

EXPERIMENTAL STUDY OF FILTER CAKE CLEANUP  
BY ACID/WATER JETTING

A Thesis

by

YANBIN ZHANG

Submitted to the Office of Graduate Studies of  
Texas A&M University  
in partial fulfillment of the requirements for the degree of  
MASTER OF SCIENCE

May 2009

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	A. Daniel Hill
Committee Members,	Ding Zhu
	Kumbakonam Rajagopal
Head of Department,	Stephen A. Holditch

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## ABSTRACT

Experimental Study of Filter Cake Cleanup by Acid/Water Jetting. (May 2009)

Yanbin Zhang, B.S., Peking University

Chair of Advisory Committee: Dr. A. Daniel Hill

The main purpose of acid/water jetting treatments currently applied in the field is to clean up the filter cake formed during the drilling process and perhaps further stimulate the wellbore by creating wormholes if acid jetting is used in carbonate formation. This purpose can be achieved for the reason that the filter cake on the borehole can be mechanically broken by the high speed jetting action, and additionally, if acid is used, some materials in the filter cake can be dissolved, which can facilitate the mechanical breaking action. The knowledge of jetting effectiveness under various conditions is crucial for the purpose of optimizing the treatment design.

In order to investigate quantitatively the effectiveness of acid/water jetting for filter cake cleanup and wellbore productivity enhancement, laboratory experiments were carried out under conditions similar to those in the field. Filter cake was deposited on the face of a 4 inch diameter core and then water or 15% HCl were used for jetting treatment. The original permeability, the permeability right after the drill-in fluid damage, and the permeability after the jetting treatment were measured and compared. The effect of overbalance pressure during the jetting treatment was investigated. CT scan was carried out for those cores that may have wormholes after the acid jetting treatment. An analysis of the mechanism for filter cake removal and wormhole creating during acid jetting treatment was proposed.

It is discovered that acid jetting can effectively remove the filter cake by penetrating and lifting it from beneath, and efficient wormhole creation can only happen when the overbalance pressure during the acid jetting treatment is above a certain value. Based on this study, several suggestions for field applications were made.

## DEDICATION

This thesis is dedicated to my family.

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## 1. INTRODUCTION

### 1.1 Background

Drilling long horizontal wells, as well as multilateral completions, has developed rapidly in recent times. The primary purpose of this practice is to increase the contact area with the reservoir in order to maximize the production. The development of drilling technique enables us to have wellbores often penetrate thousands of feet of productive zone compared with only tens to hundreds of feet in the case of traditional vertical well configurations. Unfortunately, this also contribute to a larger exposed area and longer exposure time for the drilling fluid in wells. Therefore, severe damage caused by drilling fluid has become a major concern for horizontal well productivity.<sup>1</sup>

To minimize the drilling damage, the standard practice is to drill to the top of the payzone using conventional drilling muds and then switch to the cleaner drill-in fluids to drill through the payzone.<sup>2</sup> The traditional drilling muds utilized for lubrication and cuttings transport during drilling applications contain high concentrations of clays such as bentonite. The drilling mud is known to cause surface damage due to the mud cake and deeper damage due to particle invasion and filtration. The cleaner drill-in fluids are formulated to provide the functionality of drilling muds but cause less deeper damage. The drill-in fluids are typically comprised of either starch or cellulose polymers, xanthan polymer, and sized calcium carbonate or salt particulates. The starch or cellulose polymers is used for lubrication; the xanthan polymer enhances cutting transport capabilities; the particulates provide fluid loss control.<sup>3</sup>

Even with the newly developed drill-in fluid, relatively impermeable filter cake is still deposited on the borehole wall, which, if not removed or bypassed, can result in significant reduction of well productivity or injectivity. This problem becomes especially important for long horizontal wells with openhole completions. In many cases, only flowing back the well may not be able to completely clean up all the filter cake, resulting in a limited area of active production regions along the entire wellbore.<sup>4</sup> Therefore, it is

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often necessary to apply certain clean-up procedures to make sure all filter cake is completely removed.

Modern clean-up techniques utilize mechanical force, chemical reaction, or both to attack the filter cake. Traditional mechanical methods include the use of mills on small tubing with workover rigs or snubbing units, downhole hydraulically driven drill motors with mills operated with reeled tubing units, and wireline broaching methods. These methods are often slow and may not be completely effective.<sup>5</sup> In recent years, high pressure water jetting (HPWJ) was applied in the field to remove drilling damage and achieved some good results. HPWJ depends on the physical force created by high speed water stream to clean up the filter cake and possibly create additional fractures to bypass the damage zone.<sup>6</sup> On the chemical side, because the filter cake mainly consists of xanthan polymer, starch,  $\text{CaCO}_3$  particles, and drilling cuttings, conventional chemicals means used to remove filter cake include reactive mineral acids, enzymes, chelating agents, oxidizers, or combinations of these chemicals.<sup>7</sup> When long horizontal laterals have been drilled through carbonate reservoirs, designing a chemical system and proper treatment procedure for the filter cake removal can be challenging. Because the reaction between acid and carbonate rock is fast, the primary difficulty is to make sure sufficient contact of the cleaning fluid with the filter cake throughout the entire interval and uniform dissolution in heterogeneous formations where there are high permeability streaks. One way to overcome this problem is to increase the viscosity of the cleaning fluid by adding viscoelastic surfactants.<sup>8</sup> Another way which has seen tremendous growth over the past decades is to use coiled tubing as a placement tool.<sup>9</sup> Technology, such as rotating jetting tools, has enhanced this technique considerably. Rotating jetting tools have the advantage of full 360° coverage and introduce stress cycling as a destruction mechanism for the removal of filter cake.<sup>10</sup> The acid jetting technique takes the advantage of the combination of mechanical jetting force and chemical dissolution. Acid jetting treatments in carbonate formations may further stimulate the wellbore by creating wormholes bypassing the deeper damage.

Figure 1.1 shows a typical drill string acid jetting treatment diagrammatically. Acid is pumped through jetting ports at the end of a drill string. The drill string is withdrawn as the acid is pumped. Pumping stops when each 90 foot stand of drill pipe is disconnected and laid down, so the treatment proceeds as a large number of pump/shut-in cycles.

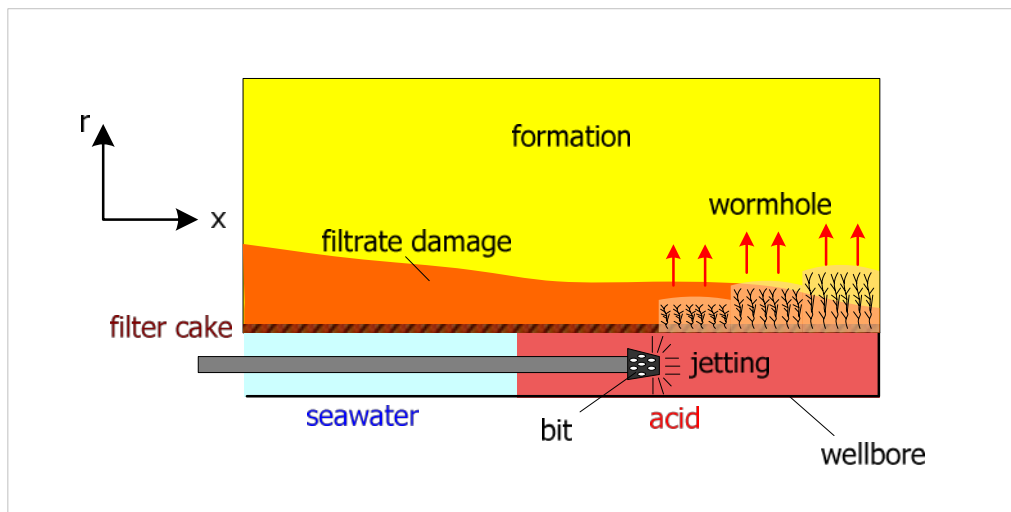


Figure 1.1 Diagram for the typical drill string acid jetting treatment (Courtesy of Dr. K. Furui<sup>11</sup>)

In recently years, many acid jetting treatments have been reported to be successful in cleanup applications of long horizontal wells and vertical wells with long target zones. Pereira *et al.*<sup>4</sup> and Onwusiri *et al.*<sup>10</sup> reported the use of rotating jet system to acidize deep water horizontal gravel packed wells. These field applications have shown many advantages of the acid jetting treatments including an enhanced uniform acid coverage, possible deeper penetration of the acid via impact pressure, 360-degree wellbore coverage, and optimum fluid usage. However, on the other hand, basic research in the purpose of understanding the complicated physical and chemical process during the acid jetting treatment is needed in order to provide guidelines for field operations.



## 1.2 Problem Summary

The most important part of this kind of research is to develop and build an experimental system which can simulate what happens in the field in the most critical aspects, so that many key factors influencing the entire process could be studied separately. This experimental system should be able to deposit filter cake, perform acid jetting, and evaluate the effectiveness of the treatment.

The most important and the most difficult part is the acid jetting part. The lab conditions have many limitations compared with a real field treatment. It is impossible to make everything in the lab perfectly similar to the field.

The core we could use has relatively small face area which means that all the acid we applied can only act on this small area. However, in the field, the acid may flow to other places in the wellbore and react with filter cake and rock far away from the place where jetting occurs.

The tubing we used for jetting has no special nozzle to control the jetting profile. However, in the field, a specialized nozzle design may increase the jetting impact dramatically.<sup>12</sup>

It is very difficult to implement moving and/or rotating jet in the lab. In the field treatment, the jet is often rotating while moving along the wellbore in order to cover all the wellbore. The rotation speed and the moving speed could be optimized in order to achieve better coverage and more efficient acid usage. However, direct experimental work is difficult to be carried out due to the complexity and expenses of the equipment design and construction.

Temperature is a very important parameter for both filter cake deposition and acid treatment. However, it is not an easy task to keep our core and the fluids at a temperature similar to the down hole considering the design of all the existing parts and apparatus. Our experiments were carried out in room temperature.

In this work, we shall not try to discuss further or solve the above problems. We will focus on another important problem which is ignored or mistreated by previous experimental works.

After the jet acid breaks the filter cake, it may create wormholes in the carbonate formation resulting in further stimulation. Traditional wormholing experiments carried out by using core flood apparatus inject the acid at constant flow rate and thus the pore volume to break through is related to the flow rate. Similar experimental schemes may not be suitable to investigate the wormholing process in acid jetting treatments. For example, some previous experiments were done with the jetting inside a small closed chamber in which the pressure during the jetting rocketed up to a very high value and all acid was forced into the rock.<sup>13</sup> This condition may never happen in the real acid jetting application because after hitting the borehole wall the acid may be either circulated or flow away to lower part of the wellbore. The acid flux going into the formation at the jetting spot does not have a simple relation with the jetting flow rate. On the other hand, the pressure at the jetting spot can be easily determined and will not change significantly during the jetting treatment. The pressure at the jetting spot is equal to the static pressure created by the column of fluid in the wellbore plus a dynamic impact pressure created by the jetting action. Before the acid jetting treatment, the borehole is filled with clean completion fluid so that a nearly balanced pressure is achieved in the wellbore against the formation. When the jetting begins, a dynamic pressure is created by the jetting action on the jetting spot. It is reported in a field treatment that about 70 psi scale impact pressure can be generated by pumping Nitrogen at 300 scf/min and acid at 0.7 bpm.<sup>10</sup> At the same time, the fluid injected into the wellbore may also change the static pressure. For example, if gas is injected with the acid, the static pressure may even decrease and underbalanced condition can be achieved. Usually it is desirable to have overbalanced pressure during the acid treatment to force the acid go into the formation to create wormholes. It is realized that the acid jetting treatment is a constant overbalanced pressure acid treatment rather than a constant flow rate acid treatment. Therefore, it is important to design experiments to investigate the effects of different overbalanced pressure during the acid jetting treatments.

### 1.3 Objective and Outline

The objective of this work is to experimentally investigate the effectiveness of filter cake cleanup and possible wormhole creation by using acid/water jetting treatment. The equipment should be designed to control the overbalanced pressure during the jetting treatment. In order to achieve this, first of all we need to carefully specify all experimental parameters which are not only similar to those applied in the field but also easy to realize at lab conditions. This will be discussed in detail in Section 2. After that, according to the experimental parameters we will use, certain equipment is selected and the experiment apparatus is set up and configured. Section 3 of this thesis will discuss all the equipment used for the experiment. Section 4 lists the detailed procedure of how to do the experiment step by step. Section 5 gives the experimental results and an analysis based on the results. Finally in Section 6, conclusion was drawn from the experimental data analysis and some recommendations for the field treatment were made.

## 2. EXPERIMENTAL PARAMETERS

### 2.1 Core Samples

The core samples we used are Texas cream chalk as shown in Figure 2.1. Their original permeabilities range from about 0.2md to 7md. We used 4 inch diameter cores because it is important to have a relatively large surface area for the filter cake deposition. The cores were cut to be 18 inches for the permeability measurement. Before the filter cake deposition we cut another 2 inches off and install the space to create a chamber for drill-in fluid deposition.



Figure 2.1 4 inch diameter 20 inch long core sample

### 2.2 Drill-in Fluid

We use a water based drill-in fluid for the filter cake buildup. All the gradients for making the drill-in fluid were provided by MI-Swaco. Table 2.1 shows all the ingredients and their amount for making the drill-in fluid. We add in some Rev Dust to simulate the drill cuttings produced during the drilling.<sup>14</sup> In the literature, different

experiments use different amounts of Rev Dust, ranging from about 5 lb/bbl to 40 lb/bbl.<sup>15,16,17</sup> In our experiment, we use 20 lb/bbl Rev Dust. The drill-in fluid properties are given in Table 2.2.

### 2.3 Filter Cake Deposition

Generally speaking there are two ways to do the filter cake deposition under laboratory conditions: dynamic deposition and static deposition. For dynamic deposition, we need to use a mud pump to dynamically circulate the drill-in fluid across the surface of the rock, which means that we keep a certain shear velocity. At the same time, we apply a certain amount of overbalance pressure. As filtrate enters the rock, a filter cake

Table 2.1 Drill-in fluid composition by Ravitz *et al.*<sup>18</sup>

Name	Product Name	Quantity per bbl		Quantity per gal				8 gal mud	
Water	Water	0.9	bbl	0.9	gal	0.9	gal	7.2	gal
Biopolymer	Xanthan Gum polymer	1.5	lb	0.0357	lb	16.2	g	129.6	g
KCl	Potassium Chloride	10.8	lb	0.2571	lb	116.6	g	933.1	g
NaCl	Salt	32.3	lb	0.7690	lb	348.8	g	2790.7	g
Organophilic Starch	Thrutrol	10	lb	0.2381	lb	108.0	g	864.0	g
Organophilic Carbonate	Thrucarb	6	lb	0.1429	lb	64.8	g	518.4	g
Sized CaCO3	Safe-Carb 10	24	lb	0.5714	lb	259.2	g	2073.6	g
Rev Dust	Rev Dust	20	lb	0.4762	lb	216.0	g	1728.0	g
pH Buffer	Caustic Potash	0.5	lb	0.0119	lb	5.4	g	43.2	g
Biocide	Myacide	0.25	lb	0.0060	lb	2.7	g	21.6	g

Table 2.2 Drill-in fluid properties by Ravitz *et al.*<sup>18</sup>

Mud Weight (lb/gal)	9.5 <sup>a</sup>
PV (cp)	15 – 20
YP (lb/100ft <sup>2</sup> )	25 - 35
API Fluid Loss (mL/30min)	<5.0
10-s Gel (lb/100ft <sup>2</sup> )	10 – 12
10-min Gel (lb/100ft <sup>2</sup> )	13 – 18
LSRV (KcP)	>30
HTHP (ml/30min)	<10.0
pH	8.5 – 9.5

of drill-in fluid solids is built up on the formation face, decreasing the filtrate invasion. However, the filter cake will also be eroded because of the shear velocity causing a shear force. The dynamic filtration rate is given by

$$u_f = \frac{C}{\sqrt{t}} + 3600b\dot{\gamma}$$

where  $u_f$  is the filtrate flux,  $C$  is the dynamic fluid loss coefficient for the filter cake,  $t$  is the exposure time, and  $b$  is a constant accounting for the mechanical stability of the filter cake.<sup>189</sup> For static deposition, we do not circulate the drill-in fluid, but only keep a certain overbalance pressure.

Dynamic filter cake deposition has the advantage to simulate the shearing process which happens in the real drilling process. However, in the lab it is not easy to maintain a backpressure for slurry fluid with a relatively high flow rate. In our experiment, we built up the filter cake by using the static deposition for 15 hours with 500 psi overbalanced pressure. The overburden pressure applied to the core should be

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<sup>a</sup> This number is missing in reference 14 and obtained by measurement in this work

around 900 psi. All experiments were carried out at room temperature. Experience shows that this combination of parameters work well.

#### 2.4 Jetting Parameters

In a field acid jetting treatment, the following parameters should be considered as important:

- Design of orifice

Under the same flow rate, the orifice diameter determines the jet velocity. Also the design of orifice determines the jet stream profile. An optimized jet stream profile can produce the maximum impact force under the same jetting velocity.

- Standoff distance

This is the distance between the jet orifice and the target. Experience shows that the optimal standoff distance for jetting is about 8 times the orifice diameter. Beyond that optimal distance, the mechanical impact force decreases.<sup>6</sup>

- Pumping rate

The pumping rate determines the jet velocity. The higher the velocity, the more mechanical impact force the jet can generate. In reality the pumping rate is limited by the equipment used.

- Duration of jetting

It is more likely to have better damage removal for longer time of jetting.

- Number of jets

More jets give more coverage of the wellbore.

- Rotation of jets and pulsation

Rotation can give 360 degree coverage of the wellbore. Pulsation can help in removing the filter cake.

- Temperature

When using acid jetting, the temperature greatly influences the reaction rate. Both the temperature of the jetting acid and the reservoir temperature should be taken into consideration for acid jetting treatment design.

- Acid type and concentration

The set up of our experimental apparatus has only one jet aiming at the center of the core face. We can easily control the standoff distance, the jetting velocity, and the jetting duration time. For the standoff distance, we set it to be about 8 times the orifice diameter. We use the 1/8 inch tubing for jetting, and the inner diameter of the tubing is about 0.04 inch. Therefore, we set the standoff distance to be about 0.32 inch. We change the jetting velocity by changing the flow rate. The flow rate we used is 100 ml/min for acid jetting and 140 ml/min for water jetting. The jetting velocity is calculated to be about 6.2 ft/s. and 8.9 ft/s respectively. In field treatment, the jetting velocity can achieve even higher than 200 ft/s in order to create a tremendous impact force. The jetting duration time we used is 20 seconds for acid jetting and 60 seconds for water jetting. All experiments were carried out at room temperature. The jetting acid we used is 15% HCl without any other additives. The jetting parameters are summarized in Table 2.3.

Table 2.3 Jetting parameters chosen for the experiments

Standoff distance (in)	0.32
Orifice diameter (in)	0.04
Flow rate (ml/min)	Acid: 100      Water: 140
Jetting duration (s)	Acid: 20      Water: 30
Temperature	Room Temperature



### 3. EQUIPMENT DESCRIPTION

#### 3.1 Equipment for Core Sample Preparation

- Core cutter

To cut our core samples we use an abrasive cut off machine manufactured by Pistorius Machine Company Inc. which is shown in Figure 3.1.



Figure 3.1 Abrasive cut off machine



Figure 3.2 Core saturation vessel

- Core saturation vessel and pump

All the core samples should be saturated with water initially before all other experiments. This is achieved by using a home-made core saturation vessel (Figure 3.2) and a vacuum pump (Figure 3.3). The vessel has a cover with a 1/8 inch Gyrolok connector in the middle. Vacuum grease is applied to the cover to make sure it is well sealed. The vacuum pump is connected to the top of the vessel sucking air out of the vessel.



Figure 3.3 Mechanical pump

### 3.2 Equipment for Drill-in Fluid Preparation

- LabWare plastic barrel

A 10 gallon LabWare plastic barrel (Figure 3.4) is used as the container for the drill-in fluid to feed the pump. The bottom of the barrel has an opening which connects to a ball valve. By closing the valve and connect/disconnect the other end, we can move the barrel around easily even with drill-in fluid in it.



Figure 3.4 10 gallon LabWare plastic barrel



Figure 3.5 A&D electronic balance

- A&D electronic balance

The electronic balance is used to measure the exact amount of each ingredient we need for making the drill-in fluid. This electronic balance is manufactured by A&D Company, Limited as shown in Figure 3.5. The model is EP-20KA with the maximum capacity up to 20kg and resolution 0.1g.



