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ANALYSIS OF REFRACTURING ACTIVITIES IN THE MAJOR SHALE PLAYS IN THE UNITED STATES

by

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This thesis consists of the following two articles, formatted in the style used by Missouri University of Science and Technology.

Paper I, found on pages 11-42, have been submitted for publication to the *Society of Petroleum Engineering.*

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ABSTRACT

Refracturing of existing horizontal multistage wells has increased over the past decade in the oil industry. This work aims to investigate all the refracturing operations in the most active shale plays in the united states (Bakken, Niobrara, Marcellus, Permian, Eagle Ford, Barnett, and Haynesville) in terms of completion technique, candidate selection, treatment types, and refracturing production efficiency. To collect the data of the refractured wells, an advanced data analytics approach was applied to separate the refractured wells from 170,000 wells reported in FracFocus, a public chemical registry for hydraulic fracturing in the United States, and combine it with DrillingInfo database, a database of oil and gas production in the United States.

More than 1200 refractured wells (2008-2020) were identified for study across the major shale plays in the United States. Trends in completions and production of these refractured wells were identified, for example, the most common type of treatment fluid used in refractured wells was hybrid fluids. In addition, an extensive literature review was conducted to identify criteria for refract candidate selection.

Using perforated length as a proxy for stage data, 39 wells of the 1200 refractured wells production were found to be sufficiently similar to be grouped for production comparisons. This analysis, coupled with individual well plots of full production histories, demonstrate that while refracturing can restore production rates significantly, the production of the refractured well commonly declines rapidly.

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TABLE OF CONTENTS

PAPER

SECTION

LIST OF ILLUSTRATIONS

SECTION Page

PAPER I

PAPER II

LIST OF TABLES

PAPER I Page

PAPER II

1. INTRODUCTION

Refracturing of existing horizontal wells has increased over the past decade. The oil price drop in 2011 prompted industry to focus on refracturing instead of drilling new wells as a means of cost reduction (Jacobs, 2015). For example, in the Eagle Ford shale play, when comparing the cost of refracturing a producing well with the cost of drilling a new one, it was found that refracturing cost was estimated to be half the cost of drilling and fracturing a new well (Fu et al., 2017). Another reason for the expansion of refracturing was the size of the produced unconventional reserves (King, 2014) and the belief that low recovery rates resulted from completions methods that left undrained portions of the play. From economic perspective, refracturing should be an economically attractive approach to produce hydrocarbons or drain untapped reserves in shale plays

Figure 1.1 illustrates a refracturing operation on a horizontal well. On the left side of this figure, the initial completion has perforation clusters with large spacing in-between them. Refracturing, shown on the right side of the figure, seeks to place new fracture clusters between the initial ones to access those undrained portions of the reservoir due to the initial completion methods. Refracturing may also extend the initial fractures as shown. The initiation, extension and orientation of the created fractures depends on stress distributions in the reservoir at the time of refracturing. Stress distribution is determined by many factors, including the type of initial completion (e.g. distance between stages), distance between wells, and pressure depletion and stress changes that have occurred in existing fractures due to production.

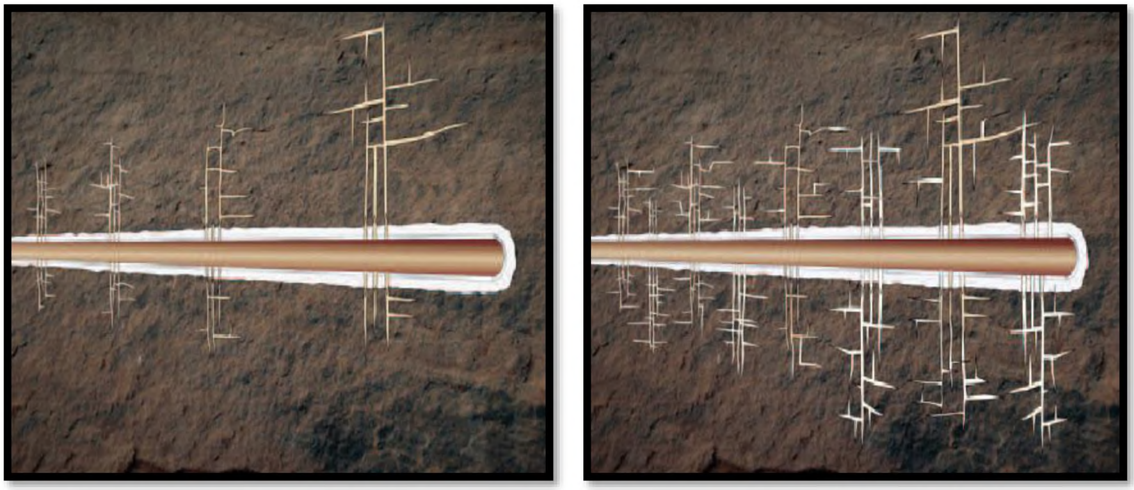

Figure 1.1. (left) A hydraulic fracturing operation created fractures (right) a refracturing operation an additional complex fracture network and new fractures (Alison & Parker, 2014)

Redistribution of stresses around fractures occurs due to opening of propped fractures (mechanical effects) and production or injection of fluids in the reservoir (poroelastic effects), (Roussel and Sharma, 2012). In a horizontal multistage fractured well, propagation of the new fracture in the formation is dependent on the stresses and pressure distribution around the producing fracture, and the cluster spacing between the fracture stages. Roussel and Sharma (2012) also demonstrate how refracture orientation depends on stress reorientation around the producing well. Stress redistribution is described in more detail in the first paper of this thesis. Figure 1.2 provides an illustration of flow induced stress reversal and refracture direction. In general, refractures tend to orient themselves normal to the existing, initial fractures.

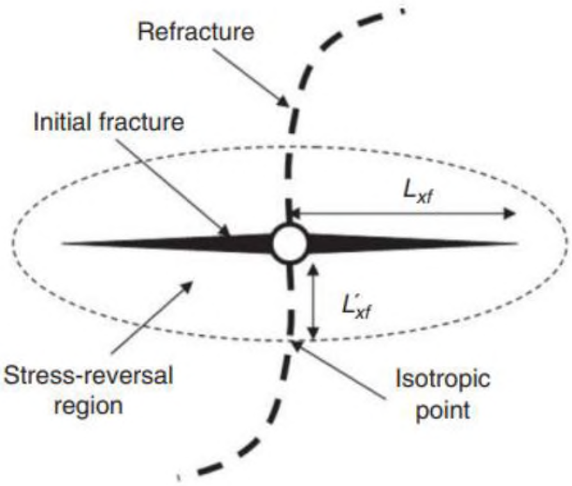

Figure 1.2. Flow induced stress reversal and refracture direction (Roussel and Sharma, 2012).

An important factor to consider before initiating a refracturing operation is the stage separation between the original fractures. When the cluster spaces of the original fractures (between the perforated intervals_ is relatively large (larger than 500 ft/stages) the probability of restimulating the untapped zones of the reservoir rock is higher. Therefore, wells with large cluster spaces are good candidates for refracturing operations (French et al. 2014; Hunter et al. 2015). The selection of refracture candidate based on stage separation is discussed in more detail in the first paper of this thesis, along with other factors of considerations for refracturing candidates Since production and pressure depletion affect stress redistribution, another factor to consider before refracturing is choosing the optimum time for the operation to be conducted. Based on research in the Barnett shale play, it has been shown that refracturing is generally more successful if wells are refractured in an early stage of production. The study showed a production gain of 2 to 4 times of initial production from the refractured wells with this approach (Wang et al., 2013).

Figure 1.3 depicts two styles of completion delivery systems for multistage fracturing in horizontal wells. On the left is an openhole sleeve type completion system, which allows multiple stages of fracturing to occur in an uncased and uncemented horizontal well. On the right is a plug-n-perf (PNP) type completion where the horizontal portion of the reservoir is cased and cemented. Multiple stages of fracturing are created by pumping down a wireline perforating gun to create several perforation clusters, and these clusters are stimulated with a single hydraulic fracturing treatment. Each stage is isolated with frac plugs until all zones are completed. At that time, the frac plug are either dissolved or drilled out and the well is placed on production. Today, most completions are PNP.

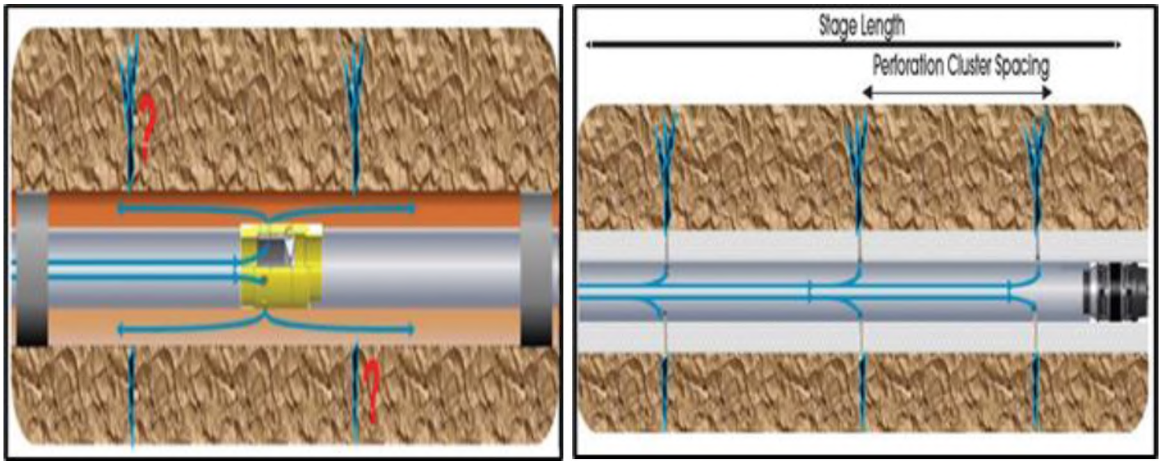

Figure 1.3. (left) Openhole sliding sleeve completion design (right) PNP design (Walzel, 2019)

While the technology of refracturing producing wells has been applied historically, it's application in refracturing multistage horizontals wells is relatively new (Dutta, 2017) and presents unique operational challenges. In a PNP completion it is recommended to use at least a gel or temporary diverter to plug the initial fractures for a period of two to four weeks (Cookson, 2020), so that new fractures can be formed. However, the use of temporary diverters as a completion technique for refracturing operations leads to a high level of uncertainty in determining the creation and direction of new fractures in the formation. As a result, some researches recommend using mechanical isolation methods, for example running an inner casing or liner. Mechanical isolation methods provide a higher level of confidence in creating new fractures, which may provide a more successful refracturing response. For example, expandable liners have been used to complete more than 15 wells in different shale plays and it showed higher productivity gain compared to the use of diverting agent technique (Jacobs, 2015).

In the first paper of this thesis, an extensive literature review was conducted of more than 80 papers about refracturing activities across the major shale plays in the united states (Bakken, Permian, Haynesville, Marcellus, Barnett, Eagle Ford, and Niobrara play) with an objective of extracting key parameters of refracturing candidate selection. Data from FracFocus and DrillingInfo wells databases were cleaned, analyzed and merged to identify 1200 refractures wells in the major shale plays between 2008 and 2020. The first paper details findings of this work.

The main objective of the second paper in this thesis is to compare the production performance of the refractured wells identified in the first paper. Using perforated length as a proxy for stage data, 39 wells of the 1200 refractured wells production were found to be sufficiently similar to be grouped for production comparisons. Table 1 in the second paper summarizes the selection criteria used to select the sample wells for the study. The short-term production comparisons, coupled with individual well plots of full production histories, demonstrate that while refracturing can restore production rates significantly, the production of the refractured well commonly declines rapidly.

2. OBJECTIVES OF THE STUDY

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2.1. MAIN OBJECTIVE

The aim of this work is to use data analytics approach to examine refracturing activities in the major shale plays in the United States.

2.2. SECONDARY OBJECTIVES

- Review refracturing literature for the most active shale plays in the United State to identify activities in the most active shale plays in the United States.
- Identify refracturing candidate selection.
- Create a comprehensive database for refractured wells combining FracFocus and Enverus DrillingInfo databases.
- Give insights into the current trend of refracturing activities in the most active shale plays in the United States in terms of treatment type.
- Compare the production response of refracturing in the most active shale plays across the United States (Bakken, Niobrara, Marcellus, Permian, Eagle Ford, Barnett, and Haynesville).

3. RESEARCH METHODOLOGY

3.1. SEPARATION OF REFRACTURED WELLS FROM FRACFOCUS

The first main objective of the study was to extract useful from FracFocus Database to create a detailed study about the refractured wells in the most active shale plays in the United States. The raw material of FracFocus contains the chemicals used in the fracturing operations for the US wells completed after 2012 in Chemical Abstract Service format (CAS format). In addition to the chemicals naming reporting flaw, some of the reported wells includes error in reporting the percentage of the chemicals used in each hydraulic fracturing ingredient. The next part of the study was to separate the refractured wells from the fractured wells in the database, the separation of the refractured wells was done through writing an IF statement to include only the refractured wells based on the appearance of the fracture operation on two different Job Start for the same well.

3.2. FRACTURE TREATMENT CLASSIFICATION

Based on the used chemicals reported in FracFocus, the fracturing treatment type were classified into four main types: Slick Water, Linear Gel, Cross Linked Gel, and Hybrid Treatment. To ensure a valid assessment of the treatment type classification, the treatment type was classified based on the used chemicals in each treatment for a single well. For instance, slick water treatment is named for the treatment composed of water, friction reducers, and clay control agent. Linear gel is named for the treatment composed of water, gelling agent. Cross linked gel treatment is for the linear gel treatment that includes cross linkers. Hybrid treatments is named for the treatments composed of the combination of all the treatment types (Al-Alwani et al., 2019).

