Field Development of Shale Gas Reservoirs

by

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14854

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Petroleum Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(PETROLEUM)

Approved by,

____

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Main Supervisor

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TRONOH, PERAK

January 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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NURSHAZAREENA SHUHADA BINTI ZAIT

ABSTRACT

Unconventional natural gas is usually found in reservoirs with relatively low permeability and thus, it can not be either extracted or produced in common ways compared to conventional natural gas. One of the natural gas which has high demand in this industry is gas from shale formation called “shale gas”. The gas is trapped in the very tiny pores spaces between the grain inside the shale formation and it is impermeable nature of the source rock. Shale gas technology has been largely raised in the United States (U.S.), since the first shale gas well was discovered here in 1821 from a well near Fredonia, New York. There are some issues on field development by using vertical drilling because it requires more time and definitely has high cost as it need to spend more time on packing and moving the rig and preparing at a new drilling site. The main objective of this paper is to propose an appropriate development plan for shale gas reservoir. In conducting this project, few research methodologies such as analysis, evaluation of result, and comparison of case study to ensure this project to be successfully completed in achieving its objectives. Field developments of reservoir consist of information from Geophysic and Geology part (G&G), Reservoir Engineering, Production Engineering, Facilities Engineering and Project Economics. One of the important development of shale gas reservoirs are depend on the technology such as horizontal drilling as well as hydraulic fracturing for optimizing the production of shale gas. Horizontal drilling is helpful in increasing the exposed section length through the reservoir, while hydraulic fracturing enhances the flow of gas from reservoir to the wellbore. Thus, this paper can be used as the guideline to have further understanding on field development of shale reservoirs.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Shale is a typical name of rock that formed from layers associated with mud or clay. However, because of geological factors, these types of layers had been compressed and compacted into a fine grained of sedimentary rock. The gas is formed within the source rock as result of transformation of sediment rocks. Then, it migrates to the surface but unfortunately, shale gas that expelled from source rock can be blocked by impermeable rock or called it as 'trap'. Two important terms in physical characteristics of shale rock are laminated and fissile. Laminated referred to the rock which is made up of many thin layers, whereas, fissile means the rock can split into small pieces along the laminations.

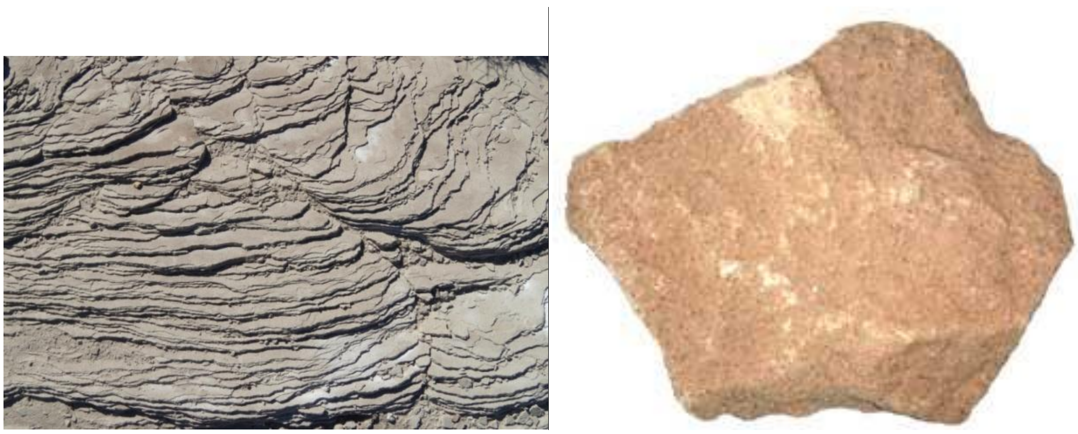


Figure 1: Shale Rock and Sandstone

Therefore, it needs specific technology to extract the shale gas from the rock formation. Shale gas can be discovered at depth 1.5 km to 3 km below the ground. For time being, U.S. is the only country that has significant commercial production of shale gas. According to study done by Energy Information Administration (EIA), it showed that in year 2010, the shale gas production in U.S. was about 23% of the total natural gas production. Then, the production of shale gas in U.S. is increasing up 45% by 2035, which is the highest ratio compared to other natural gas. (Gusilov, 2012). **Table 1** shows the location of shale gas reservoirs at all around the world.

Table 1: Location of Shale Gas Reservoirs

Country	Location
United States	Marcellus, Barnett, Eagle Foed, Haynesville
United Kingdom	Bowland Basin, Weald Basin, Northern Ireland
Canada	Montney, Horn River
Argentina	Chaco Basin, Golfo San Jorge, Neuquen Basin
China	Sichuan, Tarim
India	Cambay Basin, Gondwana Basin

The production of shale gas commonly depends on the technique applied at the reservoir such as the horizontal drilling and hydraulic fracturing. Horizontal drilling is a method that enables the wellbore to have large contact areas with hydrocarbon in the rock formation compared to vertical well. This can be proved by the numbers of horizontal wells were drilled in Barnett shale in year 2001 until 2003 was 76. Then, this number had increase to 1,870 wells around 2007-2008 that shows this technique of drilling operation is very important for shale formation. For example, the figure below shows that the shale gas production will continue to expand, and hence, it can reach the target of 45% of total volume of gas produced in U.S. on 2035. (NETL, 2011)

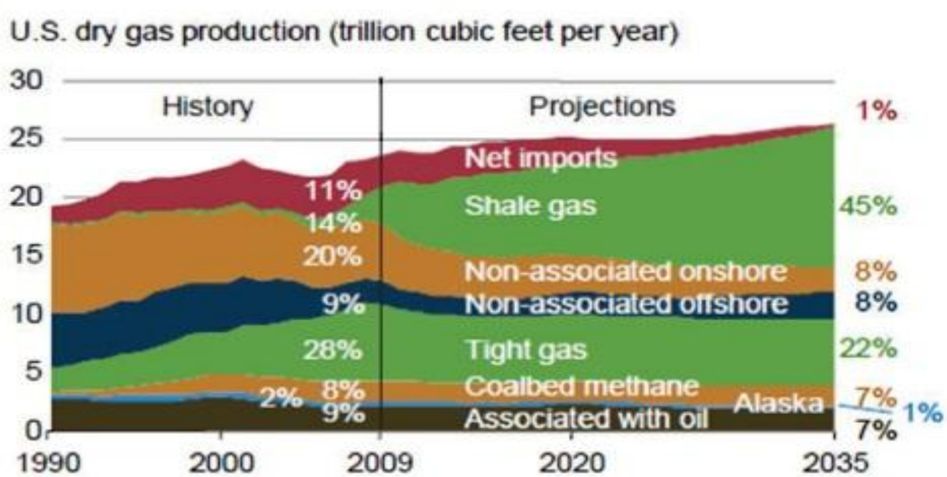


Figure 2: U.S Dry Gas Production (NETL, 2011)

However, horizontal drilling can not be performed alone without hydraulic fracturing or "fraccing". This type of stimulation helps to create a large number of fractures in the rock, so that natural gas trapped in the formation can flow from fractures of reservoir to the wellbore.

1.2 Problem Statement

Development of shale gas reservoir is more complicated compared to conventional reservoir. Due to its properties such as poor permeability required extra works to gain the information about the reservoir. As said by Murtha and Lancaster (1989), "although buildup test conducted on shale wells have the same objectives and use the same procedures as buildup tests run on other formation, certain characteristic of shale reservoirs and their well completion methods make well testing complicated". Thus, it is necessary to find out what is the problem faced by shale reservoir, and what alternatives can be used to overcome these problems.

Apart from that, poor permeability of shale formation limits the production of gas if traditional ways are used such as vertical drilling. Therefore, advanced technology need to be applied on drilling operation such as horizontal drilling. One of the problem if an operator drill a single well, they need to disassemble the drilling rig, transfer to a new location and repeat the same process to obtain the shale gas. Thus, this will create longer time for drilling operation and at the same time increase the operation cost. So, the engineers came out with pad drilling and multilateral drilling to solve these issues.

Moreover, field development of reservoir is complicated and complex procedures. Thus, it needs some basic information and guideline so that people in industry can understand on how to develop shale gas reservoirs. It will be discussed more in this paper.

1.3 Aim and Objectives

The aims and objectives of this project are:

a) To propose an appropriate development plan for shale gas reservoirs.
b) To determine the steps/precautions required during well testing.
c) To compare the effectiveness of different techniques of drilling operation.
d) To evaluate the best stimulation technique used for shale gas reservoir.
e) To generate the guideline on surface facility and production forecast.

1.4 Scope of Study

Basically, field development project contain a set of exploration and appraisal well data which is used to produce a field development plan. Exploration and appraisal well data is obtained when the location of the reservoir is confirmed. The field development project (FDP) report should cover all aspects of field development, which are as following:

- **Phase 1 :** Geology, Geophysics and Petrophysics
- **Phase 2 :** Reservoir Engineering
- **Phase 3 :** Drilling Engineering, Production Technology and Facilities Engineering
- **Phase 4 :** Project Economics
- **Phase 5 :** Sustainable Development and Health, Safety, & Environment

However, the scope for this project will be focused on the 5 criteria in Phase II and III of field development project as this project needs to be completed within 28 weeks.

1) Reservoir Engineering – Well Testing
2) Drilling – Horizontal Drilling (Single and Multilateral-well)
3) Production Technology – Hydraulic Fracturing
4) Facility Engineering – Surface Facility
5) Production – Gas Production Forecast

CHAPTER 2

LITERATURE REVIEW

2.1 Shale Formation

Generally, there are two types of categories of natural gas which are conventional and unconventional. Conventional gas is easily to be found, low-cost operation and can be extracted without complicated technique because of its higher permeability; greater than 1 millidarcy (mD). This conventional gas is well-known globally as it can be found at many areas all around the world. However, different situation is applied when dealing with unconventional gas. It has very low permeability which is less than 1 mD, thus it is unable to be extracted using conventional techniques. One of the most famous unconventional gases that already developed nowadays is shale gas.

2.2 Shale Gas

Before going further to the technology used to extract the shale gas, it is important to understand the shale formation and shale gas. Shale is a type of sedimentary rock from clastic sources that usually contain mudstones and siltstones. The fragment or layering of pre-existing rock have been undergone some natural process such as erosion, transportation, deposition and lithification before clastic sedimentary rock can be formed. This sedimentary rock which is known as shale contains organic material such as kerogen. Leg Resources (2011) explained that as time passes, the rocks become matured and ready to produce hydrocarbon from the kerogen. Hence, it will migrate in the form of oil or gas by flowing inside the natural fractures of the rock. This migration of fluid will end when they reach the trap in the impermeable rock. The physical characteristic of shale includes laminated structures, fine-grained sedimentary rock and low porosity and permeability. **Figure 3** shows the location of gas-rich shale strata.

