

COLORADO SCHOOL OF MINES

**LABORATORY EVALUATION OF PROPPANT TRANSPORT IN
COMPLEX FRACTURE SYSTEMS**

Master of Science Petroleum Engineering Thesis Proposal

for

Rakshit Sahai

09/20/2011

The attached document is a Master of Science thesis proposal for Rakshit Sahai. It contains a detailed outline of the proposed thesis work, objectives for the project and a summary of the completed coursework. Your permission and agreement with the project as outlined in this document is requested.

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Table of Contents

| | | |
|---|--|----|
| 1 | Introduction..... | 3 |
| 2 | Literature Review..... | 5 |
| | 2.1 <i>Hydraulic Fracturing in a Naturally Fractured Reservoir</i> | 6 |
| | 2.2 <i>Slickwater Fracturing Technology</i> | 7 |
| | 2.3 <i>Proppant Transport</i> | 8 |
| 3 | Objectives | 11 |
| 4 | Methodology | 12 |
| | 4.1 <i>Experimental Parameters and Test Cases</i> | 12 |
| | 4.2 <i>Experimental Set Up</i> | 14 |
| | 4.2.1 <i>Slickwater Slurry</i> | 14 |
| | 4.2.2 <i>Testing System</i> | 14 |
| | 4.2.3 <i>Slot Configurations</i> | 16 |
| 5 | Project Timeline and Coursework..... | 18 |
| 6 | References..... | 19 |
| 7 | Research Sponsor..... | 20 |

1 Introduction

Natural gas production from shale gas reservoirs has shown a rapidly growing trend over the past decade and has become a significant source of U.S. domestic gas supply. In the U.S. alone, the production from shale gas reservoirs has rapidly increased from 0.39 Tcf in 2000 to 4.87 Tcf in 2010 and contributed to 23 percent of the U.S. natural gas production in 2010 (US Energy Information Administration, 2011). The use of hydraulic fracturing in conjunction with horizontal drilling has been the “game-changer” in the petroleum industry over the past decade and has contributed to economical natural gas production from low permeability shale reservoirs. With the U.S. Energy Information Administration’s (EIA) energy projections anticipating shale gas production to approximately double by 2035 and play a dominant role in meeting US energy demands, it is expected that hydraulic fracturing will continue to play a major role in enhancing recoverable natural gas reserves and daily production from these low permeability shale formations.

Since the inception of hydraulic fracturing in 1947, fracturing technology has improved significantly over the decades. With a global paradigm shift towards exploring unconventional resources (especially shale reservoirs) over the last two decades, the industry focus has shifted towards hydraulic fracturing and nearly all unconventional wells are fractured for production to be economically viable. For shale gas development, compared to conventional gelled fluid fracturing, slickwater fracturing has become the preferred choice for stimulation. The main driving factors for change in this mindset include:

- a) Need for cost cutting as the price of natural gas declined. Slickwater fracture treatments are relatively cheap and easy to perform;
- b) Low *in situ* permeability of shale gas reservoirs such that the reservoirs aren’t able to effectively clean-up the gel. In comparison, slickwater fracturing causes little to no gel damage to the proppant pack; and,
- c) Potential of low viscosity slickwater fluids to generate longer fracture half-lengths (without excessive height growth) and thus increasing the stimulated reservoir volume.

The complexity of the fracture systems in shale gas reservoirs directly affects production and reserve recovery; whereas at the same time, conductivity of those fractures facilitates those rates

and recoveries. Little is understood about how well the proppant is transported in these complex systems. Much speculation exists in the industry as to how well the proppant “turns the corner” or, in other words, how efficiently the proppant is transported from the main fracture into subsidiary fractures, if it is at all. During the hydraulic fracturing of shale reservoirs, it has been observed that 100 mesh sand works well in some reservoirs but not in all. It is speculated that the presence of natural fractures in shale reservoirs contributes to such behavior and complicates the proppant transport in complex fracture networks.

The process of proppant transport in single vertical fractures has been previously studied using various slot flow model experiments (Kern et al., 1959, Medlin et al., 1985, and Woodworth and Miskimins, 2007). Prediction of proppant transport in complex fracture networks is important and would be useful for both designing fracture treatments and for post-treatment analysis. The purpose of this research is to evaluate proppant transport in complex fracture systems in a low pressure laboratory setting by creating a series of complex slot configurations and flowing slickwater slurries through them.

conventional resources (Halliburton, 2008 and King, 2010). It has led to the development of technology to unlock the gas reserves from the low permeability shale gas reservoirs. Much research is currently being carried out, both in the industry and in academia, to exploit the unconventional shale reservoirs and to produce the remaining trapped natural gas. Until 1999, all of the common fracturing methods in shale reservoirs included gel or foam fluids, with and without proppant (King, 2010); but with the success of slickwater fracturing in the Barnett and Antrim Shales, more importance has been given to develop slickwater frac materials over the past decade and to understand the principles related to slickwater fracturing. One such important aspect, which hasn't been given enough attention previously, is to understand the proppant transport during slickwater fracturing in complex fracture systems. An understanding of how efficiently the proppant is transported from the primary fracture into secondary (and tertiary) fractures can possibly help in designing the hydraulic fracture treatments more effectively.

