Addressing risks of hydraulic fracturing with novel drilling and stimulation technologies

Hongyuan Zhou[1], Jinghan Zhong[2], Germán Rodríguez-Pradilla[3], Leah Wilson[4], Linh Tran[5]

[1] Department of Civil Engineering, University of Toronto, Toronto, Ontario, Canada M5S 1A4; Tel.: +1 587-284-1357; hongyuan.zhou@mail.utoronto.ca

[2] Department of Civil Engineering, University of Toronto, Toronto, Ontario, Canada M5S 1A4; Tel.: +1 647-818-1939; jinghan.zhong@mail.utoronto.ca

[3] Department of Geoscience, University of Calgary, Calgary, Alberta, Canada T2N 1N4; Tel.: +1 587-215-9637; german.rodriguezprad@ucalgary.ca

[4] Department of Geoscience, University of Calgary, Calgary, Alberta, Canada T2N 1N4; Tel.: +1 403-336-0257; leah.wilson@ucalgary.ca

[5] Department of Economics, University of Calgary, Calgary, Alberta, Canada T2N 1N4; Tel.: +1 780-690-0806; linh.tran1@ucalgary.ca

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Abstract: Large scale commercial shale gas development was made possible through the advancement in hydraulic fracturing by combining horizontal drilling with multi-stage hydraulic fracturing. With the increase in hydraulic fracturing operations, occurrence of incidence concerning environment and public health and safety also increased. These concerns mainly focused on water and air quality, fresh water availability, well integrity, and induced seismicity. As a result, technologies in drilling and hydraulic fracturing discussed in this paper have been centred on addressing the concerns and reducing the risks and impacts of environmental and public health and safety. The seven drilling technologies mentioned focus on improving wellbore stability in different drilling environments which in turn can prevent environmental contaminations. Seven hydraulic fracturing technologies mentioned focus on replacing the usage of water and reducing resource requirements during hydraulic fracturing. This relieves pressure on water availability and minimizes the quantity of material exposed to the environment.

1.0 Introduction

Hydraulic fracturing (HF), is an unconventional well completion technique that involves injection of fluid and proppants into a target reservoir at high volume and pressures. This induces new and opens existing fractures to create a network of pathways for fluids to flow. HF has been used for a number of applications, such as, shale gas production, hydraulic pre-conditioning in mining, conventional oil and gas production, geothermal, and carbon sequestration (Adams and Rowe, 2013).

Since the breakthrough in shale gas production by combining horizontal drilling and multi-stage HF in the late 1990s, shale gas wells became longer, and the number of stages per well increased (CCA, 2014). This has raised public concerns about HF activities impacting the environment and public health and safety, to a point where half of the potential shale gas producing provinces in Canada have established moratoria (Winter et al., 2016). This paper addresses five major risks of HF and 14 drilling and stimulation technologies that can reduce the negative impacts on the environment, public health and safety.

2.0 Risks associated with HF

The main discussions of risks centred on environment, public health and safety are water quality, water requirement, well integrity, air pollution, and induced seismicity.

2.1 Water quality

The additives used in treatment during HF operations (Table 1) are the main sources for water contaminants. Other contaminants include methane migration from depth, and upbringing of chemicals existing in the target formation during flow back. These contaminants are introduced to surface and ground water in two ways: (1) surface spillage due to faulty facilities and accidents on site, and (2) migration through pathways created from existing and drilling induced fractures, and casing and cement leaks below the fresh groundwater zone (CCA 2014).

2.2 Water requirement

In unconventional oil and gas operations, the average volume of water used per well can range from 6,000 cubic metres (m^3) to 80,000m^3 (CCA, 2014). This volume constitutes 0.1-0.5% of the total water used in states/provinces (Long et al., 2015; Vidic et al., 2013), while locally this percentage increases to 10-40% (Jackson et al., 2014). Efforts in recycling of water used in HF, up to 90%, have been made to reduce water usage. Despite this, water usage still raise concerns, especially during drought seasons. The addition of water usage can further contribute to lowering of water level, which can potentially lead to destruction of natural habitats, deterioration of water quality, and land subsidence (Konikow, 2013).

2.3 Well integrity

Risks of well integrity failure exist throughout the lifetime of the well and after abandonment. Holes and defects in casing, improperly centralized casing installation, incomplete drilling fluid displacement, improper cement formulation, and autogenous cement shrinkage are all factors that endangers well integrity (Dusseault et al., 2000). Improper installation, cementation, and casing defects can result in uncemented space that create conduits for gas and fluid to escape (Figure 1). Cracking, deformation, and shrinkage of cement over time, reduce the strength of the seal around the well, creating additional pathways for fluids to migrate upward towards the surface (CCA, 2014). The migrated substances can escape into the groundwater and atmosphere posing environmental and health issues.

