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Drilling without fail?

A review of empirical data on well failure in oil and gas wells

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1 Executive Summary

This report reviews the empirical evidence of well failure among oil and gas wells, both conventional and unconventional, and draws some preliminary conclusions for shale gas in the UK.

The number of studies investigating failure rates of oil and gas wells is relatively limited, and the majority focus on data from the US and Canada. However a consensus emerges that well failure is widespread, with failure rates ranging from around 5% at a minimum to above 50% for older wells.

The published research into failure rates for conventional oil and gas wells shows very different estimates, arising most likely from different definitions of "well failure", but also possibly from higher risks of failure in offshore wells and differences arising from the different regulatory systems in the US and Canada. Even sources backed by the oil and gas industry indicate hundreds of incidents of groundwater contamination.

The principal causes of well failure relate to cementing. While there is the potential to address these problems through better monitoring, tighter regulations and improved cement technologies, there is a recognition that well failure is very difficult to prevent entirely.

Hydraulic fracturing for shale gas, as proposed in the UK, is likely to pose higher risks than conventional drilling, for two main reasons:

- Hydraulic fracturing involves injection of fracking fluids at high pressure. Research shows that 'injection wells' into which liquids or gasses are pumped are 2-3 times more likely to leak than conventional 'production wells'.
- Shale gas wells are drilled horizontally underground in order to access gas over a wider area. Research into conventional wells indicates that horizontal or other 'deviated' (i.e. non-vertical) wells have a failure rate four times higher than for vertical wells in the same area.

Research looking specifically at shale gas wells found failure rates in newly-drilled wells in Pennsylvania over three years to be between 6.9% and 8.9%. This was characterised as "consistent with previous industry data, and not improving".

Bloomberg New Energy Finance has estimated that between 10,000 and 20,000 wells may be needed for shale gas to replace current UK imports. Even assuming the more conservative well failure rates found in the literature - between 4.6% and 8.9% - this suggests that between 460 and 1,780 wells in the UK could have well integrity failures such as methane leaks.

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2 Summary of published research into well failure

2.1 Watson and Bachu, 2009: Evaluation of the Potential for Gas and CO_2 Leakage along Wellbores

This paper examines data from the Alberta Energy Resources Conservation Board, which collects and stores information on more than 315,000 oil, gas and injection wells in Alberta of varying ages, drilled up to 2004. The purpose of the study is to aid better design of carbon dioxide (CO_2) sequestration facilities, e.g. for natural gas storage or for energy generation with Carbon Capture and Storage (CCS). It is one of the most widely cited studies on well failure, and is referenced by, for example, the Royal Society (2012), the Environmental Protection Agency (2011) and in the 2012 short film from Josh Fox, The Sky is Pink.

The study analysed detected instances of Surface Casing Vent Flow (SCVF) or gas migration (GM). SCVF is a flow of gas through the Surface Casing Vent (a vent at ground level), and indicates migration of gas between the production and surface casing. GM refers to migration of gas into soil surrounding the well.

The study finds an overall well failure rate of 4.6% in the province of Alberta (table 2, p121). In a specific test area, identified by the Province of Alberta for more stringent testing on the basis of higher observed gas levels in soil, 15.5% of wells are affected by SCVF or GM. Among deviated (for example, horizontal) wells in the test area, the failure rate was 66%.

The author notes that the three conditions for a leak to occur are (1) a source, (2) a driving force, and (3) a pathway. In the case of oil or gas drilling and extraction, (1) and (2) are present, so the creation of a pathway will cause a leak to occur.

Among the factors found to have a major impact on well failure are:

- Geographic area: more leaks were reported in a specific test area. The authors conclude that this is likely to be due to specific geological factors in the test area, rather than the more stringent testing regime, but admit that this requires further study.
- Well deviation: horizontal or slant wells are observed to have significantly higher failure rates than vertical wells; four times higher in the test area. The study suggests that problems with casing centralisation and cement slumping may contribute to the increased incidence of leakage.
- Well type: ‘cased wells’, i.e. those with one or more layers of casing pipe inserted and cemented in, accounted for 98% of leakage cases reported. Wells which were drilled and abandoned without being cased (i.e. with no pipe inserted into the borehole, but capped and cemented) had a leakage rate of only 0.5%, compared to 14% of cased and abandoned wells. Two explanations offered for this difference are the stricter regulations for uncased wells, and the fact that the production casing itself can act as a potential leak pathway.
- Economic activity and regulatory changes: prior to 2000, high oil prices were clearly correlated with high leakage rates. At such times, wells were drilled faster and more

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frequently, "potentially leading to substandard cementing practices" (p124). This trend is less pronounced after 1999 due to regulatory improvements.