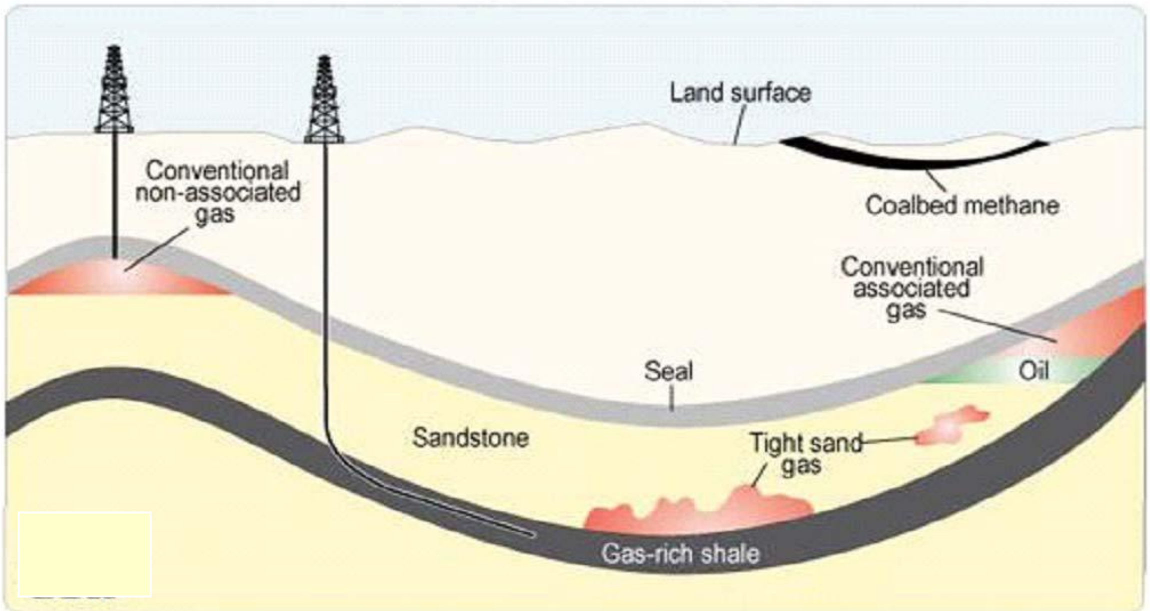


Figure 3: Schematic Diagram of Gas-rich Shale Strata

It is necessary to understand the types of shale because certain shale has their own characteristics. In general, there are three sources of shale gas which are shale source rock, shale pseudo-source rock, and fractured shale reservoir. Shale source rock is means it can expel commercial hydrocarbon in a basin, while shale pseudo-source rock appears as good source, but unfortunately it unable to contribute commercial hydrocarbon. The last type is fractured shale reservoir which indicates that there is natural fracture in the reservoir; hence, it is easily to extract the hydrocarbon from the rock formation. Basically, shale gas resources are situated below the ground level at depths of more than 6000 feet, which is known as thin layer of shale depth. (Clark, Burnham, Harto, and Horner, 2013). Shale gas can stored in two ways inside the rock formation. First, free gas which gas is held within the tiny spaces (pores) or in spaces of fractures rock. Second, adsorb gas which is gas molecules attached to rock surface. Thus, this situation makes shale gas are very difficult to be extracted form the rock formation. Sumi (2008) mentioned that the shale rock should have natural fractures, or fractures created through stimulation to ensure that the gas can be released, specifically in commercial quantities,

2.3 Technique of Horizontal Drilling

The thin layer of shale gas requires drilling horizontally for efficient and optimization of gas extraction from its rocks. If vertical drilling is applied in shale gas area, thus it will cause high-cost operation because it can not optimize the production of shale gas from reservoir. Apart from that, it will take a longer time for complete operation at that area. Thus, the best option to obtain gas from shale formation is by performing horizontal drilling in two stages. First stage is to drill in vertical direction till the drill bit reaches a distance which is about 900 ft from shale formation. From here, it starts to have directional drill to create almost accurate 90°curve for second stage. In other words, the wellbore starts to have horizontal direction as it reached the optimal depth. Clark, Burnham, Harto, and Horner (2013) also explained that usually, the length of horizontal drilling can be achieved until 5,000 feet or more but however, it depends on how long horizontal drilling operation can be done in that area by considering the optimization of gas and operation cost.

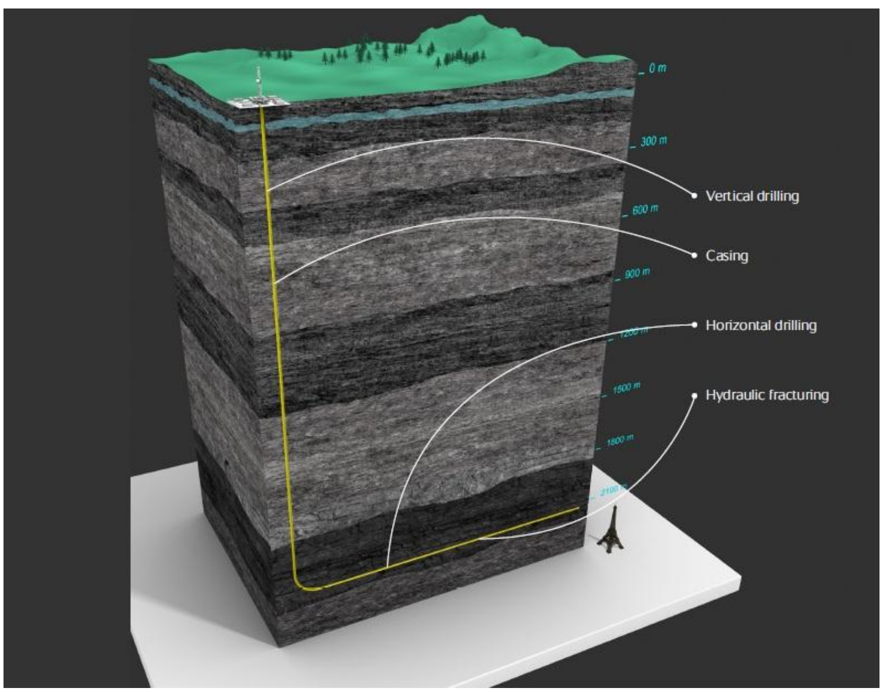


Figure 4: Schematic Diagram of Horizontal Drilling and Hydraulic Fracturing Process

The function of horizontal drilling is used to extract energy from a source that is itself runs horizontally, such as shale rock. By using this technique, it can be seen that a horizontal well resembles and correspondence to ‘J’ shape, which it can cover wider area of rock. Curtis (2011) stated that a drilling company using the horizontal technique can reach more energy with few wells. For example, this technique is successfully applied on the Marcellus Shale formation because it can extract huge amount of shale gas. Moreover, Petroleum Development Oman has shown that horizontal drilling operation has advantages such as high production rates, high oil recovery and low operation costs. Ishak, Steele, Macculay, Stephenson and Al Mantheri (1995) explained that sand control technique of wire-wrapped screen was used during the completion of horizontal wells in the carbonate reservoirs. Even though, this example discussed for oil and carbonate formation, but the technique is just the same when applied on shale gas reservoirs.

2.4 Technique of Hydraulic Fracturing

After horizontal drilling is complete, it is followed by hydraulic fracturing method. The purpose of hydraulic fracturing is to create fractures as well as fissures in shale formations and hence, allowing oil and gas to flow into the well. This proven stimulation technique was initially unveiled in 1949 in Eastern United States and then it develops until become a crucial technology in producing oil and natural gas. Fracturing will start in the bottom of the well or called it as ‘farthest’, and continues toward the heel end which is near to vertical wellbore. (Statoil, 2013). Even though, a lot of technological methods may be helpful to develop shale gas reservoirs, a perforating gun is the almost widely used technique. In term of creating perforations in the horizontal area, it is requires to have small amount of explosive charges at that particular wellbore.

Low permeability reservoirs such as shale need special stimulation technique called hydraulic fracturing to enhance the oil as well as gas flow from the formation to the wellbore and also to increase productivity. This can be done by injecting fluids and proppant at high pressure and high flow rate into a reservoir so that fractures can be created perpendicular to the wellbore based on the natural stresses of the shale formation. This technique helps to maintain the opening fractures which are created by these hydraulic fluids, so that the gas can flow easily from the formation. Clark, Burnham, Harto and Horner mentioned that number of million gallons of the fluid consisting about 98 to 99.5% proppant and water is pumped at high pressure into the well.

Meanwhile, the rest proportion of this hydraulic fluids is consisted of a mixture of chemicals to increase the fluid's properties. Usually, these kinds of chemicals also include acids, biocides, inhibitors, gels or gums, and friction reducers to enhance the gas flow from shale formation. The functions of these chemicals are shown in the table below.

Table 2: Function of Chemicals in Hydraulic Fluid

Chemicals	Function
Acid	To clean the fractures of formation.
Biocide	To prevent the growth of organism that can clog fractures.
Scale & Corrosion Inhibitor	To protect the integrity/ strength of the well.
Gel / Gum	To increase the viscosity of fluid.
Friction Reducer	To improve the ability of fluid to carry proppant into the fractures of formation.

Hydraulic fluid is pumped into the wellbore through the perforations in well casing and makes the fractures open in the shale formation. This method to ensure that it can create a path through the connecting pores and existing fractures, so that gas can flow back into the wellbore. The function of proppant is to keep the fractures open during the flows back of fluid into the well as the pressure is reduced. Generally, this type of stimulation (hydraulic fracturing) will cover up to 1000 feet of wellbore length at one time. To fulfill this condition, hydraulic fracturing needs to be done in multiple stages for each single well. This multiple stages are isolate by using cement plugs. Once the stimulation technique is completed, these plugs need to drill out from wellbore to ensure the flow of gas. The fluid produced may contain chemical substances that present naturally in reservoir such as hydrocarbons, minerals, salts, and naturally radioactive minerals which often leach into mixing fluid between hydraulic fracturing fluid and brine contained in the formation.

2.5 Pad Drilling and Multilateral Drilling

Advanced technology manages to create new concept of drilling operation which are from single well to the multi-well drilling processes. It is an alternative method to drill multiple wellbores from a single surface location. Definitely, this method can solve a lot of issues such as time, money, energy and also in perspective of environmental. Usually, an operator would drill a single location, disassemble the drilling rig, move it to a new location, and then repeat the process. (Thuot, 2014). This situation will consume a lot of time and money that would be spent for packing and moving rig at new location and also will have negative impact on the area landscape. Therefore, by using pad drilling means more wells can be drilled from a single location which can saves time and money.

Technical Advancement of Multi-Laterals (TAML) defines multi-well as wells that having one or more branches (laterals) attached back to a main wellbore. This branch can be vertical or any inclination up to horizontal direction. There are various kinds of multilateral wells. Husain et al. (2011) said that the type of multilateral well for being drilled depends upon the particular qualities in the reservoir such as:

- Geometry of multilateral-well.
- Level of complexity of multi-well in term of junction and its properties.
- Comparison of horizontal well and multilateral-well by using Computer Modelling Group (CMG).

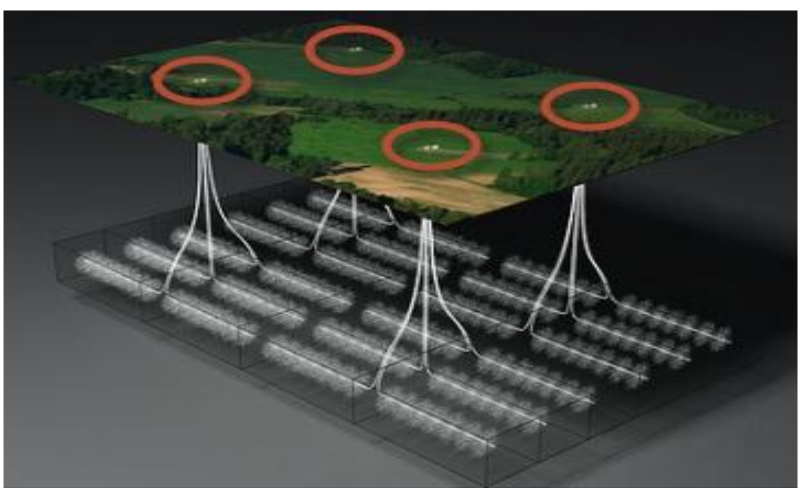


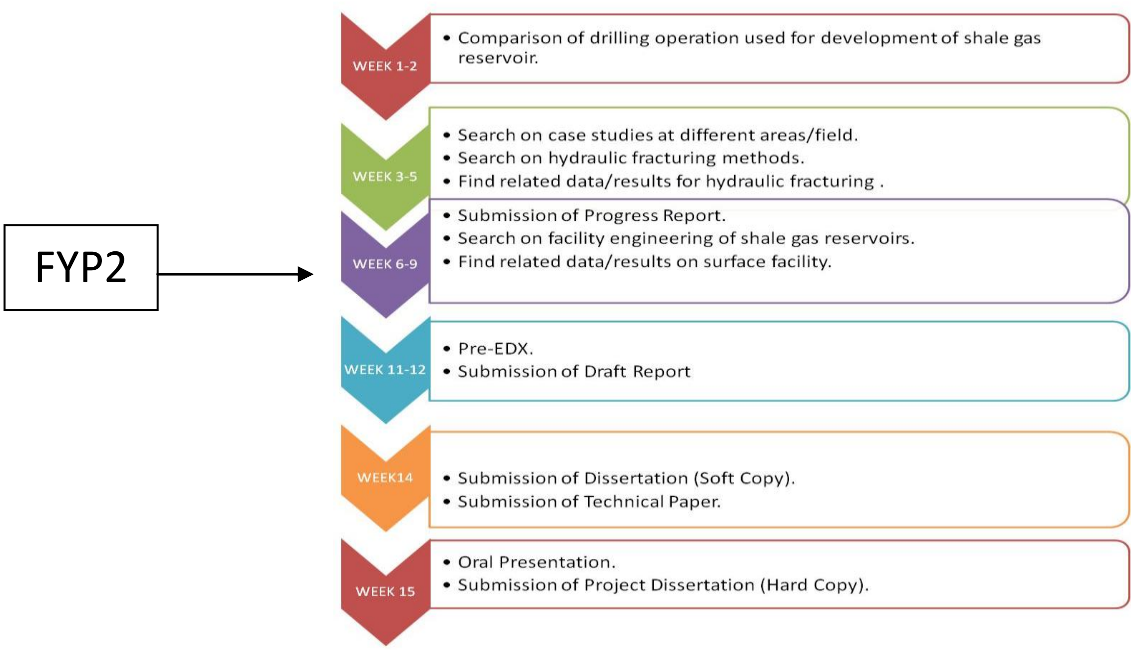
Figure 5: Illustration of pad and multilateral drilling

CHAPTER 3

METHODOLOGY/PROJECT WORK

This chapter covers detail explanations on the key milestone, Gantt chart and methodology to ensure the project to be successfully completed in achieving its objectives.