2.4 Air pollution

Risks of air pollution and greenhouse gas (GHG) emissions in HF stem from methane and chemical emissions. As described in Section 2.3, defective casings and cement create pathways in which fluid and gas can flow to the surface and escape into the atmosphere. Other sources of emissions can come from chemicals in flowback water (methane and volatile organic compounds), on-site conventional power generators, and gas flare (CCA, 2014). The substances released into the atmosphere deteriorate local air quality, contribute to global GHG impact, and endanger human health (Table 2).

2.5 Induced seismicity

Induced seismicity is generated from movement and fracturing of the reservoir rock as fluids are being injected at high pressures. The magnitude of the induced seismic events are typical not felt by most individuals (CCA, 2014). Risks of induced seismicity occur when the seismicity generated by fluid injection create sufficient ground movement that can damage buildings and disrupt public life (CCA, 2014). These seismicities are typically the result of the injected fluid diffusing into and destabilizing nearby major fault lines (CCA, 2014).

3.0 Technologies

Technologies presented can be categorized into drilling and stimulation technologies. The drilling technologies tackle challenges and reduce environmental impacts in various drilling environments. The stimulation technologies aim to reduce the quantity of water and other consumables used in HF.

3.1 Drilling technologies

3.1.1 Underbalanced drilling

Underbalanced drilling is a method of drilling where the fluid pressure inside the wellbore is less than the pore pressure in the formation. This is achieved by using drilling fluids consist of compressed gas (natural gas or air) and foam (Chen et al., 2006; Hannegan and Wanzer, 2003). The compressed air provides cooling to the drill bit, and creates less friction compared to liquid drilling fluids. This speeds up the penetration rate, reduces drilling costs, and minimizes formation damage (Nakagawa et al., 1999). At the reservoir level, the compressed air does not seal pore throats which results in better production rates (Chen et al., 2006). In depleted zones, highly fractured and porous formations, it prevents severe loss in circulation of drilling fluid (Chen et al., 2006).

3.1.2 Percussion/hammer drilling

Percussion drilling uses repeated impact load to help crush the rock, this impact load is greater than the load exerted on the rock in rotary drilling which is a benefit while drilling in hard formations. As a result of this repeated impact, the contact time is 2% of the operational time, which decreases the abrasive wear on the drilling tool (Melamed et al., 2000). Percussion drilling is self-sufficient and self-sustained as the cycle of forward-stroke (impact) and back-stroke (rebound) can be operated in resonance (Melamed et al., 2000).

3.1.3 Radial drilling

Radial drilling is a technique that drills 25-30 millimetres (mm) diameter and 50-100 meters (m) long laterals in directions perpendicular to the well casing to reduce pressure drop near the wellbore and improve drainage radius and flow profile (Figure 2) (Buset et al., 2001). Drilled laterals have controlled directions, as opposed to hydraulic fractures which are dictated by the hydro-geomechanical properties of the reservoir, thus provide a safer mean of increasing the productivities of reservoirs in sensitive areas such as near the cap rock, water table, faults, and depleted zones (Buset et al., 2001). Radial drilling can be done using conventional rotary methods, jet-impact from injection of fluids at high pressures, and plasma channel to induce electrical breakdown of rock formations (Buset et al., 2001; Guo et al., 2009; Timoshkin et al., 2004).

3.1.4 Drilling with liner/casing

While drilling in unstable and sensitive rock formations, such as depleted reservoirs, swelling shale, and high pressure zones, the risk of wellbore instability is high. Fast installation of casing strings is critical in preventing fracturing, closure, blowout, and collapse of the wellbore. Drilling with liner technology offers the ability to install the liner without pulling out the bottom-hole-assembly by having specialized liner trailing behind or implementing a displaceable drillable bit (Figure 3) (Jianhua et al., 2010; Torsvoll et al., 2010). When the target depth is reached, the liner would have already been installed in the wellbore providing support against the surrounding rock (Jianhua et al., 2010).

3.1.5 Monodiameter drilling liner

In conventional standard telescoping casing installation, the diameter of each casing is successively reduced creating a tapering of casing size. The monodiameter drilling liner uses solid expandable tubular technology to create a continuous diameter of casing in the wellbore thus reduces the tapering effect (Figure 4) (Williams et al., 2003). Having less of a tapering effect reduces the amount of drilling fluid and cement volume, casing weight, and cutting disposal, and as a result, reducing environmental impacts by lowering the chances and quantities of hazardous chemicals and waste exposed to the environment (Williams et al., 2003).