Figure 3.6 Picture of drill-in fluid tank and mixer

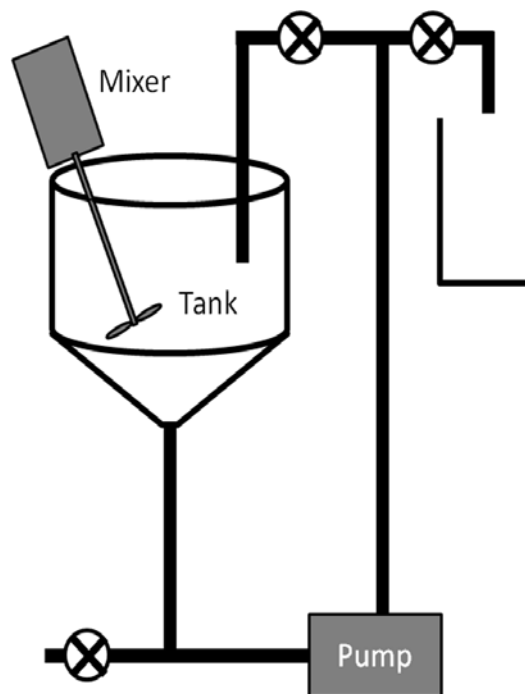


Figure 3.7 Diagram of drill-in fluid tank and mixer

- Drill-in fluid tank and mixer

The drill-in fluid tank and mixer is a home-made system (Figure 3.6) which has the capacity to make up to 50 gallons of drilling fluid at once. Figure 3.7 shows the diagram of the system which is composed of a metal tank, a mixer, a pump and some pipelines and control valves. The pump is used to circulate the fluid from the bottom of the tank back to the top and transfer the final product from the mixing tank to a container.



Figure 3.8 Picture of drill-in fluid agitator

- pH meter

It is used for testing the pH value of the drill-in fluid. Before each time of use, the meter should be calibrated with standard buffer solutions.

### 3.3 Equipment for Filter Cake Deposition

- Drill-in fluid agitator

After the drill-in fluid is prepared, we need to keep stirring it using an agitator (Figure 3.8). As long as the drill-in fluid is agitated, we can use the same barrel of drill-in fluid to deposit several cores without any problem.

- Mud pump and pipelines

A piston pump (Figure 3.9) is used to raise the mud pressure up to 500 psi. The pump is capable of maintaining a flow rate from 0.1 to 4 gallon per minute with pressures to 2000 psi. This pump was chosen due to its ability to handle high solids content.



Figure 3.9 Picture of drill-in fluid pump

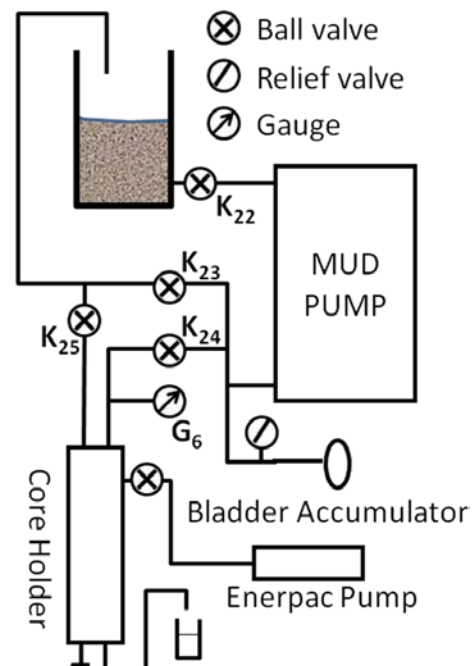


Figure 3.10 Diagram of the filter cake deposition apparatus

We use 1 inch diameter PVC tubing to feed drill-in fluid to the pump. Smaller diameter pipelines may have some trouble when working with very viscous drill-in fluid. For the output line of the pump, we use ½ inch stainless steel tubing which can withstand high pressure. There is a bladder accumulator attached to the pump outlet which works as a pulsation dampener to make the output smoother. The top of the bladder accumulator has an opening which enables the user to put in or remove gas in

the bladder so that the spring coefficient can be adjusted. For our static filter cake deposition experiment, this bladder accumulator also serves as a pressure source to maintain the drill-in fluid pressure at 500 psi. For safety reasons, there is a relief valve installed at the pump outlet. This relief valve will only open when the outlet pressure is above 1500 psi. We use three ball valves to control the drill-in fluid flow to either enter the core holder or directly go back to the barrel. The gauge on top of the core holder makes it easy to monitor the drill-in fluid pressure inside the core holder. This equipment set up can also run dynamic filter cake deposition if we have a back pressure regulator which can pinch the upstream pressure at a certain value. Figure 3.10 shows the diagram of the filter cake deposition apparatus.

- ENERPAC hydraulic pump

This hand pump is used for applying the overburden pressure to the core. The model P392 has a reservoir capacity 55 in<sup>3</sup> and can reach up to 10000 psi. This pump use motor oil as working fluid which is pumped into the annulus between the metal shell of the core holder and rubber Viton sleeve. The overburden pressure applied during the filter cake deposition is about 900 psi. Figure 3.11 shows the ENERPAC hydraulic pump.



Figure 3.11 Picture of ENERPAC hydraulic pump

- Core holder

The core holder is manufactured by the Phoenix Instruments Inc., which is designed for 4 inch diameter, 20 inch long cores. Without any spacer to take up the space inside the core holder, the core should never be less than 16 inch long. Pictures in Figure 3.12 show the core holder in detail. The core holder consists of (A) the main body, (B) inlet cap, (C) inlet holder, (D) outlet cap, (E) outlet holder, (F) outlet end piece. For the filter cake deposition, we do need a 2 inch long spacer (G) to create a space for the drill-in fluid. This stainless steel spacer is a cylinder with outer diameter the same as the core and the thickness of wall is  $\frac{1}{4}$  inch.

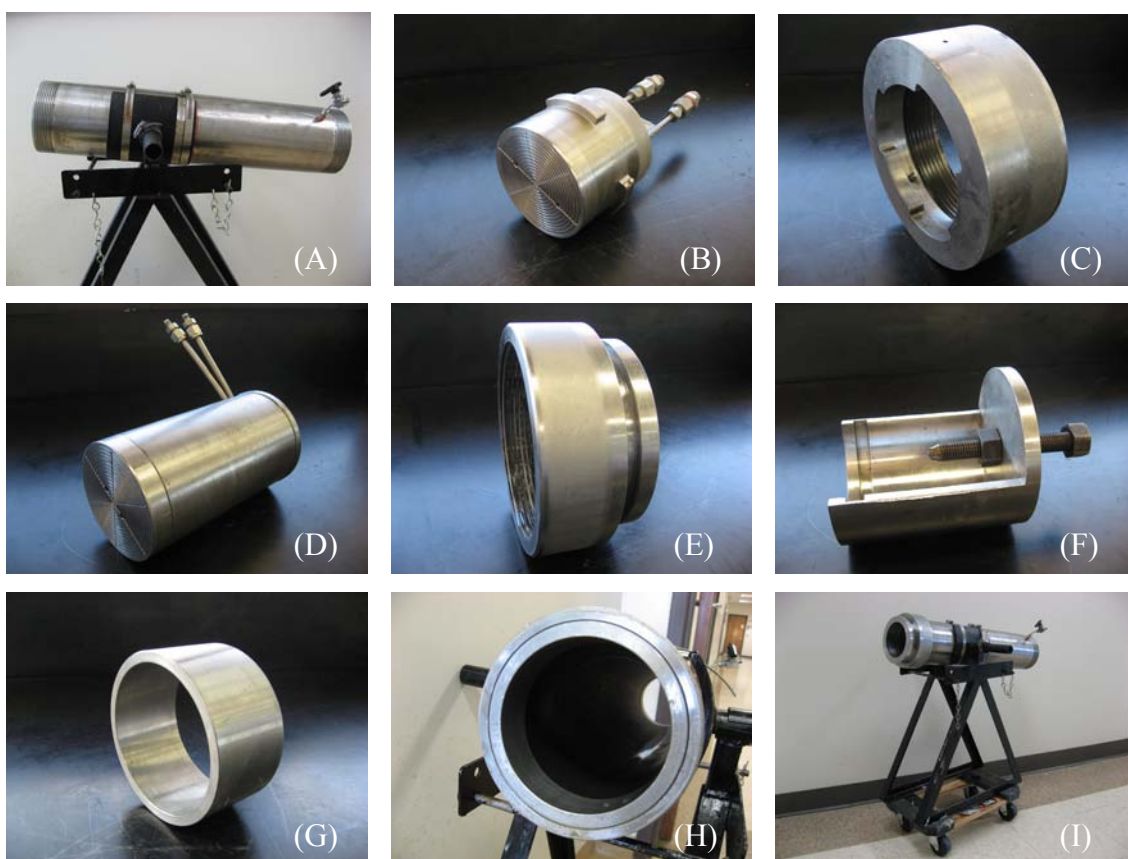


Figure 3.12 All parts of the core holder: (A) the main body; (B) the inlet cap; (C) the inlet holder; (D) the outlet cap; (E) the outlet holder; (F) the outlet end piece; (G) the spacer; (H) shows the metal ring and sleeve; (I) shows the core holder stand



The main body (A) consists of a metal cylinder, a rubber sleeve, and two metal rings at both ends. The metal rings hold the sleeve in place and the rubber o-ring between the metal ring and the metal cylinder help seal the annulus between the sleeve and the metal cylinder, within which oil is filled to apply overburden pressure. Subfigure (H) shows the metal ring at one end and the sleeve inside. As shown in subfigure (I), the main body of the core holder is fixed to a home-made stand which sits on a small wheeled cart, making it easy to move the entire core holder around. The stand is designed with hinges on both sides so that it is very convenient to rotate the entire core holder from a horizontal position to a vertical position.



Figure 3.13 Inlet cap for initial permeability measurement

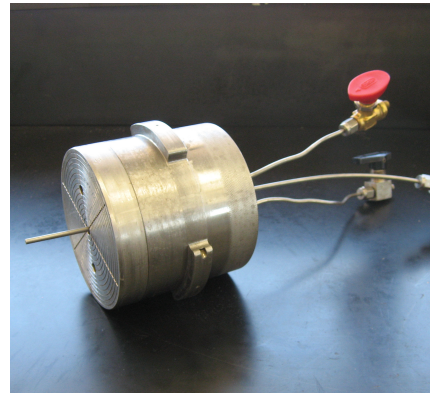


Figure 3.14 Inlet cap for jetting

The inlet cap (B) has 2 openings with  $\frac{1}{4}$  inch tubing. We do not use  $\frac{1}{8}$  tubing because small tubing raises the risk of the line plugging by the viscous drill-in fluid which contains large amount of solid material. The inlet holder (C) is screwed to the end of the main body (A) to hold the inlet cap in place. The outlet side has a different design. First the outlet holder (E) should be screwed to the other end of the main body before the installation of the outlet cap (D). The slot in the outlet end piece (F) can buckle with the end of (E). Then the screw in the middle of (F) can be tightened against the outlet cap.

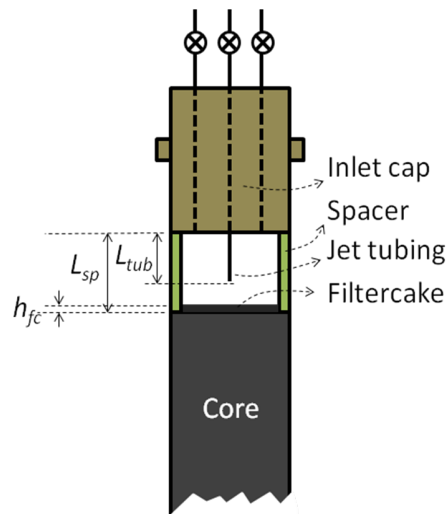


Figure 3.15 Diagram of inlet cap and spacer for jetting purpose

### 3.4 Equipment for Permeability Measurement and Jetting

- Core holder

We use the same core holder for the filter cake deposition, permeability measurement, and jetting experiments. However, for permeability measurement and jetting treatment, we use a different inlet cap. For initial permeability measurement we use the inlet cap shown in Figure 3.13. After the filter cake deposition, we will use another inlet cap which has three openings connecting to 1/8 inch tubing as shown in Figure 3.14.

As shown in Figure 3.15, in the center the tubing thrusts out of the hole as jetting port. The length of the center tubing is carefully adjusted so that the desired standoff distance can be achieved. If we use 2 inch long spacer, then this length is

$$L_{tub} = L_{sp} - L_{so} - h_{fc}$$

where  $L_{sp}$  is the length of spacer,  $L_{so}$  is the standoff distance, and  $h_{fc}$  is the thickness of the filter cake. Under our experimental conditions, the filter cake is about 0.13 inch. The standoff distance we want is 0.32 inch. Therefore,  $L_{tub}$  is calculated to be 1.55 inch.

- Teledyne ISCO D500 syringe pump

This pump is used for pumping water or acid. It has a capacity of 1000 ml and can handle a maximum pressure of 2000 psi. The pump is controlled by a programmable controller which allows the pump to run at either constant flow rate mode or constant pressure mode. This pump is very precise and reliable. For our experiment the working material is hydraulic oil. A large bottle is used as the reservoir for hydraulic oil and a rubber pipe is connected to the pump for recharge purpose. By using the same pump, we are able to pump water or acid by using accumulators. Figure 3.16 shows a picture of this pump.



Figure 3.16 Teledyne ISCO D500 syringe pump

- Accumulators

All of our accumulators are piston type. One side of the piston is filled with hydraulic oil and the other side with the fluid we want. By pumping hydraulic oil into one side, we can produce the same volume of the desired fluid from the other side. Figure 3.17 shows the water accumulator, which has a capacity of 1 gal. Figure 3.18

shows the HCl acid accumulator, which has a capacity of 500ml. The acid accumulator is made of Hastelloy corrosion-resistant metal. One should always make sure that the accumulators have the right fluid filled. If air is accidentally filled in the accumulator, the accumulator should be totally emptied and refilled again. When the experiment is done, all remaining fluid in the accumulator should be completely drained and disposed properly, and the inside of the acid accumulator should be washed with clean water.

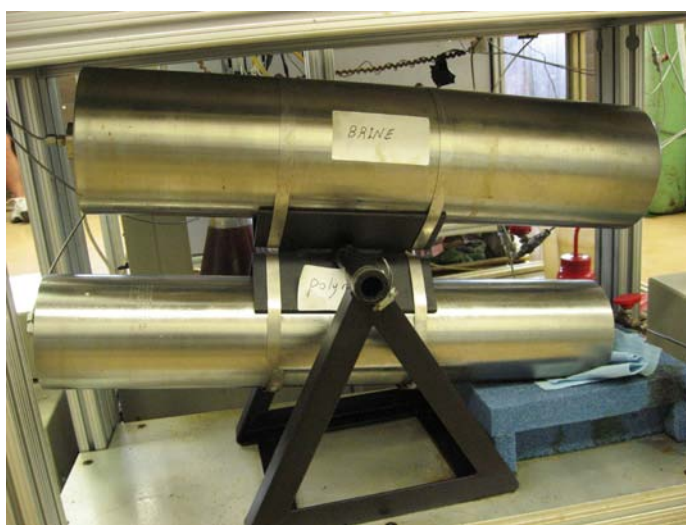


Figure 3.17 Water accumulator

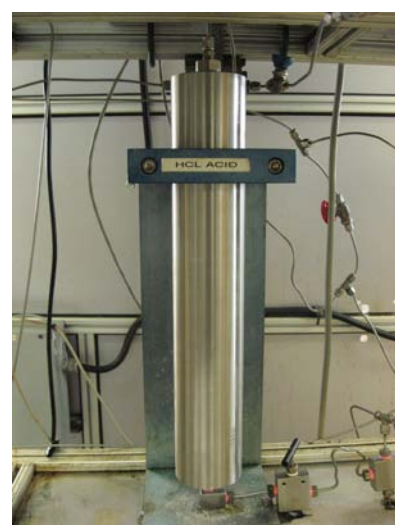


Figure 3.18 HCl acid accumulator

- PVC refill tank

This tank is used as a temporary container to recharge the accumulators (Figure 3.19). This tank has a capacity of 2 liters. The top of the tank has a ½ inch Gyrolok type connector which can connect to the compressed air source in the lab. The bottom of the tank connects to the accumulators. To refill the accumulator, first put more than the desired amount of fluid to be refilled in this tank (This is important because we do not want air to be pushed into the accumulators). Then one should connect the tank to the compressed air source and turn on the source. The air pushes the fluid into the

accumulator through certain pipelines. As the piston in the accumulator moves toward the oil side, oil will come out through certain pipelines and drip into a bottle for reuse. There are valves to control which accumulator is to be refilled.



Figure 3.19 PVC refill tank

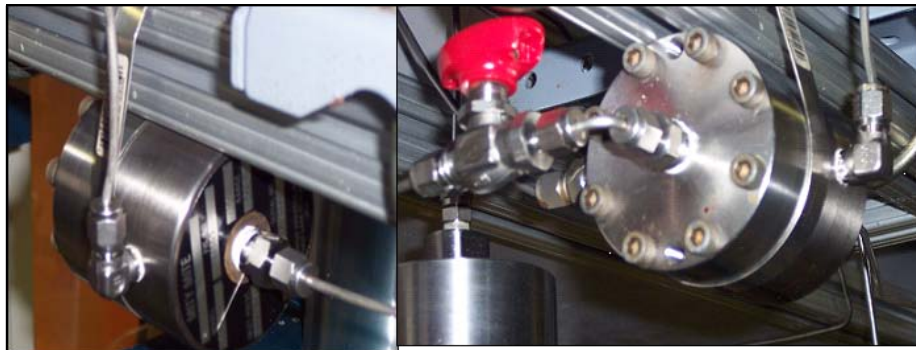


Figure 3.20 Mity-Mite S91-W back pressure regulators used on inlet side of core holder (left) and the outlet side of core holder (right)

- Back pressure regulator

The back pressure regulators we used are Mity-Mite S91-W. This type of back pressure regulator is external dome loaded and needs to be charged by a nitrogen source. The nitrogen source applies a pressure on the upper side of a Teflon diaphragm which covers the small hole connecting the inlet and outlet. Once the inlet pressure which applies on the other side of the diaphragm increased up to the nitrogen source pressure, the diaphragm is lifted and the fluid can pass the small hole and go to the outlet. It is the pressure balance on both sides of the diaphragm that pinches the upstream pressure to the value set by the nitrogen source. The range of the pressure is from 100 psi to 2000psi. This type of backpressure regulator is not able to handle slurry fluid like drill-in fluid, because the solid material in the fluid will erode the Teflon diaphragm easily. The connections to the flow lines are 1/4" NPT female threads and the connection to the charging line is 1/8" NPT female thread. For very low flow rate ( $<0.5\text{ml/min}$ ), this back pressure regulator will leak and cannot hold to the desired pressure. Figure 3.20 shows two backpressure regulators installed in the setup. One is installed on the core holder outlet side for the purpose of raising the core holder outlet pressure to a certain value; the other is installed on the core holder inlet side for the purpose of controlling the core holder inlet pressure.



Figure 3.21 Nitrogen tank with pressure regulator

- Nitrogen tank and pressure regulator

We need two nitrogen sources to provide the reference pressure for the two back pressure regulator separately. A pressure regulator is connected to the opening valve of the tank to control the output pressure for each nitrogen source. There are two gauges on the pressure regulator. One gauge monitors the pressure inside the tank; the other monitors the pressure set by the regulator. Figure 3.21 shows a picture of the nitrogen tank with pressure regulator.

- Pressure transducers

Three FOXBORO differential pressure transducers model IDP10-T26(C-D-E) 21F-M2L1 are used to measure the pressure difference between the inlet and the outlet of the core holder. These three transducers have measuring ranges of 0-30 psi, 0-300 psi, and 0-3000 psi respectively and are connected parallel to each other so that the most suitable range can be chosen by controlling the valves at both ends of the transducers. The three-transducer design enables the setup to measure a wide range of permeability with high accuracy.

The differential pressure transducers are powered by a 30 volt single DC power supply. Each of them has a LCD screen to display the pressure readings. The signal can also be transferred through cables, configured by electronic chipboard and finally read by a personal computer running the LabView program. The connections of the transmitters are with 1/8" Hastelloy C276 tubing and Gyrolok compression fitting. Figure 3.22 illustrates the pressure transducer setup.

- Data acquisition system

3 pressure transducers transfer their signals independently to a personal computer which runs a LabView program to collect the data and display the pressure in wave charts. The pressure data is collected every 5 seconds and written into a file specified by the user. If given the flow rate, core length and diameter, and fluid viscosity, the program can calculate the permeability automatically and display it on the screen. Figure 3.23 shows the front panel of the program.



Figure 3.22 Pressure transducers and there connections

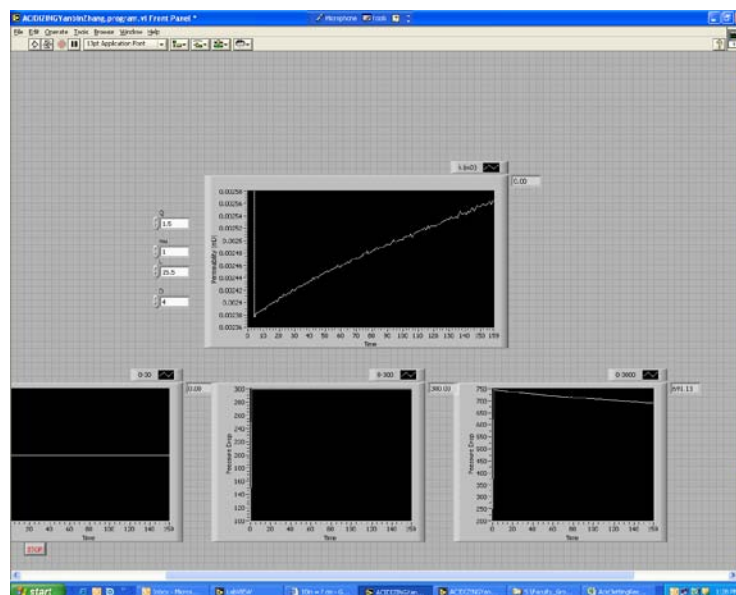


Figure 3.23 LabView program front panel for permeability measurement

- Equipment for CT scanning

The Universal HD200 x-ray CT scanner (as shown in Figure 3.24) is a high-precision instrument that can measure the porosity, saturation, fluid density and differentiation in a core sample. The scanner is a 4th generation model with a 50 cm



maximum entry diameter, a maximum scan speed of 2 sec, cross-sectional resolution of 0.27 mm x 0.27 mm. It has an automatic sample table with a travel precision of 0.1 mm. We use this equipment to obtain an image of the wormhole created in the core sample by acid jetting.