3.1 Key Milestone



3.2 Gantt Chart

DETAIL / WORK	WEEK (FYP1)														WEEK(FYP2)														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selection of Project Topic	■	■																											
Search acticles about shale gas formation. Understand the concept of horizontal drilling and hydraulic fracturing.			■	■	■																								
Submission of Extended Proposal						■																							
Search on pad drilling and multilateral drilling							■																						
Proposal Defence								■	■																				
Find out potential results for development of shale gas reservoirs										■	■	■																	
Submission of Interim Draft Report													■																
Submission of Interim Report														■															
Project Work Continues															■	■	■	■	■	■	■								
Submission of Progress Report																						■							
Project Work Continues																						■	■	■	■	■			
Pre-EDX																									■				
Submission of Draft Report																										■			
Submission of Dissertation (Soft bound)																											■		
Submission of Technical Paper																											■		
Oral Presentation																												■	
Submission of Project Dissertation (Hard bound)																													■

3.3 Research Methodology

A few methodologies are identified to be carried out in completing this project. The methodologies used are as followed:

3.3.1 Case study

- Conduct several case studies on the background, current condition technique, and improved technologies used for field development of shale gas reservoirs at selected countries by referring to related research papers, articles and journals.

3.3.2 Analysis

- Collect and analyze the result of well testing for development of shale gas reservoirs. Compare it with current conventional reservoirs.
- Analyze horizontal drilling and hydraulic fracturing from selected countries and then, compared with the technique of pad drilling and multilateral-drilling. Make comparison on advantages and disadvantages between current and improved technologies.

3.3.3 Evaluation

- Evaluate the efficiency of gas production when using horizontal drilling and hydraulic fracturing. Then, compare it with the efficiency of pad drilling and multilateral drilling for development of shale gas reservoirs.
- Evaluate the gas production forecast

CHAPTER 4

RESULTS AND DISCUSSIONS

In this section, the results will be divided into five basic topics as shown below:

- Well Test Analysis
- Drilling Operation
- Stimulation Technique
- Surface Facility
- Production Engineering

4.1 Well Test Analysis

In this section, we discuss more on the pressure buildup data from both the prestimulation and poststimulation well tests. For instance, Well Pike 31 in Devonian Shale Reservoir is used to represent these well tests. Buildup tests are very important to be conducted either on conventional or unconventional reservoirs. The objectives of these well tests are as follow:

1. To describe the reservoir condition such as reservoir pressure, skin factor and permeability-thickness product of the reservoir.
2. To quantify the effectiveness of stimulation technique.
3. Results of well tests can be used to forecast production.

Common methodology used for buildup test:

1. Flow the well at constant rate for particular period of time.
2. Shut in the well for adequate time, at the same time record bottomhole pressure versus time.
3. Analyze data by using Horner plots and type curve plots.

Lancaster et al (1989) explained that the pressure-buildup data from prestimulation and poststimulation well test can be analyzed in two ways. First, it can be analyzed by using Horner and type curve analysis technique, whereas, the second way is by performing history-matched with a reservoir simulator. The ways of well test analysis are summarized as diagram below.

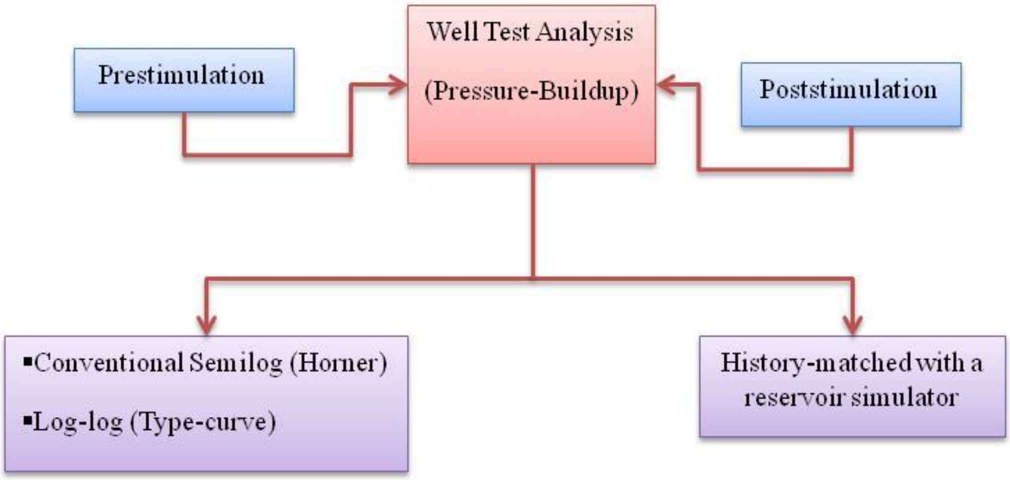


Figure 6: Well Test Analysis

The buildup test analysis of Well Pike 31 estimates a formation permeability of 0.035 md and reservoir pressure of 492 psia. This buildup test indicates that there was small nitrogen breakdown treatment which stimulated the well. The productivity of the well can be improved when the larger nitrogen fracture treatment is applied.

4.1.1 Prestimulation Pressure-Buildup Test Analysis

Prestimulation pressure-build up test indicates that the test was conducted after the nitrogen breakdown treatment. Note that this analysis used adjusted time and pressures which are known as pseudotime and pseudopressure. Peusodtime will give the units of time in hours, while pseudopressure in psia. The function of these adjusted time and pressure are to allow the use of equations derived from oil wells to analyze the gas well. Effective time also been used to adjust the pressure-buildup data to observe the effects of producing time. **Figure 7** and **Figure 8** show the Horner and type curve graphs respectively. From Horner graph, we can calculate a formation permeability = 0.035 md and a skin factor = -3.4 by using the slope of the semilog straight line. The straight line was extrapolated to a reservoir pressure of 492 psia. Using the skin factor calculated from this test analysis and also effective wellbore radius concept, it actually can estimate an effective fracture half-length which about 20 ft, then it assumes as infinite-conductivity fracture.

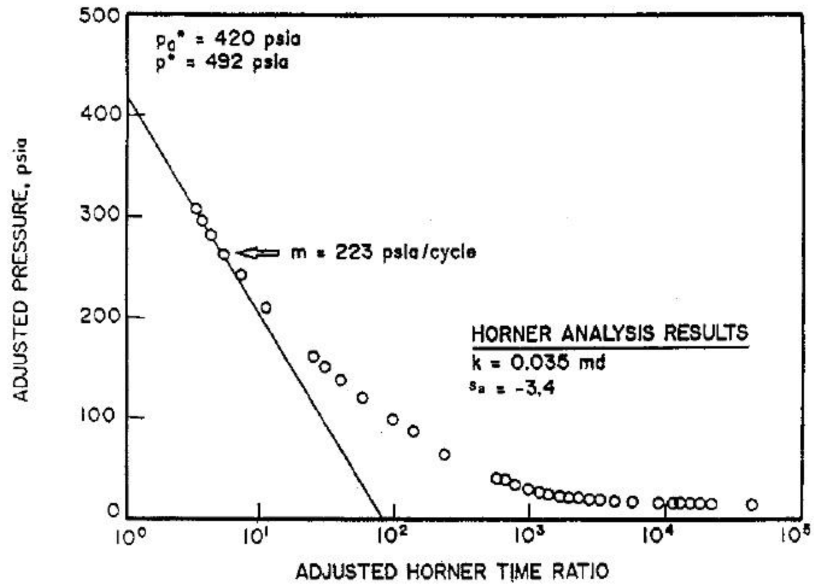


Figure 7: Horner Analysis of prestimulation pressure-buildup test from Well Pike 31 (Lancaster, 1989)

Next is type-curve analysis as shown in **Figure 8** below. The objectives of this type curve are to verify the Horner analysis and to conduct quantitative analysis. In this case, the type-curve is for radial flow with wellbore storage and skin effects. The curve $C_De^{2s} = 1.0$ shows that it matches most of the data of prestimulation buildup test. From this match, the skin factor is obtained = -3.4 which is the same value with Horner analysis.

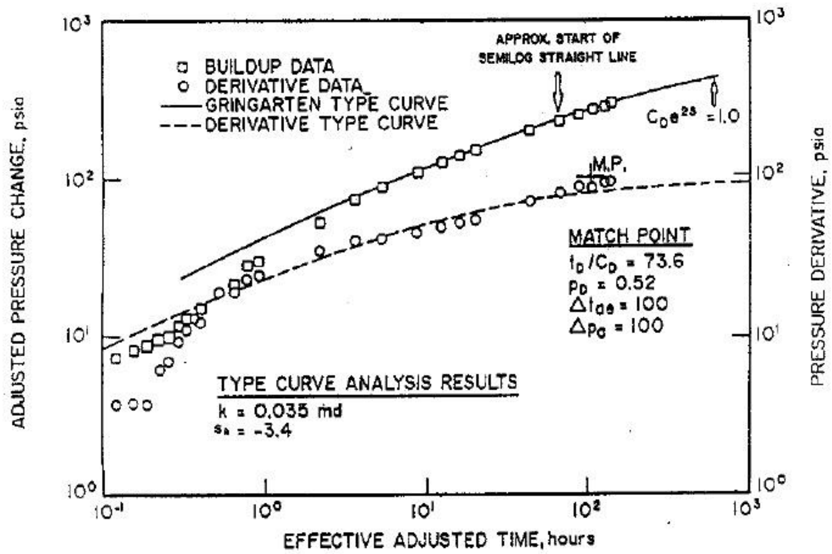


Figure 8: Type-curve Analysis of prestimulation pressure-buildup test from Well Pike 31 (Lancaster, 1989)

The test data from both prestimulation and poststimulation then were history-matched with a reservoir simulator called FRACSIM (Fracture Simulation). The function of FRACSIM is to substantiate further results from the conventional analysis. In this case, the results of two methods from Horner and type-curve analysis show that the nitrogen breakdown treatment slightly stimulated the well. **Figure 9** shows the history match of the prestimulation buildup test with the permeability = 0.035 md and skin factor = -3.6.