The study concludes that cementing factors are a primary cause of leakage, including exposed and uncemented casing, and that good quality cementing and enforced regulations are crucial to reduce leakage rates. For carbon storage, reservoirs which are penetrated by fewer wells should be considered.

A 2008 presentation by the same authors further noted that high pressure fracturing may increase the potential to damage cement in the well, as well as providing leak pathways through the multiple perforated intervals created.

Figure 1: 2008 slide from Watson & Bachu presentation

2.2 Brufatto *et al*, 2003: From Mud to Cement: Building Gas Wells

This study from the oilfield services company Schlumberger's quarterly Oilfield Review journal examines the problem of well failure and methods for improving well integrity. It reviews data from the United States Mineral Management Service on offshore wells in the Gulf of Mexico, which covers 15,500 producing, 'shut in' (temporarily sealed) or abandoned wells. The data show a failure rate of 6% among wells less than a year old, rising to over 50% in wells aged over 15 years, and a 42% failure rate overall.

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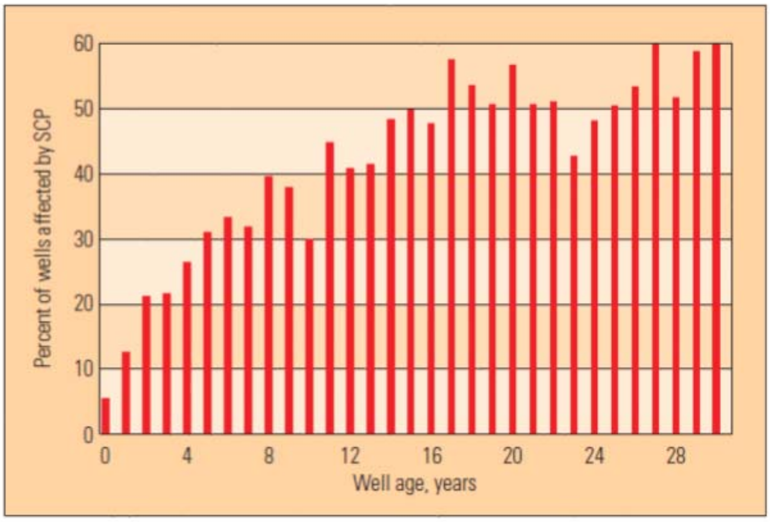

^ Wells with SCP by age. Statistics from the United States Mineral Management Service (MMS) show the percentage of wells with SCP for wells in the outer continental shelf (OCS) area of the Gulf of Mexico, grouped by age of the wells. These data do not include wells in state waters or land locations.

Figure 2: Well failure by age, from Brufatto *et al* (2003)

“Failure” here refers to the presence of sustained casing pressure (SCP), characterised as the “development of annular pressure at the surface that can be bled to zero, but then builds up again”. The term is used interchangeably with SCVF in much of the literature. However SCP does not necessarily describe an actual leak to soil or air. Other studies report that “90% of sustained casing pressures are small and can be contained by casing strength”, although “SCP represents a potential risk of losing hydrocarbon reserves and polluting aquifers and sea with hydrocarbons” (Jan Sæby, 2011). This may help account for the discrepancy between the 42% failure rate reported here and the 4.6% rate reported in Watson & Bachu. Other possible explanations are higher risks of well failure in offshore wells compared to onshore, or differences arising from the different regulatory systems in the US and Canada.

It is also worth noting that well integrity can fail *without* a pressure build up at the surface, e.g. when gas escapes (migrates) into a weaker formation such as an aquifer. As such, this study may overlook some forms of well failure.

The study then discusses causes of SCP, including tubing and casing leaks, poor mud displacement, poor cement-slurry design, and cement damage after setting. It notes that “even a flawless primary cement job can be damaged by rig operations or well activities occurring after the cement has set.” It then considers methods to reduce gas migration through zonal isolation, better cementing techniques and use of modelling software.

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2.3 Dusseault *et al*, 2000: Why Oilwells Leak

The paper discusses cement shrinkage among both oil and gas wells as a principal cause of well failure, particularly long after wells have been plugged and abandoned. While no data on well failure is cited, the study provides useful commentary on reasons for well failure.

