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VIBRATION MODIFICATION TO A.P.I. FRACTURE SHORT TERM CONDUCTIVITY TESTING PROCEDURE

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by

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Abstract

The current API Short Term Fracture Conductivity (volume number) testing procedure provided by the American Petroleum Institute doesn't consistently provide repeatable results. For example, in an independent review of three commercial lab results testing the same sample of proppant the variation between the three had a data spread of nearly 80% (Anderson, 2013). Continuing and refocusing the research performed by Kent Blair's thesis "*Modifying Fracture Conductivity Testing Procedures*" (Montana Tech, 2015), the goal of this thesis is to expand the lab research results on the use of vibration in the cell loading procedure to improve the repeatability of test results. Use of two separate methods of applying a vibration energy to the proppant loaded cell was explored with varying powers and times under vibration. The first method for the application of vibrational energy was utilizing the Vibration Test Machine which utilized a constant frequency of 50 Hz and had a varying amplitude range of zero to two millimeters. The results for this first method where promising with significant reduction of the variability in results, however, due to the inability to constantly apply a constant amplitude that was quantifiably measurable resulted in sets of results that did not undergo similar test loading procedures and such had to be removed from consideration. The second method for the application of vibrational energy was utilizing the Sonochemical Reaction Vessel which utilized a constant frequency of 20 kHz, adjustable power levels, and varying amplitudes that ranged from 0 to 1 millimeter. This application of vibrational energy to the proppant during the later loading portion of API RP–61 reduced the variance of conductivity results 70% to 90% when compared to Blair’s API RP-61 results. The values of the fracture conductivity also dramatically decreased when compared to the standard API results ranging 50% to 70% at each of the varying closure stresses specifically at the initial stresses.

Keywords: Fracture Conductivity, Proppant Testing, API-RP 61 (1989)

Dedication

I wish to dedicate this thesis to my grandfather, Afton Wayne Jolley, who taught me to always take the higher road less traveled in life.

Acknowledgements

I would like to extend a thank you to Susan and Richard Schrader. Sue was my advisor during my graduate portion of my education and professor throughout school. Rich is the lab director for the Petroleum department and has taught me how to run a proper fracture conductivity test and was immensely helpful on instrumentation troubleshooting. I would also like to thank Paul Conrad for being on my thesis committee and generating valuable feedback for me and add in the editing of this thesis. I would like to also thank my fiancé and newly wedded wife for constantly pressuring me to strive for perfection and success. These four individuals kept me on track and enabled me to complete my thesis on time.

I would also like to thank Carbo Ceramics and Halliburton. Carbo Ceramics generously donated 20/40 ceramic proppant that I used in my thesis testing. Halliburton has donated equipment to Montana Tech and built the Halliburton Research Lab where I conducted my research for this thesis. Without their generous donations, this research, prior research, and future research would not be possible

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1. Introduction

In the following thesis, an introduction of what is hydraulic fracturing and how does it apply in the petroleum industry as well as a brief discussion on how it is performed is presented. How the permeability and conductivity of the fractured rock is measured following the American Petroleum Institution's procedures API-RP 61 (1989) and API-RP 19D (2008) is performed. What some of the current observed issues that are being noted in industry with these procedures and discussing what some other researchers have analyzed. A proposed modified procedure utilizing the application of vibrational energy to the loading of the proppant material using multiple instruments and the results and analysis for each instrument. And a closing discussion of the results and a recommended forward direction of study and research.

1.1 Unconventional Downhole Stimulation - Hydraulic Fracturing

In today's modern oil and gas industry, the most widely used method to stimulate tight or low permeability hydrocarbon bearing formations is the use of hydraulic fracturing. It is the application of high pressure fluid to fracture a hydrocarbon bearing rock followed by pumping a medium material through the cracks to prevent closure of the fracture to provide a channel of less flow resistance back to the production wellbore. Discovery of tight, low permeability hydrocarbon reservoirs dates back to the middle of 20th century, but due to the limitations of stimulation technology during that period were uneconomic to pursue. Due to recent advances in this hydraulic fracturing technology since the beginning of the 21st century, these previously believed uneconomic hydrocarbon reserves have become extremely profitable for hydrocarbon exploration and production companies.

To "frac" or fracture these reservoirs, a small fracture is typically initiated through a small explosive charge in the wellbore located at a strategic depth in a portion of the reservoir. Then a typically viscous fluid is pumped downhole at pressure greater than the closure stress of the reservoir rock, physically forcing the rock to separate or fracture in respect to the stress orientations of the rock. Then a medium called proppant, which can be a sand or ceramic product, is pumped downhole carried by the fluid into the fractures in the rock. Upon the decrease or release of the pressure the fracture will close but the proppant will prevent the fracture from fully closing. This proppant will have a higher permeability value than the tight rock surrounding it. This will provide a path of least resistance for the hydrocarbons to flow to the wellbore at an increased pace thus likely increasing the overall economics of the well.

1.2 Current Fracture Conductivity Measurement

One method to measure the success of this path of flow is the fracture conductivity value. Fracture conductivity is a measure of how easily a fluid flows through a fracture and is the width of the fracture multiplied by the permeability inside of the propped fracture. To provide a theoretical consistent measurement for how the proppant would perform in the fracture, API standards for lab measurement methods were developed in the form of long and short-term fracture conductivity testing, API RP-19D (2008) and API RP-61 (1981).

These procedures essentially call for the use of a steel Hooke cell with a proppant pack height measuring a quarter of an inch between sandstone platens within to have a water dominate fluid with small amounts of dissolved KCl flown through it at a controlled rate utilizing a flow meter of some sort. The proppant pack is to undergo closure stresses of 2000, 4000, 6000, and

8000 psi which decreases the permeability of the proppant pack and affects how easily the KCl fluid flows through. The Hooke cell is to have multiple ports connected to pressure transducers to measure the drop in pressure across the cell to determine the changes in permeability as these closure stresses are applied and how the proppant pack withstands these closure stress increases. The Hooke cell as well as the KCl fluid is to be heated to a temperature that is dependent upon the proppant material that is being tested during the duration of the test. The time duration of the test is dependent upon the API procedure being performed with API-RP 19D (2008) being the long term test that is the more commonly used method within the petroleum industry and the short term API-RP 61 (1989) procedure. Industry wide the instruments utilized to perform such measurements of pressure applied during the test, temperature, flow rates, and pressure drops varies but all must meet the API procedure dependent requirements.

1.3 API Procedure Variations and Issues

In Anderson's presentation entitled "Performance of Fracturing Products" (Anderson, 2013), it is concluded that labs utilizing the same API standard testing procedure and the same proppant sample had experienced a variation in their results of nearly 80%. Blair (2015) looked further into this variation and concluded that the flaw lies within the procedure of testing to the API standard and began research into modifying the procedure to decrease the variation and improve the repeatability of the fracture conductivity test results in his thesis entitled "Modifying Fracture Conductivity Testing Procedures" (Blair, 2015). It should also be noted in SPE paper 84306 "Realistic Assessment of Proppant Pack Conductivity for Material Selection" by R.D. Barree that results reported by labs under the current method are typically overly optimistic compared to observed field results. Barree continues to discuss on how the statistical variation in the results heavily influences final product selection.

In the SPE-179125-MS paper, “The Science of Proppant Conductivity Testing- Lessons Learned and Best Practices” (Stim-Lab, 2016), the authors discuss how the results for proppant testing have to be appropriately applied due to limitations of the data. This limit was believed to lie in the variations that occur with the loading procedure, the type of material that is being tested, and the equipment used. A highlighted point of interest is the loading procedure of the proppant into the Cooke cell prior to closure stress application. API RP-61 indicates that the proppant will be loaded by hand and then leveled. This loading by hand is typically performed by pouring a predetermined volume or mass of proppant evenly throughout the cell and then utilizing a device to level out the surface. This is to be done with the minimal amount of contact with the proppant.

However, as this procedure is done by hand, it in itself introduces variance as each person will not perform the procedure exactly the same as the next. Even if the loading procedure is only performed by one person for each trail it is impossible for that one person to exactly load the proppant into the cell exactly the same way and level the proppant in the same way for every trial. Another variation that can be added prior to testing is the moving of the loaded cell to the equipment for the application of closure stress and flow rates. Each person will handle the cell differently which could introduce unintended shifting of the proppant. These lead to a variation in results that contributes to the limitations of the application of the data that is obtained for each sample tested. If the data is limited in application due to these human caused variations, why not try to remove the human caused variations.

1.4 Prior API-RP 61 Procedural Modification Work

Blair seized upon this variation that occurs to look at modifying the API conductivity testing procedure. He discussed on how at a current approximate cost of nearly $15,000 dollars to have a commercial lab perform the long-term conductivity tests on proppant that it is important to produce a reliable and repeatable result. He looked at several methods to reduce the variation by utilizing Montana Tech's dual cell system that measures fracture conductivity to the API standards. He first looked at Montana Tech's research lab which currently has two instruments capable of this measurement standard, a single and dual cell conductivity system. The dual cell system allows two samples to be tested simultaneously, which allows side-by-side comparison of identical samples under the exact same pressure input and flow rates. Blair first looked at issues occurring with the API RP-19D (2008) related to sandstone platen shear failure occurring on the edges of the platens. In the original testing procedure developed by the American Petroleum Institute, the procedure calls for "the pistons, platen shims, and test chamber should be constructed of 316 stainless steel material" (API RP 61, 1989). Blair made note of why the utilization of the steel material improved results: "Using stainless steel shims drastically reduces embedment and fine releasing during testing, because steel is not as soft as the sandstone. The steel shims can withstand higher stresses than the sandstone which eliminates the tensile failure and edge failure experienced by the sandstone platens." (Blair, 2015).

Based on Blair's recommendation to not utilize sandstone platens, this thesis research did not include that portion directed in the API RP-19D (2008). Two metal shims of 316 stainless steel material were utilized as directed in API RP-61 (1989). This is to reduce the sandstone platen shear failure error that occurs as seen in Figure 1 below.

Figure 1: Sandstone Platen Shear Failure Blair (2015)

In his research Blair focused on removing the variation from individual hand loaded proppant packs into the Hooke fracture conductivity testing cell. Instead of the API procedure guide of splitting samples, pouring in the samples, and then hand-leveling the samples evenly across the cell's bottom shim. He first looked at an injection method to simulate proppant being injected into the fractures propagated by hydraulic fracturing occurring in the field. To perform this he utilized a Hoke cylinder pressurized by a nitrogen source connected with a tube to the inflow port on the side of the Hooke testing cell for the 2% KCl measured flow. The proppant was transported with KCl solutions and a guar solution with mass of proppant being measured prior and post displacement. The KCl solutions that Blair used for this process did not suspend the proppant long enough to transport the proppant material into cell so then a guar solution was used and had poor results as well due to port plugging issues of the cell and the inability to fully remove the guar residue within the proppant pack.

Due to the cost limitations of converting the setup to avoid this plugging port issue, the method was abandoned in favor of a smaller diameter mouth of a wash bottle injection method. The outlet port of the cell was connected to a suction force to help increase the flow rate and displacement of proppant into the cell. Blair changed the loading guar concentration multiple times to increase the amount of proppant being displaced and plugging issues that occurred. To remove excess guar, the suction was left on with a KCl solution to remove the guar from the test samples. Residual guar in the proppant samples affected the results by lowering the conductivity values recorded but still resulting in high deviation of results previously seen. These results compared to the API standard hand loading procedure results by Blair in Figure 2 are seen as drastically lower but have a high variance at a closure stress of 6000 psi. The results for Blair's wash bottle injection method can be seen in Figure 2 below.