3.3. REFRACTURED DATA CLASSIFICATION

As mentioned before, the refractured wells were separated based on their appearance in more than one job date from FracFocus from the 130,000 wells reported in the original database. A sample of more than 1200 wells were obtained based on the created approach of classification with some wells including more than one refractured operation job. The selected wells were distributed among the most active shale plays in the United States which are, Niobrara, Bakken, Marcellus, Permian, Eagle Ford, Barnett, and Haynesville shale play.

3.4. COMBINING FRACFOCUS AND ENVERUS DRILLINGINFO DATABASES

Enverus DrillingInfo is a database that contains the completion and the production data of the wells produced in the United States. Enverus Drilling info was combined with the created database from FracFocus to couple the production of each of the refractured wells production before and after the refrac operation. To ensure valid assessment of the production data of the studied wells the following selection criteria was put into perspective; a certain number of wells were chosen from each shale play, and their Barrel of Oil Equivalent was calculated to include the oil and gas production under one parameter. Moreover, the production of the selected wells for each shale play were averaged and further analyzed three months post and pre refracturing to show the efficiency of refracturing as a stimulation technique.

3.5. SELECTING DATA OF INTEREST FOR EACH SHALE PLAY

To ensure the validity of averaging the production data for each play, the following selection criteria were followed for each well 3 months before and after refracturing.

To give a relative value for the BOE production for each shale play, the sample size of wells for each shale play should have the same perforation length in feet. For example, the selected wells for the Bakken play have a perforation length of 5000 ft.

The sample wells should have the same targeted formation for the fracture. To illustrate, the Nesson Formation was selected to represent the targeted formation for the Bakken Play wells. Each of the selected wells in the study have production data of six months (3months before refracture & three months after refracture).

3.6. ORIGINAL FRACS VS. REFRACS PRODUCTION DATA

Based on the followed selection method, a sample of 39 wells were obtained with a three months production before refracture and three months after refracture. Each shale play included 3 to 10 wells with the same specifications (Perforation length, Targeted Formation, well type). To further analyze the production data of each shale play, the median and the standard deviation were calculated for each of the averaged month of production before and after refracture to study the refracture production response for each of the studied wells.

PAPER

I. REFRACTURING ACTIVITES IN THE UNITES STATES — HOW MUCH DO WE KNOW SO FAR?

ABSTRACT

Refracturing old wells instead of drilling and stimulating new wells has become a new trend in the United States due to the oil prices falling in 2011. This work aims to disclose all refracturing activities in the most active shale play in the United States (Bakken, Niobrara, Marcellus, Permian, Eagle Ford, Barnett, and Haynesville) in terms of techniques, candidate selection, fracturing fluid types, and the number of refracs in one well. FracFocus was used to collect data of over 130,000 wells in the United States that were completed between 2013 to the end of 2019. The refractured wells were extracted from the database and the fracturing fluid types were classified as slick-water, linear gel, cross-linked gel, hybrid, and not reported treatments based on the presence of key chemical ingredients. After processing the data, there were over 1200 wells refractured across the most active shale plays in the United States. The results showed the most common fluid type used in refractured wells is hybrid. In terms of shale plays, Niobrara was the most active shale play with over 280 refractured wells followed by Bakken, Eagle Ford, Marcellus, Permian, Barnett, and Haynesville, respectively. Furthermore, the refracturing activities in each well were further analyzed and clustered into two groups; one or two refracs since some wells were refractured more than one time. However, over 95% of the wells were only refractured once. Moreover, refrac candidates can be identified based on

the following factors: the original wells’ cluster spacing, well spacing, proppant distribution, fracture orientation, production response from initial fracture, reservoir thickness, and permeability. The optimal ranges of the aforementioned parameters were provided to achieve the best results in terms of saving money and providing the best productivity. This will help optimizing future refracturing operations in the United States and across the world.

1. INTRODUCTION

Refracturing is a process to re-stimulate a producing well after initially being hydraulically fractured to improve its production (Jacobs, 2015). Refracturing technology is not a new technology and it has been known for a long time. Refracturing vertical wells have been active in the United States since the 1970s and it showed promising results in terms of productivity improvement. However, refracturing multi-stage horizontal wells is a relatively new process across the United States as it started to emerge in 2011 (Dutta, 2017). Due to the oil prices falling in 2011, oil companies started to shift their focus on refracturing oil and gas wells instead of drilling and completing new ones. Another factor that shifted the industry back to the refracturing activities is the reserve size of the unconventional resources and the focus of the industry on the unconventional technology of extraction (King, 2015). To further emphasize the economic benefits of refracturing, an Eagle ford well was used as an example to compare the cost of fracking a new well and refracturing the well, the economic forecast found that a new well would cost 2 to 4 million to frac; however initiating a new frac in a preexistent fractured well would cost 1 to 1.5 million (Fu et al., 2017).

The refracturing operation can be highly challenging due to the lack of data on the surface and its success is determined and controlled by many factors (Yanfang & Salehi, 2014). As a result, the industry started to study and create models to predict the success or the failure of refracturing jobs before initiating one. In fact, it is recommended to include the refrac plan in the initial stage of developing a field due to its efficiency in providing a high return of investment in a shorter time (Dutta, 2017). To predict the failure or success of refrac operation, it is important to understand the factors contributing to a successful refrac. Another complication to consider when it comes to refracturing operation is the formation of the fracs; depending on the pressure distribution created by the initial fractures and the cluster spacing between the fracture stages, a new fracture might be initiated reaching more sweet spots in the reservoir. In another case, the initial fracture would reopen and reorient in the producing section of the reservoir (Fu et al., 2017). This shows that the level of uncertainty in the refracturing operation could be a challenging case that needs to be considered before starting a refracturing operation.

The first part to consider is the completion strategy used to initiate the refrac. The use of a diversion tool is the first to consider when completing a well for a refrac. The diverter needs to remain in the initiated fracture to plug the perforated zones for at least two to four weeks (Cookson, 2020). Therefore, permanent diverters are usually used in refrac operations. Another factor to consider when completing a well for a refrac operation is the washed-out perforation due to production from original completion for several years. To resolve this problem, customized pods based on the size and the shape of the perforation are installed in the well to solve the problem of the washed-out perforation. The use of pods to plug a fraction of the wells yielded a better result compared to other completion alternatives such as straddle packer or squeezed type systems with a less expensive cost of operation (Cookson, 2020). The only drawback with the use of diverters is the level of uncertainty. When completing a refrac job with diverters, it is not easy to determine where the fracturing fluid would propagate the formation. However, using an expandable liner instead of a diverting agent gives a higher degree of certainty because it is possible to mechanically isolate the old zones to perforate new ones. Since 2009, Eventure Global Technology Company has used expandable liners for completing 15 wells in the Marcellus, Barnett, and Eagle Ford Basins (Jacobs, 2015). The process of installing expandable liners starts by installing milling tools into the cased hole to prepare for the expandable liner. The expandable liner is then installed and expanded to maximum diameter through the expansion cones sealing the old perforation and giving more space for the new perforation to be made. Although the use of diversion agent is found to be much cheaper than the use of expandable liner, the expandable liner completion in many cases yielded to higher production and profit in refracture operations. Figure 1 shows the production data of three wells produced in the Barnett Shale using refrac technology; the figure shows that well 1 which was produced through expandable liner showed production gains higher than the two offset wells (well 2 and well 3) which used diverter agent technology (Jacobs. 2015).

Another factor to consider in a refracturing operation is choosing the right candidate and the optimal time for refracturing. In a study conducted on the refractured producing wells in the Barnett Shale, the finding of the study showed that the production after the refracturing job in 171 studied wells increased 2 to 4 times of their initial production before

refracturing. The study also found that it is better to restimulate the well at a relatively early stage of production instead of waiting for too long (Wang et al. 2013). Table1 is a literature summary about refracturing operations in the most active basins around the United States

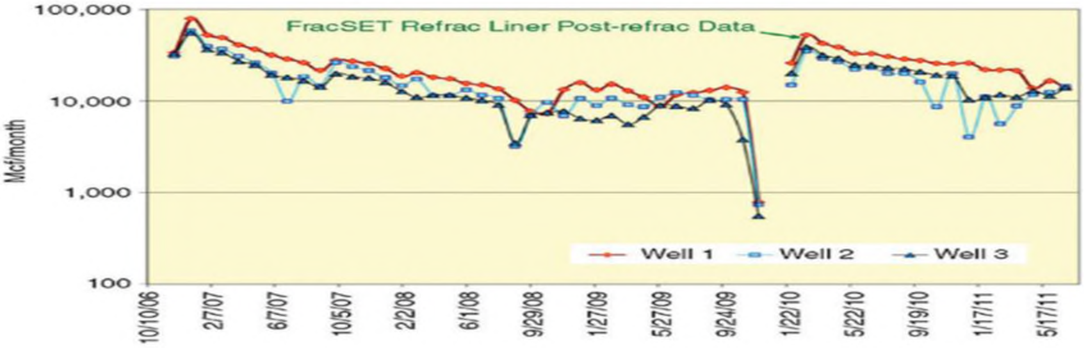

Figure 1. Production Gains from Refracture Operation in the Barnett Shale (Jacobs, 2015)

Another factor to consider in a refracturing operation is choosing the right candidate and the optimal time for refracturing. In a study conducted on the refractured producing wells in the Barnett Shale, the finding of the study showed that the production after the refracturing job in 171 studied wells increased 2 to 4 times of their initial production before refracturing. The study also found that it is better to restimulate the well at a relatively early stage of production instead of waiting for too long (Wang et al. 2013). Table1 is a literature summary about refracturing operations in the most active basins around the United States.

This work aims to understand the refracturing activates in the most active shale play in the United States in terms of state-of-the-art applications, candidate selection, and techniques. Furthermore, this work will disclose the refracturing activities over time and the treatment types used in each well.

Table 1. Refracturing Activities in the Most Active Shale Plays in the United States

Basin	Reference	Goals/ Enhancement	Notes
Barnett	Senters et al. (2019)	This paper suggests the best refracturing technique in the Barnett Shale play	The evaluation of refracturing technique are grouped into two parts; Bullhead refracturing techniques, where the refracturing operation is aimed to cover the stimulated interval, and the second group includes the mechanical isolation technique for refracturing.
	Tavassoli et al. (2013)	The study uses numerical simulation technique to predict gas production from refractured wells along with sensitivity analysis to predict the shale horizontal wells suitable for refracturing and define the optimal time for refracturing	The suggested study was applied to 188 wells in the Barnett and found only 11 wells are suitable for refracturing and the optimum time for refracturing is in the period of 3 to 5 years after initial production.
	Potapenko et al. (2009)	Redirection of refracture to stimulate intervals that were not achieved during the first stimulation job in horizontal wells.	The study introduced a novel technique of fluid diversion without mechanical intervention.
	Wang et al. (2013)	Discover how refracturing improves production by studying treatment parameters that control production from refracture wells such as; Proppant type and mass, surface shut-in pressure, Pad volume, injection rate, and treatment fluid volume	Identifying fracture formation and initial completion type is important to get optimal production from refractured wells.
	Rath & Bielicki. (2018)	Using years of production from Barnett shale reservoir to understand the trends of production from refractured wells. The study showed that the number of refractured wells is around 2% of the number of new wells each year.	Based on the findings of the study; newer wells make a better candidate when choosing a well for refracturing operation, for a well to be refractured it has to have a relatively high initial production rate.
	Lio et al. (2017)	The paper provides evidence of an increase in production through refracture operation in two tight gas wells by reorienting deep initial fractures.	The technology of refracture reorientation can be applied to increase production in oil and gas producing wells.

Table 1. Refracturing Activities in the Most Active Shale Plays in the United States (Cont.)

Basin	Reference	Goals/ Enhancement	Notes
Haynesville	Hunter et al. (2015)	Integrating multiple workflows for well candidate selection for refracturing operations and executing the type of refracturing treatment based on the selected parameters of the wells to be refractured either, completion parameter.	The suggested screening technology for refrac candidate selection was applied to several basins around the US and the refracturing candidate class was divided into; superior, good, or fair based on the production potential from refracturing.
	Xu et al. (2017)	Implementing reservoir simulation techniques to model refracturing treatment in the Haynesville to predict the performance of the refractured wells.	The suggested approach is validated by history matching of real production data from the Haynesville basin.
	Krenger et al. (2015)	The paper discusses a different design consideration to increase production from under-stimulated wells through the use of a self-removing diverting agent.	In the study, different refracture diverting techniques in the Haynesville was investigated to test their effectiveness. The chemical diversion technique was proven to be more effective in terms of full lateral coverage.
	Xu et al. (2019)	The study suggests a new method of modeling refracturing treatment in a numerical simulator with the usage of altered stresses caused by the reservoir depletion.	The simulation study is validated through production history matching from refractured wells in the Haynesville Basin.
Eagle Ford	Charry et al., (2016)	The main objective of the study is to identify the factors for a successful refracturing job based on real production data.	The research was based on real production data from 11 refractured wells located in the same field with different completion techniques.
	Mullen et al. (2017); Diakhate et al. (2015)	These papers suggest a new solution for the process of candidate selection by analyzing each solution and ranking the candidate wells for refrac operation. The papers also discuss the results of the suggested solution when applied wells in the selected field for study.	Advanced diagnosis tools were used to monitor the effect of refracturing on the stimulated well and offset producers and evaluating the concept of diverting fluids in the horizontal wells.
	Nwabuoku & El Paso (2011)	The paper addresses the problem of initial completion requirements controlled by the cluster spacing and suggests solutions	The paper studies the improvement in the well productivity due to the suggested changes.

Table 1. Refracturing Activities in the Most Active Shale Plays in the United States (Cont.)