2.1 Hydraulic Fracturing in a Naturally Fractured Reservoir

Natural fractures are present in nearly all shale formations and the existence of primary, secondary and tertiary fractures have been confirmed from various outcrops (King, 2010). Natural gas production from nano-Darcy fractured shale reservoirs relies heavily on the drilling of horizontal wells and hydraulic fracture stimulation. Over the past decade, shale formations have been stimulated with low-proppant-concentration, high-pump-rate, water-based hydraulic fracture treatments, commonly referred to as slickwater fracture treatments. Based on the studies carried out, the subcritical crack index for the shale plays have been found to be high; which confirms the presence of fracture clustering (Gale and Holder, 2010). Microseismic monitoring of hydraulic fracture treatments has also indicated fracture propagation away from the maximum horizontal stress direction, which is speculated to be due to the presence of natural fractures. From a reservoir standpoint, the presence of these natural fractures might increase the permeability locally but could possibly result in complex fracture geometry during the fracture stimulation.

Due to the presence of natural fractures, natural gas production from the shale reservoirs is highly dependent on the Stimulated Reservoir Volume (King, 2010). The results from microseismic monitoring in the Barnett Shale show the reactivation of these calcite-filled natural fractures during the stimulation, which in turn improves the efficiency of the fracture treatment

(Gale et al., 2007). Therefore, for hydraulic fracture treatment design, knowledge of both the direction of maximum horizontal stress and the geometry of the natural fractures is important.

2.2 Slickwater Fracturing Technology

Slickwater fracturing, sometimes referred to as “waterfrac” or “friction-reduced frac”, has been defined as a hydraulic fracture treatment which utilizes large amounts of water along with polyacrylamide friction reducer (or low concentrations of linear gel, generally 0.5-20lb/Mgals), clay stabilizer, surfactant and low concentrations of proppant to economically produce natural gas from low-permeability reservoirs. The first slickwater treatment was pumped in 1997 by Mitchell Energy in the Barnett Shale and delivered better results than foam and gel fracs, as shown in Figure 2.

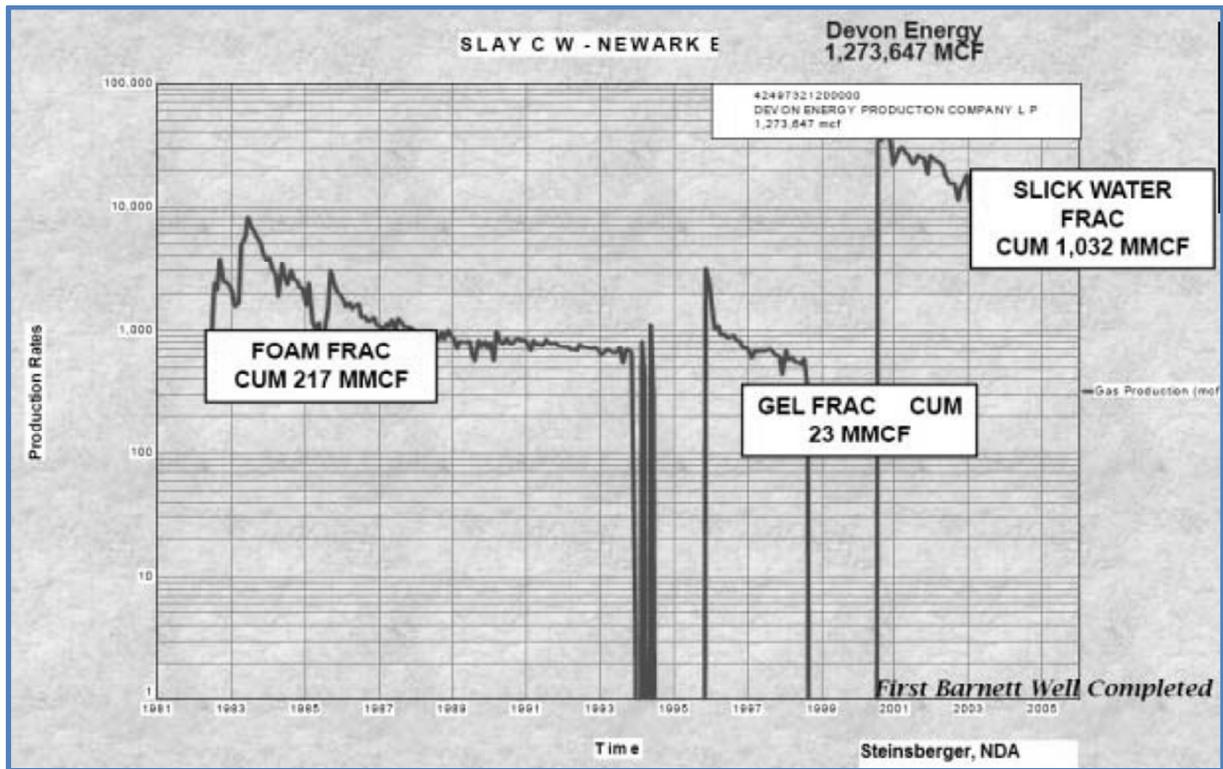


Figure 2: Refracs of shale well in Barnett Shale – Mitchell Energy (from King, 2010).