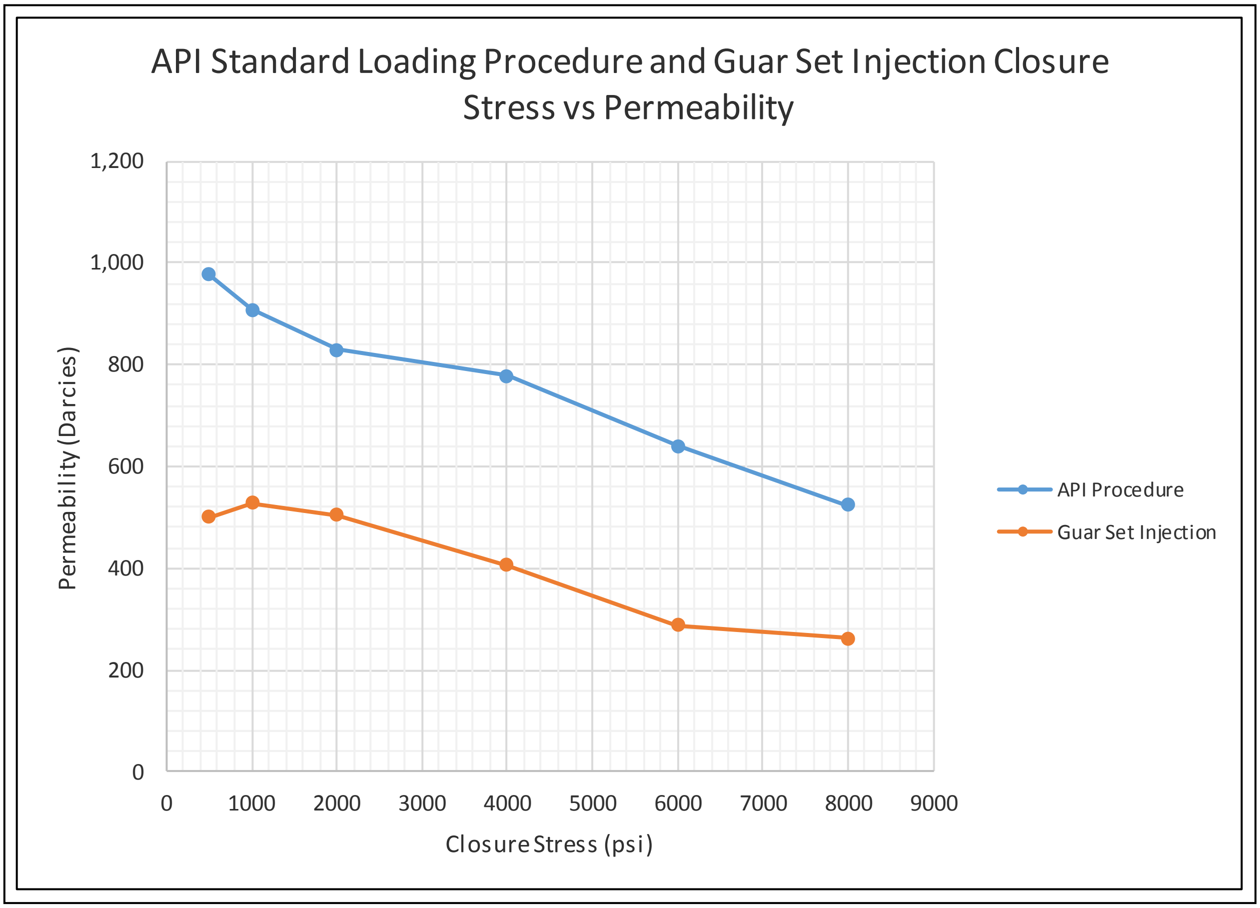

Figure 2: Guar Presence vs API Standard Loading Procedure Permeability Blair (2015)

Blair compared his injection guar solution results to the API RP-19D (2008) results but concluded that the non-displaced guar was restricting flow in the proppant pack by decreasing or clogging pore throats and was counterintuitive to improving the repeatability and reducing variation in his results but could be revisited in future experiments for improvement of lab simulation to field application.

It is stated in the API-RP 19D procedure that the proppant in the cell must not be induced to a vibration energy source due to the possibility of segregation of materials occurring. Blair concluded that through the use of a ceramic proppant that undergoes quality control measures to censure a uniform size and sphericity value that a vibration energy application would not segregate proppant material throughout the pack of varying diameters and sphericity values due to the entire sample being assumed to be identical. He utilized a ceramic proppant called CARBOLITE donated by Carbo Ceramic to Montana Tech's research labs for his research into applying a vibration to achieve a tighter pack through rearrangement of the packing structure (Blair 2015).

Blair used an AS 200 sieve shaker in the Montana Tech research lab to apply this vibration to rearrange the packing structure of the ceramic proppant. He constructed a clamp like device that could fit around the loaded cell with the .25" of proppant material, top and bottom steel shims, and testing cell. This clamp also had threaded holes on the top to be able to apply a small load to the top piston to encourage the cells to shift and then secure to the tighter and more ideal packing structures after being introduced to a vibration energy source. He utilized a level to ensure that the clamp and loaded cell was centered on the sieve shaker to ensure that proppant would not shift to one side of the cell or the other. The AS 200 sieve shaker that he utilized applied vibration on a percentage of max amplitude scale of 3.00 mm. He concluded based on the following data Table I that rearrangement was occurring at approximately 58% of the max or an estimated 1.74 mm.

Table I: Vibration Test Blair (2015)

Amplitude (% of Max)	Proppant Movement
30	None
58	Singular proppant rearrangement
68	Entire pack moves around cell

This determination was developed by not having the top piston in the cell to observe the proppant movement. Blair concluded that this rearrangement would result in tighter structure packing and reduced point loading breakage occurrence. A graphical illustration of his results after testing these vibrated cells is seen in the following Figure 3.

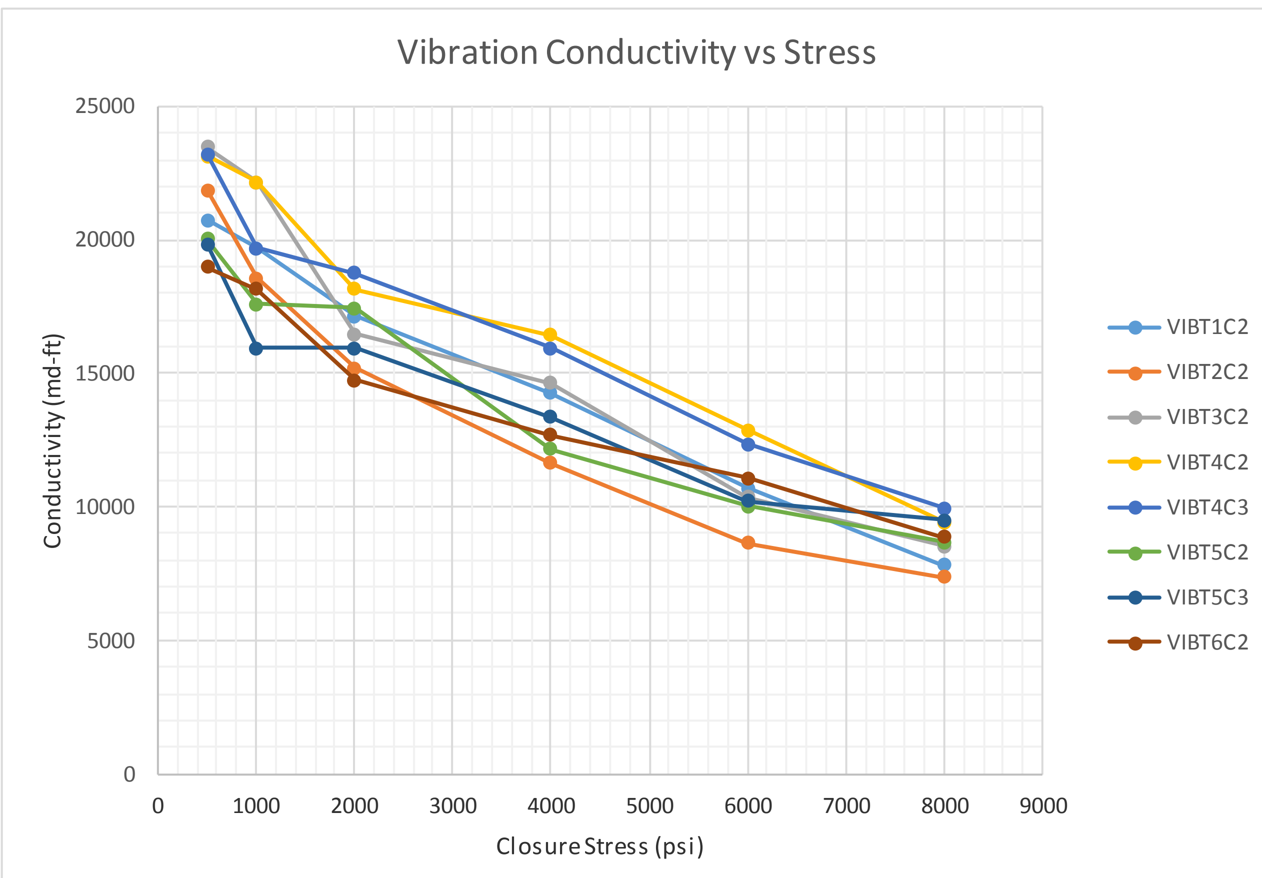

Figure 3: Blair Vibration Graphical Results

Looking more closely at this vibration modification to the API procedure data it can be seen that the results for conductivity are similar but the variance has been reduced. He concluded that overall the vibration energy being induced to tighten initial pack by shifting the packing structure of the proppant had worked. His data table of these conductivity results can be seen in the following Table II.

Table II: Blair Vibration Conductivity Values

Blair Vibration Conductivity Values				
Closure Stress (PSI)	*Test 1 Cell 2*	*Test 2 Cell 2*	*Test 3 Cell 2*	*Test 4 Cell 2*
500	20761	21854	23492	23142
1000	19706	18563	22149	22149
2000	17160	15214	16462	18141
4000	14248	11649	14630	16444
6000	10710	8624	10359	12868
8000	7831	7349	8537	9437
Closure Stress (PSI)	*Test 5 Cell 2*	*Test 6 Cell 2*	*Test 4 Cell 3*	*Test 5 Cell 3*
500	20040	18985	23204	19852
1000	17604	18141	19706	15961
2000	17446	14766	18767	15961
4000	12175	12676	15961	13360
6000	10037	11087	12367	10223
8000	8669	8860	9970	9493

Continuing off of these promising results with the use of vibration to improve the repeatability, this work focused on using other forms of vibration to decrease the variation of the short-term fracture conductivity test results with the use of the dual cell conductivity testing system, the Vibration Test Machine, and the Sonochemical Reaction Vessel.

2. Research Methodology and Procedure

2.1 Fracture Conductivity Testing Instrumentation and Models

To simulate hydraulic fracturing in the lab, a dual loading cell tester was developed by Montana Tech's Professor Richard Schrader. This tester can be seen in figure 4 below with both dual loading cells ready for testing. This tester follows the API standards RP-61 (1981) and RP-19D (2008) to measure the conductivity inside the cells.

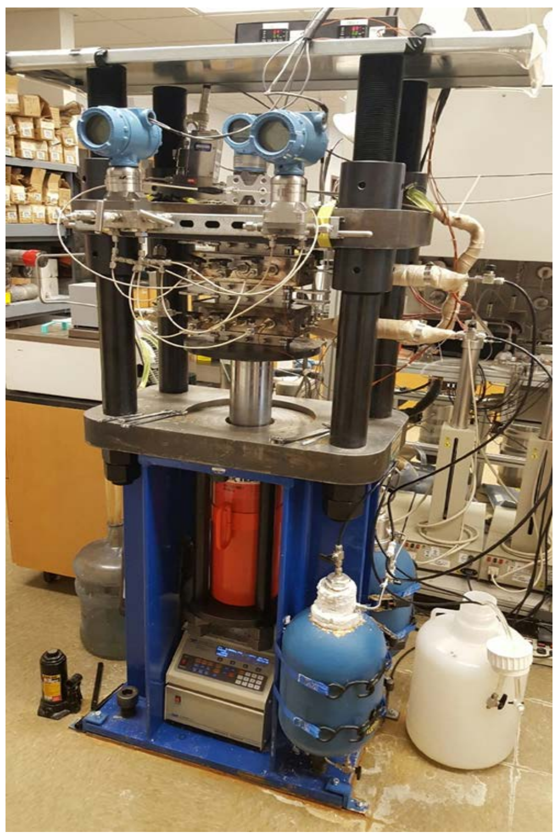

Figure 4: Montana Tech's Dual Conductivity Tester

Each cell has a separate top and bottom piston that applies a force that simulates the stresses that occur in the formation that the proppant will undergo. Metal plates of a thickness of .121" will separate the pistons and the proppant sample. The metal plates will be between 6.95" to 7" in length and 1.46" to 1.5" in width. Prior to testing, each of the test cells to be used will be zero gapped by determining the distance between piston wings at the required stresses with the metal plates between. To load the cell with proppant, mass was used and calculated from pack height dependent on bulk density that used 2 lbs./ft^2 loading. The proppant that is to be placed was massed and then placed between the plates and pistons and evenly spread out to have an approximate thickness of .25" and refrained from unnecessary agitation and additional vibration from handling prior to compression from the pistons. Each cell will be heated to an approximate temperature of 150 or 250 degrees Fahrenheit. The pistons will apply a stress load at a rate of 100 psi/min within an error of +/- 5 psi/min until a stress of 2000 psi has been reached. A brine composed of 2% KCl by mass fluid was flowed/pumped through the cell at a pressure of approximately 400 psi at a measured flow rate of 3, 6, and 12 mL/min by control of a mass flow controller to ensure constant flow rates are achieved. Pressure drop across the cell will be measured and prior to testing, the minimum pressure drop measured will be under .004 psi. Once a desired stress load has been achieved, the distance between each piston will be measured at four points to calculate the average pack/proppant height/thickness. At the desired stress load, at each of the flow rates described previously the pressure drop across the cell will be measured. Three points of data must be taken to calculate an average permeability for each of the stress rates that will be applied. Utilizing the equation to calculate proppant pack permeability in API RP-61 (2008) is seen in the following Equation 1. The component of each variable is seen following the permeability equation. For fracture conductivity the conductivity equation in SI units defined by API RP-61(2008) is shown in Equation 2 with the component of each variable defined following.

$$k = \frac{\mu Q L}{A \Delta P}$$

Equation 1

where

µ: Viscosity of a liquid at test temperature in cP.

k: Proppant pack permeability in Darcy (non-SI unit).