The abstract states; "oil and gas wells can develop gas leaks along the casing years after production has ceased and the well has been plugged and abandoned. Explanatory mechanisms include channelling, poor cake removal, shrinkage, and high cement permeability. The reason is probably cement shrinkage that leads to circumferential fractures that are propagated upward by the slow accumulation of gas under pressure behind the casing. Assuming this hypothesis is robust, it must lead to better practice and better cement formulations."

Notable findings include:

- "The consequences of cement shrinkage are non-trivial: in North America, there are literally tens of thousands of abandoned, inactive, or active oil and gas wells, including gas storage wells, that currently leak gas to surface." (Page 1).
- Cement bonds poorly to many materials, including rock: "Cement will not bond to salt, oil sand, high porosity shale, and perhaps other materials. Also, bond strength (i.e. the tensile resistance of the cement-rock interface) is quite small; in fact, the tensile strength of carefully mixed and cured oilwell cement at recommended formulations is generally less than 1-2 MPa [megapascals]. Given that fluid pressures of 10's of MPa may have to be encountered, given that pressure cycling of a well can easily debond the rock and cement (there is strain incompatibility because of the different stiffnesses), and given that de-bonding is generally a fracturing process with a sharp leading edge rather than a conventional tensile pull-apart process, a large cement bond to rock cannot be assumed in any reasonable case." (Page 3).
- Studies measuring SCVF may underestimate leakage rates. "Unfortunately, even if no gas appears at the surface, it is no guarantee that the well is not leaking. In fact, the common occurrence of household water sources being charged with deep-sourced gas is clear evidence that there are many cases of leakage where the gas simply enters the water aquifer, and may never bubble around the casing." (Page 4).

So intractable is the problem that the paper concludes by recommending that surface gas leaks can be reduced by simply leaving a section of the well uncemented, so that gas can seep into a permeable bed in the surrounding strata which can act as a drain, rather than to the surface or into aquifers.

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3 Summary of other data sources on well failure

3.1 Groundwater Protection Council, 2011

A 2011 study for the US Groundwater Protection Council has been cited by sources backed by the fossil fuels industry, including Energy in Depth, which stated in a critique of the film The Sky is Pink: “Of course, not mentioned anywhere in the new 18-minute film is the August 2011 report issued by the Ground Water Protection Council (GWPC), a study that draws on real-world field data and case descriptions from regulators representing two of the most heavily drilled states in the country: Texas and Ohio.”

This study takes an entirely different approach to studies measuring well failure to those reported above. Rather than identifying instances of SCP or SCVF, the study considers only incidents in which the state regulator had documented an occurrence of groundwater contamination caused by oilfield activities. As such this study does not take into account gas migration to air or soil, and by relying substantially on citizen complaints, is likely to omit instances of groundwater contamination that went unreported.

The study found 185 such incidents from 33,000 wells drilled in Ohio (0.6%), of which 12 (0.04%) were due to casing failure. All but one of the 185 instances involved disruption to a private water supply. In Texas, of 190,000 wells drilled, 211 incidents were found (0.1%), of which 21 were casing-related (0.01%). These incidents represented a mix of citizen complaints and contaminants detected through monitoring and environmental assessments.

3.2 Ingraffea, 2012 and 2013

Analysis of data recorded by the Pennsylvania State Department of Environmental Protection (DEP), carried out by Ingraffea (2012) of Cornell University, found a 6.2% failure rate among *newly-drilled* shale gas wells in each of 2010 and 2011, and a 7.2% failure rate in January and February of 2012. These rates were characterised as “consistent with previous industry data, and not improving”. The data was obtained through searching the DEP’s Marcellus Violations Database for all violations or inspector comments indicating that a well was leaking outside its production casing.

Ingraffea (2013) updated this data in January 2013, after “a more complete and revealing search” of the Department of Environmental Protection database revealed further evidence of well failures. This revised the well failure rates for 2010 and 2011 to 6.9% and 7.2% respectively, and updated the 2012 figure to include the whole calendar year, recording a failure rate of 8.9% in this period.