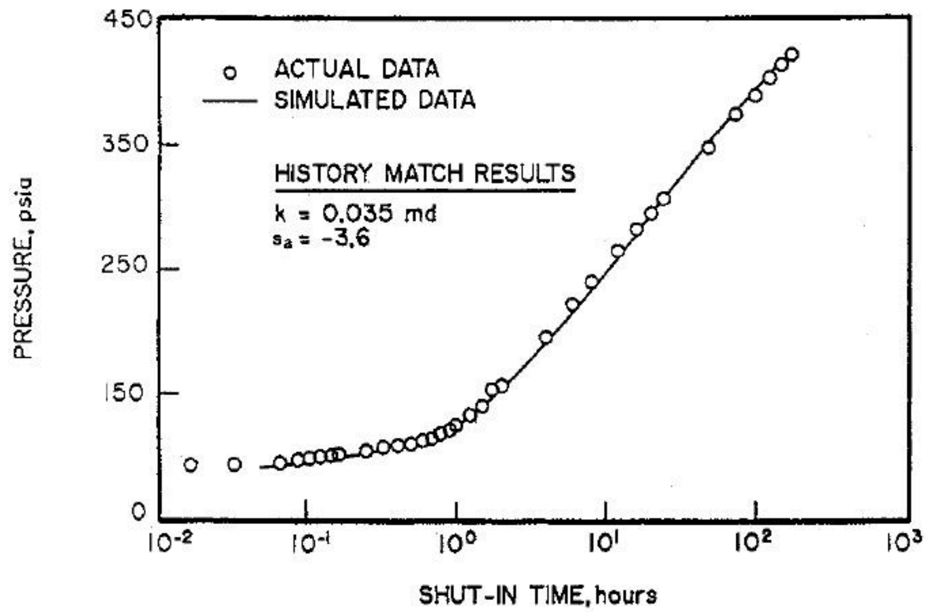


Figure 9: History match of the prestimulation buildup test(Lancaster, 1989)

4.1.2 Poststimulation Pressure-Buildup Test Analysis

The different of poststimulation with prestimulation is this poststimulation pressure-buildup test was conducted after the large volume nitrogen fracture treatment. The result from semilog analysis (Horner) shows that the permeability is same with the result from prestimulation pressure-buildup test which is 0.035 md. Whereas, the skin factor had improved from -3.4 to -4.1 due to large nitrogen treatment as shown in the **Figure 10**. The fracture half length also increases from 20 ft to 38 ft that indicates as infinite-conductivity fracture. Meanwhile, the results of type-curve and history matched are same between prestimulation and poststimulation pressure-buildup analysis.

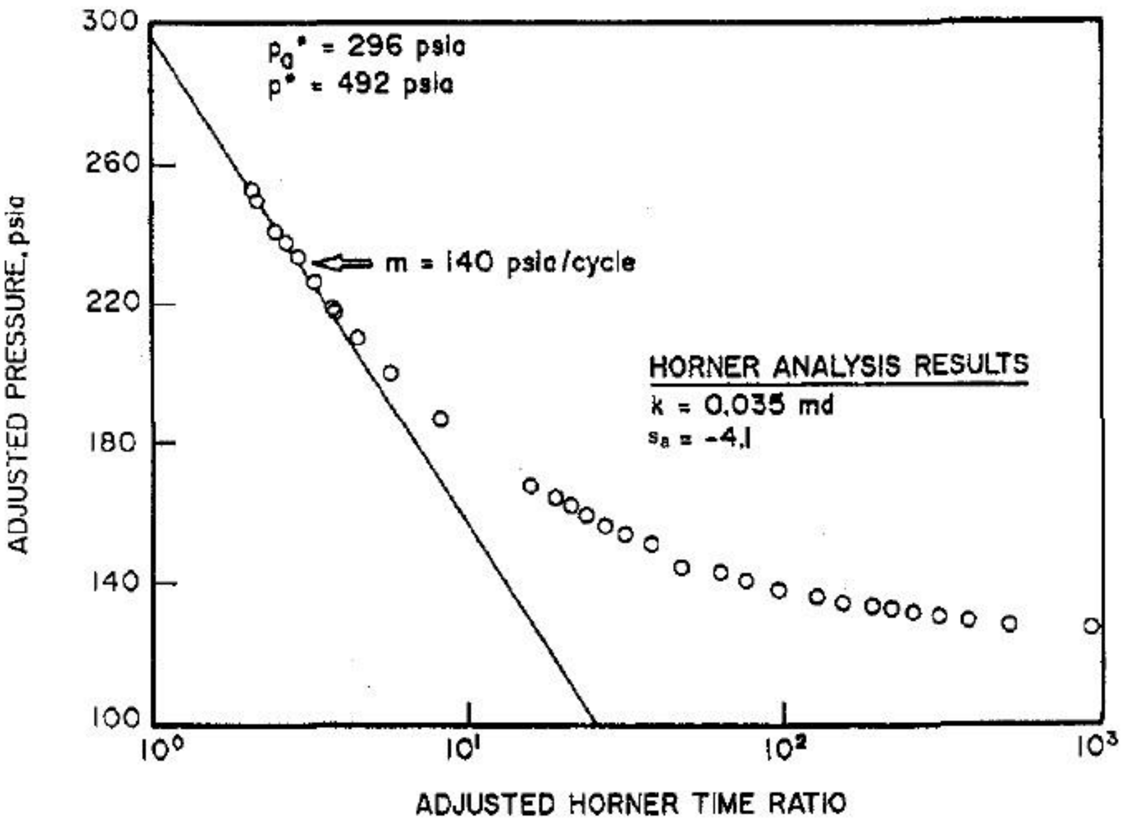


Figure 10: Horner Analysis of Poststimulation Pressure-buildup Test from Well Pike 31 (Lancaster, 1989)

4.1.3 Pressure Buildup Test Not Long Enough

Murtha, J. A., & Lancaster, D. E. (1989) mentioned the common problem of pressure buildup test in shale gas reservoirs is the test was not run long enough to achieve its objectives due to the data were masked by wellbore storage effects. A wellbore storage effect is the phenomena which affects bottomhole pressure as results when the well is shut in (pressure buildup test). Even though the well is shut in, but the gas from reservoir continues to flow into the wellbore and compress the gas that is trapped here. Thus, several ways can be done to run pressure buildup test long enough.

- Long Shut-in

  The easiest way to ensure a test is run long enough is by performing shut-in the well in the period of time that extends over wellbore storage effects. However, the flow period should generally exceed the shut-in period. Thus, the overall testing period will be two times the build-up period.

- Decreased Wellbore Volumes

  Decreased wellbore volume can shorten the time for buildup test. Wellbore volumes can be reduced by running production tubing with a packer which set a small distance above the top and at the bottom of perforation.

- Prestimulation Well Tests

  This solution can be performed to reduce time of poststimulation buildup test for wells that are to be fractured. Prestimulation buildup test is running to estimate the permeability of that treatment. This is helpful method because knowing the permeability of prestimulation buildup test can analyze poststimulation buildup test of short period.

4.2 Drilling Operation

4.2.1 Horizontal Drilling

This part will discuss on the technique used for drilling operation at shale gas reservoirs. Generally, vertical drilling is the common technique used in the industry to reach the pay zone of oil or gas. However, directional/horizontal drilling offers significant advantages over vertical drilling in developing shale gas reservoirs as shown below:

- Able to reach a much wider area of rock and natural gas that is trapped within the rock.
- Hit targets that can not be reached by vertical drilling.
- Drain a broad area from a single drilling pad.
- Increase the length of the “pay zone” within target rock unit.
- Improve the productivity of wells in fractured reservoir.

However, in term of drilling operation cost, definitely horizontal drilling has higher cost which about USD 5 to 8 million compared to vertical drilling which is about USD 1 to 3 million. Obviously, horizontal drilling is more costly as its process more complicated because it needs to add more pipe, deeper length and long horizontal run.

To understand more about vertical and horizontal drilling, Barnett Shale from the report of Partners, P. E., & Pursell, D. (2005) is used to represent the drilling operation used to develop shale gas reservoirs. Barnett is one of the largest and most avtive domestic natural gas plays in U.S.

Figure 11 shows the decline curves for vertical Barnett wells drilled in 1999 until 2003. As expected, the high initial decline rate can be seen at the early time followed by flatter decline rate in following years. Based on the graph, initial decline rate was 65% in year 1999. But then, drop to 60% and finally decline rate is observed about 10% in years 4-5.

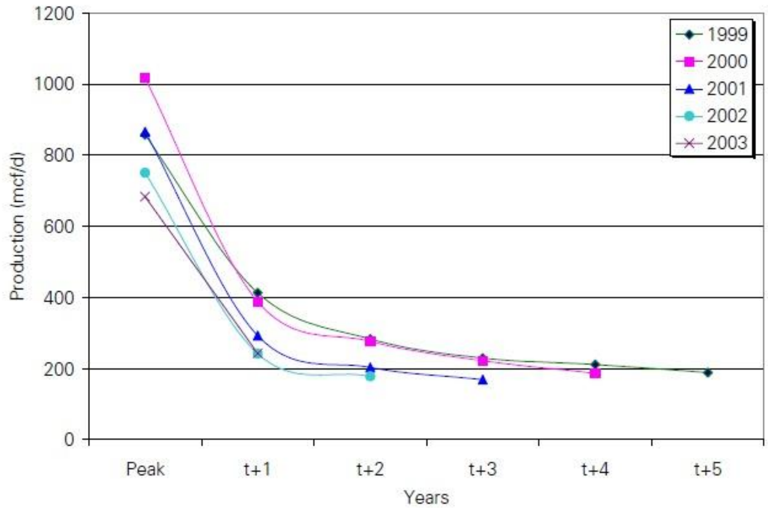


Figure 11: Vertical Well Decline Curve (Partner & Pursell, 2005)

Next, **Figure 12** shows horizontal well decline curve which it can be observed that the graphs appear to have shallower decline curve than the vertical drilling. However, in this case, there is only 2002 and 2003 data due to lack of a significant sample size. The 2003 graphs show that the initial decline rate appears to be 50-55% which is lower than the vertical well decline curve.

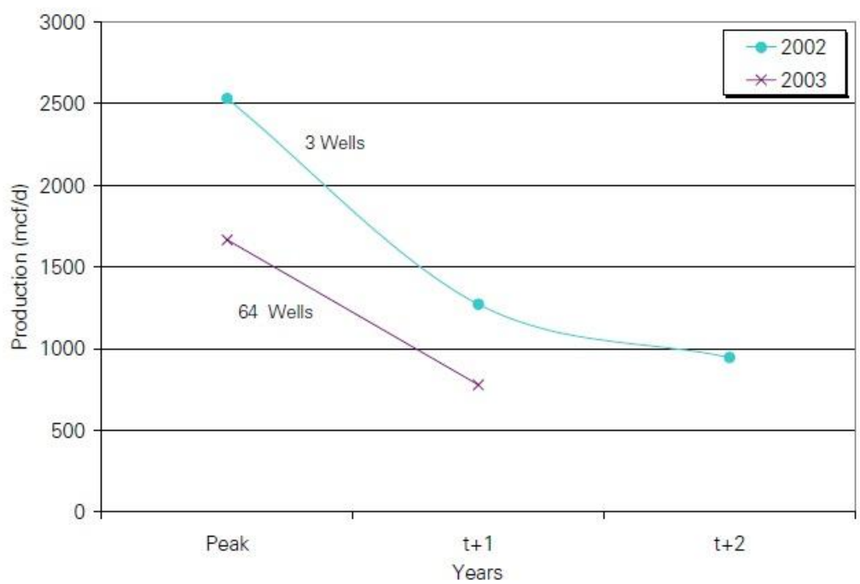


Figure 12: Horizontal Well Decline Curve (Partner & Pursell, 2005)

4.2.2 Pad and Multilateral Drilling

New technology manages to come out with brilliant idea to produce gas from multilateral well from a single pad. Husain, T.M., et al. (2011) stated the advantages of multilateral wells as follow:

- Higher production - Higher contact with the reservoirs which improve recovery.
- Decreased water/gas coning – Position of lateral within the producing formation provides enough distance to the water and gas zone.
- Improved sweep efficiency – The recovery can be increased due to the area covered by the laterals.
- Fast recovery – Production from the multilateral wells is higher than single horizontal well.
- Decreased environmental impact – Volume of consumed drilling fluids and generated cuttings during drilling multilateral wells are less compared to separated wells.
- Saving time and cost.

Figure 13 shows the comparison of cumulative gas production between multilateral-well and horizontal well done by Technical Advancement of Multi-Laterals (TAML). It can be observed that the gas production increased about 2.00e+9 standard cubic feet (scf), compared to horizontal well over a period of five years.

