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# CAN LABORATORY RESULTS FROM NEW METHODS OF MEASURING PROPPANT CONDUCTIVITY BE USED TO BETTER MODEL HYDRAULIC FRACTURES IN RESERVOIR SIMULATION?

Kofi Dabo

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by
Kofi Dabo Junior

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**Abstract**

Proppants are a key part of hydraulic fracturing, a technique in oil production that allows the production of hydrocarbons from low permeability reservoirs. The hydraulic fracturing process intends to create new fractures in the rock as well as increase the size, extent, and connectivity of existing fractures. The American Petroleum Institute (API) developed two testing procedures for measuring conductivity of proppants in a laboratory setting, namely; the Short-Term Proppant Conductivity Testing Procedure (API PR 61, 1989) and Long-Term Proppant Conductivity Testing Method (API PR 19D, 2008). However, testing methods produced inconsistent results, with a significant coefficient of variance of ±80% from one person or lab to the next when the same proppants and procedures are used (Barree et al, 2003).

As such, Montana Tech researchers have developed a number of new proppant conductivity testing methods to lower variance. These new testing procedures from Montana Tech have shown more consistent results with a reduced average variance of ±7.6% and ±14.3% in ceramic and sand proppants respectively. But these testing procedures have only been used to compare one proppant to another under laboratory conditions. This project sought to take a step further with the study by using results of laboratory proppant conductivity measurements at Montana Tech to attempt to better model fractures in reservoir simulation using well data from the Bakken unconventional formations of North Dakota.

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# 1. INTRODUCTION

Proppants are a key part of hydraulic fracturing, a technique in oil production that allows the production of hydrocarbons from low permeability reservoirs. In the hydraulic fracturing process, proppants are carried into the formation via the well in a high-pressure fluid that cracks the rock, forming the fractures. When the carrier fluid is withdrawn, the proppants remain to hold the fracture open. This process is intended to create new fractures in the rock as well as increase the size, extent, and connectivity of existing fractures. Hydraulic fracturing is a well-stimulation technique used commonly in low-permeability rocks like tight sandstone, shale, and some coal beds to increase oil and/or gas flow to a well from petroleum-bearing rock formations. The conductivity of propped fractures is a major component in the productivity of the well.

The American Petroleum Institute (API) developed two testing procedures for measuring conductivity of proppants in a laboratory setting. The first procedure, Short Term Proppant Conductivity Testing Procedure (API RP 61, 1989), was replaced by the Long-Term Proppant Conductivity Testing Method (API RP 19D, 2008). API RP 19D method included changes to help users obtain more consistent results. However, the replacement testing methods still produced inconsistent results, with a coefficient of variance of ±80% from one person or lab to the next when the same proppants and procedures are used. (Barree et al, 2003). Yet, the oil industry considers a standard coefficient of ± 20% variance in proppant conductivity to be desirable.

Montana Tech researchers have developed new proppant conductivity testing methods to lower variance. These new testing procedures from Montana Tech have shown more consistent results with an average variance of ±7.6% and ±14.3% in ceramic and sand proppants respectively. While these testing methods allow operators to compare one proppant to another, only rules of thumb exist currently to relate lab results to actual performance in the field for predicting proppant performance. It is the goal of this research to use results of laboratory proppant conductivity measurements to attempt to better model fractures in reservoir simulation. Therefore, the objective of this project is "Can laboratory results from new methods of measuring proppant conductivity be used to better model hydraulic fractures in reservoir simulation?"

# 2. BACKGROUND LABORATORY RESEARCH AT MONTANA TECH

## 2.1 Proppant types and properties

A proppant is a solid material (typically natural sand, treated sand, or man-made ceramic materials) designed to maintain an induced hydraulic fracture following a fracturing treatment. Proppant materials used in the industry today can be grouped into three main categories: rounded silica sands, resin coated sands, and fused synthetic ceramic materials. The most commonly used proppant materials are sand and ceramic proppants, and these two were the types used by earlier researchers at Montana Tech.

The dry sieve analysis is the standard way to measure the size of mesh and has been documented in the API standard testing procedures (API PR 61, 1989). The mesh size is the number of openings across one linear inch of screen and is usually between 8 and140 mesh (105 µm to 2.38 mm). For example, 16/30 mesh is 595 µm to1190 µm and 20/40 mesh is 420 µm to 841 µm. The size range of the proppant is crucial for hydraulic fracture treatment success. Characteristically, larger particle sizes provide higher fracture conductivity but are more susceptible to crushing. The size and shape of a proppant particle is important as it influences the permeability in the induced fracture. Well stimulation usually begins with smaller particle size proppant, then larger particle size proppant is added later in the process to maximize the near wellbore conductivity. Proppants with 20/40 mesh size were used in obtaining the laboratory results in by previous Montana Tech researchers.

Naturally occurring sand proppants are relatively common and inexpensive when compared to the manufactured ceramic proppants. Frac sand, or naturally occurring sand-type proppant is generally irregular in shape, although this depends on the source. Compared to other types of proppants, sand has low strength and packs together closely in fractures, resulting in a lower permeability when compared to other proppant types. Resin-coated sand is smoother and rounder in shape, and is stronger than traditional frac sand. As a result of this shape and texture, resin-coated sand does not pack as closely together and thus is more permeable than frac sand. However, ceramic proppant is the most uniform-shaped and rounded proppant. It has a high strength which results in high permeability, allowing trapped oil or natural gas to flow easily through the fractures. Figure 1 compares the strength and conductivity of different proppants.

