Project Acronym and Title:

M4ShaleGas - Measuring, monitoring, mitigating and managing the environmental impact of shale gas

FINAL REPORT ON SHALE DRILLING, COMPLETION AND PRODUCTION

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Disclaimer

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Public introduction

M4ShaleGas stands for *Measuring, monitoring, mitigating and managing the environmental impact of shale gas* and is funded by the *European Union's Horizon 2020 Research and Innovation Programme*. The main goal of the M4ShaleGas project is to study and evaluate potential risks and impacts of shale gas exploration and exploitation. The focus lies on four main areas of potential impact: the subsurface, the surface, the atmosphere, and social impacts.

The European Commission's Energy Roadmap 2050 identifies gas as a critical fuel for the transformation of the energy system in the direction of lower CO_2 emissions and more renewable energy. Shale gas may contribute to this transformation.

Shale gas is – by definition – a natural gas found trapped in shale, a fine grained sedimentary rock composed of mud. There are several concerns related to shale gas exploration and production, many of them being associated with hydraulic fracturing operations that are performed to stimulate gas flow in the shales. Potential risks and concerns include for example the fate of chemical compounds in the used hydraulic fracturing and drilling fluids and their potential impact on shallow ground water. The fracturing process may also induce small magnitude earthquakes. There is also an ongoing debate on greenhouse gas emissions of shale gas (CO_2 and methane) and its energy efficiency compared to other energy sources
There is a strong need for a better European knowledge base on shale gas operations and their environmental impacts particularly, if shale gas shall play a role in Europe's energy mix in the coming decennia. M4ShaleGas' main goal is to build such a knowledge base, including an inventory of best practices that minimise risks and impacts of shale gas exploration and production in Europe, as well as best practices for public engagement.

The M4ShaleGas project is carried out by 18 European research institutions and is coordinated by TNO-Netherlands Organization for Applied Scientific Research.

Executive Report Summary

This report summarizes current best practices and emerging technologies for shale gas drilling, completion and production operations. The work summarizes the findings from WP5 – Drilling Hazards and Well Integrity in the M4ShaleGas project. Information for the report has been gathered from peer-reviewed scientific literature, available standards/guidelines and from research reports.

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1 INTRODUCTION

1.1 Context of M4ShaleGas

Shale gas reservoir rocks are widely distributed around the world and many countries have now started to investigate their shale gas potential. Some argue that shale gas has already proved to be a game changer in the U.S. energy market (EIA 2015[1]). The European Commission's Energy Roadmap 2050 identifies gas as a critical energy source for the transformation of the energy system to a system with lower CO_2 emissions that combines gas with increasing contributions of renewable energy and increasing energy efficiency. It may be argued that in Europe, natural gas replacing coal and oil will contribute to emissions reduction on the short and medium terms.

There are, however, several concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing. There is also a debate on the greenhouse gas emissions of shale gas (CO_2 and methane) and its energy return on investment compared to other energy sources. Questions are raised about the specific environmental footprint of shale gas in Europe as a whole as well as in individual Member States. Shale gas basins are unevenly distributed among the European Member States and are not restricted within national borders, which makes close cooperation between the involved Member States essential. There is relatively little knowledge on the footprint in regions with a variety of geological and geopolitical settings as present in Europe. Concerns and risks are clustered in the following four areas: subsurface, surface, atmosphere and society. As the European continent is densely populated, it is most certainly of vital importance to understand public perceptions of shale gas and for the European public to be fully engaged in the debate about its potential development.

Accordingly, Europe has a strong need for a comprehensive knowledge base on potential environmental, societal and economic consequences of shale gas exploration and development. Knowledge needs to be science-based, needs to be developed by research institutes with a strong track record in shale gas studies, and needs to cover the different attitudes and approaches to shale gas exploration and exploitation in Europe. The M4ShaleGas project is seeking to provide such a scientific knowledge base, integrating the scientific outcome of 18 research institutes across Europe. It addresses the issues raised in the Horizon 2020 call LCE 16 – 2014 on *Understanding, preventing and mitigating the potential environmental risks and impacts of shale gas exploration and exploitation.*

1.2 Study objectives for this report

There are several unique technological challenges related to shale gas drilling, completion and production operations. We here provide an overview of these, together with a collection of operational recommendations for how to best prevent and mitigate problems.

[1] EIA (2015). Annual Energy Outlook 2015 with projections to 2040. U.S. Energy Information Administration (*www.eia.gov*).

Maintaining shale gas well integrity from drilling to abandonment requires understanding of how various parameters/choices impact safety. Topics that are discussed in this report are: shale gas drilling procedures, well cementing methods and materials, completion materials, and choice of operating parameters during well stimulation. Major knowledge gaps are pointed out, and the report aims to be a roadmap for future research and development on this topic.

1.3 Aims of this report

The report is a public dissemination summarizing the procedures applied during shale gas well drilling, completion, production and abandonment. It draws upon published scientific literature, standards and best practices, mainly from North America, since this is the most mature shale gas region today.

2 INTRODUCTION

Wells are more than holes in the ground, they are complex telescopic structures of steel and cement stretching kilometres into the subsurface. They represent a direct connection between the surface and the hydrocarbon reservoir, and they can never be removed – only plugged. It is therefore of utmost importance that **well integrity** is ensured during the life of a well. This is the case for all wells, including those used for shale gas extraction. A typical well is depicted in Figure 1.

The life of a well starts with the drilling phase, when a hole in the subsurface is first pierced by a drillbit. The hole is subsequently cased and cemented at different intervals to form the characteristic telescopic structure which is necessary to avoid hole collapse when piercing through formations with different properties. Thereafter, the well is completed with tubings, screens and other necessary devices to ensure that it can be used for production purposes. For shale gas wells, production is initiated by a stimulation phase, in which fractures are opened around the well to maximize the permeability in the surrounding shale rock and increase the flow of hydrocarbons into the wellbore. The well is thereafter producing until it is no longer economical, and the wellbore is then permanently plugged and abandoned.