Production results from other shale formations also show that the fracture treatments carried out using slickwater with low proppant concentrations resulted in equal or better performance than offset conventional wells stimulated with gel/foam fracs (King, 2010). There are several reasons that may explain this behavior: 1) reduced gel damage within the fracture, 2) reactivation of

healed natural fractures, fissures and micro-cracks to increase the stimulated reservoir volume, 3) optimal dimensionless fracture conductivity, 4) pressure dependent leakoff without significant loss of fluid into the shale pores, and 5) overall project economics.

However, due to its low viscosity, slickwater fluid shows poor proppant transport characteristics and has rapid proppant settling. As a result, most slickwater treatments include very low proppant concentrations, typically in the range of 0.25-2 ppg. Also, in order to achieve similar fracture conductivity as in the case of cross-linked fracture treatments, slickwater treatments usually involve pumping of millions of pounds of proppant along with tremendous volumes of water. Maximum pump rates are in the vicinity of 100 bpm and pump times can exceed six hours. Unlike the case of cross-linked gels, the use of low-viscosity slickwater results in long narrow fractures in the reservoir without excessive height growth.

2.3 Proppant Transport

The productivity of a hydraulically fractured well depends on having a fracture which is effectively propped over the bulk of its length and height. However, good or adequate proppant transport is a central issue in slickwater fracture treatments because of the low viscosity of the fracturing fluid. Proppant transport within a fracture is influenced by a number of factors including: fracture width, injection rate, fluid leak-off, fluid rheology, density difference between the fluid and the proppant, and proppant size (Palisch et al., 2008, and King, 2010). The hydraulic fracture simulators available in the industry can predict the proppant transport associated with gelled fluids fairly well but don't have the capability to predict proppant transport in slickwater fracturing associated with complex fracture networks. The proppant settling is fundamentally governed by Stoke's Law but is complicated because of (Gadde et al., 2004, Dayan et al., 2009, Palisch et al., 2008, and King, 2010):

- a) Dynamic state of the fluid (as the flow occurs along the fracture);
- b) Fracture wall effects;
- c) Change in settling velocities and rheology while ramping up the proppant concentration during the fracture treatment; and,
- d) Turbulence and inertial effects (caused by high fluid velocity).

Numerous laboratory experiments have been carried out in the past to understand the proppant transport in low-viscosity fluids in vertical fractures (Kern et al., 1959, Medlin et al., 1985, and Woodworth and Miskimins, 2007). These slot flow model experiments usually involved pumping slurry (water and sand) along single vertical plane with constant height and slot width. Although the flow occurred in between smooth Plexiglas plates without any fluid leakoff, performing these tests provided a visual sense of proppant movement within the fractures. Kern et al. (1959) conducted the first slot flow experiment by injecting water and sand at constant rates. As the slot was closed from the top and the bottom, the slurry flowed horizontally and because of the poor sand-carrying capacity of the water, the sand settled to the bottom before moving too far and started building a mound or “dune” of proppant. It was found that the fluid velocity in the gap between the settled sand and the top of the slot increases as more sand settles and decreases the gap size. The proppant mound continues to grow until the gap between the settled sand and the top of the slot reaches a critical value. At and above the critical (or equilibrium) velocity, the proppant transport in the slot is governed by fluidization and sedimentation (Palisch et al., 2008). During fluidization, the fluid turbulence re-suspends the sand off the stationary mound and sedimentation occurs as the proppant is transported further down the fracture. As the injection is continued, the sand bed eventually stabilizes and reaches an “equilibrium height” or a steady “traction carpet”. The “equilibrium height” of the sand bed was found to be a function of fluid velocity, sand concentration and the falling rate of the sand (which is a function of proppant size and type). As a result of fluidization and sedimentation, the sand bed continues to grow in length as sand continues to be pumped, as shown in Figure 3.

