Hydraulic Fractures for Shale Gas Production

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Abstract
Shale gas, which is extracted from wells, typically exhibits a high initial peak in production rates with a successive rapid decline followed by low production rates. However, liquid accumulation is common in shale wells and detrimental on the production rates. The optimization problem is formulated using a simultaneous implementation of the reservoir model and the optimization problem with binary variables, to model on/off valves and an imposed minimal production rate, to prevent liquid loading. A reformulation of the nonlinear well model is applied to transform the problem from a mixed integer nonlinear program to a mixed integer linear program. For short term production planning, a set of optimal production settings are solved for multiple wells with global constraints on the production rate and on the switching capacity. The reformulation to a mixed integer linear program is shown to be effective on the formulated optimization problems and allows the assessment of the error bounds of the solution.

Keywords:
MWD - Measurement While Drilling
LWD - Logging While Drilling
TOC - Total Organic Carbon
AVDT - Automated Vertical Drilling Tool

Introduction

Shale gas is known as one of the most valuable energy resources found beneath the surface.

This chapter critically looks at shale gas production through hydraulic fractures. It gives a brief summary of the geological and physical properties of shale gas and the motivation for the recovery of gas from shale gas reservoirs. Emphasis is put on the challenges associated with the recovery of gas from the tight shale rock. According to the [United States Environmental Protection Agency (EPA)], hydraulic fracturing is a process that stimulates a natural gas, oil, or geothermal well to maximize extraction. The EPA defines the broader process that includes the acquisition of source water, well construction, well stimulation and waste disposal.

1. Problem Descriptions

Extraction of natural gas from sources of organic, rich and tight shales is inherently challenging.

Due to the its permeability, hydraulic fracturing is performed at an initial phase during the development of shale gas reservoirs. The gas production from the well will typically decrease rapidly, demanding regular stimulation of the wells to maintain production. Several techniques exist for performing this stimulation.

In terms of shale gas, oil and coal formations, natural gas in shales were essentially formed from the remains of plants, animals and micro-organisms that lived millions of years ago. There are different theories on the origins of fossil fuels, where the most widely accepted is that they are formed when organic matter such as the remains of a plant or animal, are buried, compressed and heated in the earth's crust for long time. In the case of natural gas, this is referred to as thermogenic methane generation.

Determining the true porosity of a gas-filled formation has always been a problem in the oil industry. During the calibration process, water-filled formations are used to develop porosity algorithms, and under these conditions, a lower number of hydrogen atoms is equivalent to a lower porosity. Consequently, when a gas-filled formation is logged, which has a lower number of hydrogen atoms than a water-filled formation of the same porosity, the porosity estimate will be lower than the true porosity. The most well-established technique is to apply the hydraulic fracturing on a regular basis. Another strategy is to switch between production and well shut-ins in a cyclic manner. Well shut-ins allow recharging of fractures with gas and pressure build up in the stimulated regions of the reservoir. This second approach will be the focus of this research; assessing the potential of applying model-based optimization as a mean to maximize production and long-term recovery in particular.

The terms Measurement While Drilling (MWD), and Logging While Drilling (LWD) are not used consistently throughout the industry.

Although these terms are related, within the context of this section, the term MWD refers to directional-drilling measurement for decision support and for the smooth operation of the drilling, while LWD refers to measurements concerning the geological formation made while drilling.

MWD typically concerns measurements taken of the well-bore inclination from a vertical angle, and also magnetic direction from the north. Using basic trigonometry, a three-dimensional plot of the path of the well can be produced. A MWD down-hole tool is also (high-sided) with the bottom hole drilling assembly, enabling the well-bore to be steered towards a chosen direction in 3D space known as directional drilling. Directional drillers rely on receiving accurate, high quality tested data from the MWD operator to allow them to keep the well safe on the planned trajectory.

The [U.S. EPA] has acknowledged that toxic, carcinogenic chemicals such as benzene and ethylbenzene, have been used as gelling agents in water and chemical mixtures for high volume horizontal fracturing. Following the hydraulic fracture in high volume of horizontal fracturing, the water, chemicals and fracture fluid that return to the well's surface, called flow-back or produced water, may contain radioactive materials, heavy metals, natural salts, and hydrocarbons which exist naturally in the formation of shale rock.

The water-based drilling fluids, has overcome many of the technical challenges that could otherwise limit their application. This process reduces environmental impact and cost. These fluids also enhance electronic imaging quality for an improved ROI.