Q: Flow rate in cubic cm per second.

L: Length between pressure ports in cm.

A: Cross-sectional area in square cm.

ΔP: Pressure drop across cell in atm.

$$kW_f = \frac{\mu Q L}{w \Delta P}$$

Equation 2

where

k: Proppant pack permeability in Darcy (non-SI unit).

µ: Viscosity of a liquid at test temperature in cP.

Q: Flow rate in cubic cm per second.

L: Length between pressure ports in cm.

ΔP: Pressure drop across cell in atm.

w: Cell width in cm.

W_f: Proppant pack thickness in cm.

In this thesis, CARBOLITE ceramic proppant was used at the following pressures of 2000, 4000, 6000, 8000, and 10000 psi as required by API RP-61 in addition to 500, 1000, 12000, 14000, and 16,000 psi as well. At each of these ten data points, an average permeability and pack conductivity was determined at these specific stress points. CARBOLITE ceramic proppant was used to reduce variability between this thesis research data and the data of Blair's previously discussed above.

2.2 Point Loading

An issue that could be occurring that is resulting in the spread of fracture conductivity values as seen by Anderson and Blair is point loading. Point loading is a load that is applied to a specific point in structure member or is known as a concentrated load. In relation to the oil field and specifically proppant for fracture conductivity measurement, it is the load that is applied to a specific point of contact on the proppant to another proppant or formation. In the oil field, highly sought for proppant are high sphericity and highly rounded graded proppant with good compressive strength. This is due to the high point load that will occur on the proppant that will result in spalling or crushing. To reduce these breakages, increasing points of contact to spread the stress loading should reduce proppant breakage. Reducing these angular or single point loads breakage should theoretically decrease the amount of fines and shifting that would occur after breakage of the proppant. In the following Figure 5, an example of non-ideal point loading and point loading can be observed

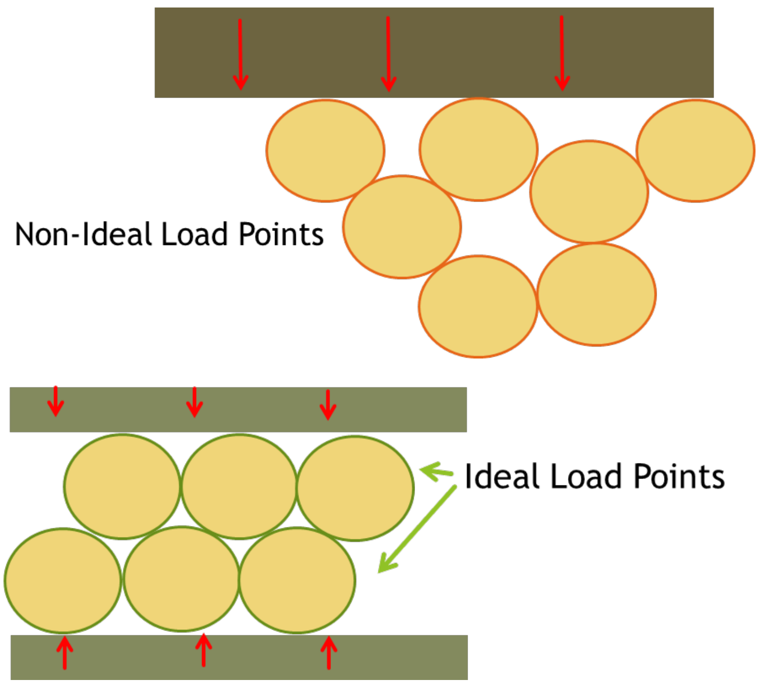

Figure 5: Theoretical Ideal and Non-Ideal Point Loading

Looking at the above Figure 5 for the non-ideal load points it can be seen that some proppant material have fewer points of contact to other proppant material surrounding them when compared to the ideal point loads in the lower portion of the figure. This results in some of these proppant materials undertaking higher loads of stress than other materials within the packing structure and result in premature failure and then create fines similar to those produced by angular points breaking off which creates possible variables that are difficult to account for when analyzing results.

By reducing or eliminating these variables from the testing procedure, variation in results from lab to lab should be reduced to produce a more consistent conductivity value for the same proppant across multiple labs. By improving these conductivity values, the overall shape of the conductivity curve versus stress should look more similar to the theoretical curve that is seen in Figure 6 below.

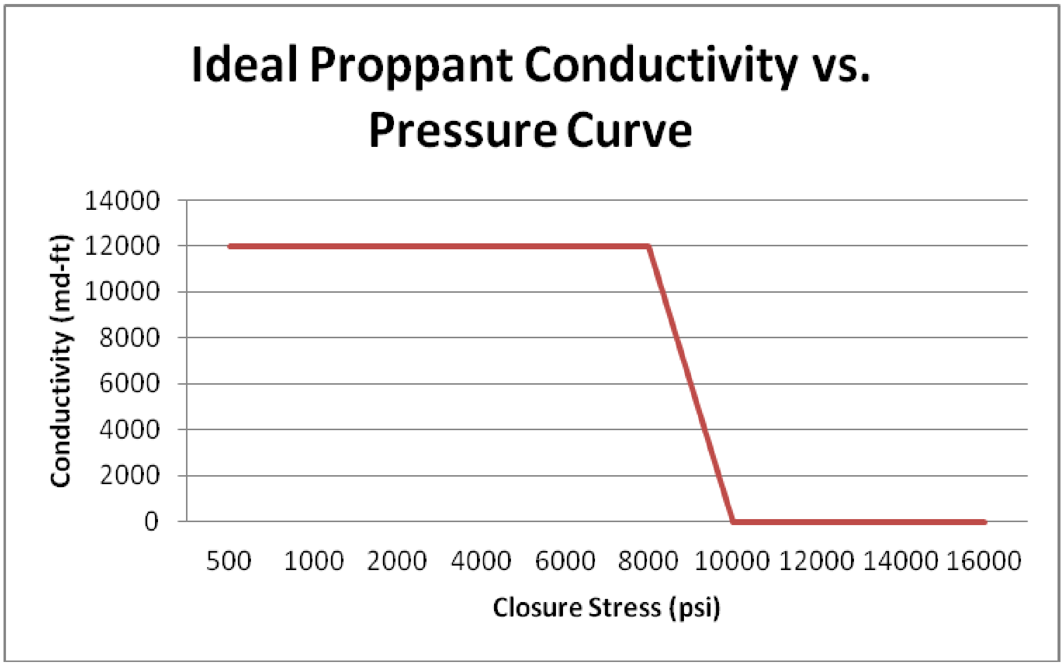

Figure 6: Theoretical Ideal Proppant Fracture Conductivity Curve

2.4 Packing Structure Arrangement

Packing structure of the proppant pack loaded into the Hooke cells helps to dictate the final results of the test performed. Looking at the results of the simulation performed by Mattson in relation to proppant pack load spread, it can be seen in the following Figure 7 that due to the arrangement of the proppant pack in the cell that point loading breakage is occurring due to the initial packing arrangement (Mattson, et al. 2014).

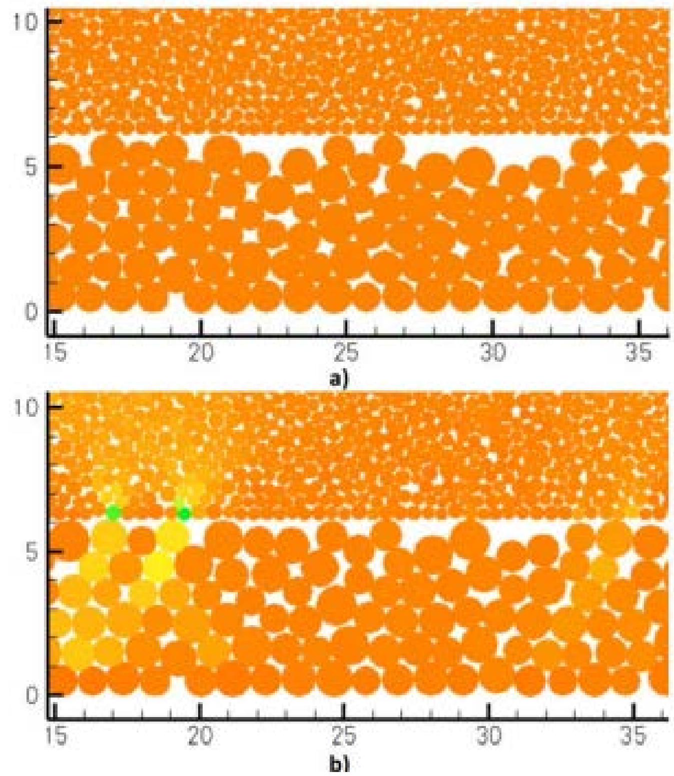

Figure 7: Cooke Cell Discrete Element Modeling Simulation
a) Initial proppant packing structure b) final proppant packing structure following load application.

It can be seen looking at image a. to b. that a rearrangement or shifting has occurred in the proppant pack. The color scale indicates that under no load stress the color is a dark orange in a. but after a stress application that a point load and likely breakage has occurred at the lighter yellowish orange and green points on the sandstone shim. In this proposed procedure, the continuation of using only metal shims to reduce this possible variation error utilized by Blair in his initial research of modifying the procedure was continued. Rearranging this proppant pack to a tighter structure should result in a more even load share among the proppant sample by increase the points of contact with the metal shim and ceramic proppant samples. This tighter structure should reduce the amount of fines and breakages that are occurring due to this initial fluffy packing structure.

Another possible benefit of this tighter initial structure is the reduction of the initial conductivity values seen in the lower closure stress values. These overestimated conductivity values could possibly lead to an overestimation of well production potential through well simulation as discussed by Barree (2003). Looking back on Figure 6, the ideal proppant conductivity vs. closure stress graph indicates that there is not a reduction in conductivity until the proppant reach the point where breakage occurs due to the closure stress applied. Another possible culprit of higher conductivity values is the lack of embedment of some of the proppant. The lack of embedment of some of the proppant grains could be resulting in higher permeability values along the proppant and shim boundary. This area of work was not explored in this paper but should be further studied to see if improvement of results are possible. After introducing a tighter initial packing structure the pack shifting, proppant rearrangement, and breakage should be minimized at the lower closure stress values that are resulting in the aggressively declining conductivity values as seen in the API-RP 61 examples shown below in Figure 8.