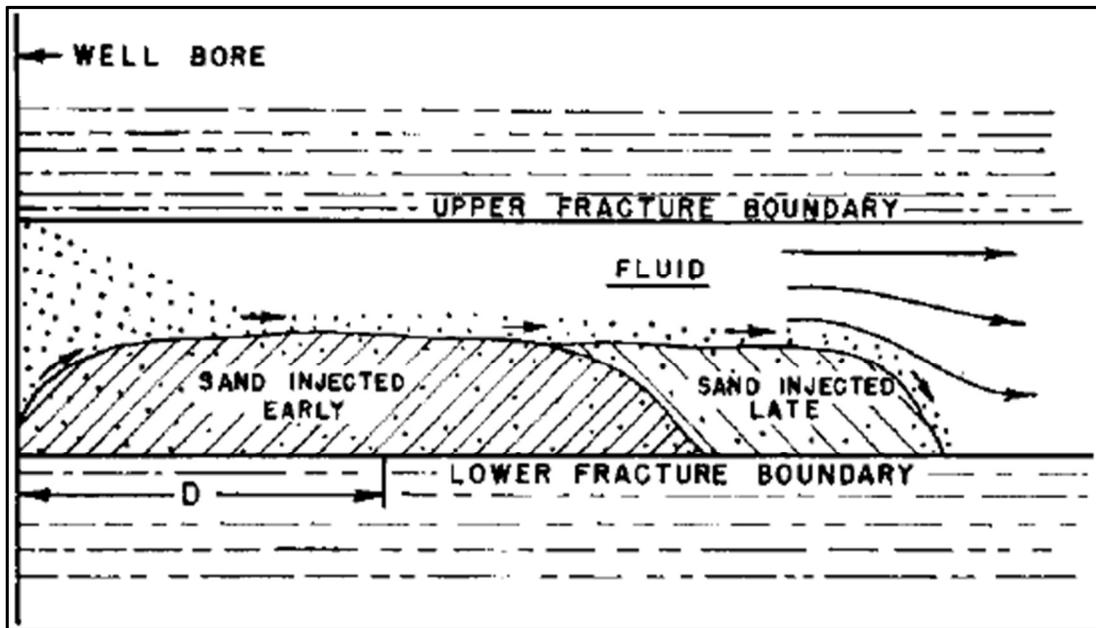


Figure 3: Sand movement and settling in slot flow experiment (from Kern et al., 1959).

With slickwater fracs, the sand injected early during the treatment is deposited closer to the wellbore than sand pumped later in the treatment. STIM-LAB, as a part of their slickwater fluid experiments, carried out their own slot experiments and obtained very similar results to Kern et al. (1959) (Woodworth and Miskimins, 2007). During actual fracture treatments in shale reservoirs, sand settling is expected to change due to fluid leak-off and viscosity reduction due to heat absorption and the consequent rise in fluid temperature.

3 Objectives

The main task of this proposed thesis research is to develop a laboratory model to study proppant transport in complex fracture network. At this stage, the tools are not available to estimate the propped fracture lengths and heights and also whether the proppant “turns” the corner or not in presence of secondary and tertiary fractures.

The proposed research is aimed to achieve the following objectives:

1. Develop and build an experimental laboratory apparatus with a series of slot configurations, representing different complex fracture scenarios, using acrylic boxes and Plexiglas. Each slot system will consist of a main slot (fracture) with a varying number of secondary slots placed at 90° angles to the main slot and tertiary fractures at 90° angles to the secondary slots;
2. Evaluate proppant transport through a series of slot configurations by varying the slot width, proppant size, proppant concentration and pump rate; and,
3. Based on the laboratory test results, develop a correlation or series of correlations that helps to understand slickwater proppant transport in complex fracture systems. Such a correlation(s) can possibly help with the designs of hydraulic fracture treatments by focusing on parameters that enhance transport.

4 Methodology

For each experiment, water and sand is to be injected using a submersible pump at a constant flow rate through an acrylic box configuration representing complex fracture networks. Although experiments will be carried out with vertical fractures initially, the slot configurations will later be modified to mimic horizontal fractures as well. General procedures can be summarized as follows:

1. Arrange the acrylic boxes to represent multiple complex fracture networks by making different configurations;
2. Fill the water tank with tap water;
3. Adjust the flow meter to the desired value;
4. Start injecting water alone by turning on the submersible pump and achieving flow equilibrium by adjusting the valves on the discharge manifold for leak-off;
5. Start adding the sand from the sand hopper at the desired rate;
6. Record the flow rate and observe the proppant transport through the acrylic box configuration. Make sure the cameras are turned on to record the proppant flow;
7. Make the required measurements and stop pumping;
8. Wait until the water has drained through the leak-off points in the system. Clean the sand remaining in the Plexiglas frame; and,
9. Repeat steps '1' to '8' as needed for the next experiment. Parameters to be varied include flow rate, sand concentration, slot width and proppant diameter.

NOTE: Pressures will not be recorded during the experiment.