The main functions of drilling fluids includes providing hydrostatic pressure to prevent formation fluids from entering into the well bore, keeping the drill bit cool and clean during drilling, carrying out drill cuttings, and suspending the drill cuttings while drilling is paused and when the drilling assembly is brought in and out of the hole. The drilling fluid used for a particular job is selected to avoid formation damage and to limit corrosion.

The main problem of this study is to calibrate a method that will allow performing hydraulic fractures without affecting the environment possible.

2. Exploration methods

According to [World Energy Outlook 2009], vertical wells tend to access only a small volume of shale. The initial fracturing of a well may take approximately 30 days, although this varies with geography, after which the gas will be produced for many years or decades, although the well may be fractured again at a later stage to improve throughput.

There are several ways or methods that gas explorers use in order to discover the gas such as seismic, drilling and well logging. This chapter shows how these three methods are being carried out. Seismic methods are applied primarily in order to determine quasi-homogeneous zones according to parameters of fragmentation, physical and chemical weathering and deform-ability of rock masses and cohesionless soil. Applied seismic methods comprise sending impulses underground and registering the resulting refracted arrivals from subsurface interfaces on a number of receivers positioned on or near the surface.

In terms of drilling: in most shale gas resources are located at depths of 6,000 feet or more below the ground level and can be relatively thin.

According to [Rotman, 2009], the efficient extraction of gas is vertically downward until the drill bit reaches a distance of around 900 feet from the shale formation.

At this point, a directional drill is used to create a gradual 90-degree curve, so that the well-bore becomes horizontal as it reaches optimal depth within the shale.

The well-bore then follows the shale formation horizontally for 5,000 feet or more, then an amount of cement is pumped into the annulus or void space between the casing and the surrounding mineral formation. After the well-bore reaches a depth below the deepest freshwater aquifer, casing and cement are installed to protect the water from contamination due to the drilling process.

The casing surrounding the horizontal section of the well through the shale formation is then perforated using small explosives to enable the flow of hydraulic fracturing fluids out of the well into the shale, and the eventual flow of natural gas out of the shale into the well.

Well logging, also known as borehole logging, is the practice of making a detailed record of the geologic formations penetrated by a borehole to get oil, gas and some other minerals. Well logs can include visual observations or be made by instruments lowered into the well during the drilling process.

Engineers and drillers often use well logs to measure depths of formation tops, thickness of formations, porosity, water saturation, temperature, types of formations encountered, presence of oil and gas, estimated permeability, reservoir pressures and formation dip ultimately determining whether a well is commercially viable or not and whether casing, cementing and completion should be ran on a well.

2.1 Production Methods

Shale gas resources are becoming an important energy source for meeting rising energy demand that will take place over the next few decades. Development of horizontal drilling and hydraulic fracturing is crucial for the economic production of shale gas reservoirs, but, it must be performed with caution and with a multidisciplinary approach.

Commercial successes in the Barnett Shale, which is currently the largest producing natural gas field, and other shale plays in the United States, have made shale gas exploration possible and development has begun to be spread all around the world.

Shale gas wells share many of the same production characteristics, of which the rapid decline of productivity is the most dominating.

This is supported by the report [World Energy Outlook, 2009] from the [International Energy Agency - IEA (WEO, 2009 The truth about Fracking)], which provides a detailed study of its potential, the last decade's production history and current production level of shale gas.

The production profiles were observed to be remarkably similar, both for horizontal and vertical wells. To elaborate, the wells exhibited an early peak in the production before a rapid decline in the rate.

For horizontal Barnett wells, the decline in production rate is reported to be averagely 39% during the first year and 50% from the first to the third year. Vertical wells appears to have a slightly slower decline in rate.

The monthly rates are reported to decline as much as 57% over the first 12 months.

The averagely initial monthly production rate for Barnett shale horizontal wells, which is in the report from IEA, showed to be approximately 0.9 million m3. Based on this value, the maximum daily flow rate qmax for the base case is set to 30000 m3/d. The wellhead pressure is set to a constant value of 10 bar, [Chris 2011. The truth about Fracking].

2.2 Reservoir characteristics of Shale gas

[Medeiros et al 2007] says: "the physical process of the gas flows in shale gas reservoirs complicatedly". Simplifications and approximations are necessary to describe the flow in the complex network of fractures, and comprehensive numerical simulations are normally required to describe these flow patterns.

According to [Carlson and Mercer 1991], analytical models of the gas flow in fractured reservoirs are normally obtained by dual-porosity and mathematical models. These models have been extended to describe the gas production in tight gas and shale gas reservoirs.