Basin	Reference	Goals/ Enhancement	Notes
Eagle Ford	Charry et al., (2016)	The paper studies the outcome of the new completion method of fluid diversion by the installation of a new casing string when refracturing in the Eagle Ford	The newly implemented completion technique proved to be efficient in a dataset of five wells by increasing the original EUR by 140%.
	Pankaj & Shukla (2018)	The paper shows the benefits of productivity gains through refracturing when using coiled tubing for the stimulation job.	When compared with the bullheading technique, the first generation of wells with 18 stages has shown 36% extra production through the initiated fractures.
Marcellus	Yi et al. (2019)	The study suggests a solution to mitigate the effect of the formation of "Hell dominated fractures"	The simulation study suggests that using small stages with more diverting agents can minimize the effect of over stimulating the dominant fracture.
	Rodvelt et al. (2015)	The paper discusses improving productivity EUR through the use of a new diversion technique to reduce cluster spacing	Based on the analytical production simulator, the suggested solution proved to be efficient for 200 wells of the investigated wells.
Bakken	Yao et al. (2007)	The papers study the prediction of stress field redistribution due to production, which affects the formation of the new fracture in a refracturing operation.	To verify the validation of the software used to achieve the suggested conclusion, a tiltmeter was used to monitor the fracture initiation in the studied wells.
	Lantz et al. (2007)	The paper discusses the refracture operation success in the Bakken reservoir in Richland county by comparing reservoir production before and after the restimulation job.	Through the seven years of production, the treatment size has remained the same, but the pumping method has changed.
	Ruhle. (2016)	The paper uses production data of refractured wells in the Bakken basin to predict the performance of future refractured wells based on their initial completion and re-completion types.	More than dozens of well have been analyzed using microseismic monitoring tools.
	Indras & Blankenship (2015)	The paper addresses the economic performance of refracturing in the Bakken shale play	Based on the circumstances of the studied well, the applied sensitivity analysis indicates that the generated net present value of refracturing is higher than drilling a new well in the Bakken Shale play.

Table 1. Refracturing Activities in the Most Active Shale Plays in the United States (Cont.)

Permian	Leonard et al. (2016)	The paper describes certain diagnostic technology tools and re-completion designs used in North America Basins to optimize refracturing.	To ensure viable results from the diagnoses, the study analyzed data of stimulation effectiveness and performance from 121 wells.
	Athavale et al. (2019)	The paper evaluates different refracturing technologies applied to under-stimulated wells in the Bone Spring formation.	Based on the outcome of the research, the use of expandable liner for isolation is more effective and it showed promising results on the refractured wells at which it was applied.
	Han et al. (2018)	The paper investigates refracturing jobs in several wells in terms of production increments based on the completion technique used.	The study applied in the Delaware Basin suggests some solutions when refracturing wells in the area of study in terms of refracturing design and data gathering.
Niobrara	Wolhart et al. (2007)	The paper reports the findings of a study conducted to measure the refrac orientation in the operations carried in the Wattenberg field.	The results of the study indicate that the reason for refracture operations success in the area of study is due to the high probability of refracture orientation in the Wattenberg field.
	Miller et al. (2016)	The paper discusses the phenomenon of fracture interference when carrying refracturing operations whether it has a positive or negative effect on the initial production of the parent well.	The results show that the initiated fracture interferences have a negative effect on the parent well production.
	Roussel & Sharma (2013)	The paper suggests a systematic approach for refracturing candidate selection based on production data and reservoir properties.	The selection method was successfully implemented on 300 tight gas wells in the Wattenberg field.

2. REFRACTURE CANDIDATE SELECTION

While refracturing is a successful operation that yields higher income by minimizing the cost of drilling a new well, not all wells can be considered a good refracturing candidate (Hunter et al. 2015). Many studies have been conducted to determine the candidacy of a well to be refractured (Charry et al. 2016). Many factors need to be taken into consideration to determine if the well is a good candidate for refracturing (Mullen et al. 2017; Diakhate et al. 2015). The following subsections present the main refrac candidate parameters.

2.1. CLUSTER SPACING

The initial completion design of the well plays an important role in determining the success rate for a refracturing operation. From a perforation standpoint, when the spacing between the perforated intervals is large, the probability of unstimulated zones of the reservoir rock is usually high, especially if the initial production of the well was lower than anticipated (McFall et al. 2017). Based on case studies on several wells, for a well to be a refracture candidate, the cluster spacing has to be larger than 500 ft/stage (French et al. 2014). Other approaches of selection suggest different values of cluster spacing; larger than 90 ft/stage (Hunter et al. 2015), and larger than 300 ft/stage (King. 2014).

2.2. WELL SPACING

Well spacing is another important consideration that is related to the initial completion design. Closely spaced wells can lead to a decrease in production due to fracture interference and pressure communication induced by the fracture hits (Sinha & Ramakrishnan 2011; McFall et al. 2017). Therefore, it is important to consider the initial well spacing when considering a refracture candidate. Producing wells spaced 500 ft., or more from infill wells can be a good candidate based on the well spacing criteria of selection (McFall et al. 2017). Another well spacing criteria of selection suggests that wells spaced less than 800 ft can be a good candidate, but certain completion techniques and Proppant volume is required to ensure refracture success (Hunter et al. 2015).

2.3. PROPPANT DISTRIBUTION

Proppant distribution is an important factor that controls the efficiency of the first fracture operation which may lead to the necessity of another fracture operation to reach unstimulated areas in the reservoir (Asala et al., 2016). On the other hand, if the initial volume per lateral foot of Proppant was known, it can be a great additive to the selection of refrac candidates. Wells that have a Proppant volume of less than 1000 lb/ft. are under-stimulated. Therefore, these wells can be a good candidate for refracturing (Hunter et al. 2015). Another study suggests to refracture wells when 30% or more of the original stages place minimal Proppant (French et al. 2014)

2.4. FRACTURE REORIENTATION

To predict the success of refracture operation, it is important to consider the orientation of the new fracture around the initial fracture (Siebrits et al. 2000). There are two contributors to the reorientation of the new fracture; mechanical and poroelastic effects (Usui et al. 2017). The mechanical effect is induced around the fracture due to the alteration of the stresses around the initiated fracture (Li et al. 2017). As the production starts from the fracture, the stress around the induced fracture increases more in the perpendicular direction than it increases in the parallel direction to the propped fracture. On the other hand, as the liquid is produced through the initiated fracture, the pressure drops more at the parallel direction of the fracture which changes the stresses around the fracture. As a result, the stresses around the fracture will be reversed. Therefore, the new fractures will be reoriented based on the new distribution of the stresses around the fracture (Lu et al. 2019). As production continues, the reversal of stresses expands around the fracture (Li et al. 2017). The stress reorientation depends on many factors including production rate, permeability anisotropy, and stresses anisotropy around the wellbore (Singh et al. 2008).

2.5. PRODUCTION RESPONSE FROM INITIAL FRACTURE

Poor production from the initial fracture can occur due to different reasons. Fracture conductivity losses could occur due to chemical interaction with incompatible drilling or completion fluids leading to sharp production decline in high producing fracture wells (Rayson & Weaver, 2012). Poor production can also occur due to Proppant pack damage as a result of poor production management such as opening the choke too aggressively, Proppant crushing or problems in Proppant distribution through the initiated frack (Hunter et al. 2015; McFall et al. 2017). Based on case studies on several refractured gas wells, some refracturing candidate selection techniques choose wells with a production gas rate of less than 700 mscf/d to be refractured (French et al. 2014). Most of the studies determine the amount of gas produced as a parameter of selection by comparing the production of the candidate well relative to the other fractured producing wells with similar reservoir qualities (Moore & Ramakrishnan. 2006; Roussel & Sharma. 2013).

2.6. RESERVOIR PARAMETER

Reservoir quality is one of the main parameters of success when considering a refracturing treatment to enhance productivity (Li et al. 2019). The key factors to consider reservoir quality for the refracturing job are; relatively high reservoir pressure after the fracturing operation indicating a high portion of unproduced gas in place, low productivity relative to other wells with the same properties, wells with high permeability and high skin value, the possibility of refracture orientation (Moore & Ramakrishnan, 2006). Other studies suggest other factors such as low water production below 25 bwpd, near a water source for fracturing fluid, and no perceived faults to avoid the risk of fracturing faulted formation (French et al. 2014).

3. DATA AND METHODOLOGY

3.1. FRACFOCUS DATA

The main requirement for this study was to extract useful data from the accessible FracFocus database to study the refracturing activities in the United States in terms of treatment type used and the number of refracturing activities in the U.S. major shale plays. To ensure a valid data analysis through the FracFocus database, it is important to have a wide understanding of unconventional well hydraulic fracturing to group the chemical given in chemical abstracts service (CAS) format based on their purpose in the hydraulic fracturing operation (Al-Alwani et al., 2019 a). The analyzed data of FracFocus contains chemical data of wells completed after 2012, each well is named in API number format, and the chemical used is mentioned in the form of CAS number. For example, water is reported as CAS= 7732-18-5. The naming of the chemical used was not the only flaw in the reporting method of FracFocus, a high number of the reported wells in the database do not have complete data and some of the used chemicals were not reported, or reported with spelling errors (Al-Alwani et al. 2019b).

3.2. COMBINING FRACFOCUS DATA

After downloading the chemical ingredients data from the FracFocus website, all the data were combined into one file for the data to be processed and analyzed. The next step was identifying the parameters to be included in the processed database such as job start date, well API number, well location, and chemical CAS number. A file was created based on the required parameters and cleaned from white spaces and saved to be used in the next step of data processing. The purpose of this study is to analyze the data of the chemicals used in the refractured wells. Therefore, the next step was separating the refractured wells from the created file. To separate the refractured wells from the data file, any well that had two different job start date in the data file was separated from the rest of the wells to be processed in the next step of the analysis. The next step of processing the researched data was classifying the chemical used in the refractured wells into 18 groups based on the CAS number reported in the original file. The created chemical groups from the CAS number are; water, proppant, acetic acid, guar gum (gelling agent), biocide, clay control, ethanol, ethylene glycol, gel breakers, hydrochloric acids, isopropanol, methanol, naphthalene, phenolic resin, potassium hydroxide, sodium chloride, solvents. The reported percentage, mass, and volume for each of these chemicals were then aggregated under each well.

3.3. FRACTURING TREATMENT CLASSIFICATION

The main purpose of grouping the used chemicals in the hydraulic refracturing operations reported in the FracFocus database is to study the treatment type based on the used chemicals. The treatment types of the refractured wells were divided into four main types of treatments; slickwater, linear gel, cross-linked gel, and hybrid treatments (Al-

Hameedi et al. 2020) To ensure a valid classification of the hydraulic fracture fluid used in each of the refractured well, the fluids used in each operation were classified based on their chemical composition. For example, slickwater treatment is the treatment consisting of water, friction reducers, and some clay control agents. Linear gel treatment is for treatment consisting of water, gelling agent (guar gum, or other chemicals). The cross-linked gel is the same as linear gel with adding some cross-linkers to increase the viscosity of the gel and hybrid treatments are the combination of the different fluid types (Al-Alwani et al. 2019c). Due to the reporting issues in the original file of FracFocus with some chemicals not being reported or being reported as "confidential", some of the treatment types in the data analysis were denoted as "not reported".

3.4. REFRACTURED DATA CLASSIFICATION

FracFocus, a public chemical registry for hydraulic fracturing in the United States, was used to collect data of over 130,000 wells in the United States that were completed between 2012 to 2020. As said earlier, the refractured wells were separated based on the job start date of the fracturing operations in the original database. To ensure the classification would only include the refracturing operations on the studied wells, the first reported treatment chemicals (the original frac) used in each well were excluded from the analysis, and each refracturing operation in a specific well was denoted by a number; number 1 for the first refracturing operation, and number 2 for the second refracturing operation to report each chemical treatment based on the refrac number for each refractured well. It is important to mention that there were some wells refractured more than two times, these wells were a very small sample (less than 20) compared to all refractured wells. Thus, these wells were eliminated from the database. A sample size of 1200 refractured wells was created based on the mentioned classification to study the refracturing operations in the United States. The refractured wells are grouped based on their distribution among the most active basins in the United States which are Bakken, Niobrara, Marcellus, Permian, Eagle Ford, Barnett, and Haynesville as shown in Figure 2.

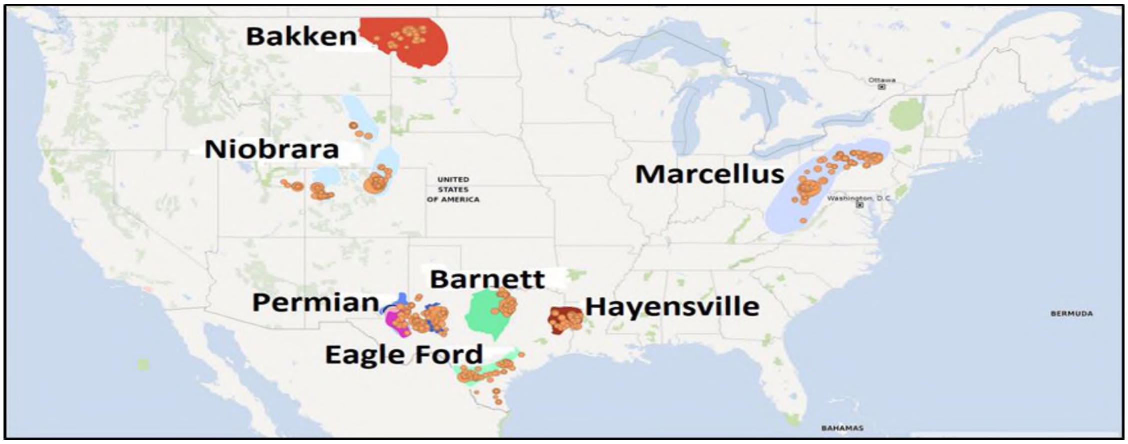

Figure 2. Refractured Wells Distribution in the Most Active Shale Plays in the United States

4. RESULTS AND DISSCUSSION

4.1. THE WHOLE UNITED STATES

Figure 3 shows the number of refractured wells in the most active shale plays in the U.S. The refracturing jobs distribution indicates that the highest refracturing activities are located in the Niobrara and the Bakken shale plays, respectively. The refracturing activities around the region of the Niobrara shale play have shown major success in terms of production through contacting new reservoir regions, which yields higher gas recovery per well (Wolhart et al. 2007). The second highest shale play is the Bakken play which has witnessed a huge expansion in terms of oil production through fracturing activities in the past recent years (Rusyn 2015). On the other hand, the Haynesville shale play in Texas has the lowest number of refracturing activities among the most active U.S. shale plays constituting 4% of the total number of refracturing activities in the studied shales.

