

Response to Interim Report on Scientific Inquiry into Hydraulic Fracturing in the Northern Territory August 2017

Dr Errol Lawson

Please note that this replaces the hard copy paper presented to the Inquiry Panel on Tuesday 8 August at Katherine.

Introduction

I understand that the Interim report is essentially a summary of the evidence received by the Panel during the first round of public hearings and community consultations, and that it follows the format of the Issues Paper which is the starting point of the Inquiry. I welcome the opportunity to respond to the Interim report and propose to address my remarks to aspects which I believe are incomplete or not addressed. I note the description of the report as Interim and, with the exception of the preliminary assessment that the practice of injecting wastewater into aquifers should not occur, I understand that the Judgement has not yet been written.

My discussions falls under two headings:

- Fracking
- Regulations- I include Social Licence in my discussion of Regulations since my research strongly indicates that both are a precondition for success in any complex multi-disciplinary project which is extended both in time and space. Baselines are also inextricably linked to a successful regulatory regime.

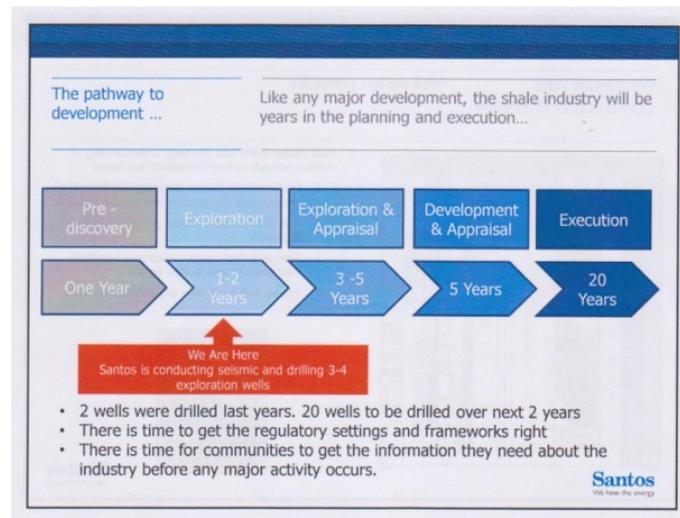
Fracking

The object of this section is to discuss incomplete coverage arising from the tendency by gas industry speakers to confine discussion of fracking to the act of fracturing the shale; or at least making the act of fracking the centre of presentations. This has inhibited discussion of long term effects and has contributed to a “dialogue of the deaf” between those for and those against fracking. This limitation contributes to the failure to precisely define the elements of the process which are central to the analyses of risk and consequences of the development of an unconventional (shale) gas industry in the Northern Territory. It has also inhibited effective consideration of the long term effects.

I understand that the Terms of Reference of the Inquiry require examination of the consequences of “fracking”, encompassing all social, economic and environmental changes from the current stage of Exploration and Appraisal through Production to Plugging and Abandonment and beyond.

Fracking

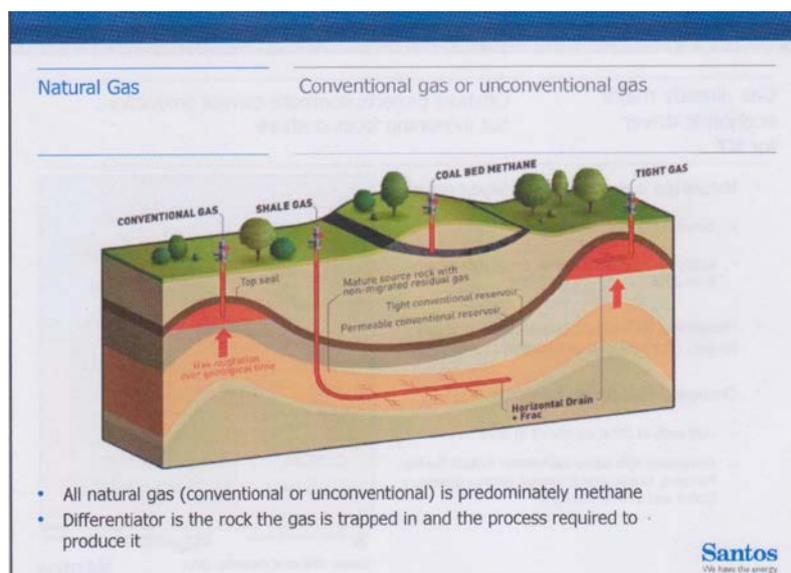
My first introduction to high volume, high pressure hydraulic fracturing of shale reservoirs for the purpose of extraction of methane was a presentation by Santos in May 2014. The slide below is from that presentation:



Titled “Pathway to Development” it identifies five stages leading to Execution which I understand to be the Production stage. Santos estimates Production to commence in 8 to 10 years from the start of Exploration and Appraisal and to last for 20 years. My early interactions with the industry spokespersons as well as my individual efforts to understand the implications of industry plans were against this 5-stage model.

People who asked about well integrity into the future beyond Production have not been given any answers of substance. The presentations centred on the diagram below, also from the Santos presentation, or some variation of it as a simplified illustration of the equipments configurations comparing unconventional gas extraction in deep shale with horizontal wells with conventional gas extraction, coal seam gas and tight gas.

With particular reference to questions on probability of well integrity failure and associated probability of aquifer contamination, the answers to “how long will the cement last” ranged from “*in perpetuity*” to *decades*. This failure to achieve a constructive dialogue set the pattern with proponents confining their representations up to the end of Production and opponents attempting to extend the consideration of risks and consequences into the post-production era.



I want to emphasise that following the Santos presentation, along with those who are concerned about the long term consequences of an unconventional gas industry, I have tried without success to get answers from the industry on the longevity of the measures taken to ensure that no harm shall ensue subsequent to the departure of the gas industry. It may be that these diagrams are at too high a level of abstraction to facilitate a reductionist examination of details.

My attention focused on the cement barriers intended to isolate the fractured shale reservoir from the surface and intervening geology and hydrology. The particular concern is that failure of the cement barriers could allow migration of residual gas from the shale into the overlying aquifer and into the atmosphere. And while there are concerns about other consequences throughout the life of an unconventional gas industry and beyond, the consequences of a contaminated aquifer on the townships, communities, industries and the environment are well into the Red zone of the Risk/Consequences matrix.

As an aside the Panel would be aware that the Tindal aquifer is currently being studied for the concentration and point spreading behaviour of contamination arising from the use of fire fighting foams at the RAAF Base. The risk of contamination was not known at the time the fire fighting foam was used and is an unintended consequence of its use. The consequences for health, property values, and horticulture, agriculture, tourism and pastoral industries are as yet unknown¹.

I trust that having expressed my deep concern at the long term consequences to aquifers of an unconventional gas industry, and my frustration at the apparent inability of the industry to pronounce definitively on failure rates of abandoned wells into the future after the industry has departed, the Panel will understand my critical response to the inclusion in section 5.3.3 of the Interim Report of information from the APPEA submission that “for wells constructed to modern standards this rate has been reported to be only .004% compared with 0.2% for older wells.” Without qualification the failure rate quoted of .004% repeated in the Interim report could be interpreted as being accepted by the Inquiry as valid and applicable to well failure rate at any time in the life cycle and beyond²

I have two guiding principles which generally keep me out of trouble. The first is *caveat emptor* which certainly applies to the NT wide unconventional gas proposition. The second is “If it looks too good to be true it probably is.” I applied both to the .004% figure and traced it back to its source. The following is an extract from Section 4.1 of the APPEA submission, *What is a Well Failure ?*

A recent review by King and King (2013) of the data from 253,090 wells in Texas found that only 4 in every 100,000 (0.004%) wells constructed to modern standards experienced a loss of well integrity, compared to 0.2% for older wells.

This led me to the referenced 2013 review by King and King titled:

¹ On 9 August 2017, Defence and the NT Government jointly announced that a limited capacity water treatment plant has been ordered to remove the PFAS from the town supply. In order to reduce the demand water restrictions are to be imposed from the end of August.

² . I should note that the APPEA submission to the Inquiry directed me to a model which is better than the Santos one, for examination of the risks and consequences of well integrity failure as a function of the stages of development from Exploration to Post-abandonment.

Environmental Risk Arising from Well-Construction Failure-Differences Between Barrier and Well Failure and Estimates of Failure Frequency across Common Well Types, Locations and Well Age. George E. King Apache Corporation and Daniel E. King WG Consulting Group. November 2013 SPE Production and Operations,

I have included the full titles of the references in the text as the titles are informative in their own right.

The 2013 King and King paper does include the figure 0.004% for newer wells in TABLE 10 under the heading *Well-Integrity Failure (Containment Lost)*. But it also includes the following in the Introduction:

Environmental risk to groundwater from the integrity of producing wells is addressed in this study, which also examines several other possibilities of environmental impact during the producing lifespan, from the end of construction until plugging and abandonment (P&A).

And again:

Estimate accuracy depends on a sufficient database of wells with documented failures, divided into (1) barrier failures in a multiple-barrier system that did not create pollution, and (2) well-integrity failures that created a leak path, whether or not pollution was created. Estimated failure- frequency comparisons are valid only for a specific set of wells operating under the same conditions with similar design and construction quality. Well age and construction era are important variables. There is absolutely no universal definition for well-failure frequency.

As the Inquiry Panel surely knows there are figures flying all over the place. They are only useful and relevant if they refer to the particular stage of the life cycle from which they were derived and *are valid only for a specific set of wells operating under the same conditions with similar design and construction quality*. The King and King paper analyses data up to the end of Production, and does not present information on failure rates in subsequent stages of the life cycle of a well.

There is another paper by George King titled:

Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbour and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. George E. King Apache Corporation 2012 SPE 152596

This paper provides the following definitions which are useful in defining at what stage in the life cycle of a well a particular set of quoted statistics and risk/consequences applies. As indicated above these definitions are more useful than the Santos model in discussing the complete suite of Risk Management including Risk Identification, Risk Mitigation and Consequences:

- Barrier Failure in a multiple-barrier system is a single failure of one of the sequence of casings and cements that are emplaced during construction of a

well. As there are several barriers in a sequence, pollution or contamination neither escape from nor enter into the well.