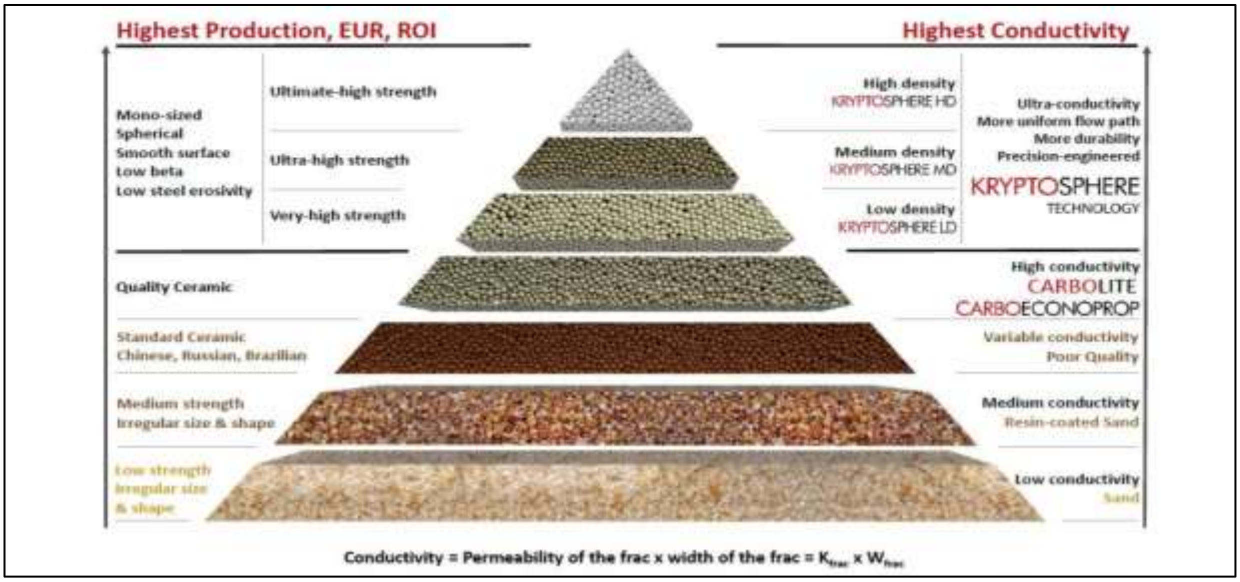


**Figure 1: Strength and Conductivity of Different Proppant Types (Carbo Ceramic, 2011).**

2.2 Proppants used in the Bakken Formation of the Williston Basin

Research to improve hydraulic fracturing techniques focuses on determining effective placement of proppants to provide and maintain fracture conductivity. The Bakken Formation of the Williston Basin is the primary source of production data for this work. Several proppants have been used since production began in the Bakken Formation because the low permeability of the formation makes the Bakken commercially viable only with the application of hydraulic fracturing (Kurz et al, 2013). Sand, ceramic, and resin coated proppant have been used in the hydraulic fracturing in this field. In some areas of production in the Bakken Formation, mixtures of proppants were used to achieve optimal impact: such mixtures included ceramic with resin-coated; as well as resin-coated with sand.

2.3 Conductivity measurement and API methods

Conductivity is the capability to flow reservoir fluids through a porous proppant medium. Conductivity is mathematically expressed as the propped width multiplied by the effective proppant permeability. The mathematical equation in SI units for the calculation of proppant pack permeability as presented in the API RP-19D (2008), can be seen in Equation 1.

$$K = \frac{\mu QL}{100A\Delta P}$$ **Equation 1**

where

K is the proppant pack permeability in Darcy,

μ is the viscosity of the test liquid at room temperature in cp,

Q is the flow rate in $cm^3/s$,

L is the length between pressure ports in cm,

A is the cross-sectional area in $cm^2$,

$\Delta P$ is the pressure drop ($P_{upstream}$ - $P_{downstream}$) in kPa.

The conductivity equation in SI units defined in API RP-19D (2008) is shown in Equation 2 below.

$$C = K * W_f$$ **Equation 2**

where

C is the conductivity,

K is the proppant pack permeability in Darcy,

$W_f$ is the pack thickness in cm.

Thus, propped width is the difference between permeability and conductivity. Proppant conductivity replicates the flow ability of a specific amount of proppant in an API flow-test apparatus. API standards for testing proppant conductivity make no reference to the distribution of proppant, correction for connection to the wellbore and degree of effective reservoir exposure. Fracture conductivity is the total of all components that affect the delivery of reservoir fluids to the wellbore, including (1) proppant conductivity, (2) propped fracture communication with the wellbore, and (3) post fracture conductivity decrease due to proppant changes under closure stress.

Fracture conductivity for a given well must be determined after the frac job is completed. It is assumed that proppant conductivity is affected by proppant and gel damage. Based on this perspective, much research about proppant conductivity actually applies to fracture conductivity, and the information that the production engineer needs dimensionless fracture conductivity (FCD). The formula for FCD shows a high contrast between fracture conductivity and formation permeability. Dimensionless fracture conductivity is expressed in the equation 3 below.

$$FCD = \frac{K_f w}{k * X_f}$$ **Equation 3**

where

$K_f$ w is the fracture conductivity in md-ft,

k is the permeability in Darcy,

$X_f$ is the fracture half-length in ft.

### 2.1.1. Short Term Conductivity Testing (API RP 61)

In October 1989, a subcommittee was constituted for the evaluation of well completion materials under the auspices of the API executive committee on drilling and production practices, and published recommended methods on how to measure short term proppant pack conductivity. Tests, apparatus and methods were developed to recognize the standard procedures and conditions necessary for conducting short term conductivity testing of different proppant materials under acceptable laboratory conditions. The test result is not precise for the prescribed test conditions and as such, scaling these results to predict field performance remains difficult. Below is the recommended procedure for the API RP 61 conductivity experiment:

- 10 $in^2$ flow path;
- Deionized or distilled water is used as the test fluid;
- Ambient temperature (75°F) is recommended;
- Closure stress is applied across the test unit at sufficient time (0.25 hours) to allow proppant sample bed to reach semi steady state condition;
- Test fluid is forced through the proppant bed;
- Proppant pack width, differential pressure and flow rate are measured at each stress;
- Pack permeability and conductivity is calculated;
- Three differential flow rates are tested at each closure stress and an average of the three flow rates is reported;
- No appreciable non-Darcy flow and inertia effects should be encountered with the above conditions in place;
- Closure stress is increased to a new level and sufficient time is allowed for the proppant bed to attain semi-steady-state condition;

- An averaged flow rate is calculated from the three flow rates tested at the new closure stress and used in the determination of pack conductivity of this stress level;
- The procedure is repeated until all desired closure stresses (1,000 to 14, 000) and flow rates have been evaluated.

After experience with API RP 61, the inconsistency in results from the method motivated a desire to create a more accurate method.

2.1.2. Long Term Conductivity Testing (API RP 19D)

In 2008, a consortium of operators, service companies and proppant suppliers commenced further study of proppant conductivity measurement to correct problems in the API RP 61 method as indicated in Table 1.

**Table 1: Recommendation for the API RP 19D**

| API RP 61 | API RP 19D |
|---|---|
| Sandstone platens were used | Replaced with steel platens or steel sheets |
| Deionized water was recommended | Replaced with 2% KCl |
| 0.25 hours was the sufficient time allowed | Recommended time at stress of 50 hours |
| Ambient temperature was okay for the test | Test temperatures of 150 – 250 °F required |

The exploded view of the API fracture conductivity test unit as illustrated below in Figure 2 was prescribed for the experiment.