3.1.6 Non-invasive drilling fluids

Non-invasive drilling fluids is a mixture of polymer, water, and can decrease the risks of contamination during drilling by limiting the fluid invasion (Reid and Santos, 2003). In depleted zones and highly fractured and permeable rock formations where drilling fluid can readily escape into the formations, chances of fluid loss and contamination of near by water sources is relatively high. Operated in overbalanced drilling conditions where the mud weight is greater than pore pressure in the wellbore, non-invasive drilling fluid is pushed into the rock and the polymer molecules plug and seal the pore throats creating a barrier against further fluid infiltration into the rock formation (Reid and Santos, 2003).

3.1.7 Invert emulsion fluid

In water sensitive rock formations, such as saline saturated formations, swelling rocks, and highly fractured zones, use of water based drilling fluids can cause swelling, washout, and other instabilities in the rock near the wellbore. Oil based fluids can be used to eliminate the effect of water on the sensitive and highly permeable formations. However, a different fluid is often used to prepare wellbore for production, proper cleanup of the wellbore is necessary to ensure adequate cementing. Invert emulsion fluid, with an acid-base chemical switch, can convert from a water-in-oil emulsion (invert) to oil-in-water emulsion (regular) (Patel, 1998). The invert fluid can be used during the drilling process to minimize wellbore instability similar to oil based fluids, and regular fluid can be used during the completion stage for cuttings and filter cake cleanup for better cementing (Patel, 1998). This eliminates the need for having different types of fluid on site, and limits the possibility and extent of environmental contamination (Patel, 1998).

3.2 Stimulation technologies

3.2.1 Gas stimulation

Gaseous injection fluids, commonly carbon dioxide (CO_2) and nitrogen (N_2) (Li et al., 2015; Rogala et al., 2013), eliminate the use of water in the stimulation process. Gases do not plug pore throats and are easier to remove, therefore production and cleanup processes are improved (Zhenyun et al., 2014). Production can be further improved if CO_2 is used, as CO_2 readily replaces adsorbed natural gas in shale (Middleton et al., 2014). However, due to the low viscosities associated with gases, their proppant carrying capabilities are problematic, and proppants carried in high velocity gas stream can induce erosion (Rogala et al., 2013). Transport and storage of gases require pressurized containers which can be a concern for safety (Rogala et al., 2013).

3.2.2 Liquid CO_2

CO_2 is liquid at -34.5 degree Celsius (°C) and 1.4 MegaPascals (MPa). It is used as a carrier fluid for proppant during stimulation instead of water due to its high viscosity at approximately 5 centipoise (cP) (Rogala et al., 2013). In the reservoir, liquid CO_2 turns into gas, which has high mobility resulting in fast and complete flowback, and can displace adsorbed methane in shales

(Liu et al., 2014). Transport and storage of liquid CO_2 can be an issue considering the low temperature and potential greenhouse effect (Rogala et al., 2013).

3.2.3 Supercritical CO_2

At temperature and pressures beyond 31.26C° and 7.38MPa respectively, CO_2 reaches its critical state, where it exhibits properties of both gas and liquid (Liu et al., 2014). Supercritical CO_2 has viscosity like gas (~0.03cP) and density similar to liquids (0.2-1 grams per millilitre [g/mL]), and zero surface tension (Shen et al., 2011). Due to the special properties of supercritical CO_2, it has high diffusion capacity, no capillary forces, and low friction (Liu et al., 2014). Like gaseous injection fluids, supercritical CO_2 also has low proppant carrying capacity (Zhou et al., 2016).

3.2.4 Liquefied petroleum gas (LPG)

Petroleum gas such as propane, butane, and methanol is compressed to liquid form and injected in the reservoir to enhance production (Hughson Tudor et al., 2009). LPG is often gelled to allow better proppant transport (Rogala et al., 2013). In the reservoir as the pressure drops, LPG changes to gas and can freely flow through fractures, resulting in rapid cleanup and little to no fluid loss (Leblanc et al., 2011). Disadvantages of LPG include the explosive nature of natural gas, specialized transport and storage equipment, and the returned gas needs to be liquefied before being injected again (Rogala et al., 2013).

3.2.5 High energy gas fracturing (HEGF)

HEGF uses high pressure gases produced from deflagration, as opposed to detonation, of propellant to dynamically initiate and propagate fractures in reservoir (Warpinski et al., 1979). In the dynamic process of formation breakdown, radial fractures in all directions regardless of in-situ stress orientations are produced, thus creating greater permeability near the wellbore (Figure 5)

(Jaimes et al., 2012). Due to the short fractures (0.3-0.5m), it is often used to pre-condition the wellbore (Rogala et al., 2013). Propellant is consumed in the deflagration process which leaves no solid waste. Careful storage and handling of propellant on the surface is necessary as it can ignite dangerously (Jaimes et al., 2012; Yang et al., 1992).