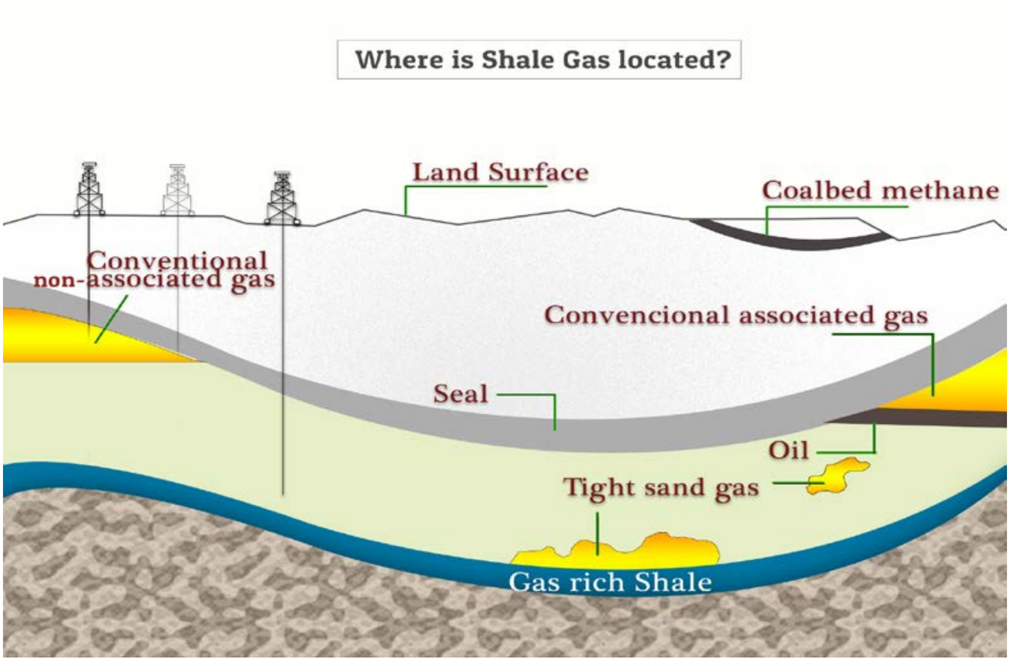
[Carlson and Mercer 1991] also says: "the shale was generally too tight for the gas to flow directly from the storage in the rock to the well".

While in conventional gas, reservoirs containing large amounts of gas flow directly from the storage pores to the well. These quantities, only last in the scale for minutes in shale gas reservoirs. [Schettler et al. 1989] says: "the gas in shales mainly consists of methane".

Due to the tightness of the shale, the gas will only travel a very short distance in the rock over a given, reasonable time span.

[Schettler et al 1989], also describes this flow through the rock itself predominately, as "a result of molecular diffusion".

The majority of the gas flowing in shales, arises from the molecules traveling the short distances from the storage in the tight rock to adjacent segments of fractures in the rock itself. The rock in this context describes a piece of tight shale rock.



The gas then flows from these small segments of fractures to larger networks of fractures in the shale.

Figure 1. Reservoir forming characteristics of unconventional natural gas resources [Nuno Ferreira, 2016].

The key characteristic of shale gas reservoirs are their low permeability.

Permeability is a measure of a materials' ability to transmit fluids, in this context, the shales ability to transmit the gas. For shale gas reservoirs, the effective permeability may often be between the ranges of 10−3 mD and 10−6 mD. [Cipolla, 2009], emphasizes the difficulties and challenges of recovering gas from shales, compared to conventional viscous reservoirs. Many factors impact the gas production from shale gas reservoirs, where the most prominent is the number and the structural complexity of fracture network.

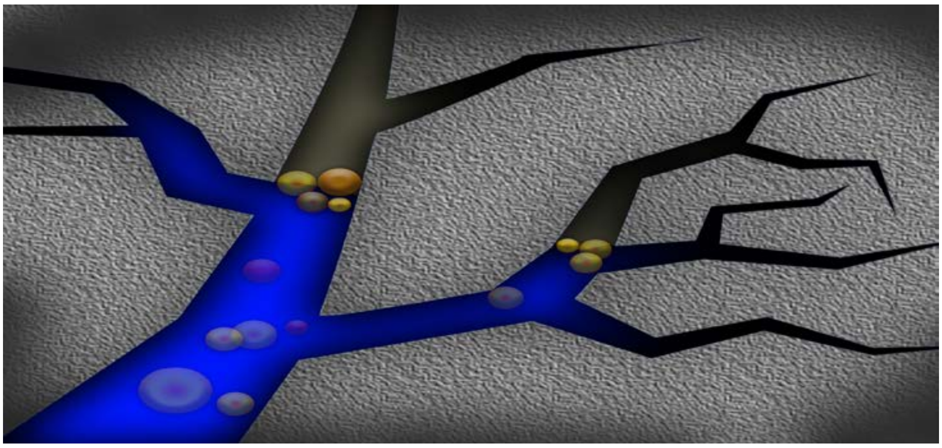
The effective conductivity of fractures and the actual permeability of the shale rock are also crucial for the productivity.