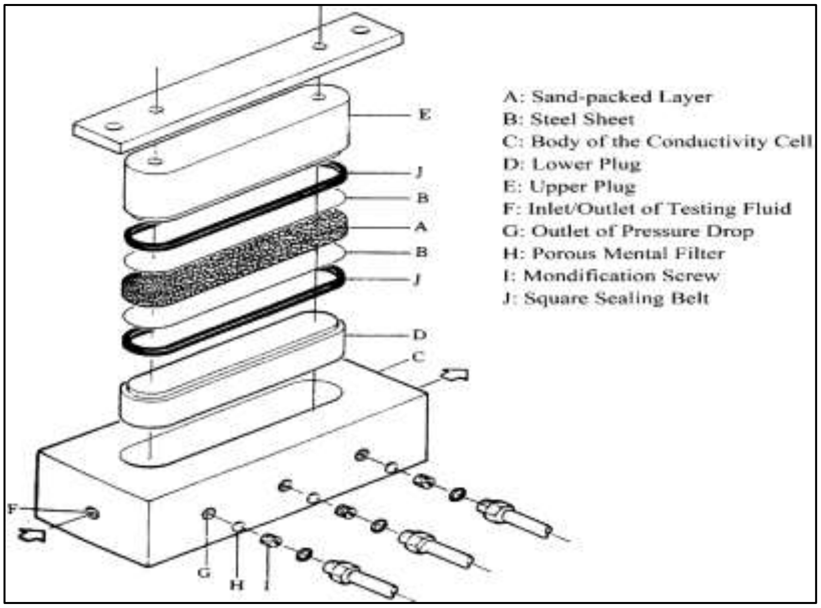


**Figure 2: Exploded view of API fracture conductivity test unit (API RP 19D, 2008)**

The procedure was documented as the long-term conductivity method and in 2006 was accepted and recognized by the International Society for Standardization (ISO) as the standard for measuring long term proppant conductivity.  However, this method, API RP 19D, still produced inconsistent results which led to further expansion of the subject at Montana Tech.

# 3. PREVIOUS MONTANA TECH LABORATORY CONDUCTIVITY RESEARCH

Montana Tech's first researcher in laboratory proppant conductivity measurement investigated cell loading procedures to reduce variation in the laboratory results (Blair, 2015). Two new cell loading techniques - guar injection and cell vibration - were tested to improve upon the cell loading and the entire conductivity measurement. However, the injection of guar solution proved problematic due to the difficulty of completely cleaning the guar from the cell. Hence, the overall permeability of proppant was reduced and resulted in an unfair comparison with the API Standard procedure.

Notably, vibration is not recommended in the API-RP 19D testing procedures due to the possibility of causing segregation of the proppant material. Nevertheless, vibration method was employed in Blair's 2015 study because the Carbolite proppant used had uniform grain size and sphericity, which made room for significant reduction in segregation during vibration. The two vibrational processes investigated were: cell vibrated inside the manufactured clamps, and AS 200 sieve shakers. The idea of using vibration was to create much tighter packs for the initial stresses which experienced very little proppant rearrangement. (Blair, 2015). The average variance produced was +16%. This result was promising and led to further application of vibration in proppant conductivity measurement. Cell vibration produced similar conductivity values to that of the API procedure, but with a considerable reduction in the overall variance as indicated in Figure 3.

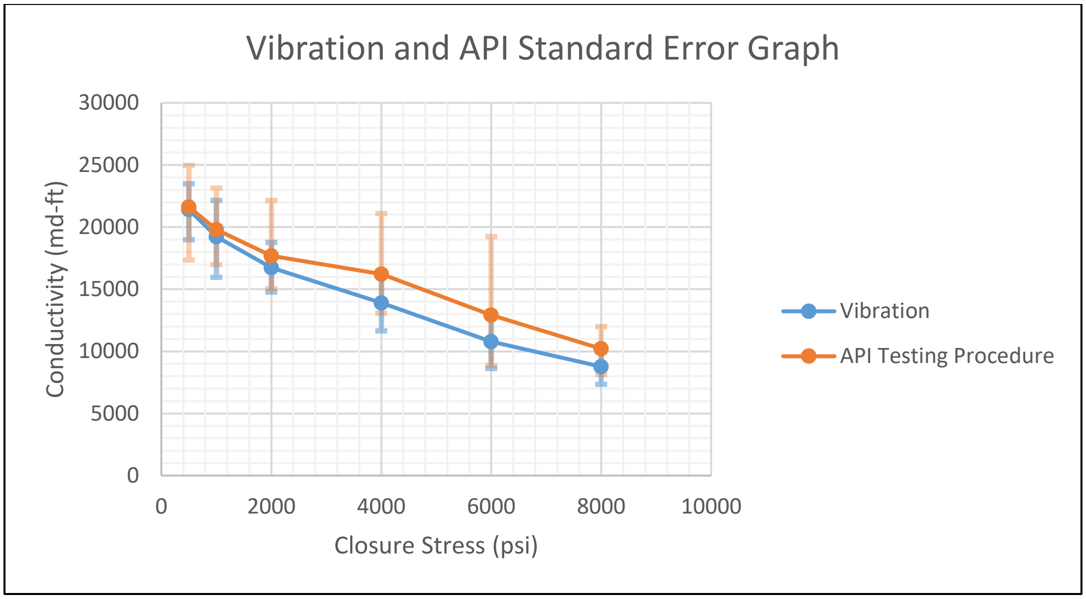


**Figure 3: Vibration and API Testing Procedure Conductivity Error Graph (Blair, 2015, pg 47)**

The promising result obtained using vibration in laboratory conductivity measurement motivated the extension of the research. Ereaux (2017) extended the work with the objective of improving the repeatability of test results. The application of vibrational energy to the proppant pack before testing was believed to restructure the grains into a more compact arrangement which eventually reduces variation. Vibration Test Machine (VTM) and Sonochemical Reaction Vessel (SRV) were the two methods of applying vibrational energy to the proppant loaded cell with variable powers and times. The results for the Vibration Test Machine procedure were promising: however, the inability to continually apply a constant amplitude led to inconsistent results, hence VTM was not considered for further investigation. However, the application of the Sonochemical Reaction Vessel vibrational energy for the API RP–61 improved the variance of conductivity results from 70% to 90% when compared to Blair's results, and 50% to 70% when compared to the standard API results ranging at each of the varying closure stresses precisely at the initial stresses (Ereaux, 2017).

Therefore, the modified procedure using the Sonochemical Reaction Vessel outperformed Blair's API procedure as well as the control API trials in terms of lower initial conductivity values. This was an indication of the 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 was 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 improved the overall process. These reductions in the variations of the conductivity test result meet the standard conductivity variations of ± 20% (Barree, et al., 2003) as indicated in Figure 4, though it promised potential for better and more repeatable results when investigated further.

