Project Acronym and Title:

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

EMERGING METHODS AND MATERIALS FOR SHALE GAS OPERATIONS

Authors and affiliation:

Kamila Gawel, Alexandre Lavrov and Malin Torsæter*

SINTEF Petroleum Research, Trondheim, Norway

E-mail of lead author(*):

malin.torsater@sintef.no

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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 is a follow-up of an earlier published report summarizing the most common procedures for shale gas drilling, completion, production and abandonment (Gawel et al., 2015). The current document gives an **overview of emerging technologies, methods and materials developed specifically for shale gas wells**. For each of them we describe:

- Its functioning and why it was developed
- Available information from laboratory or field testing
- Comparison to more conventional technologies/methods/materials

The report rounds off by summarizing gaps that still remain to be filled by new products in order to ensure minimal environmental footprint from shale gas activities.

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1 INTRODUCTION

1.1 Context of M4ShaleGas

Shale gas source 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 are 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 European publics 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 exploitation. 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.*

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

1.2 Study objectives for this report

Shale gas wells connect subsurface reservoirs of hydrocarbons with the surface. They are long "tunnels" typically constructed of cement and steel, and they are enablers of the shale revolution. Through novel well drilling and stimulation techniques (horizontal drilling and multi-stage hydraulic fracturing), shale gas resources can be economically exploited today. The wells are, however, also among the major environmental threats posed by shale operations (Davies et al., 2014). Especially the cement barriers in wells, which are important both for active and plugged wells, are of concern with respect to leakage in a long-term perspective.

The first report in M4ShaleGas Work Package 5 on "Drilling Hazards and Well Integrity" described, based on evaluations of standards and best practices, the conventional ways of executing shale gas drilling, completion, production and abandonment operations (Gawel et al., 2015). In the present report we focus on *emerging technologies, methods and materials for shale gas wells*. This includes a review of methods/products that are less established, but yet promising for increasing safety and cost-efficiency in shale gas operations.

The structure of the report follows the life-cycle of a well, from drilling and cementing, through completion and production, to the final plugging and abandonment phase. For each of these, new solutions for improving operations are presented and evaluated. It is outlined:

- Why development of the specific product/method was necessary
- How it functions and how it has been tested in practice
- How it compares to more conventional technologies/methods/materials

The report rounds off with summarizing for the reader some gaps that still remain to be filled by specialized products in order to ensure that shale gas resources can be exploited with minimal environmental footprint.

1.3 Aims of this report

The report is a public dissemination summarizing emerging technologies, methods and materials developed for shale gas well operations. It draws upon published scientific literature, patents and publically available information from vendors/service companies. Most of the information originates from North America, since this is the most mature shale gas region today.

2 DRILLING AND CEMENTING OPERATIONS

Drilling technology is at the heart of cost-efficient shale gas exploitation. Since production decline curves are steep in shale reservoirs, many wells need to be drilled and cemented quickly to ensure economically sound operations. It was the horizontal drilling technique that once kicked off the shale revolution, and methods have continued to develop since then. Today, wells in shale reservoirs are drilled and cemented at a quicker pace than ever before. In this chapter we explore the latest emerging trends of shale gas well construction – from drilling to cementing.

2.1 Drilling methods

2.1.1 Drilling with air or low-density mud

Reducing the mud weight increases the rate of penetration (ROP) during drilling, and thereby improves the cost-efficiency of shale operations. Even though drilling with bottomhole pressure below the formation pore pressure is not a novel drilling method on its own, its systematic use in shale-gas fields currently brings about major savings. In particular, the use of *air drilling* has been advocated as a means to improve the ROP in hard formations (Chen et al., 2015). In addition, the use of air drilling in the top few hundred meters of the well prevents possible contamination of water-bearing horizons with the drilling fluid. Drilling fluid handling problems, e.g. possible spills/leakages at surface, is also reduced by this method.

Improvements on the ROP can be achieved also by using managed-pressure drilling (MPD). MPD encompasses a set of drilling methods that greatly improve control of the bottomhole pressure, which is especially important when drilling wells with a narrow band of possible bottomhole pressures between the borehole stability limit and the formation fracture limit. This is common in horizontal sections, and increases the risk of mud loss into the formation or formation fluid influx. MPD has e.g. been used in the Montney shale formation in Canada, where the goal was to maximize ROP (Mammadov et al., 2015). A low-density synthetic-base mud (770 kg/m^3) was therefore used, together with a constant-bottomhole-pressure drilling technique (to reduce risk of fluid influx from high-pressure fractures). In this MPD technique, the mud weight is below the hydrostatic and pressure at the bottomhole is kept constant (in balance with the pore pressure) by a surface backpressure pump (Rehm et al., 2008). The use of MPD enabled the operator to increase the ROP from 3.32 m/h (conventional drilling) to the average of 7.4 to 10.5 m/h with MPD, i.e. it was increased by a factor of 2 to 3. Additional benefits of using low-density mud in this field history were reduced mud costs, improved cuttings transport (lower density allowed faster circulation since higher annular pressure loss can be tolerated without breaking the formation), and better cooling of the drill bit (Mammadov et al., 2015).

2.1.2 Drilling complex three-dimensional wellpaths

Another emerging trend in drilling methods for shale gas is a gradual shift in hardware usage (Hummes et al., 2012). In particular, both the curve and the lateral are now often drilled with the same rotary steerable system. This reduces the tripping time and thus improves the rate of penetration.

The use of new hardware (see Section 2.2) sometimes leads to radical changes in the drilling methods and well construction. Complex three-dimensional wellpaths are becoming steadily more common. For instance, new rotary steerable systems enable drilling of wells with a negative inclination, essentially kicking off backwards (Figure 1). Such a "negative vertical section" is part of anti-collision strategy in multi-well drilling from the same pad. In addition, it improves the reservoir exposure since it enables penetrating the reservoir with a longer horizontal section while drilling several wells from the same surface location (Hummes et al., 2012).

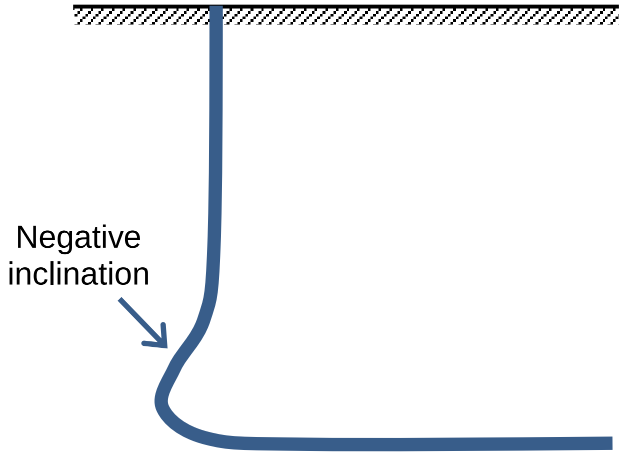

Figure 1. *Wellpath with a backward kick-off.*

2.2 Drilling equipment

Development of shale-gas resources keeps bringing about innovative drilling hardware. Examples are skid rigs, tools used for directional drilling with high build rates, improved drill bits, etc. Implementation of innovative drilling methods often calls for extra equipment to be installed either at the rig floor or as part of the bottomhole assembly. For instance, backpressure pumps, choke manifolds and automated control systems need to be installed in order to run some of the managed-pressure drilling techniques, discussed in Section 2.1. This subchapter discusses new drilling equipment that is currently improving drilling operations in shales.

2.2.1 Agitator tools

Hardware innovations may enable significant improvement to the ROP and a significant reduction of drilling costs. An example is the use of a Drilling Agitator Device, a downhole vibration tool that can improve the rate of penetration by *reducing the friction between the drill string and the borehole wall*. Excessive friction often becomes a problem while drilling deviated and horizontal wells. Friction increases torque and drag on the drillstring, aggravates the wear of the drillstring and the drill bit, and impairs the weight transfer to the drill bit. Since deviated and horizontal sections are key for accessing shale gas reserves, reducing friction may significantly improve economics of drilling for shale gas. In the Drilling Agitator Device, axial vibrations (15 to 20 Hz) are applied to the bottomhole assembly. These vibrations reduce the friction and improve the weight transfer to the drill bit. This reportedly improves the ROP by 35 % on average. The tool was successfully tested in several shale gas formations in the US, like Haynesville, Fayetteville, and Barnett Shale (Barton et al., 2011).

2.2.2 Preventing bit balling by electric potential

When drilling with water based fluids, the soft and sticky nature of shale drill cuttings can be a major problem. They absorb water from the drilling fluid, swell and stick to the bit. This is referred to as *bit balling*, and it strongly reduces the ROP and can lead to excessive shear and bit-tooth wear. The first ways developed to deal with this problem was strong fluid flow through the bit and good clearance between the teeth and the bit body. New mud recipes have also been proposed to minimize the problem. An example is high salinity muds, which are beneficial because they minimize the osmotic transfer of water from the drilling mud to the shale formation (Roy and Cooper, 1993). Oil base muds could also be used, but they are subject to severe environmental restrictions increasingly coming into effect.

Another method that has been proposed for dealing with bit balling is to use an electric potential to cause water flow to the bit/shale interface. This works because clay platelets in shale are negatively charged, and can thus be retracted from the drill bit by applying a negative potential to it. Laboratory experiments showed that the ROP was doubled when the bit was negatively charged, compared with the case when no potential was applied (Roy and Cooper, 1993). This has further been used to develop drill bit coatings for shale drilling that have a permanent negative charge. Successful application of this technology has been documented in over 20 bit runs through shale intervals in the North Sea and Gulf of Mexico (Smith et al., 1996).