All these phases of a well's life can affect well integrity, as we will see in the present report. We use an extended definition of well integrity, where it means not only to avoid leakage through/along the well – but also to avoid drilling hazards during well construction. The report outlines various threats towards shale gas well integrity, and it comes up with specific recommendations for how to minimize the environmental footprint of such operations.

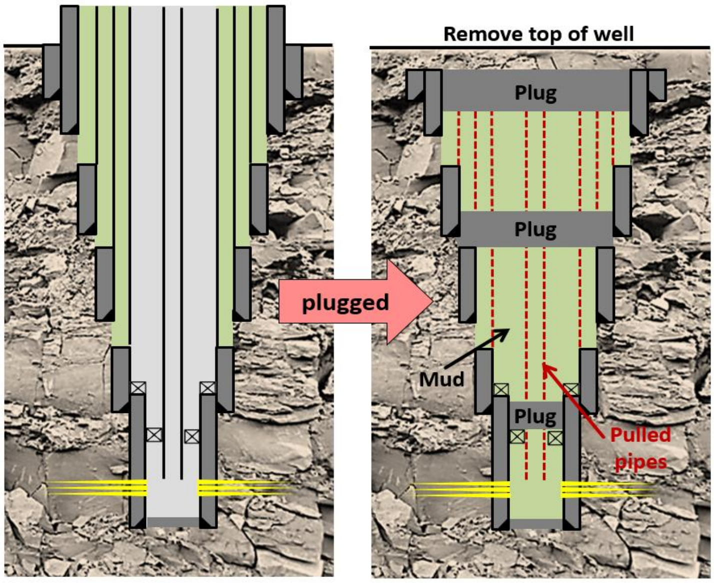

Figure 1. Example of an active (left) and abandoned (right) shale well.

3 SHALE GAS WELL INTEGRITY – IMPACT OF OPERATIONS

3.1 Drilling

Accessing shale-gas reserves requires that wells can be drilled safely and efficiently from the surface to the reservoir. A number of risks are associated with drilling such wells. In naturally-fractured rocks like gas-bearing shales, some drilling problems, e.g. borehole instabilities (collapse, fallouts, etc.) and lost circulation, are usually exacerbated. All rocks contain natural fractures. The difference between formations is not whether there are fractures or not, but how dense the fracture system is, how well-connected the fractures are, what are the fracture apertures, are the fractures sealed or open, etc. In some rocks, including gas-bearing shales, natural fractures are essential for production of hydrocarbons.

Natural fractures effectively reduce the strength of the borehole wall. As a result, borehole instabilities may occur in form of e.g. fallouts (Fig. 2). This may be facilitated by erosion by the drilling fluid flowing up the annulus. Rock debris falling from the wall into the well during drilling may lead to packoffs near the bottomhole, thereby impairing circulation of the drilling fluid and cuttings transport to the surface. Excessive torque and build-up of the bottomhole pressure (BHP) are some of the consequences of a packoff. Build-up of BHP above the lost-circulation pressure may result in severe losses of the drilling fluid into the fractures. This will reduce the hydraulic pressure imposed by the mud on the formation, which can allow formation fluids to flow into the well. At worst, mudloss can lead to a blow-out situation.

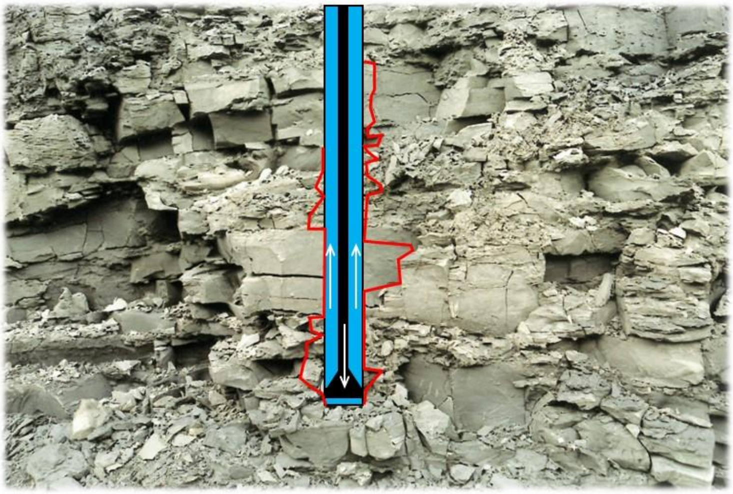

Figure 2. Fallouts/washouts caused by natural fractures when drilling through a naturally-fractured shale. Fallouts/washouts are delineated with the red line. White arrows indicate flow direction of the drilling fluid in the drillstring (downwards) and in the annulus (upwards). Drillstring is shown in black.

Fallouts create enlargements in the borehole wall, which is detrimental not only for drilling but also, at a later stage, for cementing the well. When cement is pumped up the annulus during a cement job, fallouts (or washouts, as they are commonly referred to in the context of well cementing) might not be fully filled with cement. As a result, pockets of undisplaced drilling mud (drilling fluid + cuttings) or formation fluids may remain captured as "pockets". During subsequent lifetime of the well, such pockets represent a risk since they may (a) jeopardize zonal isolation of the well and (b) act as stress concentrators if downhole temperature or in-situ stresses change (Lavrov and Torsæter, 2016).

It should be noted that even an intact borehole wall may fail if the wellbore pressure is not sufficient to support the wall mechanically. In this case, symmetric failure patterns known as "breakouts" typically develop (Fig. 3). In clay-rich rocks such as shales, such instabilities may be exacerbated because of water-sensitivity of clay minerals. Water present in the drilling fluid softens the shale and may make it swell. Both processes have detrimental effect on the borehole strength.

