



Hydraulic Fracturing of Rock Formations Part 1: Introduction and Applications



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This is the first of a two-part series of articles on the hydraulic fracturing of rock, also known as fracking. This is a technology that everyone has an opinion on, but few take the trouble to understand what it's all about.

The two parts are as follows:

- Part 1: Introduction and Applications; and
- Part 2: Fracking for Coal-bed Methane Recovery.

In this first article, the concept of fracking is introduced, different applications are discussed, the chemicals and additives used in fracking fluid are described, and a method to classify fracking according to severity and impact is considered.

Introduction

I have been planning an article on the hydraulic stimulation of gas wells in coal beds for a long time. Hydraulic stimulation improves the delivery of coal-bed methane (CBM) from such wells. The more I read about hydraulic stimulation, or CBM well conditioning, the more I realised that one first must understand hydraulic fracturing, or fracking. Hence this two-part series of articles.

Hydraulic fracturing involves pumping water and sand at high pressure into gas or oil-bearing rock to fracture it and open pathways for the gas or oil to escape to the receiving well. This is far removed from the mid-nineteenth century practice of 'shooting' a well, which used explosives instead of water, but the principle is the same. Drillers freed-up non-productive wells by creating underground explosions to loosen rock so that gas or oil could move freely. Fortunately, modern day fracking is far safer, controlled, predictable and environmentally friendly.

In this first article, I introduce the art of fracking, discuss different applications, describe the chemicals and additives used in fracking fluid, and consider a method to classify fracking based on application, severity and impact.

History of fracking

The first recorded case of fracking was in 1857 when Preston Barmore lowered gunpowder into a well at Canadaway Creek, NY, and dropped a red-hot iron down a tube, resulting in an explosion that fractured the rock and increased the flow of gas from the well (Morton, 2013). Undoubtedly spectacular, but definitely not controlled or safe...

In 1866, Edward Roberts registered a patent, for exploding torpedoes in artesian wells. This fracking method was implemented by packing a torpedo in an iron case that contained 15-20 pounds of powder. The case was then lowered into the oil well, at a spot closest to the oil source. The borehole was filled with water to increase the effect of the blast and the torpedo was detonated from the surface by connecting wires. This increased oil from the wells by up to 1200% within a week of the blast (Manfreda, 2015)

There was little innovation in fracking technology until the 1930s, when drillers started using acid to make wells more resistant to closing, and thereby increasing productivity. However, hydraulic fracturing of rock only began in the 1940s to stimulate the production of oil and gas from reservoirs that had experienced a decline in productivity. The first application was in 1947 in the Hugoton Field, Kansas, where petrol gelled with palm oil and crosslinked with naphthenic acid were combined with sand to stimulate the flow of natural gas from a limestone formation. Halliburton Oil Well Cementing Company obtained an exclusive licence in 1949 for the hydraulic fracturing process. In the first year of operations, 332 oil wells were treated with a combination of crude oil, petrol and sand. The wells increased production rates by 75%, on average.

Water-based fracking fluids was in use from 1953 and many different chemical additives were tried to improve its performance. By 1968, fracking was being used in oil and gas wells across the United States, albeit in less difficult geological formations. The application of fracking expanded during the 1980s and 1990s, when it was used to stimulate methane extraction from coal beds.

In the mid-1970s, the US Department of Energy (DOE) and the Gas Research Institute (GRI), in partnership with private operators, began developing techniques to produce natural gas from shale (Smith, 2012). Shale rock presented a challenge because of the difficulty in accessing the hydrocarbons in tight formations. Techniques employed included the use of horizontal wells, multi-stage fracturing, and slick water fracturing. The essential chemical additive for slick water fracturing is the friction reducer.

Mitchell Energy achieved commercial success with the recovery of gas from shale formations using slick water, a low viscous mixture that could be rapidly pumped down a well to deliver a much higher pressure to the rock than before. A merger between Mitchell Energy and Devon Energy in 2002 brought a rapid increase in the use of fracking with horizontal drilling in shale. George Mitchell (1919–2013) has been called the "Father of Fracking", although he can be more accurately described as the "Father of the Shale Gas Boom" (Morton, 2013).