Further assumptions of reservoir models	The flow is single phase.
	The geometry of the reservoir is cylindrical.
	The geometry of the reservoir is cylindrical.
	The entire thickness of the reservoir is perforated by a well in the center of the cylindrical reservoir model.

Table 1. Presuppositions of reservoir models, [Nuno Ferreira, 2017].

2.3 Pore structure characterization of shale gas

The matrix pore structure of shale gas and tight gas reservoirs play an important role in hydrocarbon storage and transport, which is too difficult to characterize accurately because of a predominant portion of nano-pores associated with clays and organic matter. Characterization of nano-pore structure, has great importance for the percolation mechanism and reservoir evaluation study of shale gas.



F**igure 2.** Conventional gas wells, shale gas well and the process of hydraulic fracturing [Nuno Ferreira, 2016].

There are two different gas reservoirs, they are: conventional and unconventional gas reservoirs. For conventional reservoirs, the Mercury Intrusion Technique is commonly used for pore structure analysis.

Meanwhile, unconventional gas reservoirs, with a much higher pressure, could be required for mercury to be injected into the nano-pores, and the High-Pressure Mercury Intrusion Technique is adopted mainly for the analysis of macro-pores (＞50 nm), avoiding distortion of pore structures under high pressure.

Pore size distribution, in contrast to conventional reservoirs, gas shales have very low porosity and low permeability, shale matrix possesses ruleless pore structure and a wide pore size distribution with a significant pore volume in the nano-pore range.

Many petrophysical properties of the unconventional tight gas formations are significantly different from those of conventional reservoirs. Such formations in particular have nano-scale pores and channels, a unique pore structure, the unusual wet-ability, transport, and storage properties. These differences produce the fluid flow mechanisms which are different from those in conventional gas plays, especially when the size of the pore throats differs from the size of the saturating fluid molecules by only slightly more than one order of magnitude. Despite the practical importance of this topic, very little is known about it.

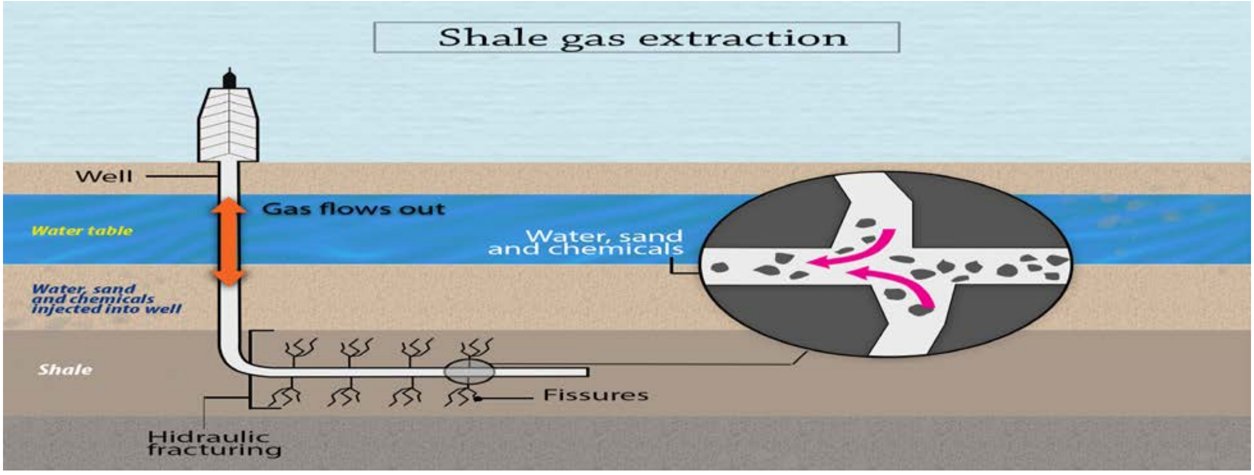


Figure 3. Illustration of shale gas extraction, [Nuno Ferreira, 2016].