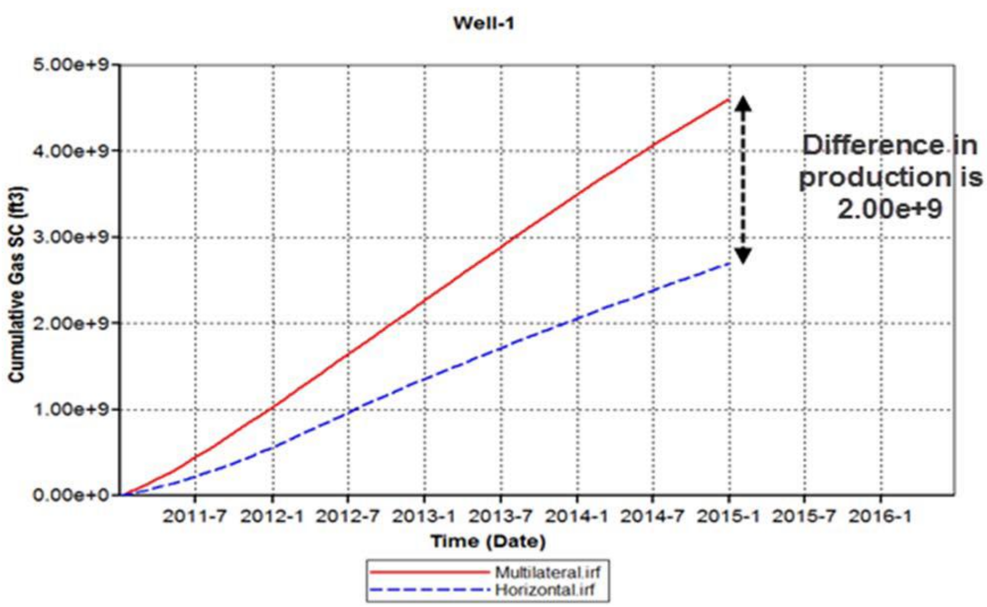


Figure 13: Comparison of Cumulative Gas Production between Multilateral and Horizontal Well (Hussain, 2011)

4.2.3 Pad Drilling Practices

This section will discuss pad drilling practices in Marcellus shale reservoir. The pad comprises an area about 5 acres in size and includes enough wells to extract the gas from 500 to 1,000 acres. In 2009, one drilling rig would drill 8 to 12 wells per year, but the number of wells doubled at certain areas. The **Figure 14** shows the reduction of drilling days and completion cost per stage for pad drilling application based on the result from Cabot Corporation in May 2013. Obviously, pad drilling practices gradually decreased the period of drilling operation as well as the cost from 2009 to 2012.

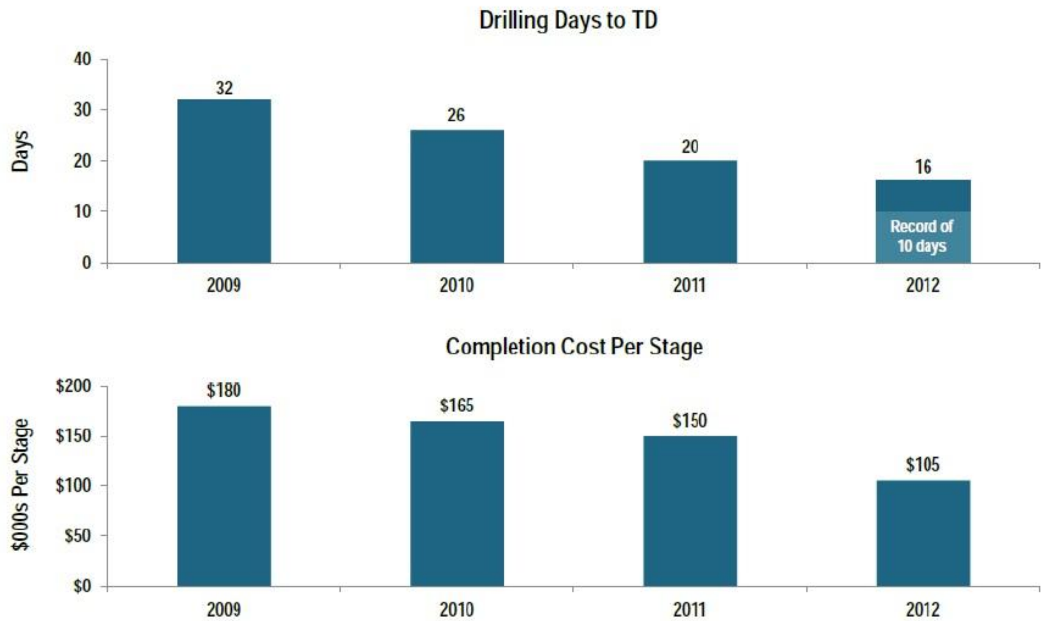


Figure 14: Drilling time and completion cost reduction over time. (NETL, 2013)

4.3 Hydraulic Fracturing

4.3.1 Effects of Different Parameters

This section will focus on the effects of different parameters on shale's breakdown pressure. Technically, breakdown pressure is used to calculate horizontal stress during hydraulic fracturing stress measurements. The parameters include fluid type, injection rate, shale bedding, acid injection and different additives. This experiment was done by using the cores from a Mancos Shale outcrop performed by Gomaa, Qu, Maharidge, Nelson, & Reed (2014).

a) Fracture Fluid Viscosity

Fluid is chosen mostly on its capability to carry proppant, but at the same time with a little attention to its ability to break down the shale formation. In this experiment, pressure drop was recorded as the function of time during the injection of four different fluids which were 3 wt% KCl solution, isobar oil, linear polymer gel (35 pptg guar), and crosslinked polymer gel (35 pptg guar). These fluids were injected into four different Mancos shale cores, respectively with an injection rate of 5 ml/min.

The injection pressure was continuously increased till the shale broke at a certain pressure (the breakdown pressure) as each fluid was injected into the core. **Figure 15** shows the viscosity of the different fluids and **Figure 16** shows the corresponding breakdown pressure obtained when pumping them into the core. It can be observed that the lowest viscosity (3 wt% KCl) solution broke down the shale formation at 1100 psi, while the highest viscosity (crosslinked gel) broke down the shale formation at 2700 psi.

Based on the results from **Figure 15** and **16,** it shows that lower fracture fluid viscosity, the lower pressure needed to break down the shale formation. Meanwhile, a higher fracture fluid viscosity will require a higher pressure to break down the shale formation. Thus, it is confirmed that the fracturing fluid viscosity has strong relationship with the breakdown pressure in a shale formation.

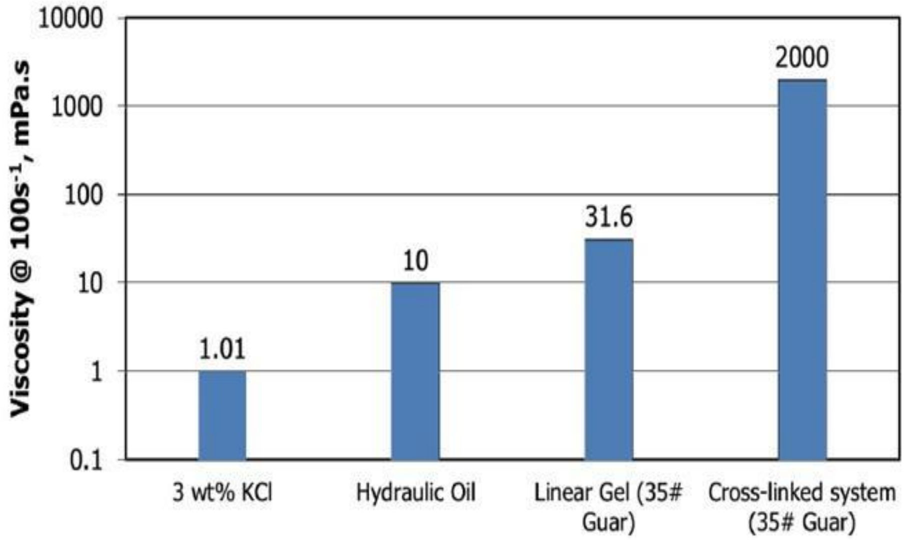


Figure 15: The viscosity of the different fluids (Gomaa, 2014)

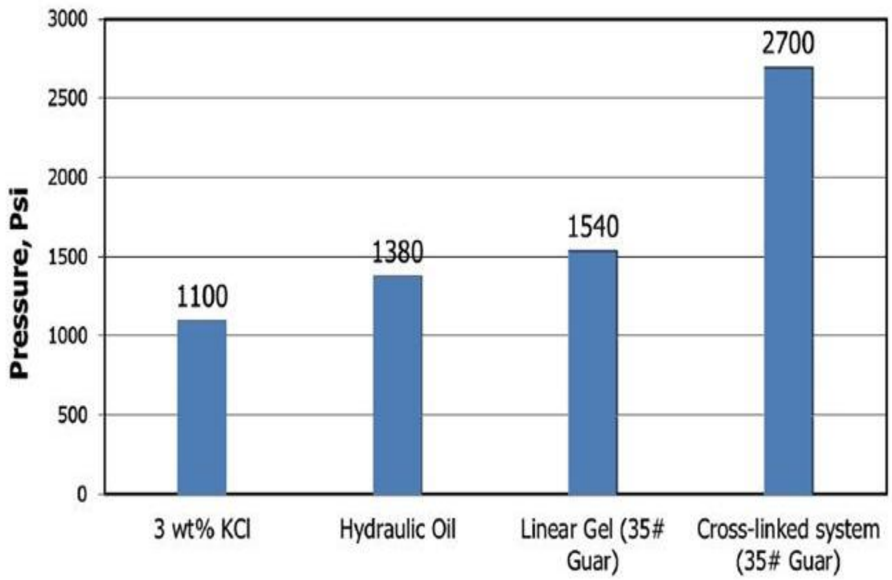


Figure 16: Breakdown pressure by using different fluids (Gomaa, 2014)

In addition, shale formations are also characterized by microfractures and existing breaks. **Figure 17** shows two different situations when low and high viscosity is injected into the shale cores. Low viscosity fluid will penetrate the microfractures and breaks easily. As results, the shale cores will be much weaker and it allows the low viscosity fluids to break the formation at low pressure.

Meanwhile, the high viscosity fluid tends to remain inside the core's hole as high viscosity fluid unable to penetrate through microfractures and breaks. For that reason, if high viscosity fluid is used, thus it requires higher pressure to break or split the shale core.

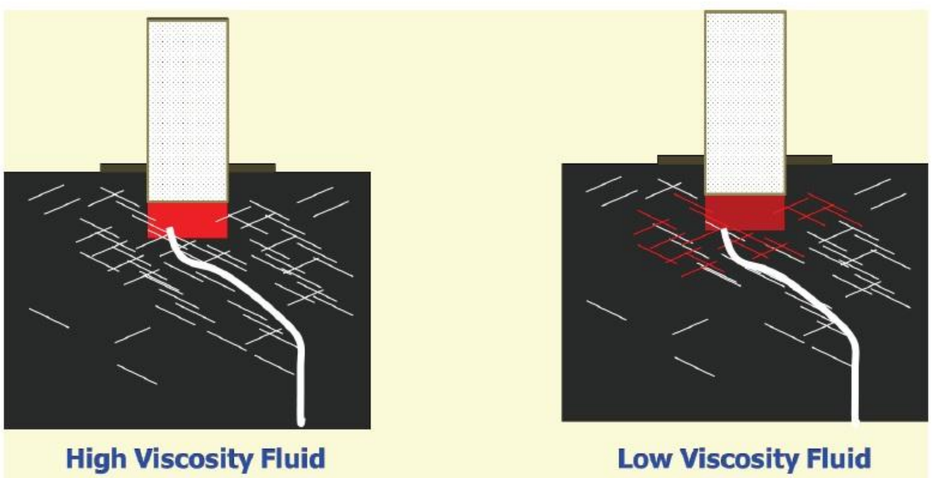


Figure 17: Illustration of fluid penetration at different viscosity (Gomaa, 2014)

b) Injection Rate

As shown in the **Figure 18**, it can be seen that higher injection rate will require less breakdown pressure. This will allow more injection fluid to flow into the shale core at higher injection rate and definitely it can transmit the injection pressure to wider area of shale fracture. Thus, injection rate is proportional to the pressure buildup pressure rate.