2.2.3 Advanced steering systems for directional drilling

Drilling economics can sometimes be significantly improved by optimizing the well path. For instance, bypassing near-fault naturally-fractured zones may prevent mud losses. As another example, improved ability to drill higher curvatures may enable setting the kick-off point deeper, thereby eliminating or reducing directional drilling in a hard cap rock (Chen et al., 2015). This may have a significant positive effect on the costs of drilling for shale gas reserves, which are normally accessed by horizontal wells.

Steering systems for directional drilling are improved all the time. Examples of new systems, particularly well-suited for shale gas drilling, are the hybrid high-build-rate rotary steerable system for drilling curves and the power rotary steerable system for drilling horizontals (Chen et al., 2015). According to (Chen et al., 2015), the former improves the ROP by reducing friction in the deviated well, while the latter improves the drilling performance and minimizes shock and vibration. Build rates of 15°/100 ft (49°/100 m) are not uncommon with modern rotary steerable systems (Hummes et al., 2012). In addition to being able to drill greater curvatures, new rotary steerable systems are equipped with near-bit gamma tools which improves navigation towards and within the reservoir (Hummes et al., 2012).

Drilling more complicated well trajectories at greater depths puts more demanding requirements on the materials used in manufacturing the bottomhole assembly. In particular, high build rates require that those materials are capable of sustaining cyclic flexural loading. Drill bits used with rotary steerable systems must be able to sustain high side forces. High build rates also call for improved control electronics and software (Hummes et al., 2012).

2.3 Drilling fluids

Gas shales are inhomogeneous, highly laminated and very brittle rocks of low permeability that are sensitive to water. These shale features pose strict requirements towards the drilling fluids (DFs) aimed for drilling through these formations. Oil based DFs (OB DFs) often satisfy shale drilling needs by providing *good lubricity* and appropriate *shale stabilization*, but stringent *environmental regulations* and *economic concerns* necessitate replacement of oil based DFs by more environment-friendly and cheaper water based fluids.

Unfortunately, the conventional water-based drilling fluids (WB DF) are poor in drilling through shales. Shale drilling requires an effective radial support stress to achieve wellbore stability. This can be provided by DF overbalance, but it induces the flow of WB DF filtrate into the shale resulting in near-wellbore pore-pressure elevation. Another reason of the flow of WB DF filtrate into the shale can be clay swelling associated with unfavorable cation exchange. This filtrate invasion may lead to in-situ stresses overcoming the strength of the shale and resulting in plastic deformation and shale failure (van Oort et al., 1996). There are at least three mechanisms that can be used to reduce WB DF filtrate invasion into shale and to improve performance of water based DFs in shale drilling: (1) increasing the filtrate viscosity; (2) reducing the shale permeability; (3) inducing osmotic pressure driven backflow of pore water that balances the flow of DF filtrate into the shale caused by overbalance. Modern DFs used in shale drilling often utilize a combination of these three mechanisms to stabilize a wellbore.

2.3.1 Potassium silicate shale stabilizers

The most common shale stabililizing WB DF are *silicate*-based (van Oort et al., 1996). They contain water soluble silicates of a general formula $M_2O \cdot nSiO_2$ where M represents monovalent alkaline metals like sodium (Na) or potasium (K) and n is a number of SiO_2 molecules per one M_2O molecule, which is typically between 1.5 and 3.3 (van Oort et al., 1996). The pH of aqueous silicate solutions is basic, and when it drops, anionic silicate oligomers present in the solution start to polymerize leading to gelation or precipitation depending on the silicate concentration. Silicates also react with ions like Ca^{2+} and Mg^{2+} forming insoluble precipitates. These effects are used to stabilize shales. When silicate DF enters shale pores it mixes with water present in pores. This reduces the pH, which results in silicate precipitation. Precipitation is enhanced if calcium or magnesium ions are present in the pore water. The precipitates provide physical barriers that prevent further DF invasion regardless of whether it is overpressure or osmosis driven (van Oort et al., 1996).

Although the silicate-based shale stabilization mechanism has been known since the 1930s (van Oort et al., 1996), there is still ongoing development of the silicate DFs (McDonald, 2012, Soric et al., 2004). For instance, McDonald has described a novel shale stabilizer based on potassium silicate with a high ratio of dissolved silicate to potassium compared to conventional DFs. This makes it more chemically reactive and prone to precipitation. These more siliceous potassium silicate DFs are more effective in preventing shale delamination and for sealing microfractures (McDonald, 2012). The silicate DF can be designed to meet different challenging conditions like presence of salt layers and anhydrite contamination (Soric et al., 2004). Each shale play is different, and thus DF suppliers offer WB DFs tailored for a given shale play. Such customized DFs have properties adjusted to the specific environments in which they will be used.

2.3.2 Physical plugging of pores with nano particles

The silicate DF shale stabilization mechanism relies on reducing shale permeability, which is achieved by means of chemical reaction. Reduction of shale permeability can, however, also be achieved by physically plugging the pores. It has been shown that different types of *nano particles* can plug shale formations leading to decreased DF filtrate loss and thus increased stability. Due to their small size and high surface area, finely dispersed nanoparticles can form tighter packing structures compared to micron-sized particles alone. Moreover they are better suited for plugging shale pore throats on filtration than their micro-sized counterparts. This tighter packing and pore throat plugging reduces permeability and filtrate influx into the shale. Figure 2 compares nano- and micro particles arrangement around pores in shale. The nanoparticles that can be used for these purposes are as follows: iron hydroxide, oxide, sulfate, sulfide, calcium carbonate (Borisov et al., 2015, Husein et al., 2013), and silica (Sharma, 2014). It has also been shown that nanoparticles can contribute to wellbore strengthening in shales (Contreras et al., 2014) (see also Section 2.4). Nanoparticles deposited in the fracture can prevent fracture formation or propagation by creating a seal between the formation and the fluid pressure in the wellbore.

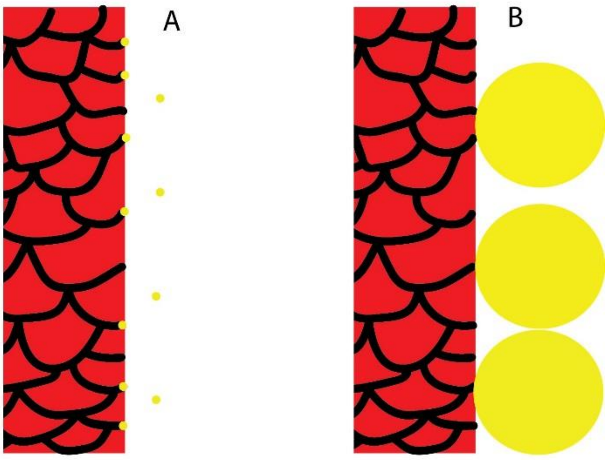

Figure 2. *Nano- (A) and micro- (B) particles arrangement around meso/macroporous shale wall. Nanoparticles plug pores while microparticles let the filtrate through.*

2.3.3 Lubricant additions to drilling fluids

We have described above how WB DFs can be designed to compete with OB DFs in borehole stabilizing while drilling through shales. Another challenge faced by WB DF developers is lower *lubricity of WB DFs* compared to OB DFs (Schuh et al., 2014). Current methodologies for improving lubricity of WB DFs involve addition of lubricants (Ls). Lubricants can be either in solid or liquid state (Skalle et al., 1999). The most common lubricants used in drilling fluids are glass or polymer beads, graphite powder, paraffins, olefins, esters and alcohols, natural and synthetic polymers (Fink, 2012). A detailed review of petroleum lubricants has been done by Fink (Fink, 2012). A good lubricant for drilling fluids is expected to have relatively high viscosity, high lubricating film strength, low pour point, low flammability, high thermal and oxidative stability, and to be noncorrosive and non-toxic. Non-toxic and biodegradable lubricants can be produced from organic sources. Kania et al. emphasize a potential utility of polyol esters of vegetable oils as biolubricants for many drilling conditions, and recommend further exploration of their potential (Kania et al., 2015).

Application of lubricants may however have some adverse effects. Liquid lubricants may change rheology of DFs or interact with other additives. Their efficiency may be lost over time due to, e.g., dilution, degradation, sticking to cuttings, or loss to the formation. Solid lubricants may plug valves in mud pulse telemetry systems or cause formation damage. Some of the challenges associated with application of common lubricants have been addressed by Schuh et al. who have developed a method to encapsulate biodegradable liquid lubricant in an inert polysaccharide micro-sized capsule (Schuh et al., 2014). The capsule protects the lubricant from interactions with other DF components and from harsh conditions (like e.g. extreme pH). When the capsule is subjected to sufficient pressure, friction, and shear, it ruptures, and the oil is released. The release occurs in areas of high friction, which is between the formation and drill string or between the bit and the formation. Thus the lubricant is released exactly where it is needed. In addition, due to encapsulation the lubricant does not change the drilling fluid rheology, pH, or viscosity (Schuh et al., 2014).

2.4 Wellbore strengthening in shale

Drilling with overbalance, i.e. with the bottomhole pressure in excess of the formation pore pressure, may lead to mud losses. One of techniques currently employed to prevent mud losses is *wellbore strengthening*. In this technique, the lost-circulation pressure of the well is increased by deliberately creating short fractures and sealing them with sized solids (Alberty and McLean, 2004, Aston et al., 2004). This can be compared to the use of nails to stabilize the rock mass in a tunnel in construction engineering.