As shown schematically in Fig. 3, breakouts are situated at two opposite locations in the borehole cross-section, namely along the minimum far-field in-situ stress acting in the cross-section. Stress anisotropy, thus, is an important factor. In general, stress anisotropy in the plane normal to the borehole axis increases the risk of borehole instabilities. As a result, in extensional (normal faulting) stress regime, deviated and horizontal wells are less stable than vertical wells. Stability of vertical wells can be adversely affected by tectonic stresses since the latter may substantially increase stress anisotropy in the horizontal plane. In shale plays located in mountainous regions, borehole instabilities may be additionally exacerbated by complicated stress regimes (e.g. the vertical stress being lower than the horizontal stresses, i.e. compressional regime, in the valleys).

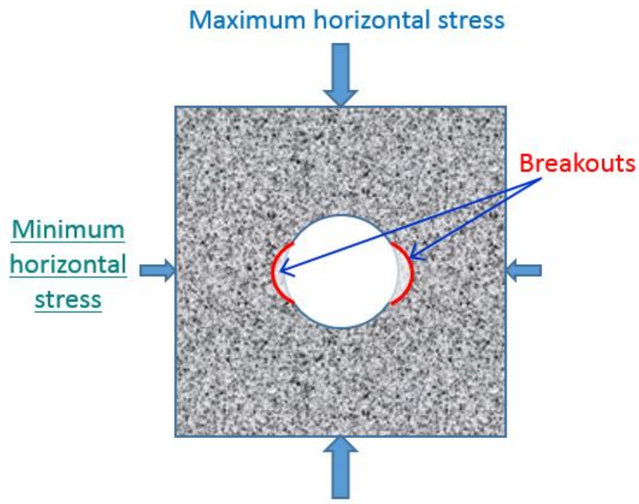

Figure 3. Breakouts around a vertical well.

When drilling with overbalance, natural fractures represent escape routes for the drilling fluid (Fig. 2). If the fractures are wide enough (i.e. sufficiently opened), drilling fluid may enter even if the bottomhole pressure is below the fracture reopening pressure. Losses are likely to stop in this case, after the fluid has propagated a certain distance into the fracture.

Losses stop because of non-Newtonian, yield-stress rheology of the drilling fluid. If the fracture is closed or its aperture is below a certain threshold (typically 100-200 µm), the bottomhole pressure must exceed the fracture reopening pressure for the fluid to enter (Lavrov, 2016b).

Combatting lost circulation in shales is a challenge since most materials sealing fractures and, thus, preventing or stopping losses, require fluid leakoff through the fracture wall. Such leakoff enables deposition of particles inside the fracture, on which then a filter cake can be built that prevents further losses. In shales, permeability is so low that there is effectively no leakoff on the time scale of a lost-circulation incident. This prevents sealing of the fracture and reduces the effectiveness of loss-prevention and lost-circulation materials. New products (additives to the drilling fluids) designed to prevent or combat lost circulation are introduced to the market every year. Development of more effective lost-circulation and loss-prevention materials will reduce the risk of occurrence and negative consequences of lost circulation in gas shales in the future.

Since natural fractures are the root cause for a great deal of drilling problems in shales, risks could be reduced by **improving formation characterization** and, particularly, **fracture characterization**. Knowing e.g. fracture apertures can help the mud engineer to size loss-prevention and lost-circulation materials better, so that they seal fractures more effectively. Knowing fracture orientations and in-situ stresses would improve the estimates of the upper mudweight limit.

Information about natural fracture systems is rarely available before drilling commences. Even if such information exists, it is usually based on image logs or core material analysis obtained from offset wells. Variability of fracture properties from well to well would, ideally, require, that fractures are characterized as the well is being drilled. This sort of "catch-22" (in order to drill a well, we need information about the formation; in order to obtain this information, we need to drill the well) has no easy technical solution.

3.2 Cement placement and bonding

There are two measures of effective zonal isolation in a well along the cement/casing and cement/formation interfaces (Nelson and Guillot, 2006): (1) shear bond and (2) hydraulic bond. The shear bond is a measure of mechanical support the casing/formation experience in the well. It is quantified by measuring the force required to initiate relative displacement of casing/formation in a cement sheath. Hydraulic bonding is a measure of how well the migration of fluids in a cemented annulus is prevented. It is quantified by measuring the maximum pressure the cemented wellbore system withstands without leaking. Both the shear and the hydraulic bonding are dependent on the quality of cement sheath both in a bulk as well as at interfaces. The cement sheath bulk and interfacial quality will depend on many factors among which are: cement slurry composition, the presence of remaining drilling fluids at casing/formation surfaces, type and roughness of the cemented surfaces. All these parameters will influence flow and packing of the cement slurry close to a casing/formation wall.

Only the presence of a wall/surface perturbs cement microstructure close to it. It has been shown that cement particle packing around the wall differs from that in bulk (Scrivener et al., 2004). The regions closest to the wall are depleted with large particles, and thus, dominated by small particles ("large" particles here still refer to sub-millimeter particles). The literature offers a two-fold explanation of the phenomena (Torsæter et al., 2015): (1) It is geometrically impossible to pack large particles close to a wall in the same way they are packed in the bulk cement and/or (2) An indirect hydrodynamic force acting in a viscous fluid called a lubrication force prevent large particles from approaching a wall. The presence of this inhomogeneity in particle size distribution close to a wall implies inhomogeneity in porosity and permeability. This in turn may affect debonding and cracking/microcracking close to interfaces. If the hydrodynamic forces are the main driving force for the observed phenomena, the packing could potentially be manipulated by changing slurry properties (dynamic viscosity) and/or applying attractive or repulsive forces between particles and the wall. It has been shown that application of electric field can affect the packing of particles and slurry adhesion to the metal surface (Lavrov et al., 2016).