- Well Integrity Failure: All barriers in a sequence fail in which fluids (oil and gas) may move from inside to outside the well (contamination/pollution) or from outside to inside the well (intrusion of salt water)
- Drilling and Completion (D&C): The phase taking the well to the point of handover to the production crew; in contractual terms this marks the delivery of a production-ready well by the supplier of construction services and its acceptance as “fit for purpose” by the production operator.
- Plugging and Abandonment (P&A). The conclusion of the life cycle of a well. Unless the regulator mandates further involvement the gas company has no ongoing interest in the well.

There is another paper short in title but long in expert panellists:

Energy Well Integrity

Nova Scotia hydraulic Fracturing review and Public Engagement Process

Lead Author: Dr Maurice Dusseaut

Expert Panellists: Dr. Frank Atherton, Dr. Michael Bradfield, Kevin Christmas, Dr. Shawn Dalton, Dr. Brad Hayes, Dr. Graham Gagnon, Constance MacIntosh, Dr. Ian Mauro & Ray Ritcey
Supporting Contributors: Fred Baechler, Margo Macgregor & Dr. David Wheeler

Sections of this paper has address stages in the life cycle of a well. *Section 6 “Well Abandonment and Long-Term Integrity”* is particularly relevant to my concern that the risks and consequences after the regulator has released the gas company from further obligations are not addressed. The Nova Scotia review addresses this issue:

In any case, most jurisdictions have “orphan well” funds, provided by a levy on production, that are used to fix wells for which an owner cannot be found; otherwise, the responsibility is that the owner fix the leaking abandoned well to the standards set by the regulatory agency. (Section 6.1 The Abandonment Procedure pages 15/16)

I would make a point which is also not addressed in the Interim report and may be absent from submissions to date. That is the Risk Management/Risk Mitigation step which is interpolated between Risk Identification and Determination of Consequences. After Risks and Consequences-of-Doing-Nothing are identified and analysed, there is a second round during which Risk Mitigation measures are developed and Consequences-after-mitigation are described. Management may require a third round or at least continuous review. Consider the three major stages in the life cycle of a well:

- Construction and Completion
- Operations
- Abandonment and Beyond

At each of these stages there are personnel involved who have different objectives, skill sets and equipments. I expect each would have their risk management plans, but each would be different in detail.

For example the Construction and Completion stage is strong on engineering, experience and equipment. The task is to deliver a well “fit for purpose”. As a defence engineer I was often in the analogous position of developing equipment for the military. With the resources to build equipment, I was also equipped to modify/repair that same equipment. My goal was to be the first to know if there was a fault and, in keeping with the engineers’ ethic, I would fix the problem before it got away from my team. Reputation, and repeat business, is built on the three drivers of schedule, cost and performance. They all contribute to Reputation but delivered performance is paramount. I have to believe that the Construction and Completion teams have similar drivers. Problems within their control would be fixed without fuss. I would expect risk during this stage to be low, but never zero. I would expect events which could lead to unwelcome consequences and are within the control of the engineers would be fixed expeditiously. Events outside the engineers’ capability I would expect to result in abandonment

During Production operations the engineers and their equipment are somewhere else. As a regulator, I would expect the operator company to have risk management plans including equipment and personnel available at short notice, not necessarily on standby, to respond to an unplanned event. With the introduction of multi-well pads there may be risk of damage to cement seals as a result of perforation and fracturing shocks transmitted to adjacent wells.

After Abandonment everyone is somewhere else. Measures to manage unwanted events beyond cessation of gas extraction are dealt with below under Regulations. That section discusses long term monitoring and expanding the Emergency Services capability to provide a first responder capability, both funded by the “orphan wells levy”.

As can be seen from the above the time lapse from occurrence of an event--the manifestation of Risk--to availability on the scene of people and equipment to prevent unwanted consequences will vary depending on the stage in the life cycle. Briefly Risk could be Low during Construction and Completion and High after Abandonment. Risk during Production is a function of the risk management measures mandated by the Regulator.

I conclude this section with the following suggestions:

- Recognise that the risk and consequences of an unconventional gas industry extend beyond the Plugging and Abandonment of wells
- In analysing information on failure rates of wells determine to which stage(s) in the life cycle of a well the information refers and the relationships of the source of the information to the NT geology and hydrology.
- In view of the caveat in the Summary of the 2013 King and King paper(see below), note that there are no valid figures presently available for failure rates of unconventional wells in the NT.

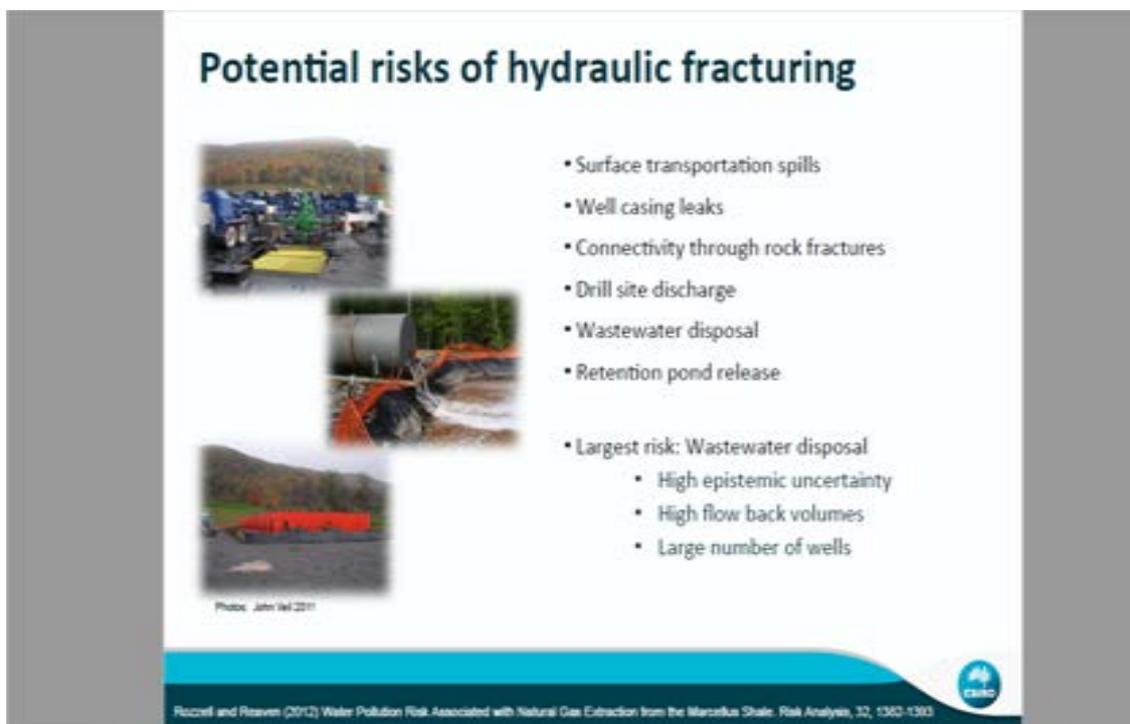
Estimated failure-frequency comparisons are valid only for a specific set of wells operating under the same conditions with similar design and construction quality Well age and construction era are important variables. There is absolutely no universal definition for well-failure. (King & King 2013)

Waste water disposal

Another activity of the unconventional gas industry in the NT which has not received sufficient attention is that of the management of the large volumes of water plus additives that are associated with fracking. At the first presentation I attended the Santos representative spoke of evaporation ponds as the standard method for managing the disposal of returned fluid after fracturing. He was quickly reminded by several in the audience that during the Wet season the NT is subject to highly localised unpredictable rain events which could easily cause an open pond to overflow. In some discussions waste water management has been excluded from Fracking as not intrinsic to the act of fracturing the shale but rather belongs to the general category of Hazardous waste treatment.

For the people who are concerned about the risks and consequences of an unconventional gas industry, wastewater management cannot be disassociated from the fracking processes and has the potential to contaminate aquifers and surface water. The following diagram titled "Potential risks of Hydraulic fracturing" is from a presentation by Damian Barrett (then of the CSIRO now GISERA) "*Unconventional gas-Community Meetings Darwin and Katherine 21/22 November 2013.*" Dr Barrett identifies the largest risk as "Wastewater disposal". Yet almost four years later the industry has no better solution than³:

- Open evaporation ponds up to the start of the Wet-notoriously uncertain.
- Road transport the unevaporated fluid and residual solids to an approved waste disposal facility-the nearest in Queensland



³ I note that Mr Crowhurst in his presentation to the Inquiry on 8 August, referred to a water treatment facility as one of the infrastructure projects which could be a spin off from an unconventional gas project which would have wider application.

The Interim report, Section 5.6 Management and Reuse of flowback and produced water does not address:

- Risks associated with open ponds overflowing in the Wet
- Risks arising from ponds stranded by impassable roads by unexpected onset of the Wet
- Scaling up risk arising from production field development and associated increased tanker traffic on NT roads.

Regulations

My immediate reaction to the chapter on Regulatory Reform in the Interim Report was the unhelpful thought that there must come a point where the lowest risk pathway is to start all over again. I offer the following comments.

Baselines

My understanding of baselines is that they can serve two purposes:

- Provide information to guide planning of new wells
- Provide the foundation for any litigation between, in this case, the gas industry and people or organisations which believe their interests have been harmed in some way as a result of the activities of the gas industry, including their subcontractors and suppliers.

Three points are obvious:

- Firstly that baselining must precede industry activities by some years in order that annual variations can be recorded.
- Secondly that in order to be useful in resolving a dispute the recording and maintenance of baselines must be by an independent authority.
- Thirdly, where work packages are contracted out, including supplier contracts, the allocation of responsibility for workmanship, and hence liability, must be known to the Regulator.

Post Plugging and Abandonment

DPIR's advice that "at the conclusion of a project the operator must demonstrate that rehabilitation of the site has been carried out.....in order to become eligible to receive the Environmental rehabilitation Security Bond." leaves the government exposed to high risk of having to fund harm that may take decades to manifest itself. Surely it is not beyond the wit of governments to develop mechanisms to "keep industries' feet near to the fire" for the long term

The Nova Scotia Review *Energy Well Integrity* states *most jurisdictions have "orphan well" funds, provided by a levy on production* to deal with the case of the missing responsible entity. A possible solution to manage the problems associated with loss of well integrity of abandoned wells is monitoring. Issues arising include:

- What to monitor? Presence of methane at the surface and/or in groundwater; pressure in the abandoned casings.
- How long for/how often? Only experience will tell; start off conservatively.

