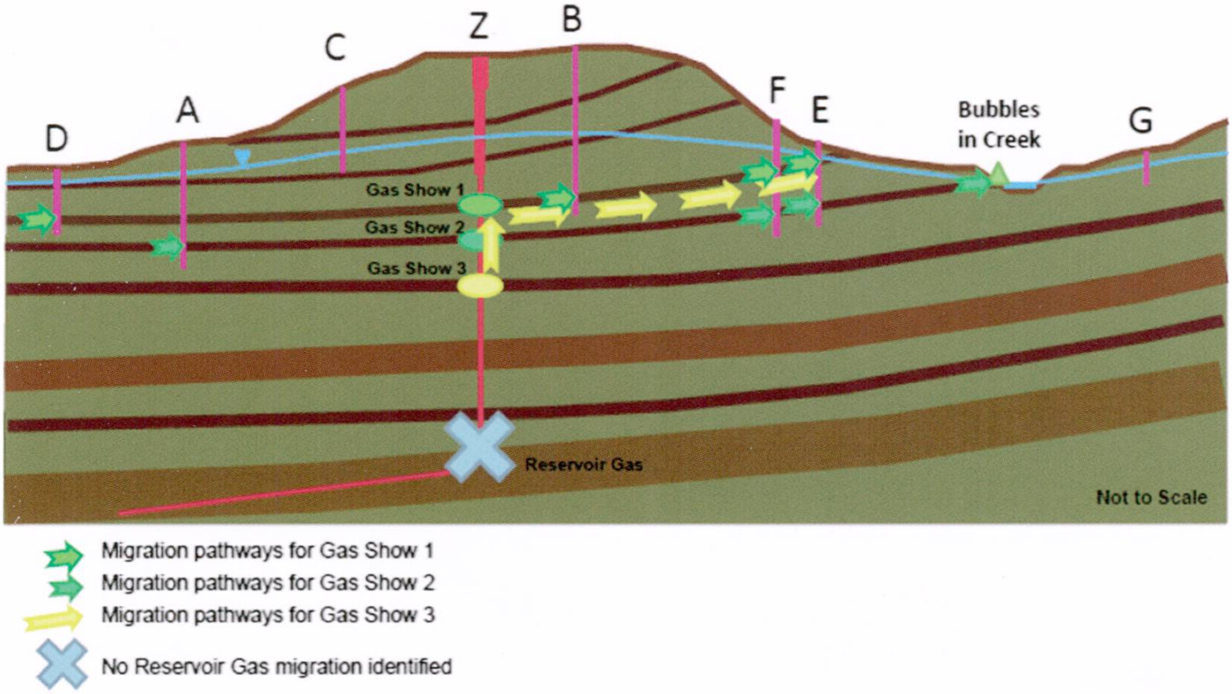


Fig. 3: Stray Gas Forensics to distinguish methane in water well sample from multiple unrelated methane sources including thermogenic sources (Sueker et al. 2012).

hypothesis «Leaking oil and gas wells have long been recognized as a potential mechanism of subsurface migration of thermogenic and biogenic methane, as well as heavier n-alkanes, to the surface». Quoting all potential failure cases of the casing/cement system known in literature it must be THE main problem zone, if hydraulic fracturing has to be ruled out.

«An analysis of 75.505 compliance reports for 41.381 conventional and unconventional wells in Pennsylvania drilled from January 1, 2000 – December 31, 2012, was performed with the objective of determining complete and accurate statistics of casing and cement impairment» (Ingraffea et al. 2014). It remains to be demonstrated, how compliance reports should be able to prove cement impairment?

Pennsylvania state inspection records – according to (Ingraffea et al. 2014) – show *«compromised»* cement and/or casing integrity in 0.7-9.1% of the active oil and gas wells drilled since 2000, with a 1.6-2.7 fold higher risk in unconventional wells spudded since 2009 relative to conventional well types. Ingraffea et al. (2014) further conclude: «Hazard modeling suggests that the cumulative loss of structural integrity in wells across the state may be actually higher than this, and upward 12% for unconventional wells drilled since January 2009. This wide range of estimates is influenced by the significantly higher rates of impairment in wells spudded in the NE counties of the state (average 12.5%, range 2.2-50%), with predicted cumulative hazards exceeding 40%.»