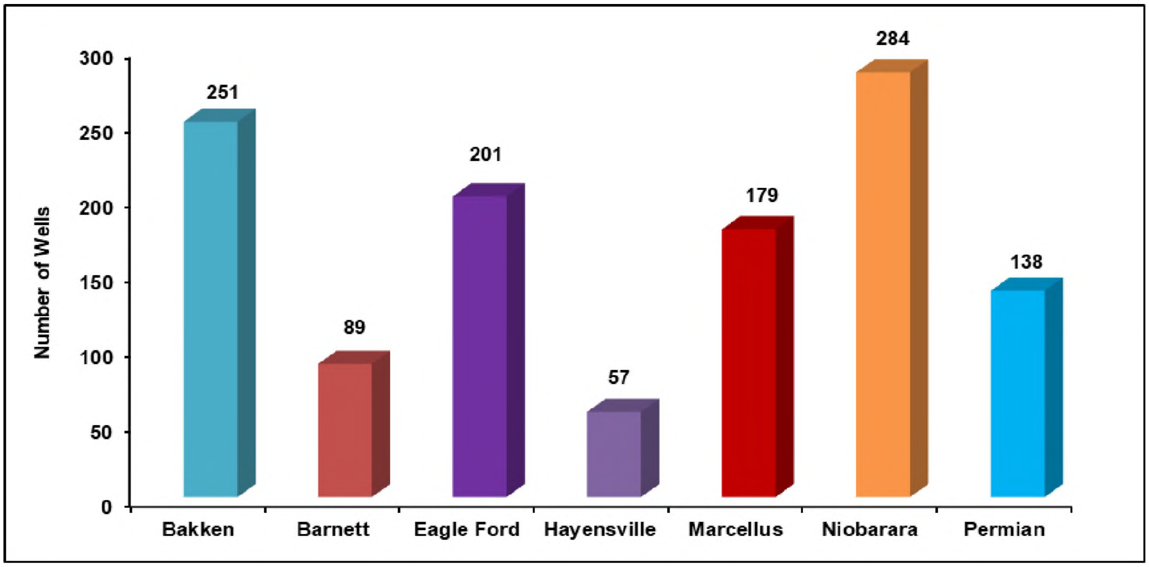

Figure 3. Number of Refractured Wells Distribution in the Most Active Shale Plays

Based on the obtained results of the study, the years 2014 and 2018 were the most active years in terms of refracturing operations. The oil price drop in these years can be a valid reason for the industry to focus on refracturing instead of new wells drilling activity. From a treatment type point of view, the most used treatment was the hybrid treatment covering 52% of the applied treatments on the refractured wells of the study. As mentioned before, hybrid treatment is the treatment type at which a combination of different treatment types (slickwater, linear gel, and cross-linked gel) is applied to the same well at different stages. The second highest treatment was the not reported treatments, 31% of the studied treatments were not reported due to the reporting issues associated with the FarcFocus database. The treatment type distribution is followed by slickwater, linear gel, and cross-linked gel treatments, respectively. Nonetheless, for the original fracture operations for the studied sample (1200 wells) across the major shale plays in the United States, hybrid treatment was also the most common treatment type. On the other hand, for the first and second refractures, the data haven't shown a trend in the usage of a specific treatment type after the original refracs. In other words, original treatment types are not a parameter in the candidate selection process (besides proppant distribution which was discussed earlier). Figure 4 summarizes the discussed findings of the study in terms of refracturing treatments over the past seven years.

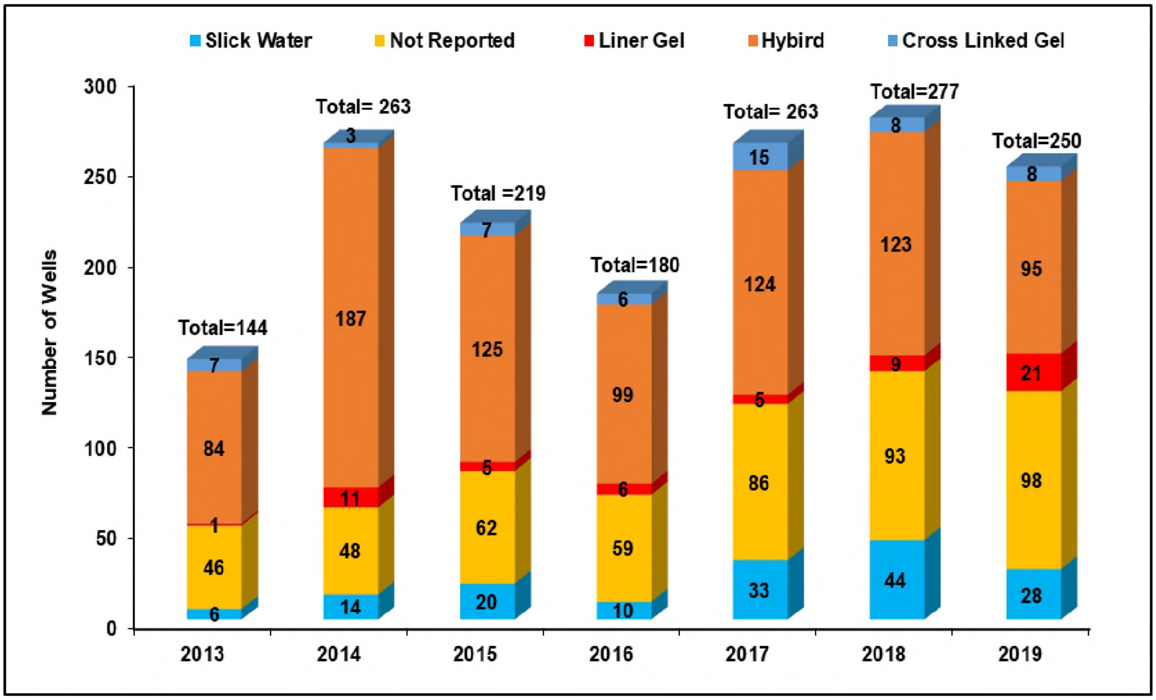

Figure 4. Number of Refracturing Treatments Distribution over Time in the Most Active Shale Plays in the United States

For the wells refractured more than once, only 7% of the treated wells required a second refracture, indicating a high first treatment success rate. Figure 5 shows the number of wells restimulated with either one or two refracture operations and the treatment types used for each of the reported wells.

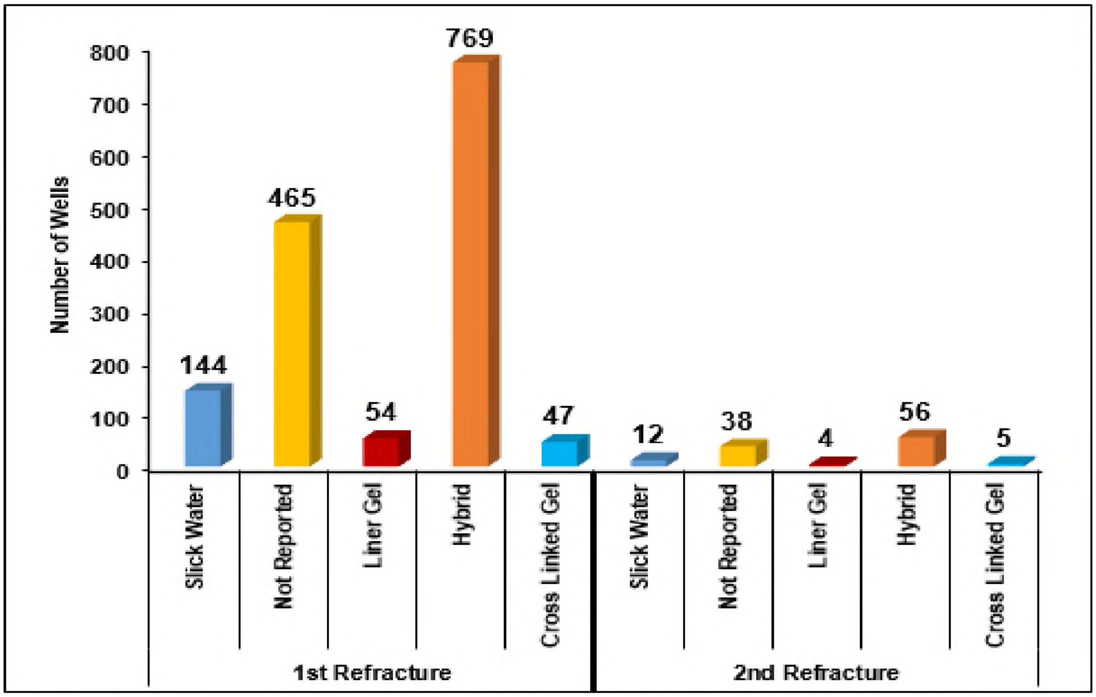

Figure 5. Number of Refracturing Operations on the Studied Wells

4.2. BAKKEN AND NIOBRARA SHALE PLAYS

Figures 6 and 7 show the number of refracturing treatments overtime for the Niobrara and Bakken shale plays. The most active shale plays around the United States in terms of hydraulic refracturing activates are the Niobrara and Bakken shale plays covering more than 40% of the refracturing activities in the most active shale plays around the U.S. In terms of refracturing treatment used, for both shale plays, the most used treatment type is the hybrid treatment covering more than 50% of the treatments used in the refracturing operations.

In 2018, the Bakken shale play has witnessed a high number of refracturing activities, which then went back to normal in 2019. However, for the Niobrara, the years 2014, 2015, 2017, and 2019 were highly active in terms of refracturing operations per year. The Niobrara shale play had 21second refracturing operations and the Bakken had 23 second refracturing operations, making the Bakken shale the shale with the highest number of second refracturing operations among the studied shale plays as shown in Figure 8.

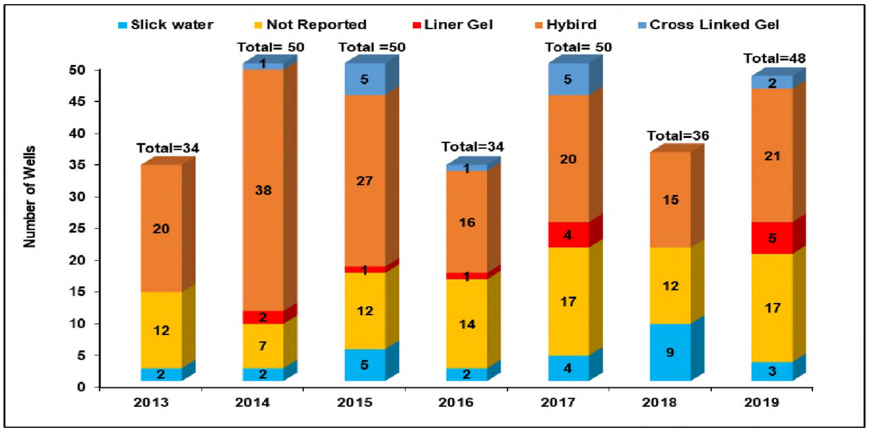

Figure 6. Number of Refracturing Treatments Distribution over Time in the Niobrara Shale

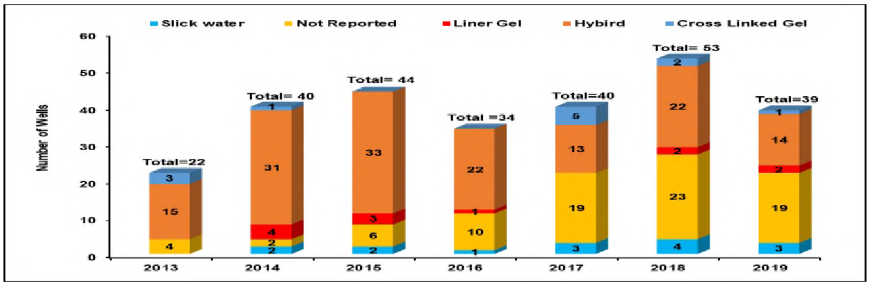

Figure 7. Number of Refracturing Treatments Distribution over Time in the Bakken Shale

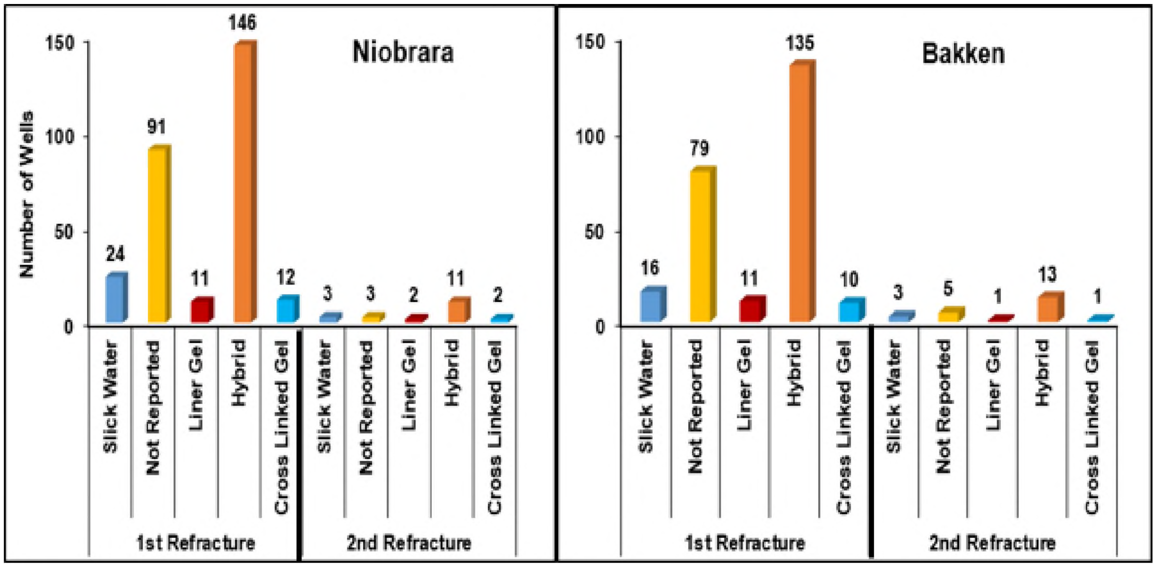

Figure 8. Number of Refracturing Operations on Niobrara & Bakken Wells

4.3. EAGLE FORD AND MARCELLUS SHALE PLAYS

30% of the refracturing activities are located in the Eagle Ford and Marcellus shale plays. In terms of size, the Marcellus shale gas play is bigger than the Eagle Ford shale play. However, they both have almost the same size of refracturing activities with almost 50% of the refracturing treatments being hybrid treatments. On the other hand, according to a study conducted by Al-Alwani et al. (2019b) for all original frac jobs (not including refractured wells) which used wells until the end of 2018 showed that the most common fracturing treatment in the Marcellus shale was slick water.