Figure 3.24 Picture of the CT scanner front side (left) and back side (right) (Courtesy of Engineering Imaging Laboratory, Department of Petroleum Engineering, Texas A&M Engineering)

## 4. EXPERIMENT PROCEDURE

### 4.1 Experiment Preparation

- Core sample preparation

The core samples we ordered were 4 inch in diameter and 20 inch long. During the transportation, the edge of the core may have some damage. Before we measured the permeability we need to cut the core to be 18 inch long by using the core cutter. The steps are as follows:

1. Measure the length and mark the point where we will cut through;
2. Put the core on the stand with the marked point at the blade position;
3. Turn on the cooling water;
4. Wear protecting mask and gloves;
5. Turn on the machine;
6. Hold the core with both hands tightly and slowly push the core toward the blade;
7. When finish cutting, turn off the machine and cooling water.

Before measuring the permeability and doing the acid jetting experiments, it is necessary to saturate the core with water. It usually takes two people to open and close the cover of the saturation vessel. The steps are as follows:

1. Disconnect the 1/8 inch pipe connecting the saturation vessel to the pump;
2. Open the cover;
3. Take the previous core out of the vessel;
4. If there is not enough water left, add some water;
5. Put the new core in the vessel;
6. If the thread of the cover do not have enough vacuum grease, apply some;
7. Close the cover;
8. Connect the pump to the top of the cover;
9. Turn on the pump;
10. Wait for at least 24 hours before turning off the pump and taking the core out of the vessel.

- Recharge the syringe pump

Before permeability measurement and jetting experiment, make sure that there is enough hydraulic oil in the pump. Experience shows that one permeability measurement needs 300 – 500 ml to be pumped, and for jetting, the volume to be pumped is determined by jetting flow rate times the duration time. The jetting process should never be interrupted. For permeability measurement, it is all right to recharge the pump in the middle of the experiment. The steps are as follows (see Figure 4.1):

1. Close valve  $K_2$  and open valve  $K_1$ ;
2. Make sure there is enough hydraulic oil in container  $D_1$  and then start the pump using refill mode; the flow rate is usually set to be 80 ml/min and can be adjusted using the control panel;
3. The pump will stop automatically when it is full.

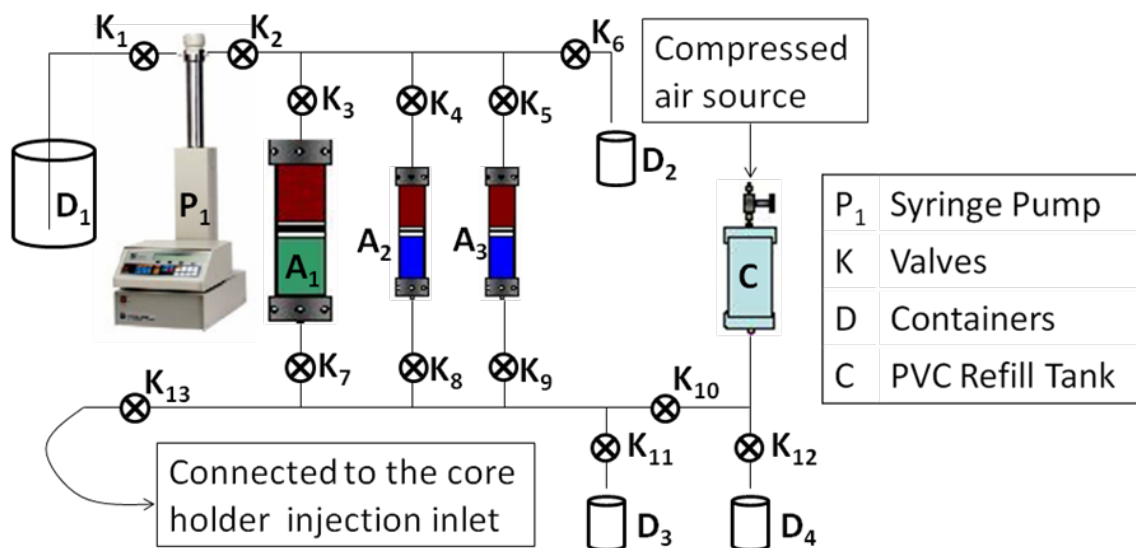


Figure 4.1 Syringe pump, accumulators, PVC refill tank and their connections

- Refill the accumulators

Before permeability measurement and water jetting experiment, make sure that there is enough water in the water accumulator. Before acid jetting experiment, make sure there is enough acid in the acid accumulator. For one permeability measurement, at least 500 ml water should be guaranteed in the accumulator. Because it is impossible to see directly how much fluid remains in the accumulator, it is necessary to make a record of how much fluid is put into the accumulator initially and how much is used during the experiment. Also it is noted that to refill 500 ml of fluid into the accumulator may take over 1 hour. It is important to schedule enough time for refilling the accumulators. The steps are as follows (see Figure 4.1):

1. Open  $K_{12}$  to vent out the remaining fluid in the PVC refill tank; empty  $D_2$  by pouring the remaining hydraulic oil into  $D_1$ ;
2. Close all valves;
3. Put in water or acid in the PVC refill tank through the top opening; take a note on how much fluid has been put in;
4. Connect the compressed air source to the PVC refill tank; open the compressed air source;
5. Open one of  $K_3, K_4, K_5$  and one of  $K_7, K_8, K_9$  for the accumulator to be refilled; open  $K_{10}$  and  $K_6$ ;
6. There should be hydraulic oil coming out from  $K_6$  and dripping into  $D_2$ ; the volume of hydraulic oil in  $D_2$  indicates the volume of water or acid refilled into the accumulator; It is very important to make sure that the PVC refill container is never empty during the refilling process; close valve  $K_{10}$  and add more water or acid if necessary;
7. Once the desired amount of fluid has been filled into the accumulator, close all the valves and take notes on how much fluid has been refilled to keep track of the remaining amount of fluid in the accumulator;
8. Vent the remaining fluid in the PVC refill tank if necessary by opening  $K_{12}$ , and then disconnected the compressed air source;

9. Reuse the hydraulic oil in  $D_2$  by pouring it back to  $D_1$  for future pump recharge.

If the PVC refill tank is empty during the refilling process, air will be pushed into the accumulator. This will give us a huge problem. To fix this, the following step is needed (see Figure 4.1):

1. Open  $K_2$ ,  $K_{11}$ , and the valves at both ends of the accumulator; use the pump to push all liquid plus air out of the accumulator through  $K_{11}$  into  $D_3$ ;
2. When the piston of the accumulator moves to the end, the pump pressure will increase very quickly; when that happens, shut down the pump;
3. Refill the accumulator from the very beginning.

- Assemble and disassemble the core holder

To assemble the core holder with the core, one needs to (see Figure 3.12 for reference):

1. Rotate the core holder to horizontal position;
2. If spacer is used, first put it in the core holder near the inlet side;
3. Install the inlet cap and screw the inlet holder tightly onto the main body;
4. Put the core in the core holder through the outlet side; push the core all the way toward the inlet side until the core or the spacer hits the inlet cap;
5. Install the outlet holder and then put the outlet cap in the core holder; push the outlet cap all the way into the core holder until it hits the core;
6. Install the outlet end piece and screw the big bolt in the middle all the way; use a wrench to tighten the bolt;

To disassemble the core holder, one needs to:

1. Rotate the core holder to horizontal position;
2. Open the valve on the side of the core holder main body to let the mechanic oil flowing out of the core holder in order to release the overburden pressure; use a container to catch the oil coming out; wait until little oil comes out before trying to disassemble;
3. Loosen the big bolt on outlet end piece and remove the outlet end piece;

4. Screw out the inlet holder carefully without moving the inlet cap;
5. Take the inlet cap out of the core holder; use a big container to catch the fluid pouring out if necessary;
6. Pull out the outlet cap; it is not necessary to remove the outlet holder;
7. Remove the spacer from the inlet side if it is necessary;
8. Push the core from the inlet side; sometimes the core may get stuck with the metal ring on the outlet side; when this happens, try to move the core holder vertically; when the core comes out of the outlet side, it is easy to pull it out of the core holder;
9. Clean the inside of the core holder with paper towels.

#### 4.2 Initial Permeability Measurement

The core sample should be cut to be 18 inch and fully saturated with water before the initial permeability measurement. The equipment setup diagram is shown in Figure 4.2 and the procedure is as follows:

1. Recharge the pump and refill the water accumulator if necessary;
2. Assemble the core holder using the inlet cap showed in Figure 3.13 and rotate the core holder vertically on the stand;
3. Connect the inlet and outlet pipelines; there are two lines at both the inlet side and the outlet side; one is the flow line and the other is the pressure transducer line;
4. Connect the overburden line to the port on the side of the core holder body; apply overburden pressure to about 300 psi by using the ENERPAC Hydraulic Pump;
5. Start the pump in constant flow rate mode using about 10 ml/min flow rate to inject water into the core holder;
6. As the inlet pressure increases, use the ENERPAC Hydraulic Pump to increase the overburden pressure as well; make sure that the overburden pressure is always at least 300 psi higher than the inlet pressure;
7. Once the inlet pressure increases to 700 psi and keeps increasing, we need to decrease the flow rate by using the pump controller in order to make sure that the

inlet pressure is not too high; higher inlet pressure means higher overburden pressure, and to apply an overburden pressure higher than 1200 psi is dangerous because the core may be crushed and the sleeve may be broken;

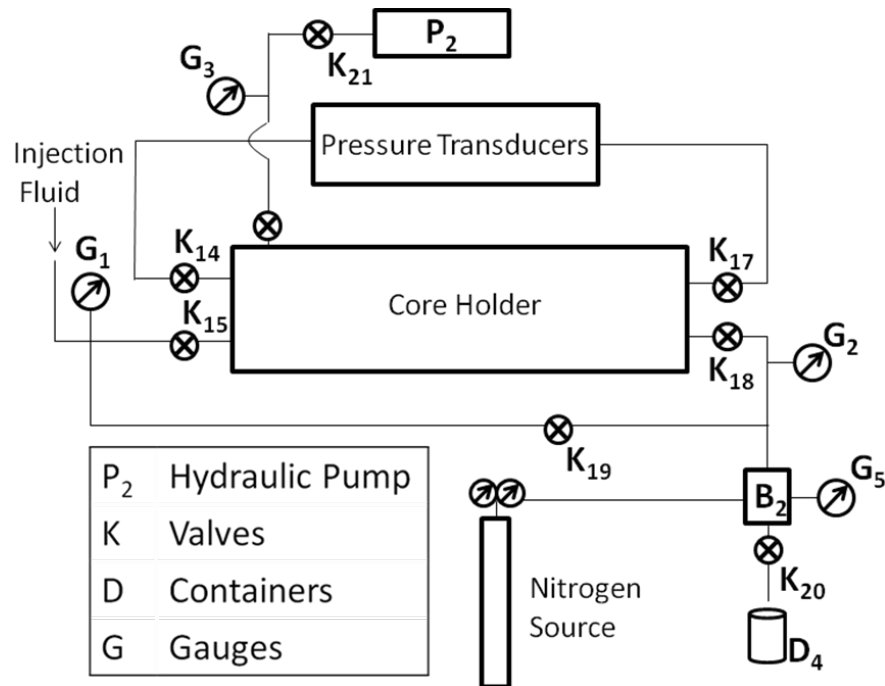


Figure 4.2 Diagram of equipment setup for initial permeability measurement

8. If the permeability of the core is very low, we can also use the constant pressure mode of the pump to maintain a constant pressure at the inlet by pumping as much as possible;
9. Wait until the water production from the core holder outlet line is continuous and steady; measure the production flow rate and compare it with the injection rate; under constant flow rate, if the pressure difference changes very slowly and the production rate equals the injection rate, we have reached steady state;

10. When the system is in steady state, record the flow rate from the pump and the pressure difference between the inlet and the outlet measured by the transducer; if using the computer data collecting system, the pressure data can be read directly into the computer;
11. Stop the pump; open the valve  $K_{19}$  to release the inlet pressure; release the overburden pressure by turning the knob located at the end of the ENERPAC pump; open valve  $K_6$  (see Figure 4.1) to release the syringe pump pressure;
12. Close injection valve  $K_{13}$ ; close the water accumulator valves  $K_3$  and  $K_7$ ;
13. Disconnect the four core holder inlet and outlet lines; disconnect the overburden pressure line;
14. Disassemble the core holder.

#### 4.3 Drill-in Fluid Preparation

Drill-in fluid should be made before the filter cake deposition. Usually it takes about 6 hours to make 10 gallons of drill-in fluid. The diagram of the equipment setup is shown in Figure 3.7 and the procedure is as follows:

1. Clean the mud barrel, mud tank and mixer;
2. Based on the total drill-in fluid volume we want to make, calculate the amount needed for each ingredient;
3. Put it into the mud tank the amount of water needed;
4. Using the electronic balance, measure the amount of NaCl and KCl needed;
5. Turn on the mixer and the pump before adding any solid ingredients;
6. Add NaCl and KCl into the mud tank and wait until the salts are dissolved completely;
7. Using the balance, measure the amount of Thrutrol, Thrucarb, and Safe-Carb 10 needed (see Table 2.1 for detail);
8. Add these three ingredients in sequence; wait at least 30 min in between;
9. Measure and add in Rev Dust accordingly;
10. Before adding Xanthan Gum polymer, make sure that the fluid in the mud tank is homogeneous; when adding Xanthan Gum polymer, add a small dose (5-10g)



each time, and wait until the powder disappear completely before adding the next dose;

11. Measure and add the Myacide;
12. Measure and add Caustic Potash;
13. Wait until the drill-in fluid is homogenous; then measure the pH by using the pH meter or a pH test paper; if the pH is not in the range 8.5 – 9.5, add more Caustic Potash to adjust the pH value;
14. Make sure the drill-in fluid is homogenous and then pump the drill-in fluid to the mud barrel;
15. Clean the mud tank, mixer, pump and pipelines by running water several times.

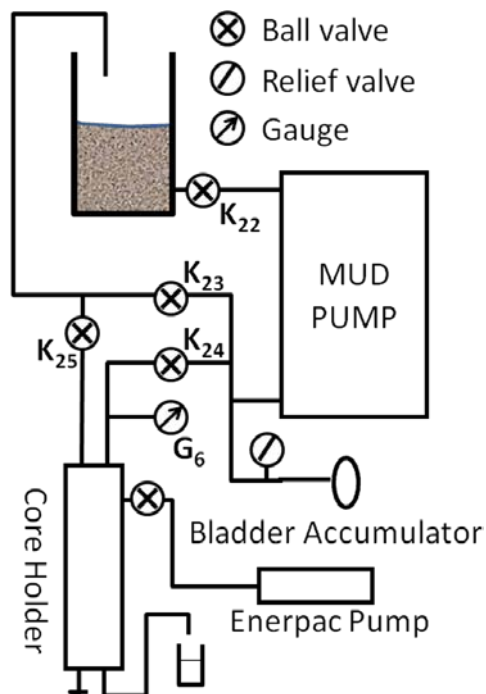


Figure 4.3 Diagram of equipment setup for filter cake deposition

#### 4.4 Filter Cake Deposition

Before filter cake deposition, the core should be cut to be 16 inch and about 8 gal drill-in fluid should be prepared in advance and put into the mud barrel. A diagram of the equipment setup is shown in Figure 4.3. The steps are as follows:

1. Connect the outlet of the mud barrel to the mud pump input line;
2. Assemble the core holder with the inlet cap showed in Figure 3.12 (B) and the 2 inch spacer as shown in Figure 3.12 (G);
3. Rotate the core holder to be vertical on the stand and move the stand to a good position in order to connect the pipelines to the inlet cap of the core holder;
4. Put a small container under one of the outlet line of the core holder; shut the valve for the other outlet line;
5. Connect the overburden line to the core holder and apply about 500 psi overburden pressure;
6. Open  $K_{22}$ ,  $K_{23}$  and start the pump to circulate the drill-in fluid for a while in order to make sure the pump and connections have no problem;
7. Open  $K_{24}$ ,  $K_{25}$  and close  $K_{23}$  to fill the void space in the core holder with drill-in fluid;
8. Close  $K_{24}$  and wait for the reading of gauge  $G_6$  to increase to 500 psi; increase the overburden pressure to about 900 psi at the same time;
9. Stop the pump when the pressure reading of  $G_6$  reaches 500 psi; if there is no leak, this pressure can be maintained for a long time;
10. Wait for 15 hours; if the pressure reading of  $G_6$  decreases too much, start the pump again to raise the pressure up to 500 psi;
11. After 15 hours deposition, open  $K_{25}$  to release the pressure; release the overburden pressure at the same time;
12. Disconnect the two inlet lines of the core holder and move the core holder away;
13. Loosen the bolt of the outlet end piece, remove the inlet holder and then the inlet cap carefully; when taking the inlet cap out, be prepared with the drill-in fluid pouring out from chamber created by the spacer; try not to disturb the filter cake;

14. Move the core holder to the core flood apparatus for further experiments.

#### 4.5 Water/Acid Jetting

This is the core part of the experiment which is done by three steps. First, we need to measure the permeability right after the filter cake deposition. Second, we do water/acid jetting. Third we measure the permeability again after the jetting. After the filter cake deposition, the inlet cap is carefully removed, but we will not touch the spacer and the core in order not to disturb the filter cake. Then we install another inlet cap with three input lines as shown in Figure 3.13. After that we screw the inlet holder and tighten the bolt in the outlet end piece. When this is done, we finish assembling the core holder and we will not try to disassemble any part of the core holder until all experiments are finished.

A diagram of the apparatus is shown in Figure 4.4. Compared with Figure 4.2, the only difference is that we now have three input lines for the inlet side of the core holder. The middle one should be used as the injection/jetting line. For the other two, one is used for pressure transducers and the last one is specially designed as a bypass for the injection fluid. This bypass line is controlled by a back pressure regulator  $B_1$ . During the jetting process, this back pressure regulator can pinch the pressure in the inlet of the core holder to a certain value so that we can achieve a constant pressure difference between the inlet and the outlet of the core holder.

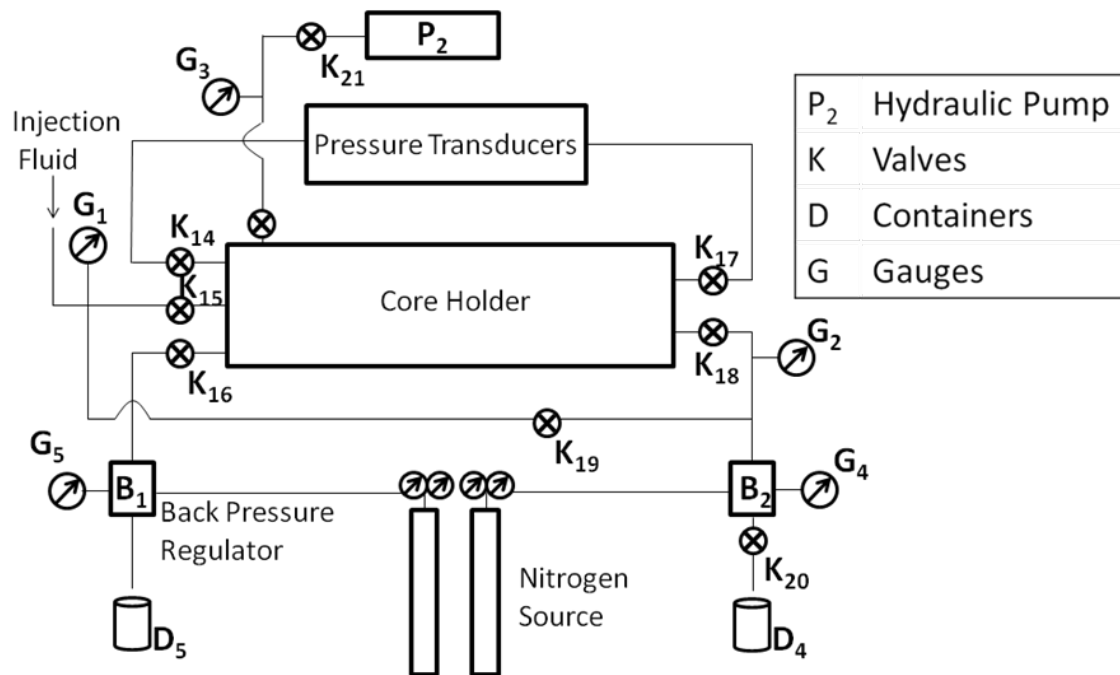


Figure 4.4 Diagram of equipment setup for acid jetting

The detailed steps are as follows:

1. Rotate the core holder to be vertical on the stand;
2. Use a large syringe to put water into the chamber inside the core holder; make sure that all void space is filled with water;
3. Connect all the three inlet lines and two outlet lines of the core holder;
4. Connect the overburden line and apply 200 psi overburden pressure;
5. Close valve K<sub>16</sub> and measure the permeability just as described in section 4.2; record the permeability with filter cake;
6. Close valve K<sub>20</sub> and keep injecting water; because the permeability with filter cake is very low, we can only inject at very low flow rate;
7. Wait until the outlet pressure is built up to around 500 psi;
8. Stop the pump and wait until the inlet pressure and the outlet pressure are the same; the core reaches equilibrium state;

9. Set the back pressure regulator B1 to a pressure value higher than the equilibrium pressure in the core; open valve  $K_{16}$ ;
10. Start the computer program to collect the pressure difference between the inlet and outlet;
11. For acid jetting, switch to acid accumulator;
12. Start jetting by pumping at a high flow rate for a certain time period; turn off the pump after jetting is complete;
13. Stop the computer program to obtain the pressure difference vs. time during the jetting period;
14. Close  $K_{16}$  and measure the permeability again;
15. Disassemble the core holder as instructed in section 4.1 and 4.2.