In shale-gas horizontal wells cementing long intervals in shale formations is needed and a good bonding between cement and shale is of special importance. It can be expected that cement bonding to the shale formations of low permeability may be different compared to the bonding with more porous rocks especially if any drilling fluid or filter cake remains at the formation surface (Opedal et al., 2014, Opedal et al., 2015). As drilling fluid choices may influence the quality of the cement sheath and thus zonal isolation (Opedal et al., 2015), testing the chosen drilling muds for the selected formation in view of cement-shale bonding is highly recommended. Evaluation of the permeability of a specific cement-shale system is needed (Kjøller et al., 2016).

3.3 Stimulation

In most cases, shale-gas recovery requires stimulation. The stimulation is done by hydraulic fracturing (HF) of gas-bearing shale rocks after perforating selected intervals of the casing string. HF relies on pumping large amounts of fracturing fluid into the well. When the downhole pressure exceeds a certain threshold value (the formation breakdown pressure), hydraulic fractures are formed. Usually, however, the horizontal well is too long to be effectively fractured along the entire well length. Thus, it has to be divided into shorter sections by setting plugs. Then each section is fractured separately. First, the section that is most remote from the well head and then sequentially the closer ones. This sequential fracturing is called "multi-stage fracturing". Fracturing is sometimes performed simultaneously in two parallel horizontal wells from the same pad. During this simultaneous stimulation fractures created around each well propagate toward each other. This technique, called "zipper fracturing" creates more complex fracture networks and enables a larger reservoir volume to be stimulated (Rafiee et al., 2012, Waters et al., 2009).

HF fluid can carry proppant - a particulate material designed to keep incipient fractures open and thus to facilitate gas backflow after the well is depressurized. Once HF is finished and downhole pressure decreased, the gas pore pressure pushes the fracturing fluid out of the fracture and up the well simultaneously displacing fracturing fluid and formation water to the surface. Only a fraction of water-based HF fluids is recovered, while majority is adsorbed by the formation (Brzycki, 2016). This so-called flowback water is typically reused in another fracturing project, otherwise, it has to be disposed of. As management of large quantities of flowback water is a challenge for HF projects, water-free fracturing technologies (Middleton et al., 2014, Middleton et al., 2015, Rogala et al., 2013) allowing for more than 90% of HF fluid recovery are being developed (Gawel et al., 2016).

Still, however, fracturing using water-based fluids is the most common stimulation technique, and so-called "slickwater" is perhaps the most frequently used water-based fracturing fluid (Gawel et al., 2015, Gawel et al., 2016). Main slickwater components are water, friction reducing polymer, and proppant. Polymer is added at low concentrations. Thus the viscosity of slickwater fluids is relatively low. Because of the low viscosity, the fluid needs to be pumped at high rates in order to induce fractures and has a limited capability to suspend and transport proppant particles (Palisch et al., 2010). Proppant transport capabilities of water-based HF fluids can be enhanced by increasing the fluid viscosity. This is typically done by adding polymers or partially gelled polymers as viscosity enhancers. Such fluids are capable of transporting larger amounts of proppant than slickwater but on the other hand, they pose larger risk of formation damage due to filter cake formation. To avoid this, viscosity reducers, called also breakers, are used. Breakers degrade polymers and thus reduce HF fluid viscosity after the fracturing is finished (Palisch et al., 2010). Typical for water-based fracturing fluids is that they contain large amounts of chemicals with different functionalities. Among them are acids, corrosion inhibitors, biocides, oxygen scavengers, iron precipitation control agents, scale inhibitors, clay stabilizers (Arthur et al., 2009). The large number of chemicals used in fracturing raises environmental concerns and thus is an additional motivation driving the development of water-free fracturing technologies.

3.3.1 Impact of fractures on well integrity

Very little is known about the influence of pressure applied during hydraulic fracturing on well integrity in general and more specifically on the integrity of well construction elements, e.g. cement (and other sealing materials) and casing. Excessive fluid pressure during hydraulic fracturing could provide the driving force for initiation and propagation of fractures in longitudinal and transverse directions (Wang and Dahi Taleghani, 2014).
In cases of low confining pressure, fractures may propagate also within the annulus (Wang and Dahi Taleghani, 2014). Fracture direction and shape are determined by the orientation of the well, location and orientation of perforations, and directions of the principal in-situ stresses (Gawel et al., 2015, Wang and Dahi Taleghani, 2014). Fractures have a tendency to propagate along the direction perpendicular to the minimum principal stress. However, the stress field near a wellbore can be different from the far-field in-situ stress. This will lead to rotation (twisting) of the fracture according to the changes in the direction of the minimum principal stress. Fracture twisting is particularly common in deviated and horizontal wells, when the borehole axis does not coincide with any of the

in-situ principal stress directions. Fracture twisting may significantly impair the productivity of the stimulated well as it may lead to the formation of a bottleneck-shaped fracture near the well that may constrain proppant transport.

The inefficiency of transporting proppant deep into the fracture is known as "proppant screen-out" (Daneshy, 2003). In addition, in naturally-fractured formations, initiation and propagation of hydraulic fractures are significantly affected by the natural fracture system (Lavrov, 2016b, Lavrov et al., 2014). Upon encounter with a natural fracture, the growing hydraulic fracture may be arrested or offset, or may simply continue propagation. An offset fracture is a potential candidate for proppant screen-out (Fig. 4). Numerical models of hydraulic fracturing used for shale gas reservoirs should be able to account for these effects when predicting productivity of a stimulated well.

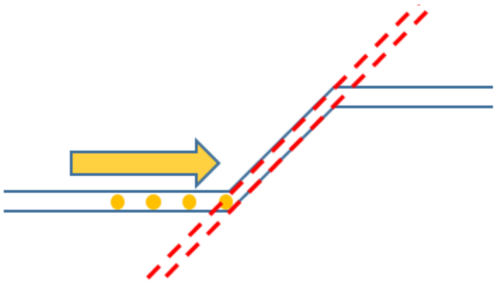

Figure 4. Proppant screen-out caused by an offset fracture. Hydraulic fracture (solid blue lines) is offset by a natural fracture (dashed red lines). As a result, proppant particles (yellow) cannot enter the narrow inclined portion of the fracture. Yellow arrow indicates the direction of fluid flow and proppant transport.