Wellbore strengthening by fracturing and sealing was first proposed for use in permeable rocks, e.g. reservoir sandstones. In such rocks, the wellbore strengthening material (sized solid particles) builds an immobile bridge inside the fracture at some distance from the fracture mouth. The fine fraction of the wellbore strengthening material is then deposited on the bridge. Filtration of the base fluid into the high-permeability rock leads to strength build-up in the bridge, while the deposited fine fraction ensures low permeability. The resulting seal protects the fracture tip from the wellbore pressure. This prevents further fracture propagation, even when the wellbore pressure is subsequently increased, e.g. because of a pressure surge when running in hole or because the mud weight is increased in order to drill an abnormally pressured formation further down. Mechanical strength of the bridge prevents it from falling back into the wellbore when the wellbore pressure is reduced (e.g. when pulling out of hole). It also prevents it from being moved further into the fracture when the wellbore pressure increases. Wellbore strengthening in high-permeability rocks can be applied as part of continuous circulation (in that case, the solid particles building the bridge and seal are often called the *loss-prevention material*) or as a squeeze treatment. In a squeeze treatment, the circulation is stopped, a pill having relatively high volume fraction of wellbore strengthening material is placed in the annulus against the formation to be strengthened, and the treatment is squeezed into the formation (Lavrov, 2016c).

Both factors affecting the performance of a wellbore strengthening treatment, i.e. the mechanical stability of the bridge and its permeability, depend on the permeability of the rock. If the same treatment as used in sandstones is applied in a low-permeability rock, such as shale, the resulting bridge might be unstable, and its permeability might not be low enough to protect the fracture tip, because the fluid present in the treatment still remains in the fracture. During subsequent reduction of the wellbore pressure, the seal may be moved towards the fracture mouth and out of the fracture.

Low-permeability formations have long been a major challenge for lost-circulation prevention. Progress in the design of drilling fluids and additives brings about new pill composition that can prevent losses in shales. One such pill is based on a blend of particulates with a cross-linked polymer (Aston et al., 2007). The bridging particulates are graphite as well as coarse, medium, and fine marble. The solids content of the bridging material can be from 20 to 100 lb/bbl (57 to 285 kg/m^3). The polymer sets when placed in the fracture, and thereby ensures low permeability of the bridge without the need for filtration of the base fluid into the rock. It also ensures adhesion between the seal and the fracture faces, and thereby improves the stability of the seal.

The pill was tested in the Arkoma shale formation at a depth of 4020 ft (1225 m). A 500-ft long interval of a 8-3/4" well was treated by squeezing the pill in stages. The increase in the lost-circulation pressure created by the treatment was sustained during subsequent drilling. Among the key factors determining the success of the treatment were sufficiently high squeeze pressure and the wide particle size distribution of the particulate (2-800 µm), which enabled bridging and sealing of fractures having different apertures, possibly also natural fractures usually present in shale (Aston et al., 2007).

2.5 Cementing operations

After a section of the well has been drilled, a steel casing pipe is cemented in place to stabilize the wellbore and to protect towards flow of formation fluids between subsurface zones. The cement barriers created during well construction are important, as they often need to act as permanent barriers also after the well has been plugged. This means that they should survive repeated hydraulic fracturing operations, where pressures inside the casing pipe typically exceed 8000 psi, without radially fracturing or degrading. In the present subchapter we discuss some emerging methods and materials that have been developed to improve shale gas well cementing operations.

2.5.1 Polymer centralizers for improved cement placement

Running in casing is more difficult in horizontal and deviated intervals because of the increased drag force. While the casing can slide down in vertical wells, it needs to be pushed down by the casing above in high-angle wells. During cement placement in horizontal wells, casing rotation is often used to improve the mud displacement efficiency. In horizontal and deviated wells, such rotation may be difficult if possible at all. Centralization of casing in horizontal and deviated wells is essential in order to avoid mud channels during cement jobs. All the above factors, i.e. drag, torque, and eccentricity, call for improvements in casing centralization in gas-shale wells.

Technological advances have been focused here on improved materials that would reduce friction between the casing pipe and the centralizer's inner surface, in case of centralizer not fixed to the casing. For instance, a *low-friction polymer centralizer* was found to maintain nonzero standoff in the entire lateral section of a well drilled in Eagle Ford shale (Sanchez et al., 2012).

2.5.2 Special cements for shale gas wells

Cement placement in complex well geometries require optimized rheological properties of the slurry. In addition, shale is a water-sensitive formation type, meaning that slurries should be tailored to bond well with, and solidify as intended, adjacent to a shale wall. The mechanical properties of the cement after solidification should also ensure sufficient durability to withstand the thermal, chemical and mechanical loads that must be expected during shale gas production operations. All of these challenges cannot be solved by a single cement mixture, but special cements are continuously developed for shale gas operations. Some common shale well cements are discussed in the following:

- **Salt cements.** Cement with salt (sodium chloride) additions were first the preferred alternative for cementing shale and bentonite formations. Water-sensitive shales containing montmorillonite, illite and chlorite were found to obtain a better bond to cement with such mixtures (Slagle and Smith, 1963). This is because a higher salinity of the cement slurry compared to in shale pores will ensure that water is transported from the shale and into the cement (instead of the opposite way). The cement slurry is dependent on having access to enough water to harden appropriately. Drawbacks with salting of cements is, however, retarded solidification and enhanced casing corrosion.
- **Latex additions:** Cement can be mixed with latex to enhance its rheological, mechanical and elastic properties. For a long time, this additive could not be used in all wells, as traditional styrene/butadiene latex mixtures were difficult to keep stable at high temperatures – and since chlorides in the blend could cause latex coagulation. For freshwater-sensitive high pressure high temperature (HPHT) wells it was thus not common to apply this additive. Recently, however, it has been reported that by adding a proprietary monomer and tailoring the concentrations of styrene and butadiene, a latex-based cement usable in shale wells has been developed. It is reported that this special cement has been applied with success in the Haynesville shale (Pavlock et al., 2012). This is an especially challenging shale play, as it has extended-reach, horizontal wellbores in a HPHT environment. Tight annular clearances and a narrow pore-pressure/fracture-gradient further complicates the use of conventional cement slurries here.
- **Expanding cements:** The so-called Flexible, Expanding Cement Systems (FECS) are special cements with greater flexibility than conventional cements. These systems also have very high solid volume fractions (50 to 60%). They have a linear expansion of 0.2-0.4% upon solidification, and are designed to be durable for wells subjected to fracturing operations. Such materials have successfully been applied in the Marcellus shale play. After six months, no sustained casing pressure has been observed in the Marcellus shale wells cemented with this material even if the stimulation pressures exceeded 9000 psi (Williams et al., 2011). The drawbacks with this material is a lower cement density, lower Young's modulus and lower compressive strength of the set cement.
- **Lightweight cements:** When drilling and cementing weak, naturally fractured shales with low fracture gradients, it is necessary to use a low-density cement slurry. Some ways of lowering the density of cement is to add gypsum or calcium chloride, microspheres or gas bubbles (foamed cement). All of these methods yield unpredictable results in shales, and research has therefore been conducted to develop a light weight cement slurry for shale operations. A new mixture, based on a silicate component that efficiently ties up excess water, is the result of this work (Kulkarni and Hina, 1999). This has been used to cement 65 wells in the Devonian shale. The success rate, defined as cement being able to cover all desired zones, was over 60%. This is a great improvement, as two stage cementing or squeeze after primary cementing was necessary when ordinary cements were applied.

2.5.3 Novel materials that can possibly replace cement

The widespread use of cement in the well construction industry owes mainly to its availability and price rather than its durability and mechanical properties. It is a material that is known to degrade upon chemical and thermal loading, and that is prone to fracturing over time. As a result of these shortcomings, several novel materials are proposed that could possibly replace cement for well construction (or well plugging) purposes. A short overview of some promising materials is given in the following:

- **Thermosetting polymers and resins**: In many cases it is beneficial to use a material more flexible and less permeable than cement as a seal. Thermosetting polymers and resins have been proposed as materials for well construction, well remediation and well plugging (Bosma et al., 2001, Phan and Xie, 2015). These cure from their pumpable liquid state into a solid at a given temperature. This curing temperature can be adjusted by tailoring the composition. The application of thermosetting polymers and resins have so far mainly been used for remediation and well plugging purposes (Beharie et al., 2015). It is, however, possible that they can be used as annular sealants in the future. The main drawbacks with using these materials is their shrinkage upon curing and the unknown bonding quality to different formation types.
- **Expanding alloys:** Some metal alloys expand upon solidification (like water). Bismuth is a known element in such alloys, but they can also be based on Gallium or Antimony. If they have melting temperatures above the typical downhole temperatures in wells, they can be placed in well annuli in solid form and melted (e.g. by an induction heater) to from an annular barrier (Bosma et al., 2004). Alternatively, a container can be designed that allows for the material to be placed in the well in molten form. Alloys based on Bismuth will expand by over 3% when subsequently cooled down, thus reducing the formation of microannuli at seal interfaces which is common upon cement solidification (Carpenter et al., 2004). Compared to for cement, the thermal conductivity of expanding alloys are also more similar to that of the steel casing, thus reducing microannulus formation as a result of downhole temperature variations (e.g. caused by on/off injection of cold fluids). While the alloy-casing bond is probably adequate, it is unclear whether a good bond quality can be achieved towards all formation types (Lund et al., 2016).
- **Swelling clay:** When in contact with water, swelling clays increase their volume with many hundred percent. Such materials have thus been proposed as well plugging materials (Garrett et al., 2005). This includes dumping swelling clay, e.g. bentonite, in particulate form into the well. Subsequent hydration will then help the clay to form an impermeable plug. Clay is a material compatible with the surrounding rock formations, but it is still difficult to place and hydrate in well annuli. It is, however, possible that swelling clays already present in shale formations can be used as annular barriers. It has been demonstrated in the North Sea that shale layers can creep/swell and form tight annular barriers that ensure zonal isolation (Williams et al., 2009).

3 WELL COMPLETION, STIMULATION AND PRODUCTION

Only a small portion of shale plays with natural fracture networks can be exploited without stimulation. The vast majority of shale formations require hydraulic fracturing. The purpose of hydraulic fracturing is to increase permeability of the formation in order to allow the entrapped gas to be released. Stimulation of a well starts after the well has been drilled, completed by placing a casing and after selected intervals of the casing have been perforated (Gawel et al., 2015). In the following we will discuss new innovations related to hydraulic fracturing methods and –hardware that have been developed to maximize production from shale gas plays.