We have to differentiate between indicators (e.g. pressure) at the wellhead/annulus of a well and the immediate conclusion, that these indicators would already be a proof of loss of integrity or relevant impairment of a well. These indicators are symptoms, but not real causes themselves (see also EnergyInDepth 2014), they are symptoms for potential weaknesses or a barrier defect. However, further tests and analysis are necessary to reveal their significance.

Another aspect is the supposed cumulative risk of unconventional wells in comparison with conventional wells. Unconventional wells are generally characterized by good initial production, followed by a strong decline of production and pressure after the first year. This does not increase the risk of leakages, rather the contrary. Because of that it is hard to believe that unconventional wells should be more often «compromised»

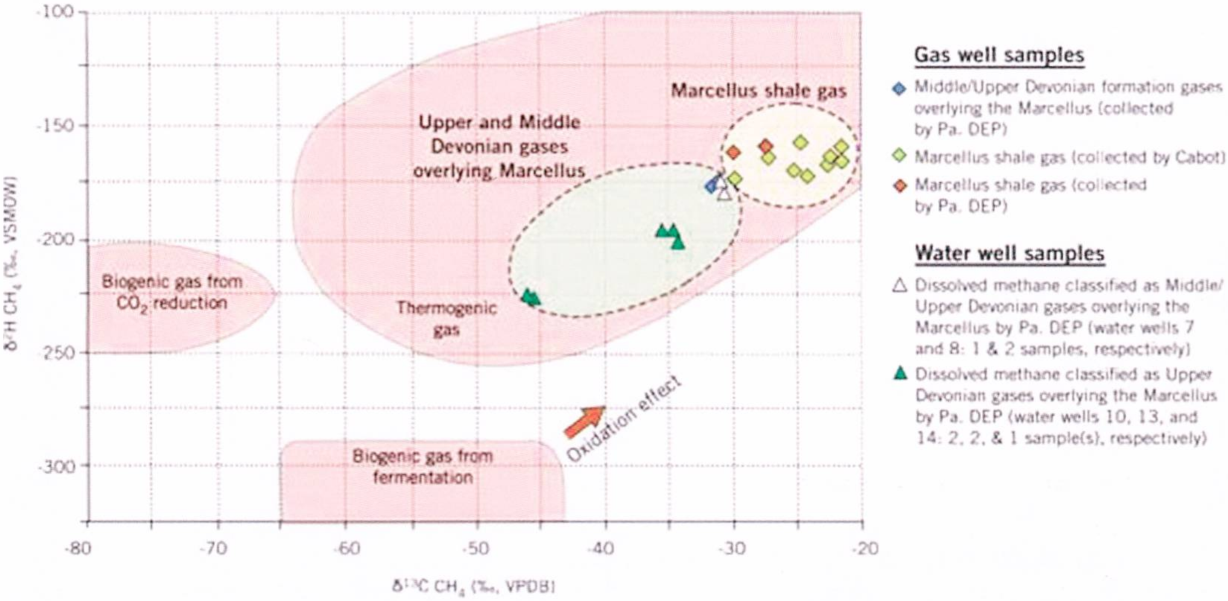


Fig. 4: Comparison of Susquehanna County Methane Isotopic Signatures (Molofsky et al. 2011).

than conventional wells. Many wells in the initial phase of the shale gas boom were drilled by smaller companies and a strong need of low cost drilling with two casing strings only: surface casing and production casing, but no intermediate casing. Conventional wells were the domain of the established players who had followed more conservative designs.

The statistics at least correlate with the higher number of methane problems in the NE of the Marcellus region with a known strong presence of «stray gas» and in combination with a slim well design this is not surprising.

Recent investigations from Darrah et al. (2014) from Duke University on 113 drinking-water wells in Pennsylvania and 20 samples from the Barnett area in Texas, found methane contamination in ground water table caused by impaired well construction, however, «not fracking».

According to their analysis gas geochemistry data would implicate leaks through annulus cement (4 cases), production casings (3 cases), and underground well failure (1 case) rather than gas migration induced by hydraulic fracturing deep underground. Darrah et al (2014) feel quite confident according to Snow (2014): «our data clearly show that the contamination in these clusters stems from well-integrity problems such as poor casing and cementing».