- Who is responsible? Has to be the Regulator funded from the production levy
- Labour intensive? Modern SCADA (surveillance, communications and data acquisition) could easily automate the monitoring of several wells reporting on a routine basis or by exception when a parameter exceeds a predetermined limit.

As suggested above, the Emergency Services could be expanded to provide first responder capability to any change reported by the remote monitoring system. The availability of more specialised capability would have to be resolved by the Regulator and the gas industry.

Regulatory Regime

Many submissions express concern at the capability of the DPIR to supervise the operations of the mining industry especially an unconventional gas industry which is new and when fully developed will be geographically dispersed as opposed to localised as are extractive mines e.g. Ranger, Mt Todd, MacArthur River. I share those concerns particularly that the discussions on “regulatory regimes” focus on the documentation of whatever it is the doer must do (the objectives) and the penalties for failure to perform; or more likely, the failure to escape detection of non-compliance.

I contend that a regulatory regime is much more than a document. It includes the inspectors and the resources which enable them to do their job. A regulatory regime becomes a robust regulatory regime when the overseers are experienced and knowledgeable in the industry and are in sufficient numbers with the necessary resources. Above all else, any regulatory regime can be undermined once the industry learns that upper management, including the political class, is willing to intervene in its workings. It may be that there is an optimum mix of objectives and prescriptions, with the Regulator reserving the right to increase the prescriptions in order to enforce compliance or relax the prescriptions as confidence and trust develops between the supervised and the supervisors.

The following discussion draws on my experience in Defence and Defence Industry. I believe it can be generalised to be relevant to the problem of regulating an unconventional gas industry.

The Japanese⁴ (Nonaka, I. & Takeuchi, H. 1995) suggest that 80% of an organisation's knowledge of how to conduct its operations is tacit knowledge, which is located in the shared experiences of the participants and the evolved agreements on “how things are done”-the *habitus* of Pierre Bourdieu⁵. These shared experiences do not map onto an organisation chart, cannot be captured on a project flow chart, on a decision tree or on a list of processes. They exist in a structure of networks of interpersonal relationships which

⁴ The Knowledge Creating Company, How Japanese Companies Create the Dynamics of Innovation, New York: The Oxford University Press.

⁵ Bourdieu, P. (1986). The Forms of Capital. In J.G. Richardson. (Ed.), *Handbook of Theory and Research for the Sociology of Education* (pp. 241-258). New York: Greenwood Press.
Bourdieu, P. (1991). *Language and Symbolic Power*. Cambridge, UK: Polity Press.

parallel the formal structure and which take time to form; they provide the vehicles where “novel problems” are solved. In Bourdieu’s model of a social structure, these multiple networks constitute the Social Capital and I suggest they the source of a Social Licence.

Both formal documented regulations and informal network based structures are necessary preconditions for any enterprise to succeed. The term, Social Licence may be an alternate way of recognising the importance of legitimising the role of networks.

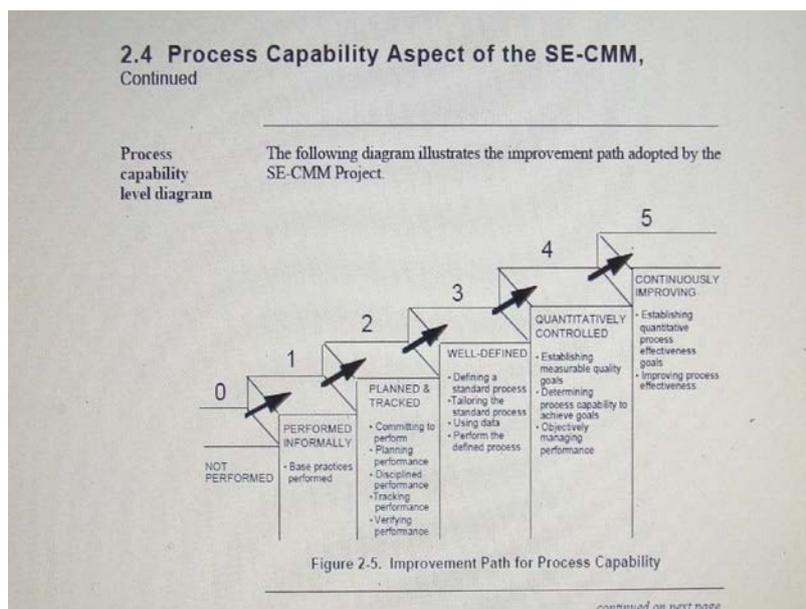
Capability Maturity Models (CMM)

A second aspect of management of a complex enterprise is highlighted by the Capability Maturity Model (CMM). This is an analytical tool introduced to the Defence domain which examines the relative capabilities of the customer (Defence) and Supplier (Industry). As with the discussion above, I believe the model is applicable to the relationship between the DPIR and industry.

Capability Maturity Modelling:

- shows up strengths and weaknesses of an organisation
- Examines three Key Process Areas: Engineering, Projects and Organisation
- Defines five levels of Capability in each area ranging from Level 1 Performed Informally to Level 5 Continuously Improving
- Defence mandates Level 3 “Well Defined”
- Difficult to rate capability of the NT Government as a Regulator any higher than Level 1-”Performed Informally”-mainly because of the dispersal of responsibilities throughout several agencies/departments.

The diagram below shows the five levels of capability and the improvement path expected of organisations doing Defence business, including the Defence Acquisition agency.



I am not proposing the NT regulator adopts this characterisation of relative capabilities. My understanding is that defence did not adopt the process as it clashed with the prevailing Managerialism philosophy. It does demonstrate where difficulties can easily arise when a regulator is not adequately trained, staffed and resourced. I assume that industry would rate itself as Level 3 for its internal processes. I note that Marketing and Public Relations are not included in the assessment processes.

I conclude that there is a significant risk arising from mismatch between Industry and Government, between regulators and the regulated.

Dr Errol Lawson
9 August 2017

Energy Well Integrity

Nova Scotia Hydraulic Fracturing Independent Review and Public Engagement Process

Lead Author: Dr. Maurice Dusseault

Expert Panellists: Dr. Frank Atherton, Dr. Michael Bradfield, Kevin Christmas, Dr. Shawn Dalton, Dr. Brad Hayes, Dr. Graham Gagnon, Constance MacIntosh, Dr. Ian Mauro & Ray Ritcey
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Cased, cemented wells are designed and drilled to access various types of resources beneath the surface of the Earth. Groundwater, oil and gas, thermal energy, salt, sulphur, and even deeply-buried leachable mineral ores are accessed through designed wellbores. This discussion paper on Energy Well Integrity focuses on typical onshore unconventional oil or gas wells, which are generally similar to wells used for conventional oil or coal bed methane production. The major topics covered in this paper are well design, construction, use and abandonment. Issues of cementing practices and gas migration pathways are given special emphasis because they are key aspects in establishing and understanding well integrity.

Discussion Paper: Energy Well Integrity

How to Read this Paper

This discussion paper will in due course form the basis of a chapter in the full report produced for the *Hydraulic Fracturing Independent Review and Public Engagement Process in Nova Scotia*.¹ The paper should be read in conjunction with the *Primer on Hydraulic Fracturing*² which we released on March 10th 2014. This paper has been prepared to describe typical onshore unconventional oil or gas wells, and explores a number of issues, including cementing practices and gas migration pathways. The major topics covered are well design, construction, use and abandonment. The paper only addresses environmental impacts as they relate to energy well integrity. Other potential environmental impacts of hydraulic fracturing or issues relating to land rights or ownership of the resource, among other topics, will be covered in other discussion papers and the final report. To see a full list of other topics being considered in chapters of the final report, and to view the tentative release schedule for discussion papers, please visit the project document page on our website.

How to Provide Feedback on this Paper

We now invite feedback on this discussion paper – for example if there are any aspects that are not clear or which require further explanation. Please email your feedback to hfreview@cbu.ca with ‘Energy Well Integrity’ in the subject line using the feedback form available on the website³. We request that you do not make comments directly in the PDF document and prefer to receive feedback using the form provided, in an email or word attachment, or alternatively please write to HF Review, Verschuren Centre for Sustainability in Energy and the Environment, Cape Breton University, P.O. Box 5300, 1250 Grand Lake Road, Sydney, Nova Scotia, B1P 6L2. Feedback on this chapter can be received at any time until June 20th, 2014. All feedback received will be taken into account in the final version of the document.

Thank you



Dr David Wheeler
President of Cape Breton University, on Behalf of the Expert Panel, June 3rd, 2014

¹ See the Verschuren Centre (Cape Breton University) website <http://www.cbu.ca/hfstudy> for full details of the study and all project documentation.

² Available from <http://www.cbu.ca/hfstudy>

³ The discussion paper feedback form is available here: <http://www.cbu.ca/hfstudy/resources/project-documents>

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Discussion Paper: Energy Well Integrity

EXECUTIVE SUMMARY

Development of unconventional oil and gas resources using modern well cementing and completion techniques leads to generally excellent wellbore integrity, but, as in any industrial activity, there will never be a 100% success in sealing all wellbores against all possibilities of future leakage. Technological advances are helping to reduce the incidence of leaking wells and are providing means for better quality control and leak detection capabilities. The most common well integrity issue is slow leakage of methane around the external casing, but the consequences of such leaks, although negative from a climate change perspective, are not a great threat to health because natural gas is not a toxic substance, the frequency of substantial leaks is low, and the leakage rates are low as well. When leakage is identified, methods exist to rectify the problem. Although rigorous statistics remain elusive, it seems that the number of problems encountered in Alberta and British Columbia, both relatively mature regulatory environments, is not large.

Because possible future unconventional resource development in Nova Scotia would take place using modern technology with multiple wellbores installed at each drilling site, it is a relatively straightforward task to establish good monitoring and regulatory practices to ensure that the site is geologically understood, that wells are properly installed, and that well abandonment is done according to best practice guidelines. The establishment of an appropriate monitoring and regulatory system for onshore Nova Scotia will clearly be needed if unconventional oil and gas resource development ever takes place.