The entire acid jetting equipment setup is shown in Figure 4.5.

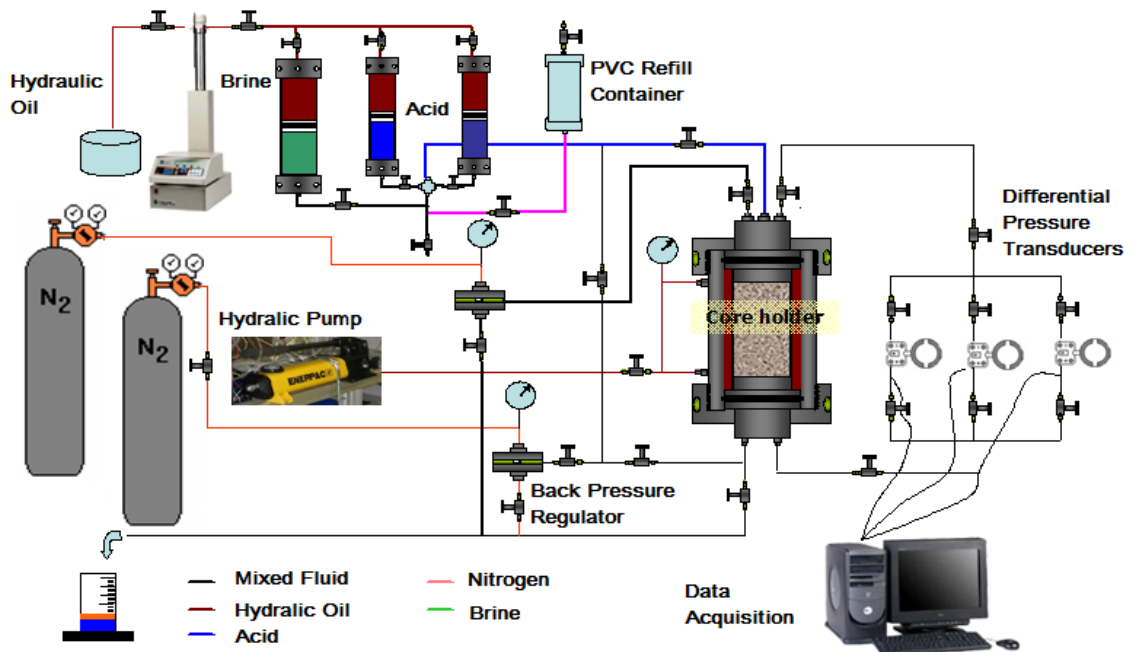


Figure 4.5 Diagram for the entire acid jetting equipment setup

#### 4.6 CT Scanning

CT scanning is performed in order to get the image of wormholes created by the acid jetting in the core samples. Major steps are:

1. Start the control system and wait for proper heat up;
2. Put the core sample on the sample table, move the sample table so that the scanning location indicated by the laser beam is at one end of the core sample;
3. Configure all the necessary parameters for scanning by using the control system; our core sample is 16 inch long and 200 equally spaced slices of scanning are taken;
4. Transfer the obtained image data to a personal computer;
5. Use VoxelCalc software developed by KehlCo Inc. to process the data to get 3D images

## 5. RESULTS AND ANALYSIS

### 5.1 Results of Jetting Experiments

Eight experiments were done successfully with six of them using 15% HCl acid jetting; the other two uses water jetting. The original permeability  $k_{original}$ , the permeability with the filter cake  $k_{damage}$ , and the permeability after the jetting treatment  $k_{recover}$  were measured for each core sample under various overbalanced pressures.

The results of the measurement are shown in Table 5.1.

Figure 5.1 shows the pictures of core sample C1 inside the core holder with the spacer after the filter cake deposition and after the acid jetting experiment. From Figure 5.1 (a) it is observed that the filter cake firmly attached to the core face and was very smooth and uniform in thickness. Both (a) and (b) demonstrate that the filter cake was not disturbed if the inlet cap was taken off and installed very carefully.

Table 5.1 Results of acid/water jetting experiments

Core No.	Original Perm (md)	Perm with Filter cake (md)	Jetting Conditions		Perm After Jetting (md)
			Water/Acid	Overbalance Pressure (psi)	
C1	6.3	0.4	Acid	550	10.5
C5	0.24	0.05	Acid	230	0.24
C9	1.1	0.06	Acid	150	0.75
C6	0.37	0.11	Acid	95	0.44
C10	0.25	0.1	Acid	50	0.28
C8	0.3	0.06	Acid	0	0.3
C4	0.56	0.11	Water	270	0.07
C7	6.8	0.3	Water	130	0.3

A typical pressure response during the permeability measurement is shown in Figure 5.2 (see Appendix A for all figures). The pressure drop was approaching a

constant value over time indicating that the system was approaching steady state. The steady state pressure drop was then determined and the permeability is calculated by

$$k = \frac{122.78q\mu L}{D^2\Delta p}$$

where  $q$  is the flow rate (ml/min),  $\mu$  is the viscosity (cp),  $D$  is the core diameter (in),  $\Delta p$  is the pressure drop (psi), and  $k$  is the permeability (md).



Figure 5.1 Core sample C1 (a) after filter cake deposition, and (b) after the acid jetting treatment

A typical pressure response during the jetting treatments is shown in Figure 5.3 (see Appendix B for all figures). Before the jetting began, the overbalanced pressure was controlled to be small. When jetting began, the overbalanced pressure rapidly increased to the pressure we set by using the back pressure regulator and kept nearly constant until the jetting stopped. The pressure began to drop after the jetting stopped.

After the jetting treatment and the final permeability measurement, the core holder was taken apart and the condition of the filter cake and the core were examined. The pictures of all core samples after the jetting treatment are shown in Figure 5.4. For all the acid jetting experiments, the filter cake was more or less dissolved and/or detached from the core face. For cores C5, C6, C10, and C8, the filter cake was broken



into several pieces and flowed out with water and spent acid when the inlet cap was removed. For C1 and C9, some part near the center of the filter cake was dissolved completely and other parts of the filter cake became thinner and softer. For the two water jetting experiments, the filter cake was almost intact after the jetting treatment. Only a small dent in the middle of the filter cake could be observed. Observation of the cores shows that only C1, C6, and C9 have relatively large holes on the core faces indicating possible wormholes created. For C5, C9, and C8, the core face center was etched by acid dissolution. For C6 and C10, the entire core face was evenly eroded by acid.

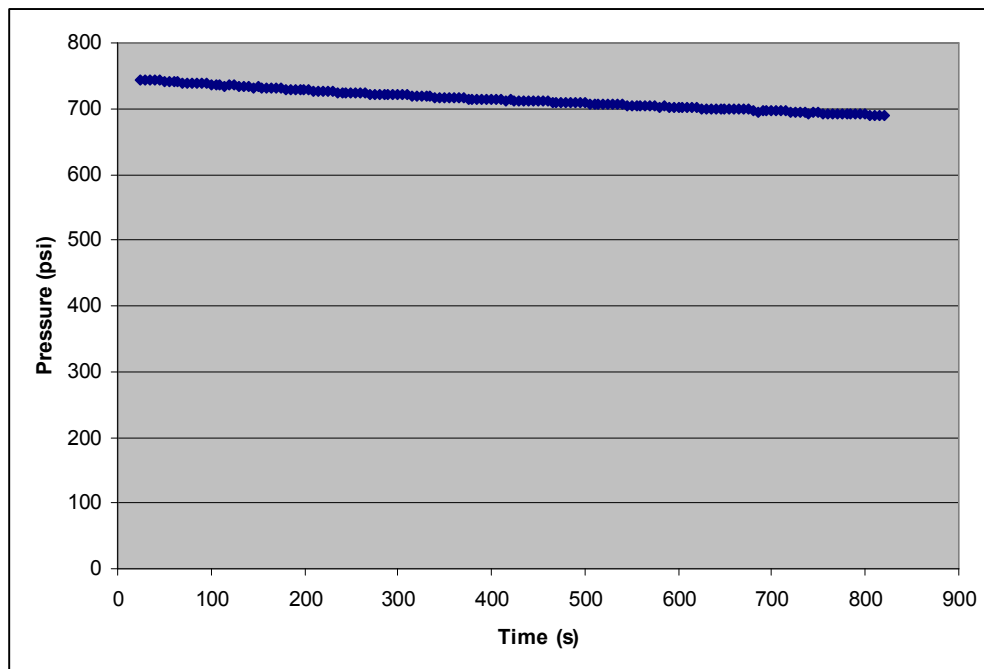


Figure 5.2 Pressure response during permeability measurement for C8 after acid jetting

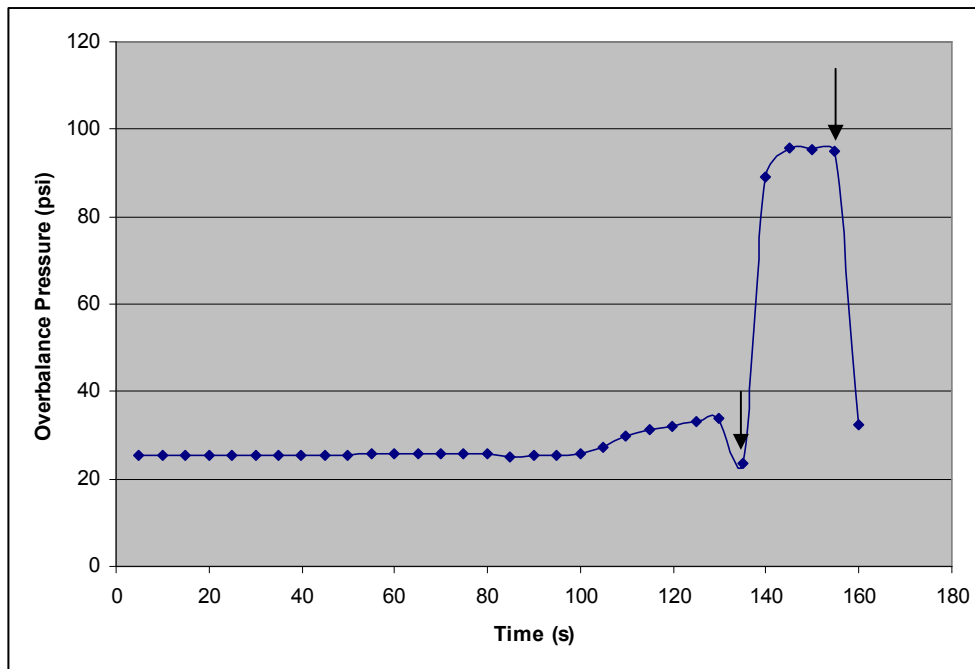


Figure 5.3 Pressure response during the jetting treatment of C6; two arrow shows the begin and end of jetting

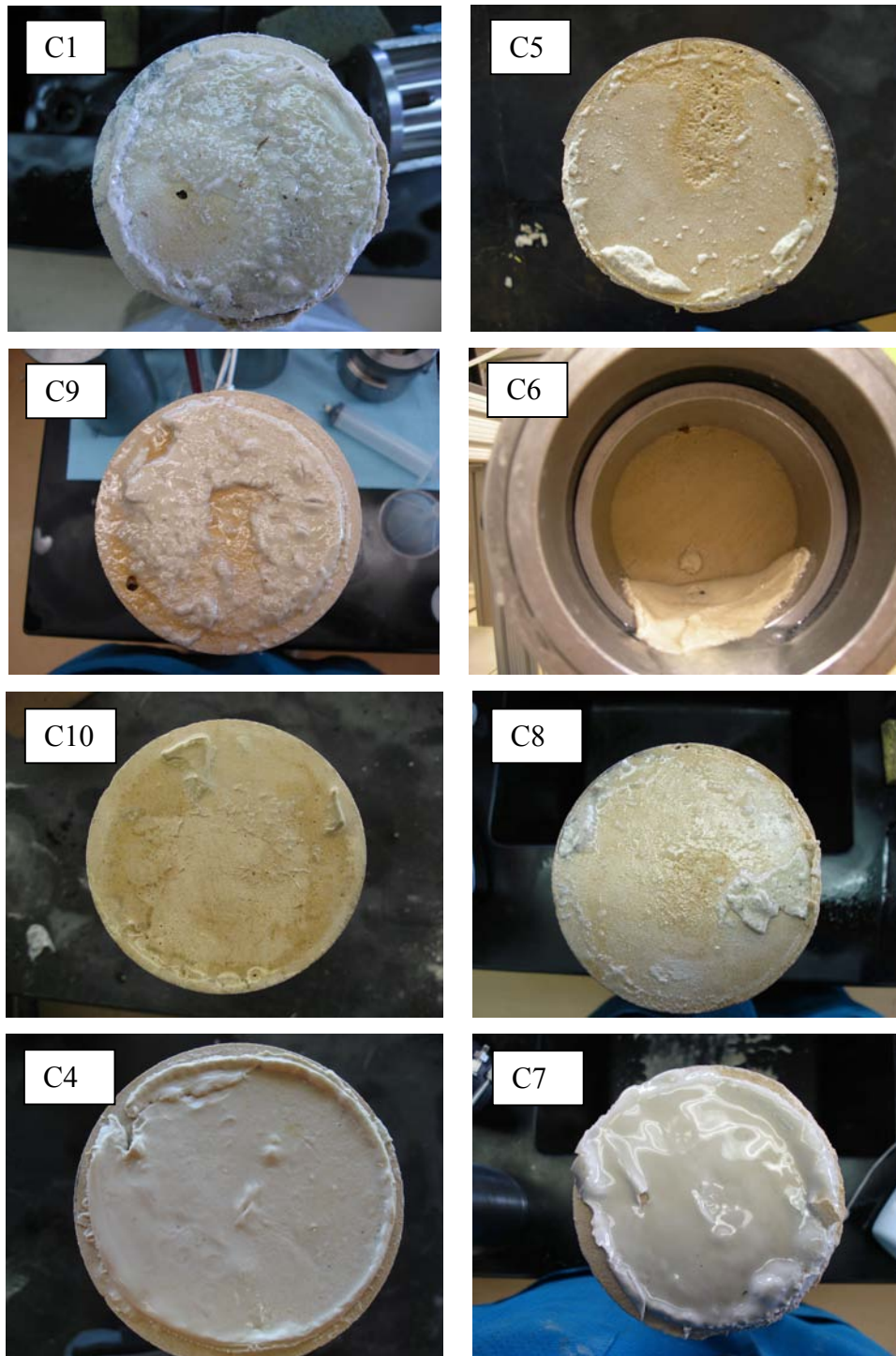


Figure 5.4 Core sample faces after the jetting treatment

## 5.2 Results of CT Scan

CT scans were done only for cores C1, C6 and C9 which have holes on the core faces. The CT scan pictures are shown in Appendix C. From the 136 cross section images for C1 shown in Figure 5.5, it can be observed that the wormhole was created in the low density or probably high permeability region. Figure 5.6 shows the 3D images of the void spaces inside three core samples. Two worm holes can be clearly observed in C1. The smaller one initiated from near the center of the core face and propagated about 1.5 inch into the core. The larger one initiated from near the edge and propagated and branched toward the inner part, extending about 8 inches, half of the total core length. However, no wormhole but many vugs can be found in C9 and C6.

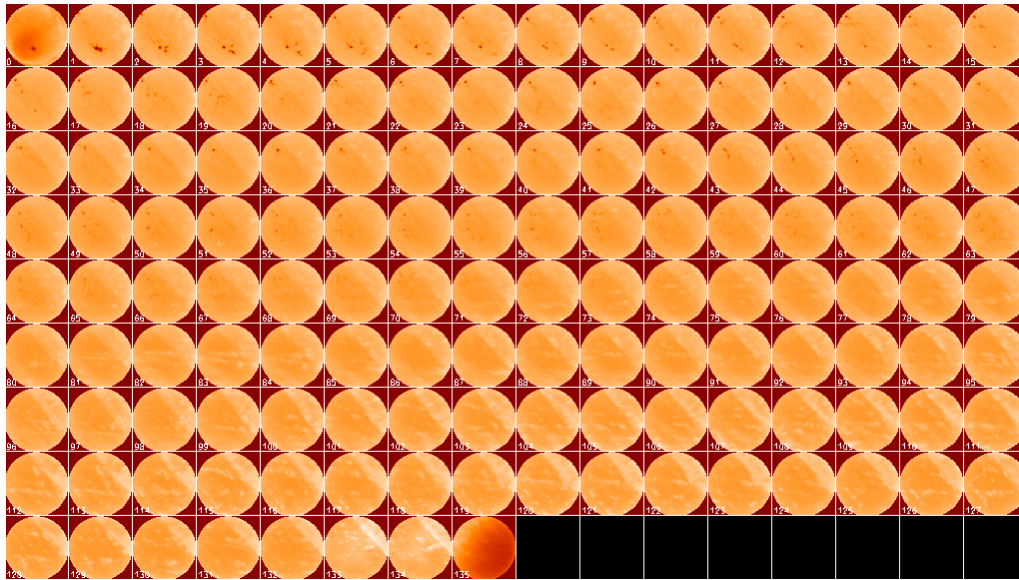


Figure 5.5 Cross section pictures of the CT scan for C1

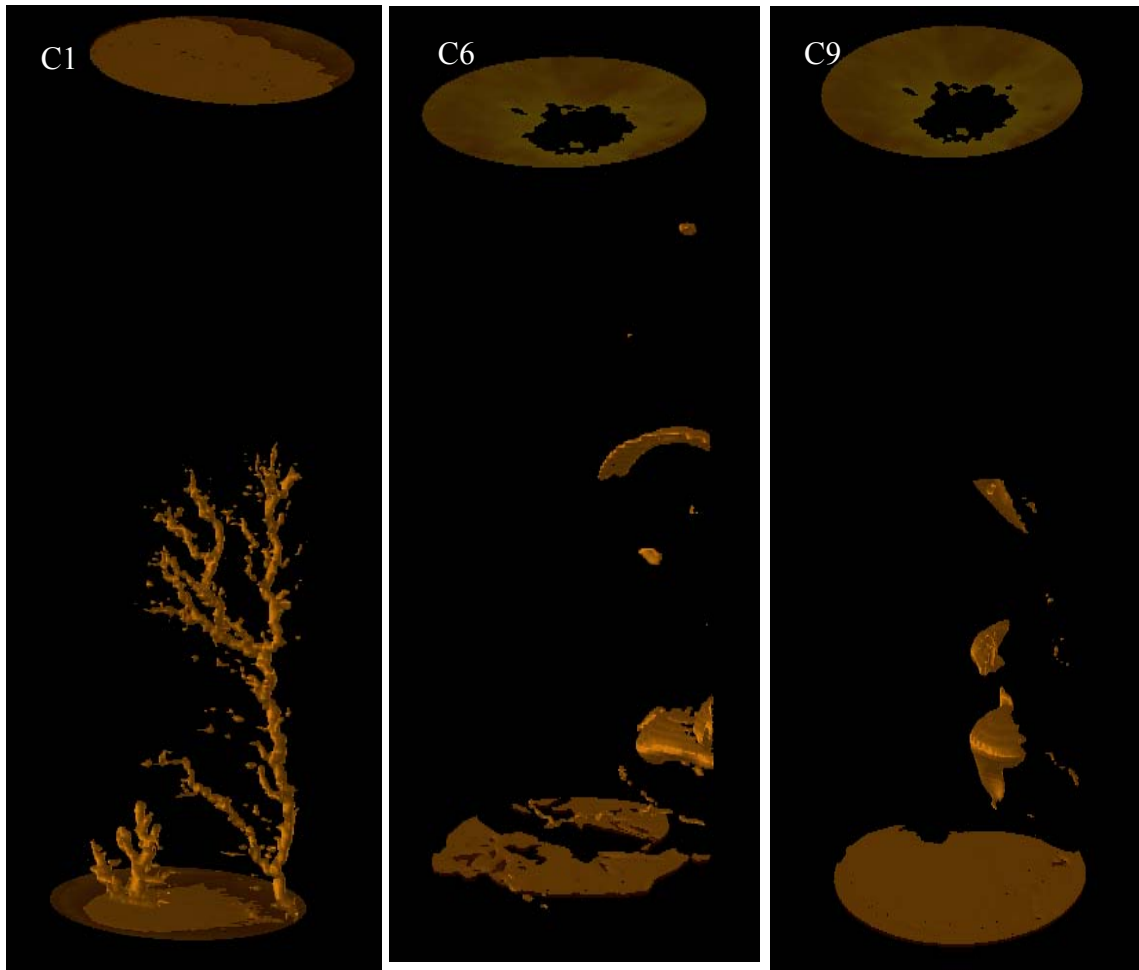


Figure 5.6 CT scan 3D images for C1, C6, and C9

### 5.3 Analysis

To show the experimental data more clearly, we plot  $k_{original}$ ,  $k_{damage}$ , and  $k_{recover}$  for all core samples in a bar chart as shown in Figure 5.7. Most core samples have low original permeabilities around or below 1 md except C1 and C7 which are above 6 md. Thus C1 and C7 were treated with acid jetting and water jetting respectively to facilitate the comparison. From Figure 5.7, we can see that the permeability with the filter cake is much smaller than the original permeability for all core samples, which indicates that the filter cake does cause a large additional pressure drop. From Figure 5.7, we can also see

that for two water jetting experiments, the permeability after jetting is almost the same as the permeability with filter cake which means that the water jetting fails to clean up the filter cake. In contrast, we can see a significant increase in permeability after the acid jetting treatment.