Discussion

a. This report clearly states that the researchers (who initially related groundwater impairment to hydraulic fracturing) did after further studies not find any link between hydraulic fracturing and water contamination, which is a very strong result in itself.
b. Did the study find evidence of well integrity failure? Despite the strong conviction of the researchers questions remain. The sample in the Barnett area is challenged by a study of the Texas Railroad Commission (RRC 2014), which did not find any well in the Parker County with well integrity problems, which could be the cause for methane contamination in ground water.
c. Are the statistics of «compromised» wells plausible at all? Information from EnergyIn-Depth (2014) raises concerns about the plausibility of numbers in the studies of

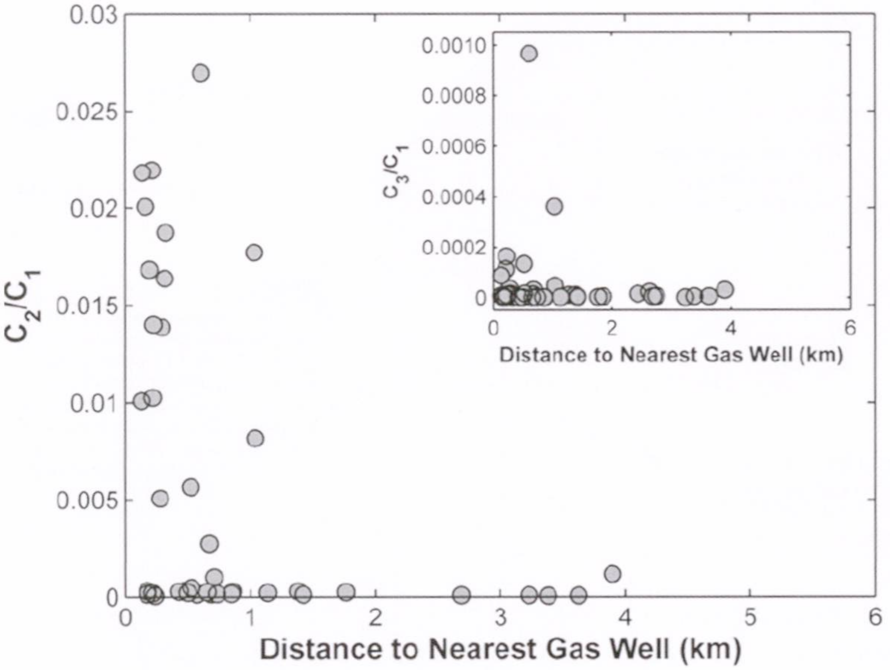


Fig. 5: The ratio of ethane/methane (C_2/C_1) and (inset) propane/methane (C_3/C_1) concentrations in drinking water wells as a function of distance to natural gas wells (kilometers) (Jackson et al. 2013).

Duke University (Ingraffea et al. 2014) which supposedly support very high failure rates of wells. In 2011 the Ground Water Protection Council looked at more than 34.000 wells drilled in Ohio from 1983 to 2007 and more than 187.000 wells drilled in Texas between 1993 and 2008. The GWPC data reveal a well failure rate of 0.03% in Ohio and only 0.01% in Texas (GWPC 2011).

We can draw several conclusions from these investigations:
Before embarking in heavy shale drilling campaigns with many wells it is crucially important to understand the local/regional geology also above the targeted shale formations. If shallow gas (or «stray gas») is present (something that has to be expected in large parts of Pennsylvania), extensive work has to go into baseline studies to provide a robust foundation for the design and execution of wells.
Well integrity has to be in the focus, especially in geological settings with stray gas concentrations. Well design, construction and monitoring have to be performed with high degree of professionalism. This is the purpose of «Well Integrity Management».
While ensuring that well integrity is a universal obligation for all oil and gas (production) wells, the author selected to focus on issues and solutions in the Marcellus area, because it shows a hydrocarbon province with higher challenges than most other shale gas production areas and also demonstrates industry's best practice dealing with this issue.

2 Well Integrity: Definition and Standards

Norway: In the Norwegian system for standards for the petroleum sector Well Integrity is defined in Norsok D-010 (2013) as «application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well».
Norsok D-010 is a functional standard and sets the minimum requirement for the equipment/solutions to be used in a well, but it leaves it up to the operating companies to choose the solutions that meet the requirements. It also specifies that «there shall be *two well barriers available during all well activities and operations*, including suspended or abandoned wells, where a pressure differential exists that may cause uncontrolled outflow from the borehole/well to the external environment». This sets the foundation for how to operate wells and keep the wells safe in all phases of the development.