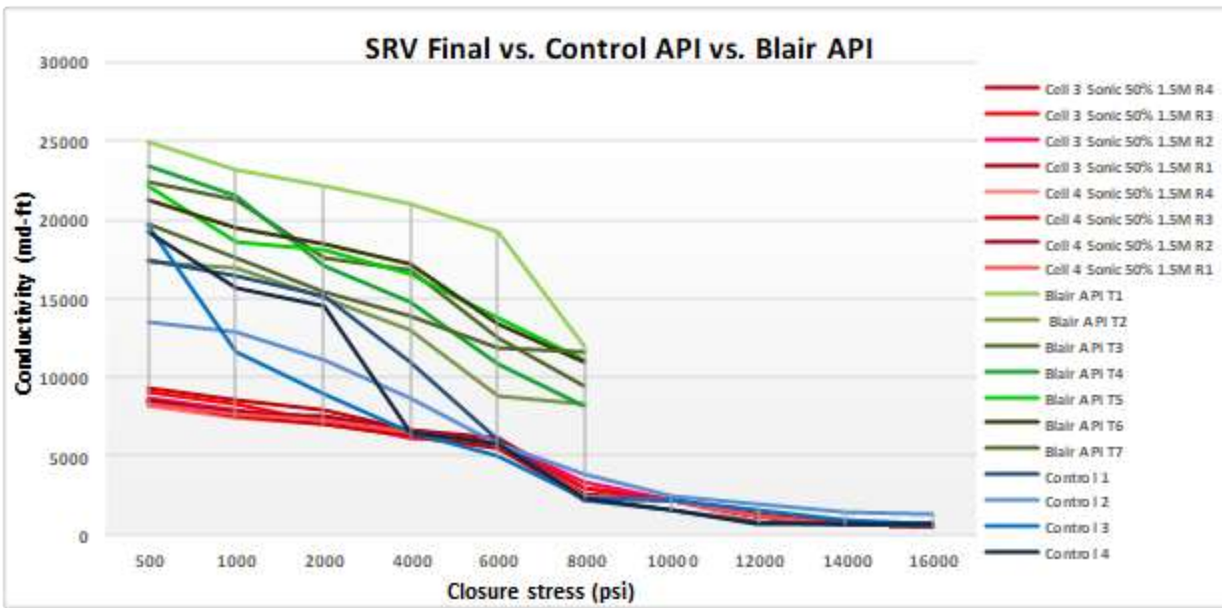


**Figure 4: Comparison of Ereaux's SRV Results with Control API and Blair's Result's (Ereaux, 2017)**

3.1 Final Methods Developed at Montana Tech

The most recent laboratory conductivity methods began with the extension of vibration methods. Prior to diving deeper into the application of vibrational energy in the study, some naming conventions were made for some of the existing methods and the new methods to be developed (Richard, 2020). The two short term and non-vibrational methods developed were the Hybrid API Method I and the Hybrid API Method II. Table 2 shows and compares details of the Hybrid API Methods with API RP 61 and API RP 19D.

**Table 2: Comparison of Hybrid API Methods and API RP 61 and API RP 19D**

| CHARACTERISTIC | API RP 61 | API RP 19 D | HYBRID API METHOD I | HYBRID API METHOD II |
|---|---|---|---|---|
| Test fluid | Deionized water | 2% KCl Solution | 2% KCl Solution | 2% KCl Solution |
| Temperature (°F) | 75 | 150-250 | 150-250 | 150-250 |
| Platens | Sandstone Core | Stainless steel | Stainless steel | Stainless steel |
| Time at stress (hours) | 0.25 | 50 | 0.25 | 1 |
| Load rate (psi/min) | 500 | 100 | 500 | 100 |

Subsequently, vibrational energy and processes were investigated to assess the possibility of obtaining consistent and improved conductivity test results. The proppant loaded in the conductivity cell was vibrated prior to testing in the conductivity testing system. Two vibration methods were developed, namely; Vibration Process A and Vibration Process B. Vibration Process A was developed previously by Ereaux (2017). Some modifications were made to the Vibration Process A by Richard (2020) to create Vibration Process B.

### 3.1.1. Combined testing procedures

The combination of vibrational processes (Process A and Process B) and Hybrid API Methods (I and II) reduce variance by improving the pack structure through vibration prior to conductivity measurement. Three new methods, namely; Sonic Method 1, Sonic Method 2, and Sonic Method 3 were developed from the combination of earlier methods to improve conductivity test results.

### 3.1.2. Sonic method 1

Sonic Method 1 is the combination of Hybrid API Method I and Vibrational Process A. This method was developed by Ereaux (2017) and eight (8) experimental trials were conducted with ceramic proppants. The results proved promising with the attainment of an average variance of 6.5%. This outcome set a new direction for the entire study by seeking to improve the vibrational process. Richard's work (2020) began with an attempt to replicate Sonic Method 1, and four ceramic proppant trials were conducted. From the results obtained, it was clear that there was significant agreement between Ereaux and Richard's results.

However, Richard acknowledged that the results are distinctly grouped, representing some human influence in the Sonic Method 1 procedure. Therefore, Vibration Process B was suggested as a potential for reducing the human influence. This result was the motivation for the development of Vibration Process B, which subsequently led to the development of Sonic Method 2.

3.1.3. Sonic method 2

Sonic Method 2 was developed as a procedural revision by Richard (2020) to correct and improve the variance shown in Sonic Method 1. The process consists of the combination of Hybrid API Method I with Vibrational Process B. With this new method, twelve runs were conducted using ceramic proppant out of which only seven were considered valid due to some mechanical challenges. The seven Sonic Method 2 trials produced consistent results shown in Figure 5.

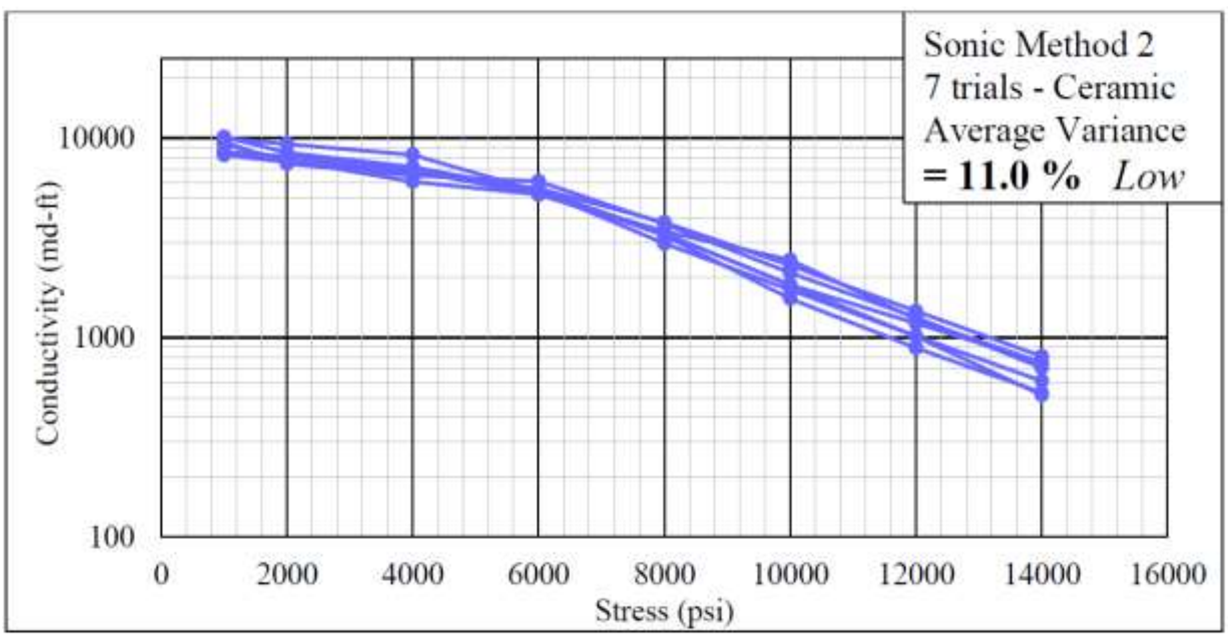


**Figure 5: Sonic Method 2 results (Richard, 2020)**

Sonic Method 2 produced average variance of ±11% signifying a marked improvement over both ±24.5% produced by Hybrid API Method I and the ±44% recorded from the Hybrid API

Method I Composite data set (Richard, 2020). The results obtained demonstrate the potential of vibration to improve the consistency of conductivity results.