Nova Scotia geological conditions are reasonably stable; this should lead to a low incidence of poor wellbore integrity for the following reasons:

- Moderate tectonic stresses and strong rock mean that wellbore quality will be excellent, leading to high quality primary cementing operations, and therefore fewer cases of leaking wells.
- Except in Nova Scotia's coalbed areas, there appear to be few gas sands at shallow depth that might lead to problems with intermediate-depth gas migration behind the casing.
- Oil and gas in Nova Scotia are likely to be sweet (little or no associated hydrogen sulphide gas), making all operations easier and casing life longer.

1. INTRODUCTION

Cased, cemented wells are designed and drilled to access various types of resources beneath the surface of the Earth. Groundwater, oil and gas, thermal energy, salt, sulphur, and even deeply-buried leachable mineral ores are nowadays accessed through designed wellbores. This introduction to Energy Well Integrity will focus on typical onshore unconventional oil or gas wells, which are generally similar to wells used for conventional oil or coalbed methane production. The major topics to be covered are well design, construction, use and abandonment. Issues of cementing practices and gas migration pathways are given special emphasis because they are key aspects in establishing and understanding well integrity.

Well Design is carried out through a process that involves assessment of the subsurface geology, knowledge of the shallow groundwater, understanding of the nature of the fluids to be produced (oil, gas, water), and knowing the nature of the service to which the wells will be exposed (temperatures, pressures, fluid chemistry). This engineering design process is informed by decades of experience for millions of oil and gas wells worldwide, over 500,000 in Canada alone, and approximately 163 in onshore Nova Scotia⁴. Of these, only 37 penetrated more than 1 km deep, which is relevant because if shale gas development takes place in Nova Scotia, it is likely to be deeper than 2 km.

Once a design has been established to meet specific development needs, a site is chosen, prepared, a drilling rig hired, and **Well Construction** takes place through drilling of a wellbore and installation of a set of concentric steel casings cemented into place. Well construction practices have also evolved over many decades, as greater experience has been gained in different geological conditions, and as new materials and techniques have been developed.

After the last casing has been cemented into place, another wellbore section may be drilled and special equipment installed, or more conventional perforation technology may be directly used to provide access to the target shale strata that contain the gas. **Well Completion** practices such as perforating and hydraulic fracturing are designed to provide access from the steel-cased well to the potentially productive geological formations. Hydraulic fracture stimulation⁵ increases the surface contact area of the formation so that fluids may be produced more effectively – giving a commercially viable recovery rate and a higher recovery factor (% of the resource ultimately produced). Since the technique was first introduced in the late 1940's, more than a million wells have been hydraulically fractured worldwide,

⁴ These numbers have been generously provided by Government of Nova Scotia personnel.

⁵ The first paper to be released by the Hydraulic Fracturing Panel was a Primer on Hydraulic Fracturing; the Primer will form the basis of one chapter in the final report. See the Primer for technical details about fracture stimulation: <http://www.cbu.ca/hfstudy/resources/project-documents>

most of them in the USA. About 175,000 wells have been hydraulically fractured in Alberta⁶ starting with the Pembina Oilfield in the early 1950's. In Nova Scotia, a total of 11 wells have been fractured, eight for coalbed methane production evaluation, and three for assessing shale gas potential.⁷ However, current hydraulic fracturing approaches are substantially larger in volume and injection rate, compared even to a decade ago. Some have speculated that, in the future, 95% of all wells in North America will be hydraulically fractured.¹

Well Operation comprises the period of time from initiation of fluid production to the end of commercially viable production. During this time, the well may be re-stimulated to encourage production, and there may be periods when the well is shut-in for one of a number of technical or commercial reasons. For example, the well may be held in an inactive status to conform to agreed-upon limits (prorated production), awaiting a decision to re-stimulate or develop another formation intersected by the wellbore, waiting for equipment availability, or awaiting abandonment.

Once the resource that can be accessed by a single well has been developed and depleted, the well must be abandoned properly and the ground rehabilitated. **Well Abandonment** involves making sure that the wellbore possesses integrity, rectifying any problems that might exist, then placement of a series of sealing plugs, usually only within the innermost open part of the well, to insure that there is no pathway for fluids to migrate from one zone to another, or to migrate up to the surface. Abandonment implies that all surface disturbance that does not constitute infrastructure of local value (access roads for example) be returned to stipulated standards set by regulatory agencies.

Well integrity refers to the maintaining of the purpose of the cemented steel casing strings: isolating zones to prevent fluid flow between zones, confining flow to the interior of the cased well, detecting and remediating any breaches arising from operational wear or installation flaws, and protection of the surface (atmosphere, ground surface, groundwater) from any negative effects of fluid migration.

This design, construction, operation and abandonment process, like all activities involving the exploitation of deep fluid or mineral deposits, takes place within a regulatory framework that is a provincial responsibility. **Regulatory guidelines** have been developed in all provinces that have a significant oil and gas industry, although by virtue of the size and age of its oil industry, Alberta's regulatory organization, the AER (Alberta Energy Regulator), is the senior one in Canada. Many

⁶ <http://environment.alberta.ca/04131.html>;
<http://www.capp.ca/aboutUs/mediaCentre/NewsReleases/Pages/governments-regulate-shale-gas.aspx>;
<http://www.oilandgasinfo.ca/fracopedia/hydraulic-fracturing-explained/>

⁷ These numbers have been generously provided by Government of Nova Scotia personnel.

provinces take advantage of the vast amount of work that has gone into development of AER regulatory guidelines.⁸

Wells drilled to access unconventional oil and gas resources are not significantly different from other wells used in the oil and gas industry around the world. However, the relatively recent developments of long horizontal wells, multi-stage hydraulic fracturing, and multi-well pad design are somewhat novel, compared to the old paradigm of one vertical wellbore per surface site, so consideration should be given to the impacts of changing development practices.⁹

2. WELL DESIGN

The design of an unconventional oil and/or gas well requires that decisions be made in advance for the size of the steel casings to be placed in the wellbore. This depends on many factors; several of the most important of them are listed here:

- What is the desired diameter of the final portion of the wellbore? Different completion technologies may require different borehole diameters for the installation of well completion equipment.
- What is the depth to the Base of the Ground Water Protection zone (BGWP)? This depth may be stipulated by regulation (e.g. 150 m from surface), or by the geochemistry of the groundwater, as is done in Alberta for example.¹⁰
- Are there formations between the surface casing depth and the target formation that are prone to instability during drilling and must therefore be protected with an intermediate casing?
- What is the target formation and depth of the well, and if a horizontal leg is to be drilled, where will it be and how long will it be?

Once the design is finalized, the permit application for regulatory approval is filed. The design details must allow for some flexibility; for example, if the length of the horizontal well is designed to be 2.0 km, drilling difficulties may truncate this length somewhat.

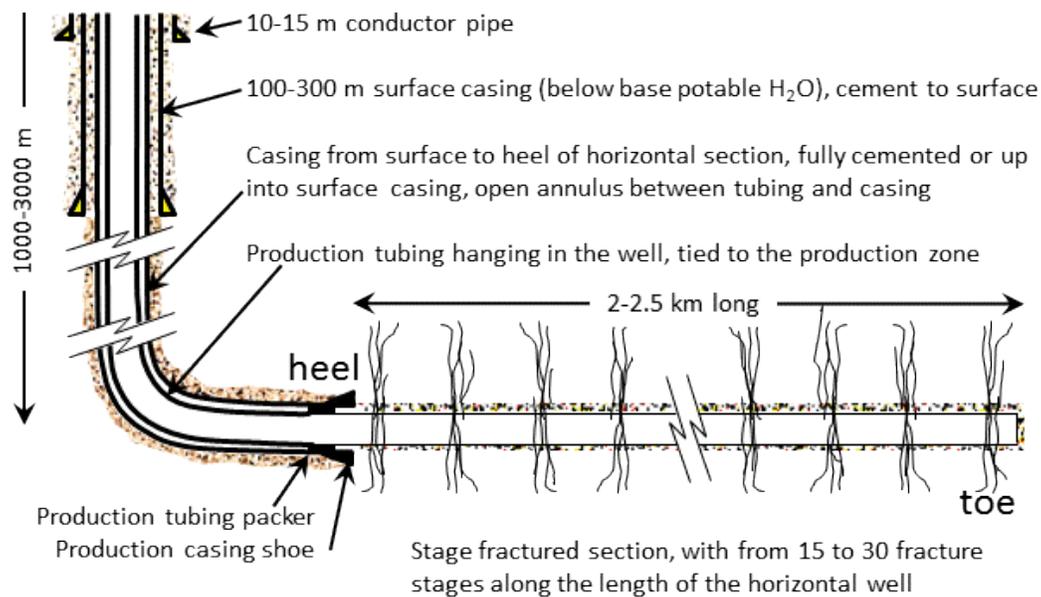
⁸ An idea of how the oil and gas industry is regulated in Canada can be obtained by studying the AER website and their various guidelines and enforcement actions: <http://www.aer.ca/> As an example, the rules for land reclamation can be found at this webpage: <http://www.aer.ca/abandonment-and-reclamation/reclamation>

⁹ For a broad yet detailed discussion of various potential environmental impacts of shale gas development in a Canadian context, refer to the following publication: Council of Canadian Academies, 2014. *Environmental Impacts of Shale Gas Extraction in Canada*. Ottawa (ON): The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction, Council of Canadian Academies. Commissioned by the Council of Canadian Academies for Canada Environment, May 01, 2014. The author served on this Expert Panel, and the sections in the Report on well integrity were in large part formed by the author.

¹⁰ Alberta defines the BGWP as 4000 ppm tds (parts per million total dissolved solids such as sodium chloride). "Water containing TDS concentrations below 1000 mg/litre is usually acceptable to consumers..."; quote from WHO 1996, *Total dissolved solids in Drinking-water*. In Guidelines for drinking-water quality, 2nd ed. Vol. 2. *Health criteria and other supporting information*. World Health Organization, Geneva, 1996. WHO/SDE/WSH/03.04/16.

Two possible designs for new wells targeting unconventional resources in Nova Scotia are sketched in the following diagrams, one vertical, one horizontal; many other detailed differences in well design configurations are possible.