UK: UK Oil & Gas has updated its «Well Integrity Guideline» by July 2012 (Oil&GasUK 2012) and developed a new comprehensive regulative framework which is called «UK Onshore Shale Gas Well Guidelines» (UKOOG 2013) and specifies in a similar manner all relevant aspects of «good industry practice and reference to relevant legislation, industry standards and practices»: Well Design and Construction (Casing, Cementing, Barrier Planning), Management Supervision and Competence, as well as Well Examination during Design and Construction (also «well examiners visiting the well site to examine certain well integrity and fracturing operations on site in real time» – to build trust) and Abandonment.

US: The most comprehensive and also in the oil and gas industry widely used system of standards stems from the American Petroleum Institute (API), which has developed standards for oil and natural gas operations since 1924. API's formal consensus process is accredited by the American National Standards Institute (ANSI). API-standards are developed in an open process that requires regular review of its more than 600 standards (Emmert 2012).
API has issued the following main guidelines and recommended practices (RP) for Hydraulic fracturing operations especially relevant to well integrity:

- API Guidance Document HF1: Hydraulic Fracturing Operations – Well Construction and Integrity Guidelines (API 2009)
- API Standard 65-Part 2, Isolating Potential Flow Zones During Well Construction (API 2010)

API states in the Guidance Document HF1 (API 2009) that «Maintaining well integrity is a key design principle and design feature of all oil and gas production wells. Maintaining well integrity is essential for the two following reasons:

1. To isolate the internal conduit of the well from the surface and subsurface environment. This is critical in protecting the environment, including groundwater, and in enabling well drilling and production.
2. To isolate and contain the well's produced fluid to a production conduit within the well.»

«Although there is some variability in the details of well construction because of varying geologic, operational settings, the basic practices in constructing a reliable well are similar. These practices are the result of operators gaining knowledge based on years of experience and technology development and improvement.»

The general principles (Sec. 3) describe the main steps as follows:

«Groundwater is protected from the contents of the well during drilling, hydraulic fracturing, and production operations by a combination of steel casing and cement sheaths, and other mechanical isolation devices installed as part of the well construction process.»

«The primary method used for protecting groundwater during drilling operations consists of drilling the wellbore through the groundwater aquifers to a depth sufficient to protect the groundwater, immediately installing a steel pipe (= casing) and cementing this steel pipe in place. This surface casing will be cemented normally from bottom to the top, completely isolating groundwater aquifers. Similar regulations are in effect in all countries and normally enforced rigidly.»

The steel casing protects the zones from material inside the wellbore during subsequent drilling operations and, in combination with other steel casings (intermediate and production casing) and cement sheaths that are subsequently installed, protects the groundwater with multiple layers of protection for the life of the well.

«The subsurface formation containing hydrocarbons produces into the well, and that production is contained within the well all the way to the surface. This containment is what is meant by the term ‹well integrity›.»

Design and execution are then followed by regular monitoring during drilling and production operations, further periodically testing to insure that integrity is maintained. The standards are describing the main elements of the well design program, which are most relevant for hydraulic fracturing and establishing well integrity in Sec. 3 («Well design and Construction»).

In 12/2010 API released Standard 65-2, a special standard dealing with practices for isolating potential flow zones (API 2010). This standard refers not only to possible blowout situations threatening loss of well control, safety of personnel, the environment, and drilling rigs themselves. They also point towards the typical geological situations described in chapter 1 in the Marcellus region. A second objective is to help prevent Sustained Casing Pressure (SCP), also considered a serious industry problem.

API 65-2 defines barrier elements as either physical or operational. Physical barrier elements are classified as hydrostatic (fluid columns), mechanical (e.g. seals, packer, plugs), or solidified chemical materials (= usually cement). Operational barriers are practices that result in activation of a physical barrier (e.g flow detection devices). While physical barriers dominate the process, the total system reliability of a particular design is dependent on the existence of both types of barriers.

It is worth mentioning that both the casing design and process of setting casings, and the process of cementing design and cementing are interdependent. The quality of the cement sheath depends very much on the design and running & cementing execution operations of the casing strings and the associated equipment.