3.1 Hydraulic fracturing

During hydraulic fracturing stimulation, a fracturing fluid is pumped to the wellbore in order to increase the downhole pressure. When the pressure exceeds the strength of the rock, hydraulic fractures form and propagate in the rock. Upon development, fractures can be loaded with proppant – a particulate material that keeps fractures open. Once fracturing has been executed, the well is depressurized, and the gas migrates through fractures into the well. The pore pressure of the formation pushes the fracturing fluid, now mixed with formation water, into the well and back to the surface. This water, called "flowback water" can either be reused or be disposed of. Usually, only 10-30% of the total water used in fracking is recovered, while a great part is absorbed by the rock (Brzycki, 2016). *Management of the flowback water* is a big challenge of contemporary fracturing technologies and motivates the development of water-free fluids.

The fracturing using water based fluids can be regarded as a standard stimulation technique. It comprises "slickwater" fracturing and fracturing using more viscous fluids than "slickwater" (Gawel et al., 2015). Slickwater is a water-based fluid of rather low viscosity containing a low fraction of friction reducing polymer and proppant. Slickwater has to be pumped at high rates in order to induce fracturing. *Large volumes of water are required* in a slickwater fracture treatment (IOGCC, 2016). Due to its relatively low viscosity, slickwater has a limited capability to suspend and transport proppant particles (Palisch et al., 2010). High absorption of slickwater in fracture networks leads to reduced water recovery and potential for *formation damage*, meaning that reservoir pores become plugged and production reduced (Palisch et al., 2010).

Some of the above-mentioned limitations can be overcome by applying fluids with viscosities several orders of magnitude higher than the slickwater viscosity. The higher viscosity of such fluids is achieved by adding viscosity enhancers – linear or crosslinked polymers. Fluids with enhanced viscosity can disperse and transport larger amounts of proppant compared to slickwater. On the other hand, they may to some extent plug the formation by forming a filter cake and thus require a breaker (viscosity reducer) to allow releasing the proppant after the fracturing is completed (Palisch et al., 2010).

In addition to proppants and viscosity modifiers, fracturing fluids usually contain a *large number of other chemicals*, e.g. acids, corrosion inhibitors, biocides, oxygen scavengers, iron precipitation control agents, scale inhibitors, clay stabilizers (Arthur et al., 2009). This large number of chemicals used in fracturing raises environmental concerns.

3.1.1 Development of Proppants and Chemicals

Proppant and chemicals for hydraulic fracturing have been under constant development since the very beginning of the hydraulic fracturing adventure. This development is targeted at 1) improved performance and reduced costs and 2) more environment-friendly solutions.

Proppants are particles used to keep the incipient fracture open during a HF treatment. The conventional proppants include sand, ceramic, nutshells, and glass beads. The mechanical strength of the conventional proppants is often not sufficient to withstand loads applied when the fracture closes. Crushing of proppants generates fines that can migrate with a backflow and reduce the fracture permeability or even plug a proppant pack. In order to avoid this, *high-strength proppants* are being developed (Andrews, 1987, San-Miguel et al., 2012, Kachnik, 1987, Eldred et al., 2013). *Coating proppant particles* with organic polymers can to some extent prevent crushing or fines migration or both (Zoveidavianpoor and Gharibi, 2015). This is because a polymer coating either may improve the proppant strength or may act as a trap to keep the produced fines in place as depicted in Fig. 3. The most common types of polymers used for proppant coating are epoxy, furan, phenolic, polyurethane, polyester, and vinyl ester resins (Zoveidavianpoor and Gharibi, 2015, Hussain et al., 1997). The resin coating can be reinforced by fibers. The fibers can be e.g. glass, ceramic or carbon. The proppants coated by reinforced polymer shell better withstand the closure stress exerted in the fracture, help to maintain better conductivity and permeability of the formation for a longer time, and provide better resistance to undesired flowback (Hussain et al., 1997). The resistance to flow-back is also high where a portion of the fibers protrude from the resin coating to interlock with fibers of other proppant particles (Hussain et al., 1997). The resistance to flow-back was also found to depend on proppant particle shape (Graham and Kiel, 1970),(Alary and Parias, 2013, Vincent et al., 2004).

Figure 3. *Schematic illustration of proppant particles: Left: no coating – producing fines, Middle: polymer coating – fines migration limited, Right: polymer-fiber composite coating – proppant backflow limited.*

Polymer coating is also a remedy for another challenge associated with proppant application, namely, scale formation. Scaling reduces fracture conductivity and thus hinders production. It can be caused by proppant dissolution and subsequent re-mineralization in the pack (Weaver et al., 2008). Thus, appropriate proppant polymer coating can reduce scaling by preventing particle surfaces from dissolving.

Proppants can also be used as a *delivery system*. Porous ceramic proppant particles may be infused with various chemicals that need to be delivered directly to fractures (Howe et al., 2016, Bourne and Read, 1999). The chemicals that may be practical to have infused can be scale inhibitors, corrosion inhibitors (Bourne and Read, 1999), oxygen scavengers, biocides or surfactants (Kaufman and Becker, 2009), or breakers and/or tracers (Duenckel et al., 2014). The infused proppants can be used in combination with standard proppants. The infusion provides a controlled release of chemicals and thus better control over production processes and long-term production assurance.

The productivity of shale gas wells is governed by the conductivity of the proppant bed which is dependent not only on the proppant type and size but also on the fluid properties and wettability of the solid surfaces with fluids. The wettability, of a solid surface can be defined as the preference of this surface to come into contact with the wetting phase (a fracturing fluid or a gas). For example, a water-wet proppant surface will preferentially stay in contact with water and result in a high capillary pressure. The high capillary pressure may negatively affect proppant bed conductivity on gas backflow. It has also been emphasized that wettability and capillary pressure within the proppant bed affects conductivity. Interfacial tension can be reduced by using specially designed surfactant-based fluids, and this significantly enhances production (Penny et al., 2012). In addition to surfactants, nanoparticles may be used to alter the wettability of the proppant present in the fracture (Holcomb et al., 2010).

The most recent inventions associated with proppant placement also address: localization of tagged proppant (Smith, 2014), and preventing proppant backflow by applying consolidation methods (Cannan et al., 2015, Smith, 2014).

Fracturing fluids are transporting the proppants to the fractures. Their main components are viscosifying agents and friction reducers. Both components are most often polymer based and are also a subject of recent developments. Biopolymers such as guar and cellulose derivatives, xanthan gum and modified starches are often used as viscosifying agents. In order to generate the required viscosity polymer chains must be properly hydrated. In case of dry polymers the hydration process is often slow thus they require being pre-hydrated in the hydration unit before mixing with other hydraulic fracturing fluid components. In addition to the hydrating equipment, significant amount of energy and water is required during the hydration process. These downsides were driving forces for a development of a fast-hydrating guar powder for hydraulic fracturing applications (Kesavan et al., 2007),(Deysarkar et al., 2011). The improved hydration does not only result in a shortened hydration time but also reduced amount of the polymer needed to reach the required viscosity which may translate to reduced costs and formation damage (Deysarkar et al., 2011).

The similar polymer-hydration problem refers to friction reducing agents that are added to hydraulic fracturing fluid in order to minimize the amount of energy required to pump the fluid through the well (Blair et al., 2004). The most common friction reducers belong to the family of high molecular weight linear polymers. Polyacrylamide, its derivatives and copolymers are typically used as friction reducers (Boothe et al., 1975). As the time and mixing needed for their full hydration is longer than usually required there is a need for rapidly hydrating friction reducing agents. Thus, friction reducers with improved hydration capabilities are under development (Kumar et al., 2014, Sanders et al., 2016).

After the fracturing is finished and proppant placed in the fracture the viscosity of the fracturing fluid is reduced to facilitate the fluid and gas backflow. This is done by the use of so called breakers. Breakers are substances that either disrupts cross-links between polymer chains or degrade polymer chains. The degradation results in reduced molecular weight and concomitant reduction in viscosity. However, the polymer to fulfil its viscosifying function has to be protected from the action of the breaker or rather the breaker action has to be delayed. This is often done by encapsulating a breaker (Norman and Laramay, 1994). The protective mechanism provided by encapsulation relies on the reduced diffusion of the breaker through the imperfectly isolating polymeric capsule and thus delayed viscosity degradation.

3.1.2 Water-free stimulation

The water sensitivity of some shale formations may lead to high water absorption, which not only negatively affects fracture conductivity and formation permeability but also results in large losses of HF fluids into the formation. These challenges with water-based HF fluids motivated the development of non-water based fracturing fluids (Rogala et al., 2013).