Careful prediction of fracture growth and **optimization of well placement** are especially important in zipper fracturing performed from multi-well pads. It is crucial for well integrity that fractures generated from one well do not reach and cross another well. Such an inadvertent fracture propagation towards another well may create a parasitic hydraulic communication between the wells, as was observed e.g. in Eagle Ford shale in the U.S. (Ridley et al., 2013). Prediction and optimization of fracture growth is important not only in the proximity of another producing well but also around plugged and abandoned wells (Montague and Pinder, 2015). Knowledge of in-situ stress state is needed in order to optimize well placement and orientation. Such optimization can reduce the potential adverse near-well effects of hydraulic fracturing. For optimization of hydraulic fracturing in deviated and horizontal wells, modelling tools able to predict propagation of fractures in three dimensions are needed.

3.3.2 Erosion of well construction elements

Fracturing fluids containing proppants are abrasive. They can erode well construction elements both while HF fluids are pumped downhole and during their backflow after the well is depressurized. Susceptible to erosive damage are the following well construction elements: production tubing, wellhead equipment, openings in the completion (Venkatesh, 1986). Abrasive wear of well elements can be reduced (1) by preventing flowback of proppant; (2) by designing non-abrasive proppants; and (3) via improved design of well elements in terms of geometry and materials used (e.g. high-strength alloys and ceramic couplings).

Proppant flowback can be avoided by applying screens. These can either be conventional metal sand screens or systems made of more erosion-resistant materials, e.g. advanced ceramics (Muessig et al., 2011). Such ceramic materials are claimed to be resistant to wear and have high temperature and corrosion stability also at higher temperatures. Another approach towards preventing proppant flowback is the use of flowback-resistant proppant. It has been shown that proppant's ability to stay in place and resist flowback depends on proppant shape and coating (Alary and Parias, 2013, Coronado and Baycroft, 2006, Graham and Kiel, 1970, Hussain et al., 1997, Vincent et al., 2004). Covering the proppant particles with polymer coatings with protruding fibres can limit their return with back flowing HF fluid by mechanically trapping them between rough fracture surfaces and between each other (Hussain et al., 1997). The abrasive effect of proppants with protruding fibers during proppant flow into the well has however not been discussed in (Hussain et al., 1997). Another approach utilized to prevent proppant flowback is consolidating the proppant bed by using e.g. epoxy resin (Murphey et al., 1989).

The abrasive action of proppant can be reduced by covering particle surfaces with coatings having low friction coefficient, e.g. antimony trioxide, bismuth, boric acid, calcium barium fluoride, copper, graphite, indium, fluoropolymers, lead oxide, lead sulphide, molybdenum disulphide, niobium diselenide, polytetrafluoroethylene, silver, tin, or tungsten disulphide or zinc oxide. The coating not only reduces roughness of the particles by eliminating sharp edges but also acts as lubricant by reducing friction between particles and surfaces they are in contact with (Coronado and Baycroft, 2006).

The abrasive action of proppant can be most deteriorating on those well elements where impingement of HF fluid on well element is considerable. One of the examples can be discharge of HF fluid from a production string to the wellbore that may cause wear of casing and other well components. In order to mitigate these abrasive effects, fluid flow diverting systems can be applied (Frosell et al., 2013, Li et al., 2013). This flow diverting systems may comprise e.g. a tubular string including a fluid discharge apparatus with a curved flow path that redirects the fluid so that it does not grate well elements.

3.3.3 Corrosion of metal casings/tubulars

Acid stimulation, high oxygen content, or presence of microorganisms or sour gas (H_2S) and CO_2 in a well may lead to corrosion of metal well construction elements (Purdy et al., 2016). The corrosion threatens not only well integrity, but also well productivity, as corrosion products may lead to formation damage.

In order to protect metal casing and tubing from acidic corrosion, corrosion inhibitors have to be applied along with acid stimulation. Although the metal pipes used for well construction can be corrosion resistant (e.g. carbon or chrome steels), they may corrode anyway as corrosion rates during acid stimulation are higher than under normal production conditions. Thus such acid treatments require either different or higher concentrated corrosion inhibitors to protect steels compared to standard hydraulic fracturing stimulation (Kelland, 2009).

There are several corrosion protection mechanisms that can be utilized in acid stimulation. They rely on (1) inhibition of reduction and oxidation reactions that are the main cause of the corrosion at the metal surface or (2) strong adsorption of the corrosion inhibitor and formation of an organic protective film on the metal surface (Camila G. Dariva, 2014).

If sulphate-reducing or acid-producing bacteria have propitious conditions in the wellbore, they can grow and proliferate. This growth can be supported by the presence of biopolymers often used as viscosity enhancers in HF fluids (Struchtemeyer and Elshahed, 2012). Production of iron sulphide or hydrogen sulphide are often associated with corrosion in wells, which may negatively affect both well integrity and productivity. In order to deal with bacterial corrosion, biocides have to be applied. Biocides are chemicals used to prevent bacterial growth in fluids pumped into the well. Glutaraldehyde is, by far, the most commonly used biocide – but other chemicals can be used as well (Struchtemeyer et al., 2012).

Oxygen present in fracturing fluids can also contribute to enhanced corrosion of metal pipes and process equipment. This problem is usually approached by applying oxygen scavengers. Oxygen scavengers are chemicals that react with oxygen, thereby removing it from production fluids. Examples include: sulphite (M_2SO_3), bisulphite ($MHSO_3$), and metabisulphite ($M_2S_2O_5$) salts (Kelland, 2009).

4 OTHER FACTORS IMPACTING WELL INTEGRITY

In addition to drilling, well construction and hydraulic fracturing, which have been outlined in the preceding chapter, other factors can also impact shale gas well integrity. These are e.g. formation displacements, downhole temperature variations and long-term barrier degradation. These are discussed in this chapter.