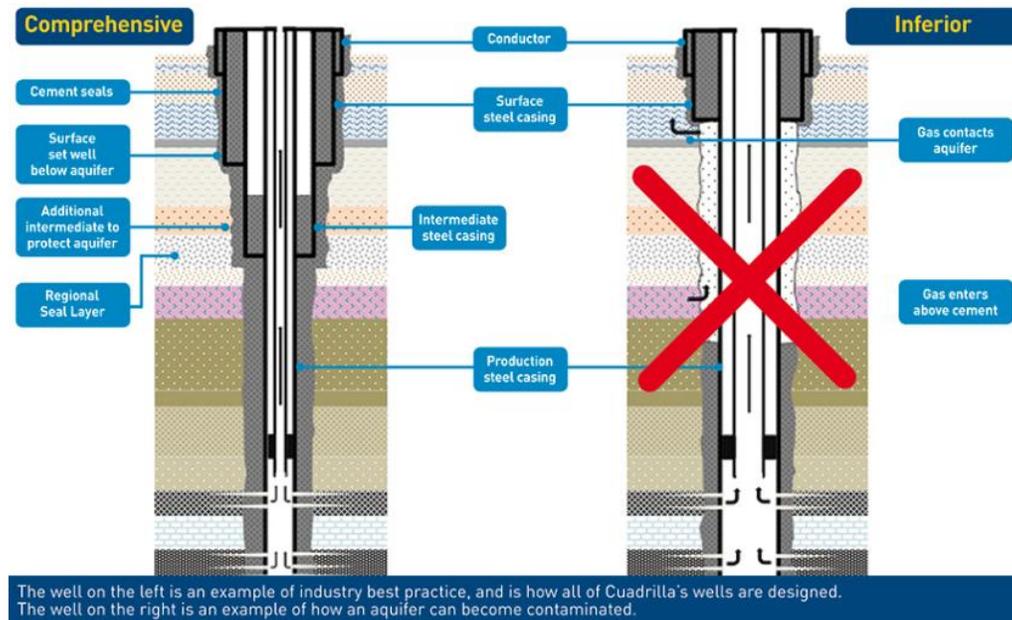
Figure 1: A Typical Unconventional Oil and Gas Well with a Long Horizontal Section and no Intermediate Casing String (probably not needed in Nova Scotia)



In onshore Nova Scotia, large volumes of gas at depth and pressures far above hydrostatic pressure (10-11 MPa/km) do not exist. Hydrostatic pressure is considered “normal”, in contrast to the condition of “overpressure”, which refers to pressures substantially greater than the pressure from a static column of water. Thus, in contrast to offshore Nova Scotia where pressures far above hydrostatic¹¹ are well-known, it is not necessary to take exceptional measures to guard against a gas blowout; standard well designs and safety measures are sufficient to address the small risk of a blowout.

¹¹ For good geological reasons, the much younger oil and gas-bearing formations offshore Nova Scotia often have exceptionally high pressures, sometimes approaching twice the pressure that would be expected from a vertical column of water. Such high pressures require great care in drilling, the use of additional safety devices and techniques, and the installation of one or two additional casing strings.

Figure 2: Contrasting Older and Newer Vertical Wellbore Designs



Courtesy of Cuadrilla website: <http://www.cuadrillaresources.com/protecting-our-environment/well-design/>

3. WELL CONSTRUCTION

3.1. Drilling and Casing the Well

A finished oil or gas well has several casing sections that are cemented in place to the surrounding rock or to the previous casing section. Each casing section is assembled from many joints of steel pipe, and each may be referred to as a “casing string”. The major casing strings that might be used in an onshore Nova Scotia energy well are listed here.

The first element in creating good wellbore integrity is to make sure each casing joint is properly connected to the previous one so that no fluid leakage can take place through the connection. To this end, the casing strings are assembled by experienced crews with specialty equipment to provide the right make-up torque and avoid any cross-threaded connections. A properly assembled casing string has adequate pressure integrity for its entire length, and this integrity is tested to meet regulatory standards before well assembly is complete.

The **Conductor Pipe** is a thin steel casing placed into a large diameter hole drilled to a depth of 10 to 20 m using a typical water-well drilling truck. The pipe is lowered into the open hole, with some sacks of cement or concrete and gravel placed to fill the gap between the steel and the soil. This conductor pipe

is then connected to the drill rig system so that as the surface casing hole is drilled, the drilling fluids can be contained and circulated through the tanks.

To install the **Surface Casing**, a suitable diameter vertical hole, 12¾" (324 mm) is a typical size, is drilled with a bentonite-water fluid (drilling "mud") to a depth below the deepest useful groundwater, or to an agreed-upon depth such as 150 or 200 m. A strong steel casing (e.g. 10¾" (273 mm) diameter) is placed into the hole and cemented to the surface. When the cement has set adequately, a flange is welded on to the casing, and a blow-out preventer and other sealing equipment for assurance of security and unimpeded fluid circulation are firmly bolted to the flange so that deeper drilling can be executed with minimal risk.

In Nova Scotia, because essentially all of the groundwater being used in the province is less than 100 m deep, mandating a specific depth such as 150 m for the base of surface casing would seem to be appropriate minimum.

An **Intermediate Casing** string may be required if there are unstable formations to be traversed during drilling, if there are numerous thin and uncommercial oil and gas zones in the rocks above the production zone that must be more carefully isolated, or if there are high formation pressures that could lead to drilling risks. In Nova Scotia, because the rocks from the surface casing shoe to the potential targets at depth are competent and pressures are moderate, it is likely that an intermediate casing string would not be required. If an intermediate casing string was required, the surface casing has to be larger than 10¾" (273 mm) diameter to accommodate the additional concentric casing string. Generally, the intermediate casing string is cemented all the way to surface.

The **Production Casing** is the final cemented casing string placed in the bore hole. It may be placed all the way to the end of the horizontal section, or the horizontal part may be left open for placement of special equipment, as in Figure 1. In either case, the production casing is cemented, either all the way to surface, or well into the previous intermediate casing string so that a seal is ensured. The high alkalinity of the cement also protects the steel casing from deterioration if there are acidic fluids in the formation such as carbon dioxide (CO₂) or hydrogen sulphide (H₂S) acid gases dissolved in water.

3.2.Cementing Practices

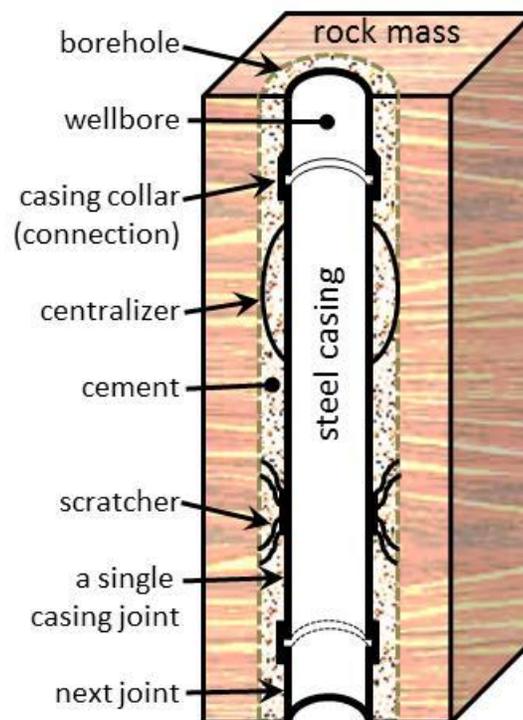
Well cementing requirements and testing are areas covered in part by mandated regulations. The goal is to achieve a continuous, effective seal between the casing and the rock mass, or between the current casing and the previous casing, so that the steel cased wellbore has full pressure integrity along its entire length, for the period of time and the range of conditions it will experience. If this integrity is inadequate at the beginning of the process, just after the hole is completed, or if this integrity is breached any time during active well operation, the operator must fix the problem. With modern cementing practices and quality control, having to immediately repair a new well is a rarity. Also, because the production casing is not exposed to mechanical wear, wellbore integrity is seldom an issue

after the well is properly completed. Nevertheless, as discussed later, behind-the-casing gas migration continues to be an issue in a small percentage of energy wells.¹²

As each casing string is assembled and lowered down the borehole, centralizers and scratchers are attached to the steel casing (Figure 3). The tendency in the industry is to increase the number of centralizers and scratchers to assure a better seal for the region between the casing and the rock mass.

Centralizers are springs designed to keep the casing in the center of the hole so that the cement slurry completely surrounds the casing. Before cement is pumped, the casing string is lifted up and down 25-35 m and rotated to clean the borehole wall. Scratchers help remove drilling mud caked on to the borehole wall, and often special chemical solutions precede the cement placement to help dislodge this mud cake. To place the cement, a rubber plug is placed inside the casing, then cement slurry is placed on top of the rubber plug as it is pumped to the bottom of the casing (the shoe). Once the plug hits the shoe, it opens, and the cement slurry flows out of the shoe and up and around the casing. Once the appropriate volume of cement is mixed, a second wiper plug is placed in the casing to displace all of the cement into the exterior annulus while wiping the inside of the casing clean.

Figure 3: Casing-Cement-Rock System, with Centralizers and Scratchers



¹² See Footnote 9 for the relevant reference

Once the cement is placed around the casing, it is allowed to set for a stipulated time period, and drilling proceeds. If it is the production casing, it is logged with special acoustic tools called “bond logs” to assure that a good cement-rock seal has been achieved, and pressure tested before completing the well.

Well cement is placed as a water-Portland cement slurry, and the great majority of wells in Canada use Class “G” Oilfield cement and a slurry density of about 2.05 g/cm³. In some applications, additives may be used to improve the properties of the cement. Replacing 70-75% of the cement with silica flour (finely ground quartz – SiO₂) is required in thermal wells to create cement that is stronger and more resistant to thermal dehydration. Special cement formulations are used in the presence of salt beds to avoid dehydration and shrinkage. Latex-based additives are said to lower the permeability of the cement and give it more ductility (the ability to deform without losing sealing characteristics). In cases where natural gas entering the cement is a concern, chemicals are added to scavenge the gas and resist the development of gas channels. Foamed cements counteract the natural tendency of neat cement slurries to shrink a small amount when setting. Use of additives is typically not mandated or controlled by the regulatory agency; it is the responsibility of the owner of the well to assure that appropriate cement formulations and additives are used in the conditions encountered so that the energy well is properly sealed and ready for service.