Gases like CO_2 and/or N_2 being either in liquid or gaseous phase were used for fracturing since late 70's-early 80's (Bullen and Lillies, 1983, Freeman et al., 1983). The main advantages of using gases for fracturing are their ability to self-clean up after the pressure is released, elimination of formation damage typically associated with water-based fracturing fluids, and elimination of the risk, costs and environmental issues associated with reinjection or utilization of back-produced water. Middletone et al. discuss pros and cons of utilization of supercritical CO_2 as a fracturing fluid, and they emphasize the following points: 1) increased desorption of methane adsorbed in organic-rich parts of the shale during supercritical CO_2 fracturing and 2) the potential of shale gas plays to become a major utilization option for CO_2 sequestration (Middleton et al., 2015). Despite its undeniable advantages, fracturing with gases is not free from limitations, among which are e.g. costs and safety issues associated with handling large volumes of gases (Middleton et al., 2015). Despite the limitations, there are already some gas-based fracturing technologies commercially available. Ecorp Stim has developed water-free and chemical additive-free methods to stimulate shale-gas formations. The technologies include:

- **Propane stimulation.** This utilizes liquid propane carrying proppant as a fracturing fluid. Liquid hydrocarbons can be gelled using gelling agents (Jones and Taylor, 2000) to increase the viscosity and proppant carrying capability. Such hydrocarbon-based water-free fracturing fluid should not wash out any salts, heavy metal ions or radioactive substances from the formation thus reducing the risk of formation damage and detrimental environmental consequences. After the fracturing is finished, the well is depressurized and the propane flows back together with the natural gas. This is illustrated in Figure 4. According to EcorpStim, the main benefits of applying propane are: (1) 95-100% of propane can be recovered and reused, and (2) there is no need for any chemical additive. The drawback of propane technology is gas flammability and the potential risk for explosion while storing and handling it (Stim, 2015). This gelled propane technology was first used for shale stimulation in 2007 by the Canadian company GasFrac. Since then, over 1500 operations of shale stimulation using this technology have been performed by operators in Canada and the United States.
- **Non-flammable propane stimulation** technology utilizes fluorinated form of propane (heptafluoropropane) as a stimulation fluid. The fluorination eliminates the risk associated with the flammability while sustaining the fluid recovery ability.
- **Light alkanes stimulation (LAS)** is a new concept developed by ecorpStim in 2015 (Stim, 2015). It employs 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)]. These hydrocarbons occur in the liquid/oil form under ambient conditions. LAS fluids are non-flammable and non-toxic.

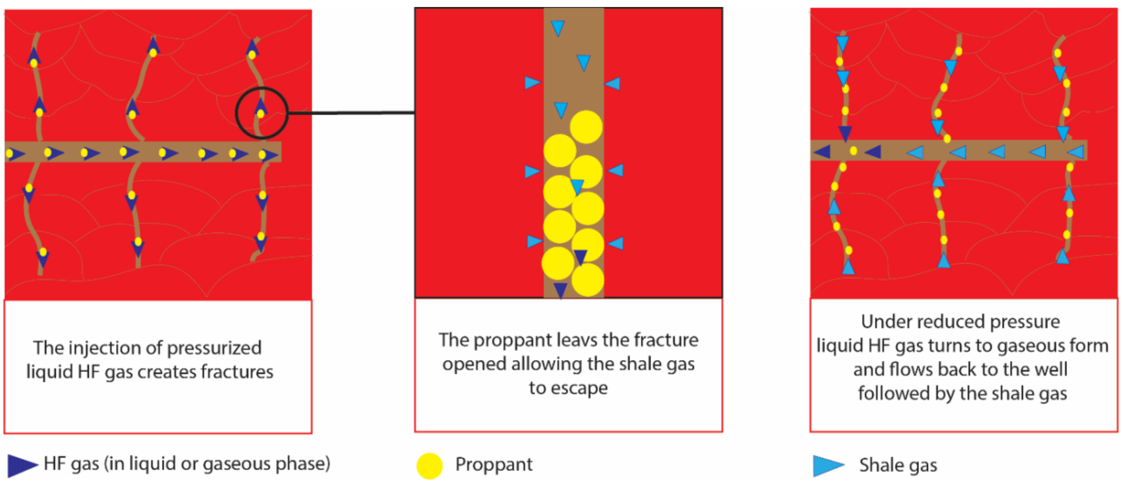

Figure 4. *Propane stimulation (adapted based on information on EcorpStim webpage).*

The above mentioned water-free fracturing technologies are nowadays considered as "game changers" within hydraulic fracturing. Although the price of hydrocarbon-based fracking fluids is rather high the number of their undeniable advantages may possibly make them competitive to water-based fluids especially in water scarcity regions.

3.2 Completion hardware

3.2.1 Fracturing equipment and techniques

Three types of fracturing techniques and equipment are currently used in horizontal shale-gas wells (Yuan et al., 2013):

- plug-and-perforate;
- ball-activated frac sleeves;
- coiled-tubing-operated frac sleeves.

The traditional fracking technology, plug-and-perf, is used in cased boreholes. A bottomhole assembly (BHA) is run in hole on a wireline. The BHA contains composite plugs and perforation guns. The frac stage is isolated by the composite plugs once the BHA has been positioned for the stage. The guns are fired, creating the perforations. The BHA is pulled out of the hole, and the fracturing fluids are then pumped through the perforations into the formation, creating hydraulic fractures. The BHA is then lowered into the well again to do the next stage. Running in hole and pulling out of hole for each stage introduces substantial nonproductive time in the stimulation process. The plug-and-perforate technology also requires large volumes of fluids. In addition, composite plugs set downhole to isolate each stage need to be milled out before production can start. New techniques and hardware are therefore continually developed in order to optimize the fracturing process and its footprint on the surface.

Ball-activated frac sleeves and coiled-tubing-operated frac sleeves are examples of such new technologies. In ball-activated frac sleeves, balls of progressively larger size are dropped into the well. The balls hit matching seats in the sleeves, opening the ports and enabling the frac fluid to flow into the formation. The hierarchy of ball sizes enables the staging from the toe up along the lateral. Nonproductive time is thereby significantly reduced, as compared to the plug-and-perf technology.

In coiled-tubing-operated frac sleeves, sleeve ports are opened using a specially designed BHA run in well on a coiled tubing. A collar locator is used to position the BHA. No balls or plugs are used, which eliminates the post-job mill-out operation. This type of sleeve also enables more stages (up to 29 in the case study presented in ref. (Algadi et al., 2014)) and tighter spacing between the stages. Also the nonproductive time between the stages is only 8 min (Algadi et al., 2014).

While the plug-and-perforate technology has been in use for decades, the development of frac sleeves is largely due to the massive use of fracturing in horizontal wells used to develop unconventional resources onshore. The frac sleeve technology paves the way for many hardware innovations. For instance, telescopic ports can be used in ball-activated frac sleeves in order to facilitate fracture nucleation (Wibowo et al., 2014). When the ball dropped into the sleeve reaches a landing baffle, the port opens and the telescopic structure punches into the rock. It creates a short pre-fracture which then serves as a nucleation spot for the hydraulic fracture when a frac fluid or a proppant slurry start streaming through the port (Fig. 5). Eight ports are installed on each frac sleeve, with a 45° phasing.

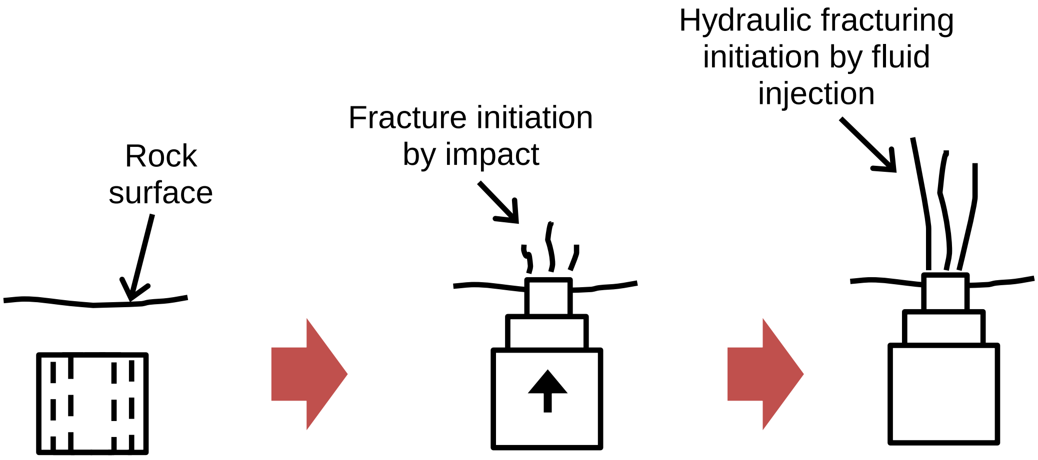

Figure 5*. Fracture initiation by means of a telescopic impact port in a ball-activated frac sleeve assembly. Red arrows indicate the sequence of events. Black arrow indicate mechanical force (impact) of the telescopic port. Blue arrow indicates fluid flow through the port. Left-hand panel: telescopic port before extension. Central panel: telescopic port extends and hits the rock creating nucleation fractures. Right-hand panel: frac fluid or proppant slurry is injected through the port creating hydraulic fractures. Several ports can be active per fracturing stage.*

Another innovation in ball-activated ball sleeves is the use of a single ball to activate several sleeves in a stage. The ball is released at the surface and is carried down the well with the fracturing fluid. After the ball hits the baffle in the first sleeve of the stage, the pressure builds up in the sleeve, opens up and extends the telescopic port, and opens up the baffle so that the ball can travel further, to the next sleeve that needs to be activated in the stage. The same ball can thus open multiple sleeves per stage.

Balls remaining in the sleeve after the fracturing has been completed need to be removed from the well in order not to block the flow path during production. The balls can be either brought to surface by flowback or they can be removed, together with the landing baffles, during a millout operation (Tompkins et al., 2013). An alternative is an innovative technology that makes use of a disintegrating material for the balls (Wibowo et al., 2014).

Long horizontal wells are difficult and expensive to cement. This motivates the use of open hole completion techniques. Mainly three methods are used (Bellarby, 2009):

- **Use of open hole packers:** ECP (External Casing Packers) elastomer or mechanical packers. The sleeves can be the same as for cased completion e.g. drop-ball or coiled tubing. Fracture containment can be adjusted by varying distances between packers. By using a single packer between each sleeve a large annulus is exposed to pressure and multiple fractures are possible. In order to improve the fracture containment, packers can be spaced closer.
- **Retrievable (straddle) packer** arrangement with coiled tubing. The benefit of straddle is that it can be reset and repositioned. This allows for creating many fractures in one trip. It is well suited for multiple small fractures as the pressure rating of the straddles and injection rates through the tubing can be restrictive.
- **Hydrajetting nozzle** on coiled tubing. The nozzle jets the formation and initiates the fracture. The jetting cause a reduction in wellbore pressure, which reduces the probability of multiple fractures.