4.1 Formation displacements

Both injection of fluids like e.g. HF fluids into hydrocarbon reservoirs or depletion of the reservoirs are associated with stress changes within the reservoir as well as within the overlaying strata. Sometimes the stress changes are large enough to enable reactivation of faults or natural fractures, or induce shear deformation of rock formations, or cause subsidence. Subsidence is a downward shift of the Earth's surface due to the removal or movement of subsurface material. Subsidence is often associated with natural gas or oil production. When natural resources are being extracted from the reservoir, the initially high pressure in the reservoir gradually declines over the production timeline. As a result, the part of the overburden weight that was previously supported by the pore fluid is now supported by the rock matrix. This results in rock deformation and subsidence at the Earth surface.

During depletion, total and effective stresses change in the reservoir and, less so, in the overburden and sideburden (Fjær et al., 2008, Lavrov, 2016a, Santarelli et al., 1998, Zoback, 2007). In particular, total horizontal stresses decrease in the reservoir. This may create problems during infill drilling since, in extensional tectonic regime, lower horizontal stresses mean lower fracture gradient. In addition, these stress changes may promote slip reactivation on normal faults in the reservoir in extensional regime. In the overburden, on the other hand, stress changes during depletion may facilitate reactivation of reverse faults in compressional tectonic regime. These stress changes may affect well integrity, in particular, mechanical stability of the cement sheath (Lavrov and Torsæter, 2016) and structural integrity of the casing (Dusseault et al., 2001).

Flexure above a compacting reservoir may generate shear stresses in the overburden that can cause horizontal shear failure and slippage along weakness planes, such as those found in shale (Hamilton et al., 1991, Tian et al., 2015). The slippage can cause bending of wells and, in particular, cause deformation of the casing string (Dusseault et al., 2001, Hamilton et al., 1991). Similarly, tectonic forces in tectonically active regions may threaten well integrity (Doornhof et al., 2006). Hydraulic fracturing may lead to reactivation of existing faults (Rutqvist et al., 2013), which may have negative consequences for well integrity (Reagan et al., 2015).

4.2 Downhole temperature variations

New non-water based fracturing technologies are designed to meet water-sensitivity challenge in some shales. Water sensitivity may lead to high water absorption inside the rock matrix. This absorption, in turn, may result in sometimes large losses of water-based HF fluids into the rock matrix and may negatively affect conductivity of incipient fractures and formation permeability (Rogala et al., 2013). Use of water-free fracturing fluids can prevent these detrimental effects. Water-free fracturing fluids are mostly gases either in liquid or gaseous form. Examples are CO_2 and N_2 (Bullen and Lillies, 1983, Freeman et al., 1983), propane (Jones and Taylor, 2000), heptafluoropropane (non-flammable propane) (Stim, 2015), light alkanes (low molecular weight alkanes; hydrocarbons consisting only of hydrogen and carbon atoms where all molecular bonds are single (general chemical formula C_nH_{2n+2} where n is a number of carbon atoms)) (Stim, 2015). Non-water-based HF technologies have been reviewed in (Gawel et al., 2016). A schematic illustration of fracturing process using water-free fracturing fluid is shown in Fig. 5. First, the water-free fracturing fluid carrying proppant is pumped into the well, and fracturing is performed. Next, the well is depressurized, and the fracturing fluid turns to gaseous form and flows back to the well followed by shale gas. Proppant left in the fractures keeps them opened and facilitates flow of shale gas from the naturally fractured formation through the created fractures to the well.

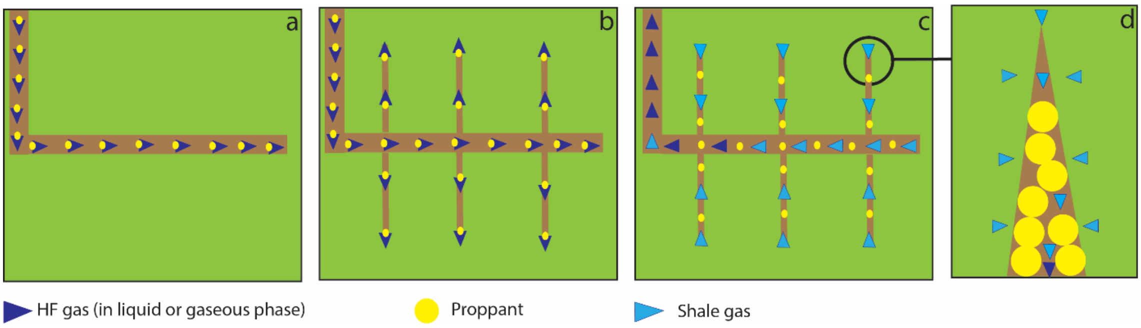

Figure 5. Hydraulic fracturing using water-free fracturing fluids: The injection of pressurized liquefied HF gas (a) creates fractures (b). Under reduced pressure, liquefied HF gas turns to gaseous form and flows back to the well followed by the shale gas (c). The proppant leaves the fracture opened allowing the shale gas to flow into the well (d).

Avoiding formation damage is only one of several benefits from using gases as HF fluids. Another significant advantage is the ability to self-clean up after the pressure is released. According to some gaseous HF fluids providers, up to 95-100% of the fracturing fluid can be recovered and reused. This reduces environmental risks and eliminates costs associated with reinjection or utilization of back-produced water. It has to be emphasized that such gaseous HF fluids do not wash out any salts, heavy metal ions or radioactive substances from the formation and thus reduce the risk of detrimental environmental consequences. Moreover, no chemical additives are needed, which makes the fluids environmentally compliant.