### 3.1.4. Sonic method 3

Sonic Method 3 was the final procedure developed and is a combination of Hybrid API Method II and Vibration Process B. In experimenting with this newest method, twelve loaded proppant cells were tested by Richard (2020) with six trials using ceramic proppant and the other six using sand proppant. This method also utilized independent pourers (adding the proppant to the cell) to evaluate the extent of human influence on cell loading. Twelve tests were conducted using independent pourers for ceramic and sand proppants. The results are presented below in Figures 6 and 7 respectively.

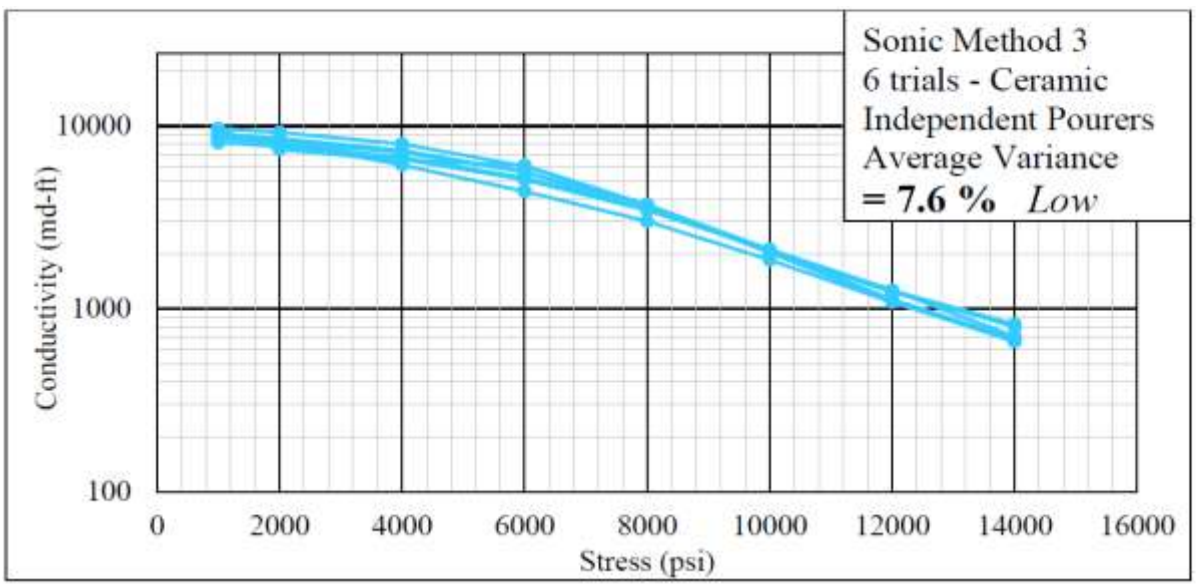


**Figure 6: Sonic method 3 results for ceramic proppant**

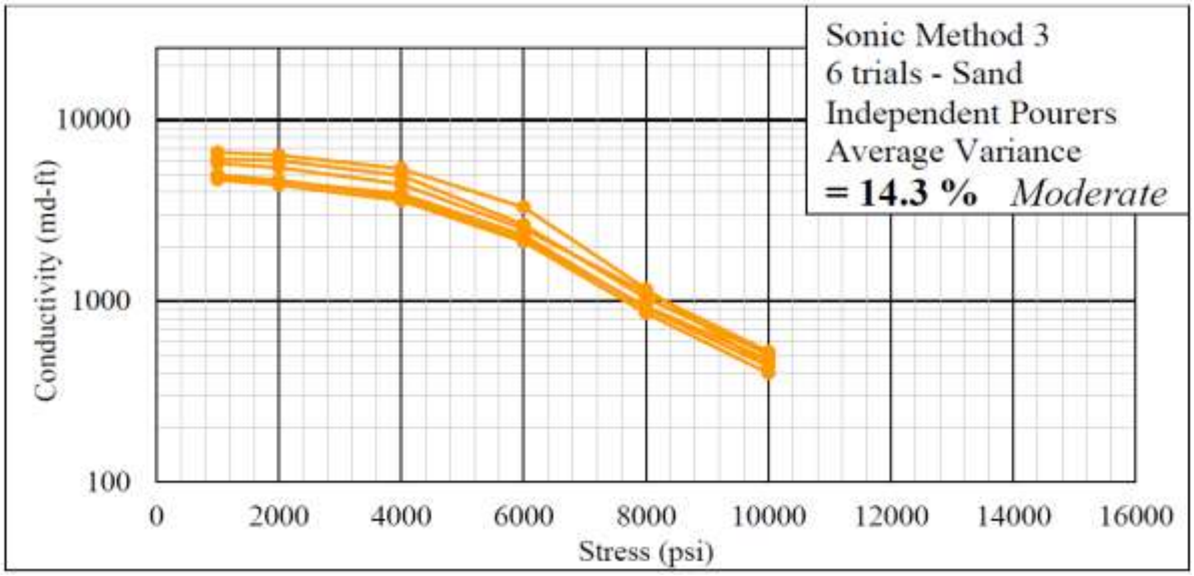


**Figure 7: Sonic method 3 results for sand proppant**

The results indicated an improved consistency of conductivity results for ceramic and sand proppant, with an average variance improvement from 9.1% to 7.6% and 19.9% to 14.3% for ceramic and sand proppant respectively. Error as a result of human influence on the cell loading procedure or packing structure were assessed, and it was concluded that human influence was absent in the cell loading process.

3.2 Factors affecting proppant procedures

In summary, there are major factors to be considered during general laboratory conductivity measurements such as: closure stress, proppant particle size, distribution, shape, concentration, strength, and time for stress application. The downhole wellbore environment has significant differences from the lab environment. The propped fracture is subject to damage and its conductivity may be degraded by several in-situ factors. These factors include proppant filling reduction, fracture width reduction, porosity reduction and flowing reduction (Zhou et al, 2011). Therefore, the lab results may not directly translate to the field applications, and experience suggests it might overestimate proppant conductivity.

# 4. METHODOLOGY

## 4.1 Overview

The main purpose of the research was to use the laboratory conductivity data to better model fractures using real Bakken well data. This project focused on reservoir simulation models for a fractured well using Bakken data from literature (Table 3) and a well database (www.drillinginfo.com) focusing on two wells where the proppant used matched the ceramic and sand proppant used in the Montana Tech laboratory. The laboratory conductivity obtained using the Sonic 3 method was used as described below.

Simulation Models

1. Unfractured model: This model used the values listed in Table 3 and the parameters in Table 4, but contained a well completed without hydraulic fractures.