4.1 Experimental Parameters and Test Cases

For this study, in addition to varying the slot complexity, parameters including slot width, proppant size, proppant concentration, and pump rate will be varied to observe how they affect the proppant transport in these slot systems. Proppant/sand will be dyed to make sand movement more visible during the experiments. Proppant sizes will be 30/70 and 100 mesh. Basic slot widths will be 0.215", 0.155" and 0.1075". Table 1 show a matrix of the anticipated tests.

| Table 1 – Tests to be performed | | | | | | |
|--|--------------|------|------|------|------|-------|
| Slot Width (inch) | 0.215 | | | | | |
| Lab Flow rate (gpm) | 65.8 | | | | | |
| Prop Conc (ppg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 |
| Pound/min | 16.5 | 32.9 | 49.4 | 65.8 | 98.8 | 131.7 |
| Lab Flow rate (gpm) | 43.9 | | | | | |
| Prop Conc (ppg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 |
| Pound/min | 11.0 | 21.9 | 32.9 | 43.9 | 65.8 | 87.8 |
| Lab Flow rate (gpm) | 32.9 | | | | | |
| Prop Conc (ppg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 |
| Pound/min | 8.2 | 16.5 | 24.7 | 32.9 | 49.4 | 65.8 |

| | | | | | | |
|----------------------------|--------------|------|------|------|------|------|
| Slot Width (inch) | 0.155 | | | | | |
| Lab Flow rate (gpm) | 47.5 | | | | | |
| Prop Conc (ppg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 |
| Pound/min | 11.9 | 23.7 | 35.6 | 47.5 | 71.2 | 94.9 |
| Lab Flow rate (gpm) | 31.6 | | | | | |
| Prop Conc (ppg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 |
| Pound/min | 7.9 | 15.8 | 23.7 | 31.6 | 47.5 | 63.3 |
| Lab Flow rate (gpm) | 23.7 | | | | | |
| Prop Conc (ppg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 |
| Pound/min | 5.9 | 11.9 | 17.8 | 23.7 | 35.6 | 47.5 |

| | | | | | | |
|----------------------------|---------------|------|------|------|------|------|
| Slot Width (inch) | 0.1075 | | | | | |
| Lab Flow rate (gpm) | 32.9 | | | | | |
| Prop Conc (ppg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 |
| Pound/min | 8.2 | 16.5 | 24.7 | 32.9 | 49.4 | 65.8 |
| Lab Flow rate (gpm) | 21.9 | | | | | |
| Prop Conc (ppg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 |
| Pound/min | 5.5 | 11.0 | 16.5 | 21.9 | 32.9 | 43.9 |
| Lab Flow rate (gpm) | 16.5 | | | | | |
| Prop Conc (ppg) | 0.25 | 0.5 | 0.75 | 1 | 1.5 | 2 |
| Pound/min | 4.1 | 8.2 | 12.3 | 16.5 | 24.7 | 32.9 |

4.2 Experimental Set Up

The experimental apparatus for this research will include pumping slickwater slurry through the testing system developed to study the proppant transport during slickwater fracture treatment. As mentioned previously, the testing system will include several slot configurations as described in section 4.2.3.

4.2.1 Slickwater Slurry

For this experimental study, tap water with different sizes of proppant (30/70 and 100 Mesh) will be used to mimic the slickwater fracturing slurry.

4.2.2 Testing System

The laboratory experiments are to be conducted in a large Plexiglas frame (4'11" x 3' x 3'), as shown in Figures 4 and 5. The apparatus consists of a submersible pump, sand hopper, water tank, Plexiglas frame, water-filled acrylic boxes, flow meter, flow line, inlet manifold and the discharge/leak-off manifold. A water tank (with inner dimensions 3'6" x 10.5" x 1'1.5") will be used to store the water and is kept on a transmission lift. The height of the transmission lift has been adjusted to minimize the head pressure by keeping the pump outlet at the same height as the manifold inlet. Sand will be stored in the sand hopper with the opening positioned directly above the water tank. The submersible pump (which has been modified to handle water and sand) is connected to the inlet manifold via a braided rubber hose (with a 90^o bend) and a flow line made up of 1.25" Schedule 40 PVC tubing. The flow meter, installed between the pump and the inlet manifold, can measure the slurry (water and sand) rate in real-time during the course of the experiments. An inlet manifold, with six ball-valves (ID of each inlet is approx. 0.6"), is attached to the outside of the Plexiglas.

Different slot configurations (discussed in detail in Section 4.2.3) are to be made (within the large Plexiglas frame) using Plexiglas plates and will be supported by the water-filled acrylic boxes (1' x 1' x 1' each). In order to have a closed system, a top cover is installed and is held in place using clamps (as shown in Figure 5). A discharge/leak-off manifold, with five ball-valves, is installed on the large Plexiglas frame with two main functions: 1) to keep the closed system in equilibrium during the experiment, and 2) to recycle the water and to keep up with the water

injection rate. Two leak-off points are also installed on the top cover, to stop accidental ballooning of the top cover.