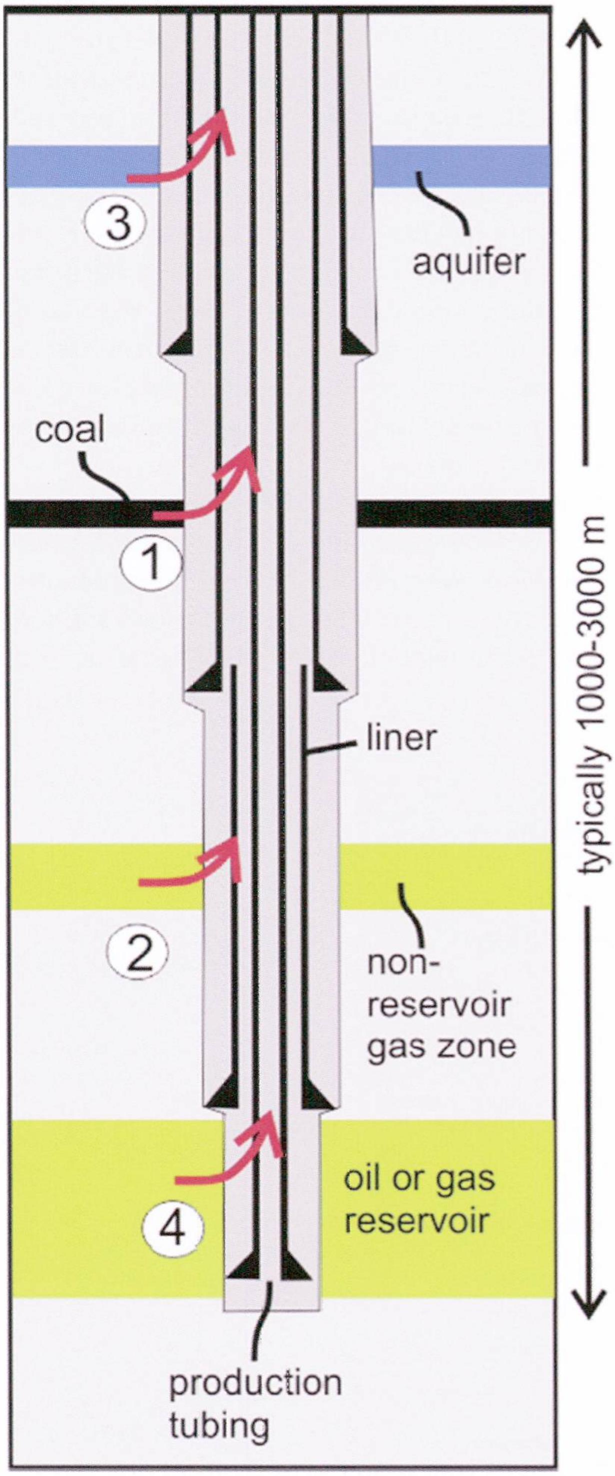


Fig. 6: Schematic diagram of typical sources of fluid that can leak (via failure mechanisms) through a hydrocarbon well. 1 - gas-rich formation such as coal, 2 - non-producing gas or oil formation, 3 - biogenic or thermogenic gas in shallow aquifer, 4 - oil or gas from oil/gas reservoir (Davies et al. 2014).

However, both elements individually and in combination have to create sustainable barriers for the lifetime of the well to avoid any fluid leakage and migration outside of the well system.

3 Best Practice to Avoid Methane Leaks

For cementing not only accepted *design best practices* are relevant, but also accepted *execution best practices*. The cementing practices are specified in great detail in API 2010, outlining all activities to be considered to be important for good cementation, e.g.: Engineering Design, Wellbore Preparation and Conditioning, Cement Job Execution, Casing Shoe Testing, Post-cement Job Analysis and Evaluation.

Prohaska & Thonhauser (2012) are discussing the main failure scenarios (Fig. 6), if barriers against inflow and upward flow/migration are not intact after cementing: Leaking tubings and casings (connection), poor cement allowing gas migration behind casing, (partly) missing cement allowing fluid inflow into annulus and upward migration to wellhead or between individual formations or into groundwater, etc.