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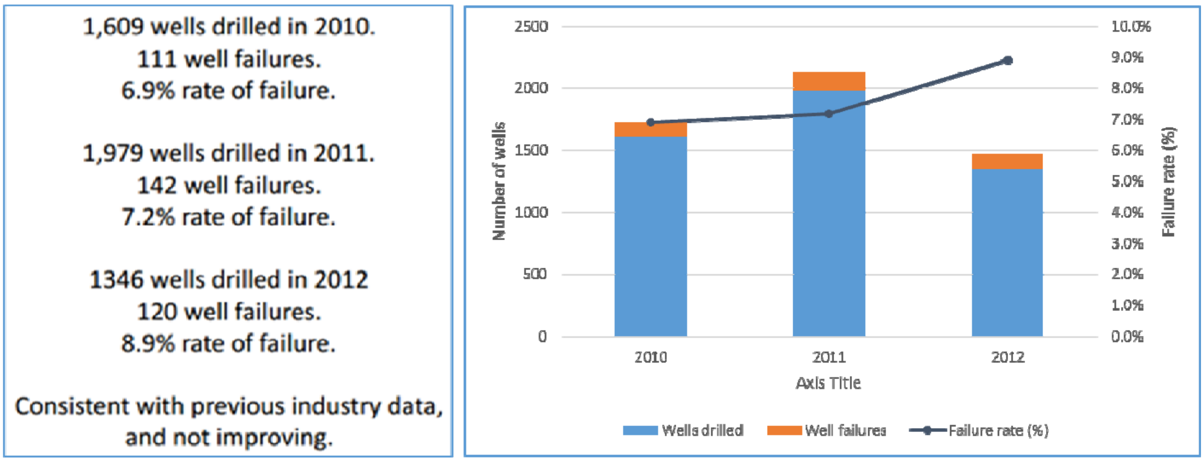

Figure 3: Revised results of survey of leaking wells in the Pennsylvania Marcellus shale play based on violations issued by the DEP and well inspector comments, from Ingraffea 2013.

Ingraffea concludes that “the most recent experience with shale gas wells in the Pennsylvania Marcellus play reflects long term, world-wide industry data with respect to new wells with compromised structural integrity. Operator-wide statistics in Pennsylvania show that about 6-7% of new wells drilled in each of the past three years have compromised structural integrity. This apparently low failure rate should be seen in the context of a full buildout in the Pennsylvania Marcellus of at least 100,000 wells, and in the entire Marcellus, including New York, of twice that number. Therefore, based on recent statistical evidence, one could expect at least 10,000 new wells with compromised structural integrity.”

3.3 Norwegian Petroleum Safety Authority, 2006

A 2006 Norwegian Petroleum Safety Authority study into well integrity was published in 2010 in the SPE Production & Operations journal (Vignes and Aadnøy, 2010). The study examined a representative sample 406 out of 2,682 offshore production and injection wells on the Norwegian Continental Shelf, and found that 18% of wells had well integrity ‘failures, issues or uncertainties’, and that a further 7% had been completely ‘shut’ in owing to integrity issues.

A presentation by Randhol and Carlsen (2008) for the Scandinavian research organisation SINTEF discussed these results in the context of other data on well integrity in the North Sea, finding the data consistent with its own. It also noted that injection wells were 2-3 times more likely to leak than producer wells (where injection wells are pipes into which water or other fluids are pumped, and producer wells are wells designed for oil and gas extraction). Injection wells are discussed in the context of carbon sequestration, however the same risks might be expected to apply to shale wells, which are injected during the hydraulic fracturing process.

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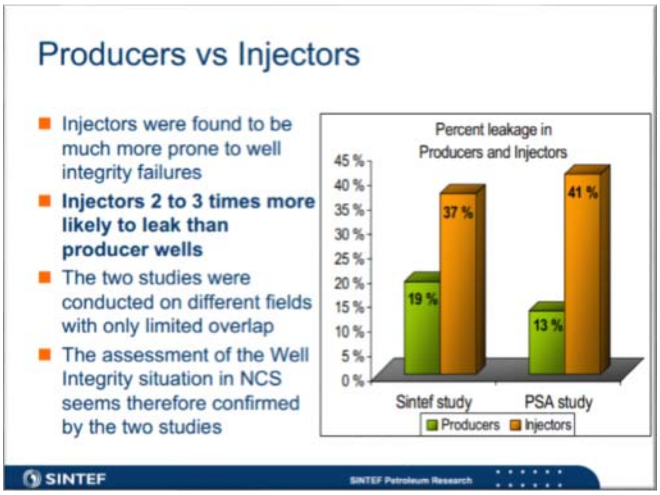

Figure 4: Slide from Randhol and Carlsen (2008)

3.4 University of Calgary, 2010

A University of Calgary paper (Nygaard, 2010) on well design and integrity for CO_2 sequestration reviews much of the same research as covered in this paper, and as such is not reviewed in depth here. A couple of noteworthy points are made in its discussion of the evidence. For example, the paper notes: “The main observation from these studies is that cased wells as (sic) more prone to leakage than drilled and abandoned wells, and injection wells are more prone to leakage than producing wells. […] If wells are plugged and abandoned permanently, both Gray *et al*, 2007 and Carlsen and Abdollahi, 2007 [...] suggest the casing steel be removed before installing the final cement plugs. This will remove the most-likely leakage path along the casing.”