Figure 9 shows that the Eagle Ford shale play witnessed very high hydraulic refracturing activities over the past three years (2017 to 2019). On the other hand, Figure 10 shows that the most active time for the refracturing activities in the Marcellus was the year 2017 with 36 wells being refractured that year. The Marcellus shale play had a decline in the refracturing operations in the past 2 years (2018 to 2019).

As shown in Figure 11, both shale plays had a few second refracturing operations on their refractured wells with 15 wells in the Eagle Ford and 14 wells in the Marcellus, constituting a total number of 29 second refracturing operations over the past seven years in both shales plays.

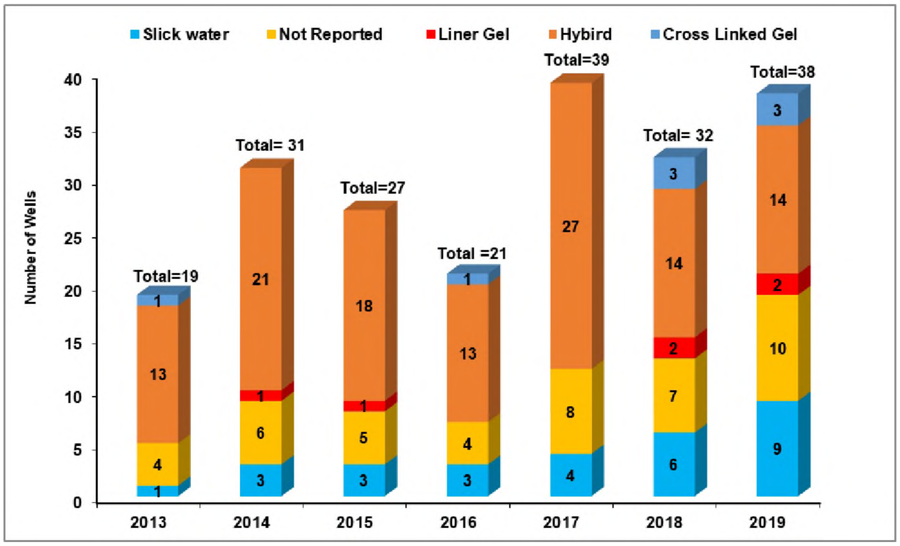

Figure 9. Number of Refracturing Treatments Distribution over Time in the Eagle Ford Shale

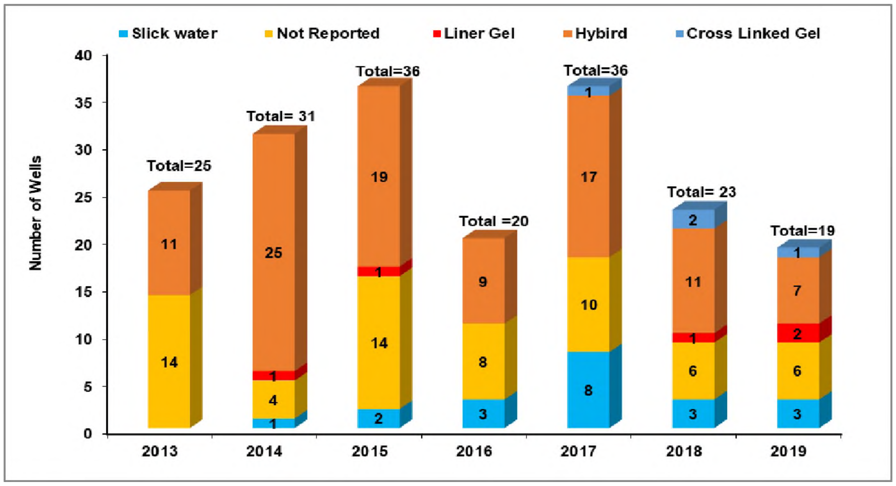

Figure 10. Number of Refracturing Treatments Distribution over Time in the Marcellus Shale

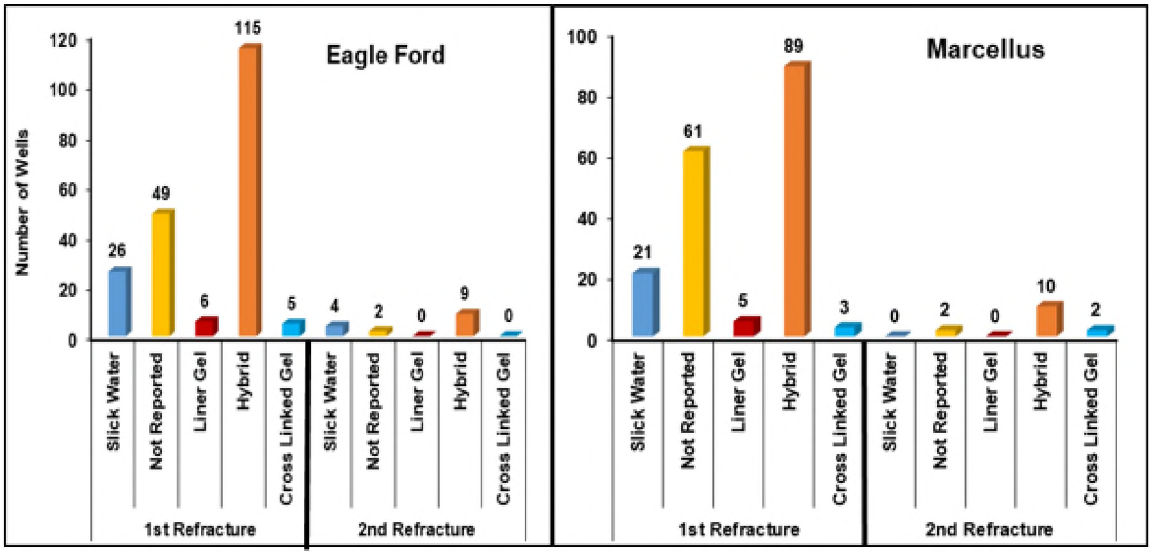

Figure 11. Number of Refracturing Operations on Eagle Ford & Marcellus Wells

4.4. BARNETT, HAYNESVILLE, AND PERMIAN SHALE PLAYS

The other 30% of the refracturing activities are located in the Barnett, Haynesville, and Permian shale plays. Located in Texas State, the three basins have high fracturing activities. However, based on the refracturing operation size compared to the other studied shale plays, these shale plays have the lowest number of refracturing activities, with the Haynesville having only 57 refracturing operations over the past 7 years. The three shale plays along with the Eagle Ford are located in Texas and together they represent 40 % of the refracturing activities in the United States.

Figure 12 shows the number of refracturing activities in the past seven years in the Barnett shale play. Figure 12 shows an increase in the refracturing activities over the past two years (2018 to 2019) in the Barnett shale play. However, for the Haynesville shale play, the year 2015 was the most active year in terms of refracturing operations as shown in Figure 13.

In the Permian shale play, the number of refracturing operations has increased in the year 2017 then it went back to normal by 2019 as shown in Figure 14.

Only 17 wells from a total of 284 refractured wells in the three shale plays were refractured twice. Of these wells, 7 wells in the Barnett, and 6 wells in each the Haynesville and the Permian as shown in Figure 15.

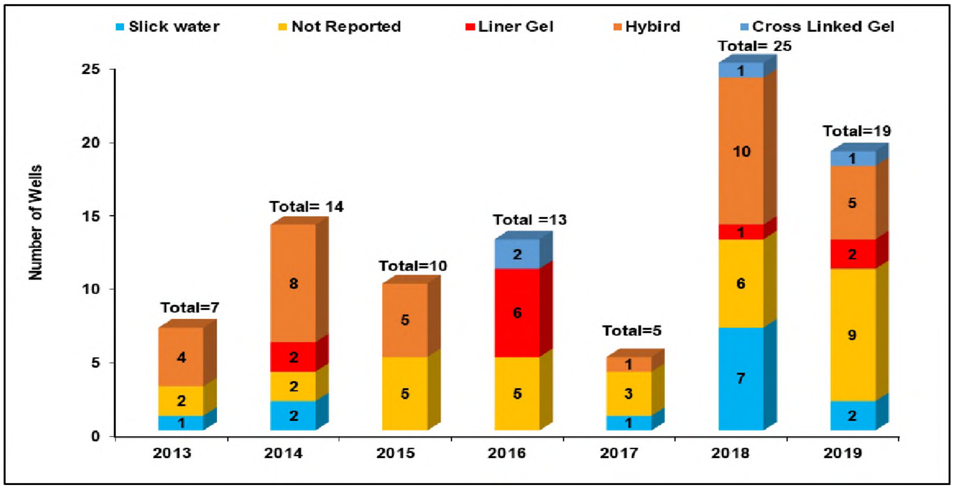

Figure 12. Number of Refracturing Treatments Distribution over Time in the Barnett Shale

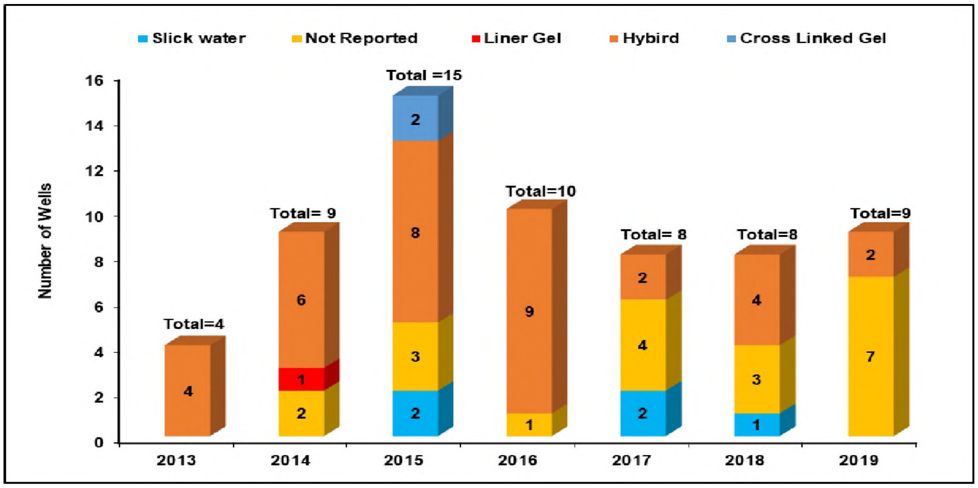

Figure 13. Number of Refracturing Treatments Distribution over Time in Haynesville Shale

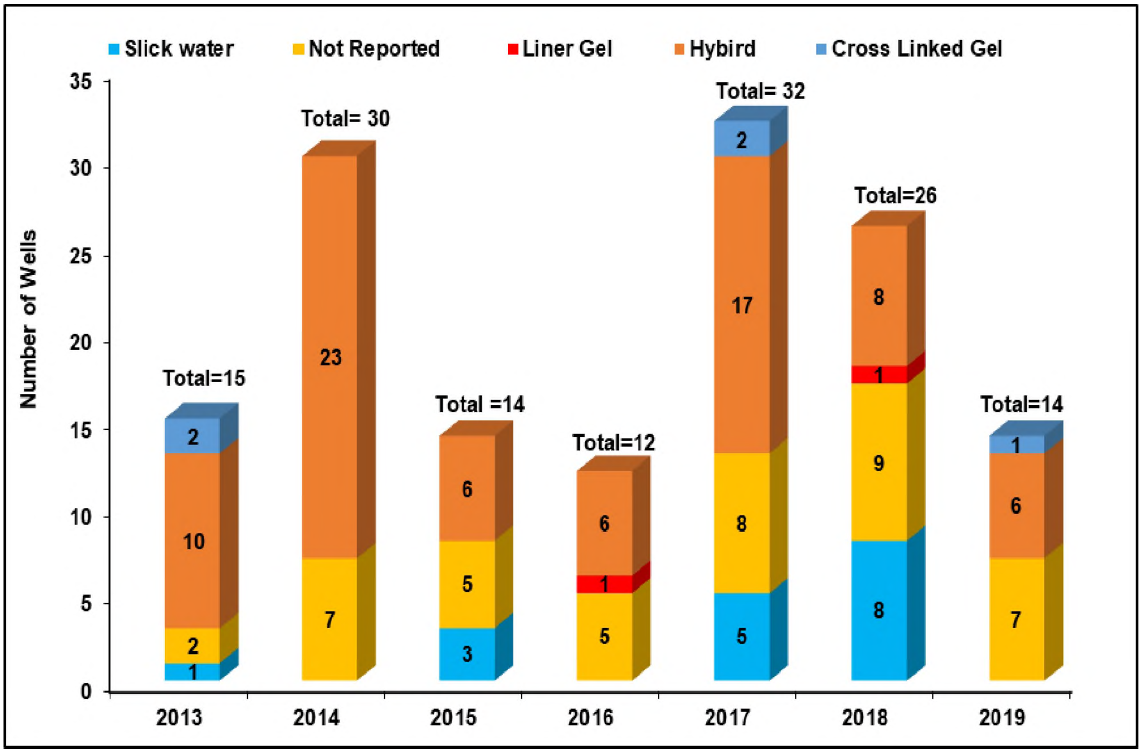

Figure 14. Number of Refracturing Treatments Distribution over Time in the Permian Shale