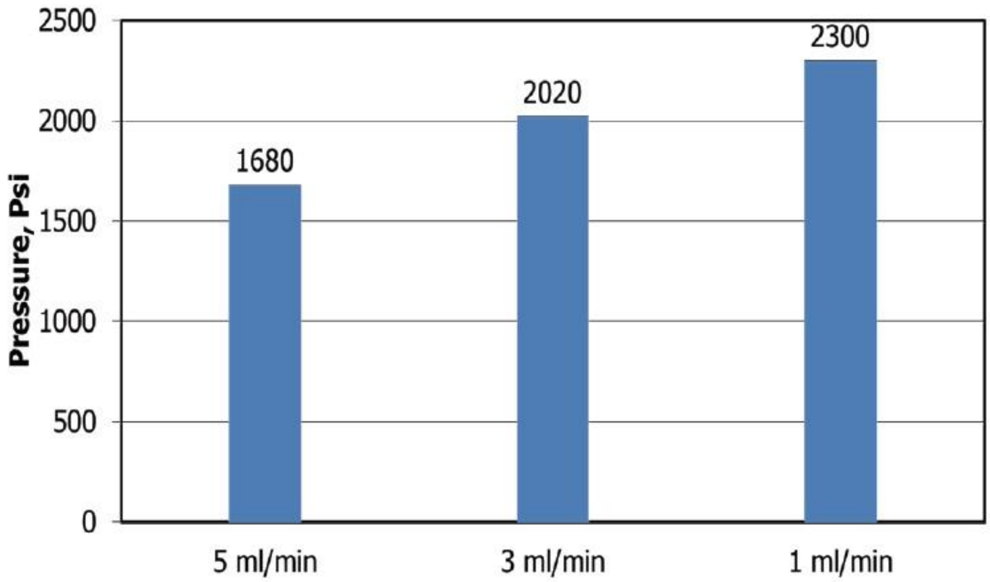


Figure 18: Pressure vs Injection Rate (Gomaa, 2014)

c) Friction Reducers

Increase the friction reducers concentration will increase the breakdown pressure of shale formation. As shown in **Figure 19**, adding 1 gpt (gallons per 1,000 gallons of frac water) increased the breakdown pressure by 240 psi which is from 1680 to 1920 psi. Meanwhile, when the concentration is increased to 4 gpt, the breakdown pressure will increase by 920 psi (from 1680 psi to 2600 psi). In other word, it is difficult for injection fluid to enter the microfractures and breaks of shale formation when using high concentration of friction reducers and then it requires high breakdown pressure.

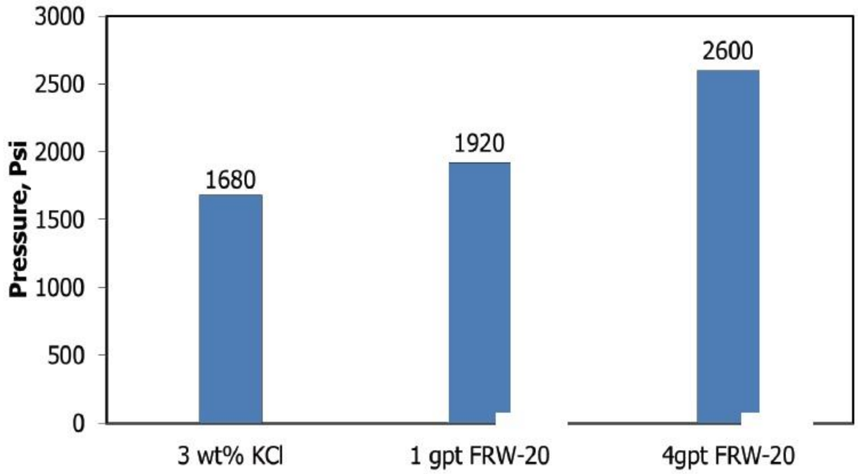


Figure 19: Pressure vs Friction Pressure Concentration (Gomaa, 2014)

Figure 20 shows clearly that injection fluid of 3 wt% KCl can flow easily due to its less viscosity when compared to 1 and 4 gpt. High volume of fluids could be injected as time increases. As been explained earlier, higher viscosity of solution such as 1 and 4 gpt will lead to high shale breakdown pressure. Increasing the friction reducers concentration can reduce the flow of injection fluid inside the core that makes the breakdown pressure to increase as well to ensure it can enter the shale fractures.

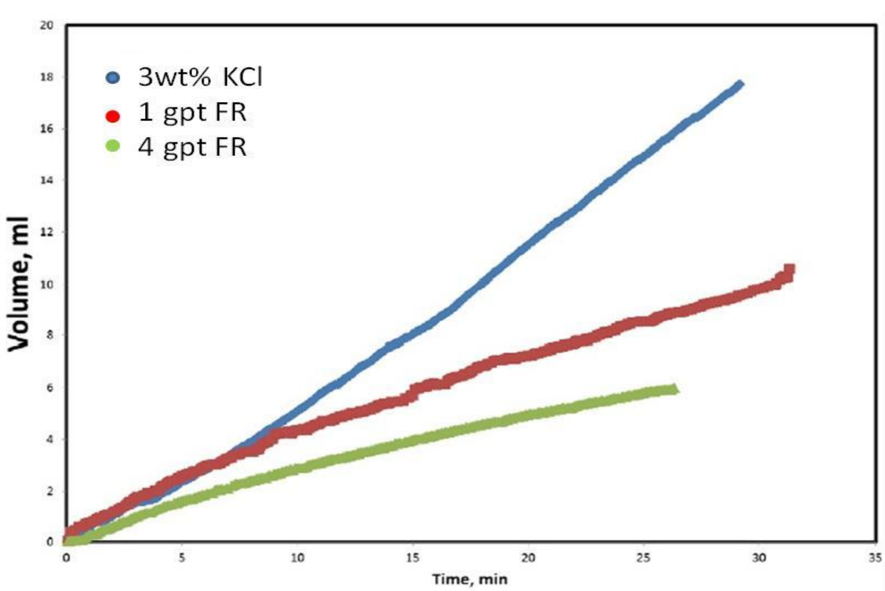


Figure 20: Volume of injected fluids vs. Time (Gomaa, 2014)

d) Acidic Fluids

The experiment was performed by injection of acidic fluid in front of a crosslinked gel. It can be seen that the breakdown pressure required to fracture the shale formation is high which is 2640 psi is. But then, the breakdown pressure reduced dramatically to 800 psi when injecting 3ml of 15 wt% HCl before the crosslinked fluid as shown in the **Figure 21**. The results of this experiment confirmed that the acidic fluid decreased the breakdown pressure because the acidic fluid enhances the leakoff, and thus creates additional channels of shale formation during the fracture initiation. Even tough, the crosslinked gel shows highest viscosity, but it still can reduce its pressure breakdown by injecting acidic fluid.

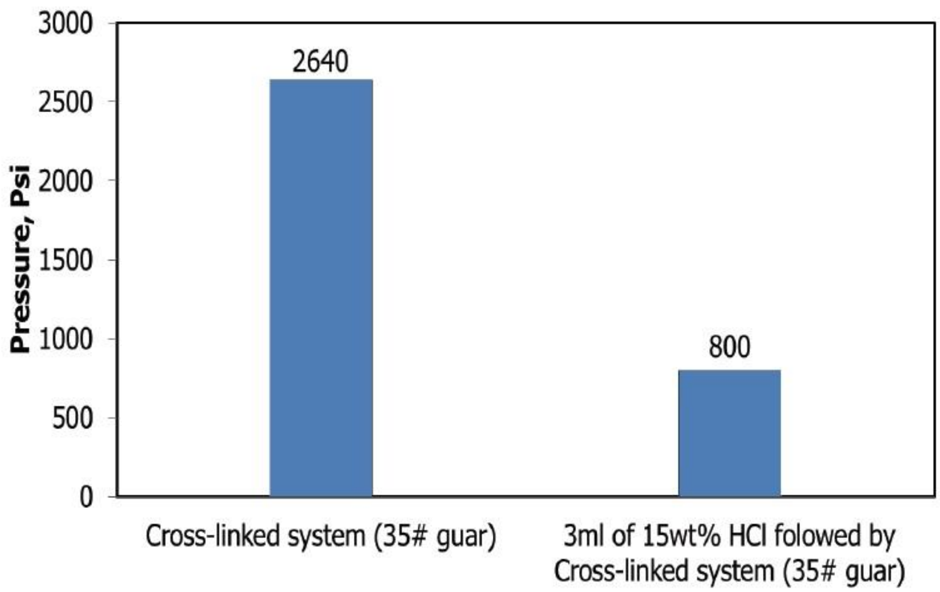


Figure 21: Breakdown Pressure vs. Injected acidic fluid (Gomaa, 2014)

e) Nitrogen as Fracture Fluids

Figure 22 shows the different pressure breakdown when using different type of fracture fluids. For 3 wt% Kcl required 1680 psi to create fracture of shale formation. But the different scenario is observed when using nitrogen (N_2) as fracture fluid. N_2 was able to reduce the breakdown pressure even more to 800 psi. This is happen because N_2 is a gas which can propagates more easily into the microfractures. As a result, N_2 can be more efficient at transferring the injection pressure to more weak points because the ability of gas to store pressure energy. Thus, N_2 can break the shale formation at lower pressure.

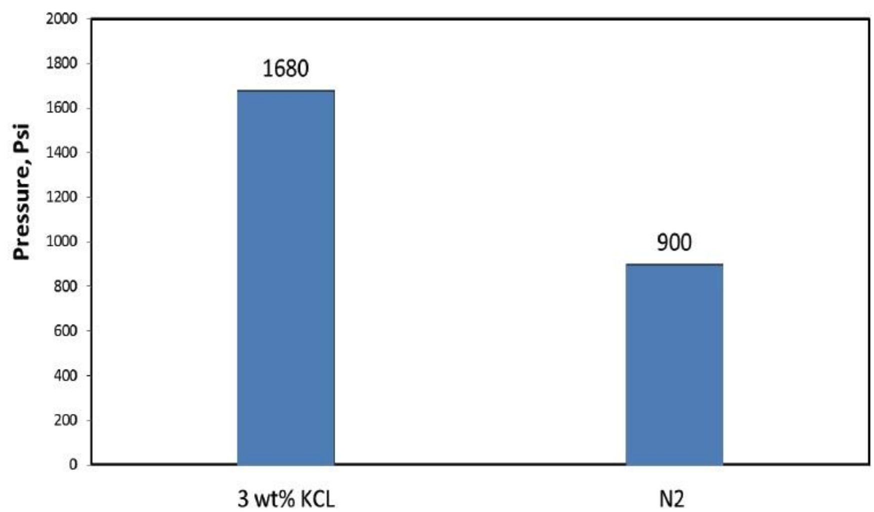


Figure 22: Pressure vs. Fracture fluids (Gomaa, 2014)

4.3.2 Channel Hydraulic Fracturing Technique

This section will discuss the results obtain from the simulation and case study in the Marcellus shale as explained by Ayaji, Walker, Wutherich and Sink (2011). They mentioned that there was increased in gas production from the new technique compared to conventional fracturing method.

The function of hydraulic fracture is to pump fracture treatments with high viscosity gelled fluids together with large quantities of proppant so that conductive channels of shale formation can be created from reservoir to the wellbore. This stimulation method creates stable channels or paths for hydrocarbons to flow through rather than depending on the proppant pack permeability. It has been proven to significantly improve conductivity as the pressure drop across the fracture is decreased. At the same time, it will increase effective fracture half-length, and thus improved production.

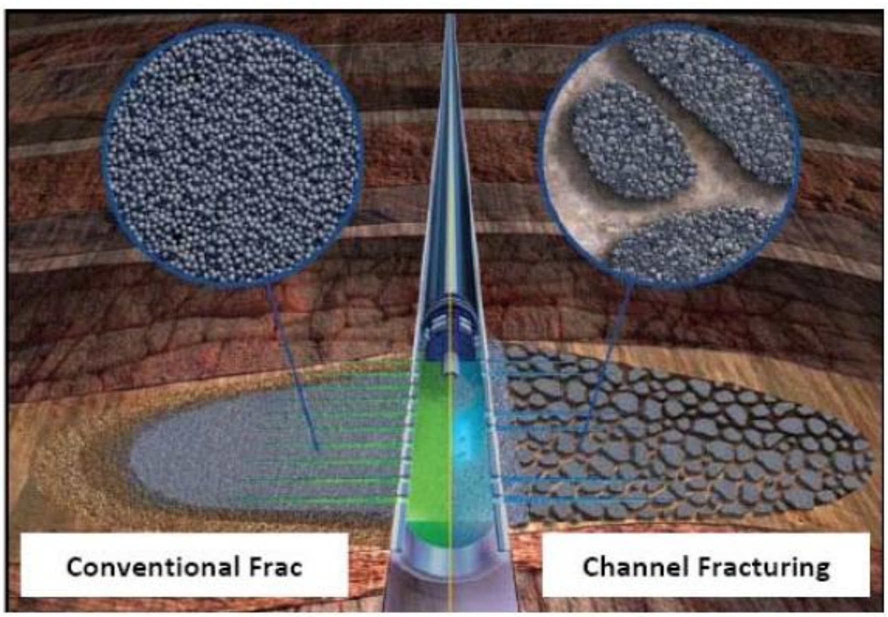


Figure 23: Comparison between Conventional Frac and Channel Fracturing (Ayaji, 2011)

4.4 Surface Facility

4.4.1 Wellpads Facilities

Typically, shale gas field is made up of wellpads, which is each of it attaching a variable number of well heads between 4 and 20. A wellpads' function is to handle biphase gas/water saturation. However, tri-phase separators still can be employed for significant condensate production. Separator skid is usually used for each wellhead so it will have better control on production and also better management for sand production and flowback water due to hydraulic fracturing technique. Another important function of wellpads is the gas lift supply for case of excessive high water cut in the tubing.