3.2.2 Erosion mitigation in HF wells

Fracturing fluids containing proppants are abrasive and can erode well structures. These abrasive forces act both on pumping the fluids downhole as well as on their backflow. Preventing abrasive wear of well structures is realized in a two-fold manner: (1) via improved design of well elements in terms of geometry and materials used (e.g. high-strength alloys and ceramic couplings), and (2) backflow prevention. New modeling tools are also developed for predicting this type of damage. They couple erosion models with computational fluid dynamics (CFD) models, and can be used to simulate a range of hydraulic fracture operating conditions to predict locations and degree of material loss in components (Farahani et al., 2011).

During discharge of fluid from a tubular string in the wellbore, casing and other structures in wells can be eroded. In order to reduce this erosion a system that mitigates abrasive action of fluids can be used (Frosell et al., 2013). The system comprises a tubular string including a fluid discharge apparatus. The fluid discharge apparatus includes a curved flow path that directs the fluid away from the tubular wall and thus reduces impingement of the fluid on this well structure.

To avoid proppant backflow screens can be used. Sometimes conventional sand control methods could not be applied due to the insufficient erosion resistance of the supporting metal screens. Alternative materials showing higher hardness and consequently better erosion resistance have been proposed for screen design. The use of advanced ceramics showing resistance to wear, high temperature and corrosion stability even at higher temperatures have been described (Muessig et al., 2011).

4 DISCUSSION

This report has summarized some emerging technologies, methods and materials for shale gas well operations. As innovation is a continuous process, the review does not intend to be a complete overview. We have, however, ensured to cover innovations related to most stages of a well's life cycle. While drilling, cementing and production were fields of many new emerging innovations, only few technologies/methods targeted the permanent abandonment phase of shale gas wells. Only plugging material development was described, but these were similar to the annular barrier materials described in Section 2.5.3 of the report.

In general, the Technology Readiness Level (TRL) of the emerging technologies were relatively high. Most of them had already been field tested in shale gas wells. This is natural, as commercialization or publication is required for the technology to be visible enough to be noticed and described. Emerging technologies with low TRL levels are probably still being kept in-house by service companies and vendors until the necessary intellectual property rights have been secured.

In general, it was observed that the research and development (R&D) targeting shale gas well technology has focused more on cost-efficiency of drilling and completion than on well integrity. This is understandable, since a great number of wells need to be constructed to exploit shale gas resources, but the safety aspect deserves more attention. As a wrap-up, the remainder of this chapter will outline some technology and knowledge gaps that still remain to be filled with innovative products/materials to minimize the environmental footprint of shale gas well operations.

4.1 Remaining technology- and knowledge gaps

4.1.1 Wellbore strengthening and lost circulation

Wellbore strengthening has been successfully used in high-permeability rocks, such as reservoir sandstones. Its application in shale are met with varying success. The reason is that the wellbore strengthening material (solid particles added to the drilling fluid) can only effectively plug the fractures created during wellbore strengthening, if the fluid can rapidly drain into the rock. In low-permeability shales, this is much harder to achieve than in sandstones. The development of wellbore strengthening material that could show a *consistently* high performance in shales is still an outstanding task.

Good lost circulation materials (LCM) for shales are also difficult to design because of insufficient and unreliable information about properties of natural fractures. Today, there is no LCMs available that efficiently stop losses into fractures wider than 5 mm (Lavrov, 2016c). Currently, fracture characterization techniques, such as image logs, can usually provide reliable information only about fracture dip and spacing, but not the fracture apertures.

4.1.2 Cement placement in shale gas wells

Fractures in gas-bearing shales may potentially represent escape paths for cement in well cementing operations. During annular well cementing, cement may escape into the natural fractures exposed in the annulus if the pressure in the annulus exceeds the fracture reopening pressure. This will give shorter annular barriers, which can be a threat towards the robustness of the well and its long-term integrity.

It is usually recommended that all natural fractures must be plugged before cement pumping starts. If, however, some fractures remain open or new fractures are created during cement pumping, lost circulation material needs to be added to the cement slurry in order to stop losses. A multitude of such materials are available for use in drilling fluids. Using LCMs in cement, however, is more challenging since these materials often increase the viscosity or yield stress of cement. Developing lost circulation materials that do not significantly compromise pumpability of the cement slurry is still an outstanding issue. New materials or cement types that would simplify the cementing of long inclined and horizontal sections in wells would also be of great benefit.

4.1.3 Assessing the sealing ability of annular cement

In order to ensure that pumped cement has ended up as a tight annular seal, it is beneficial to run a temperature log right after cement placement. The cement location can then be revealed, since cement solidification is an exothermic reaction. Such logs are, however, not commonly run during well construction – since it is not required and tripping in and out of the well with logging tools is time consuming. The development of multi-purpose well tools including temperature logging (or other logging methods that can detect cement presence) could thus be beneficial.

It should also be noted that neither the temperature log, nor the conventional cement bond log, can reveal whether there are smaller defects in the annular cement sheath such as channels, microannuli or enhanced porosity. This can only be detected (e.g. by Doppler shift methods) if a leakage has developed through them. Furthermore, the bonding quality of the cement to the drilled rock formation is very difficult to assess by logging. It is therefore still unknown which muds/preflushes/spacers are the best adapted to ensure optimal sealing ability towards different shale types.

In general, more industry focus should be directed towards:

- Developing smart/sensing cements (or cement replacement materials) that can give information about their sealing ability *before* leakage occurs.
- Developing new logging methods or new "loggable" materials that can simplify barrier verification work. As a first step, a better understanding should be obtained on how to detect annular sheath defects by logging.
- Focusing on long-term integrity issues when developing cements, muds, preflushes and spacers. The cement needs to withstand repeated fracturing operations, while the muds/spacers/preflushes are coating the formation walls when cement is placed in the well.

4.1.4 Frac job design

Hydraulic fractures can be offset, deflected, or arrested when they meet a natural fracture (Lavrov et al., 2014, Lavrov et al., 2016). This is schematically shown in Figure 6. In order to design fracturing jobs in shale gas reservoirs, information about the in-situ, natural fracture network should be available and should be used as input in hydraulic fracturing models. The permeability of a fracture is also stress sensitive (Lavrov, 2016b). During production, the effective normal stresses in the reservoir increase, which reduces the fracture apertures (Lavrov, 2016a) and may reactivate faults and shear fractures in the reservoir and overburden (Holt et al., 2016). Knowing the properties of fractures (apertures, connectivity, conductivity, normal and shear stiffness) is essential for predicting the evolution of reservoir permeability in shale-gas reservoirs during depletion. Fracture closure during depletion is one of the reasons for notoriously low recovery rates in carbonate reservoirs in the Middle East (often as low as 10 %).

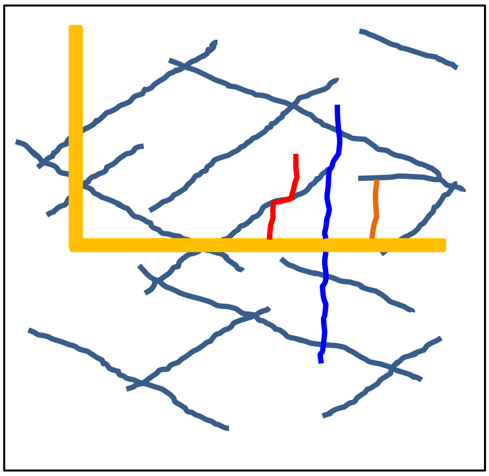

Figure 6*. Propagation of hydraulic fracture (red) in a naturally fractured reservoir. Wellbore is shown in yellow. Natural fractures (two predominant sets) are shown as dark blue lines. Induced, hydraulic fractures are shown as red, brown, and bright blue lines. Hydraulic fractures can be deflected by natural fractures (red), arrested by natural fracture (brown), or unaffected by natural fractures (bright blue).*

To optimize hydraulic fracturing jobs, another outstanding issues is how to model fracture propagation in naturally fractured rocks. Currently, two-dimensional and pseudo-three-dimensional numerical codes are routinely used to design frack jobs in conventional reservoirs. Such codes, when applied to design frac jobs in naturally-fractured reservoirs, may yield poor predictions. The fracture length, propagation trajectory, fracture aperture, fracture height and fracture permeability may be estimated inaccurately. The development of reliable, accurate, calibrated, and fast fracturing codes for shale-gas reservoirs is still an outstanding task. Ongoing research activities should make such simulations available to the industry in the near future (Lavrov et al., 2016).

4.1.5 Water usage and chemicals

The high amount of water used for hydraulic fracturing, together with the many chemicals used in the fracturing fluid, raises environmental concerns. Leakages through wells or formations is a risk, and the large amounts of back-produced water needs to be safely disposed of. It also makes hydraulic fracturing operations more difficult to perform in regions with water scarcity.

A trend in research and development is thus to move towards *non-water based fracturing fluids*. There are, however, outstanding safety issues related to this technology – as large volumes of fracturing gases need to be handled. More laboratory and field testing is needed to optimize such operations.

However, especially the use of CO_2 for fracturing has some clear environmental benefits. If the frac job is designed properly, it could combine long-term geological sequestration of CO_2 with production of clean-burning natural gas.

5 CONCLUSIONS

The report provides a summary of emerging technologies, methods and materials developed for shale gas wells. Some are developed specifically for shale gas wells, while others have been developed for other purposes – but are very promising for application in shale operations.

The review covers new drilling techniques and equipment, cementing materials and procedures and new completion, stimulation and production technology. It was found that most of the new technologies/methods targeted cost-efficiency of shale gas wells, and less focus was on the long-term well integrity and environmental aspects.