3. Drilling and Completion

Drilling is mostly classified in two different terms i.e Directional and Horizontal.

3.1 Directional Drilling

Directional drilling or slant drilling is the practice of drilling non-vertical wells.
It can be broken down into four main groups: oil field directional drilling, utility installation directional drilling, directional boring, and surface in seam, which horizontally intersects a vertical well target to extract coal bed methane.

When directional drilling is combined with hydraulic fracturing some rock units which were unproductive when drilled vertically can become fantastic producers of oil or natural gas.

Wells are drilled directionally for several purposes:

A. Increasing the exposed section length through the reservoir by drilling through the reservoir at an angle.

B. Drilling into the reservoir where vertical access is either difficult or not possible. For instance an oilfield under a town, under a lake, or underneath a difficult-to-drill formation.

C. Allowing more wellheads to be grouped together on one surface location allows fewer rig moves, less surface area disturbance makes it easier and cheaper to complete and produce the wells. For instance, on an oil platform or jacket offshore, 40 or more wells can be grouped together. The wells will fan out from the platform into the reservoir below.

D. This concept is being applied to land wells, allowing multiple subsurface locations to be reached from one pad, reducing costs.

E. Drilling along the underside of a reservoir-constraining fault, allows multiple productive sands to be completed at the highest strati-graphic points.

F. Drilling a "relief well" to relieve the pressure of a well producing without restraint. In this scenario, another well could be drilled starting at a safe distance away from the blowout, but intersecting the troubled well-bore. Then, heavy fluid is pumped into the relief well-bore to suppress the high pressure in the original well-bore causing the blowout.

3.2 Horizontal Drilling

Horizontal oil and gas well drilling has become one of the most valuable technologies ever introduced in the business. Unlike a directional well that is drilled to position a reservoir entry point, a horizontal well is commonly defined as any well in which the lower part of the well bore parallels the oil zone. The angle of inclination used to drill the well does not have to reach 90° for the well to be considered a horizontal well. Applications for horizontal wells include the exploitation of thin oil-rim reservoirs, avoidance of draw-down-related problems such as water/gas coning and the extension of wells by means of multiple drain holes.

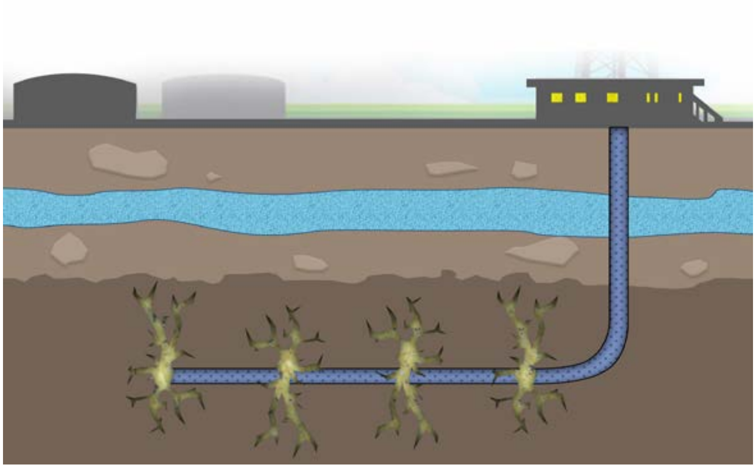


Figure 4. Horizontal drilling being performed, [Nuno Ferreira, 2016].

Horizontal wells have become a preferred method of recovering oil and gas from reservoirs in which these fluids occupy strata that are horizontal or nearly, because they offer greater contact area with the productive layer than vertical wells.

While the cost factor for a horizontal well may be as much as two or three times that of a vertical well, the production factor can be enhanced as much as 15 or 20 times, making it very attractive.

To give an idea of the effectiveness of horizontal drilling, using horizontal drilling can lead to an increase in reserves in place by 2% of the original oil in place.

The production ratio for horizontal wells versus vertical wells is 3.2 to 1, while the cost ratio of horizontal versus vertical wells is only 2 to 1.

Nowadays there are 3 main types of horizontal wells: Short Radium, Medium Radius and Long Radius.

Horizontal oil drilling can be used in many situations where conventional drilling is either impossible or cost prohibitive. This is by no means an exhaustive list, but it should get explorers thinking about the possibilities of horizontal directional drilling.