2. Laboratory Ceramic model: This model is the same as the unfractured model and also has a hydraulic fracture on the well designed using the laboratory data for ceramic proppants.

3. Laboratory Sand model: This model is the same as the unfractured model with the addition of a hydraulic fracture on the well designed using the laboratory data for sand proppants.

4. High Permeability model: This model shares the same parameters as the other three, but in this case the fractures were designed with a high permeability of 10,000 md.

**Table 3: Middle Bakken Formation Parameters and Their Sources**

| PARAMETERS | VALUE | UNIT | SOURCE |
|---|---|---|---|
| Thickness | 40 | ft | Cipolla et al, 2018 |
| Porosity | 0.01 | | Ramakrishna, 2010 |
| API Gravity | 41.5 | | Hawthorne et al, 2017 |
| Gas specific gravity | 0.9 | | Geri et al, 2019 |
| Permeability | 0.005 | md | Pitman et al, 2001 |
| GOC | 1,200 | scf/bbl | Cipolla et al, 2018 |
| GOR | 12,000 | scf/bbl | Lorwongngam et al, 2019 |
| Temperature | 100 | degree celsius | Janet et al.2001 |
| Average Fracture Length | 685 | ft | Tran et al, 2011 |
| Well depth | 20,000 | ft | Lorwongngam et al, 2019 |
| Lateral Length | 10,000 | ft | Lorwongngam et al, 2019 |
| Oil Compressibility | 10*10^-6 | 1/psi | Tran et al, 2011 |
| Water Compressibility | 3*10^-6 | 1/psi | Tran et al, 2011 |
| Formation Compressibility | 3*10^-6 | 1/psi | Tran et al, 2011 |
| Boi | 1.377 | rbl/stb | Tran et al, 2011 |
| Initial Oil Viscosity | 0.593 | cp | Tran et al, 2011 |
| Total Compressibility | 11.8*10^-6 | 1/psi | Tran et al, 2011 |
| Bubble Point Pressure | 3,500 | psi | Cipolla et al, 2018 |
| Mini Pressure | 2,500 | psi | Cipolla et al, 2018 |
| Max Pressure | 6,500 | psi | Cipolla et al, 2018 |

**Table 4: Parameters Used in Building the Models**

| PARAMETERS | VALUE | FIELD UNIT |
|---|---|---|
| Top limit for subsea elevation | 8,000 | ft |
| Base limit for subsea elevation | 8,040 | ft |
| Length of model in X-direction (Xmax) | 10,720 | ft |
| Length of model in Y-direction (Ymax) | 1,360 | ft |
| Height of grid block | 4 | ft |
| Layers | 10 | |
| Surface elevation | 2,000 | ft |

The development strategy selected for the models was 500 psi for the bottom whole pressure (well pressure production control). The wells were cased and completed with a simple completion, and used production dates of November 2, 2011 to October 1, 2013.

4.1.1. Applying Sonic 3 Data to the Simulation Models

In building the fracture models, a closure stress value of 6,500 psi was used as it represents the average closure stress for the formation of interest (Schmidt et al, 2011). As such, an interpolation was done between the nearest SRV Method 3 laboratory closure stresses, 6,000 and 8,000 psi for sand and ceramic as can be seen in Tables 5 and 6 below.

**Table 5: Conductivity values for ceramic proppant using sonic method 3 (Richard, 2020)**

| Closure stress (psi) | Average Conductivity (md-ft) | | Absolute Difference (md-ft) | Percent Difference (%) |
|---|---|---|---|---|
| | Long-term | Sonic Method 3 | | |
| 1000 | 9888 | 8863 | 1026 | 10.4 |
| 2000 | 9032 | 8342 | 690 | 7.6 |
| 4000 | 7514 | 6993 | 521 | 6.9 |
| 6000 | 5186 | 5321 | 135 | 2.6 |
| 8000 | 2953 | 3518 | 565 | 19.1 |
| 10000 | 1736 | 2036 | 300 | 17.3 |
| 12000 | 1049 | 1177 | 129 | 12.3 |
| 14000 | 659 | 742 | 82 | 12.5 |
| Average | - | - | - | 11.1 ± 5.5 |

**Table 6: Conductivity values for ceramic proppant using sonic method 3 (Richard, 2020)**

| Closure stress (psi) | Average Conductivity (md-ft) | | Absolute Difference (md-ft) | Percent Difference (%) |
|---|---|---|---|---|
| | Long-term | Sonic Method 3 | | |
| 1000 | 6468 | 5487 | 981 | 15.2 |
| 2000 | 5857 | 5236 | 621 | 10.6 |
| 4000 | 3532 | 4325 | 793 | 22.5 |
| 6000 | 1306 | 2510 | 1205 | 92.3 |
| 8000 | 549 | 1004 | 455 | 82.8 |
| 10000 | 276 | 464 | 188 | 68.1 |
| Average | - | - | - | 48.6 ± 36.6 |

The conductivity values corresponding with 6,500 psi closure stress obtained for sand and ceramic were 2,133.5md-ft and 4,870.3 md-ft respectively. From the laboratory data, the average frac width and its corresponding pack permeabilities (from equation 4) were 0.017ft (0.205in) and 125 $*10^3$md for sand, and 0.018ft (0.212in) and 276 $*10^3$md for ceramic proppant.

$$K_{lab} = \frac{c}{w_f}$$ **Equation 4**

Where

$K_{lab}$ is the laboratory proppant pack permeability in Darcy

*c* is the proppant conductivity, md-ft

$w_f$ is the laboratory width or thickness of the conductivity cell in ft.

Equation 5 is used to scale the laboratory permeabilities of the sand and ceramic proppants to that of the models in the simulator.

$$W_{flab} * K_{lab} = W_{fmodel} * K_{fmodel}$$ **Equation 5**

This yielded 53.3 md and 121.8 md as the model permeabilities of sand and ceramic proppants respectively.

In building the fracture models, 40 fractures were built for both sand and ceramic models. The fractures were built with a length of 685ft, fracture height of 40ft and orientation of 90 degrees to suit the dimensions of the model. Each fracture was built with their corresponding permeability and width, 53.3md and 0.017ft for sand model and 121.8md and 0.018ft for ceramic model respectively. Figure 9 below shows a fractured well showing all the 40 fractures.