However, Prohaska & Thonhauser (2012) conclude: «If existing standards and current best practice are followed, groundwater contamination, resulting from well integrity failure, is very unlikely to happen.»

Meanwhile several states in the US (Ohio 2014) have adapted their guidelines for design and construction of shale gas wells in order to improve well integrity (Pennsylvania «Chapter 78 Oil and Gas Wells» early 2011, Texas «Well Integrity Rule» May 2013, Ohio early 2014).

Major changes have been introduced for *cementing surface casing* (casing setting depth, cementing to surface, minimum cement volume, use of centralizers, minimum thickness of cement sheath, etc.) **and for casing design. New regulations are requiring an *intermediate casing string*.**
As mentioned above, previously shale gas wells in the Marcellus region did not have intermediate casing strings, which was very likely the reason for gas migration from stray gas accumulations.

The typical design of well integrity for unconventional onshore wells (Fig. 7) is shown by Cuadrilla Resources – the front runner of UK shale gas development. It requires always at least three layers of steel casing at depths penetrating the aquifer.
The surface casing, the intermediate casing and the production casing are cement-sealed and extend below the aquifer. The intermediate casing is an integral part of well design to establish a second steel, cement-sealed layer of well protection extending well below the level of the aquifer, which creates a barrier against a possible leakage path from the shale reservoir (or other lateral gas inflow) up to the aquifer. The difference between the new and old («inferior») design is shown in Fig. 8.
Prohaska & Thonhauser (2012) are presenting a comprehensive list of typical Best Practices for establish effective cement barriers. Besides important general rules, the selection of the right cementing process is depending on specific requirements for geology, purpose and design of the well and specific experience.
One very relevant example of cement design is given by McDaniel & Watters (2014) for the Marcellus Shale. The cyclic hydraulic fracturing process after cement has set and the challenge of stray gas migration are

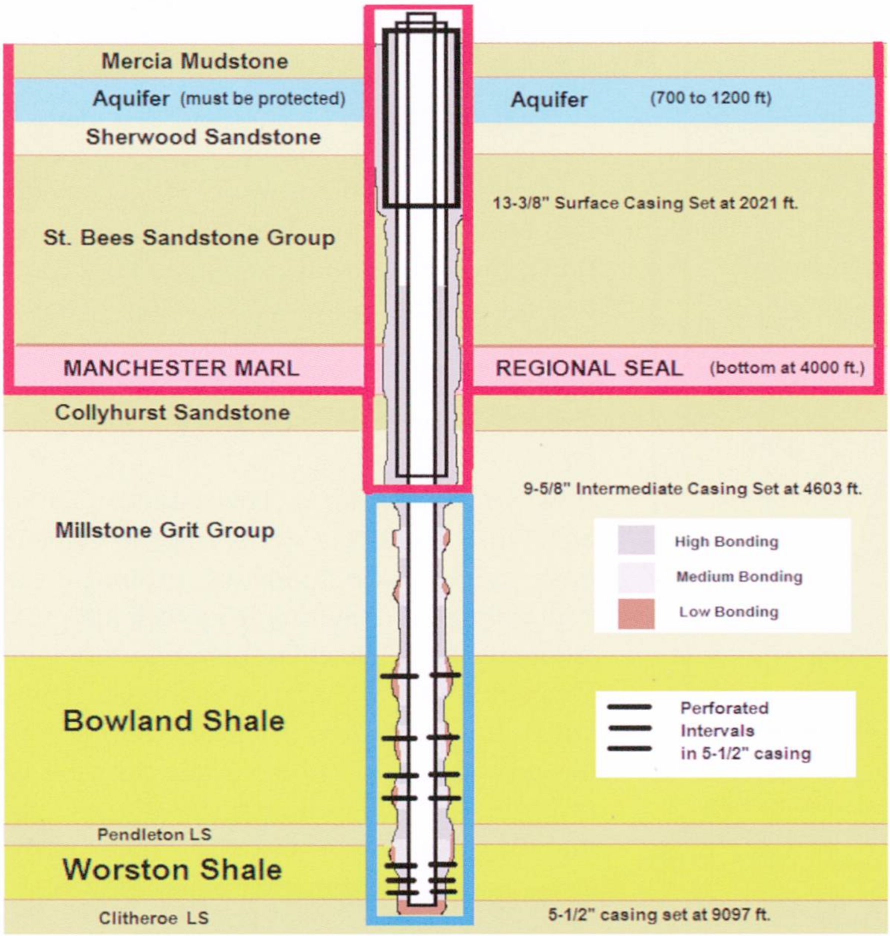


Fig. 7: Wellbore Integrity Design for Cuadrilla Preese Hall#1 (Cuadrilla 2014).