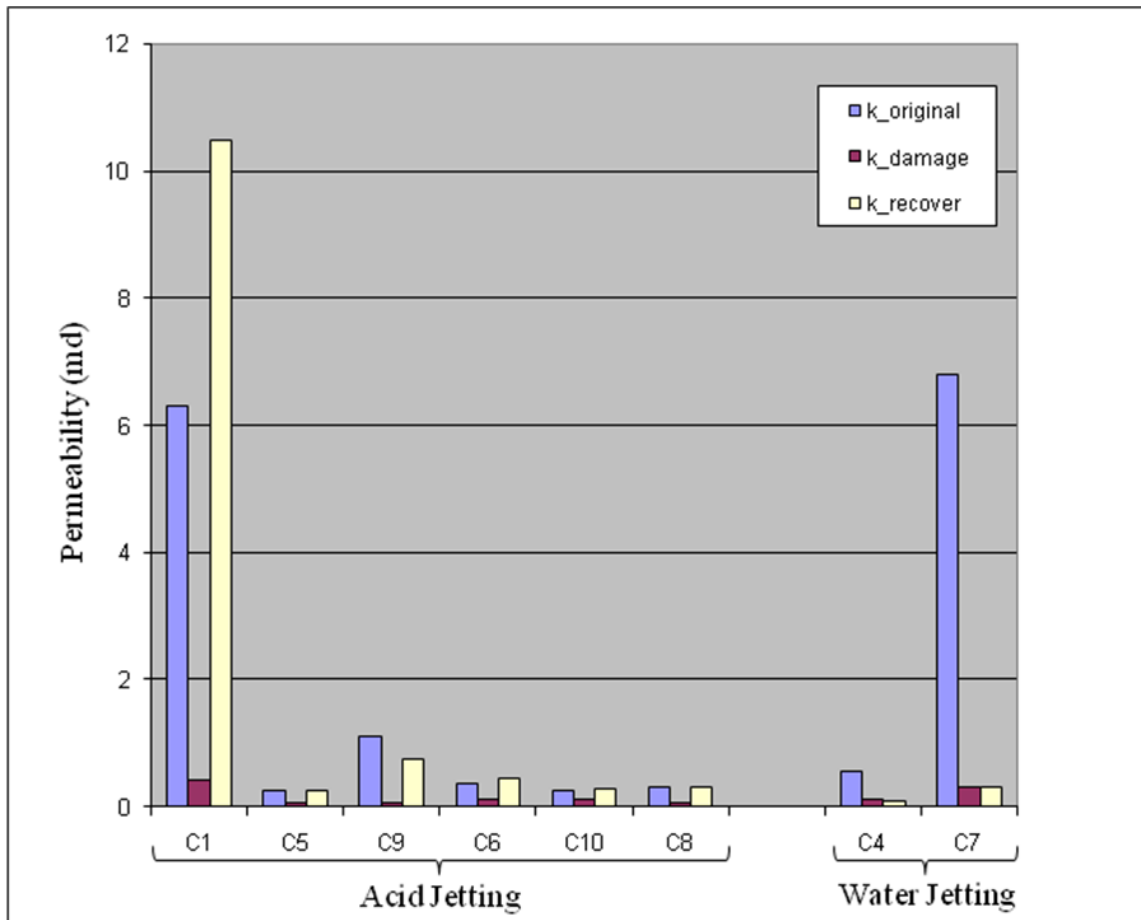


Figure 5.7 The original permeability, the permeability with filter cake, and the permeability after jetting measured for all core samples

Two parameters were introduced in previous work to quantitatively evaluate the drill-in fluid damage and jetting effectiveness. The Ratio of Damage  $R_d$  and the Jetting Effectiveness  $R_s$  are defined as:

$$R_d = \frac{k_{damage}}{k_{original}}$$

$$R_s = \frac{k_{recover}}{k_{original}}$$

$R_d$  is used to evaluate the drill-in fluid damage to the core.  $R_s$  is used to evaluate the effectiveness of the jetting treatment in the recovering of the original permeability and possible stimulation.  $R_d$  is always below 1 and smaller value means more severe damage.  $R_s$  will equal 1 if the jetting treatment restores the permeability to the original value. If the drill-in fluid causes no deeper damage to the core, then  $R_s$  should be equal to 1 if the filter cake is completely removed.  $R_s$  will be greater than 1 if further stimulation is achieved possibly by wormhole creation. The calculated  $R_d$  and  $R_s$  for all the core samples are plotted in Figure 5.8.

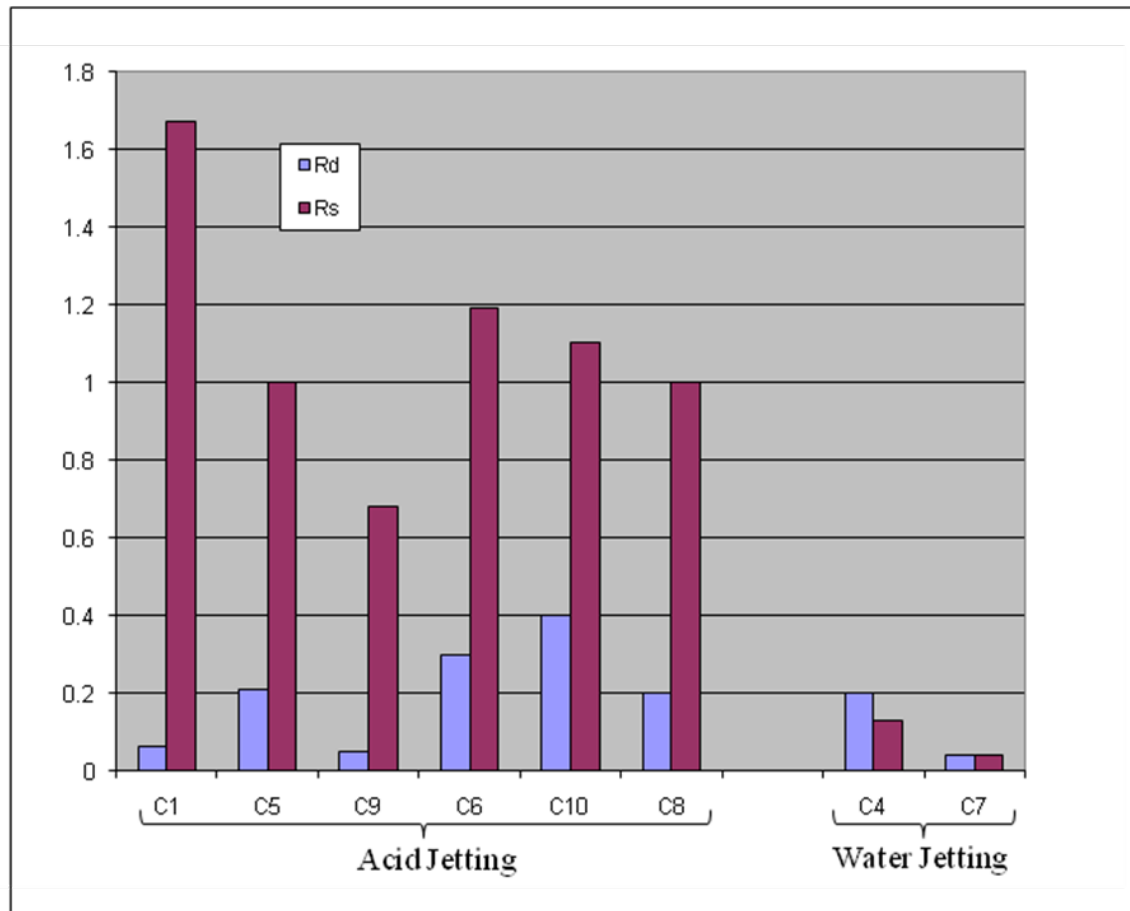


Figure 5.8  $R_d$  and  $R_s$  calculated for all core samples

From Figure 5.8 we can see for relatively high permeability cores C1, C7, and C9,  $R_d$  is smaller than 0.1. In contrast, for the rest of the cores which have permeabilities lower than 1 md,  $R_d$  is about 0.2 or even higher. The fact is that a higher permeability core tends to have a thicker filter cake and more severe damage. Figure 5.8 also shows that  $R_s$  is equal to or larger than 1 for most acid jetting cases, but smaller than 0.2 for the two water jetting cases. The acid jetting treatment should be considered successful in general because it was able to clean up the filter cake. For core C1, further stimulation was achieved by creating wormholes. However, the water jetting treatment failed to clean up the filter cake because the mechanical force generated was not high enough to



penetrate the filter cake. Higher velocity should be necessary for water jetting to be effective.

It is proposed that when the jet acid hit the center of the filter cake, the mechanical force and the chemical dissolution combined together easily penetrate the filter cake. Because of the impact pressure created by the jetting force, the pressure at the jetting spot in the center should be higher than the peripheral pressure and the acid may attack the material beneath the filter cake and make the filter cake detach from the core face. This filter cake removing mechanism consumes much less acid than just soaking the filter cake with acid. The latter usually has to dissolve most calcium carbonate in the filter cake. Once the acid gets beneath the filter cake, it is possible to find a “weak” point on the core face and create wormholes. This process is illustrated diagrammatically in Figure 5.9.

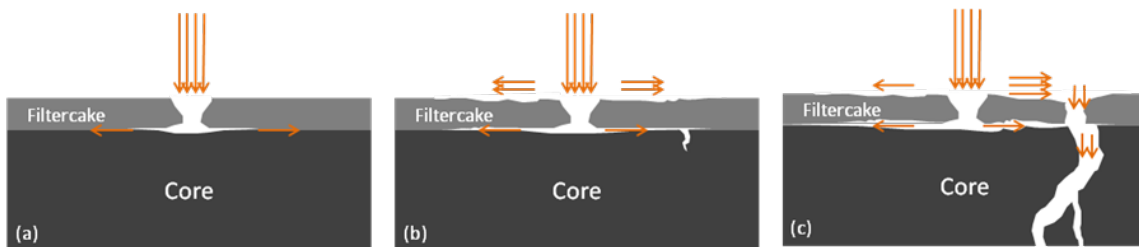


Figure 5.9 A possible situation during the acid jetting treatment. (a) the jetting acid penetrates the filter cake and attack beneath the filter cake; (b) Filter cake further detached from the core face and possible wormholes initiate; (c) The filter cake is removed and the wormhole propagates

The experimental results show that the overbalanced pressure has a significant impact on the wormhole creation during acid jetting treatment. It is observed that for low overbalanced pressure the acid-rock reaction is of the face dissolution type. This can be seen clearly in the picture of C5 and C8 of Appendix D. Core C8 was treated with no overbalanced pressure, and except for the jetting impact there was no driving force to

push the acid into the core resulting in very small flux of acid into the core. Therefore, the acid only reacted with the filter cake and the surface of the core. Core C5 was treated with 230 psi overbalanced pressure, which was still not enough to create wormholes. The only core sample that had wormholes was C1, which was treated by 550 psi overbalanced pressure during acid jetting. Also it is noticed that C1 has a relatively high original permeability, which means that the same overbalanced pressure will result in a higher flux of acid into the core than in low perm cores. The overbalanced pressure should be above a certain value in order to achieve efficient wormhole propagation. The actual flux that is driven into the core determines the wormholing efficiency. This flux, which changes with time, is difficult to be measured directly in the experiments. Estimation can be obtained by calculating the steady state flux under the same overbalance pressure. The calculation results are shown in Table 5.2.

Table 5.2 The steady state interstitial velocities for cores treated by acid jetting

Core	Original Permeability (md)	Overbalance Pressure (psi)	Steady State Flux (cm/min)
C1	6.30	550	0.3481
C5	0.24	230	0.0055
C9	1.10	150	0.0166
C6	0.37	95	0.0035
C10	0.25	50	0.0013
C8	0.30	0	0.0000

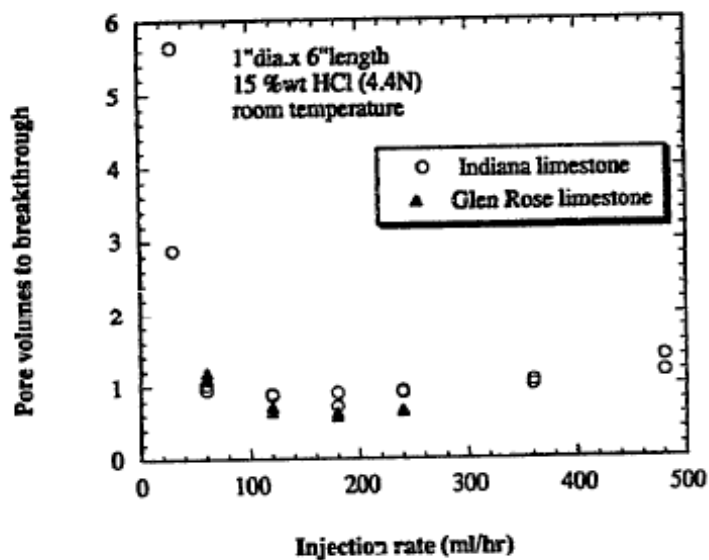


Figure 5.10 Pore volumes to breakthrough as a function of injection rate by Wang *et.al.*<sup>20</sup>

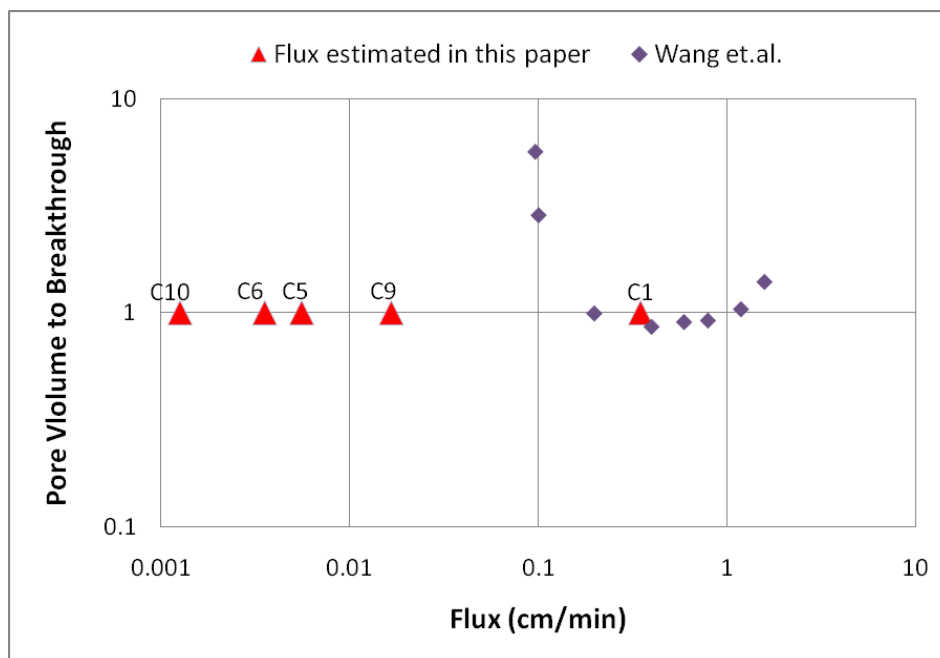


Figure 5.11 The estimated flux (red triangles) in the graph of pore volume to breakthrough as a function of flux obtained using data from Wang *et.al.*<sup>20</sup> (blue dots)

Traditional core flood acidizing experiments done with constant flow rate are able to find the optimum flow rate which has the highest efficiency in wormhole propagation. Figure 5.10 from Wang *et.al.*<sup>20</sup> shows the pore volume to breakthrough as a function of injection rate for limestone using 15%wt HCl under room temperature. The curves show a very steep slope below the optimum injection rate that are most efficient in wormhole creating (corresponding to the minimum point of the curve). This means that the wormhole creating efficiency deteriorates fast as the flow rate becomes smaller than the optimum flow rate. Figure 5.11 shows the fluxes estimated in Table 5.2 and the experimental data in Figure 5.10 converted to flux in the same plot. It is clearly seen that the estimated interstitial velocity of C1 is very close to the optimum flux while the interstitial velocities of all other cores are far away to the left. This corresponds with the observation that only C1 had wormholes created during the acid jetting treatment.

It would be interesting if we can interpret the experimental results in term of the skin factor. It is noted that the permeability we measured after the filter cake deposition is actually the average permeability of the core and the filter cake, which depends on not only the filter cake but also the core original permeability and length. Therefore, it is not clear how much damage the filter cake may cause by only looking at this averaged permeability. For simplicity, let us assume that no deeper damage is caused by the drill-in fluid. Then for the experimental core flood configuration, the pressure drop across the filter cake, the core, and the total pressure drop can be calculated as

$$\Delta p_f = \frac{\mu L_f q}{A k_f}$$

$$\Delta p_L = \frac{\mu L q}{A k_o}$$

$$\Delta p_{total} = \frac{\mu(L + L_f)q}{A k_d}$$

where  $A$  is the cross section area,  $k_o$  is the original permeability of the core,  $L$  is the length of the core,  $k_f$  is the permeability of the filter cake,  $k_d$  is the overall permeability

of the damaged core,  $L_f$  is the thickness of the filter cake, and  $\mu$  is the viscosity. From the simple relation  $\Delta p_f + \Delta p_L = \Delta p_{total}$ , we obtain

$$\frac{L_f}{k_f} = \frac{L + L_f}{k_d} - \frac{L}{k_o} \approx L \left( \frac{1}{k_d} - \frac{1}{k_o} \right)$$

The approximation is justified because  $L_f \ll L$ . Now let us assume that we have a well with wellbore radius  $r_w = 0.328 \text{ ft}$ . The addition pressure drop caused by the filter cake can be written as

$$\Delta p_s = \frac{141.2 \mu B q}{k_f h} \ln \left( \frac{r_w + L_f}{r_w} \right) \approx \frac{141.2 \mu B q}{k_f h} \frac{L_f}{r_w}$$

The approximation is justified because  $L_f \ll r_w$ . Then the skin factor is given by

$$s = \frac{k_o h \Delta p_s}{141.2 \mu B q} = \frac{k_o L_f}{k_f r_w}$$

where  $\frac{L_f}{k_f}$  is obtained using the experimental data. Then the skin factor can be

calculated as

$$s = \frac{k_o}{r_w} L \left( \frac{1}{k_d} - \frac{1}{k_o} \right) = \frac{L}{r_w} \left( \frac{k_o}{k_d} - 1 \right) = \frac{L}{r_w} \left( \frac{1}{R_d} - 1 \right)$$

For all the core samples, this skin factor caused by the filter cake is calculated and listed in Table 5.3. From Table 5.3 we observe that the skin factor caused by filter cake deposition can be very large especially for high permeability reservoir. If there is no deeper damage, by total removal of the filter cake through acid jetting, the skin can be restored to 0. However, if the drill-in fluid caused some deeper damage to the formation, even though the filter cake can be completely removed a damage zone will still give a positive skin. If the permeability of the damage zone is only one tenth the original reservoir permeability, and the damaged zone extends to 0.5ft into the formation, and the drainage radius is 2980 ft, then the skin factor calculated from Hawkin's formula is:

$$s_{wh} = \left( \frac{k}{k_s} - 1 \right) \ln \frac{r_s}{r_w} = (10 - 1) \ln \frac{0.5 + 0.328}{0.328} = 8.3$$

The deeper damage can only be effectively removed by creating wormholes during the acid jetting treatment. The wormhole length according to CT scan of C1 is about 8 inches (0.667ft). Since the wormholes bypass the damage zone, the skin factor can be calculated as:

$$s_{wh} = -\ln \frac{r_w + L_w}{r_w} = -\ln \frac{0.328 + 0.667}{0.328} = -1.1$$

A slightly negative skin could be achieved. The productivity index is calculated as:

$$J = \frac{q}{p_e - p_{wf}} = \frac{kh}{141.2B\mu[\ln \frac{r_e}{r_w} + s]}$$

The ratio of productivity index before and after the acid jetting would be

$$\frac{J_{after}}{J_{before}} = \frac{\ln \frac{r_e}{r_w} + s_f}{\ln \frac{r_e}{r_w} + s_{wh}} = \frac{\ln \frac{2980}{0.328} + 63.7}{\ln \frac{2980}{0.328} - 1.1} = 9.1$$

Therefore, a dramatic increase of productivity could be achieved by acid jetting.