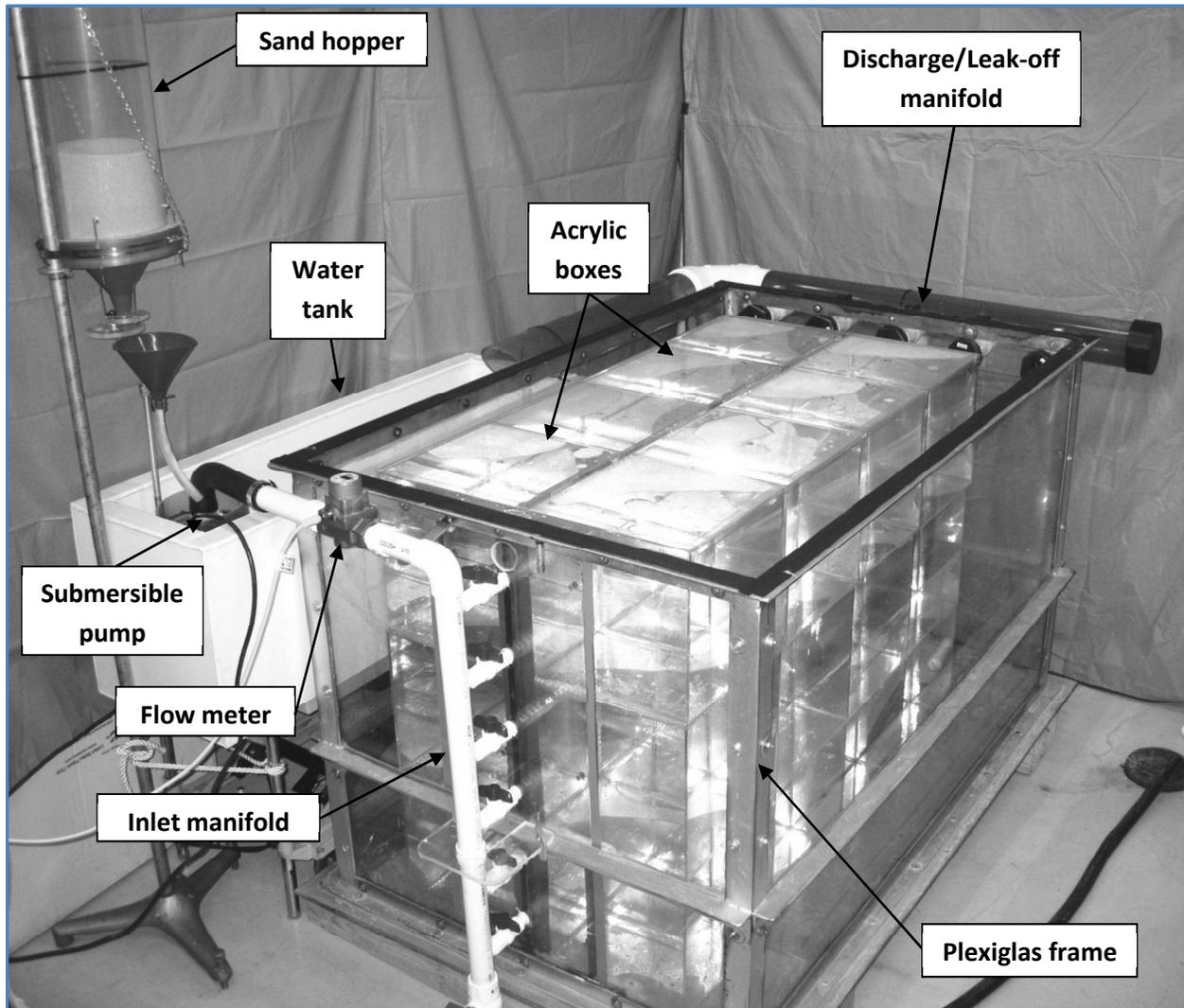


Figure 4: Testing system showing different parts of apparatus (without top cover).