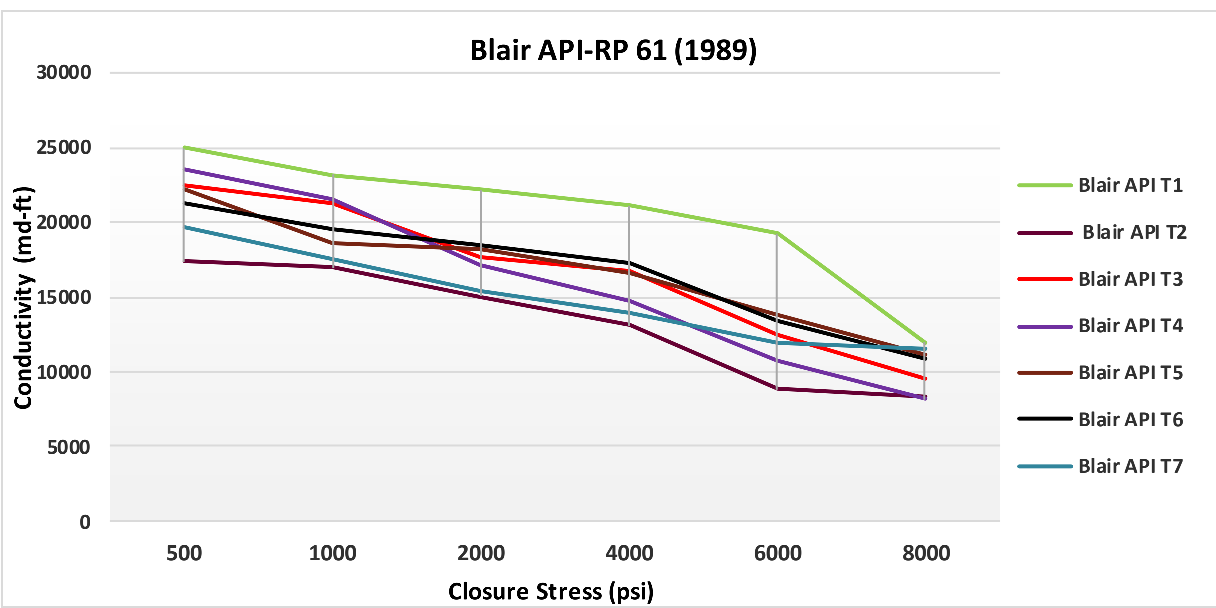

Figure 8: Blair API-RP 61 (1989) Results

2.5 Performed Procedure

The current procedure outlined by API RP-61 (2008) is in place to ensure repeatable and consistent results between multiple labs. However as seen by Anderson (2013) and Blair (2015), this is not the case and large variations are occurring that indicate that the procedure is flawed in some way that denies repeatability. Blair looked at the loading methods and in a small amount the application of vibration to the loading of sequence to reduce initial packing "fluff". Looking at the article "Realistic Assessment of Proppant Pack Conductivity for Material Selection" (Barree, 2003) as well as Blair (2015) indicates initial packing that is unstressed is likely to be the problem which influences the measurement of pack permeability.

Using the API RP-61 (2008) procedure has flaws that Blair (2015) has already proven result in variation of the results. Following a similar ideology, the metal shims utilized in the API RP-61 (1989) procedure in place of sandstone shims was utilized to reduce embedding and fine release from the fracturing of the sandstone platelets.

It was proposed to continue Blair's research and try to improve the results by introducing a vibration energy in varying amplitudes and frequencies under varying lengths of time to prepared cells prior to being introduced to a controlled flow of brine and loading stress. This was performed using two different vibration energy sources. One will be the Vibration Test Machine and the other is the Sonochemical Reaction Vessel. During the vibrational process, a light loading stress will be applied to encourage that tight packing occurs and remains. It is proposed to take ten different measurements at stresses of 500, 1000, 2000, 4000, 6000, 8000, 10000, 12000, 14000, and 16000 psi with flow rates of 3, 6, and 12 ml/min and calculate the average permeability and conductivity at each data measurement point. To help minimize point loading and help proppant pack sorting, a ceramic proppant was used that utilizes quality control protocols to ensure roundness and sphericity of each individual proppant. It is also proposed to use an additional high temperature gasket sealant to ensure no leakage under pressure occurs to aid the rubber piston gasket ring. Several control tests were run using the API-RP 61 procedure with the same ceramic proppant. By doing this it helped determine if the vibration energy applied helped decrease the variance of conductivity that is being seen that is possibly occurring due to initial sample packing and point loading. The procedure is bulleted following.

2.5.1 Procedure

- Ensure cell, cell pressure ports, and cell wall are all clean and free of obstruction.
- Prepare loading cell to stop lower piston movement with rubber piston gasket in place. Utilize a lubricant so rubber gasket moves up cell wall easily to minimize stress to gasket.
- Add the .121" metal shim to the top of the lower piston.
- Use set screws to lock the bottom piston top including metal shim to cell top wall to a distance of 1.50 inches using a caliper. This restricts movement of the bottom piston through the test.
- Apply high temperature gasket sealant around the edge of the metal shim and cell wall. Remove all additional sealant that doesn't reside in possible gap between wall and piston.

Figure 9: Hooke Cell with .121" Metal Shims and Gasket Sealant

- Measure out proppant sample of 63.1 grams of Carbo Ceramic Light 20/40.
- Apply mesh screens to cell wall pressure ports.
- Slowly pour proppant sample into cell evenly throughout.
- Utilize a flat ended tool to spread proppant evenly through cell.
- Apply top .121" metal shim on top of proppant in cell as evenly as possible to ensure no proppant shifting occurs.
- Place electric cell heater around cell and tighten in place.
- Apply high temperature gasket sealant to top of metal shim to cell wall gap carefully to ensure no proppant shifting under metal shim. Remove all excess.
- Insert top piston with rubber piston gasket in place. Lubricate gasket so rubber gasket moves easily up the cell wall to minimize stress to gasket.

- Place cell in clamp.
- Place cell in or on vibrational energy source such as the vibration test machine or sonochemical reaction vessel.
- Apply vibrational energy for desired time; lightly and evenly tightening clamps on cell throughout duration.
- Remove cell from energy source and evenly loosen clamps. Be careful not to drop or shake cell which can reduce tight proppant packing through shifting.
- Place cell in proper tester carefully and apply heat to raise cell temperature to 250 degrees Fahrenheit. Leave cell to reach equilibrium for several hours to allow any thermal expansion that will occur.
- Be careful, cell is hot. Connect pressurized brine source of 400 psi to cell and flow controller. Ensure high temperature rubber o-rings are in place to prevent leaking and pressure escape.
- Connect pressure transducers in cell ports. Apply controlled flow through cell to remove any compressible air. Bleed out any air in lines or in pressure transducers.
- Seal cell and ensure pressure drop across cell is zero. If not ensure transducers are properly calibrated and no leaks are occurring.
- Begin flow through cell and proceed with procedure in API RP-61.
- Take ten different measurements at stresses of 500, 1000, 2000, 4000, 6000, 8000, 10000, 12000, 14000, and 16000 psi with flow rates of 3, 6, and 12 ml/min.
- Calculate proppant permeability and conductivity.
- Clean cell after cooling. Discard of proppant.

This procedure was performed multiple times at varying amounts of vibrational energy and application time to determine if vibration increased the repeatability of results as well as improve the overall shape of the conductivity curve under varying stresses.

The results of these experiment trials was then compared to other results performed by Blair through the calculation of theoretical standard deviations and variation. According to the authors of “Realistic Assessment of Proppant Pack Conductivity for Material Selection” (Barree, et al. 2003), it was determined that a range of ±20% in conductivity variations is an acceptable results range. With this newly proposed procedure, the goal is to produce variations of less than ±20% to obtain this desired lab accuracy range.

3. Results

3.1 Gapping the Hooke Cells

Prior to performing these lab experiments, the Hooke cells where assembled together utilizing the metal shims in place of the sandstone platelets and then subjected to the required temperature change of 150º F or 250º F for several hours to allow for any thermal expansion that should occur. The cells were then subjected to the previously discussed testing closure stresses that would be undergone in these experiment trials and the zero gap or lack of proppant pack data would be obtained for determining the distance between the cell measurement wings at the zero value. This process is important to insure experiment controls are in place and that the data obtained is accurate.

3.2 API Control Results

Even though the equipment and ceramic proppant that was to be used in this experiment was the same that was utilized by Blair, it was concluded that multiple runs following the API-RP 61 standard procedure should be performed to have separate comparisons. This was done to ensure controls and to highlight the vast difference in results that can occur even when utilizing the same equipment and material. The trials that were run for this also included the additional data collection points at the extra closure stresses as indicated in the previously described lab procedure. These API trial results can be seen in the following Figure 10 shown below.

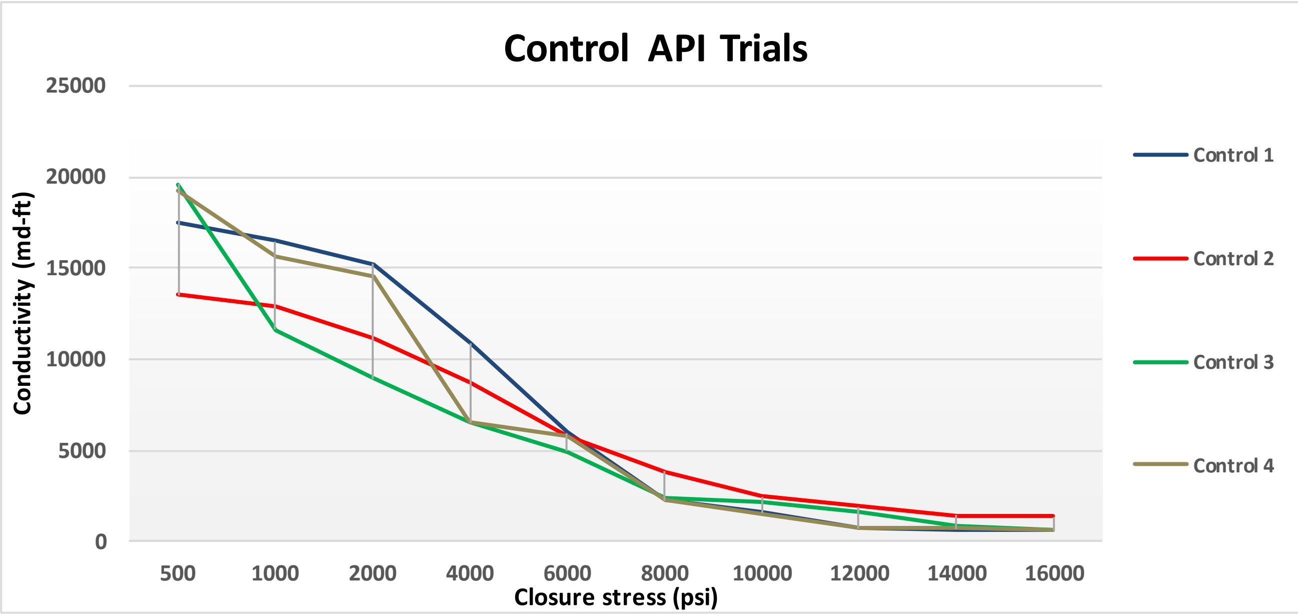

Figure 10: Control API Trials Graph

It can be noted that when these API results performed for this thesis are placed on a similar excel graph as that of Blair's that the values seen for the trials vary drastically at each of the closure stresses represented on the horizontal x-axis. This representation is seen in the following Figure 11 and highlights that even though the exact same equipment and quality controlled materials was utilized in these trials following the same procedure the results varied immensely. This confirms that the current API procedures for testing proppant fracture conductivity are flawed in some way and is likely occurring during the loading procedure.