Table 5.3 Skin caused by the filter cake calculated using experimental data

Core No.	Original Perm (md)	Skin
C1	6.3	63.69
C5	0.24	15.29
C9	1.1	77.24
C6	0.37	9.49
C10	0.25	6.10
C8	0.3	16.26
C4	0.56	16.26
C7	6.8	97.56

## 6. CONCLUSIONS AND RECOMMENDATIONS

### 6.1 Conclusions

The experimental apparatus designed and developed is capable of handling the deposition of filter cake on a 4 inch diameter core face and acid/water jetting treatment with various parameter configurations. For water/acid jetting experiment, a backpressure regulator was successfully used to control the overburden pressure during the jetting process. This new design opens another route for the acid to go out of the injection chamber, which simulates the situation in the real wellbore treatment where acid may be diverted to other location after hitting the borehole wall. 6 core samples were treated with 15% HCl acid jetting and 2 core samples were treated with water jetting.

Conclusions drawn from these experimental results include:

- The acid jetting treatment can successfully remove the filter cake by penetrating the filter cake in the center and lifting the filter cake from beneath. Therefore, only a small portion of the calcium carbonate is dissolved by acid, making the jetting treatment more acid efficient than conventional acid soaking.
- The acid jetting treatment may not need very high jetting velocity to penetrate the filter cake because of the chemical dissolution power, which provides a less demanding requirement for the surface pumping system.
- Water jetting in the experiment was not able to penetrate the filter cake and failed to clean up the filter cake mainly because the jetting velocity is not high enough. Water jetting entirely depends on the mechanical force and a much higher jetting velocity is necessary.
- Efficient wormhole creation can only happen when the overbalance pressure during the acid jetting treatment is above a certain value, which may depend on the acid concentration, the flow rate, the permeability and other properties of the rock, etc. Face dissolution rather than wormholing will occur for low overbalanced pressure acid jetting treatment.

## 6.2 Recommendations for Acid Jetting Treatment

Based on the experimental results we have obtained, the following suggestions can be made:

- If the purpose of the acid jetting treatment is only to clean up the filter cake, the volume of acid needed could be less than the volume that can dissolve the filter cake completely if a good coverage of the wellbore can be achieved by a rotating jet.
- For acid jetting to clean up the filter cake, the jetting velocity does not need to be as high as water jetting.
- If creating wormholes is not the purpose of acid jetting treatment, it would be better not to create a large overbalanced pressure so that less acid will be lost into the formation and more acid can react with filter cake.
- If it is necessary to create wormholes in order to bypass deeper damage, sufficient overbalanced pressure should be created during the jetting treatment to cause a high enough flux to create wormholes. This could be achieved by isolating the zone to be treated by packers and pumping at a relatively high flow rate.



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## APPENDIX A

## PRESSURE RESPONSE DURING PERMEABILITY MEASUREMENT

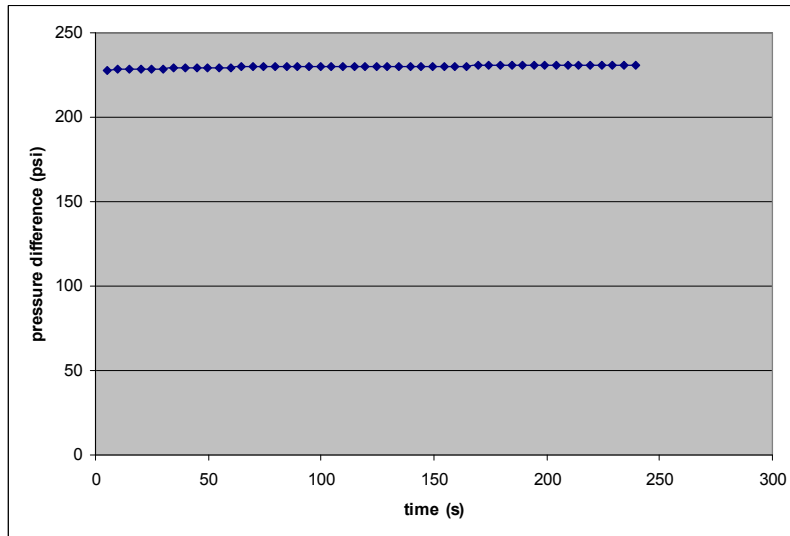


Figure A-1 Pressure response in measuring C1 original permeability ( $q = 10\text{ml/min}$ )

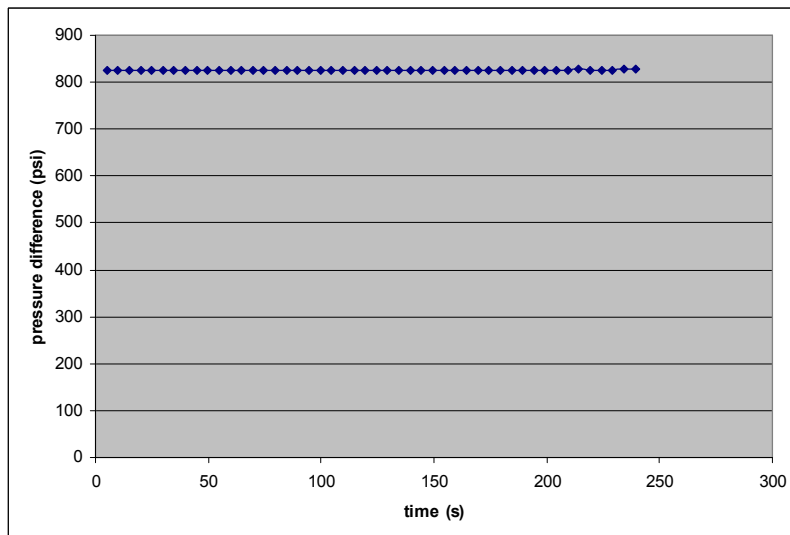


Figure A-2 Pressure response in measuring C1 permeability with filter cake ( $q = 3\text{ml/min}$ )

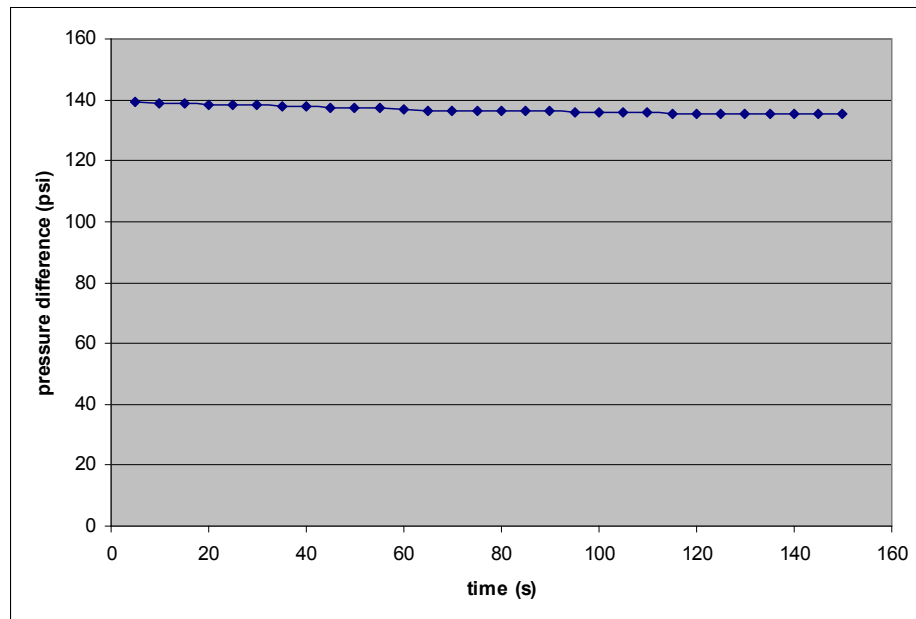


Figure A-3 Pressure response in measuring C1 permeability after acid jetting ( $q = 12\text{ml/min}$ )

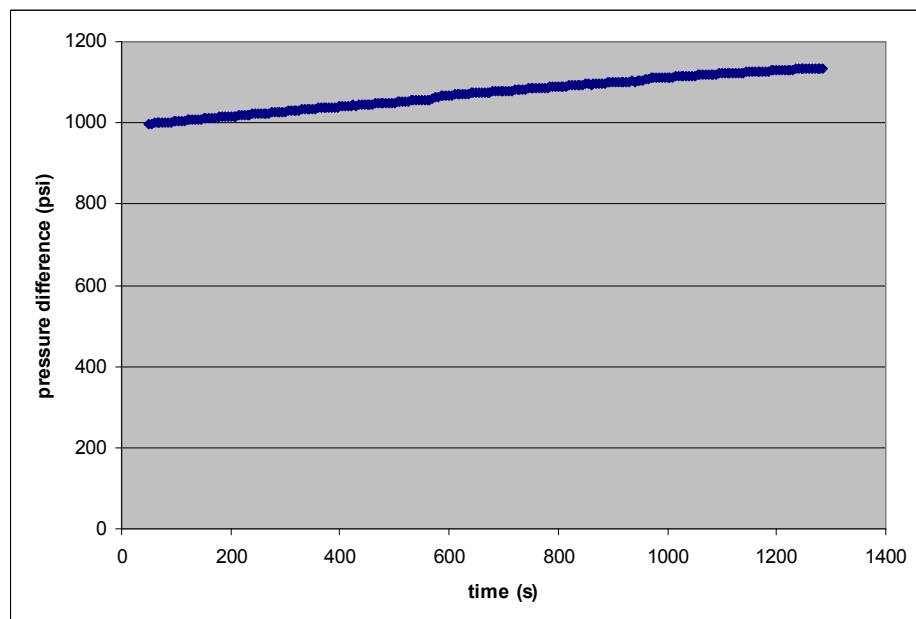


Figure A-4 Pressure response in measuring C5 original permeability ( $q = 2\text{ml/min}$ )

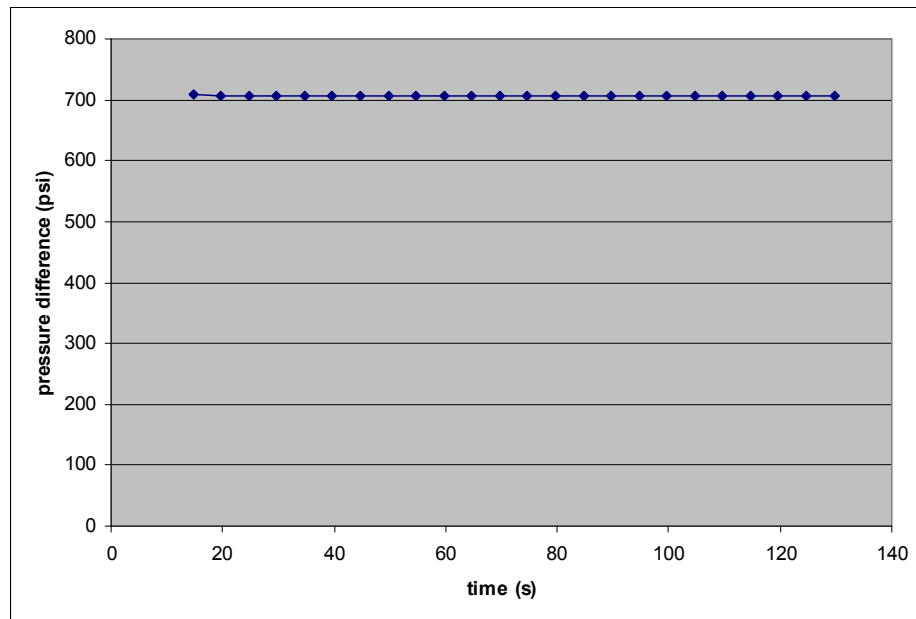


Figure A-5 Pressure response in measuring C5 permeability with filter cake ( $q = 0.27\text{ml/min}$ )

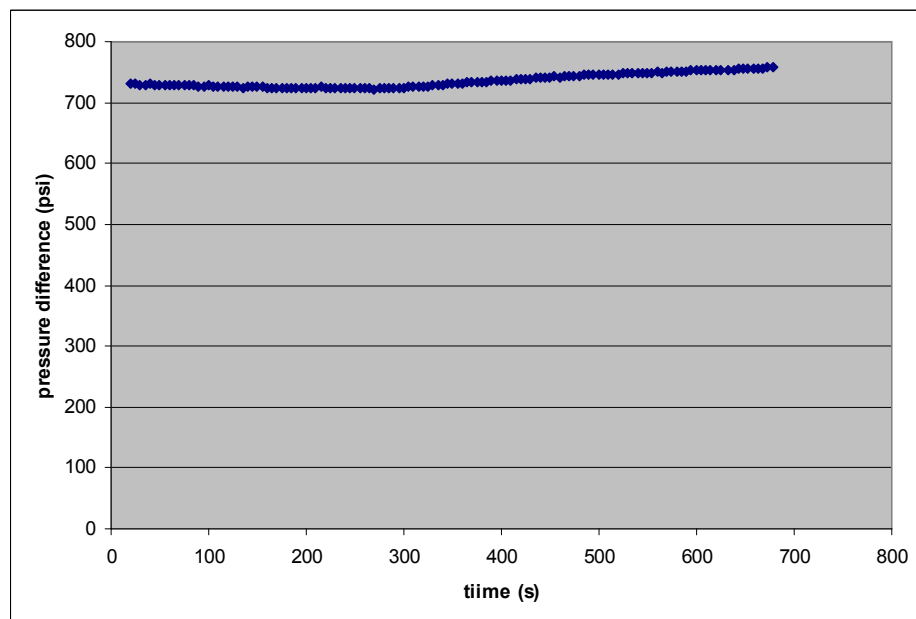


Figure A-6 Pressure response in measuring C5 permeability after acid jetting ( $q = 1.46\text{ml/min}$ )

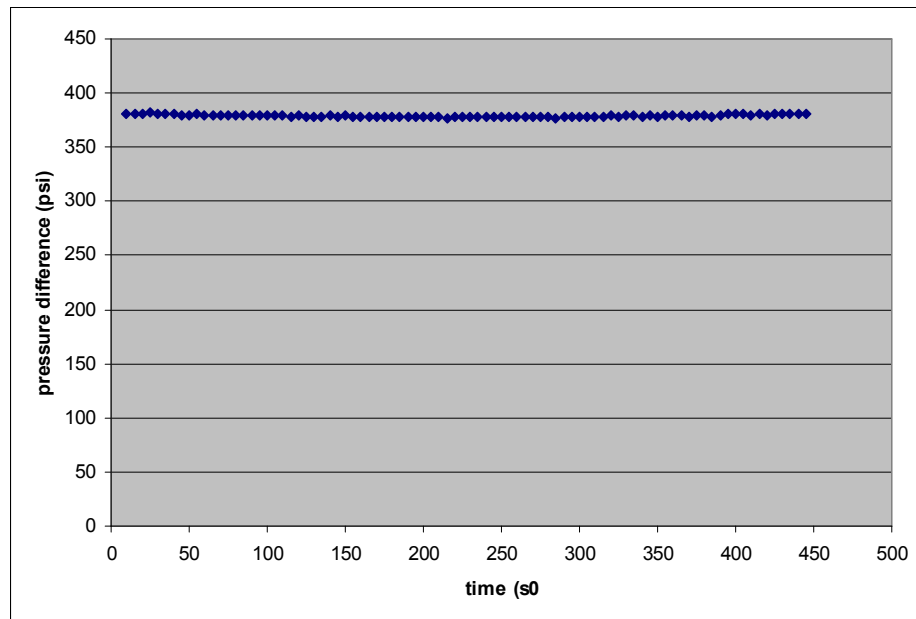


Figure A-7 Pressure response in measuring C9 original permeability ( $q = 3\text{ml/min}$ )

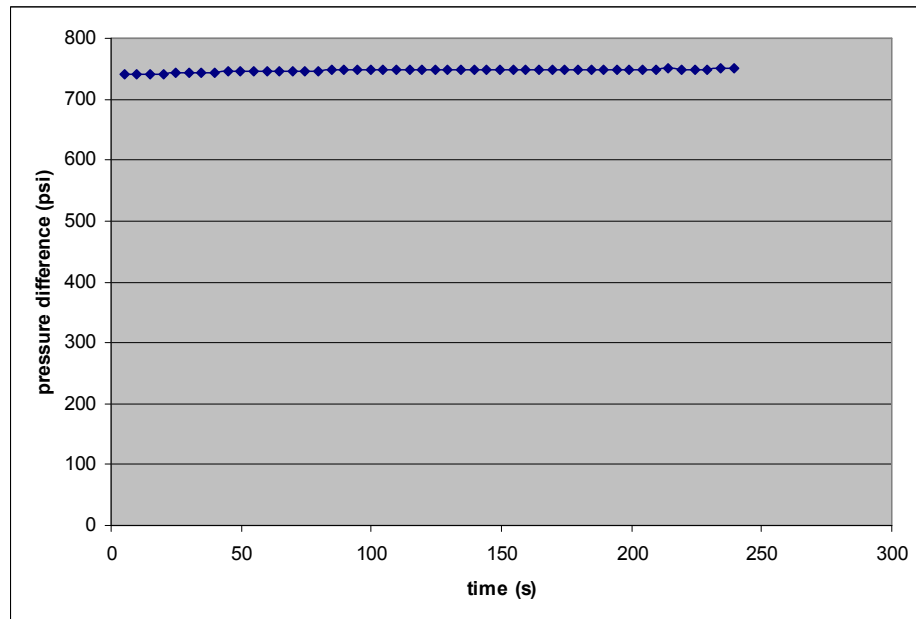


Figure A-8 Pressure response in measuring C9 permeability with filter cake ( $q = 0.4\text{ml/min}$ )

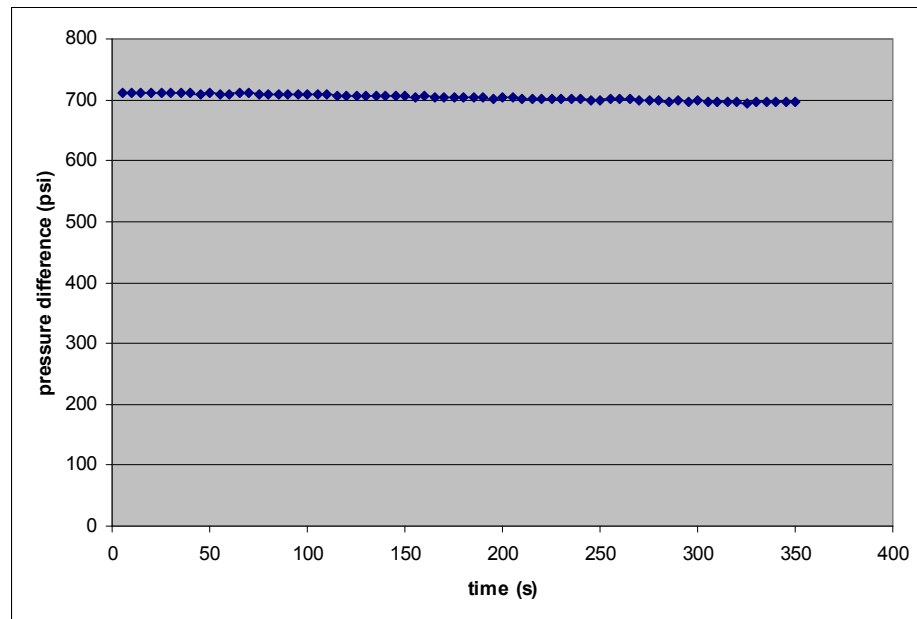


Figure A-9 Pressure response in measuring C9 permeability after acid jetting ( $q = 4.2\text{ml/min}$ )

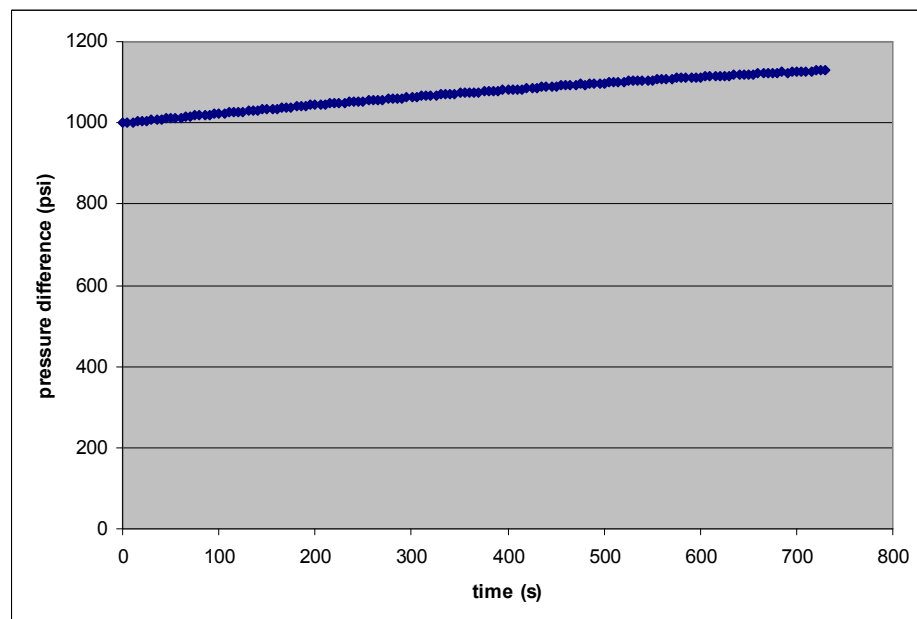


Figure A-10 Pressure response in measuring C6 original permeability ( $q = 3\text{ml/min}$ )