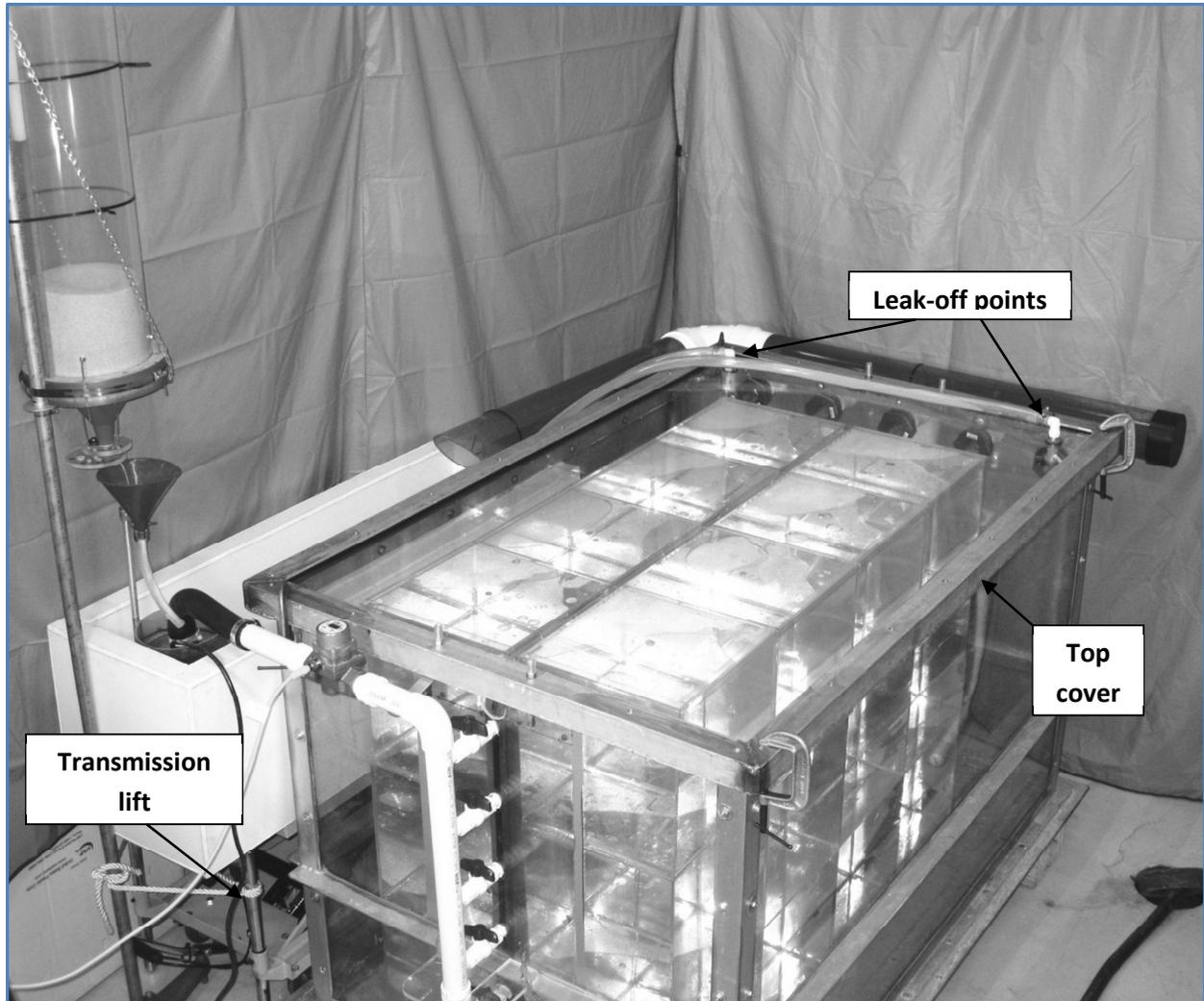


Figure 5: Testing system showing different parts of apparatus (with top cover).

4.2.3 Slot Configurations

For this study, six different slot configurations are to be included for each slot width, as shown in Figure 6. Each slot system will consist of a main slot (fracture) with a varying number of secondary slots (placed at 90° angles to the main slot) and tertiary slots (placed at 90° angles to the secondary slots) to increase the complexity of the slot configurations.