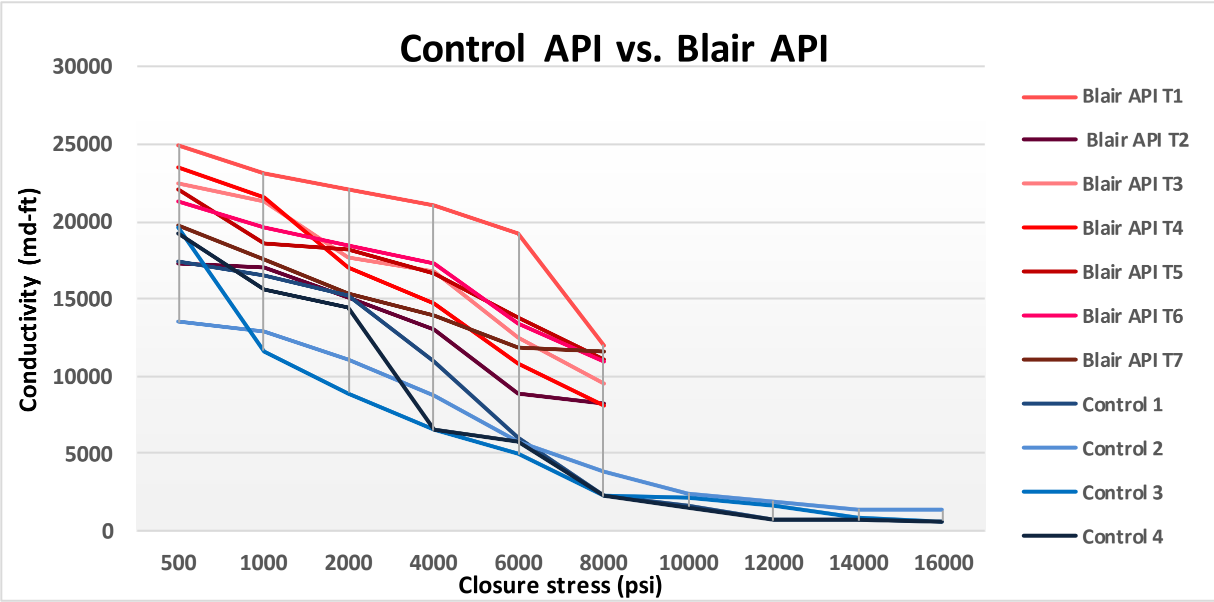

Figure 11: Comparison of Control API Trials to Blair API Trials Graph

3.3 Vibration Test Machine

After the proppant had been loaded into the cell and steel shims had been placed on the top and bottom of the pack, a high temperature rubber gasket sealant was used to seal the gap between the cell wall and the metal shims to prevent leaks and unintentional flow that could distort results. The cell was then put together in the normal fashion but prior to being connected to the conductivity testing apparatus as well as the flow meters was placed in essentially two homemade c-clamps and then gently placed atop the Vibration Test Machine (VTM) as shown in the Figure 12 below. The clamps where then tightened slightly and evenly as possible to induce a small load across the proppant pack.

Figure 12: Loaded Hooke Cell with Clamps on VTM

To apply varying amounts of energy and thus amplitude a turn knob was adjusted to set the desired setting. The duration of time for each set of trials varied to determine how long the application of energy and level of energy induced the best results. During the time of energy application, the clamps where evenly tightened to ensure the load remained as constant as possible. It was noted that during this time, the clamps tightened easily indicating that the proppant pack height within the cell had decreased from the initial height of approximately a quarter of an inch. This indicates that the “fluffy” initial pack had possibly been reduced to a tighter initial pack structure allowing increased points of contact between the proppant grains to allow for increased load sharing throughout the proppant.

The clamps were then released evenly across the cell and gently placed into the conductivity testing apparatus that meets the requirements of the API RP-61 procedure and tested following the normal API RP-61 procedure with the additional testing points of varying closure stresses.

3.3.1 Vibration Test Machine Results and Analysis

In the following Figure 13 below we can see the results for the trials utilizing the VTM as well as two controls that followed the original API RP-61 procedure for short term conductivity testing with the additional testing points of varying closure stresses. The varying times and percentage of energy application based by the position of the knob on the apparatus is presented in the key of the graph on the right hand side.

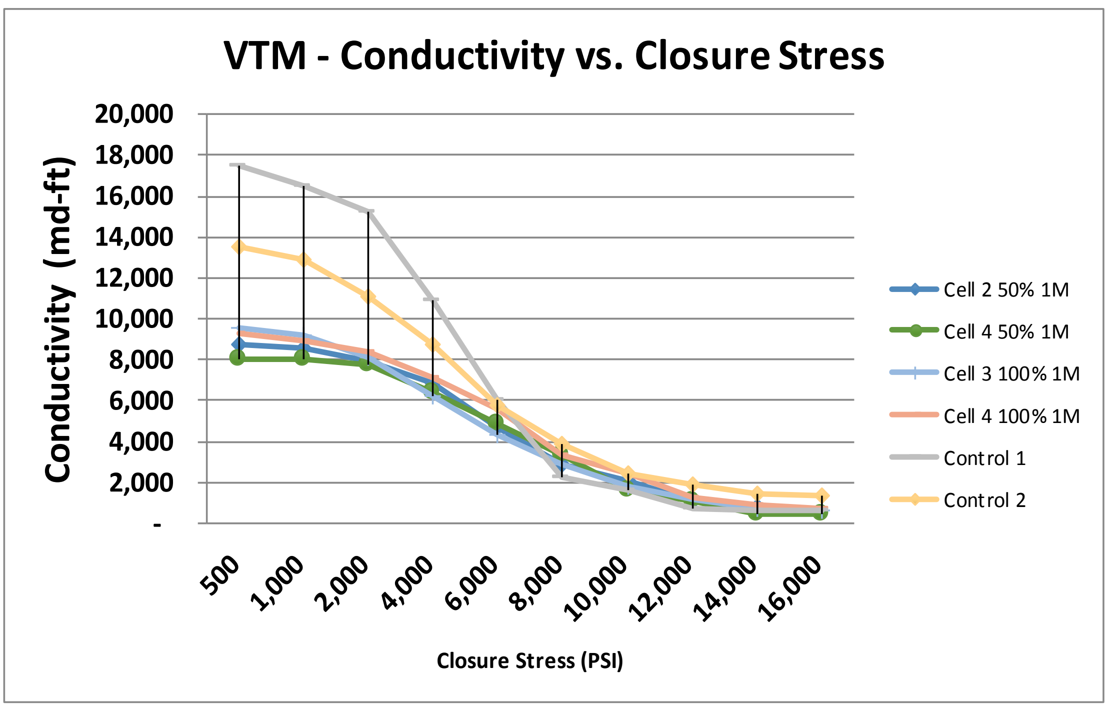

Figure 13: Vibration Test Machine Results Graph

It can be seen in a comparison of the trails that underwent the vibrational energy application from the VTM against two of the API RP-61 followed procedures that a significant reduction of the initial "fluffy" pack has been reduced in the initial five closure stress points of data collection. Note that the legend on the right hand side of the graph has two separate sets of VTM trials with varying percentages. This percentage is an indication of the level of power application that was controlled through the use of the knob on the VTM. Looking closely at the VTM trials, it can be seen based on the two separate trials that the lower application of power percentage had lower initial results than that of the higher power application trails. Looking at the following Table III the values of conductivity for each of these trails in the above Figure 13 is represented.

Table III: VTM Trial Results Conductivity Data

Vibration Test Machine Conductivity Results						
Closure Stress (psi)	*Cell 2 50% 1M*	*Cell 4 50% 1M*	*Cell 3 100% 1M*	*Cell 4 100% 1M*	*Control 1*	*Control 2*
500	8702	8066	9543	9313	17474	13533
1000	8533	8037	9238	8964	16499	12870
2000	7939	7743	8084	8365	15238	11127
4000	6874	6363	6229	7119	10927	8737
6000	4700	4823	4318	5607	5996	5771
8000	2848	3334	2861	3304	2250	3835
10000	2025	1636	1804	2404	1612	2469
12000	1064	1032	1185	1264	744	1892
14000	781	460	669	872	661	1433
16000	593	444	614	742	602	1353

Looking at the above data Table III as well as the VTM trials graph that the conductivity values for the lower power percentage application are lower than that of the higher power percentage application. This could possibly be due to too much vibrational energy being applied and the small evenly applied load isn't applied in a swift enough or even enough manner to not allow the proppant material to bounce around within the cell possibly creating a slightly fluffier initial pack than its lower power application counterpart.

These results seem promising as the variation in the results has obviously been reduced when compared to the API procedure results seen in Figure 8. Another positive aspect of improvement was the reduction of the initial conductivity values for the initial closure stress points that can be seen in the above Table III and Figure 13 when compared to the control trials following the API procedure. Looking back at Figure 6 which is theoretically the ideal representation of conductivity results, the VTM trials didn’t have the aggressive decline at the initial closure stresses as the API trials providing for more accurate results.

However, as the VTM apparatus was examined during the application of the vibrational energy it could be seen that the measuring method for amplitude, a spirit level, doesn’t provide precise numerical values of the amplitude that is being induced during the constant 50 Hz frequency but rather a possible range of values that does not stay constant when the power is being applied. This likely does not indicate that the amplitude being applied is varying during the process but is possibly difficult to replicate exact conditions for every loading process which induces variations between trials. Because of these possible variation potentials, only four trials of recordable error free data where performed due to the apparatus limitations. The results from the trials are promising to show that the process was moving in the correct direction as the research progressed forward.

3.4 Sonochemical Reaction Vessel

In following the prescribed procedure that was also utilized in the VTM, after the proppant had been loaded into the cell with steel shims and a high temperature rubber gasket sealant was used to seal the gap between the cell wall and the metal shims to prevent leaks and unintentional flow that could distort results. Then put together in the normal fashion but prior to being connected to the conductivity testing apparatus as well as the flow meters was placed in essentially two homemade c-clamps and then gently placed within the Sonochemical Reaction Vessel (SRV) as shown in the Figure 14 below. The clamps where then tightened slightly and as evenly as possible to induce a small load across the proppant pack.

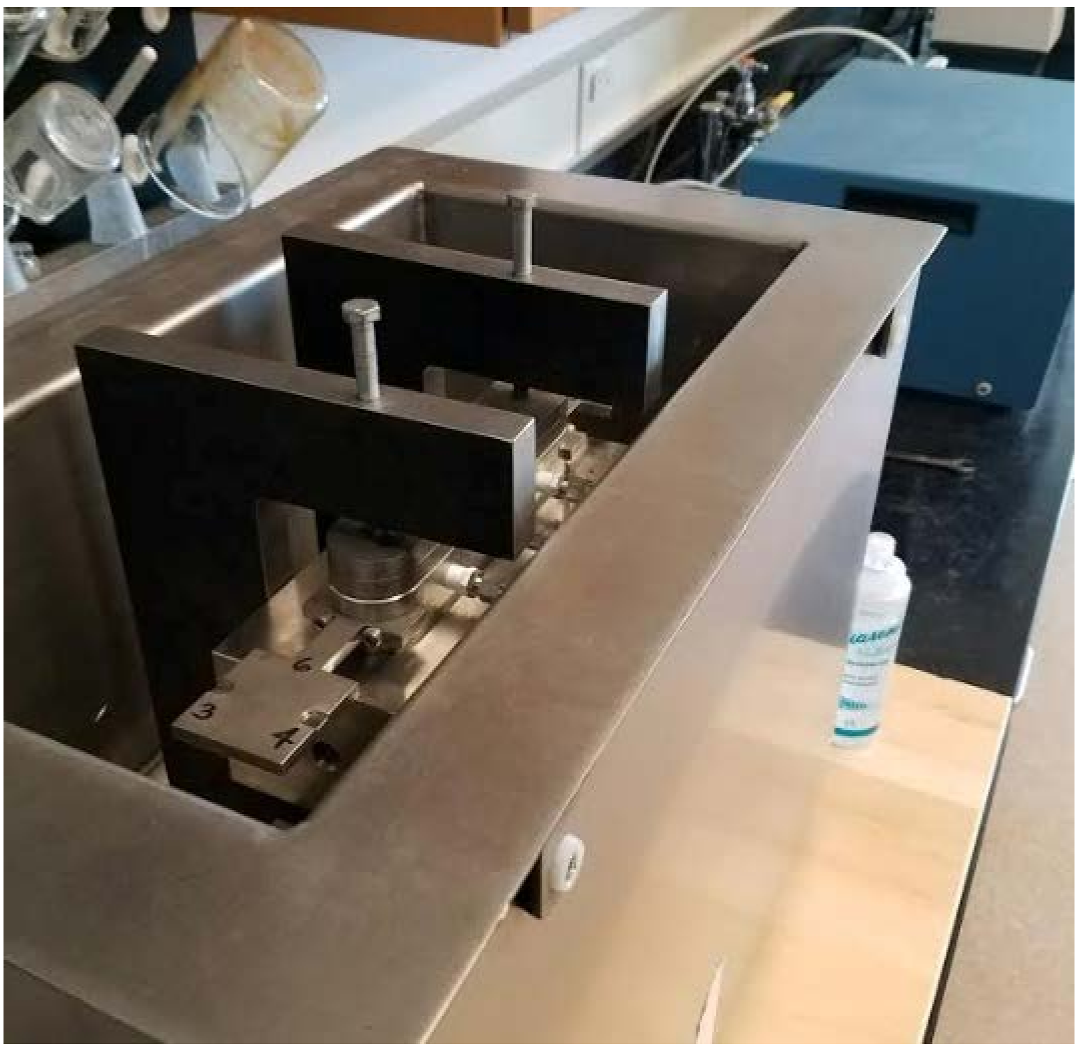

Figure 14: Loaded Hooke Cell with Clamps in SRV Vessel

To apply varying amounts of energy and thus amplitude a turn knob was adjusted up or down to achieve these desired applications. The duration of time for each set of trials were varied to determine how long the application of energy and level of energy induced the best results. During the time of energy application, the clamps where evenly tightened to ensure the load remained as constant as possible. It was noted that during this time, the clamps again tightened with ease indicating that the proppant pack height within the cell had decreased from the initial height of approximately a quarter of an inch. This once again indicates that the "fluffy" initial pack had possibly been reduced to a tighter initial pack structure allowing increased points of contact between the proppant grains to theoretically allow for increased load sharing throughout the proppant.