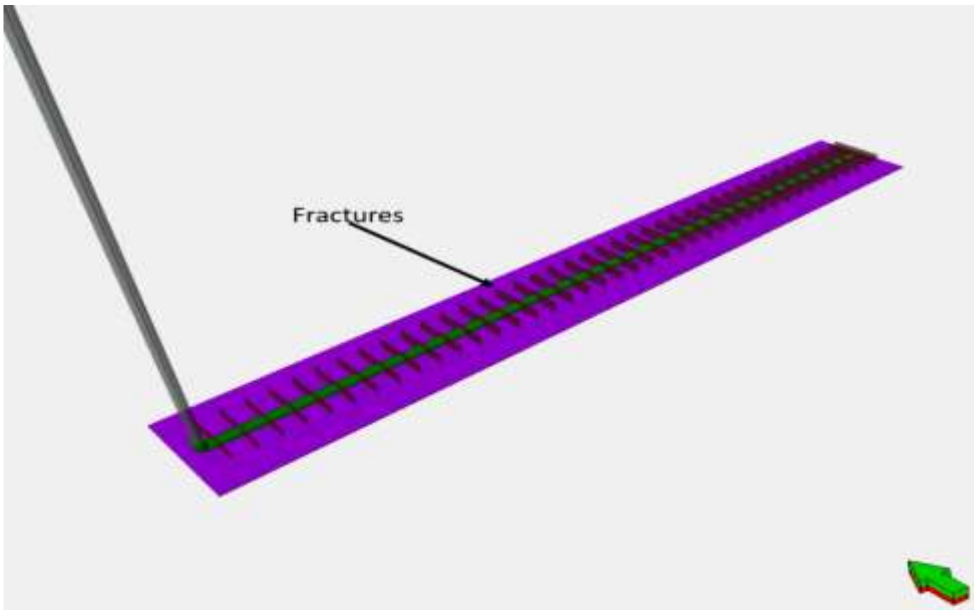


**Figure 8: Ceramic fractured well showing all the 40 fractures**

# 5. RESULTS AND ANALYSIS

## Laboratory Ceramic Model Result

Figure 9 shows the cumulative oil production of three simulation models (unfractured, laboratory ceramic and high permeability fracture) and includes the measured cumulative production from the Bakken well fractured with ceramic proppant.

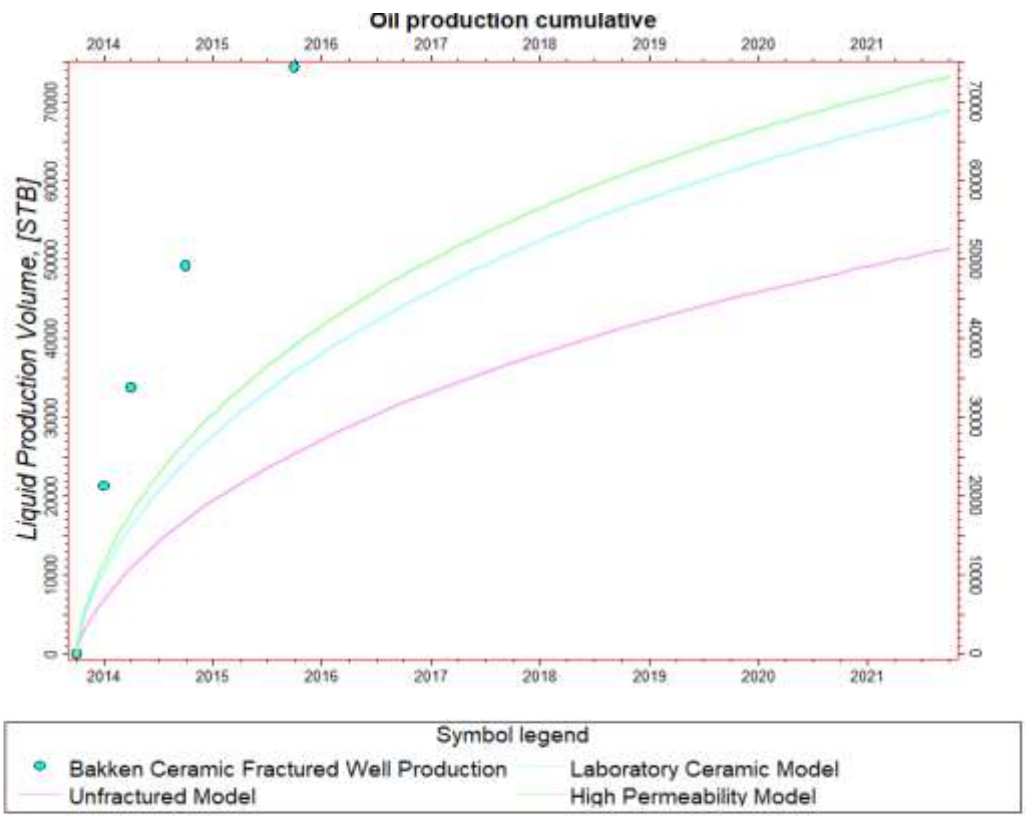


**Figure 9: Comparison of production data with Lab Ceramic Model, Unfractured Model and High Permeability Model**

The three simulation models all fell short of matching the actual production. As expected, the unfractured model recorded a much lower production, and the introduction of fractures brings the simulation results closer. However, the high permeability model out-performed the model using the laboratory data.

5.1 Results of Laboratory Sand Model

The results of the comparison of the cumulative production from the sand fractured well to the unfractured, Laboratory sand and High Permeability models as presented in Figure 10 shows a similar trend, but there also is an unusual high production for this well that may make it a poor choice to model. This is an unusual well deep for a sand fractured well, and with a short lateral length. The depth and lateral length of this sand well was about 14,000ft deep and 4,000ft respectively.