These new technologies may cope well with some challenges water-based fracturing fluids have but on the other hand open for new questions and challenges. Some gaseous fracturing fluids show significant Joule-Thomson cooling effect upon well depressurization (Middleton et al., 2014, Rogala et al., 2013). This may lead e.g. to ice formation inside tubings and X-mass tree at the top-side (Rogala et al., 2013), which may restrict the gas flow. Such effects are easily detectable at the surface and are thus easy to prevent, but the impact of Joule-Thomson cooling effect associated with depressurization of a fractured well on well integrity has not yet been assessed. It has been shown, however, that temperature changes inside the well resulting from e.g. pumping of hot or cold fluids may lead to deterioration of well elements (De Andrade et al., 2014, Roy et al., 2016, Todorovic et al., 2016). In the laboratory experiments, the most susceptible to failure on hot thermal cycling was the cement sheath (De Andrade et al., 2014), while even a single temperature fall event below water freezing point was detrimental for both rock and cement (Todorovic et al., 2016) and led to the formation of a crack along the wellbore model used in the experiments. As partially water saturated rocks are susceptible to the temperature drops below 0 °C, it is important to assess temperature changes inside the well on depressurization, especially when gaseous fracturing fluids showing strong Joule-Thomson effects are used. There exist already experimental setups designed to follow changes associated with temperature variations in miniaturized wellbore models (De Andrade et al., 2014, Todorovic et al., 2016). Fig. 6 shows a schematic of such an exemplary setup. A downsized well composed of metal pipe cemented inside a hollow rock cylinder is locked in a pressure cell. The pressure in the cell is adjusted by pumping a nonreactive gas. The cell is placed on a cooling/heating stage driven by a temperature controller. Cooling of the plate is achieved by pumping liquid nitrogen, while heating is done by means of electrical resistance. The specimen can be made from any types of rock and sealing material. Any structural changes associated with thermal cycling can be followed by X-ray tomography as the pressure cell can be designed to be X-ray transparent (De Andrade et al., 2014).

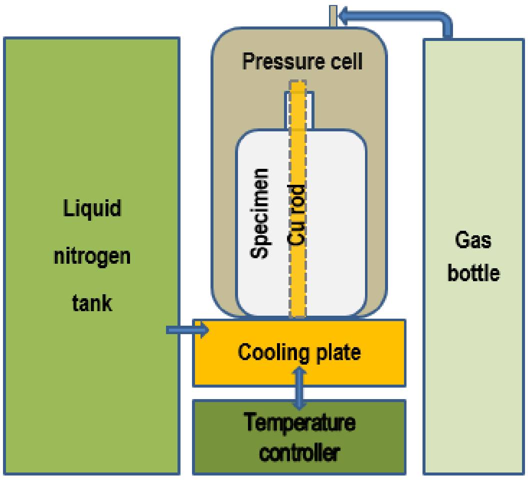

Figure 6. Schematic of an exemplary experimental setup for thermal cycling experiments. Based on (De Andrade et al., 2014).

Joule-Thomson cooling in water-free fracturing is not the only example where large temperature variations in a well may occur. Pumping cold fracturing fluids into a hot reservoir will also cause volumetric changes of well-construction materials. As expansion coefficients of steel, cement and rock are different, such temperature variations in a well result in thermal stresses in these materials. Numerical simulations show that these temperature-induced stresses can be detrimental for well integrity as they may lead to cracking or debonding at interfaces and inside cement (Lavrov and Torsæter, 2016, Roy et al., 2016, Todorovic et al., 2016).

4.3 Long-term barrier degradation

Well barrier elements have to pass technical and operational requirements defined by standards (e.g. NORSOK D-010 at The Norwegian Continental Shelf) in order to be qualified for the intended use. The standards define how to perform qualification tests for well elements; however, they do not specify any long term integrity tests for the well barrier elements (Vignes, 2011). The main long-term well barrier degradation mechanisms are erosion, corrosion, scale formation, temperature and pressure loads, and fatigue. The oil and gas industry emphasizes the need for long-term integrity testing in order to minimize well integrity failure. An important factor to avoid incidents caused by unintentional leaks is a routine control of well barrier performance.

In addition to routine testing of standard well barrier materials, there is a need for qualification of new well barrier materials (Fjær et al., 2016, Vignes, 2011, Williams et al., 2009). The latter two suggest testing a potential of nature forces, in forming a barrier around well. It has been recognized that, during and after drilling, shale formations can be displaced, which leads to a reduction in wellbore diameter. Shale creeping and shear and tensile failure were defined as main potential causes of this effect. This phenomenon, unwanted during drilling, may, however, be utilized to seal the annular space around the casing. Bond logging tools providing information about the presence or absence of sealant behind the casing often indicate presence of solid material well above the cement layer. This suggests that shale formations tend to fill the adjacent empty space which can be regarded as a self-healing. As traditional cementing is expensive and time consuming the innovative shale self-healing approach can be a viable alternative. Another example of cement substituents may be Sandaband product (Gjedrem, 2007, Svindland, 2004), which is a mixture of fluidized unconsolidated particles providing low permeability by means of particle sorting. According to the inventors, the material, when placed, becomes solid but remains fluidizable (does not harden) and thus holds tight. Any movement of matter around the plugging material causes the material to become liquid and reshape without fracturing; thus, it should be able to remain impermeable and meet the long-term integrity requirements.

5 DISCUSSION

The report provides a summary of shale gas drilling, completion and production operations, and how they impact well integrity. Under each topic, some recommendations are given (bullets) of how to minimize the environmental footprint of the operation.

Drilling: challenges are mainly related to the natural fractures typically occurring in shales. These can cause borehole instabilities and lost circulation.

- Develop more effective lost-cirulation/loss-prevention materials for shale drilling.
- Develop methods of improved formation characterization, particularly fracture characterization (this is also important for improving well cementing and optimization of hydraulic fracturing jobs).

Cementing: challenges are due to breakouts/fallouts creating enlargements in the borehole which are difficult to fill with cement - and can cause leakage paths along the wellbore. Also ensuring good bonding between cement and rock/casing is a challenge.