3.2.6 Foamed/aerated fluids

Foam/aerated fluids reduce the quantity of liquid used in HF by exchanging part of liquid with gas, typically nitrogen. Mixture of liquid, gas, surfactants, and stabilizers provide a wide range of viscosities depending on the foam ratio. Foam / aerated fluid reduce swelling effects in water-sensitive reservoirs and permeability damage due to water trapped in fractures, however, it is not possible to completely eliminate those issues (Rogala et al., 2013).

3.2.7 Impulse sand fracturing

Impulse sand fracturing is a technique that injects proppant/sand into the reservoir in pulses, creating open-flow channels to increase the capacity of fracture conductivity (Figure 6) (Gillard et al., 2010; Qian et al., 2015; Tinsley and Williams, 1975). To prevent proppant pulses from dispersing while being transported in the reservoir, fibrous materials are added to give structure to the proppant pulses. This ensures that the channels stay open (Gillard et al., 2010).

In a pilot test in Sulige Gasfield, Ordos Basin, the application of impulse sand fracturing used 28.3% less proppant, and increased post-fracturing daily output by 26.8% (Qian et al., 2015).

4.0 Conclusions/key points

Risks of HF are centred on water and air contamination, water usage, well integrity, and induced seismicity. Technologies advances in drilling and stimulation can address some of the aforementioned risks. Drilling technologies summarized in this paper provide means of safely targeting sensitive and weak formations, increase well integrity and consequently reduce water contamination and environmental impact. Stimulation technologies discussed either replaces water with other fluids or reduce water and proppant usage while maintaining acceptable production. This results in relieving regional water demand, and reducing the occurrence and impact of environmental contamination.

Technologies discussed can be considered "exotic" and cost associated with implementing such technologies can be comparatively high. It is not within the scope of this study to consider the cost of each technologies mentioned. However, it is recognized that cost is a decision making variable in the holistic assessment of appropriate implementation of HF technologies. As technology in drilling and stimulation continue to advance, their efficiency and cost effectiveness are expected to increase, and environmental impact of HF can be further reduced.

5.0 Tables and figures

Table 1. Additives used in HF treatment (CCA, 2014).

Additive type	**Purpose and description**
Water	Fresh water
Proppant	Maintains fracture openings
Friction reducer	Reduces friction pressure, decreases the necessary pump energy and subsequent air emissions
Disinfectant (Biocide)	Inhibits the growth of bacteria that can destroy gelled fracture fluids or produce methane-contaminating gases
Surfactant	Modifies surface and interfacial tension and breaks or prevents emulsions, aiding fluid recovery
Crosslinker	Used for gels that can be either linear or cross-linked. The cross-linked gels have the advantage of higher viscosities that do not break down quickly
Scale inhibitor	Prevents mineral deposits that can plug the formation
Corrosion inhibitor	Prevents pipes and connectors rusting
Breaker	Introduced at the end of a fracturing treatment to reduce viscosity and release proppants into the fractures and increase the recovery of the fracturing fluid

Clay stabilization	Prevents the swelling of expandable clay minerals, which can block fractures
Iron control	Prevents the precipitation of iron oxides
Gelling agent	Increases the viscosity of the fracturing fluid to carry more proppant into fractures
pH adjusting agent	Adjusts/controls the pH to enhance the effectiveness of other additives

Table 2. Air emission and concerns in HF operations (CCA, 2014).

Substance	**Source**	**Concern**
NOx, SOx, VOCs	Diesel engines, natural gas compressors, fluid evaporation	Ozone precursors (smog) impacts on human health (e.g., lung disease)
BTEX and other HAP	Venting, fugitive emissions, flaring, fluid evaporation	Potential impacts on nervous system
Particulates	Diesel engines, flaring	Lung diseases (air quality)
Methane	Venting, fugitive emissions	GHG emissions
CO_2	Diesel aggregates, flaring, fugitive emissions	GHG emissions