Applications of fracking

Hydraulic fracking is used far wider than the oil and gas industry (Adams & Rowe, 2013). It is used to great effect in many different applications, including:

- **Water well production enhancement:** Just as hydraulic fracking is used to increase the rate and efficiency of recovery for oil and gas, it can also be used to improve the yield of water wells in fractured rock aquifers. A section of the well is isolated using packers and water is introduced to generate pressures up to approximately 200 bar to wash out existing fractures and propagate them to connect with others within the aquifer. No chemical additives or proppants are used. This technique has successfully been done not only in the US, but also in India, Australia and South Africa;
- **Mining Applications:** Hydraulic fracking also has mining applications where it can be used to induce controlled rock caving. In the event of a massive, un-fractured ore body, some form of pre-conditioning is needed to initiate caving and to reduce the size of caving materials. Hydraulic fracturing in boreholes drilled into the ore body is the preferred method of performing this preconditioning process. Fracturing pressures can be up to 700 bar. Fracking has also been proposed for uranium mining in which it will be used to inject substances that will dissolve the uranium so that it can then be pumped to the surface;
- **Rock stress determination:** Hydraulic fracking can be used by geologists to measure stress levels within the Earth. A section of borehole is isolated between two inflatable packers and the pressure is raised by pumping fluid into it at a controlled rate until a fracture occurs in the borehole wall. The magnitudes of the principal stresses are calculated from the pressure readings. Normally only pure water is used, and pressures are typically a maximum of 400 bar but can be as high as 1050 bar;
- **Conventional oil and gas production:** Hydraulic fracking has been used for many years to stimulate production from low yielding wells. Fracture stimulation in this industry typically uses injected fluid that includes chemical additives and proppant. The formations being treated is normally already permeable, and very high injection flow rates are necessary to build pressure in the treatment region. Injection pressures can be as high as 1 400 bar. The total volume of injected fluid is generally more than 1 ML;
- **Geothermal energy production:** Hydraulic fracking is used in geothermal systems to enhance heat extraction to produce electricity. Geothermal energy production involves the injection of water in a well, heating the water by geothermal energy, and extraction of the same water as steam or hot water from a second well. Hydraulic fracturing is used to establish a flow pathway between the injection and extraction wells;
- **Carbon sequestration:** Carbon capture and storage in suitable geologic formations is one way to reduce greenhouse gas emissions to atmosphere. The

range of suitable geologic formations includes coal basins, depleted oil and gas reservoirs and saline aquifers. Hydraulic fracturing may play a role in this industry in future to improve access to these formations and enhance their carrying capacity;

- **Coal mine methane (CMM) drainage:** CMM drainage is performed in coal seams prior to mining for safety and environmental reasons and can create an additional income stream. Hydraulic fracturing is used to enhance the production of methane from the coal. The scale of treatments varies widely, but are normally smaller than CBM stimulation fractures.
- **Coal-bed methane (CBM) extraction:** Hydraulic fracturing in CBM wells is performed to open conductive channels and stimulate the flow of methane to the wellbore. The CBM reservoirs are closer to the surface than most conventional oil and gas reservoirs or shale formations, thus requiring lower pressures, less volume and fewer additives in the fracturing fluid. Fracture pressures are up to 350 bar and total injected volume per fracture ranges up to 500 m³.
- **Waste disposal in deep-wells:** Hydraulic fracking is used to open up suitable areas in deep rock formations for the disposal of saline liquid waste, so called deep-well injection of liquid waste streams.

As the fracking technology continues to advance, it is likely to become applicable in currently unforeseen ways.

Stages of fracking

There is a range of hydraulic fracturing techniques and several different approaches may be applied within a specific area. Hydraulic fracturing programmes and the fracture fluid composition vary according to the engineering requirements specific to the formation, wellbore and location. A typical hydraulic fracture programme will follow the stages below as a minimum (Fink, 2013; FracFocus, 2019):

- **Spearhead stage:** This initial stage is also referred to as an acid or prepad stage. It involves injecting a mix of water with diluted acid, such as hydrochloric acid. This serves to clear debris from the wellbore, providing a clear pathway for fracture fluids to access the formation. The acid reacts with minerals in the rock, creating starting points for fracture development;
- **Pad stage:** The generation of the fractures takes place by injecting the pad, a viscous fluid, but without proppants, to break the rock formation and initiate the hydraulic fracturing of the target area;
- **Proppant stage:** After the fractures develop, a proppant must be injected to keep them open. When the fracture closes, the proppant is locked in place and creates a large flow area and a conductive pathway for hydrocarbons to flow into the wellbore. Viscous fluids are used to transport, suspend, and allow the proppant to be trapped inside the fracture; and

- **Flush stage:** The job ends eventually with a flush stage, in which flush fluids and other clean-up agents are applied. A volume of fresh water is pumped down the wellbore to flush out any excess proppant that may be present in the wellbore.