As horizontal well drilling can be used in these scenarios:

1. Under buildings, roads and other surface obstructions.
2. Under active sites where surface operations precluded drilling equipment.
3. To efficiently extract soil vapor.
4. To identify the causes of decreased well performance.
5. To place leak detection sensors beneath solid or hazardous waste landfills.
6. To install gas collection systems at landfills or similar waste dump.

7. To stabilizing hillsides for mine waste dumps or other unstable granular soil masses.
8. To install groundwater collection galleries in shallow aquifers for private or public water supply.
9. To convey fluids between vertical wells and treatment facilities.

3.3 Drilling Methodology

Most horizontal wells begin at the surface as a vertical well. Drilling progresses until the drill bit is a few hundred feet above the target rock unit.

At that point the pipe is pulled from the well and a hydraulic motor is attached between the drill bit and the drill pipe. The hydraulic motor is powered by a flow of drilling mud down the drill pipe. It can rotate the drill bit without rotating the entire length of drill pipe between the bit and the surface.

This allows the bit to drill a path that deviates from the orientation of the drill pipe. After the motor is installed, the bit and pipe are lowered back down the well and the bit drills a path that steers the well bore from vertical to horizontal over a distance of a few hundred feet.

Once the well has been steered to the proper angle, straight-ahead drilling resumes and the well follows the target rock unit. Keeping the well in a thin rock unit, requires careful navigation. Down-hole instruments are used to determine the azimuth and orientation of the drilling. These methods can multiply the yield of natural gas or oil from a well. Many profitable wells would be failures without these methods.

3.4 Disadvantages of Horizontal Drilling

Until the arrival of modern down-hole motors and better tools to measure inclination and azimuth of the hole, directional drilling and horizontal drilling was much slower than vertical drilling, due to the need to stop regularly and take time-consuming surveys, and due to slower progress in drilling itself.

These disadvantages have shrunk over time, as down-hole motors became more efficient and semi-continuous surveying became possible.

What remains, is a difference in operating costs: for wells with an inclination of less than 40 degrees, tools to carry out adjustments or repair work can be lowered by gravity on a cable into the hole. For higher inclinations, more expensive equipment has to be mobilized to push tools down the hole. Another disadvantage of wells with a high inclination was that, prevention of sand influx into the well was less reliable and needed higher effort.

Again, this disadvantage has diminished such that, provided sand control is adequately planned, it is possible to carry it out reliably. Therefore, directional drilling can be used to reach targets that cannot be drilled with a vertical well.

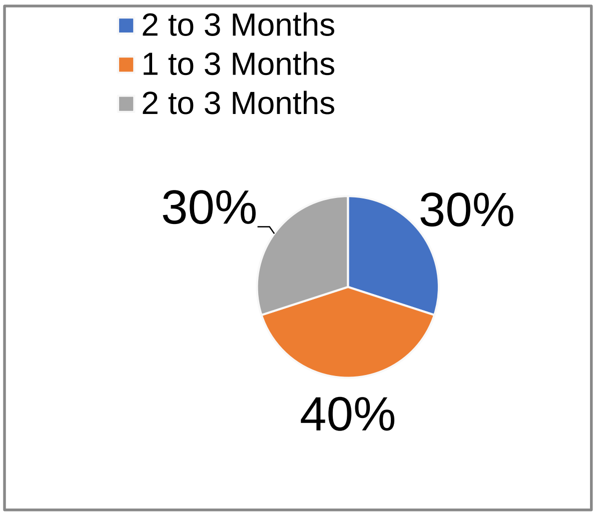
4. Operation Process and Methods

4.1 Operation Process

The operation process, involves the high-pressure injection of hydraulic fracturing fluid such as primary water, containing sand or other proppants suspended with the aid of thickening agents into a wellbore to create cracks in the deep-rock formations through which natural gas, petroleum and brine will flow more freely. When the hydraulic pressure is removed from the well, small grains of hydraulic fracturing proppants either sand or aluminum oxide hold the fractures open. This operation increases in seismic activity following hydraulic fracturing along dormant or previously active, unknown faults are sometimes caused by the deep-injection disposal of hydraulic fracturing flow-back and produced formation brine. Fracturing rocks at great depth frequently becomes suppressed by pressure, due to the weight of the overlying rock strata and the cementation of the formation.

This suppression process is particularly significant in fractures which require the walls of the fracture to move against this pressure. Fracturing occurs when effective stress is overcome by the pressure of fluids within the rock. The minimum principal stress becomes tensile and exceeds the tensile strength of the material. Fractures formed in this way are generally oriented in a plane perpendicular to the minimum principal stress, and for this reason, hydraulic fractures in well bores can be used to determine the orientation of stresses.