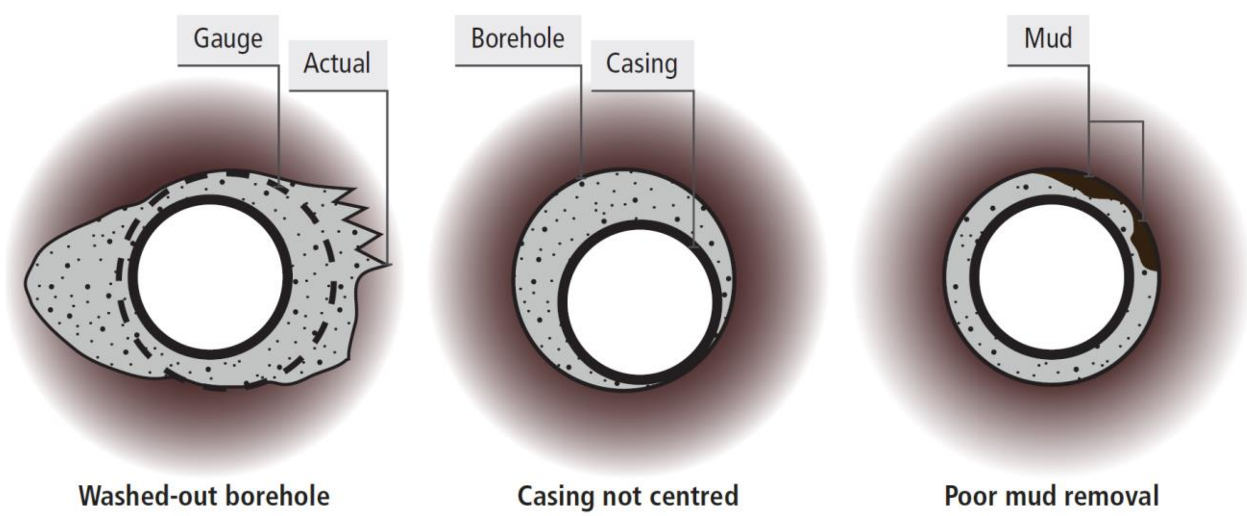

Figure 1. Cementing issues (CCA, 2014).

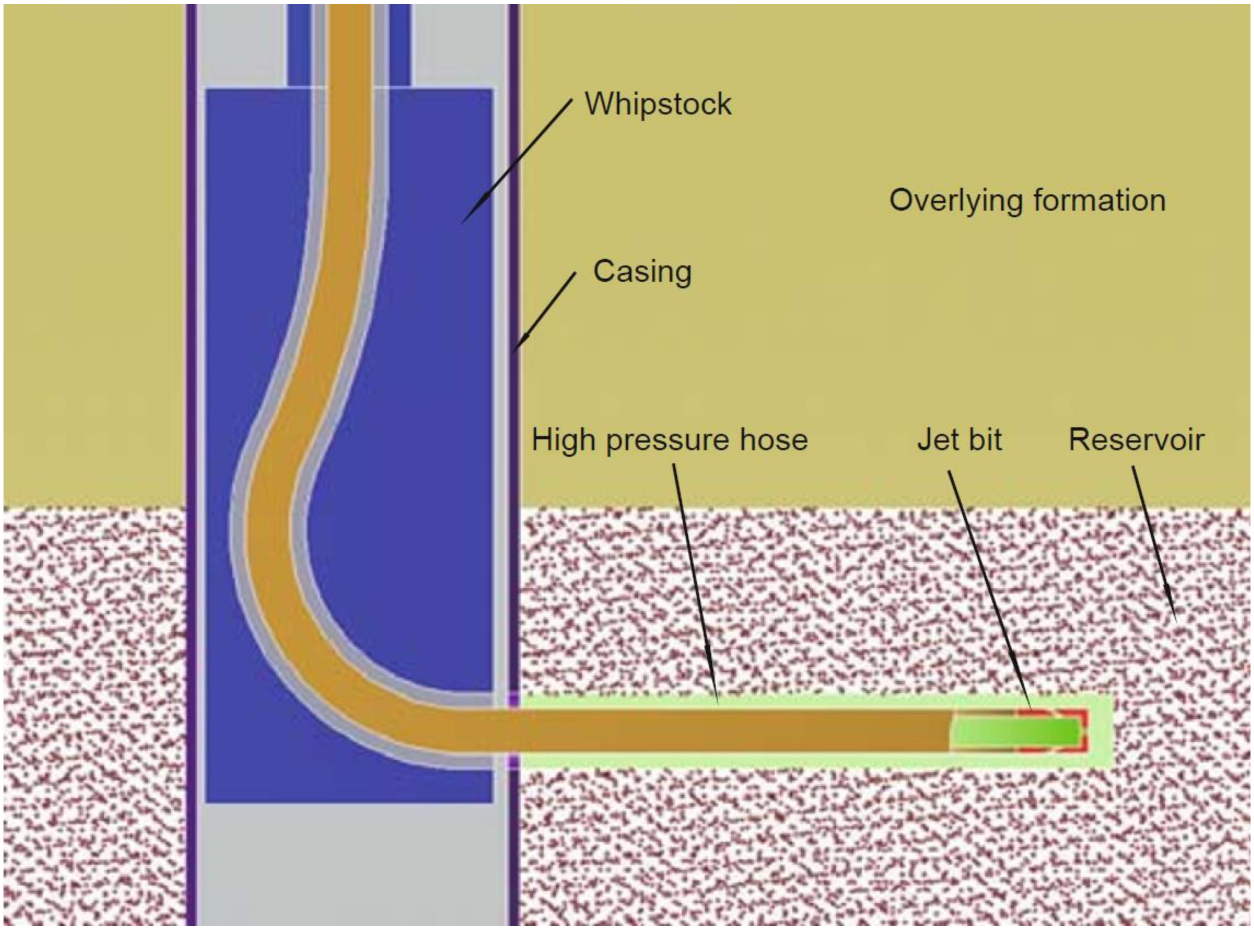

Figure 2. Radial drilling schematic (jet-impact) (Guo et al., 2009).