Components of fracking fluid

Opening comments

Fracking fluid is made up according to many different recipes, according to the preferences of the driller and the characteristics of the rock that is being fractured. In fact, up to 750 different components have been identified in fracking fluid. The natural gas industry supports the disclosure of what is used in the hydraulic fracturing process to interested and affected parties. The only proviso is that proprietary fracking fluid composition and business information is kept confidential. Depending on the application, between 3 and 12 chemical additives are used in fracking fluid with a median of 10 additives (US EPA, 2015).

Nowadays, most fracking fluids are water-based. Aqueous fluids are economical and, if used with chemical additives, can provide the required range of physical properties. Additives for fracking fluids serve three purposes, namely:

- They enhance fracture creation;
- They enable proppant to be carried into the fractures; and
- They minimize damage to the rock formation.

Although different compositions of fracking fluid are used for the different stages of fracking, a typical composition of such a fluid is shown in Figure 1.

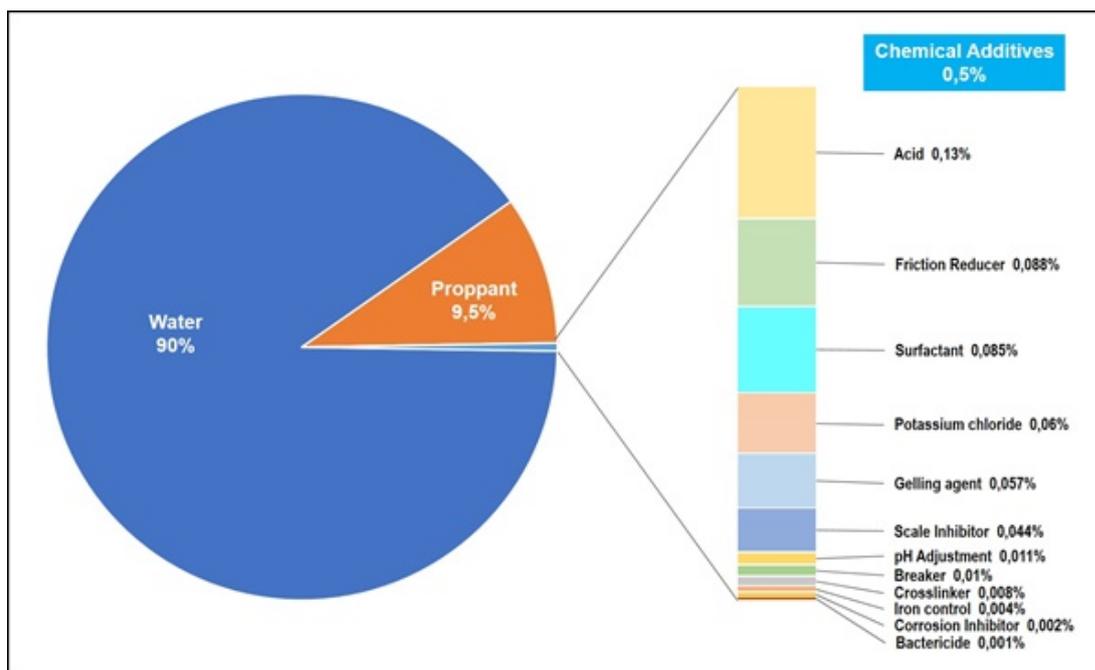


Figure 1: Typical composition of fracking fluid

Ninety percent of fracking fluid is made up of water, and another 9,5 percent is proppant. The remaining 0,5 percent of the fracking fluid is made up of chemical additives. Although their percentages may be small, chemicals play a crucial role in fracking. The different components of fracking fluid are discussed below.