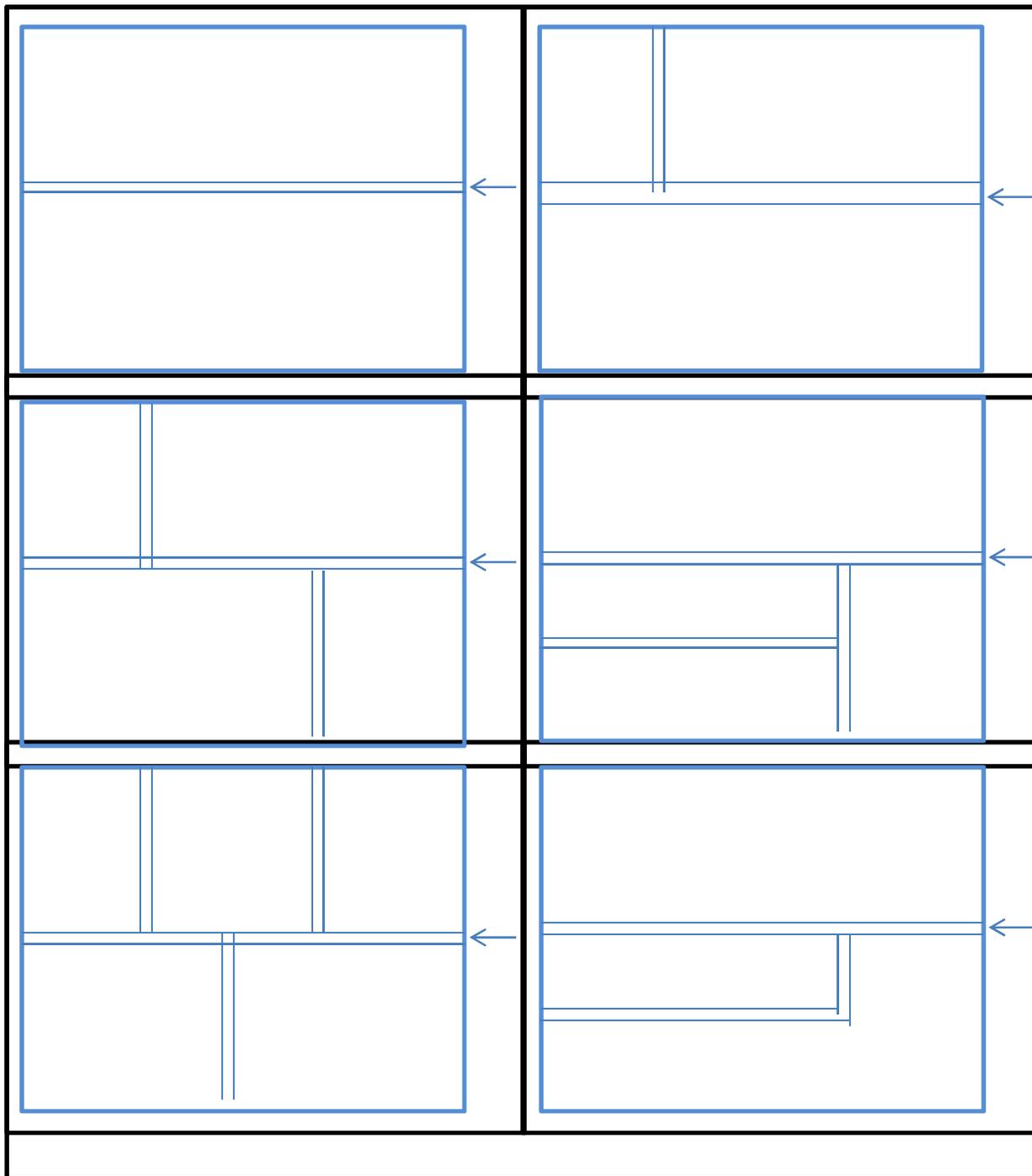


Figure 6: Top-view of six different planned slot configurations (the arrow shows the direction of slurry injection in the main slot for each case).

5 Project Timeline and Coursework

Table 2 presents a proposed timeline to achieve the project objectives. The target completion date is Summer 2012.

| Table 2 – Proposed Activities and Timeframe Breakdown | | | | | | | | | | | |
|--|------------------|--|--|--|--------------------|--|--|--|--------------------|--|--|
| Activities | Timeframe | | | | | | | | | | |
| | Fall 2011 | | | | Spring 2012 | | | | Summer 2012 | | |
| Committee Meeting | | | | | | | | | | | |
| Literature Review | | | | | | | | | | | |
| Develop and build the experimental apparatus | | | | | | | | | | | |
| Sensitivity Analysis | | | | | | | | | | | |
| Results Analysis | | | | | | | | | | | |
| Thesis Writing | | | | | | | | | | | |
| Thesis Defense | | | | | | | | | | | |

For successful completion of a Master of Science degree from the Petroleum Engineering department at Colorado School of Mines, it is required to complete a minimum of 24 graduate credit hours of course work and a minimum of 12 credit hours earned by research credit. Table 3 shows a listing of courses that have been completed and the current courses for Fall 2011. Table 4 shows a summary of the coursework and research credits completed to date.

| Table 3 – Coursework and Research Credits | | | | |
|--|------------------|---------------------|--------------|--------------|
| Term | Course ID | Course Title | Hours | Grade |
| Fall 2010 | | | | |
| Spring 2011 | | | | |
| Summer 2011 | | | | |
| Fall 2011 | | | | |
| Fall 2011 | | | | |

| Term | Course ID | Graduate Research | Hours | Grade |
|-------------|------------------|--------------------------|--------------|--------------|
| Fall 2010 | | | | |
| Spring 2011 | | | | |
| Fall 2011 | | | | |

| Table 4 – Credits Summary | |
|---------------------------------------|---------------|
| Course Work Credits | /24.00 |
| Research Work Credits | /12.00 |
| Total MS Graduate Credits | /36.00 |
| Cumulative Grade Point Average | /4.000 |

6 References

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7 Research Sponsor

This research work will be undertaken at the Petroleum Engineering department, Colorado School of Mines and is sponsored solely by Southwestern Energy. Southwestern Energy is an independent energy company, primarily engaged in domestic natural gas and crude oil production and has major operations in Texas, Pennsylvania and New Brunswick, Canada. With rapidly growing activity in the Fayetteville and Marcellus Shale plays, results from this research can possibly help the company in improving the effectiveness of the hydraulic fracturing treatments.