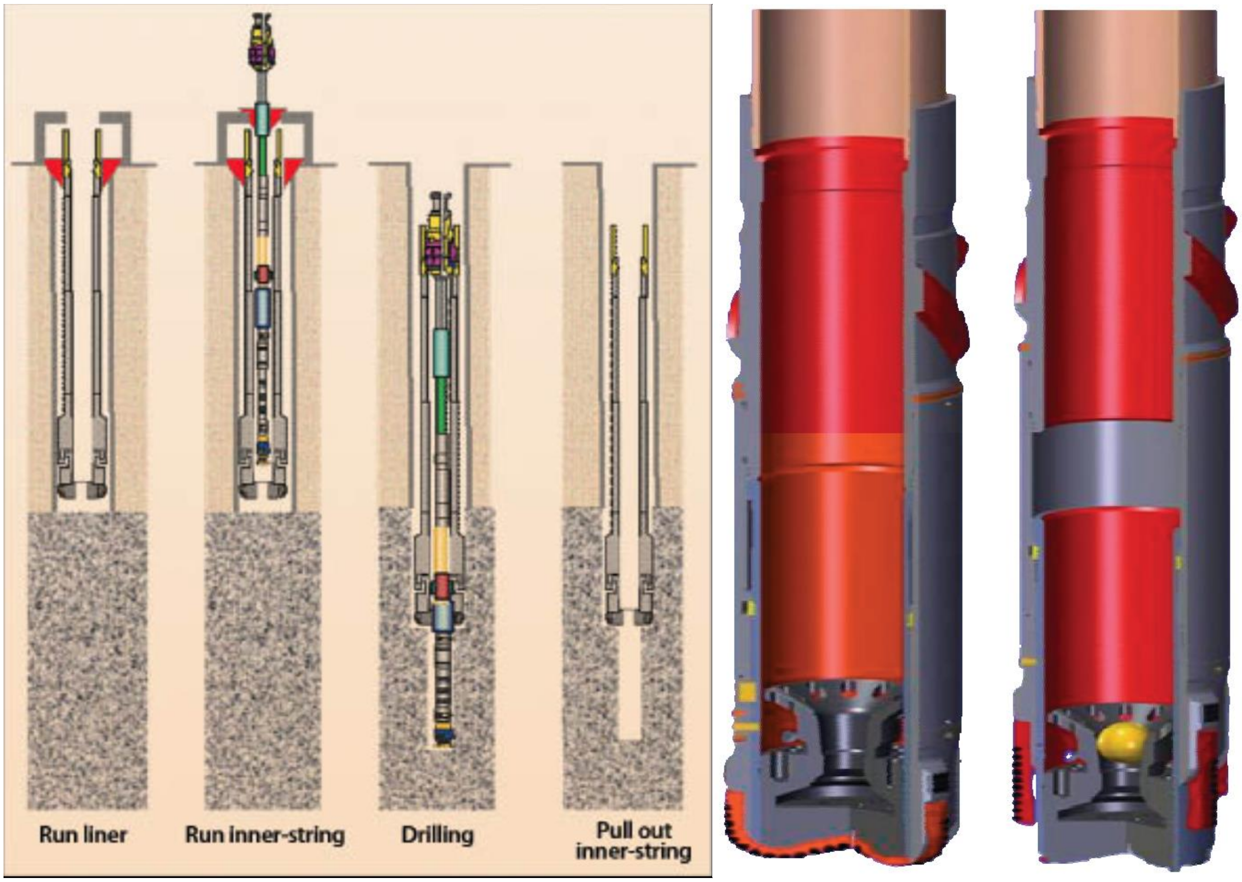

Figure 3. Drilling with liner technology; left: trailing liner (Torsvoll et al., 2010), right: displaceable drillable liner (Jianhua et al., 2010).