The clamps were then released evenly across the cell and the loaded cell was gently lifted out of the SRV "bath". The cell was gently placed into the conductivity testing apparatus that meets the requirements of the API RP-61 procedure and tested following the normal API RP-61 procedure with the additional testing points of varying closure stresses.

3.4.1 Initial Test Results and Analysis

The following Figure 15 is a graphical representation of the results from the preliminary trials utilizing the SRV. These trails underwent the prescribed procedure and used varying amounts of vibration energy application by utilizing differing percentages of total power potential. The maximum percentage applied in these trials was 80% unlike the 100% utilized with the SRV as limitations with amp limitations with the laboratory electrical system was in place and could not be upgraded in a timely manner economically. In these SRV trials, the amount of time was also varied to see if duration of vibrational energy application had an influence on the overall results.

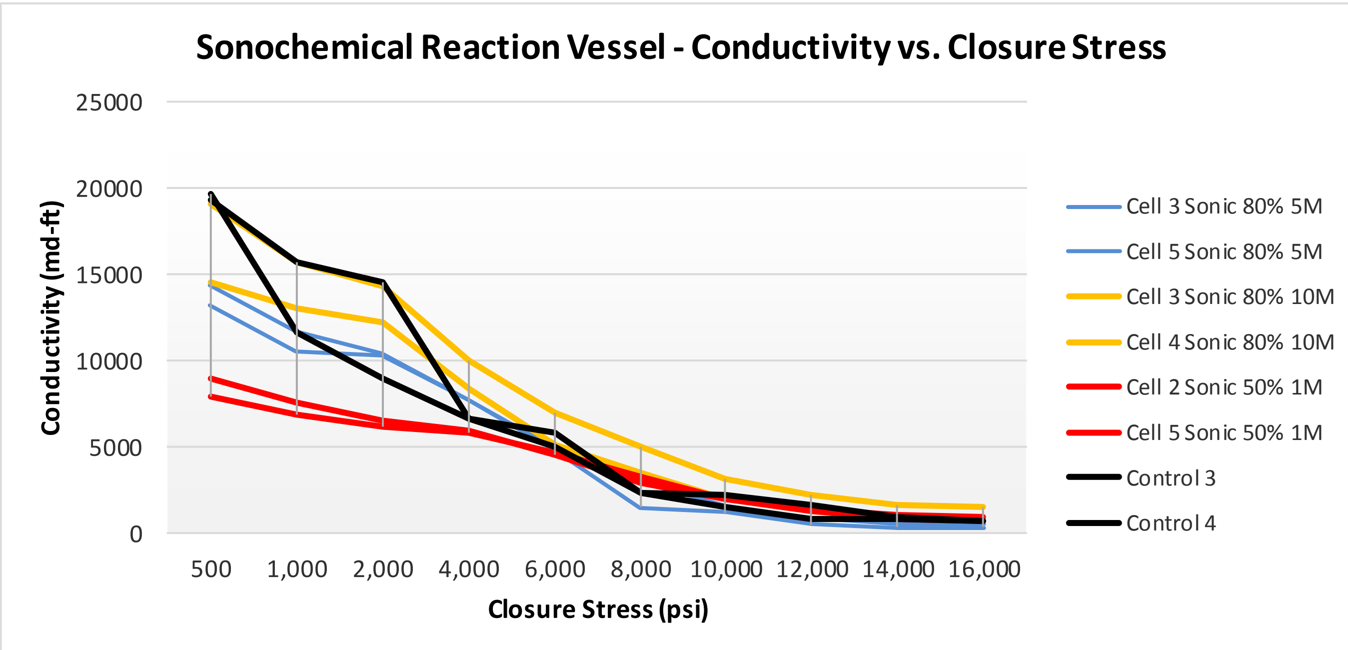

Figure 15: Initial Sonochemical Reaction Vessel Results Graph

It can be seen in a comparison of the trails that underwent the vibrational energy application from the SRV against two of the API RP-61 followed procedures that most trials saw a reduction of the initial "fluffy" pack has been reduced in the initial five closure stress points of data collection. Note that the legend on the right hand side of the graph has three separate sets of SRV trials with varying percentages or times. This percentage is an indication of the level of power application that was controlled through the use of a knob on the SRV. Looking closely at the SRV trials, it can be seen based on the two separate trials that the lower application of power percentage had lower initial results than that of the higher power application trails. Looking at the following Table IV we can see the values of conductivity for each of these trails in the above figure.

Table IV: Initial SRV Trial Results Conductivity Data

Sonochemical Reaction Vessel Initial Conductivity Results			
Closure stress (psi)	*Control 1 (MD-FT)*	*Control 2 (MD-FT)*	*Cell 2 Sonic 80% 5 Min (MD-FT)*
500	19618	19302	14388
1000	11614	15639	11694
2000	8905	14508	10402
4000	6555	6539	7717
6000	4935	5819	4748
8000	2338	2296	1418
10000	2150	1523	1163
12000	1601	722	458
14000	871	714	277
16000	637	644	254
Closure stress (psi)	*Cell 3 Sonic 80% 10 Min (MD-FT)*	*Cell 4 Sonic 80% 10 Min (MD-FT)*	*Cell 5 Sonic 80% 5 Min (MD-FT)*
500	19014	14503	13147
1000	15657	13039	10538
2000	14250	12224	10236
4000	9941	8296	7675
6000	6898	5031	4955
8000	4944	3433	2879
10000	3141	1956	1497
12000	2189	1215	816
14000	1616	881	473
16000	1518	746	429
Closure stress (psi)	*Cell 2 Sonic 50% 1 Min (MD-FT)*	*Cell 5 Sonic 1 Min (MD-FT)*	
500	8943	7874	
1000	7545	6820	
2000	6450	6078	
4000	5927	5751	
6000	4460	4581	
8000	2909	3166	
10000	1965	1909	
12000	1301	1263	
14000	1000	737	
16000	886	699	

For the higher energy input of 80% of power capacity for the SRV and a time duration of ten minutes, the conductivity values when compared to that of the controls following the API procedure are similar. For example, when Cell 2 80% 10 Min is compared to Control 2 the conductivity values are almost mirrors of each other at the same closure stress measurement points. The relative consistency of conductivity values seen utilizing the VTM is not present here in the SRV conductivity values that underwent the maximum power input and the longest input of vibrational energy in the initial trials. This could be possibly due to the proppant in the cell bouncing and shifting unevenly due to the inability to swiftly maintain a constant load upon the material as energy is being applied or the material is shifting unevenly as the constant load is being applied.

The conductivity values for the higher energy input at 80% of power capacity and for a time duration of five minutes for the initial closure stresses are significantly lower than that of the controls following the API procedure at most of the initial measurement points. The variation in conductivity values between the trials were also less than that of the controls following the API procedure. Looking at the difference of results between the trials that underwent ten minutes of energy application to those that only underwent five minutes of application, the lower time duration had more constant results. This is a possible indication that longer amounts of time at the same energy input levels does not necessarily reflect a more positive result.

The trials that underwent the lower energy application and low time duration conductivity results as seen in the above Table IV have the lowest conductivity values and lowest visual variation as seen in the above Figure 15. When compared to the control conductivity values at the closure stress of 2000 psi, there was an approximate reduction ranging from twenty-five to sixty percent. This was a positive indication that the initial fluffy pack had been reduced to a tighter packing structure.

From these initial results, it was concluded that the next set of trials should be performed to confirm that the lowest apparent visual variation between trials and the lowest initial conductivity values are obtained by the application of low vibrational energy for a short time duration. These trials would also confirm the similar results seen when the VTM was utilized.

The use of the SRV was more applicable in the ability of consistent power levels than that of the VTM as the SRV utilized not only a more sophisticated turn knob but a visual meter to indicate the power level being utilized as well. From this observation, only the SRV was utilized as trials proceeded forward to confirm prior results.

3.4.2 Second Round Test Results and Analysis

After the preliminary results from the SRV, Figure 16 is a graphical representation of the results from the final trials utilizing the SRV. These trails underwent the prescribed procedure and used a constant vibration energy application of fifty percent of the total power potential. In these SRV trials, the amount of time was held constant at a low time duration of one and a half minutes to confirm that the best results for this experiment where seen at lower times of energy application.

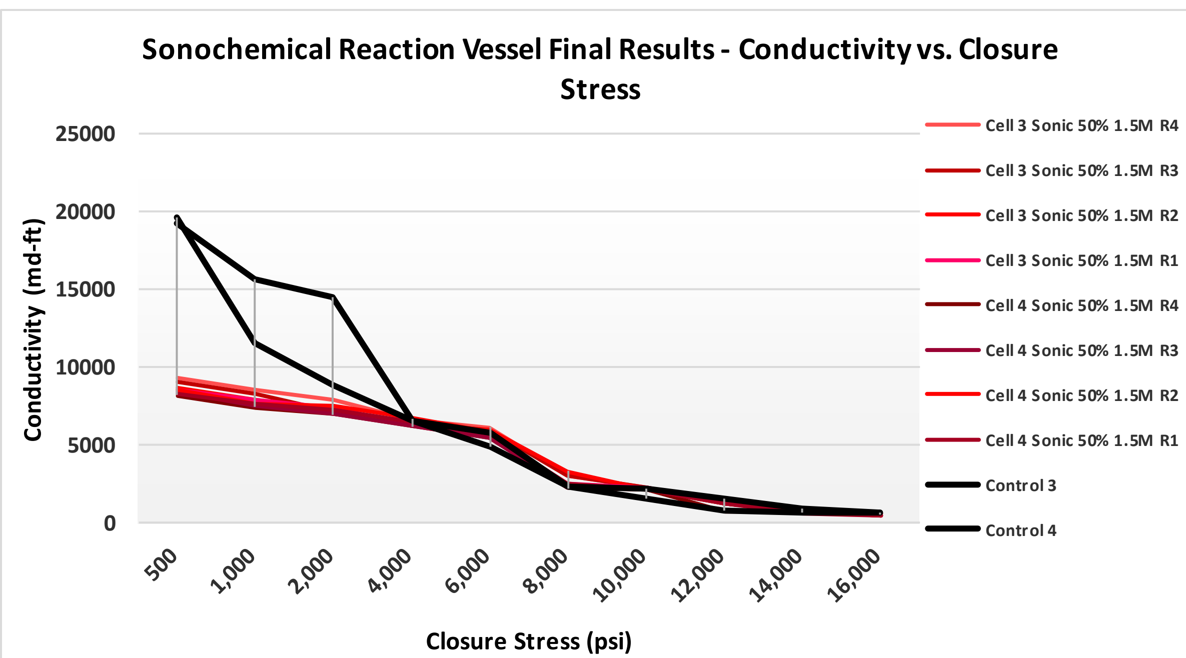

Figure 16: Final Sonochemical Reaction Vessel Results Graph

A total of eight trials where performed following the vibrational energy application procedure after the proppant material had been loaded into the cell utilizing these conditions of lower vibrational energy being applied for a short period of time. The fracture conductivity testing apparatus once again met all the requirements of API RP-61 for short term conductivity testing and data was obtained at the required closure stresses as well as the additional closure stresses obtained for evaluation purposes for this experiment. It should be noted that in the above Figure 16 that the colors in the legend on the right side of the graph had been changed to better highlight the difference between the API RP-61 procedure with the additional data collection closure stress points in black and the modified procedure with the application of the vibrational energy to the loaded proppant material in the prepared cell for short time durations in shades of red.