The best guarantee against future leaky well problems is a high quality initial well installation (primary cementation), so attention should be paid to well casing and cementing. Although well cementing does not have to take place under direct supervision of a professional engineer, it is important to verify that the appropriate materials and procedures are used and that the installed well meets mandated performance criteria (pressure tests, bond log quality). In this way, future issues relating to well integrity and risks of interaction with shallow aquifers will be minimized. In Nova Scotia, there appear to be no exceptional conditions such as very unstable shales, high pressures, numerous gas zones, or serious lost-circulation¹³ zones that would impede high quality installation of cement-sealed casings.

4. WELL COMPLETION

Once a wellbore has been drilled and cased, it is necessary to “complete” the well, linking it to the rock mass so that oil or gas can flow at a rate that is commercially viable. Pathways must be created between the wellbore and the rock mass at many locations (Figure 1) so that a large rock volume of rock is accessed. From 15 to 40 “stages” will be fractured along the horizontal well for shale gas development, spaced as closely as 30-40 m in some low-permeability fields, as much as 120-150 m apart in other formations of higher permeability. There are several different methods to do this, of which the two most common are described in Appendix A. Well completion generally has no effect on well

¹³ A lost-circulation zone is a bed of extremely high permeability through which the drilling fluid can escape without forming a seal. Usually, such zones are associated with limestones and dolomites that have been locally dissolved, leaving large cavities and channels, or intensely fractured rocks with wide-open fractures.

integrity in the long term or the short term, as all the activity is taking place at the bottom of the well, and the critical part of the wellbore where good seals are needed and casing must be intact is the section from the producing formation to the surface. Later in this discussion paper, the remote possibility of interwell communication during hydraulic fracturing is discussed, as this involves a potential impairment of wellbore integrity.

5. WELL INTEGRITY DURING PRODUCTION

Production of gas or oil may take place directly into the production casing, but more commonly a production tubing string is attached to the bottom of the casing, and all the fluids being produced (gas or oil, plus a small amount of formation water in some cases) pass through this production tubing out of the wellhead to be processed. This means that the annulus between the production tubing and the production casing is inactive, and can be monitored for any pressure changes that might indicate a loss of pressure integrity during the production life, which may extend to two or three decades.

5.1. Gas Migration during Production

With some technologies and in some geological environments, maintaining wellbore integrity is challenging because of severe demands placed on the casing-cement system. For example, this occurs in thermal wells for heavy oil production, where steam at temperatures as high as 325°C may be injected through the production/injection tubing. Not only does this cause thermal expansion and contraction, it accelerates electrochemical corrosion of the steel casing and can dehydrate shales around the wellbore, leading to a loss of wellbore integrity through the opening of a pathway outside the casing and cement. Other reasons for casing integrity loss include large-scale reservoir compaction and casing rupture, or the triggering of formation shear between the reservoir and the overlying rock as the result of large changes in pressure.

There is a low likelihood of casing integrity loss in Nova Scotia because the formations are low porosity and therefore resistant to shearing, the temperature effects imposed upon the wellbore are minor, and the volume changes associated with the depletion of a shale gas reservoir are very small, compared to a conventional gas reservoir. All these factors, plus the fact that the pressure in the productive horizon is being lowered because of continued depletion, means that maintaining well integrity would be relatively straightforward. Any problems will most likely be associated with seepage of gas, not oil or saline water, because gas is buoyant.

If loss of casing integrity is observed at any time during production, the operator must fix the problem. This involves identifying the location and nature of the leakage problem, implementing a suitable method to stem the leak such as perforating and pressure-squeezing a sealant into the region behind the casing (“perf-and-squeeze”), followed by placement of an expanding steel sleeve (a casing patch) to restore the pressure integrity of the production casing.

During production, the annulus between the surface casing and the production casing is monitored for gas flow (called SCVF – Surface Casing Vent Flow). There is often a small amount of gas escaping from this annulus, and often much of the SCVF gas is coming from intermediate depth zones – thin gassy zones that are not commercially exploitable, or even from organic matter deterioration at depths as shallow as a few hundred meters – called biogenic gas. There are regulatory guidelines for how much SCVF is permitted during production, and it is important not to allow this gas pressure to build up, as this would promote the forcing of the gas outside of the surface casing shoe, where it can migrate toward lower-pressure regions such as shallow aquifers and the surface.¹⁴

Gas wells have no moving parts (pumps or sucker rods) unless they produce a lot of liquids which must be lifted to the surface to allow gas production to continue unimpeded; oil wells, however, may have such equipment. In wells so equipped, production tubing is invariably installed, so although there can be some mechanical wear of the tubing, wear of production casing is extremely rare because all the moving parts reside inside the production tubing string or right at the bottom of the wellbore.

There is a reasonable chance that producing wells will be entered during their life span in order to do some stimulation of production to extend the economic usefulness of the wellbore. In the extreme, a new horizontal section could be drilled, or the old section entirely re-fractured to open new pathways for oil or gas to flow to the wellbore. In such cases, the practices followed are similar to those discussed in the Well Completion Appendix, and before the activity, it is common (or it could be mandated) to run another cement bond log to give some assurance that the behind-the-casing pathway has remained sealed.

5.2. Leakage Behind the Casing

It appears that the major well integrity issue in the unconventional oil and gas industry is related to gas migration outside of the production casing, up around the surface casing, and interacting with shallow groundwater or venting to the surface.^{15,16} This pathway, as well as other subsurface pathways shown in Figure 4, is common to all oil and gas wells¹⁷, and is now discussed in more detail. Although stray gas has been studied in the literature¹⁸, there is not much quantitative information about the behind-the-casing pathway, and this suggests that assessment of groundwater and natural methane occurrences

¹⁴ Harrison, S.S., 1985, Contamination of aquifers by overpressuring the annulus of oil and gas wells: *Ground Water*, v. 23, no. 3, p. 317-324.

¹⁵ Watson, T., and Bachu, S. 2009, Evaluation of the potential for gas and CO₂ leakage along wellbores: *SPE Drilling & Completion*, v. 24, no. 1, p. 115-126 (SPE 106817).

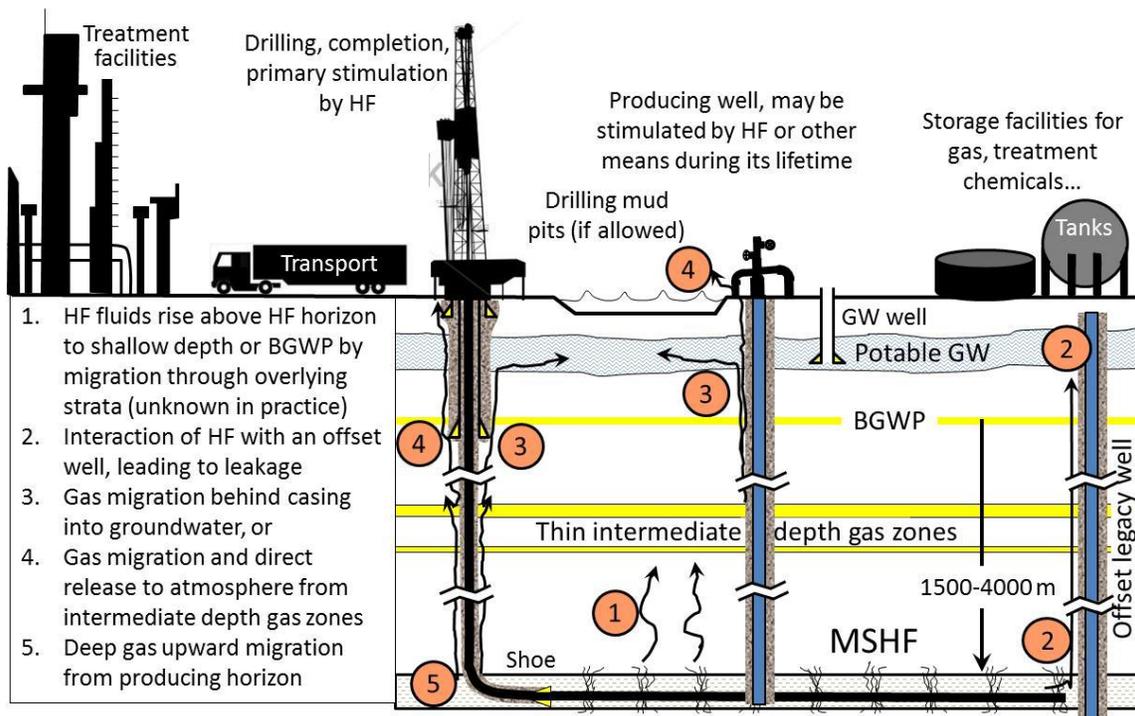
¹⁶ Dusseault, M.B., Gray, M.N. and Nawrocki, P. 2000, Why oilwells leak: Cement behaviour and long-term consequences: *Society of Petroleum Engineers SPE* 64733.

¹⁷ Dusseault, M.B. and Jackson, R. 2014. Seepage pathway assessment for natural gas to shallow groundwater during well stimulation, production, and after abandonment. Accepted for publication by *Environmental Geology*, preprint available.

¹⁸ Gorody, A.W., 2012, Factors affecting the variability of stray gas concentration and composition in groundwater: *Environmental Geosciences* v. 19, no. 1, p. 17-31.

would be an important activity in areas that may experience oil and gas development. Surface casing vent flow data must be registered with the regulatory agency; for example, the AER keeps records of all occurrences, therefore there are excellent statistics available in this area, in contrast to gas migration behind casing, where there are few data, insufficient to draw strong quantitative conclusions.

Figure 4: Potential Subsurface Contamination Pathways



Pathway 1 has triggered much concern among opponents of unconventional oil and gas development. However, there is apparently no known case of fracturing liquids or gas migration from the target horizon directly up through the rock mass to the surface or into shallow aquifers. Monitoring of the active fracturing process for hydraulic fracture rise shows that induced fracturing terminates in the zone above the target formation, and induced fractures do not rise a thousand metres or more to the surface.¹⁹ Pathway 1 remains speculative, and compared to other pathways, can reasonably be left to effective monitoring and regulatory controls in the context of possible onshore Nova Scotia oil and gas development.