Proppants

Hydraulic fracturing creates fissures in the rock, but when the pressure of the fracking fluid is reduced the newly created fissures and cracks will close again. Proppants are introduced into the fracking fluid to penetrate and keep the fractures open, thereby forming conductive channels within the rock formation through which hydrocarbons can flow. A proppant is a hard and solid material, typically sand, small diameter ceramic materials, or sintered bauxites. Sand has a relatively low strength, which can be improved by resin coating.

The proppant must stay in position and prop open the conductive channels for the productive life of the well. The flowback of a proppant following fracture stimulation treatment is a major concern because of the possible damage to equipment and loss in well production rate. Proppant related degradation of the fracture conductivity can be caused by flowback, mechanical failure of the proppant grains, chemical damage or dissolution from the additives, and proppant embedment.

The shape and size of the proppant is important because shape and size influence the final permeability through the fracture. A wide range of particle sizes and shapes will lead to a tight packing arrangement, reducing permeability/conductivity. A controlled range of sizes and preferential spherical shape will lead to greater conductivity. Typical proppant sizes are generally between 8 and 140 mesh (106 μm to 2.36 mm), although a much narrower range is normally specified, say a 10/50 or 20/40 cut.

For the fracking fluid to be able to carry the proppant into the fractures, the fluid must be viscous enough to prevent the proppant from settling out before it has been carried to the desired position.

Chemical additives

The following is a list of the primary groups of chemical additives used in fracking fluid recipes:

- **Acids:** Acids, like hydrochloric or muriatic acid, are used in fracking fluids to dissolve the minerals in the rock, soil and sand below the ground. This helps to initiate cracking and crack propagation. Typical acid concentration used is 15%. Acid also cleans out cement and debris around the perforations in the wellbore to facilitate the ingress of subsequent fracking fluids into the rock formation. Acid reacts with minerals to create salts, water and carbon dioxide.
- **Gelling agents:** Gelling agents, such as guar gum or hydroxyethyl cellulose, are added to the fracking fluid to increase the viscosity; it effectively thickens the water.

This enables the fracking fluid to accept higher concentrations of proppant, reduces the fluid loss to improve fluid efficiency, and improves proppant transport. The chemical structure of some gelling agents also allows for crosslinking. Gelling agents are broken down by breakers and returns with the flush water;

- **Crosslinkers:** Occasionally, a cross-linking agent is used to enhance the characteristics and ability of the gelling agent to transport the proppant. These compounds may contain boric acid or ethylene glycol. When cross-linking additives are added, a breaker solution is usually added later in the frack stage to break down the gelled solution into a less viscous fluid;
- **Breakers:** Breakers, like ammonium persulphate, allows for the breakdown of the gel polymer chains. Breakers can also be used to control the timing of the breaking of the gelled fluids to ensure enough time for proppant to be transported into the fractures. The gel should be completely broken within a specific period after completion of the fracking process for ease of flushing. Breakers react with gel and crosslinkers to form ammonia and sulphate salts which are flushed out;
- **Friction reducers:** Friction reducers, like polyacrylic acid, polyacrylamide or mineral oil, are used in the production of slick water and minimises friction between the fracking fluid and the pipe, thereby reducing the pressure needed to pump fluid into the wellbore. Friction reducers remain in the rock formation where they are broken down by micro-organisms. A small amount may be returned with the flush water;
- **Clay stabilisers:** Rocks within water-sensitive shale and clay formations absorb fracking fluid, which causes the rock to swell and drastically reduce formation permeability, as well as lead to wellbore collapse. Potassium chloride is a temporary clay stabiliser in freshwater-sensitive formations and helps prevent this swelling. Alternatives are choline chloride and choline bicarbonate, both of which are biodegradable;
- **Surfactants:** These additives are used to decrease liquid/surface tension and improve fluid passage through pipes in either direction. Surface active agents, like isopropanol, are included in most aqueous treating fluids to improve the compatibility of aqueous fracking fluids with the hydrocarbon-containing reservoir. Surfactants are usually returned to surface with the flush water;
- **Scale inhibitors:** Scale control prevents the build-up of mineral scale that can block fluid and gas passage through the pipes. A scale inhibitor, such as ethylene glycol, is used to control the precipitation of certain carbonate and sulphate minerals in pipelines. Most of the scale inhibitors will be returned to surface with the flush water;
- **Corrosion inhibitors:** Corrosion inhibitors are required in acidic fracking fluid mixtures because acids will corrode steel tubing, well casings, tools, and tanks. Corrosion inhibitors, such as n-dimethyl formamide, and oxygen scavengers, such as ammonium bisulphite, are used to prevent degradation of the steel well casing. Most of the corrosion inhibitors will be returned to surface with the flush water;