Generally, wellpad gaseous effluents are piped to a central treatment plant so that hydrocarbons can be treated to meet sales specification. Then, the separated liquids (gas) will be either transmitted by pipeline or stored in the tanks at wellhead, which can be periodically transferred by truck. Other situation such as hydrocarbon condensate present at the wellhead, they can be delivered directly to a refinery or to the gas treatment plant.

Salt water production is usually disposed by using dedicated reinjection wells. However, recently there is an issue to avoid reinjection by focusing on water treatment, so that it can optimize shale fracturing activities supply by recycling the water itself. **Figure 24** explains the above description.

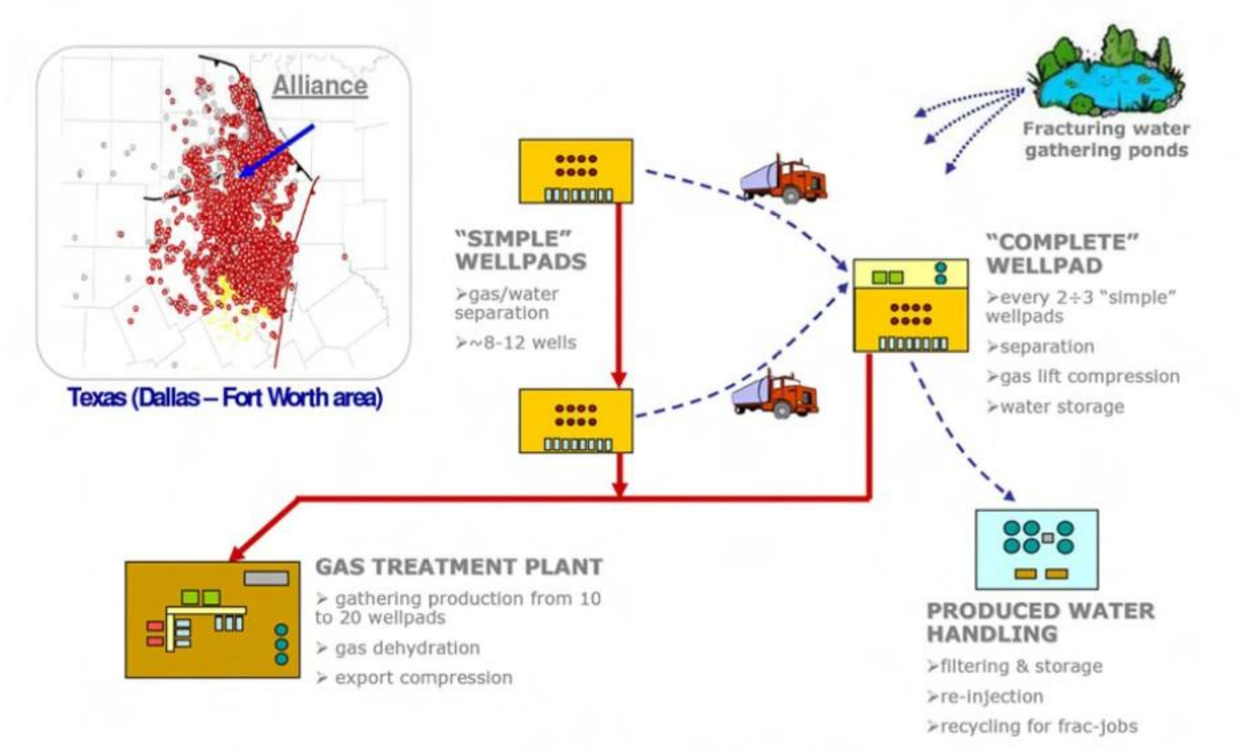


Figure 24: Shale gas field surface architecture scheme (Mancini, Zennaro, Buongiorno, Broccia & Chirico, 2011)

One of the important aspects about shale gas development is the wellpad facilities. They have to be simple, cost effective, secure and compliant with the subsurface simultaneous operations as they need to be replicated many times during progressive development. It also requires to be interconnected with large multi-branched network. Here, the operation of gathering network can be said as totally crucial because shale gas well pressures and flow rates are swing regularly along the decline trend.

Last but not least, in this unconventional development surely affects contracting strategies and sale gas production profile. When there is close interaction exists between Exploration, Development, Production and Marketing, definitely shale gas projects becomes profitable compared to conventional resources. The important factors to maximize the returns of a given project include the cost, efficiency optimization of each of above aspects and also the optimization of the integration at basin level.

4.4.2 Multi-well Production Facility

This case study has been done by Hutchinson (2014) through his paper published for Unconventional Resources Technology Conference. He mentioned that there was an independent oil and gas operator asked for assistance in establishing modular, multi-well facilities for its Western U.S. well sites. To summarize the project at high level, the gathering facilities in this case were focused on the transportation of gas and commingled oil and water through two separate pipelines to a central processing facility (CPF).

CPF which is situated near the wells has the function to support the production needs of multiple wellheads, interim storage for oil and water, provides three-phase separation, and also export support for natural gas, oil and water from a single, centralized site. The efficiency of multi-well system for long period can be maximized through consolidation of processing functions and sharing them amongst multiple wells. Thus, it can save the operators processing and reduce maintenance costs for servicing of the various wells.

The system had been hydraulically optimized according to well type-curves and total expected production data so that it can maximize the capacity and reduce pressure drop. Apart from that, mobile, skid mounted pigging facilities were used to prevent blockage and line accumulation, and make it easy for relocation when pipelines were extended.

Generation of Multi-Well Production Facility

- First generation of multi-well production facility – Allowed well completions to be staggered into a central location. The number of compressors and gas scrubbers were reduced as well as the tank battery capacity through consolidating gas production.
- Second generation of the multi-well production facility – Reduced equipment requirements by introducing bulk separation with test units for allocation. This reduced equipment usage, thus allowed for further land savings.

- Third generation of the multi-well production facility – Meshed the multi-well design with the CPF and gathering system. Here, the stage of three phase separation and tank storage were eliminated as the production was delivered directly into the gathering system and then to the CPF.

Advantages of Multi-Well

- Economic Costs Savings
  Multi-well is the cost saving technology of drilling as it can produce gas from several zones through the same pad across multiple locations in a reservoir. The production can be optimized by using this technology, and at the same time it will have better manage equipment costs. Moreover, the period for site construction can be reduced due to centralization of multi-wells and equipment functions. As a result, it allows for improved speed-to-market with more products and contributing more revenue.

- Safety and Risk
  Integrating between strong engineering technology and safe facilities design will reduce the risk during increasing production at well sites. When these two factors combine together, definitely they can create high volume site with high level of safety.

- Environmental
  The centralized multi-well facilities design can reduce the site's environment impact. This situation can be achieved as it decreases land disruption and has better management on handling source emissions. Furthermore, multi-well sites lower the quantity of additional acreage required for extra pads, and thus hydrocarbons can be produced successfully as the amount of subsurface disturbance decreases.

Table 3 shows an example of the efficiency gains due to properly implemented multi-well optimization project. It shows that the operators can see their equipment requirements decrease for each project generation. It shows that the number of wells per node are increases for each generation but however, the number of separators requires for multi-well are decreases. As project generation increases, the size of land used per well reduces which describes that less environmental impact in that area. The optimization can be observed when the amounts of oil (bbl/day) and gas (MMscfd) increases as the number of wells per production facility increases within 3 months.

Table 3: Multi-well Optimization Project Lifecycle (Hutchinson, 2014)

	Project Generation 1	Project Generation 2	Project Generation 2.1	Project Generation 3
Site Footprint	525 x 375 (4.5 acres)	550 x 450 (5.7 acres)	575 x 530 (7 acres)	400 x 400 (3.7 acres)
Number of Wells per Node	8	16	32	32
Number of Separators	16	12	12	10
Land Use per Well	0.56 acres	0.36 acres	0.22 acres	0.12 acres
GAS (MMSCFD)—Peak expected	10	10	15	15
OIL (BBL/day)—Peak expected	2,450	4,000	6,000	6,000
Time to Build	3 months	3 months	3 months	3 months

4.4.3 Gathering and Processing

The production of shale gas at the surface needs to be gathered into the natural distribution and transmission network. Generally, the gathering lines required 6 in – 20 in of diameter pipelines to transmit the raw natural gas to processing facilities. The process of removing condensate and water from the raw gas occurs at the wellhead before it can be transferred to the gas processing facility. From here, other constituents in gas should be removed in order to make sure the processed gas fulfills pipeline specifications.

Natural gas processing started with the removal of acid gases includes carbon dioxide, hydrogen sulphide, and organo-sulphur compounds. From here, the natural gas stream will undergo dehydration process to remove water as well as removal of mercury and nitrogen. Next, gas stream will pass through demathanizer to split natural gas from the pipeline-quality gas which is sent to transmission lines. Further separation process can be done at NGL fractionation where the high value of ethane, propane, butane and C5+ can be separated. This separation process is shown in flow-chart below.

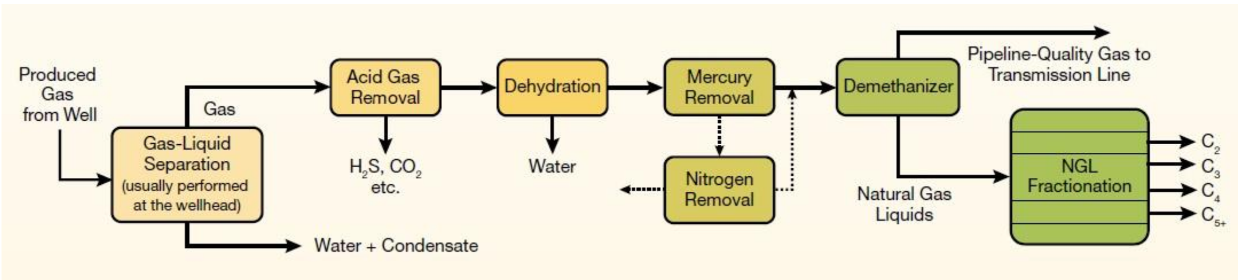


Figure 25: Series of processing steps at the wellhead and processing plant. (Goellner & Hamilton, 2012)

4.4.4 Transport Natural Gas to Market

The natural gas is transported from processing facilities to market via transmission pipelines which is 20 to 48 in diameter. However, the establishment of transmission and distribution network still requires modification to increase the natural gas demand.

4.5 Gas Production Forecast

4.5.1 Production Potential of Devonian Shales

This section will discuss more on the production potential at Devonian shale in state of Ohio. Based on the report published by Kuuskraa and Wicks (1983), they analyzed different parameters that can affect future production based on the three cases as explain below.

- Radial stimulation (r’w = 30 ft)
- Small vertical fracture (x_f =150 ft) – hydraculic fracturing with small volumes of fluid (< 40,000 gallons)
- Large vertical fracture (x_f =600 ft) – advanced technology with large volumes of fluid (> 150,000 gallons)

They stated that the production potential from the target sequence of Devonian shales ranges from 6.2 Tcf to 22.5 Tcf. **Table 4** shows the value of production potential in 40 years by using different stimulation method. Borehole shooting and current field development practices have low value of production potential. Meanwhile, high end of the range reflects well stimulation by advanced stimulation technology such as vertical fracturing and radial stimulation and also alternative field development method.