Some identified unfilled knowledge- and technology gaps were:

- **Information about fracture networks.** There is still insufficient and unreliable information about properties of natural and induced fractures and how fractures interact with each other. This impedes the development of lost circulation materials, cement/mud additives and frac job design.
- **Cement placement in wells.** The complex geometries and long inclined/horizontal sections of shale gas wells pose difficulties when it comes to primary well cementing. There is no way of optimizing all cement properties at once by means of additives, and optimizing its flow can e.g. hamper its solid mechanical properties. New materials or new placement methods could simplify this process in the future.
- **Annular barrier verification.** It is still difficult to verify that cement in well annuli forms a tight annular barrier without channels, microannuli or other defects. New "loggable" materials or new logging methods could potentially solve this problem.
- **Long-term cement integrity.** Little information is still available on how well cement withstands repeated hydraulic fracturing operations, where pressures can exceed 8000 psi. More flexible materials than cement could possibly be beneficial to prolong the life of shale gas wells.
- **Reduced use of water in fracturing operations.** Many regions with shale gas reserves have water scarcity, and there is also a lot of risks associated with handling of back-produced water from shale gas wells. Thus, a trend is to move towards reduced use of water in frac jobs. More research and development is necessary to understand how to optimize such operations, especially if pressurized gases are part of the design.

6 REFERENCES

ALARY, J. A. & PARIAS, T. 2013. Method of manufacturing and using rod-shaped proppants and anti-flowback additives. Google Patents.

ALBERTY, M. W. & MCLEAN, M. R. A physical model for stress cages. SPE paper 90493 presented at the SPE Annual Technical Conference and Exhibition held in Houston, Texas, 26-29 September 2004. 2004.

ALGADI, O., FILYUKOV, R. & LUNA, D. 2014. Multistage hydraulic fracturing using coiled tubing-activated frac sleeves: case study from the Permian basin. SPE paper 170821 presented at the SPE Annual Technical Conference and Exhibition held in Amsterdam, The Netherlands, 27-29 October 2014.

ANDREWS, W. H. 1987. Bauxite proppant. Google Patents.

ARTHUR, J. D., BOHM, B. K., COUGHLIN, B. J., LAYNE, M. A. & CORNUE, D. 2009. Evaluating the Environmental Implications of Hydraulic Fracturing in Shale Gas Reservoirs. Society of Petroleum Engineers.

ASTON, M. S., ALBERTY, M. W., DUNCUM, S., BRUTON, J. R., FRIEDHEIM, J. E. & SANDERS, M. W. 2007. A new treatment for wellbore strengthening in shale. SPE paper 110713 presented at the 2007 SPE Annual Technical Conference and Exhibition held in Anaheim, California, U.S.A., 11-14 November 2007.

ASTON, M. S., ALBERTY, M. W., MCLEAN, M. R., DE JONG, H. J. & ARMAGOST, K. 2004. Drilling fluids for wellbore strengthening. . *In:* 87130, I. S. P. (ed.) *IADC/SPE Drilling Conference held in Dallas, Texas, U.S.A., 2-4 March 2004.*

BARTON, S., BAEZ, F. & ALALI, A. 2011. Drilling performance improvements in gas shale plays using a novel Drilling Agitator Device. SPE paper 144416 presented at the SPE North American Unconventional Gas Conference and Exhibition held in The Woodlands, Texas, USA, 14-16 June 2016.

BEHARIE, C., FRANCIS, S. & ØVESTAD, K. H. 2015. Resin: An Alternative Barrier Solution Material. Society of Petroleum Engineers.

BELLARBY, J. 2009. Developments in Petroleum Science, Well Completion Design.

BLAIR, C. C., CHANG, K. T., TREYBIG, D. S. & GERKEN, K. S. 2004. Use of dispersion polymers as friction reducers in aqueous fracturing fluids. Google Patents.

BOOTHE, J. E., MARTIN, F. D. & SHARPE, J. A. J. 1975. Friction reducing compounds for use in hydraulic fracturing fluids. Google Patents.

BORISOV, A. S., HUSEIN, M. & HARELAND, G. 2015. A field application of nanoparticle-based invert emulsion drilling fluids. *Journal of Nanoparticle Research*, 17.

BOSMA, M. G., CORNELISSEN, E., DIMITRIADIS, K., PETERS, M. & WORRALL, R. 2004. In-situ casting of well equipment. Google Patents.

BOSMA, M. G. R., CORNELISSEN, E. K. & SCHWING, A. 2001. Method for plugging a well with a resin. Google Patents.

BOURNE, H. M. & READ, P. A. 1999. Well treatment. Google Patents.

BRZYCKI, E. 2016. *Explore Shale* [Online]. Available: http://exploreshale.org/.
BULLEN, R. S. & LILLIES, A. T. 1983. Carbon dioxide fracturing process and apparatus. Google Patents.
CANNAN, C., LIENG, T., JOHNSON, D. E. & CONNER, M. 2015. Compositions and methods for use of proppant surface chemistry to improve proppant consolidation and flowback control. Google Patents.
CARPENTER, R. B., GONZALEZ, M. E., GRANBERRY, V. & BECKER, T. E. 2004. Remediating Sustained Casing Pressure by Forming a Downhole Annular Seal with Low-Melt-Point Eutectic Metal. Society of Petroleum Engineers.
CHEN, Z. Y., MOH, T. C., PHAN, V. C., LI, W., LIU, D., WANG, R. G., LIM, J. M., LI, W. J. & HUANG, B. 2015. Drilling evolution in Changning shale gas block of Central China. SPE paper 176141 presented at the SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition held in Nusa Dua, Bali, Indonesia, 20-22 October 2015.
CONTRERAS, O., HARELAND, G., HUSEIN, M., NYGAARD, R. & ALSABA, M. Experimental investigation on wellbore strengthening in shales by means of nanoparticle-based drilling fluids. Proceedings - SPE Annual Technical Conference and Exhibition, 2014. 193-208.
DAVIES, R. J., ALMOND, S., WARD, R. S., JACKSON, R. B., ADAMS, C., WORRALL, F., HERRINGSHAW, L. G., GLUYAS, J. G. & WHITEHEAD, M. A. 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. *Marine and Petroleum Geology,* 56**,** 239-254.
DEYSARKAR, A. K., VASUT, D., DADOO, A. P. & KASHYAP, B. 2011. High performance guar for hydraulic fracturing and other applications. Google Patents.
DUENCKEL, R., CONNER, M., CANNAN, C., CADY, D., LEASURE, J., LIENG, T., ROPER, T. & READ, P. A. 2014. Composition and method for hydraulic fracturing and evaluation and diagnostics of hydraulic fractures using infused porous ceramic proppant. Google Patents.
ELDRED, B. T., WILSON, B. A., GARDINIER, C. F. & DUENCKEL, R. J. 2013. Proppant Particles Formed From Slurry Droplets and Method of Use. Google Patents.
FINK, J. 2012. Petroleum Engineer's Guide to Oil Field Chemicals and Fluids.
FREEMAN, E. R., ABEL, J. C., KIM, C. M. & HEINRICH, C. 1983. A Stimulation Technique Using Only Nitrogen.
FROSELL, T. J., SEVADJIAN , E. E., FRIPP, M. L. & ECHOLS, R. H. 2013. Erosion reduction in subterranean wells. Google Patents.
GARRETT, J., LEROUGE, J. & TAYLOR, M. 2005. Well abandonment plug. Google Patents.
GAWEL, K., LAVROV, A. & TORSÆTER, M. 2015. Shale gas well drilling, completion, production and abandonment operations (Report 5.1). *In:* H2020 PROJECT: M4SHALEGAS - MEASURING, M., MITIGATING, MANAGING THE ENVIRONMENTAL IMPACT OF SHALE GAS (HTTP://WWW.M4SHALEGAS.EU/DOWNLOADS/M4SHALEGAS%20-%20D5.1%20-

%20REVIEW%20OF%20SHALE%20GAS%20DRILLING,%20COMPLETION%20AND%20PRODUCTION%20-%20NOV.%202015.PDF) (ed.).
GRAHAM, H. L. & KIEL, O. M. 1970. Method of propping fractures with ceramic particles. Google Patents.
HOLCOMB, D. L., WASAN, D. T. & NIKOLOV, A. D. 2010. Method for Intervention Operations in Subsurface Hydrocarbon Formations. Google Patents.
HOLT, R. M., GHEIBI, S. & LAVROV, A. 2016. Where does the stress path lead? Irreversibility and hysteresis in reservoir geomechanics. ARMA paper 16-496 prepared for presentation at the 50th US Rock Mechanics / Geomechanics Symposium, Houston, Texas, USA, 26-29 June 2016.
HOWE, S. C., CANNAN, C. & ROPER, T. 2016. Methods and systems for infusing porous ceramic proppant with a chemical treatment agent. Google Patents.
HUMMES, O., BOND, P., JONES, A., SYMONS, W., BISHOP, M., SERDY, A., POKROVSKY, S. & POLITO, N. 2012. Using advanced drilling technology to enable well factory concept in the Marcellus shale. IADC/SPE paper 151466 presented at the 2012 IADC/SPE Drilling Conference and Exhibition held in San Diego, California, USA, 6-8 March 2012.
HUSEIN, M. M., ZAKARIA, M. F. & HARELAND, G. 2013. Novel nanoparticle-containing drilling fluids to mitigate fluid loss. Google Patents.
HUSSAIN, H., MCDANIEL, R. R. & CALLANAN, M. J. 1997. Proppants with fiber reinforced resin coatings. Google Patents.
IOGCC, G. 2016. *Frac Focus Chemical Disclosure Registry* [Online]. Ground Water Protection Council and International Oil & Gas Compact Commission. Available: https://fracfocus.org.
JONES, C. K. & TAYLOR, G. N. 2000. Gelling agent for hydrocarbon liquid and method of use. Google Patents.
KACHNIK, J. L. 1987. Durable, high-strength proppant and method for forming same. Google Patents.
KANIA, D., YUNUS, R., OMAR, R., ABDUL RASHID, S. & MOHAMAD JAN, B. 2015. A review of biolubricants in drilling fluids: Recent research, performance, and applications. *Journal of Petroleum Science and Engineering,* 135**,** 177-184.
KAUFMAN, P. B. & BECKER, H. L. 2009. Porous composites containing hydrocarbon-soluble well treatment agents and methods for using the same. Google Patents.
KESAVAN, S., NEYRAVAL, P. & BOUKHELIFA, A. 2007. Fast hydrating guar powder, method of preparation, and methods of use. Google Patents.
KULKARNI, S. V. & HINA, D. S. 1999. A Novel Lightweight Cement Slurry And Placement Technique for Covering Weak Shale in Appalachian Basin. Society of Petroleum Engineers.
KUMAR, M., KOCZO, K., SPYROPOULOS, K., TERRACINA, J., LEATHERMAN, M. D., FALK, B. & FALANA, O. M. 2014. Friction reducer compositions comprising an acrylamide polymer and a silicon polyether. Google Patents.
LAVROV, A. 2016a. Dynamics of Stresses and Fractures in Reservoir and Cap Rock under Production and Injection. *Energy Procedia,* 86**,** 381-390.
LAVROV, A. 2016b. Fracture permeability under normal stress: a fully computational approach. *Journal of Petroleum Exploration and Production Technology***,** 1-14.