- Develop improved cementing and mud removal routines. This involves testing the compatibility between selected cements and the shale formations in the well, and evaluating the permeability along the cement-shale interface. One innovative approach involves application of voltage on the casing during cement hardening.
- Develop improved logging methods for detecting defects behind casing in cemented well annuli.

Stimulation: The hydraulic fracturing of shale-gas wells can impact well integrity. The most detrimental would be fracturing along the annulus or even in the well cement. Moreover, fracturing fluids containing proppants are abrasive and can erode well construction elements during pumping/flowback. Acid stimulation can lead to corrosion, which threatens well integrity.

- Develop methods for improved prediction of fracture growth during stimulation.
- Develop methods for optimization of well placement to avoid fracturing along the annulus or cross-over of fractures from one well to another (parasitic hydraulic communication). This is important not only between active wells, but also around plugged and abandoned wells.
- Develop methods for reducing abrasive wear of well elements, e.g. by preventing proppant flowback (e.g. by using screens, proppants coated with fibres, consolidating the proppant bed with resin), designing non-abrasive proppants (proppant coating) or more robust well design (fluid flow diverting systems, high-strength components).
- Develop methods for protecting metal casing and tubing from acidic corrosion (inhibitors, formation of an organic protective film on the metal surface, biocides against acid-producing bacteria, use oxygen scavengers).

Other factors, such as rock deformation and displacement, downhole temperature variations and long-term barrier degradation can also affect shale-gas wells. Formation displacements are often caused by fault reactivation, while the temperature variations are especially pronounced when using non-water fracturing fluids (in water-sensitive shales). Long-term barrier degradation is a common challenge in all well types.

- Develop methods for monitoring the effect of different types of formation displecement on well integrity
- Develop a better understanding of how to safely use non-water fracturing fluids without subjecting the well to damaging temperature cycles.
- Develop standardized methods for qualifying new well barrier materials (replacements for cement).

6 CONCLUSIONS

This report is a summary of the literature on how shale gas drilling, completion and production operations impact well integrity. The outstanding knowledge gaps and improvement potential on well integrity in shale-gas wells are summarized in Table 1. In addition to the issues listed in Table 1, standards defining long-term integrity tests of well barrier elements for shale-gas are needed.

Table 1. Current practices and improvements on well integrity in shale-gas wells.

Drilling, completion and production processes	Current practices	Suggested improvements	Benefits from improvement	Responsibilities
Effect of hydraulic fracturing and refracturing on the integrity of the well being stimulated	Empirical knowledge from field cases. Predictions based on oversimplified hydraulic fracturing models (usually 2D or even 1D).	Laboratory studies and numerical simulations of possible debonding and damage to cement sheath. Three-dimensional numerical models and laboratory replicas of fracture growth in the near-well area. Better design of hydraulic fracturing jobs.	Prevention of well-integrity loss and sustained casing pressure buildup in stimulated wells	Research institutes in collaboration with operators
Effect of hydraulic fracturing on well integrity during re-fracturing	Empirical knowledge from field cases. Predictions based on oversimplified hydraulic fracturing models (usually 2D or even 1D).	Laboratory studies and numerical simulations of possible debonding and damage to cement sheath. Three-dimensional numerical models and laboratory replicas of fracture growth in the near-well area. Better design of hydraulic fracturing jobs.	Prevention of well-integrity loss and sustained casing pressure buildup in stimulated wells	Research institutes in collaboration with operators
Effect of hydraulic fracturing on well integrity in another well	Empirical knowledge from field cases. Predictions based on oversimplified hydraulic	Field tests and three-dimensional numerical models of fracture breakthrough into neighboring well.	Prevention of leakage and spurious hydraulic communication between wells	Research institutes in collaboration with operators

Drilling, completion and production processes	Current practices	Suggested improvements	Benefits from improvement	Responsibilities
	fracturing models (usually 2D or even 1D).	Improved monitoring of hydraulic fracture propagation. Better design of hydraulic fracturing jobs.		
Mud losses during drilling through shale and cap rock	Mud weight control based on rudimentary knowledge of in-situ stresses and natural fracture networks	Improved characterization of reservoir and cap rock through better interpretation of image logs, more frequent stress measurements and better interpretation of formation pressure tests.	Reduced losses, improved well control, thus reduced non-productive time, reduced costs and reduced damage to the environment	Operators, service companies, and research institutes
Cement losses during primary well cementing	Control of cement sheath height using cement bond log. Control of cement's hydraulic integrity by casing shoe test.	Reduced need for squeeze cementing; improved height of cement sheath.	Improved well integrity during drilling and production	Operators, research institutes and service companies.
Gas influx during drilling	Overbalance drilling. Still influxes may happen in abnormally-pressured transition zones as well as after losses.	Improvements of kick diagnostics based on early signs. Improved formation characterization by e.g. better interpretation of formation tests.	Improved safety and reduced environmental impact during drilling	Operators, service companies and research institutes
Gas influx during primary well cementing ("gas migration")	Management of cement slurry properties and setting time	Improved formation characterization. Improved primary-cementing practices based on laboratory experiments and numerical simulations.	Improved quality of cement sheath; reduced cement sheath conductivity	Operators, research institutes, service companies

Drilling, completion and production processes	Current practices	Suggested improvements	Benefits from improvement	Responsibilities
Improved wellbore stability during drilling and running casing	ECD management based on insufficient information about in-situ stresses and rock properties	Improved well design, e.g. orientation and positioning of wells. Improved knowledge of formation stresses, pressure, and rock properties.	Reduced washouts (thus improved cement sheath quality). Fewer packoffs (thus reduced incidents of not being able to run in casing).	Operators in collaboration with research institutes
Undocumented long-term behavior of materials (incl. cement) under downhole conditions	Limited information based on lab tests.	Improved material characterization. Improved testing protocols. Improved monitoring of well integrity.	Improved well integrity, especially in long term.	Research institutes in collaboration with government agencies and operators.

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