¹⁹ Fisher, K., and Warpinski, N. 2012, Hydraulic-fracture- height growth: Real data: SPE Production & Operations, v. 27, no. 1, p. 8-19 (SPE 145949-PA). This article, based on hundreds of cases of data collection in practice, discusses fracture vertical growth, showing that induced fractures terminate far below the groundwater level, generally close to the top of the target formation several kilometers down.

Pathway 2, fluid migration up an offset well during hydraulic fracturing, has happened at least once in practice in Canada. In the fall of 2012, injected fluids rose to the surface in an offset legacy well producing from the same formation during active fracturing of a horizontal well north of Calgary, AB. This incident caused the AER to issue a detailed study of the event (<http://www.aer.ca/>), and led to the issuance of new guidelines to reduce the probability of such an incident in the future.²⁰ In Alberta alone, over 450,000 oil and gas wells have been drilled, so the presence of active or legacy wells must be considered during planning for drilling and well stimulation. By contrast, in Nova Scotia, there are only a few abandoned legacy wells that penetrate deep into the shale gas strata, and the locations of these wells are well-known, so the risks of fluid migration into these wellbores during hydraulic fracturing or other production activities are likely minimal.

Pathways 3 and 4 are the pathways of greatest concern, especially after well abandonment when the inside-the-casing pathway has been plugged. Because of cement placement issues and cement shrinkage²¹, gas influx from intermediate-depth gas zones can lead to the development of gas columns behind the external casing, and the buoyancy of the gas leads to slow seepage, either into shallow aquifers or to the surface where methane enters the atmosphere. General methane emissions including all fugitive gas sources from natural gas development has recently been studied²², but there exist no systematic regional studies of gas migration from energy wells in Canada or elsewhere. Such studies have been recommended (see reference in footnote 4), and would serve as an excellent guide to development of regulatory requirements to reduce the incidence and rate of gas migration. In Nova Scotia, because there are few intermediate-depth gas-bearing zones except in the coalbeds of the northern part of the province, these two pathways are expected to be far less frequent compared to some other jurisdictions such as eastern Alberta where there may be a half-dozen thin gas sands at depths of 200 to 1000 m (below the surface casing shoe but above the producing zone).²³

Pathway 5 in Figure 4 comprises leakage of target formation gas upward along the outside of the casing toward the surface. Such cases seem to be associated exclusively with poor primary cementation of wells, or in wellbores that were subjected to severe conditions during service. Because a reservoir is depleted by production, the fluid pressure drops to lower values than in the fluids above the reservoir. This inhibits gas migration and acts against the formation of a continuous buoyant gas zone behind the casing. In addition, the lower 1000 m of a 2000-4000 m deep casing string (Figure 1) is likely to be well-

²⁰ AER, 2013, Directive 083: Hydraulic Fracturing – Subsurface Integrity: May 21, 15 pages, The Alberta Energy Regulator, Calgary, Alberta, Canada, <http://www.aer.ca/documents/directives/Directive083.pdf>

²¹ Reddy, B.R., Xu Y., Ravi, K., Gray, D. and Patillo, P.D. 2009, Cement shrinkage measurement in oil-well cementing --- a comparative study of laboratory methods and procedures: SPE Drilling & Completion, v. 24, no.1, p. 104-114 (SPE-103610-PA).

²² Pétron, G., and 29 others, 2012, Hydrocarbon emissions characterization in the Colorado Front Range - A pilot study: Journal Geophysical Research, Atmospheres, v. 117, D04304, doi:10.1029/2011JD016360.

²³ Erno, B., and Schmitz, R. 1996, Measurements of soil gas migration around oil and gas wells in the Lloydminster area: Journal of Canadian Petroleum Technology, v. 35, no. 7, p. 37-46.

sealed because of the high pressure of the column of liquid cement during primary cementation of the production casing. Pathway 5 would be of limited concern in Nova Scotia providing that good quality assurance of the primary cementing operation is maintained.

This leaves only Pathways 3 and 4 as significant concerns, and indeed there is good evidence that a significant percentage (from a few % to as many as 10%)²⁴ of oil and gas wellbores in some areas experience gas migration. It is generally straightforward to differentiate between shallow biogenic or coalbed methane and the deep gas found in unconventional oil and gas formations²⁵, so once a gas migration event has been identified during operations (by the company) or at a later date, sampling and analysis helps reveal the source and gives clues about the pathway. It is a standard regulatory requirement that the corporation report gas migration events. Once the source is located, perf-and-squeeze operations can be used to shut the pathway above the source and greatly reduce the chances of further gas seepage.

Although an undesirable event from a greenhouse gas and aesthetic perspective, the impact of methane entering potable water sources is not a serious *health* issue in comparison to many other chemical contaminants.²⁶ Gas in groundwater is a widespread natural phenomenon, especially in geological conditions where there are deep or shallow methane sources, such as coalbeds, intermediate depth gas accumulations, and other organic sources. The gas in water wells may even come from great depth under the right geological circumstances.^{27,28} Gas entering shallow groundwater wells may be a nuisance, including exceptionally an explosion hazard, but other than making groundwater unpalatable in some cases, no severe health impacts appear to have been demonstrated at this time..

However, a recurring issue in well integrity assurance and development of unconventional oil and gas in new areas is the lack of scientific-quality baseline groundwater data.²⁹ Often, the only data available are from local water wells which may be tapping only one zone or may be mixing water from several groundwater zones, or may be contaminated by organic matter in the well. If only this quality of data is

²⁴ Bexte, D.C., Willis, M., De Bruijn, G.G., Eitzen, B. and Fouillard, E. 2008. Improved cementing practice prevents gas migration. *World Oil Magazine*, June Issue

²⁵ Molofsky, L.J., J.A. Connor, A.S. Wylie, T. Wagner, and S.K. Farhat, 2013, Evaluation of methane sources in groundwater in Northeastern Pennsylvania: *Groundwater* v. 51, no 3, p. 333-349.

²⁶ Goldstein B.D., Brooks, B.W., Cohen, S.D., Gates, A.E., Honeycutt, M.E., Morris, J.B., Orme-Zavaleta, J., Penning, T.M. and Snawder, J. 2014. FORUM on The Role of Toxicological Science in Meeting the Challenges and Opportunities of Hydraulic Fracturing. *Toxicological Sciences* **139(2)**, 271–283.

²⁷ Wilson, B., 2014, Geologic and baseline groundwater evidence for naturally occurring, shallowly sourced, thermogenic gas in northeastern Pennsylvania: *AAPG Bulletin*, v.98, no. 2, pp. 373-394.

²⁸ Stahl, W., E. Faber, B.D. Carey, and D.L. Kirksey, 1981, Near-surface evidence of migration of natural gas from deep reservoirs and source rocks: *AAPG Bulletin*, v. 65, no. 9, p. 1543-1550.

²⁹ Jackson, R.E., A.W. Gorody, B. Mayer, J.W. Roy, M.C. Ryan, and D.R. Van Stempvoort, 2013, Groundwater protection and unconventional gas extraction: the critical need for field-based hydrogeological research: *Groundwater*, v. 51, no. 4, p. 488-510.

available, it becomes more challenging to address cases where there is a concern over the source of methane (or other compounds) in the groundwater.

6. WELL ABANDONMENT AND LONG-TERM INTEGRITY

6.1. The Abandonment Procedure

Once the commercial life of a shale gas well is over, often fifteen or more years, it must be abandoned according to stipulated practices laid down by the regulatory body. If there is any detectable surface casing vent gas flow, which occurs in perhaps 10-15% of wellbores³⁰, or evidence of seepage or loss of pressure integrity between the intermediate string and the production string, remediation must be implemented to reduce such flows to negligible values before the well is sealed. This would typically involve perforate-and-squeeze of neat cement slurry into the location of the casing above where the gas is percolating. Cement bond logs, temperature logs, and noise logs may be used to identify the source of the gas migration to guide the location of the perforating action, and the well will have to be monitored for SCVF before abandonment. Exceptionally, several perf-and-squeeze operations may be required to reduce seepage rates to mandated levels.

Once these activities are done, or if the well has displayed no SCVF gas emissions and it is not necessary to attempt to seal the behind-the-casing pathway, the wellbore can be plugged and abandoned. Plugging a well requires that the geological information for the well be used to locate zones above where plugs should be placed, and there are regulatory criteria that must be followed. Each plug includes a mechanical seal, a metal or polymer bridge plug placed inside the casing, and an amount of cement sufficient to seal 30 to 50 m of the wellbore on top of the bridge plug. A number of these seals will be placed along the length of the production casing so that the interior of the wellbore is sealed.

Statistics are available on the total number of wells that have been drilled, that are active, and that have been plugged and abandoned. Worldwide, the majority of wells drilled have been in the United States, about 2.5 million since 1950, and somewhat more than 500,000 in all of Canada (mainly in Alberta). Probably 70% of these wells have been plugged and abandoned, and although there are many instances of gas migration, which must be fixed when noted, there do not seem to be major environmental problems arising from the existence of these abandoned wells at this time. This is not an easy statement to verify because methane seepage has not been considered by toxicologists as an issue worthy of their attention, and this is supported by the lack of publications in this area. Certainly, there are many areas in the world (Pennsylvania, central Alberta) where natural seepage of methane is endemic, and major health concerns have not been identified at this time. In any case, most

³⁰ Surface casing vent flow data are registered with the regulatory agency; therefore, there are excellent statistics available in this area, in contrast to gas migration behind casing, where there are few data, insufficient to make strong quantitative conclusions.

jurisdictions have “orphan well” funds, provided by a levy on production, that are used to fix wells for which an owner cannot be found; otherwise, the responsibility is that the owner fix the leaking abandoned well to the standards set by the regulatory agency.

Perf-and-squeeze operations are less likely to be needed in Nova Scotia, for reasons discussed before and because general oilfield practice continues to improve. If they are, there is a concern that in very stiff dense rocks, the high pressures needed to force the cement into the cement-rock system will tend to wedge open natural fractures that could serve as future pathways behind the casing. This is less of a concern in jurisdictions such as Alberta where the rocks in the upper portion of the wells tend to be ductile and granular in nature (ductile shales, clayey high-porosity sandstones, porous coaly seams...). Better sealing agents that can flow into small cracks and which tend to wet the surfaces of the cracks would be more effective than cement to seal wellbores, but such materials (low viscosity resins for example) have not been widely adopted. As in many other cases, there is insufficient publicly available data on the efficacy of practices such as cement squeezing, and there is also a reluctance to adopt somewhat more demanding and expensive techniques for sealing wells.