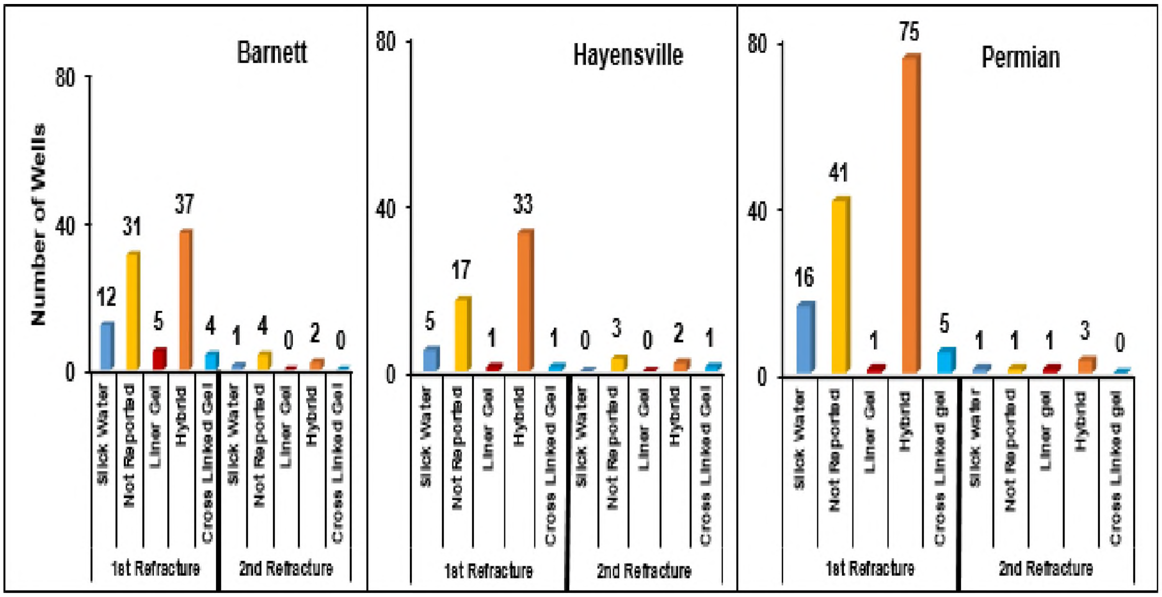

Figure 15. Number of Refracturing Operations on Barnett, Haynesville, and Permian Wells

5. CONCLUSION

Refracturing horizontal wells has been an active trend in the oil and gas industry over the past years due to economic challenges in the industry. In this work, data from 1200 wells were collected from FracFocus database registry and utilized to study refracturing activities in the most active shale plays in the United States. Treatments types were classified based on key chemicals as slickwater, linear gel, cross-linked gel, hybrid, and not reported treatments. Original, first, and second refractures were also identified for each shale play. The following conclusions were made based on this study:

- 1200 wells were refractured across the major shale plays in the United States. Of these wells, 284 in the Niobrara, 251 in the Bakken, 201 in the Eagle Ford, 179 in the Marcellus, 138 in the Permian, 89 in the Barnett, and 57 wells in the Haynesville.
- Over the past seven years across the major shale plays in the United States, the year 2018 was the most active year with 277 refracturing operations.
- The most common fluid type used in the refracturing operation is hybrid constituting 52% of the total number of treated wells followed by; not reported treatment (31%), slickwater (10%), linear gel (4%), cross-linked gel (3%).
- Due to the reporting and formatting issues with the FracFocus database in naming some of the chemicals, some of the treatment types were classified as “Not Reported” in the study.
- 9.7% of the 1200 studied wells were refractured more than once. Most of these wells are in the Bakken shale play where more than 9 % of the wells were refractured more than once.

- Bakken shale play was the most active play in terms of second refracturing operations with more than 9% of its refractured wells being refractured again.
- Refrac candidate selection can be identified based on the following factors: cluster spacing, well spacing, proppant distribution, fracture reorientation, production response from initial fracture, and reservoir properties.
- Of the reported wells in the study, 40 % of the wells are in Texas, which shows the major size of refracturing activities in the State of Texas.

The refracturing operations were most active in The U.S. during the years 2014 and 2018. A valid reason for the increase in the refracturing activity can be due to the oil price drop during that period.

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II. ASSESMENT OF THE PRODUCTION GAIN FROM REFRACTURED WELLS IN THE MAJOR SHALE PLAYS IN THE UNITED STATES

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ABSTRACT

Over the past decade, the oil industry witnessed an expansion in the refracturing activates instead of drilling and fracturing new wells. This work aims to test the efficiency of the refracturing treatments by analyzing the post refracturing production trend of wells in the most active shale plays in the United States (Bakken, Niobrara, Marcellus, Permian, Eagle Ford, Barnett, and Haynesville). FracFocus— a public chemical registry for hydraulic fracturing in the United States — was used to collect data of more than 130,000 wells in the United States completed between 2012 and 2020. The refractured wells were separated from the database and analyzed separately. In this study, 39 refractured wells (Barnett wells were vertical, Niobrara wells deviated, and the other shale plays were horizontal) in the created database were further processed by adding their production data from DrillingInfo — a database of oil and gas production in the United States — to analyze the production data of the refractured wells and test the efficiency of refracturing as a stimulation technique to increase production. After processing the data, each shale play refracturing production was separately analyzed before and after refracturing. In terms of production gain, the results showed that the selected wells in the Eagle Ford shale play

yielded the highest production gain from refracturing with a 174% increase of production post refracturing followed by Bakken (160%), Marcellus (133%), Barnett (46%), Niobrara (43), Haynesville (34%), and Permian (32%), respectively. Overall, based on the results of the production data, the highest production gain from refracturing is achieved during the second month after refracturing and the decrease of production gain starts during the third month after refracturing. On the other hand, the results showed that there are more factors than formation type and perforation length that needs to be considered to predict the production response of refracturing as some wells showed a high gain during the first three months after refracturing, while other wells showed a lower production gain during the first three months after refracturing. Moreover, the refracturing operations have shown a production increase in vertical (Barnett shale), deviated (Niobrara wells), and horizontal (all other shale plays) wells. This work will give clear insights into the efficiency of refracturing as a stimulation technique to restore depleted wells' productivity. This work can also be classified as a reference for further studies in the refracturing activities in the U.S. major shale plays.

1. INTRODUCTION

Since the oil price drop in 2011, refracturing old wells and producing from shale reserves have become a new trend in the oil industry in the United States. Refracturing operations aim to maximize production through refracturing old fractured wells (Jacobs, 2015). The technology itself is not new and it has been known and active in the United States since the 1970s. However, the process of refracturing horizontally drilled multistaged wells is a new technology that started to appear in the industry back in 2011 (Dutta, 2017). Since the oil price drop in 2011, refracturing shale reserves started to emerge in the industry due to the size of the unconventional reserves and the economic viability of producing through refracturing (King, 2014). To highlight the economic efficiency of refracturing, when comparing the cost of refracturing an existent well and fracturing a new well in the Eagle Ford, it was found that the cost of producing through a refracture is 1 to 1.5 million dollars, while the profit of producing through a new fracture is estimated to be 2 to 4 million dollars (Fu et al., 2017).

Refracturing operations have some drawdowns associated with the availability of data on the surface and their rate of success is determined by many factors (Yanfang & Salehi, 2014). Therefore, it is important to consider all the associated factors of success of a refracturing operation and include a refrac plan in the initial stage of the well development phase to get a high return of investment in a short period (Dutta, 2017). One of the main factors of the refracturing operation success is the formation of the refrac. The refracture formation depends on the pressure distribution around the pre-existent fracture and the cluster spacing between the fracture stages. In some cases, a new fracture would be initiated and reaching more of the un-depleted spots in the reservoir, which dramatically increases the production of the well. However, in other cases, the refracture would be initiated through reopening the initial fracture (Fu et al., 2017). All these factors contributing to the refracture formation can lead to a high level of uncertainty that requires an intensive analysis of data before starting a refracturing operation.

Another factor to consider before starting a refracture operation is the completion fluid diversion technique for the operation. To successfully implement a refracture operation, the diverter used must remain plugging the pre-existent frac for at least two to four weeks period (Cookson, 2020). As a result, permanent diverters are recommended to be used in refracture operations. However, the use of diverter as a refracture completion technique can lead to a high level of uncertainty. When completing with diverting agents, it becomes difficult to determine the direction in which the fracture would propagate the formation. As a result, it is recommended to use expandable liners to control the flow direction of the fracture through mechanically isolating old zones and perforating new ones. The expandable liners have been used to complete more than 15 wells in the Marcellus, Barnett, and Eagle Ford from 2009 to 2015 (Jacobs, 2015). Although using a diversion agent is found to be cheaper than using an expandable liner as a diversion technique, expandable liner showed higher productivity gains in different cases (Jacobs, 2015).

Another important factor to consider for a refracturing operation is the depletion stage of the fractured well. A study conducted on 171 wells in the Barnett shale indicated that the production increased 2 to 4 times their initial production after refracturing, based on the studied well. The study concluded that it is better to refracture wells at an early stage of depletion (Wang et al., 2013).

In the Barnett Shale, a study was carried to predict the viability of refracturing 188 gas wells through reservoir simulation. The study suggested that the optimal time for refracturing the selected candidates is within a period of 3 to 5 years after initial production. The study also found that only 11 wells can be considered a good candidate for the refracture operation (Tavassoli et al., 2013). Another study conducted by Rath & Bielicki (2018) supported the claim of the previous study claiming that the number of refractured wells is only 2% of the number of new wells drilled each year in the Barnett Shale. However, other studies in the Barnett shale indicated a high increase of production from refracturing through the reorientation of the initiated frac from the pre-existent frac by introducing a new technique to divert the fracture fluid direction without mechanical interventions (Potapenko et al., 2019)

On the other hand, the Haynesville shale has witnessed a development in the refracturing operations over the past years. Reservoir simulation studies have been conducted in the Hayesville shale to predict the performance of refracturing operations on some of the wells in the play. One of the studies suggested a new method of modeling refracture by taking into consideration the alteration of the stresses around the producing fracture (Xu et al., 2017; Xu et al., 2019). Another study in the Haynesville shale suggested a new technique of completion that could be implemented in the refractured wells. The suggested completion technique considers using a self-removing chemical diverting agent to increase the production of the fractured wells (Krenger et al., 2015). In terms of refracturing candidate selection, a study was conducted in the Haynesville shale to select the perfect wells for refracturing operation. The study found that the main factors of selection are the initial completion of the wells, depletion stage, and stress distribution in the formation around the original fracture (Hunter et al., 2015).

In the Eagle Ford shale, a new completion method of fluid diversion was studied in five refractured wells and proven to be valuable through increasing the EUR by 140% through reaching un-depleted zones in the produced reservoir (Cadotte et al., 2018). In the same basin, another study was conducted by Pankaj & Shukla (2018) showed a major gain in the refrac production when using coiled tubing for the stimulation job, showing a production gain of 36% over other completion techniques. Other studies suggested a new solution for the process of candidate selection when choosing the right well for refracturing operations based on completion design, cluster spacing, initial production rate, and well spacing (McFall et al., 2017; Diakhate et al., 2015).

In the Marcellus shale, studies have suggested the use of small stages to mitigate the effect of "hell dominated fracture". In the Marcellus, it is also suggested to minimize the cluster spacing between stages when refracturing as it was proven to be more efficient based on the refractured wells production in the Marcellus (Yi et al., 2019; Rodvelt et al., 2015).

One of the most active plays in the United States is the Bakken play. The success of refracture operations was tested in the Bakken shale by comparing the production gains from the refracture, which showed high refracture production gain (Lantz et al., 2007). In a study conducted by Yao et al. (2007), a stress field redistribution was studied in detail through a surface tiltmeter to monitor the fracture initiation. Using the redistribution around the initiated fracture, the study predicts the initiation of the new fracture; either forming from a pre-existent fracture or formed as a separate fracture. The refracturing operations in the Bakken play have proven to be economically viable. Based on a study conducted by Indras & Blankenship (2015), it was proven that the generated net profit from refracturing is higher than the profit generated from drilling and fracturing a new well.

The refracturing operations were also tested in the Permian Basin. The stimulation effectiveness was reviewed in detail by comparing refracture production with the pre-refracturing production in the Permian basin in a study conducted by Leonard et al. (2016). The findings of the study indicated that in order to justify a successful refracturing operation, a detailed cost/benefit analysis of the isolation and diversion methods is required. Another study was carried in the Bone spring formation refractured wells to evaluate the refracturing completion technique by Athavale et al. (2019). The study found that the use of expandable liners as a diversion technique yields higher profit and production from the refractured wells.

In the Niobrara shale, a study conducted by Wolhart et al. (2007) showed the effect of refracture orientation in improving the productivity of the well through refracturing. The paper takes into consideration the effect of pressure distribution around the initial fracture on the refracture orientation in the Wattenberg field. In another study in the Niobrara shale showed the negative effect of refracture hits interference on the parent well in the Niobrara play (Miller et al., 2016). In the study, detrimental effects on the production of the parent wells were noticed due to the refracture interference from the offset child wells in the Niobrara.

This work aims to study the refracturing activities in the most active shale play in the United States in terms of production after refracturing. Besides, this study will compare the production gain through refracturing of each of the studied shale plays based on formation type and perforation length of the fracture.