- Developing the Well
- Completion and Simulation
- Operation and Production



Graphic 1. Brief summarization of the Operation process, [Nuno Ferreira, 2017].

4.2 Operation Methods

A hydraulic fracture is formed by pumping fracturing fluid into a well-bore at a rate sufficient to increase pressure at the target depth, to exceed that of the fracture gradient of the rock.

The fracture gradient is defined as pressure increase per unit of depth relative to density and is usually measured in pounds per square inch, per square foot or bars.

The rock cracks, and the fracture fluid permeates the rock extending the crack further and further, and so on.

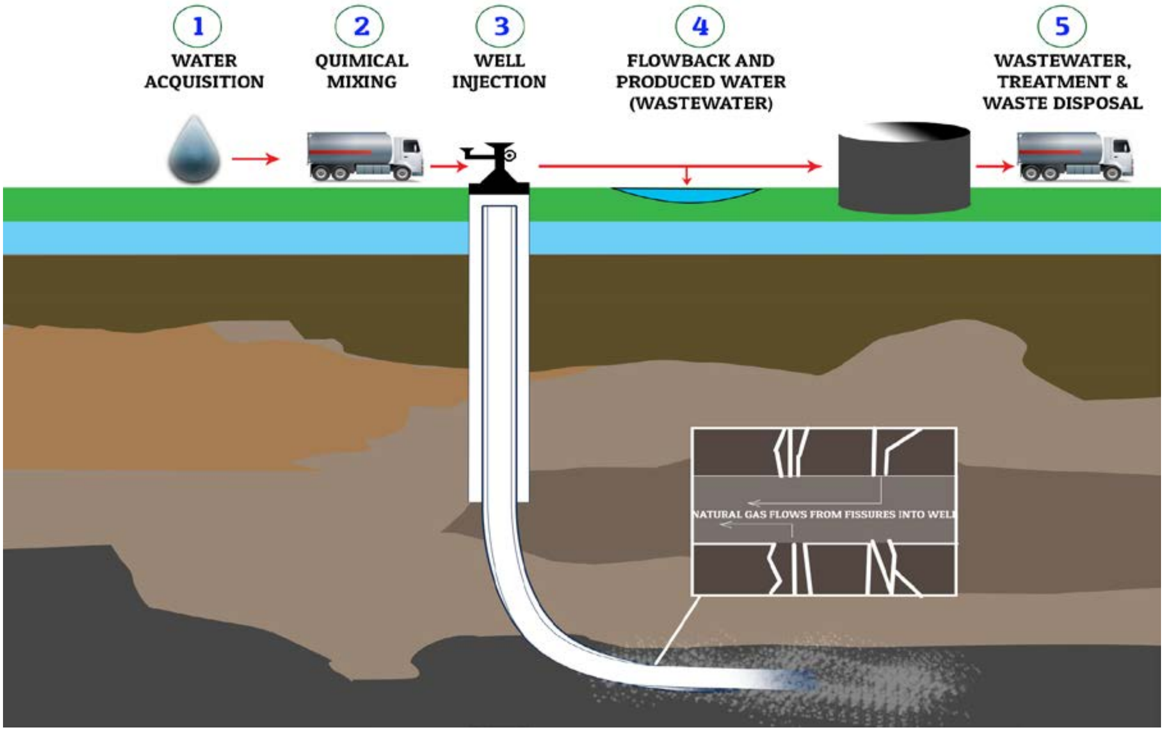
Operators typically try to maintain its decline following treatment, by introducing a proppant into the injected fluid.

Materials such as grains of sand, ceramic, or other particulate, thus preventing the fractures from closing when injection is stopped and the pressure is removed. The propped fracture is permeable enough to allow the flow of gas, oil, salt water and hydraulic fracturing fluids to the well.

During the process, fracturing fluid leak-off (loss of fracturing fluid from the fracture channel into the surrounding permeable rock) occurs.

If not controlled, it can exceed 70% of the injected volume. This may result in a formation matrix damage, adverse formation fluid interaction and altered fracture geometry, thereby decreasing efficiency.

The location of one or more fractures along the length of the borehole is strictly controlled by various methods that create or seal



holes in the side of the well-bore.

Hydraulic fracturing is performed in cased well-bores and the zones to be fractured are accessed by perforating the casing at those locations.