- **Iron control agents:** Iron control or stabilising agents such as citric acid or hydrochloric acid, are used to inhibit precipitation of iron compounds by keeping them in a soluble form. These agents typically react with minerals to create salts, water and carbon dioxide;
- **Biocides/Bactericides:** Biocides/bactericides such as quaternary amines, amides, aldehydes and chlorine dioxide, are added to prevent enzymatic attack of the polymers used to gel the fracturing fluid by aerobic bacteria present in the base water. In addition, biocides and bactericides are added to fracturing fluids to prevent the introduction of anaerobic sulphate reducing bacteria into the reservoir; and
- **pH buffers:** pH buffers, such as sodium or potassium carbonate, sodium hydroxide, monosodium phosphate, formic acid and magnesium oxide, help maintain the effectiveness of other components. Buffers adjust the pH of the base fluid so that dispersion, hydration and crosslinking of the fracking fluid polymers can be engineered. Because some buffers dissolve slowly, they can be used to delay crosslinking for a set period to reduce friction in the tubing.

Ranking of fracking intensity

Different applications of fracking technology have much in common, but can be differentiated based on some of the physical aspects of fracturing, namely:

- **Fracture Creation/propagation:** This deals with reason for performing the frack. Are we simply trying to determine the strength of the rock formation, are we trying to propagate fractures, or simply open and clean existing fractures?
- **Volume of Injectate:** Here we consider the total volume of fracking fluid used, as well as the injection flow rate;
- **Nature of the Injectate:** The composition of the injected fluid is regarded as one of the major differentiating characteristics;
- **Hydraulic Pressure:** Here we consider the maximum hydraulic pressure applied to the rock formation during fracking;

Adams and Rowe (2013) proposed a new terminology based on these aspects to allow clear differentiation between the many different types of hydraulic fracturing operations. Unfortunately, this approach is not in widespread use, but could enable practitioners, regulators and the general public to make a distinction between the many different operations. The terminology and approach for ranking the intensity of fracking is presented in Figure 2.

Primary Categories	Application	Characteristics	Sub-Categories
Type A	Applicable to water well hydraulic fracturing and geotechnical Tests such as hydro-jacking.	<ul style="list-style-type: none"> No actual new fractures created; Existing fractures are opened and possibly washed out; and injected volume though it would be typically less than 10 000 litres. 	None
Type B	Applicable to rock stress testing and rock burst amelioration.	<ul style="list-style-type: none"> New fractures are generated; Little or no attempt is made to propagate these fractures; and Injected fluid volume is less than a few hundred litres per fracture. 	None
Type C	Applicable to hydraulic fracturing for block caving, coal mine methane (CMM) and coal-bed methane (CBM)	<ul style="list-style-type: none"> New fractures are generated; Some attempt is made to propagate these fractures; and Fluid volume per fracture is limited to less than 100 000 litres. 	Type C – plain water Type C(a) – water with additives Type C(p) – water with proppant Type C(ap) – water with additives & proppant
Type D	Applicable to some CBM stimulation, conventional reservoir and multi-zonal, unconventional hydraulic fracturing (i.e. shale formations).	<ul style="list-style-type: none"> New fractures are generated; Fractures are propagated to produce the stimulation desired; and Fluid volume per fracture is typically more than 100 000 litres. 	Type D – plain water Type D(a) – water with additives Type D(p) – water with proppant Type D(ap) – water with additives & proppant

Figure 2: A terminology for ranking the intensity of fracking

Closing remarks

Hydraulic fracturing isn't new, and has been practiced for more than 100 years. It's been improved upon and renovated over long periods of time. The application of fracking to gas resources in shale formations and coal beds is a factor of rising energy cost.

There is continual progress in minimising the impact of fracking on the environment. The use of acids in the fracking process is being reduced, or stopped altogether. Hydrocarbon additives to water-based fracking fluid is being phased out and replaced by more environmentally acceptable alternatives.

Current research into fracking and the use of fracking fluids focuses on the use of cryogenic fluids such as liquid carbon dioxide and liquid nitrogen. Work on the use of supercritical carbon dioxide is also at an early stage.

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