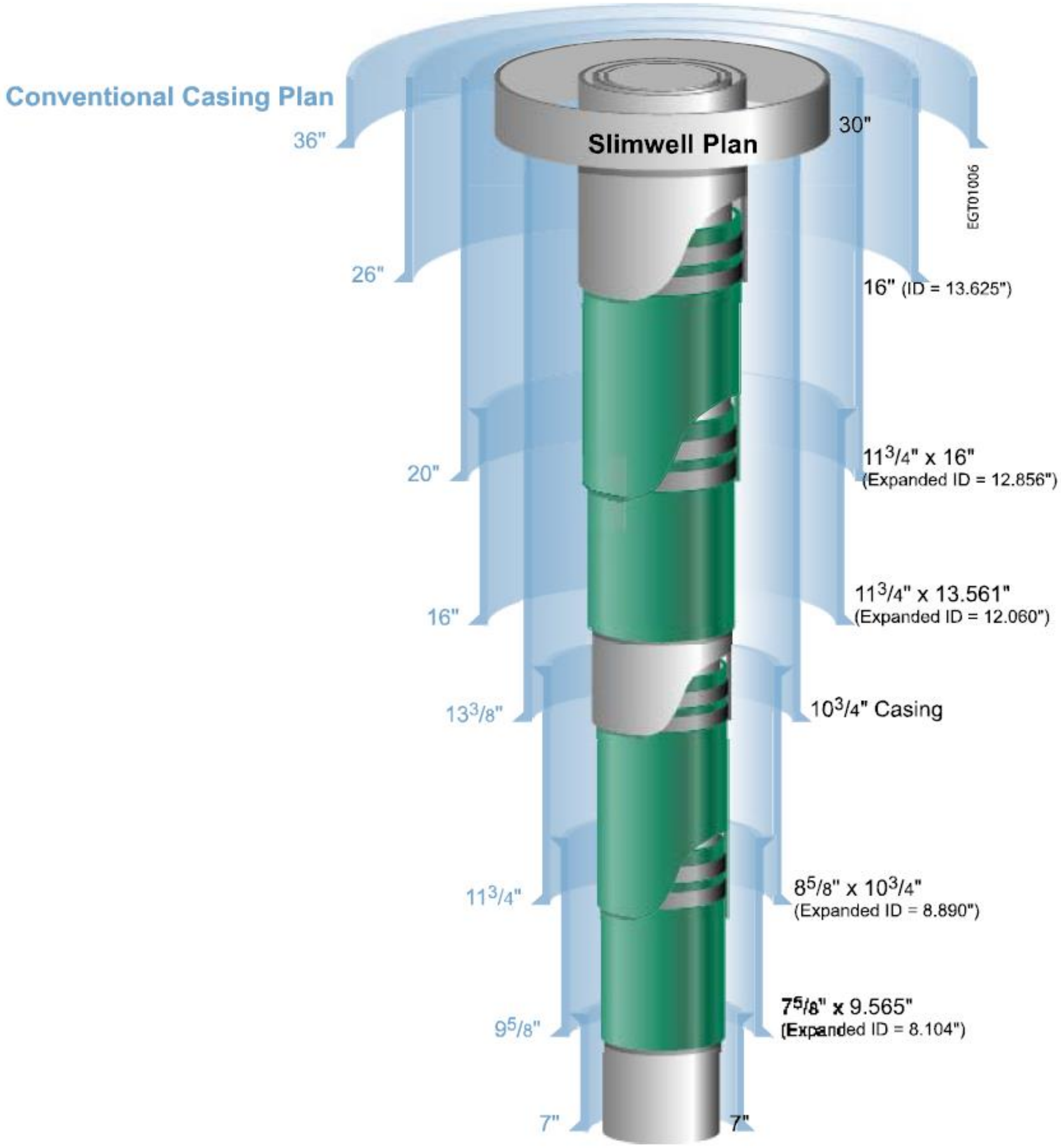

Figure 4. Monodiameter liner (Williams et al., 2003).