2. DATA AND METHODS

2.1. FRACFOCUS DATA PROCESSING

The base data created for this study were extracted from the publicly accessible FracFocus database. FracFocus is a database created in 2011 to report all the chemicals used for the hydraulically fractured wells across the United States. In a previous study, the refractured wells were separated from the original data of the FracFocus database based on the job start date of the fracturing operations. The refractured wells were then processed and transformed into usable inputs (Shammam et al., 2021). In this study, the refractured wells database was further processed by eliminating the refractured wells that have a duration of less than one-month period between the original and the second fracture.

2.2. JOINING FRACFOCUS AND ENVERUS DATABASES

Enverus DrillingInfo is a database that contains the production and completion data of the produced oil and gas wells in the United States. Therefore, merging the two databases would give the ability to couple each refractured well with its production data before and after the refracturing operation. The next stage of data processing was joining the refractured wells taken from the processed FracFocus database with Enverus DrillingInfo database based on the well API number provided in both databases. The main objective of the study is to analyze the refracturing production for each shale play separately. From each shale play, a certain number of wells were selected, and their barrels of oil equivalent (BOE) production were averaged and analyzed three months before and after refracturing.

2.3. SELECTING DATA OF INTEREST FOR EACH SHALE PLAY

To ensure a valid averaging of production, for each shale play the following selection criteria were followed before averaging the production of each play:

1. Of the selected wells for each shale play, the wells should have approximately the same perforation length to give a relative representation of production gain to one another. For example, of the selected wells in the Eagle Ford, the perforation length

was around 5000 ft, while for the Bakken play the perforation length of the selected wells is 10000 ft.

2. The selected wells should have the same targeted formation of refrac. For instance, the targeted formation used for the wells in the Bakken play was the Nesson formation to ensure fair averaging for the selected wells for each play.
3. To ensure fair production gain comparison, each of the refractured wells should have at least three months of production before and after the refracturing operation. Table 1 shows a summary of the perforation lengths, targeted formations, and the number of wells for each shale play.

Table 1. Summary of the Selected Data

Shale Play	**Perforation Length (ft)**	**Targeted Formation**	**Well Type**	**Number of Wells**
Bakken	10,000	Nesson Formation	Horizontal	5
Barnett	250	Barnett Formation	Vertical	3
Eagle Ford	5000	Eagle Ford Formation	Horizontal	10
Haynesville	5000	Haynesville Formation	Horizontal	3
Marcellus	6500	Marcellus Formation	Horizontal	3
Niobrara	NA	Green River Formation	Deviated	5
Permian	5000	Delaware-Wolfcamp	Horizontal	10

2.4. ORIGINAL FRACS VS. REFRACS PRODUCTION DATA

Based on the previous selection criteria, a total number of 39 wells were examined. Each shale play included 3 to 10 refractured wells with the same specification (targeted formation, perforation length, wells type). For each shale play, average monthly production and average cumulative production were calculated three months before and after refracturing. Although the perforation length and the type of formation are the same for the studied wells for each play, there was still some variance in the monthly production between the wells. Therefore, standard deviation and median were included in the process of analyzing the data to show the variability and the skewness of production data for each month of production between the averaged wells.

3. RESULTS AND DISCUSSION

3.1. PRODUCTION GAIN PER SHALE PLAY

To calculate the production gain through refracturing, for each shale play, the 6-month period of production is divided into three months before refracturing and three months after refracturing. Each month's gain is then calculated by dividing its production after refracturing by its production before refracturing (e.g. month 1 after refrac divided by month 1 before refrac, and the same is true for months 2 and 3 before and after refracs). An average value for the monthly production gain is then calculated to represent the average three-month production gain for each shale play. Figure 1 shows the production gain from refracturing activities of the selected wells in each shale play. The percentage of increase distribution indicates the highest production gain is in the Eagle Ford play followed by the Bakken play. On the other hand, the lowest production gain occurs in the selected wells of the Permian and Haynesville plays, both plays have shown a low production gain of 32% and 34 %, respectively. The high variability in refractured wells production shows the importance of selecting the right candidate for refracturing before starting the stimulation process. Furthermore, the selected refractured vertical wells in the

Barnett shale have shown 47% increase from the original fracture, and the selected deviated wells for the Niobrara green river formation have shown 43% increase from original fracture.

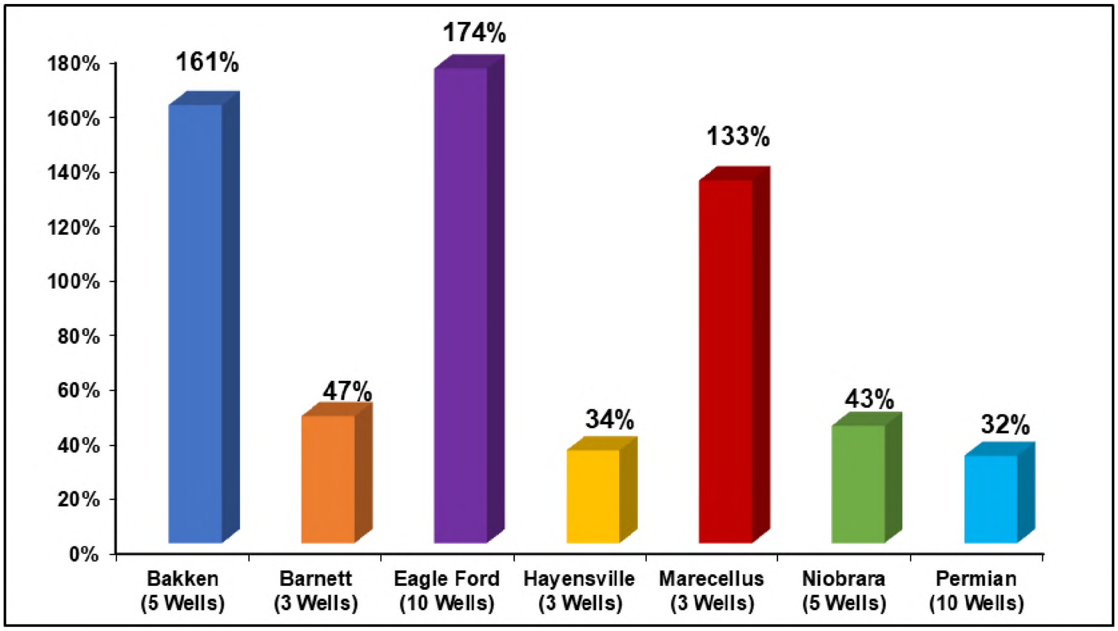

Figure 1. Refracturing Average Production Gain Per Play

3.2. BARNETT SHALE PLAY (PERFORATION LENGTH = 250 FT)

To examine the refracturing operations in the Barnett shale play, three refractured vertical wells were selected based on the criteria mentioned in the data and methods section. Figure 2 shows the average, median, and standard deviation of the production of three refractured wells; three months before and three months after refracturing. In terms of average monthly production, Figure 2 shows that the increase of production from refracturing was the highest during the second month after the refracturing operations exceeding 300 monthly BOE and then dropping below 270 BOE in the third month after refracturing.

Comparing the production of the studied wells, the median gives a better representation of the central tendency of the studied wells since the median is the middle of the data. Therefore, the median of the BOE produced was also taken into consideration when comparing the production of the studied wells before and after the refracturing operation. For the first and second months prior to refracturing, the average and median were significantly different. This shows that the data are skewed from the middle. On the other hand, the median and average of month 3 before refracturing as well as the first three months after refracturing were not significantly different, especially for the second month after refracturing, meaning the data are decently centered. The standard deviation was also calculated and shown in Figure 2 which measures the variability of the data. In other words, the standard deviation can show the variability in the response of each well to the refracturing operations in the studied area. The highest standard deviations were observed in the 2nd and 3rd months after refracturing. This shows that the refracturing response can be significantly different from one well to another. Thus, there are other factors than the formation type and perforation length that control the response to the refracturing operation for the refracturing production since in this case some wells produced higher than other wells with the same formation type and perforation length.

The cumulative production is also shown in Figure 2. The studied wells have shown major production gain in the second month after the refracturing operation, showing a production gain of more than 165 BOE compared to the 1st month of production after refracturing. Furthermore, the studied wells in the Barnett play have shown a refracture production gain of 47% through refracturing. To sum it up, the refracturing activities in vertical wells provided successful results in terms of production enhancements. A daily production history of a well located in this shale play is included in the Appendix.

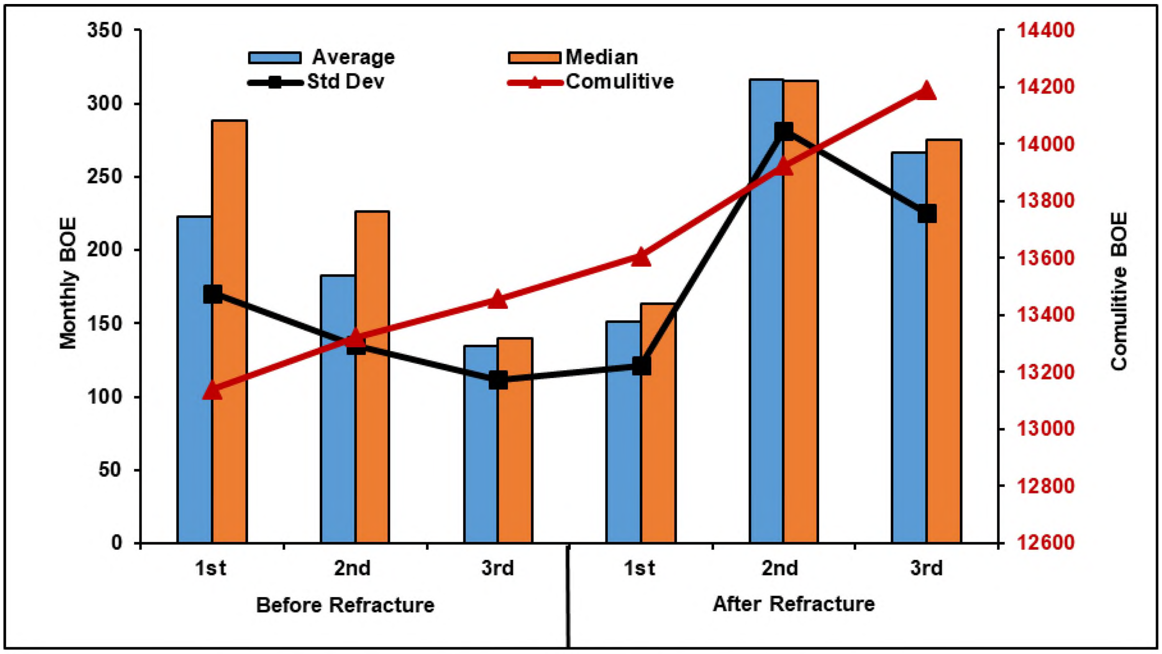

Figure 2. Refracturing Production Gain in the Barnett Play

3.3. EAGLE FORD, HAYNESVILLE, AND PERMIAN SHALE PLAY

Figure 3 shows the production gain from the refracturing operations in the Eagle Ford shale generated from the production data of 10 wells with 5000 ft perforation length. Based on the average production gain, the first month of production after refracturing showed the highest gain of production with an average of 7400 BOE, which dropped to a gain of 6800 BOE compared to the month before refracturing. However, based on the median of the produced wells, the produced wells reached their highest production in the 2nd month after the refracturing operation reaching a median increase of 3000 BOE compared to the 3rd month before refracturing, which has been the case for most of the studied plays in this study.

In Figure 3, the lowest value of standard deviation appears in the month before the refracturing operation, showing that the variability in the production of the studied wells before the refracturing operation is not significant. Nevertheless, there is a high variance in the production response to the refracturing operation in the months after refracturing operations, showing that in the studied wells, the refracturing production is different from one well to another and cannot be predicted based on the formation type and perforation length factors only.

The cumulative production of the refractured wells has shown a major increase in production after refracturing with an increase of 8000 BOE in cumulative production in the first month after refracturing, which kept increasing over the three months after refracturing. In terms of production gain, the Eagle Ford shale wells had the highest production gain among the studied plays reaching a 174% increase from initial production after refracturing.

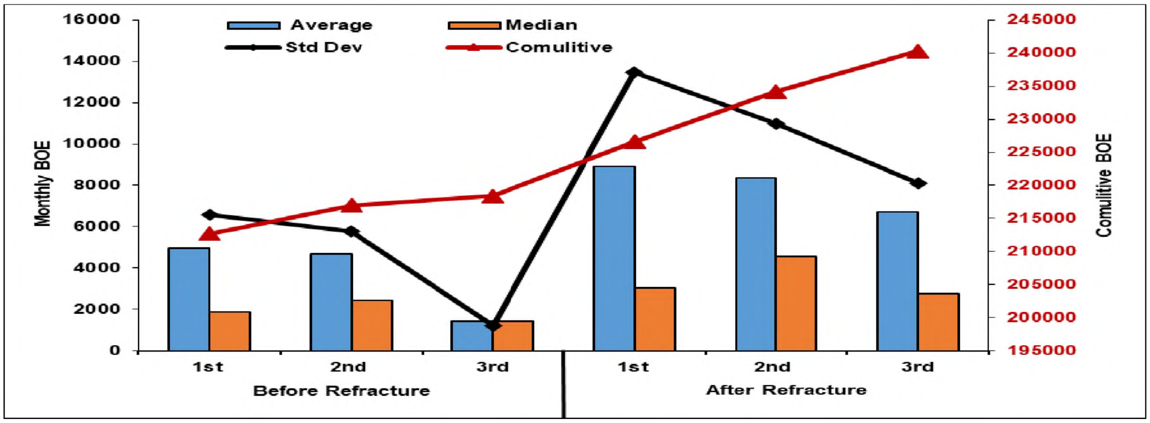

Figure 3. Refracturing Production Gain in the Eagle Ford Play

Figure 4 shows the production gain of refracturing operations in the Haynesville play based on analyzing the production data of 3 wells in the play. As shown in Figure 4, the highest gain of production was shown in the first month of production after the refracturing operation and the production kept increasing for two months after refracturing before it dropped down in the third month after refracturing. In terms of median monthly production, Figure 4 shows that the increase of production from refracturing was highest during the second month after the refracturing operations exceeding 45000 monthly BOE and then dropping to 40805 BOE in the third month after refracturing.