6.2. Long-Term Wellbore Integrity

Once a well is properly abandoned and there is no detectable leakage, is there a chance that Pathways ③ and ④ could develop? The answer to this question is yes: there is evidence that the development of slow gas migration can take place years after abandonment if a buoyant gas column develops behind the casing. In such cases, the gas seepage rate may be small, but it may remain entirely undetected if the gas is entering shallow aquifers rather than venting visibly at the surface. Furthermore, if gas migration is detectable at the surface, there is a very high probability, almost a certainty, that some gas is entering into sand aquifers behind the surface casing. In Alberta, especially in the Lloydminster area and the heavy oil fields of east-central Alberta, gas migration long after abandonment is not uncommon. The gas seepage rates are low, and the environmental impacts are almost certainly small³¹, but as mentioned previously, the incidence and rates of such events remains unquantified. Only if surface-visible evidence of a leaking well is noted and reported is it re-entered and re-sealed.

How long after abandonment will the sealed wellbore integrity be maintained? The answer to this question is not well-known at present. Modern well cementation practices are barely 60 years old, and the life-span of steel in the ground, subjected to electro-chemical corrosion (the steel is a good electrode), is not known, nor is it known if gas migration pathways could develop once the casing has corroded and is breached in many places. This is a complex question that is also worthy of investigation, starting with assessment of some old wells in Ontario, New Brunswick and Alberta, for example. At the present time, there is no evidence of significant increases in the incidence of leaky wellbores with time,

³¹ The Environmental Impacts discussion paper, which will form the basis of another chapter in the final report, will cover this subject in more detail. This paper is scheduled for release in June 2014. See the hydraulic fracturing review’s project documents page for more information: www.cbu.ca/hfstudy/resources/project-documents

but the studies remain at the anecdotal level in large part because old wellbore sites are not subjected to systematic re-examination over time. As mentioned in the first section (see Footnote 4), the report issued in May 2014 by the Council of Canadian Academies deals with many issues related in particular to shale gas wells, but which are also common to all conventional and unconventional oil and gas wells.

7. SUMMARY AND CONCLUSIONS

Unconventional oil and gas development using modern well cementing and completion techniques leads to generally good wellbore performance, but there will never be a 100% success level in sealing all wellbores against all possibilities of future leakage. Continued technological advances are helping to reduce the incidence of gas migration around active and abandoned wells through improvements in cementing methods (for example more centralizers, better denser cement formulations etc.), new materials for correcting leakage problems, better methods for detecting poor-quality cement behind the steel casing in the hole, even better methods of detecting slow methane seepage around old abandoned wellbores. Despite all these advances, human error will always occur; in the case of oil and gas wellbores, the risks associated with inadequate well integrity are not great, as shown by years of experience with hundreds of thousands of wells in the western provinces. Nevertheless, vigilance and explicit quality assurance practices are necessary to keep incidents of human error low, and to rectify problems that may have arisen because of such an error.

The most important wellbore integrity problem, at least in North America and perhaps internationally, seems to be gas seepage along the outside of casing, and this may not be a severe environmental problem because the incidence of leaking wells can easily be reduced, the seepage rates are small in general, and the environmental consequences of seepage of natural gas into aquifers and into the atmosphere are not catastrophic, albeit undesirable.

Because any possible unconventional oil and gas development in Nova Scotia would take place using modern technology with multiple wellbores installed at each drilling site, it is a relatively straightforward task to establish good regulatory practices in advance to ensure that the site is geologically understood, that wells are properly installed with good quality assurance, and that well abandonment is done according to best practice guidelines. The mature regulatory practices of jurisdictions such as Alberta could serve as a guide to the establishment of a system in Nova Scotia, with minor modifications as deemed necessary by local regulators, scientists and engineers. Operators can be required to be vigilant and that the data be made public so that concerns about activities and impacts may be subject to transparent oversight.

Developments in regulatory practices continue to be made. For example, a multi-level groundwater monitoring well at each multi-well drilling site may be required in the future in some jurisdictions, and is

currently being debated in the regulatory world. If this is mandated, the well should be installed under the supervision of a licensed third-party before the first borehole is drilled, and the groundwater well should be sampled and analyzed initially and each two to three years thereafter and until ten years after the last well is abandoned. In this way, a problem with energy wellbore integrity that impacts groundwater could be identified soon and corrective measures taken before a more severe problem develops over a larger area. Because each unconventional oil and gas multi-well pad would be draining the gas from an area of several square kilometers (4-6 km²), the number of sites will remain few and fairly widely spaced, so that it is far easier to detect issues and rectify them.

The natural advantages that exist in Nova Scotia shale gas regions would lead to a much lower incidence of poor wellbore integrity compared to historical practices in other jurisdictions if development should ever take place. A few of these are listed here:

- Moderate tectonic stresses and strong rock mean that wellbore instability during drilling will be largely absent; high quality wellbores lead to higher quality primary cementing operations, and therefore fewer cases of leaking wells.
- Except in the coalbed areas, there appear to be few gas sands at shallow depth that could lead to problems with intermediate-depth gas migration behind the casing.
- Shale gas in Nova Scotia is likely to be sweet gas (little to no H₂S), making all operations easier and casing life longer.

According to analysis by Hayes and Ritcey³², any significant development of Nova Scotia's unconventional oil and gas would not take place for several years, perhaps much longer. This gives Nova Scotia time to establish appropriate monitoring and regulatory systems if the possibility of such development emerges, and to benefit from more technical advances in cementation, measurements, and general scientific knowledge about well integrity.

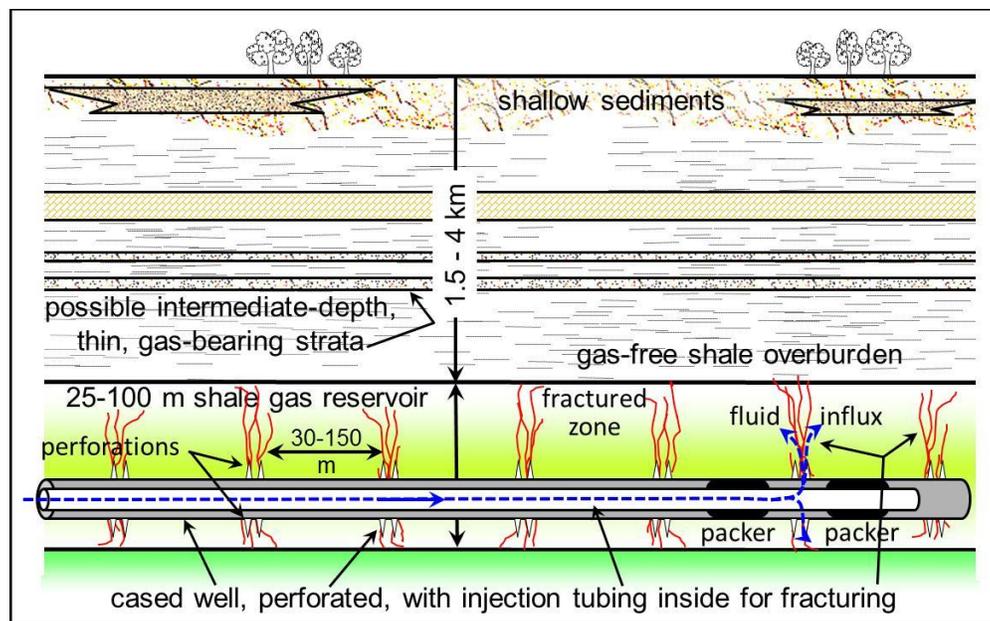
³² The discussion paper by Hayes and Ray titled: The Potential Oil and Gas Resource Base in Nova Scotia Accessible by Hydraulic Fracturing, is available on the hydraulic fracturing review website: www.cbu.ca/hfstudy/resources/project-documents.

Appendix A: Well Completion for Unconventional Oil and Gas Wells

a. Perforate-Isolate-Fracture

In this approach (Figure A1), the production casing is installed to the toe of the well and cemented. To pierce it, perforating devices about 3 m long are sequentially placed at each location and detonated to create a set of 30 to 90 holes 15 to 20 mm in diameter. Then, another section is perforated, and so on until all the locations for well stimulation are finished. Now, injection tubing³³ with a double packer system is lowered into the wellbore, and the packers are expanded against the inside of the casing to isolate one or several of the perforated zones. This group of perforations now becomes the channels through which hydraulic fracturing is carried out. Note that the production casing is protected against any issues that might arise from repeated high pressure flexing of the cemented casing.

Figure A1: Completing a Multi-Stage Well Using Perforating and a Packer Fracturing System



Once hydraulic fracturing is carried out successfully at one site along the horizontal wellbore, the packers are released, moved to isolate another section of the horizontal well, and the hydraulic fracture well stimulation process is repeated. There may be various flow tests done during or after the process for evaluation, and the procedure can allow for flow-back fluids to return to the surface immediately

³³ The word “tubing” describes a string of pipe that is suspended in the hole without cement (e.g. production tubing), or that is introduced into the hole for a special purpose, such as perforating or fracturing. Once operations cease, tubing is removed from the well. Tubing protects the integrity of the production casing.

after each fracturing period. Once the well is completed, the injection tubing is removed, production tubing is installed if required (Figure 1), and the well placed on production.

b. Sliding Sleeve Fracturing

The most widely adopted new method for completing an unconventional oil and gas well is the sliding sleeve and drop-ball method (Figure A2 - <http://www.packersplus.com/>). This method was perfected in Alberta and usually makes completing a well easier and quicker.

As in Figure 1, the horizontal section is left as an open hole but a special assembly with fluid ports, sliding sleeves, and chemically expanding packers is installed and tied into the production casing and attached to a tubing string. To access the formation, after the packers have swelled, a small ball is dropped to seal the internal port, pressure is increased to slide a sleeve towards the toe of the horizontal section to open the ports, and hydraulic fracturing is carried out. For the next stage, a slightly larger ball is dropped to seal the next internal port, and pressure is used to open the next sleeve, and so on. The balls dissolve slowly in water and debris is flushed out so the wellbore can produce freely.

Figure A2: The Sliding Sleeve and Ball Method for Shale Gas Well Completion