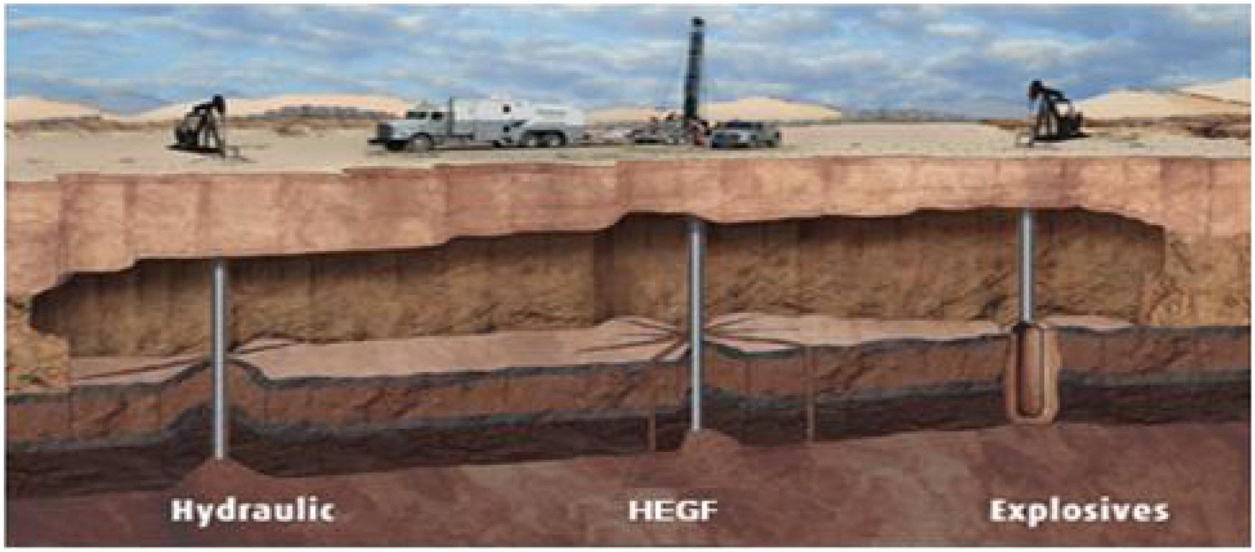

Figure 5. HEGF fracture pattern (Jaimes et al., 2012).

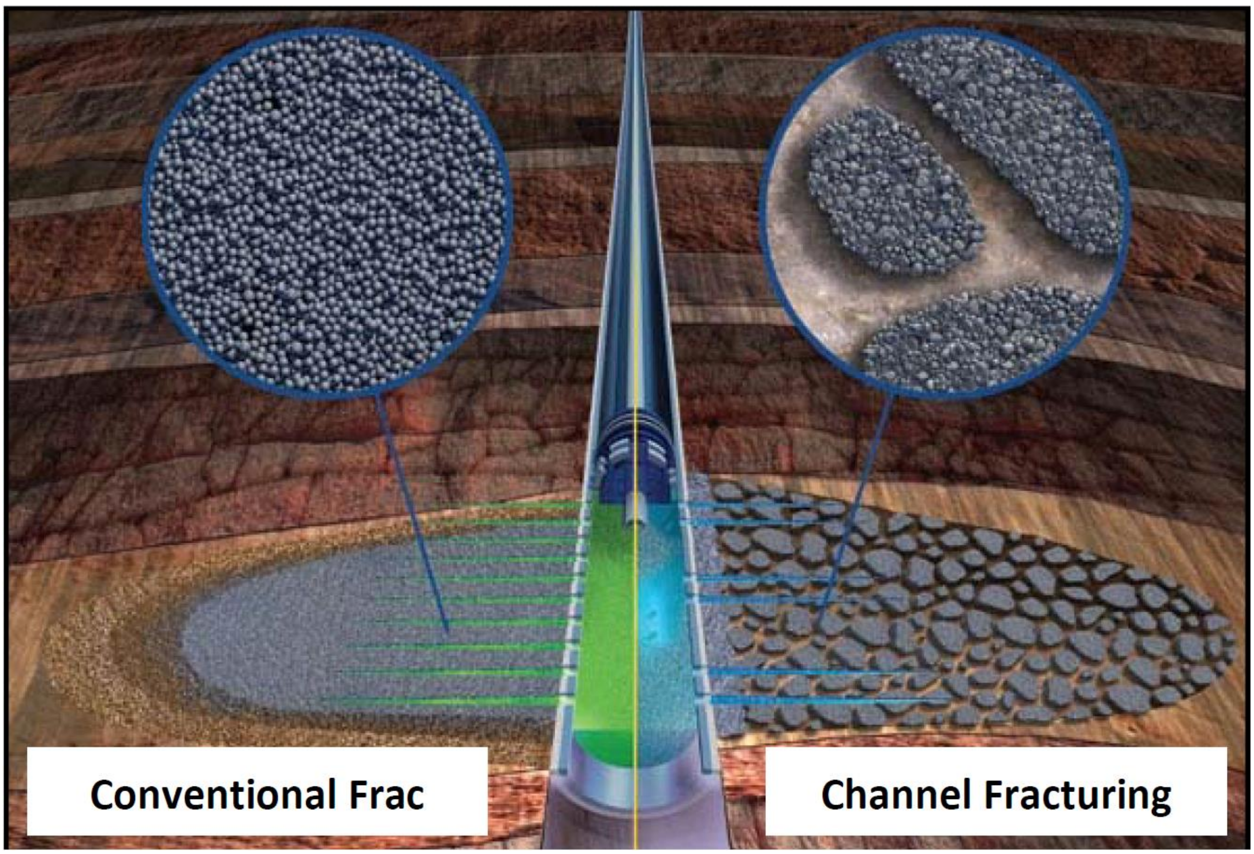

Figure 6. Impulse sand fracturing (Gillard et al., 2010).

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