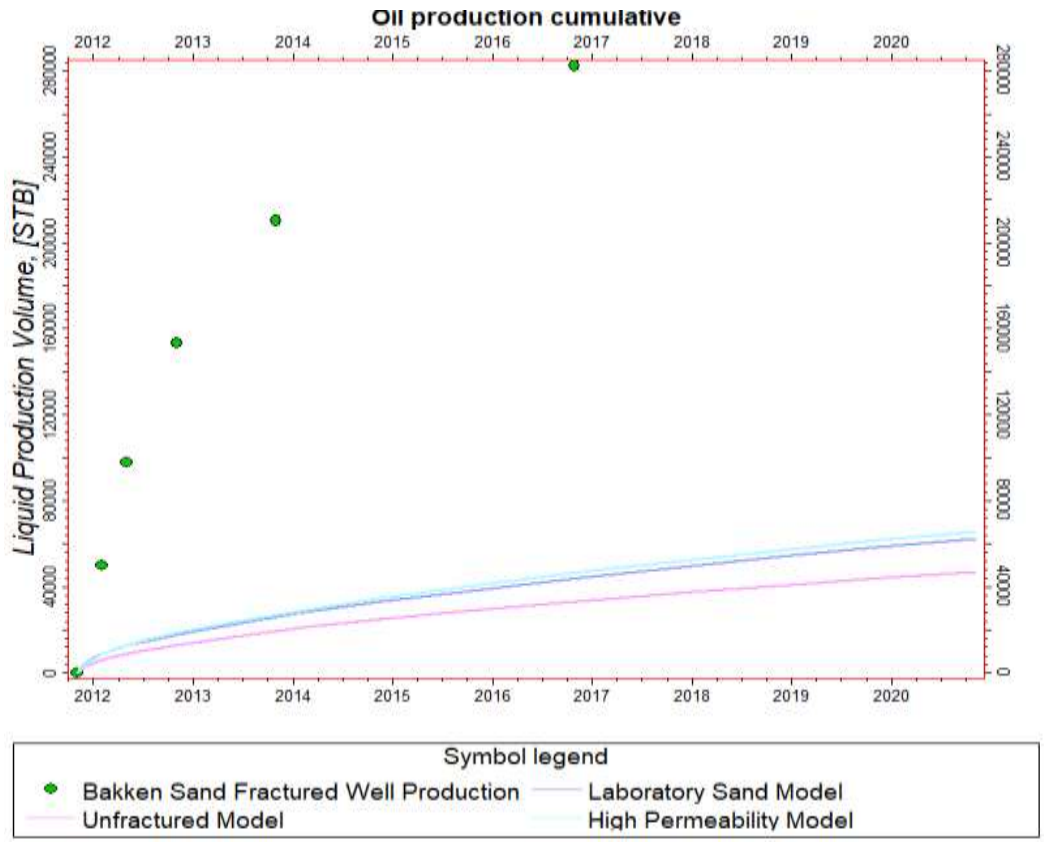


**Figure 10: Comparison of production data with Lab Sand Model, Unfractured Model and High Permeability Model**

For these reservoir and wellbore characteristics, the high permeability model recorded an incremental recovery increase of 42% over the unfractured model.  Similarly, the laboratory sand and ceramic models had an incremental recovery increase of 12.9% and 33% respectively over the unfractured model.

Subsequently, the dimensionless fracture conductivity for the models was estimated (using equation 3). The laboratory sand model had the lowest the dimensionless fracture conductivity, followed by the laboratory ceramic model. The model with the highest dimensionless fracture conductivity was the high permeability model. From the approximation, the dimensionless fracture conductivity for the laboratory sand, laboratory ceramic and high permeability models were 1,246, 2,844 and 233,577 accordingly.

# 6. CONCERNS, CONCLUSION AND RECOMMENDATIONS

## 6.1 Concerns

1. Is the simulation software sensitive enough to show a significant difference based only on a change in fracture permeability?
2. How do we ensure a good model to begin with, as history matching an unconventional reservoir has challenges?

## 6.2 Conclusions

1. This work did not show an improvement in modeling fractures by using the lab data.
2. Literature suggests that laboratory data in general overestimates the field performance of propped fracture (Zhou et al, 2011). However, the simulation results suggest that the literature values of formation permeability of 0.005 md and porosity of 0.01 were low compared to the actual values around the wells of interest.
3. The models built using the laboratory data underestimated production more than the high permeability models. If the goal was to match the production data, an even higher fracture permeability could be used.

## 6.3 Recommendation

1. A better technique in Petrel such as using a tartan grid is encouraged to better assess the performance of each of the fractures.

2. More well data (minimum of ten) with associated measured porosity and permeability data is suggested for future works.

# 7. REFERENCES

API RP19D, Recommended Practice for Measuring the Long-term Conductivity of Proppants, First Edition (ISO 13503-5: 2006, Identical). 2008. Washington, DC: API.

API RP61, Recommended Practice for Evaluating Short Term Proppant Pack Conductivity.1989. Washington, DC: API.

Barree, R. D., Cox, S. A., Barree, V. L., & Conway, M. W. (2003, January 1). Realistic Assessment of Proppant Pack Conductivity for Material Selection. Society of Petroleum Engineers. doi:10.2118/84306-MS

Blair, K. 2015. Modifying Fracture Conductivity Testing Procedures. Thesis, Montana Tech of the University of Montana, Butte, MT (December 2, 2015).

Cipolla, Craig, Motiee, Monet, and Aicha Kechemir. "Integrating Microseismic, Geomechanics, Hydraulic Fracture Modeling, and Reservoir Simulation to Characterize Parent Well Depletion and Infill Well Performance in the Bakken." Paper presented at the SPE/AAPG/SEG Unconventional Resources Technology Conference, Houston, Texas, USA, July 2018. doi: https://doi.org/10.15530/URTEC-2018-2899721

Ereaux, B. 2017. Vibration Modification to A.P.I. Fracture Short Term Conductivity Testing Procedure. Thesis, Montana Tech of the University of Montana, Butte, MT (December 8, 2017).

Geri, Mohammed Ba, Ellafi, Abdulaziz, Ofori, Bruce, Flori, Ralph, and Huosameddin Sherif. "Successful Implementation of High Viscosity Friction Reducers from Laboratory to Field Scale: Middle Bakken Case Study." Paper presented at the SPE/AAPG/SEG Unconventional Resources Technology Conference, Denver, Colorado, USA, July 2019. doi: https://doi.org/10.15530/urtec-2019-447

International Organization for Standardization, "Procedures for measuring the long-term conductivity of proppants," ISO 13503-5, July, 2006.

Lorwongngam, Apiwat Ohm, Cipolla, Craig, Gradl, Christian, Gil Cidoncha, Jose, and Bruce Davis. "Multidisciplinary Data Gathering to Characterize Hydraulic Fracture Performance and Evaluate Well Spacing in the Bakken." Paper presented at the SPE Hydraulic Fracturing Technology Conference and Exhibition, The Woodlands, Texas, USA, February 2019. doi: https://doi.org/10.2118/194321-MS

Merkel, Richard, McChesney, Jeromy, and Kenneth Tompkins. "Calculated Determination of Variable Wettability in the Middle Bakken and Three Forks, Williston Basin, USA." Paper presented at the SPWLA 59th Annual Logging Symposium, London, UK, June 2018.

Pitman, J. K., Price, L. C., and LeFever, J. A., 2001, Diagenesis and fracture development in the Bakken Formation, Williston Basin: Implications for reservoir quality in the middle member: U.S. Geological Survey Professional Paper, v. 1653, p. 1-19.

Ramakrishna, S., Balliet, R., Miller, D., et al. 2010. Formation Evaluation in the Bakken Complex Using Laboratory Core Data and Advanced Logging Technologies. Paper SPWLA 2010-74900 presented at the SPWLA 51st Annual Logging Symposium, Perth, Australia, 19–23 June.

Richard, S. 2020. Improved Methods of Measuring Short-Term Proppant Conductivity. Thesis, Montana Tech of the University of Montana, Butte, MT (April 8, 2020).

Tran, Tan, Sinurat, Pahala, and R. A Wattenbarger. "Production Characteristics of the Bakken Shale Oil." Paper presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA, October 2011. doi: https://doi.org/10.2118/145684-MS

Wang, D., Dawson, M., Butler, R., Li, H., Zhang, J., and Olatunji K., " Optimizing Water Chemistry to Improve Oil Recovery from the Middle Bakken Formation." Paper presented at the SPE Improved Oil Recovery Conference, Tulsa, Oklahoma, USA, April 2016. doi: https://doi.org/10.2118/179541-MS

Zhou, Desheng, Zhang, Gang, Ruan, Min, He, Anwu, and Dengfeng Wei. "Comparison of Fracture Conductivities from Field and Lab." Paper presented at the International Petroleum Technology Conference, Bangkok, Thailand, November 2011. doi: https://doi.org/10.2523/IPTC-14706-MS