LAVROV, A. 2016c. *Lost Circulation: Mechanisms and Solutions,* Oxford, Elsevier.
LAVROV, A., LARSEN, I. & BAUER, A. 2016. Numerical modeling of extended leak-off test with a pre-existing fracture. *Rock Mechanics and Rock Engineering,* 49**,** 1359-1368.
LAVROV, A., LARSEN, I., HOLT, R. M., BAUER, A. & PRADHAN, S. 2014. Hybrid FEM/DEM simulation of hydraulic fracturing in naturally-fractured reservoirs. ARMA paper 14-7107. *the 48th US Rock Mechanics / Geomechanics Symposium held in Minneapolis, MN, USA, 1-4 June 2014.*
LUND, H., TORSÆTER, M. & MUNKEJORD, S. T. 2016. Study of Thermal Variations in Wells During Carbon Dioxide Injection.
MAMMADOV, E., OSAYANDE, N., BREUER, J. & AL-HASHMY, W. 2015. Predicting and optimizing ROP in competent shale by utilizing MPD technology. SPE paper 174805 presented at the SPE Annual Technical Conference and Exhibition held in Houston, Texas, USA, 28-30 September 2015.
MCDONALD, M. A novel potassium silicate for use in drilling fluids targeting unconventional hydrocarbons. Society of Petroleum Engineers - SPE Canadian Unconventional Resources Conference 2012, CURC 2012, 2012. 290-298.
MIDDLETON, R. S., CAREY, J. W., CURRIER, R. P., HYMAN, J. D., KANG, Q., KARRA, S., JIMÉNEZ-MARTÍNEZ, J., PORTER, M. L. & VISWANATHAN, H. S. 2015. Shale gas and non-aqueous fracturing fluids: Opportunities and challenges for supercritical CO2. *Applied Energy,* 147**,** 500-509.
MUESSIG, S., ESCHENMANN, P., WILDHACK, S. & LESNIAK, C. 2011. Ceramic Screens, an Innovative Milestone in Sand Control. Society of Petroleum Engineers.
NORMAN, L. R. & LARAMAY, S. B. 1994. Encapsulated breakers and method for use in treating subterranean formations. Google Patents.
PALISCH, T. T., VINCENT, M. & HANDREN, P. J. 2010. Slickwater Fracturing: Food for Thought.
PAVLOCK, C., TENNISON, B., THOMPSON, J. G. & DARBE, R. P. 2012. Latex-Based Cement Design: Meeting the Challenges of the Haynesville Shale. Society of Petroleum Engineers.
PENNY, G. S., CRAFTON, J. W., CHAMPAGNE, L. M. & ZELENEV, A. S. 2012. Proppant and Fluid Selection To Optimize Performance of Horizontal Shale Fracs. Society of Petroleum Engineers.
PHAN, X. K. & XIE, M. 2015. Sealant material for subterranean wells. Google Patents.
REHM, B., SCHUBERT, J., HAGHSHENAS, A., PAKNEJAD, A. S. & HUGHES, J. (eds.) 2008. *Managed pressure drilling,* Houston: Gulf Publishing Company.
ROGALA, A., KRZYSIEK, J., BERNACIAK, M. & HUPKA, J. 2013. Non-aqueous fracturing technologies for shale gas recovery. *Physicochemical Problems of Mineral Processing,* 49**,** 313-321.
ROY, S. & COOPER, G. A. 1993. Prevention of Bit Balling in Shales: Some Preliminary Results.
SAN-MIGUEL, L., DICKSON, K. R., FUSS, T. & STEPHENS, W. T. 2012. High strength proppants. Google Patents.

SANCHEZ, A., BROWN, C. F. & ADAMS, W. 2012. Casing centralization in horizontal and extended reach wells. SPE paper 150317 presented at the SPE/EAGE European Unconventional Resources Conference and Exhibition held in Vienne, Austria, 20-22 March 2012.

SANDERS, M., FELLING, K., THOMSON, S., WRIGHT, S. & THORPE, R. 2016. Dry Polyacrylamide Friction Reducer: Not Just for Slick Water. Society of Petroleum Engineers.

SCHUH, F. J., CORAGLIOTTI, A., DICICCO, C. D., NAGATANI, R. A., REA, A., CARLTON, T., JOHNSON, P. & NOBLE, R. 2014. Characterization of Encapsulated Oil as an Additive to Water-Based Drilling Fluids: Operational Improvements in Lubricity, Drag, and ROP. Society of Petroleum Engineers.

SHARMA, M. M. 2014. Improved Drilling and Fracturing Fluids for Shale Gas Reservoirs. *RPSEA Report 09122-41.FINAL*.

SKALLE, P., BACKE, K. R., LYOMOV, S. K., KILAAS, L., DYRLI, A. D. & SVEEN, J. 1999. Microbeads as Lubricant in Drilling Muds Using a Modified Lubricity Tester. Society of Petroleum Engineers.

SLAGLE, K. A. & SMITH, D. K. 1963. Salt Cement for Shale and Bentonitic Sands.

SMITH, H. D. 2014. Lithology and borehole condition independent methods for locating tagged proppant in induced subterranean formation fractures. Google Patents.

SMITH, L., MODY, F. K., HALE, A. & ROMSLO, N. 1996. Successful Field Application of an Electro-Negative 'Coating' to Reduce Bit Balling Tendencies in Water Based Mud. Society of Petroleum Engineers.

SORIC, T., MARINESCU, P. & HUELKE, R. 2004. Silicate-Based Drilling Fluids Deliver Optimum Shale Inhibition and Wellbore Stability. Society of Petroleum Engineers.

STIM, E. 2015. *No Water - No Chemicals - Higher Efficiency: Developing and implementing breakthrough extraction technologies for unconventional resources* [Online]. eCORP Stimulation Technologies LLC. Available: http://www.ecorpstim.com/.

TOMPKINS, R., SMITH, N., WELLHOEFER, B., YUYI, S., RHODES, B. & STIVERS, P. 2013. Factors affecting effective millout of multistage fracturing sleeves in horizontal wellbores. SPE paper 163899 presented at the SPE/ICoTA Coiled Tubing & Well Intervention Conference & Exhibition held in The Woodlands, Texas, USA, 26-27 March 2013.

VAN OORT, E., RIPLEY, D., WARD, I., CHAPMAN, J. W., WILLIAMSON, R. & ASTON, M. 1996. Silicate-Based Drilling Fluids: Competent, Cost-effective and Benign Solutions to Wellbore Stability Problems. Society of Petroleum Engineers.

VINCENT, M. C., MILLER, H. B., MILTON-TAYLER, D. & KAUFMAN, P. B. Erosion by proppant: A comparison of the erosivity of sand and ceramic proppants during slurry injection and flowback of proppant. Proceedings - SPE Annual Technical Conference and Exhibition, 2004. 3327-3343.

WEAVER, J. D., RICKMAN, R. D. & LUO, H. 2008. Fracture-Conductivity Loss Due to Geochemical Interactions Between Manmade Proppants and Formations. Society of Petroleum Engineers.

WIBOWO, H., GAUDETTE, S. L. & CARREJO, N. 2014. A more advanced multistage completion system for fracturing. IADC/SPE paper 170535 presented at the IADC/SPE Asia Pacific Drilling Technology Conference held in Bangkok, Thailand, 25-27 August 2014.

WILLIAMS, R. H., KHATRI, D. K., KEESE, R. F., LE ROY-DELAGE, S., ROYE, J. M., LEACH, D. L. R., PORCHERIE, O., ROTTLER, P. & RODRIGUEZ, J. 2011. Flexible, Expanding Cement System (FECS) Successfully Provides Zonal Isolation Across Marcellus Shale Gas Trends. Society of Petroleum Engineers.

WILLIAMS, S. M., CARLSEN, T., CONSTABLE, K. C. & GULDAHL, A. C. 2009. Identification and Qualification of Shale Annular Barriers Using Wireline Logs During Plug and Abandonment Operations. Society of Petroleum Engineers.

YUAN, F., BLANTON, E., CONVEY, B. & PALMER, C. 2013. Unlimited multistage frac completion system: a revolutionary ball-activated system with single size balls. SPE paper 166303 presented at the SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, USA, 30 September 2 October 2013.

ZOVEIDAVIANPOOR, M. & GHARIBI, A. 2015. Application of polymers for coating of proppant in hydraulic fracturing of subterraneous formations: A comprehensive review. *Journal of Natural Gas Science and Engineering,* 24**,** 197-209.