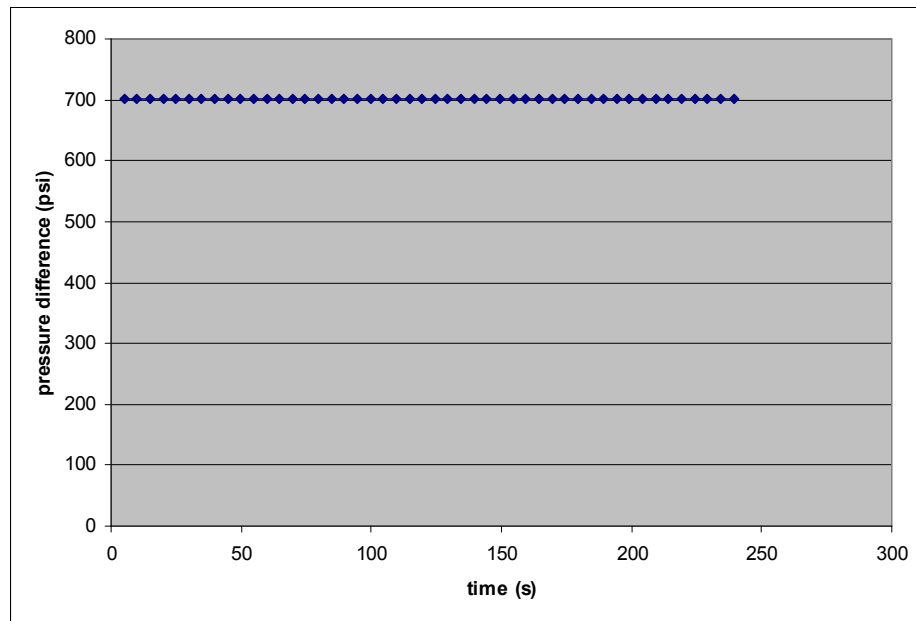


Figure A-11 Pressure response in measuring C6 permeability with filter cake ( $q = 0.6\text{ml/min}$ )

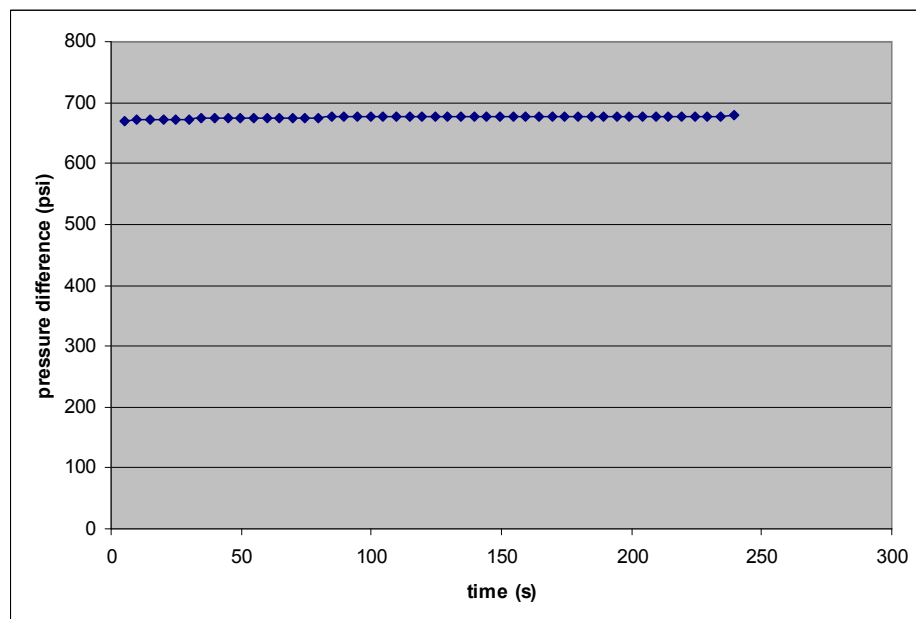


Figure A-12 C6 Pressure response in measuring permeability after acid jetting ( $q = 2.4\text{ml/min}$ )

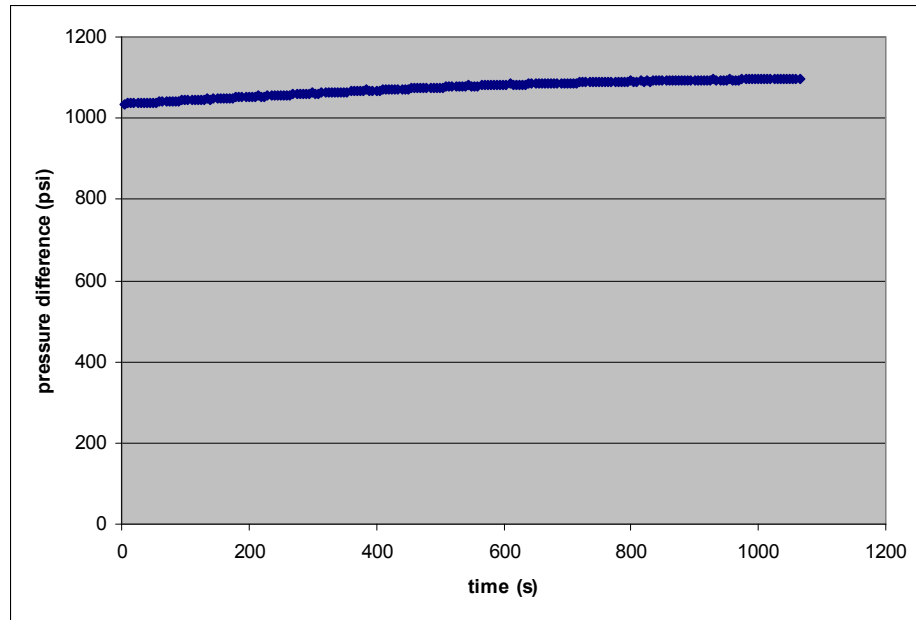


Figure A-13 Pressure response in measuring C10 original permeability ( $q = 2 \text{ ml/min}$ )

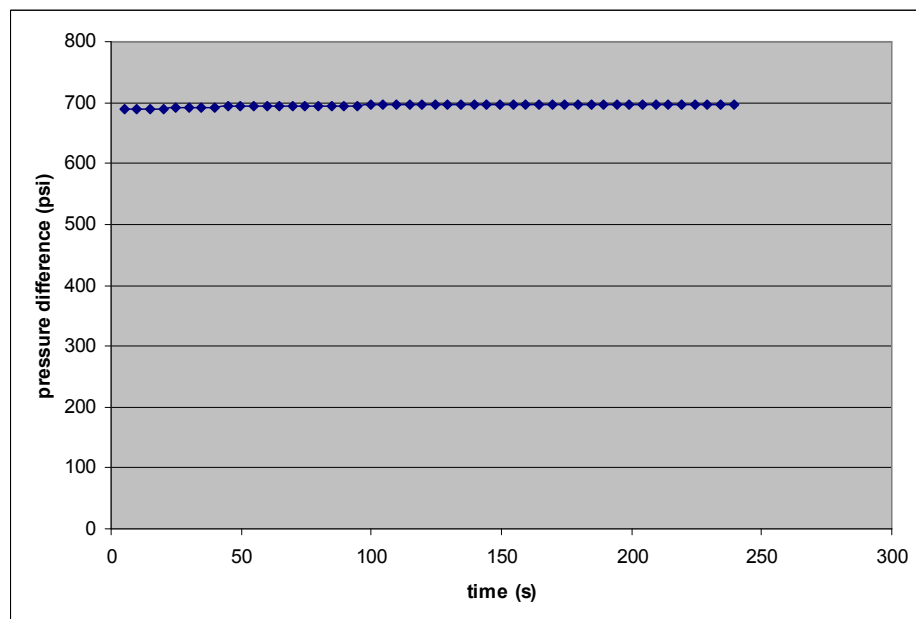


Figure A-14 Pressure response in measuring C10 permeability with filter cake ( $q = 0.6 \text{ ml/min}$ )

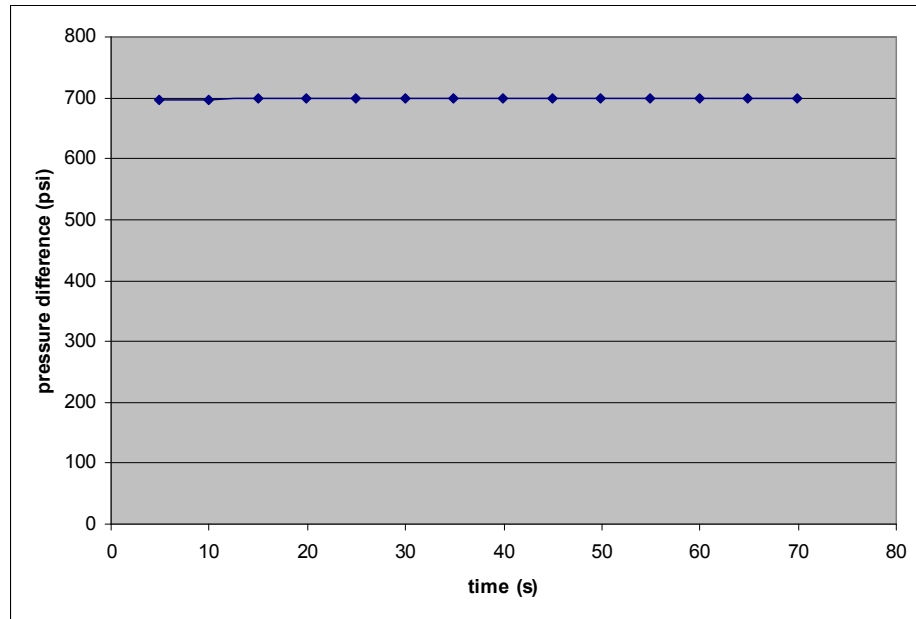


Figure A-15 Pressure response in measuring C10 permeability after acid jetting ( $q = 1.5\text{ml/min}$ )

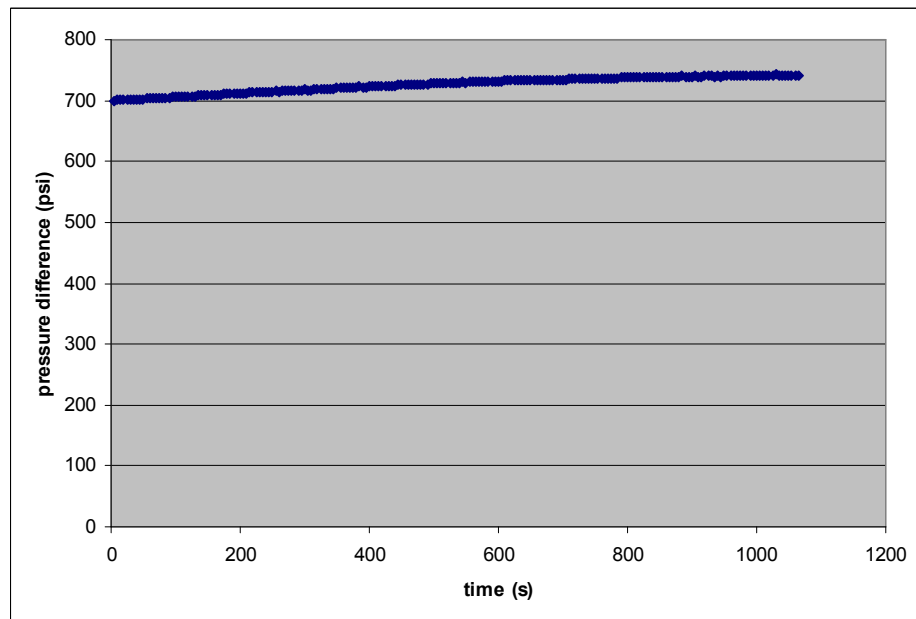


Figure A-16 Pressure response in measuring C8 original permeability ( $q = 1.8\text{ml/min}$ )

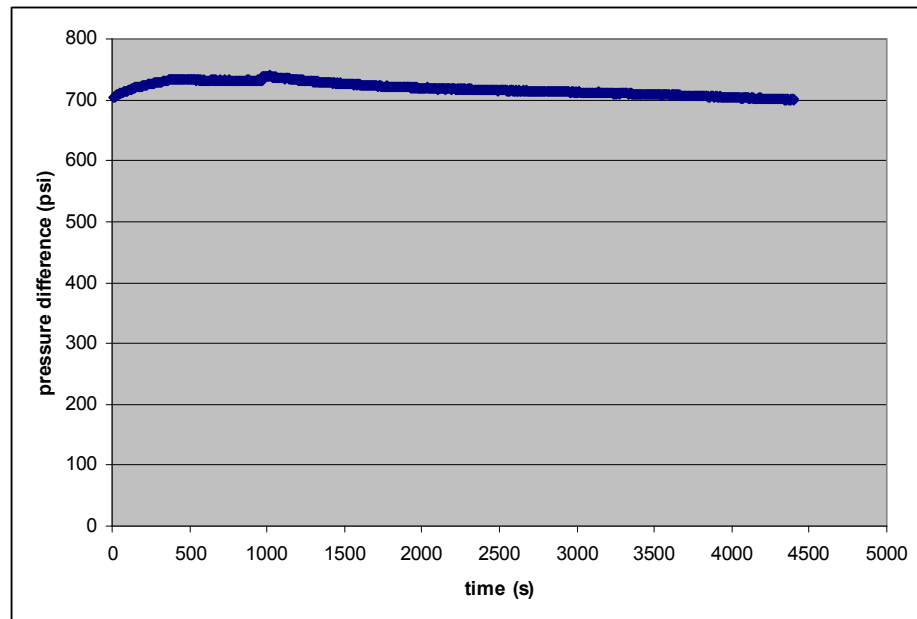


Figure A-17 Pressure response in measuring C8 permeability with filter cake ( $q = 0.4 \text{ ml/min}$ )

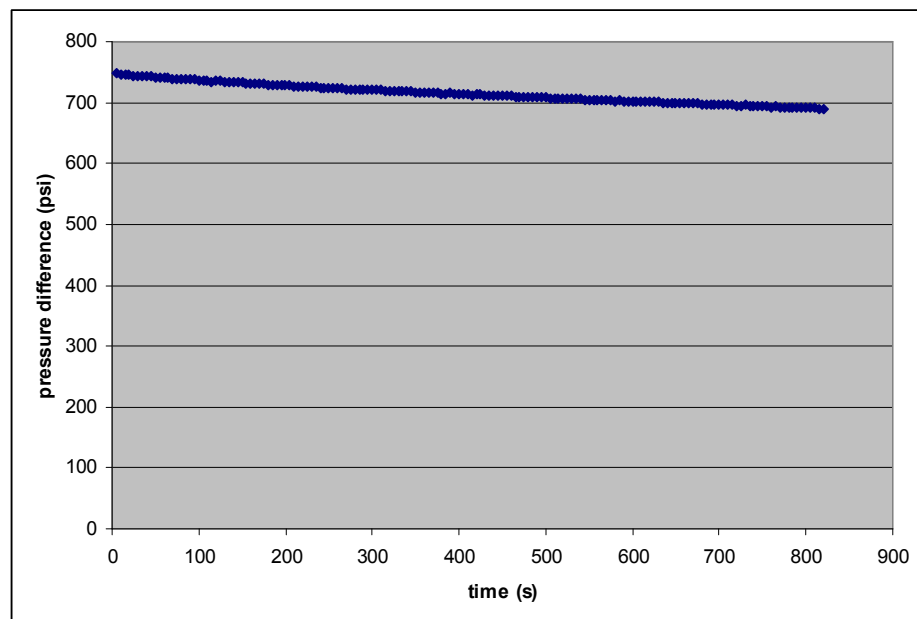


Figure A-18 Pressure response in measuring C8 permeability after acid jetting ( $q = 1.5 \text{ ml/min}$ )

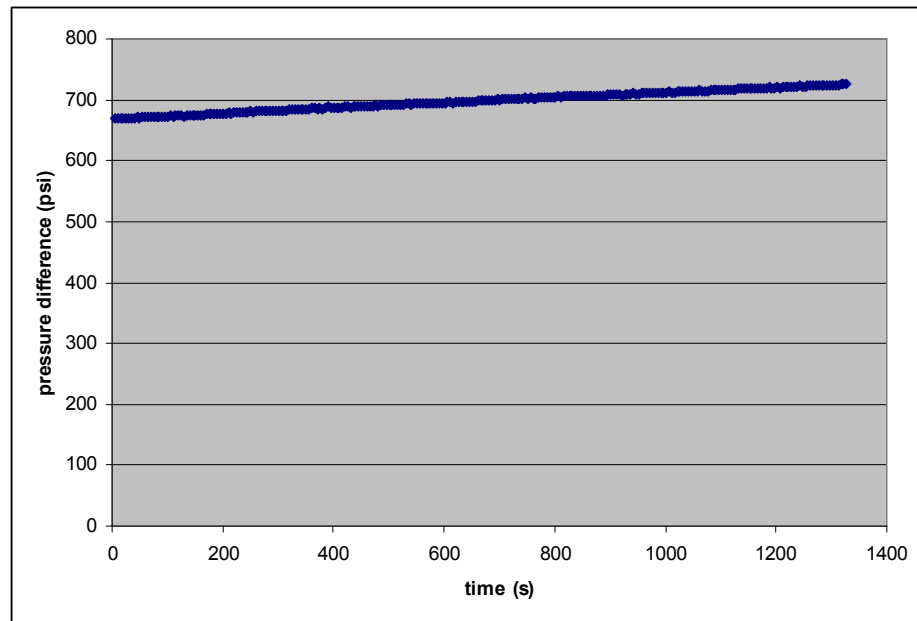


Figure A-19 Pressure response in measuring C4 original permeability ( $q = 3\text{ml/min}$ )

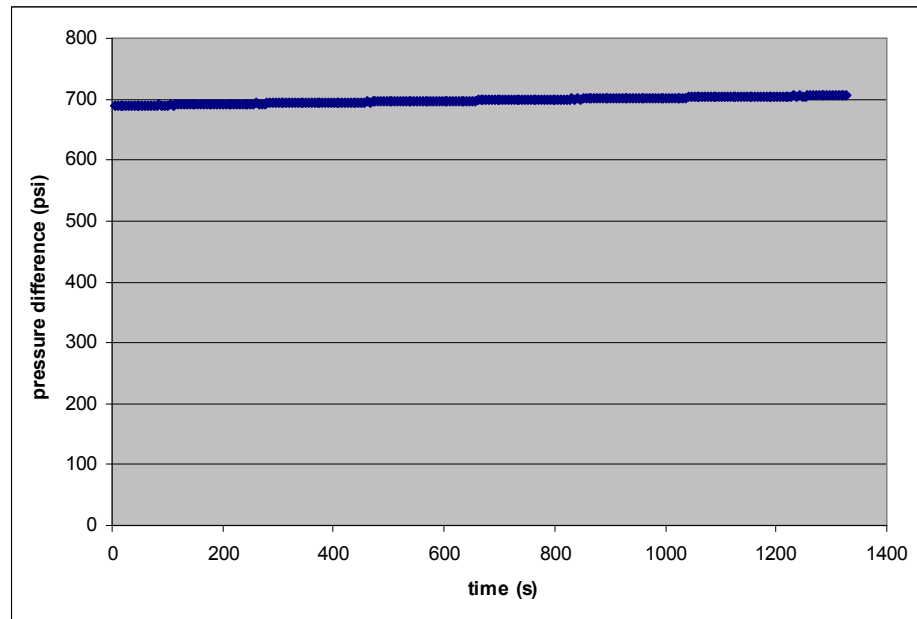


Figure A-20 Pressure response in measuring C4 permeability with filter cake ( $q = 0.6\text{ml/min}$ )

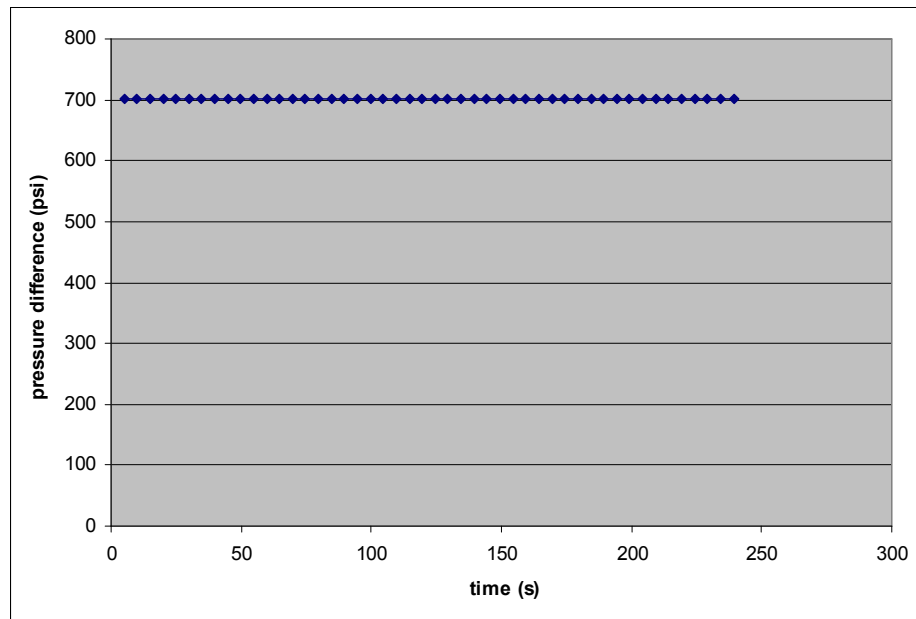


Figure A-21 Pressure response in measuring C4 permeability after water jetting ( $q = 0.4\text{ml/min}$ )