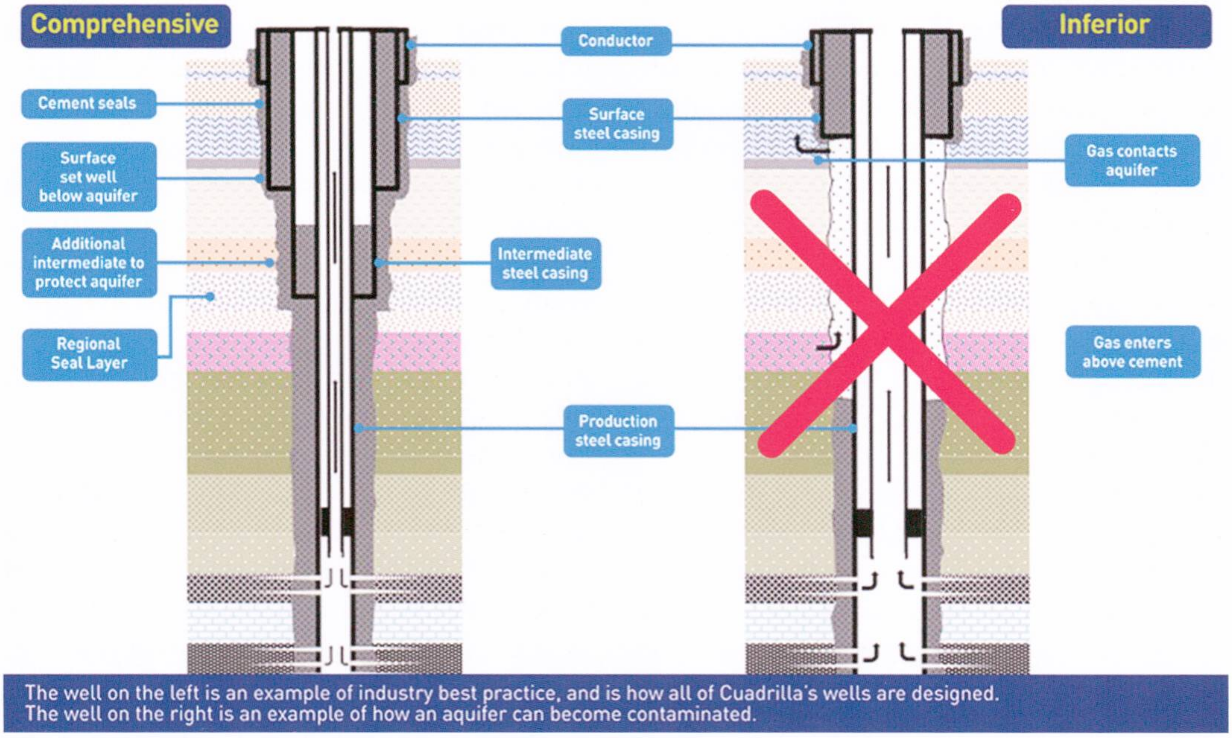
important design criteria. There are proven cement compositions available which can cope with multi-fracturing applications (additives, such as polymers, bentonite, gypsum, foam). Instead of its traditional brittleness and high compressive strength, cement should allow some (elastic) deformation to withstand pressure fluctuations during multi-fracturing operations.

The paper shows that cement integrity of the intermediate casing may be caused by mechanical damage to cement seal rather than through unset cement. Compressive strength is therefore not a good indicator for seal durability, the latter can be reached by different cement compositions. Cement durability can be correlated to inelastic strain potential, mechanical properties and tensile strength of the cement system. Further work will be directed towards as correlation between «Applied Energy vs. Energy Resistance».

For the given situation with combination of cyclic stresses (short term) and resisting gas migration long term both aspects need to be considered. Special cement testing is under development with parameters such as tensile strength, inelastic strain, flexural strength, impact strength and mechanical properties to determine the cement's ability to resist energy applications.