The low end of the range reflects well stimulation by borehole shooting and current field development practices. The high end of the range reflects application of advanced stimulation technology (vertical fracturing and radial stimulation) and usage of alternative field development methods. Production by Area and stimulation technology is shown in the Table below.

Table 4: Production Potential, by Area and Stimulation Method (Kuuskraa & Wicks,1983).

Partitioned Area	Total Drillable Area (Sq.Mi.)	Gas in Place (TCF)	Production Potential (TCF) in 40 years			
			Borehole Shooting	Radial Stim. r'w = 30''	Small Vertical Fracture xf=150''	Large Vertical Fracture xf=600''
I	543	4.1	0.84	1.16	1.58	2.35
II	3577	12.4	2.95	4.06	4.67	6.21
III	2869	4.4	1.46	1.98	2.33	3.04
IV	2641	24.8	0.84	1.35	1.78	3.38
V	313	0.4	0.05	0.06	0.06	NA
VI	1035	3.3	0.04	0.07	0.09	0.2
TOTAL	**10978**	**49.4**	**6.18**	**8.68**	**10.51**	**15.18**

Another important parameter that can affect the production in the future is the pattern of drainage. In their analysis, three types of drainage had been examined to discover which drainage pattern will give highest cumulative gas recovery for three stimulation technologies mentioned earlier. The three types of drainage include:

- Square pattern
- 3 x 1 pattern
- 6 x 1 pattern

Figure 25 and **26** show the illustrations for 3 x 1 pattern for two types of stimulation which are radial stimulation and induced fracture, respectively. The result of cumulative gas recovery is shown in **Table 5**.

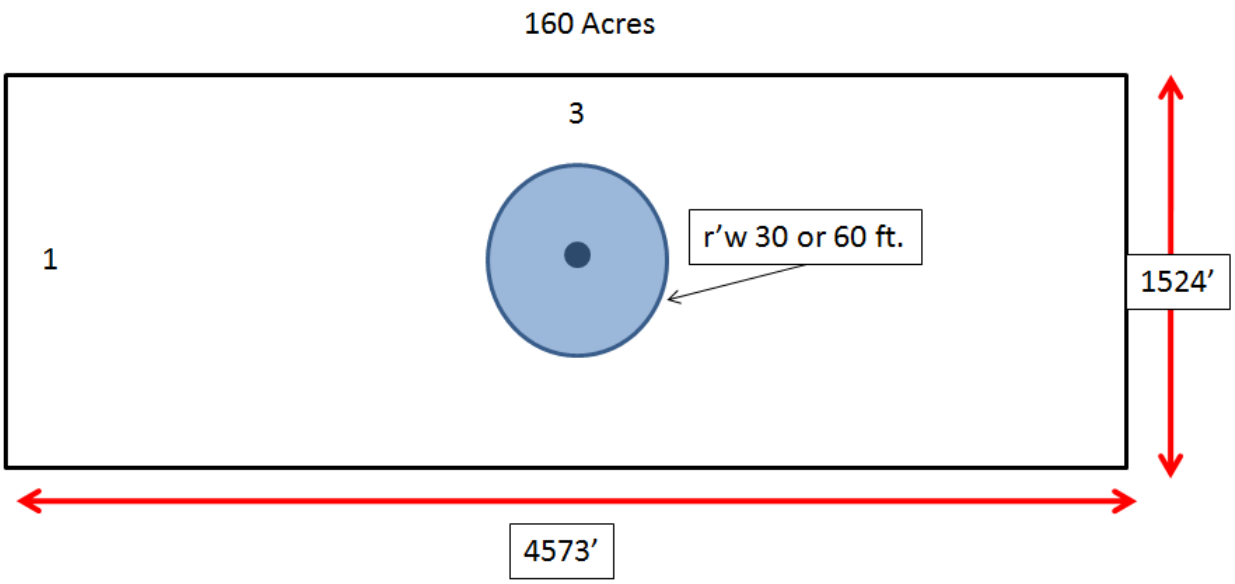


Figure 26: Radial Stimulation Schematic (Not to scale) (Kuuskraa & Wicks,1983).

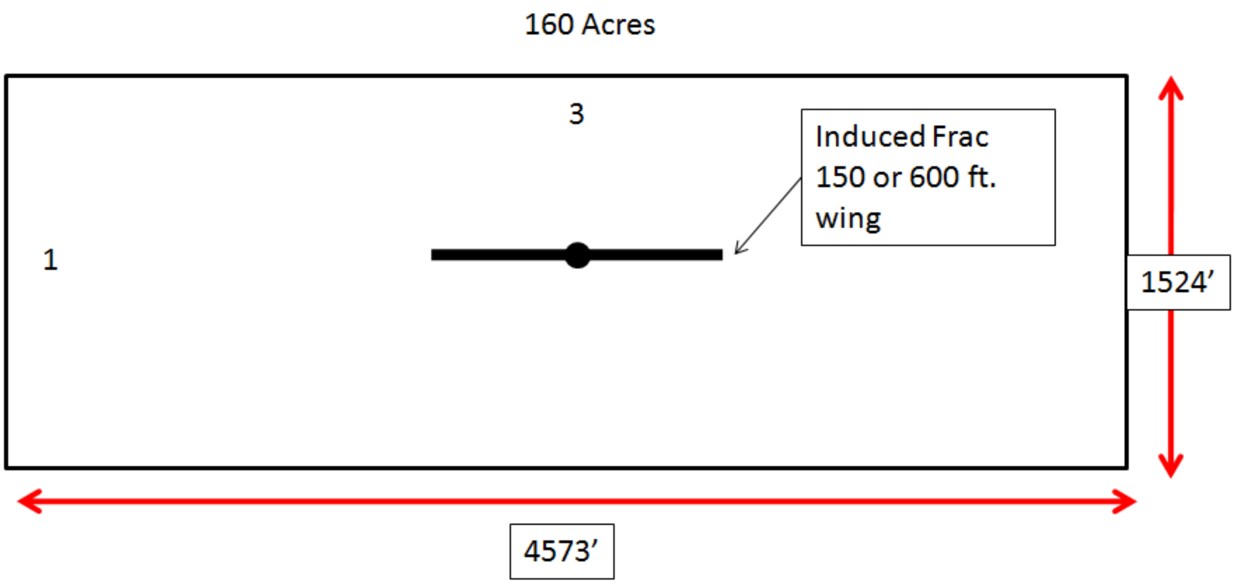


Figure 27: Induced Fracture Schematic (Not to scale) (Kuuskraa & Wicks,1983).

Table 5: Effect of drainage pattern on cumulative gas recovery (Kuuskraa & Wicks,1983).

Stimulation Technique	Cumulative Gas Recovery From Alternative Pattern (MMscf)		
	Square Pattern	3 x 1 Pattern	6 x 1 Pattern
Borehole Shooting			
10 years	63	63	63
40 years	206	206	206
Radial Stimulation			
10 years	94	99	95
40 years	261	274	263
Large Vertical Fracture			
10 years	172	190	180
40 years	402	434	414

Based on the results above, the analysis shows that stimulation by using borehole shooting has small effect on cumulative gas recovery for all three types of drainage pattern compared to other stimulation techniques. In other word, radial stimulation and large vertical fracture show that the recovery efficiency is improved about 5 to 10 %. However, the most effective drainage pattern shape is shown by 3 x 1 pattern as the value of cumulative gas recovery is slightly higher than 6 x 1 pattern. Even though, drainage pattern can affect the gas recovery, but technically it still depending on other parameters such as stimulation technique and the permeability in the region. Further study can be done in the future to figure out the optimal drainage pattern shape based on the well stimulation practices and variety of geologic variables.

4.5.2 Forecast for Marcellus Shale Gas Production

One example forecast for shale gas production can be represented from Marcellus wells as described by Considene, Watson, Entler and Sparks (2009). The estimation of shale gas production was around 40 million cubic feet of gas per day (MMCF/D) in 2008. After the drilling projection in 2009, the productivity was targeted to increase about 170 MMCF/D and reaches greater than 550 MMCF/D in 2010. The gas production keep increasing from 1,800, 2,900 and 4,000 MMCF/D fr year 2012, 2015 and 2020 respectively. Apart from drilling activities, the production forecast also affected by water issues, stimulation technique, facilities difficulties, and regulation policies of field development. This forecast can be illustrated as the figure below.

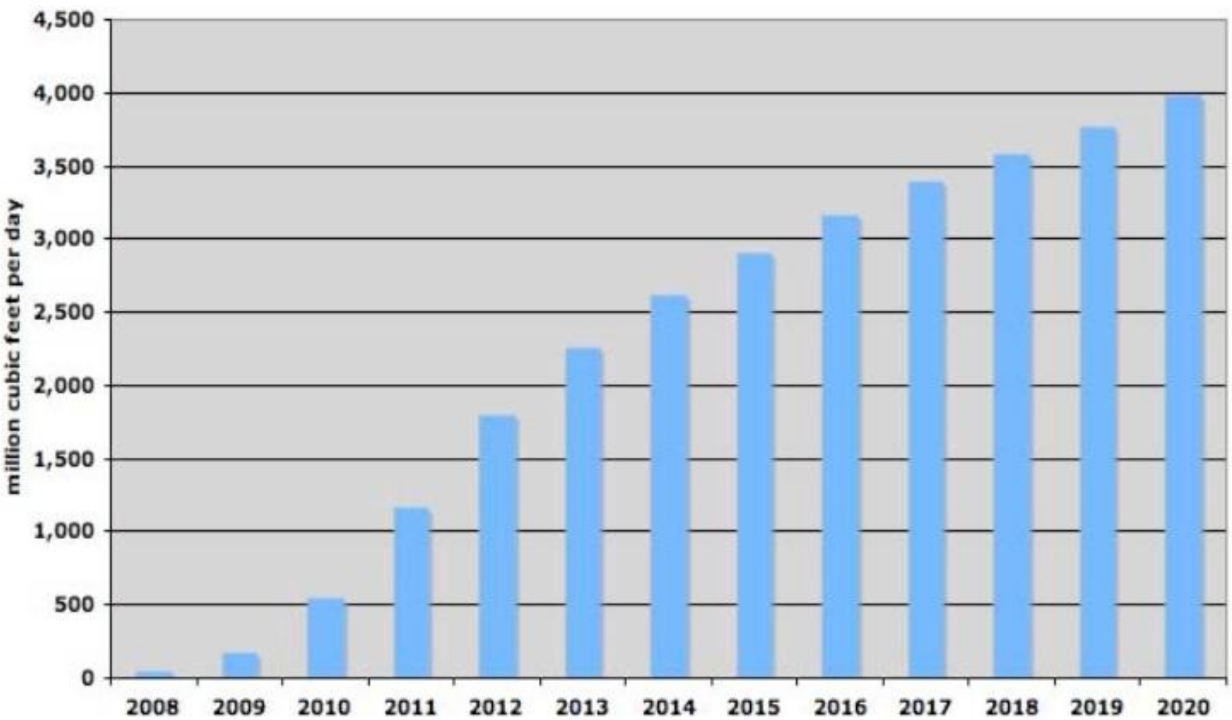


Figure 28: Forecast for Marcellus Shale from 2009-2020 (Considine, Watson, Entler & Sparks ,2009)

CHAPTER 5

CONCLUSION & RECOMMENDATION

Based on previous studies done by the researchers, it is discovered the field development of shale gas reservoir is almost the same with the conventional reservoir in term of G&G, reservoir, drilling, production and facility engineering. However, there is some part of the development plan that needs to be modified so that it suits the shale characteristics. Usually, shale gas reservoir requires extra or additional work due to its very low permeability of shale formation.

It is much recommended to drill in horizontal direction and also by performing pad and multilateral drilling to optimize the gas production. Furthermore, there are several problems that can occur when conducting pressure buildup tests on shale gas reservoir. So, we need to find out the best solutions to overcome these problems. The improvement and modifications can be done in term of stimulation technique. More procedures are necessary to create the channels for the gas to flow through, and a much higher volume of fluids is required than with the production from sandstone (tight gas) as it is naturally more porous and permeable than shale rock. Therefore, it is very important to consider all the parameters discussed in this project, so that appropriate field development of shale gas reservoirs can be implemented.

As recommendation, this project can be continued in term of environmental issues. There a lot of previous studies and research papers discussed about pollutions that occur due to development of shale gas reservoirs. Instead of focusing on development of advanced technology of shale gas production, we also need to consider the environmental aspect for interest of society.

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