F**igure 5.** Hydraulic Fracturing being processed horizontally, [Nuno Ferreira, 2016].

4.3 Principals of Shale gas fractures

There are different principals of shale gas fractures that must be followed, not just for the economy of the country but also to prevent a negative impact on the environment.

Principals are meant to be acknowledge before exploring shale gas in an area of hydraulic fracture procedures.

Not acknowledging the principals of shale gas fractures and production may result in lives being put in danger, a negative environmental impact and other non-environmentally and economically profitable impacts.

Therefore, it is extremely important to know all the major principles before beginning the exploration of a certain area for shale gas extraction.

Principals:

1. Plan ahead of developments and evaluate possible cumulative effects before granting license;
2. Carefully assess environmental impacts and risks;

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3. Ensure that the integrity of the well is up to best practice standards;
4. Check the quality of the local water, air, soil before operations start, in order to monitor any changes and deal with emerging risks;
5. Control air emissions, including greenhouse gas emissions, by capturing the gases;
6. Inform the public about chemicals used in individual wells;
7. Ensure that operators apply best practices throughout the project.

4.4 Equipment used in Shale Gas Extraction and Production

The machine mostly used to perform deep drilling is called a Drilling rig. It is able to create holes in the earth as well as in the sub-surface.

Drilling rigs are massive structures used to drill water wells, oil wells or natural gas extraction wells and are also small enough to be moved manually by one person and are called augers.

These Drilling rigs can sample sub-surface mineral deposits, test rock, soil and groundwater physical properties and can also be used to install sub-surface fabrications, such as underground utilities, instrumentation, tunnels or wells.

Drilling rigs can be mobile equipment mounted on trucks, tracks or trailers, or more permanent land or marine-based structures.

The term "rig" therefore, generally refers to the complex of equipment that is used to penetrate the surface of the earth's crust. Using these drilling rigs, can easily reach the depth hole needed by the operator and its convenient to be used as it can also be moved manually.

There are many types and designs of drilling rigs with many drilling rigs capable of switching or combining different drilling technologies as needed.

5. Opportunities and Challenges

• Strong market demand	• The lack of top-level design;
• The resources potential is big and can adopt the resources;	• Exploration and development model to guide the need to be strengthened;
• All aspects of high attention, social capital investment enthusiasm is very high;	• Geological foundation work is weak
• Shale gas exploration rights market has been liberalized;	• The core technology behind;
• Foreign technology can be used for reference, there are technical accumulation in the countries;	• Support the early development of preferential policies;

• Equipment localization and low labor costs;	• Infrastructure construction is lagging behind;
• Technology and engineering services market is huge;	• Environmental protection pressure
• More investment opportunities and financial markets.	

Table 2. Opportunities and Challenges faced during the process of exploration and production of Shale Gas, [Nuno Ferreira, 2017].

5.1 Summary of the whole process

PERIOD	ACTIVITY	METHODS	EXPECTATION-RESULTS
Two to three months	Developing the well	Drilling rigs	
One to three months	Completion and Stimulation	Fracturing Equipment	
Two to three months	Operation	Hydraulic fractures producing oil and natural gas	20 to 40 or more years of production

Table 3. Overview of the period and expected results of the exploration process, [Nuno Ferreira, 2017].

5.2 Conclusion

This research concludes that, shale gas exploration through hydraulic fractures is a great technological innovation that results in abundance of oil and natural gas.

It shows the development of the study of hydraulic fractures for shale gas production applied to shale gas wells. As the time passes, more countries are starting to extract and produce shale gas through hydraulic fractures. It is a risky exploration because during the extraction process, chemical substances are introduced into the drilling pipes to break the rocks underground, therefore once the production begins, the chemical substances must be removed out from underground so that the gas may flow out the rocks. By the time the substances are being removed, it passes through the potable water and, somehow, the chemical substances might contaminate the drinking water.

The shale gas resources are becoming an important energy source for meeting rising energy demand within the near future. The development of horizontal drilling and hydraulic fracturing is crucial for the economic production of shale gas reservoirs. It must be performed with caution and with a multidisciplinary approach.

Hydraulic fractures for shale gas production are an extraordinary field of study with many different ways and methods to extract and produce shale gas. The results obtained indicates that the entire process of developing a well, typically takes between two to three months: a few weeks to prepare the sides, four to six weeks to drill the well and then between one to three months for completion activities which includes one to seven days of stimulation. These two to three months of investment may result in a well that will produce oil, or natural gas for 20 to 40 years or more.

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