It can be seen in the above Figure 16 that the results for the modified procedure utilizing low vibrational energy for short time durations has drastically outperformed the control trials following the API RP-61 short term conductivity testing procedure. With a consistent visual reduction of the initial conductivity values as well as the lack of the drastic near exponential reduction of the conductivity values over the first third closure stress data points seen in the API RP-61 procedure control trials the modified procedure utilizing the SRV performed better in the goal for reducing the initial fluffy pack by introducing a tighter initial packing structure. The overall shape of the decline also more closely follows the desired shape of the ideal fracture conductivity graph as illustrated in Figure 6 than that of the API procedure control trials. Looking at the following data Table V we can see the values of conductivity for each of these trails in the above Figure 16.

Table V: Final SRV Conductivity Results

Sonochemical Reaction Vessel Final Conductivity Results		
Closure stress (psi)	*Control 3 (MD-FT)*	*Control 4 (MD-FT)*
500	19618.0	19301.5
1000	11614.4	15638.8
2000	8905.0	14507.5
4000	6555.0	6539.4
6000	4934.8	5818.8
8000	2338.3	2296.4
10000	2150.5	1523.5
12000	1600.8	721.8
14000	871.3	713.6
16000	636.9	643.8
Closure stress (psi)	*50% Vibration Cell 3 R1 1.5M (MD-FT)*	*50% Vibration Cell 4 R4 1.5M (MD-FT)*
500	8485.3	8184.9
1000	7844.2	7414.7
2000	7383.1	6998.9
4000	6264.5	6299.7
6000	5778.9	5453.1
8000	2537.9	2226.3
10000	2198.0	2162.5
12000	1221.1	755.3
14000	704.0	722.9
16000	520.8	607.0
Closure stress (psi)	*50% Vibration Cell 3 R4 1.5M (MD-FT)*	*50% Vibration Cell 4 R3 1.5M (MD-FT)*
500	9338.1	8394.0
1000	8544.2	7508.9
2000	7896.3	6998.9
4000	6630.8	6251.0
6000	6134.6	5520.4
8000	2973.6	2291.7
10000	2211.6	2193.2
12000	1214.9	1264.3
14000	770.7	732.8
16000	560.9	625.6
Closure stress (psi)	*50% Vibration Cell 3 R3 1.5M (MD-FT)*	*50% Vibration Cell 3 R2 1.5M (MD-FT)*
500	9027.1	8636.1
1000	8277.5	7947.4
2000	7162.6	7230.3
4000	6415.0	6197.5
6000	5937.6	5937.6
8000	2992.0	3338.2
10000	2203.9	2182.1
12000	1232.6	1218.5
14000	714.0	704.0
16000	515.5	519.6
Closure stress (psi)	*50% Vibration Cell 4 R2 1.5M (MD-FT)*	*50% Vibration Cell 4 R1 1.5M (MD-FT)*
500	8544.2	8338.8
1000	7622.5	7694.8
2000	7502.6	7277.6
4000	6700.9	6555.0
6000	5834.7	5696.3
8000	2424.0	2495.6
10000	2147.6	2170.9
12000	1226.8	1221.1
14000	698.5	631.2
16000	487.6	495.1

The trials that underwent the lower energy application and low time duration conductivity results as seen in the above Table V have significantly lower conductivity values when compared to the control conductivity values. For example, at the closure stress of 2000 psi there was an approximate reduction ranging from ten percent to fifty percent in conductivity. This was a positive indication that the initial fluffy pack had been reduced to a tighter packing structure.

In the following Figure 17, an additional comparison of the modified procedure using the low vibrational energy application for short time durations was compared to some of Blair's results from his trials following the API RP-61 (1989) procedure. It should be noted that in the below Figure 17 that the colors in the legend on the right side of the graph had been changed to better highlight the difference between Blair's API RP-61 (1989) procedure results in darker colors and the modified procedure with the application of the vibrational energy to the loaded proppant material in the prepared cell for short time durations in shades of red.

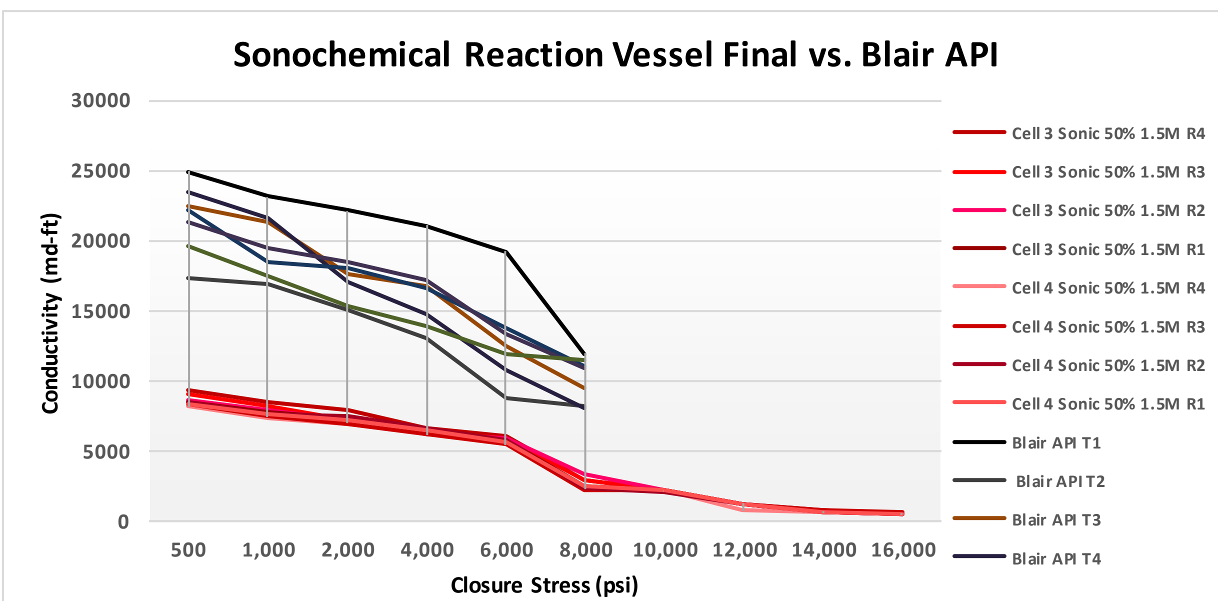

Figure 17: Comparison of Final SRV Results to Blair API Results

Observation of the data for the modified procedure can be seen to have significantly less variation and to have lower conductivity results visually compared to the data that came from the API method trials. At the initial data collection closure stress point of five hundred psi, the reduction ranges from approximately forty-five percent to sixty-five percent in this comparison of data sets.

The following Figure 18 is another comparison of modified procedure using the low vibrational energy application for short time durations to some of Blair's API RP-61 results as well as the control API RP-61 trials performed for this thesis experiment. It should be noted that in the below Figure 18 that the colors in the legend on the right side of the graph had been changed to better highlight the difference between Blair's API RP-61 procedure trial results in different shades of green, the API control trial results in different shades of blues, and the modified procedure with the application of the vibrational energy to the loaded proppant material in the prepared cell for short time durations in different shades of red.

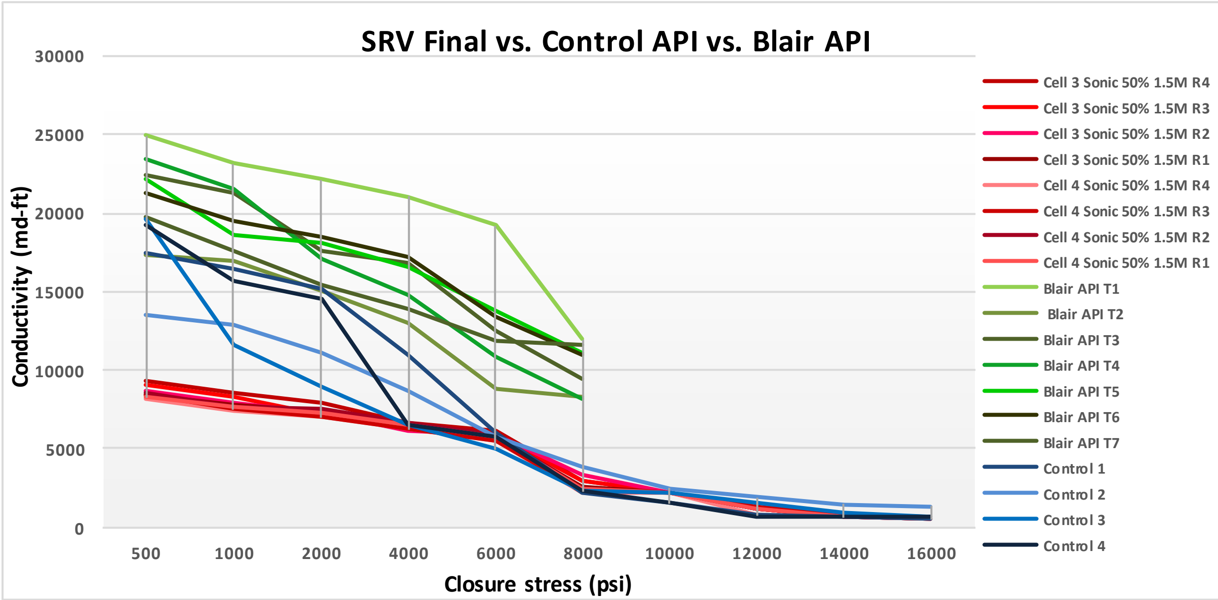

Figure 18: Comparison of Final SRV Results to API Trial Methods

The above graphical Figure 18 shows a couple different visual observations. First, the modified procedure appears to outperform Blair's API procedure as well as the control API trials in terms of lower initial conductivity values that indicate a reduction of the fluffy initial proppant pack structure through the proppant pack structure rearrangement and consistency and repeatability from one trial to the next. This is a positive indication that the modified procedure using the low vibrational energy application for short time durations during the loading of the proppant prior to testing the material overall improved the process.

4. Statistical Analysis and Comparison

4.1 Average Conductivity

The first step was to calculate the average conductivity value at each of the individual closure stresses ranging from 500 psi to 16000 psi. This was done using the following Equation 3:

$$\overline{a} = \frac{\sum x}{n}$$

Equation 3

where

x is the fracture conductivity values

n is the number of samples

$\overline{a}$ is the mean

Σ is the summation

The following Table VI is the average conductivity values for each of the closure stresses measured for the modified procedure using low vibrational energy input and short time duration trials which are labeled and referred to as Modified Vibration Method (MVM) for the remainder of this paper, the control API procedure trials, Blair's vibration modification trials, and Blair's API procedure trials.

Table VI: Mean Conductivity Values

Mean Conductivity Comparison (MD-FT)				
Closure Stress	*MVM*	*Control API*	*Blair Vibration*	*Blair API*
500	8618.6	17481.7	21416.2	21633.1
1000	7856.8	14155.5	19247.6	19811.0
2000	7306.3	12444.2	16739.6	17700.1
4000	6414.3	8189.6	13892.9	16214.1
6000	5786.7	5630.2	10784.3	12915.1
8000	2659.9	2680.1	8768.4	10208.4
10000	2183.7	1938.8	-	-
12000	1169.3	1239.7	-	-
14000	709.8	919.6	-	-
16000	541.5	809.1	-	-

Looking at the above Table VI, it can be seen that there are significantly lower mean conductivity values for the MVM method when compared to that of the API RP-61 methods. It can be noted that the significant difference visually noted between the control API trials and Blair's API trials (2015) are confirmed with the data in this table. The lower average conductivity results for the MVM method compared to Blair's modified vibration lead to the conclusion that the use of more sophisticated equipment that are destined for a similar application are better suited for these trials compared to a sieve shaker. The difference in the mean between the two separate API methods can be contributed to the hand loading variance that is occurring utilizing the API method. This can't be ignored as the equipment, materials, and process was exactly the same with the only difference being the operator of the trials. These conductivity mean results help to illustrate that the MVM procedure improves results through the reduction of the initial fluffy pack and highlight the variation that can occur between operators utilizing the same material product.