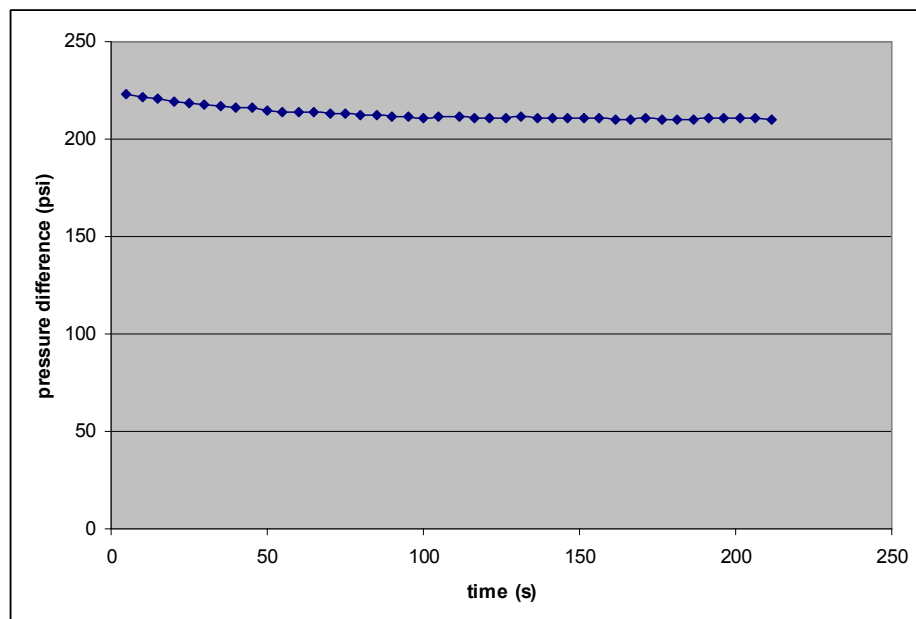


Figure A-22 Pressure response in measuring C7 original permeability ( $q = 10\text{ml/min}$ )

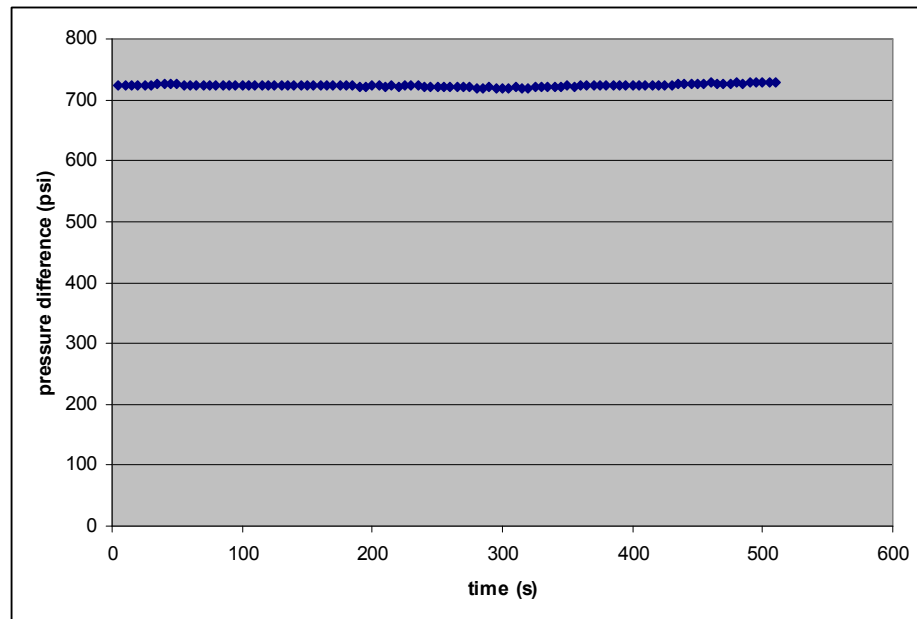


Figure A-23 Pressure response in measuring C7 permeability with filter cake ( $q = 1.6\text{ml/min}$ )

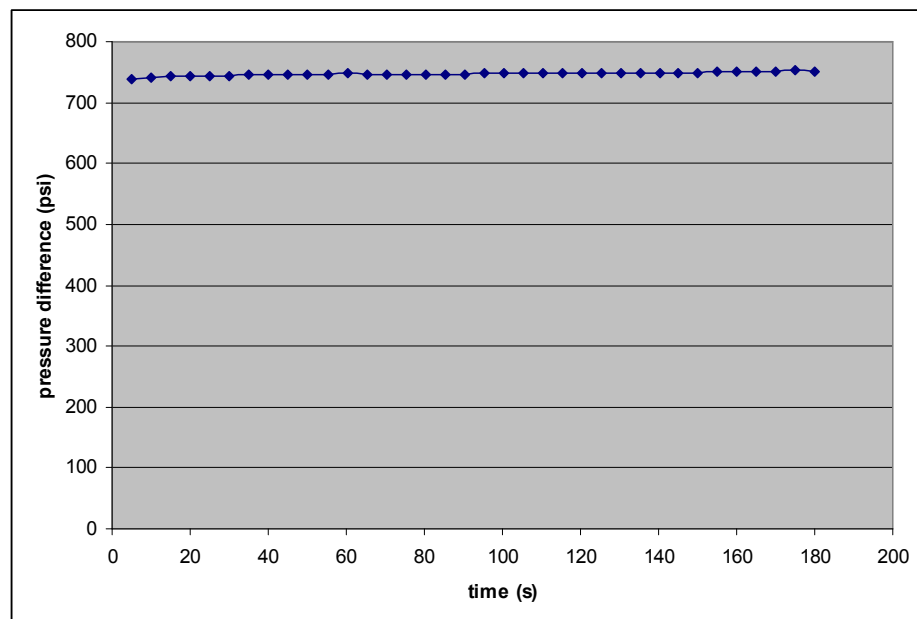


Figure A-24 Pressure response in measuring C7 permeability after water jetting ( $q = 1.6\text{ml/min}$ )

## APPENDIX B

## PRESSURE RESPONSE DURING JETTING

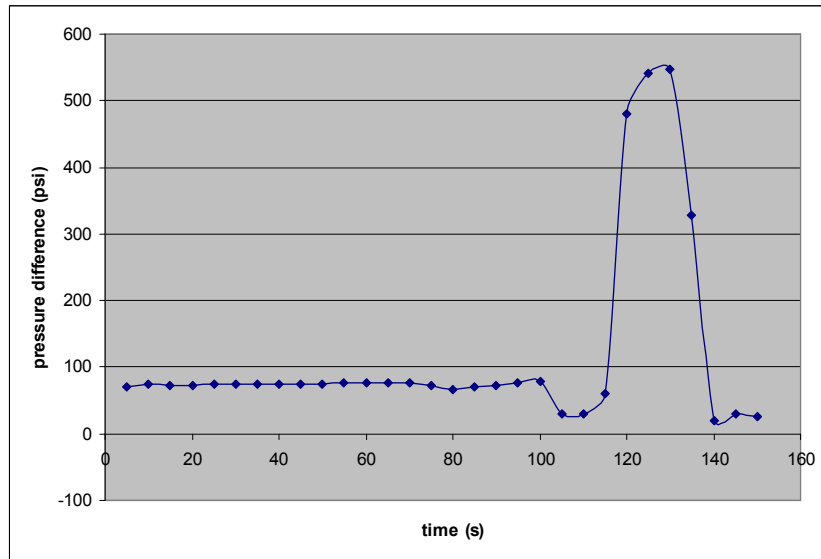


Figure B-1 C1 pressure response during acid jetting

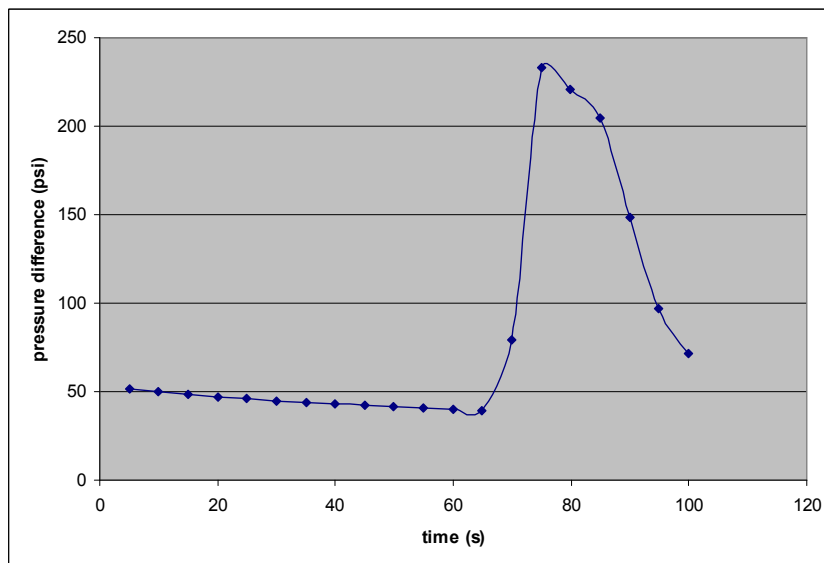


Figure B-2 C5 pressure response during acid jetting



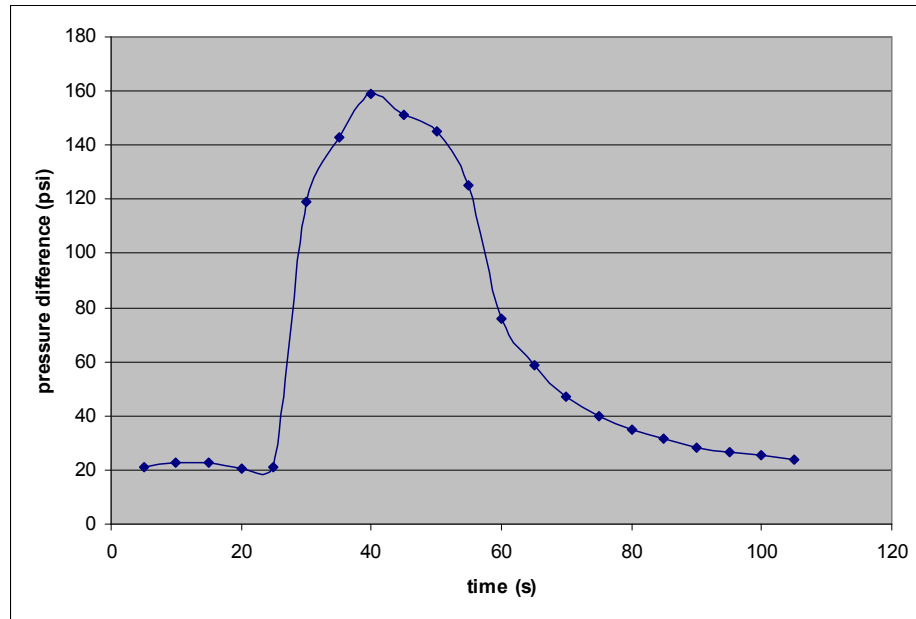


Figure B-3 C9 pressure response during acid jetting

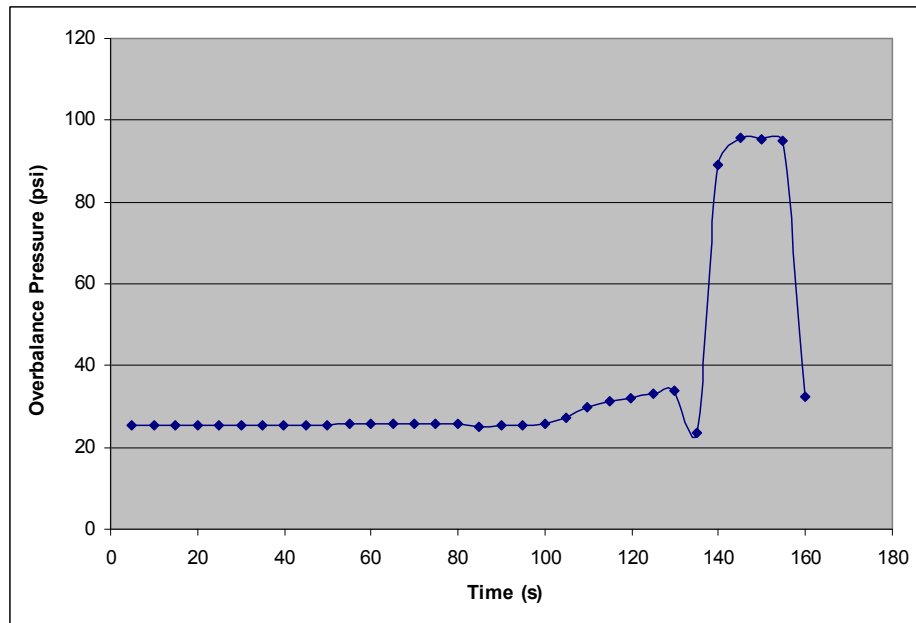


Figure B-4 C6 pressure response during acid jetting

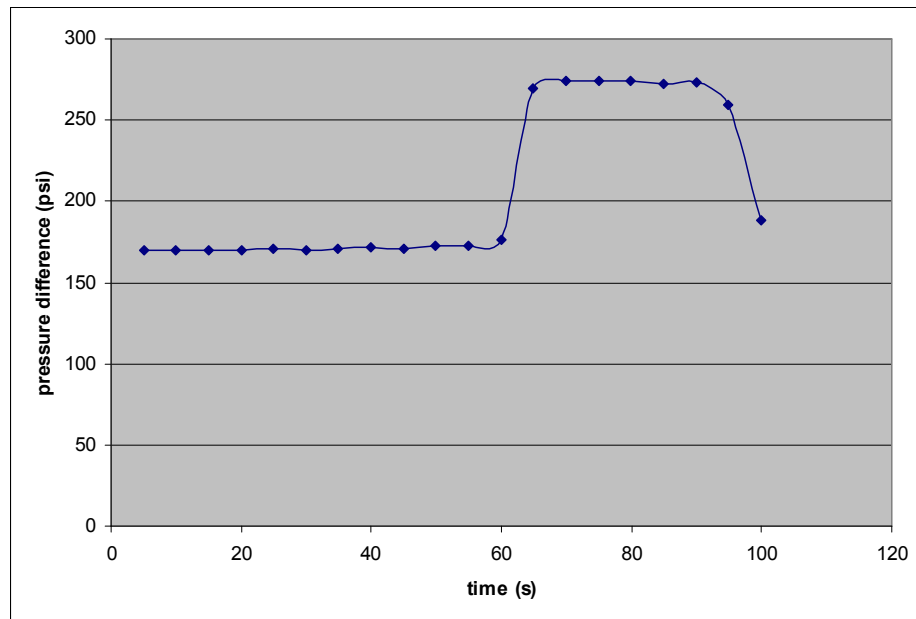


Figure B-5 C4 pressure response during water jetting

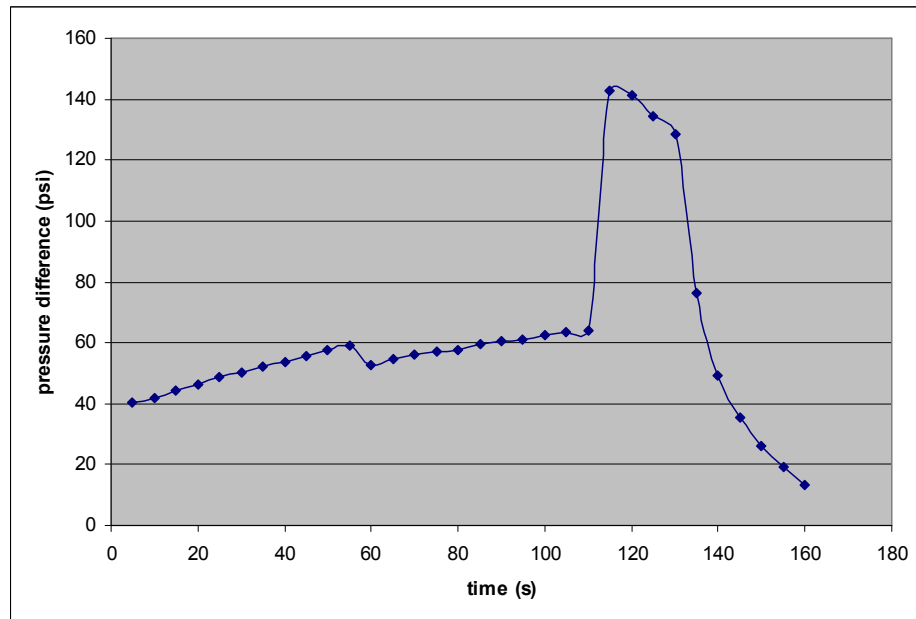


Figure B-6 C7 pressure response during water jetting

APPENDIX C  
CT SCAN PICTURES

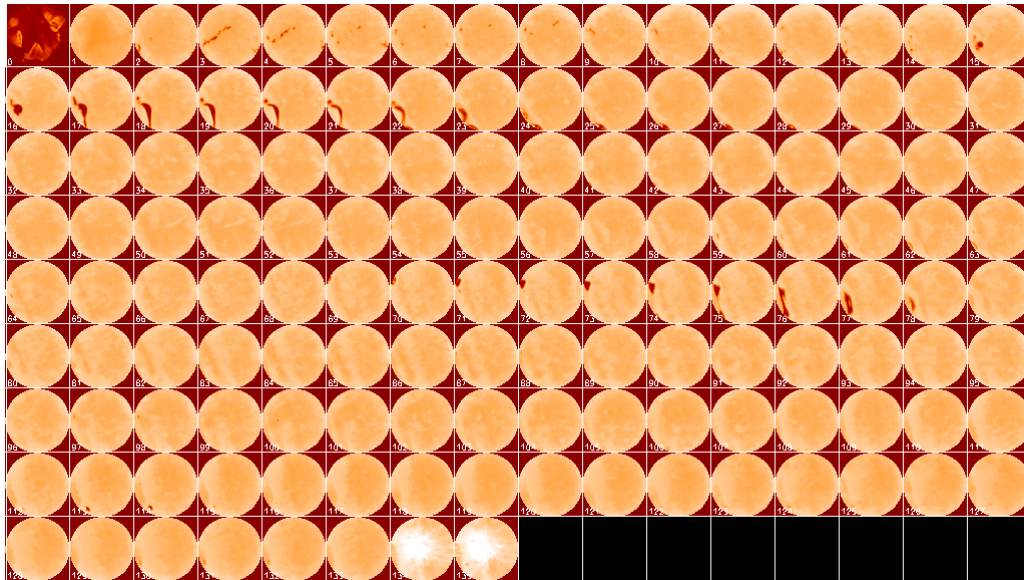


Figure C-1 Cross section pictures of the CT scan for C6

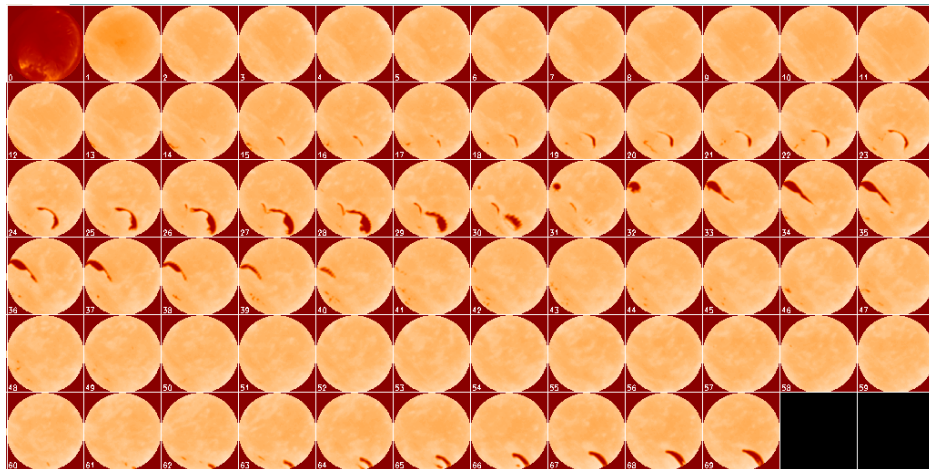


Figure C-2 Cross section pictures of the CT scan for C9

## VITA

Yanbin Zhang received his Bachelor of Science degree in physics from Peking University in China in 2006. He then entered Rice University as a PhD student in the Department of Electrical and Computer Engineering. After studying for one year at Rice, his interest turned to petroleum engineering. In 2007 he transferred to Texas A&M University to study petroleum engineering for his master's degree.

Mr. Zhang may be reached at 3116 TAMU - 719 Richardson Building, College Station, TX 77843-3116. His email is [zhangyb\\_2@hotmail.com](mailto:zhangyb_2@hotmail.com).