This emphasises the findings of Dusseault *et al* (2000) on the causes of well failure, as the shrinkage of cement away from the well casing causes the casing to act as a pathway from source to surface.

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4 Potential implications for the UK

What does the research above suggest could happen if shale gas extraction is developed at significant scale in the UK?

The first conclusion is that, despite the claims of the industry, wells do fail and well failures are extremely likely in the UK. Regulation might reduce the number of failures but is extremely unlikely to eliminate them completely. Well integrity checking is clearly key to reducing well failure, but supposedly independent well integrity checks can still be carried out by an employee of the company doing the drilling[1].

The research, although limited on these issues, also shows that the type of wells that the industry will be using in the UK – "deviated" wells with horizontal sections, and injection of fluid at high pressure – are more likely to fail than conventional wells.

How many well failures could there be in the UK? The answer clearly depends on how many wells are drilled and what failure rate is assumed.

Tyndall estimated in 2011 that, over a 20 year period, approximately 3,000 wells would need to be drilled to deliver sustained annual output equivalent to 10% of the UK's national consumption.

However, given the significantly increased recent shale gas reserve estimates by the British Geological Survey, a much larger number of wells now seems possible:

- Francis Egan, Chief Executive of Cuadrilla, which hopes to drill for shale gas in Lancashire, has spoken of 4,000 wells[2],
- The Institute of Directors, in its report 'Getting shale gas working' (2013, p127) includes a scenario with 100 well pads, each with 40 lateral wells,
- Bloomberg New Energy Finance (2013) has estimated that, depending on the rate of gas flow, between 10,000 and 20,000 wells may be needed for shale gas to replace current UK imports.

Assuming the more conservative well failure rates found in the literature (between 4.6% and 8.9%) and using the well numbers from Bloomberg New Energy Finance, suggests that the number of wells encountering integrity failures such as methane leaks in the UK could be between 460 and 1,780[3].

The higher observed failure rates suggest that several thousand wells in the UK could, over time, be affected by integrity problems such as Sustained Casing Pressure. While it is not known how many of these wells might encounter more serious problems, they would pose increased risks of problems such as methane leaks and pollution of aquifers or groundwater.

[1] See evidence given to the House of Lords Economic Affairs Committee, 3 December 2013 – Peter Baker of HSE says "*It is right that operators have the option of using someone that they directly employ"*
[2] See evidence given to the House of Lords Economic Affairs Committee, 5 November 2013.
[3] 4.6% of 10,000 gives 460 at the lower end, and 8.9% of 20,000 gives 1,780 at the upper end.

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Appendix – Additional data

This appendix covers, for reference purposes, some further data sources which are estimates or do not lend themselves to generalisation, but have been cited elsewhere in discussions of well integrity.

US Environmental Protection Agency (EPA), 1992

A well failure rate of 16.7% for the USA has been widely cited elsewhere[4]. The data is sourced from an estimate provided by the EPA to the New York Times in 1992. The New York Times reported that "the Federal Environmental Protection Agency estimates that there are about 1.2 million abandoned oil and gas wells nationwide and that some 200,000 of them *may not be properly plugged*" (emphasis added). This makes clear that the figure of 16.7% is derived from a rough estimate by an EPA spokesperson, and not from an empirical study of well failure rates. As such it has not been considered a reliable source, although it is within the range of other well failure rate data observed.

Queensland Department of Employment, Economic Development and Innovation, 2010

In a study by the Australian State of Queensland (2010), a total of 58 gas wells were inspected and tested at three Queensland gas fields, following a number of complaints from residents. Of these wells, 26 (45%) were found to have integrity issues. The small number of wells studied, and the fact that the area had been marked for inspection due to a high number of complaints by residents, are reasons to avoid generalizing from this result.

Society of Petroleum Engineers, 2009

A well failure rate of 34% has been reported in the UK's North Sea, For example, in a 2011 industry presentation by well services company Archer (2011). This figure is sourced to an estimate from participants in a 2009 Society of Petroleum Engineers forum on North Sea Well Integrity Challenges, in 2009. The Archer presentation summarises: "100 participants indicated the no. of wells with at least one anomaly. Average 1,600 out of 4,700 active wells." As such, the figure is clearly an educated estimate.

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[4] For example, the short film The Sky is Pink from Gasland director Josh Fox, which brings together a number of data sources on well failure.

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