Evaluation techniques are also needed to investigate, if well integrity has been reached and is still maintained, focusing on the main failure scenarios for any possible leakage. Which specific method or tool is effective in proving cement isolation of a zone? Which method or tool should be required on the surface casing cement or other cement strings as a part of initial well construction (or, if not required, when it may provide useful information)? API Standard 65-2 (2010) gives guidance on different tools and their results.

King (2012) gives a very useful and pragmatic summary on cement evaluation by pointing out, that *«The only cement test method that can confirm zone-to-zone isolation is a pressure test.»* Pressure tests are mandatory before drilling fresh formation after cement has set. This formation integrity test is paramount to prove that there is a seal.



The well on the left is an example of industry best practice, and is how all of Cuadrilla's wells are designed.
The well on the right is an example of how an aquifer can become contaminated.

Fig. 8: Well design with and without intermediate casing (Cuadrilla 2014).

Temperature logs are run usually to determine the top of cement within a time-window. It is important to know, if the cement has been placed where it should be.

Cement bond logs (CBL) have proven to be a widely used and accepted method. Cement bond logs can give a reasonable estimate of bonding and a semi-quantitative idea of presence or absence of larger cement channels, but will not certify pressure or fluid isolation of a zone. To provide an effective seal and isolation of a zone, only part of the total cement column must be channel free. Cement channels may be present in parts of the cement, but as long as there are one or more significant, continuous sections of channel-free cement, isolation of the zone along the wellbore will be adequate.

Finally, we have to mention situations during the operations phase of a well, when pressure is emerging in the annuli of a well, which may eventually be considered Sustained Casing Pressure (SCP). Do these situations mean that a vital barrier in the well is broken or impaired?

While improved design has been updated in regulations, there is strong activity at present in API but also in the industry and regulatory bodies of states with emphasis on testing and, if deviations exist, re-establishing the integrity of wells which have critical pressure in the annulus. API has not yet published Guidelines on SCP. Valuable guidance is given by Norsok (2013) and Oil&GasUK (2012) under Sec. 9 «Annulus Management». Monitoring and analysis is important to ensure a leak or breach of a well barrier is detected early and that corrective action can be taken before the problem escalates (Norsok 2013).

At the Stray Gas Incidence and Response Forum 2012 in Cleveland, Ohio, Arthur et al (2012) presented «holistic well evaluation» methods with the focus on testing the annulus situation of shale gas wells showing annulus pressure: Pressure build-up testing, External Well Integrity testing (visual inspection, venting rate testing, volumetric analysis, geology review, assessing casing & cement: CBL, temperature & noise logging).

A combination of testing methods and analysis can be used effectively to assess well integrity, but most testing methods do not offer an absolute and definitive answer regarding well integrity. Regulatory agencies tend to seek methods that provide a black & white answer, but tend to recognize the complexities.

Physical remedial activities, such as perforating the production casing and squeezing cement or other products are challenging. Often, specialty products, such as micro-fine cement, resins, etc. may be required, and assuring perforations are sealed for purposes of production operation must also be considered.

4 Conclusions

In the early phase of shale gas production, especially in the northeastern part of the Marcellus region in Pennsylvania, US, methane contamination of groundwater has been recognized and quickly attributed to hydraulic fracturing.

Investigations revealed that many water wells in the region were containing natural gas contaminations from direct communication with the ubiquitous stray gas formations, even without the presence of any gas production well. A best practice approach clearly calls for comprehensive baseline studies and close monitoring during shale gas drilling and development.

Both for conventional and unconventional oil and gas production, well integrity is a prerequisite for safe long-term production. While hydraulic fracturing could NOT be proven to be the cause of methane contamination of groundwater formations, several US-states (e.g. Ohio, Pennsylvania, Texas), as a consequence of the lessons learned, have been tightening the regulations for oil and gas wells, among others demanding an intermediate casing string in combination with strict rules for cementing the surface casing string. Evaluation methods are available to investigate the quality of these vital barriers in oil and gas wells. If necessary, repair methods have to be applied or as a last resort the well to be abandoned.

With proper barriers in place groundwater formations can be safely protected and leakage of methane into the atmosphere avoided. European countries (e.g. UK, Norway, Germany) have regulations in place which already require best practice solutions to maintain well integrity for the lifetime of a well.

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