4.2 Standard Deviation

Utilizing the mean fracture conductivity value, the standard deviation which is the quantity calculated to indicate the extent of deviation for a group as a whole was calculated using the following Equation 4:

$$S = \frac{\sum (x-\overline{a})^2}{(n-1)^{.5}}$$

Equation 4

where

s is the standard deviation

$\overline{a}$ is the facture conductivity mean

n is the number of samples

x is the fracture conductivity values

Σ is the summation

The following Table VII is the standard deviation values for each of the closure stresses measured for the MVM trials, the control API procedure trials, Blair's vibration modification trials, and Blair's API procedure trials.

Table VII: Standard Deviation of Conductivity Values

Standard Deviation Comparison				
Closure Stress	*MVM*	*Control API*	*Blair Vibration*	*Blair API*
500	382.7	2796.7	1485.1	2507.1
1000	388.3	2295.1	2112.3	2277.4
2000	294.9	2962.1	1180.9	2356.7
4000	192.0	2096.6	1678.5	2670.9
6000	226.6	473.6	1340.2	3246.0
8000	394.6	771.1	876.0	1575.1
10000	22.0	449.3	-	-
12000	168.0	597.1	-	-
14000	39.3	353.8	-	-
16000	51.2	363.3	-	-

In the above table, it can be seen again that there are significantly lower standard deviation values for the MVM method conductivity values when compared to that of the API RP-61 methods similarly seen in Table VI for the conductivity mean values. The lower standard deviation values for the MVM method compared to Blair's modified vibration again lead to the conclusion that utilizing such equipment such as the VTM and SRV are better suited for this modified procedure application than a material sieve shaker. Comparing the difference in the standard deviation values between the two separate API methods, the difference in the lower closure stress values are relatively insignificant until the closure stress of 6000 psi is reached. At this point the difference is significantly greater. These standard deviation conductivity values further illustrate that the MVM procedure improves results by providing a more repeatable trial results for the same materials and the application of applying vibrational energy to the loading process before the testing is taking a step in the right direction to obtaining consistent and reliable results.

4.3 Variance

Utilizing the standard deviation, the variance can be calculated which is used to measure how far the set of numbers vary from the average calculated value and was calculated using the following Equation 5:

$$\text{Sample Variance} = s^2$$

Equation 5

where

s is the standard deviation

s^2 is the variance

The following Table VIII is the variation values for each of the closure stresses measured for the MVM trials, the control API procedure trials, Blair's vibration modification trials, and Blair's API procedure trials.

Table VIII: Variance of Conductivity Values

Variance Comparison				
Closure Stress	*MVM*	*Control API*	*Blair Vibration*	*Blair API*
500	146,428	7,821,567	2,205,598	6,285,704
1000	150,778	5,267,376	4,461,845	5,186,623
2000	86,972	8,774,139	1,394,492	5,554,122
4000	36,870	4,395,926	2,817,344	7,133,495
6000	51,336	224,328	1,796,188	10,536,238
8000	155,705	594,526	767,306	2,480,842
10000	486	201,842	-	-
12000	28,234	356,573	-	-
14000	1,541	125,144	-	-
16000	2,626	131,992	-	-

Looking above, the significant difference in the variance for the MVM method when compared to that of the API RP-61methods is holding constant as seen when compared to the tables for the mean and standard deviation conductivity values. The lower variance occurring between trials measuring conductivity for the MVM method when compared to Blair's modified vibration confirm prior noted observations. Another interesting occurrence was the significant change in variance that started to occur at a closure stress of 6000 psi. It would be expected at these higher closure stresses that the permeability for the samples would be approaching a similar value due to proppant materials failing due to unequally spread loads due to the lack of point loads and tightening the structure resulting in lower standard deviation values and thus a lower variance. However, for Blair's API results the variance increased drastically then started to fall as expected which is a possible indication of grain rearrangement occurring after the closure stress that was being applied increased.

In the following Table IX is the calculated percent reduction in variance for conductivity values at each of the closure stresses for data collected for the MVM method performed in this experiment compared to Blair's API trials.

Table IX: Comparing MVM Trials to Blair API Trials (2015)

Precent Reduction			
Closure Stress (PSI)	*Mean*	*Standard Deviation*	*Variance*
500	-60.2%	-84.7%	-97.7%
1,000	-60.3%	-82.9%	-97.1%
2,000	-58.7%	-87.5%	-98.4%
4,000	-60.4%	-92.8%	-99.5%
6,000	-55.2%	-93.0%	-99.5%
8,000	-73.9%	-74.9%	-93.7%

Observation of the conductivity data leads to the conclusion that a reduction in variance of over 90% has occurred when comparing the MVM trials to those trials performed by Blair (2015) following the API procedure. These reductions in the variations meet the conductivity variations target goal of ± 20% set at the beginning of this thesis lab experiment are within the laboratory accuracy parameters for a given proppant type and size (Barree, et al.2003).With the new loading procedure, MVM, the initial variations that occur due to the hand loading portion of the API-RP 61 procedure appear to have been reduced which has reduced some of the variation experienced with fracture conductivity analysis testing improving the applicability of the data obtained.

5. Conclusion

1. The application of vibrational energy to a cell loaded with a ceramic proppant prior to the API-RP 61 (1989) testing procedure reduced the variation of fracture conductivity results measured at multiple closure stresses when utilizing a ceramic proppant material by reducing the amount of grain rearrangement that occurred during the testing.

2. The use of more sophisticated energy application instrumentation allows for measurable vibrational amplitude and improved accuracy of vibrational energy input.

3. The variations that are being seen in the proppant fracture conductivity results on the same tested materials is likely occurring during the loading phase of the procedure and is not due to variations in equipment utilized from lab to lab.

4. Results improve as the user becomes more familiar with the loading and testing process.

5.1 Forward Direction Recommendations

1. Perform the MVM vibration energy application procedure on sand proppant that has been sieved to ensure grain size for multiple trials and compare to the API-RP 61 procedure to see if results carry over from ceramic proppant to sand proppant.

2. If testing is to continue on the effects of applying vibrational energy to conductivity tests at Montana Tech, it is recommended to purchase a vibrational instrument that can be attached to the fracture conductivity testing apparatus built following the API-RP 19D

(2008) and API-RP 61 (1989) parameters. This is to reduce any possible variation that can occur by releasing the light load after applying the vibrational energy and the moving of the cell.

3. It is recommended to continue research on the effects of applying vibrational energy following the MVM procedure and then following the testing time duration that occurs for the API-RP 19D (2008) procedure to see if variation is reduced and similar results occur. API-RP 19D (2008) is the current industry standard for proppant conductivity testing. A reduction in conductivity variation for the long-term testing procedure would likely be invaluable for the petroleum industry and improve the ability to confidently apply results to industry applications.

4. Because the results from the MVM procedure were so promising for short-term conductivity tests, more research into what the optimal vibrational amplitude and time duration of energy application should be performed to a loaded cell to determine the lowest variation in conductivities results.

5. It is recommended to continue the research into injecting a guar based fracture fluid into the proppant pack performed by Blair (2015) after the MVM procedure has been performed to further advance the research into the direction of real world field application simulation.

6. It is recommended to purchase a digital measurement device to determine the proppant pack height as the use of the current metal measuring device to determine distance between the cell wings attached to the cell pistons puts the user within close proximity to contacting an extremely hot surface.

7. The steel tubing that is utilized to connect the testing cell to the testing instrumentation should be replaced as the disconnection and reconnection after multiple tests has

led the ends to form slight bends in the tubing that can lead to leakage due to inability to properly tighten the connections to the cell.

8. It is recommended to look at improving the initial packing structure further by utilizing shims that allow some embedment of the grains. The material tested must also resist shear failure seen in the sandstone platelets.

9. Further comparison of the MVM method for short term conductivity tests should be compared to long term conductivity tests following the API RP-19D procedure to see if results are similar. This could reduce overall test time by showing vibrating the short term tests provides comparable results to the long term test results.

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7. Appendix A:

Final SRV Results Table					
Closure Stress (PSI)	*Cell 4 Run 3 (MD-FT)*	*Cell 4 Run 2 (MD-FT)*	*Cell 4 Run 1 (MD-FT)*	*Cell 4 Run 4 (MD-FT)*	*Cell 3 Run 4 (MD-FT)*
500	15,366.5	15,641.4	15,265.4	14,983.6	17,094.7
1,000	13,746.2	13,954.1	14,086.4	13,573.6	15,641.4
2,000	12,812.5	13,734.5	13,322.8	12,812.5	14,455.4
4,000	11,443.3	12,267.1	12,000.0	11,532.5	12,138.7
6,000	10,106.0	10,681.3	10,427.9	9,982.7	11,230.3
8,000	4,195.4	4,437.5	4,568.6	4,075.5	5,443.6
10,000	4,014.9	3,931.5	3,974.1	3,958.7	4,048.7
12,000	2,314.5	2,245.8	2,235.5	1,382.6	2,224.0
14,000	1,341.5	1,278.6	1,155.6	1,323.4	1,410.8
16,000	1,145.3	892.6	906.3	1,111.1	1,026.8
Closure Stress (PSI)	*Cell 3 Run 3 (MD-FT)*	*Cell 3 Run 2 (MD-FT)*	*Cell 3 Run 1 (MD-FT)*	*API Control 1 (MD-FT)*	*API Control 2 (MD-FT)*
500	16525.5	15809.6	15533.5	24774.8	31988.6
1,000	15153.1	14548.9	14360.0	23560.1	30203.8
2,000	13112.1	13236.1	13515.8	20368.9	27894.8
4,000	11743.5	11345.5	11468.1	15994.3	20003.5
6,000	10869.7	10869.7	10579.1	10564.2	10977.2
8,000	5477.4	6111.1	4646.0	7021.3	4119.4
10,000	4034.5	3994.7	4023.7	4520.4	2951.1
12,000	2256.4	2230.6	2235.5	3463.7	1362.3
14,000	1307.1	1288.8	1185.8	2623.3	1209.2
16,000	943.7	951.2	953.5	2477.5	1102.5

7.1 Appendix B:

Summary Blair Guar Inject Test Set (2015)									
Closure Stress (psi)	Conductivity (md-ft)	Standard Deviation	Variance	Max Conductivity (md-ft)	Min Conductivity (md-ft)	T-Test (variance differnces)	T-Test (Root)	T value	Degrees of freedom
500	17,336	1,754	3,076,297	1,883	3,208	1,337,429	1156	3.72	12
1000	15,495	1,516	2,297,338	2,059	1,973	1,069,137	1034	4.17	12
2000	14,082	1,512	2,285,321	2,094	1,706	1,119,920	1058	3.42	12
4000	11,657	2,132	4,547,537	3,250	3,544	1,668,719	1292	3.53	12
6000	8,911	2,004	4,017,986	2,820	2,790	2,079,175	1442	2.78	12
8000	6,796	1,364	1,859,794	1,695	2,674	620,091	787	4.33	12

Summary Blair Vibration Test Set (2015)									
Closure Stress (psi)	Average Conductivity (md-ft)	Standard Deviation	Variance	Max Conductivity	Min Conductivity	T-Test (variance differnces)	T-Test (Root)	T value	Degrees of freedom
500	21,416	1485	2,205,598	2075	2,431	1,173,657	1083	0.20	13
1000	19,248	2112	4,461,845	2902	3,287	1,298,677	1140	0.49	13
2000	16,740	1181	1,394,492	2027	1,973	967,758	984	0.98	13
4000	13,893	1678	2,817,344	2551	2,244	1,371,239	1171	1.98	13
6000	10,784	1340	1,796,188	2083	2,160	1,729,700	1315	1.62	13
8000	8,768	876	767,306	1202	1,419	450,319	671	2.15	13

SIGNATURE PAGE

This is to certify that the thesis prepared by Blake Ammon Ereaux entitled "VIBRATION MODIFICIATION TO A.P.I. FRACTURE SHORT TERM CONDUCTIVITY TESTING PROCEDURE" has been examined and approved for acceptance by the Department of Petroleum Engineering, Montana Tech of The University of Montana, on this 8th day of December, 2017.

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