Based on the standard deviation of the monthly BOE of the produced wells, before the refracturing operation of the 3 studied wells, some wells were highly producing while other wells were relatively producing a lower value of BOE, which is the main reason for the high standard deviation of the monthly BOE being higher in the month before refracturing. However, the production response to the refracturing operation of the selected wells is relatively closer with a lower variability of the monthly BOE in the 3rd month of production after the refracturing.

The cumulative production is also shown in Figure 4. The studied wells have shown a slight production gain in the second month after the refracturing operation. The studied wells in the Haynesville play have shown a refracture production gain of 34% from initial production after refracturing, which indicates a low production in the studied wells of the Haynesville compared to the studied wells located in different shale plays.

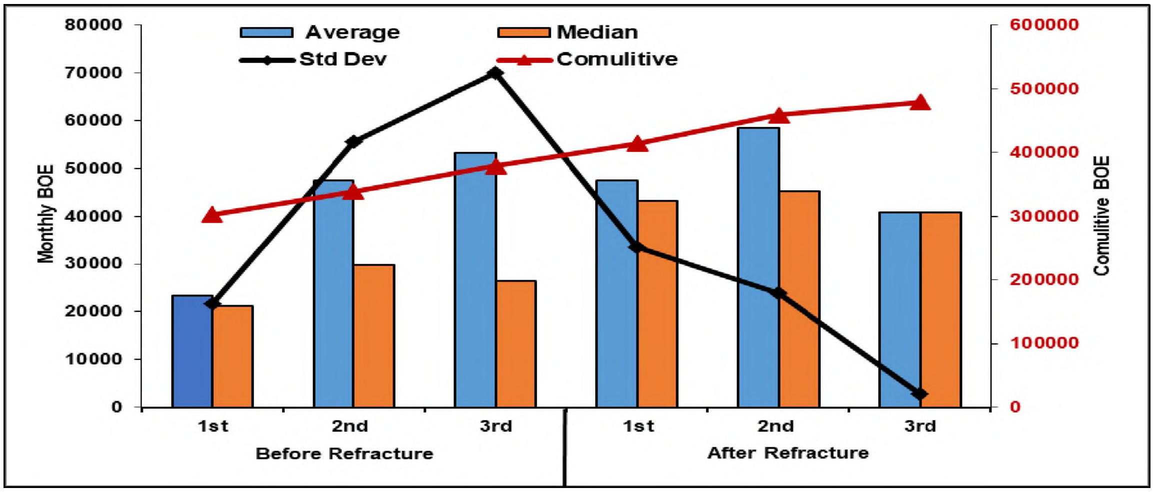

Figure 4. Refracturing Production Gain in the Haynesville Play

Figure 5 shows the production gain of 10 wells in the Delaware-Wolfcamp formation in the Permian shale. In terms of production gain from refracturing, the highest gain of production was obtained during the second month after refracturing with a median gain of 15000 BOE and it went slightly lower by the third month after refracturing, decreasing by a value of 1000 BOE in the third month of production after refracturing. Although all the selected refractured wells had the same formation type and perforation length, the standard deviation was relatively high for all the months before and after refracturing, showing a high variation of production in the 10 studied wells in the Delaware-Wolfcamp formation.

As shown in Figure 5, over the months after refracturing, the studied wells have not shown any major gain in terms of cumulative production. As a result, the studied wells in the Permian play showed the lowest production gain from refracturing with an increase of 32% of initial production. A daily production history of the wells located in these shale plays is included in the Appendix.

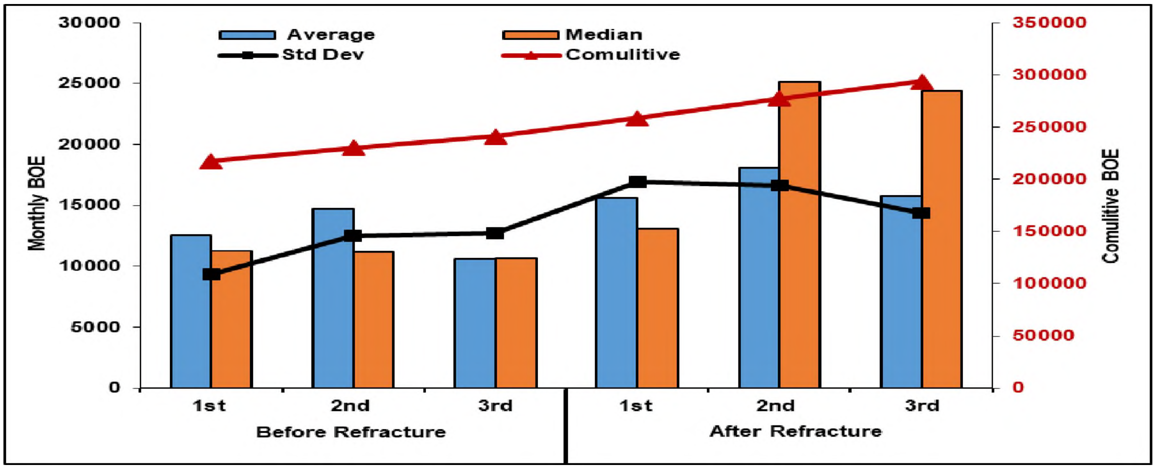

Figure 5. Refracturing Production Gain in the Permian Play

3.4. MARCELLUS SHALE PLAY (PERFORATION LENGTH = 6500 FT)

Figure 6 shows the production gain of 3 refractured wells in the Marcellus play with a perforation length of 6500 ft. In terms of average production, the highest production was achieved during the second month after refracturing an average of more than 3500 Monthly BOE. The production gain of the second month after refracturing was maintained for the next month as well showing a promising refracture gain in the in the studied wells of the Marcellus.

Based on the fluctuation of the standard deviation curve in Figure 6, it could be noticed that the response to the refracturing operation was different in the 2nd and 3rd months after refracturing with some wells producing higher than other wells. The selected wells in the Marcellus have shown a major gain of production from refracturing restoring 133% of initial production. A daily production history of a well located in this shale play is included in the Appendix.

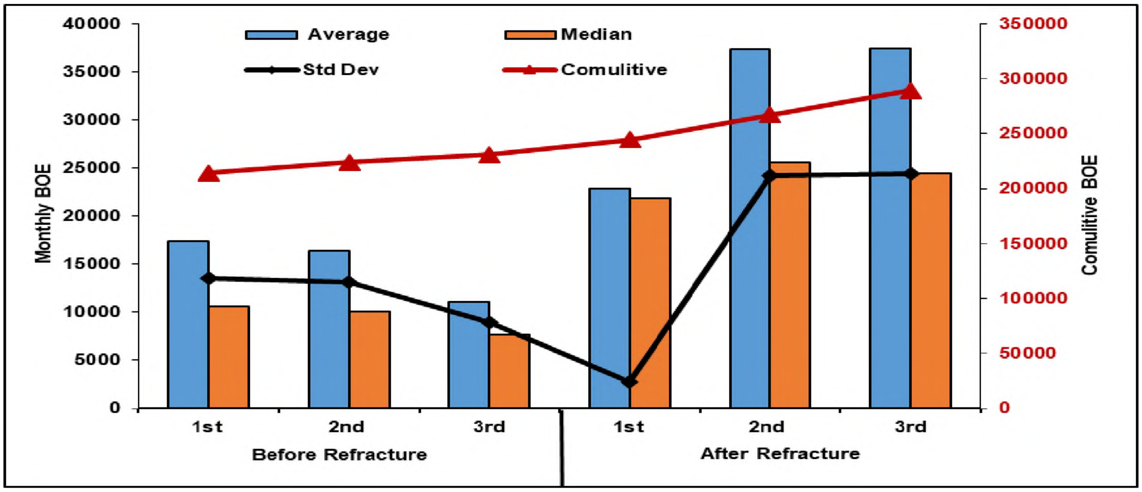

Figure 6. Refracturing Production Gain in the Marcellus Play

3.5. BAKKEN SHALE PLAY (PERFORATION LENGTH = 10,000 FT)

Figure 7 shows the refracturing production gain based on the production of 5 wells in the Nesson formation in the Bakken play with a perforation length of 10,000 ft. In terms of production gain from refracturing, the studied wells in the Bakken play had a very high production gain from refracturing with an increase of 160% of production after refracturing. As shown n Figure 7, the highest increase of production was gained during the 1st and 2nd months after refracturing and started to drop by the third month after refracturing with a median drop of 1000 BOE and an average drop of 2000 BOE. As a result of the high productivity of the second month after refracturing, the highest increase in the average cumulative production of the studied wells is achieved during the third month of production after refracturing

In Figure 7, based on the standard deviation of the 5 studied wells, the increase of production from refracturing was different between wells with some wells producing higher than other wells from refracturing. However, based on the median and average monthly production it can be perceived that the overall production from refracturing is very high in the Bakken play as mentioned before. A daily production history of a well located in this shale play is included in the Appendix.

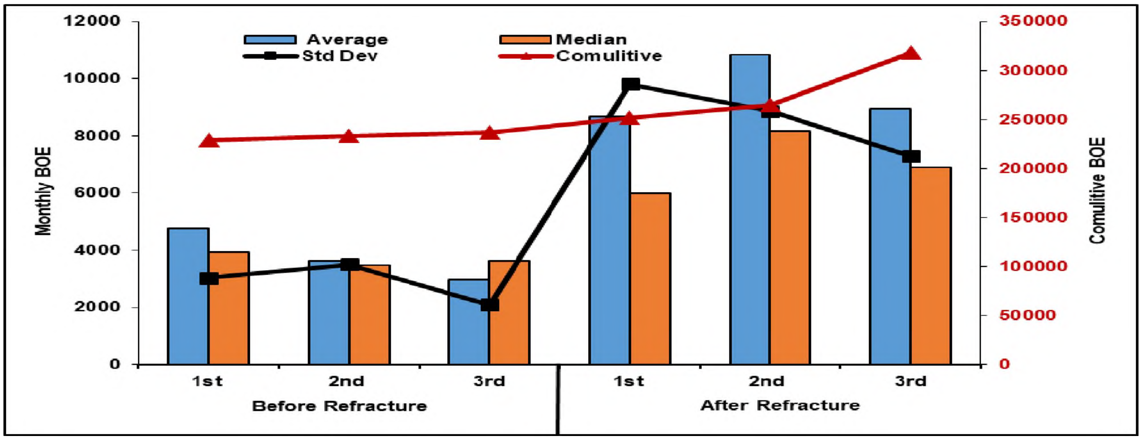

Figure 7. Refracturing Production Gain in the Bakken Play

3.6. NIOBRARA SHALE PLAY

Figure 8 shows the refracturing production gain of 5 wells in the green river formation in the Niobrara shale play. In terms of production gain, 43% of initial production was restored from refracturing operation for the studied deviated wells in the Niobrara play. The major gain of production occurred in the second month after refracturing reaching an average Monthly production of more than 2000 BOE. However, based on the production data there was no major increase of production form refracturing in the studied deviated wells in the Niobrara play. Based on the high value of standard deviation, the variation of production between the wells is relatively high, showing a different response of production to refracturing through the studied wells. A daily production history of a well located in this shale play is included in the Appendix.

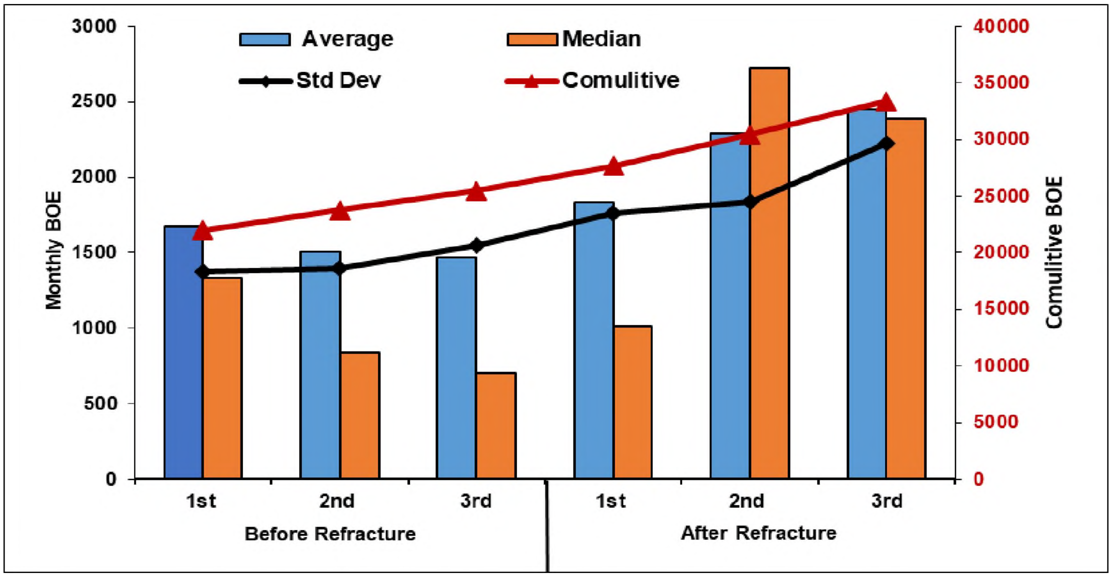

Figure 8. Refracturing Production Gain in the Niobrara Play

4. CONCLUSION

Refracturing horizontally drilled wells has been an active trend over the past decade. In this research, the refracturing process has been analyzed and diagnosed based on the production data of 44 wells located in the most active shale plays in the United States. Based on the analyzed production data, the following conclusions were made:

- Overall, the refractured wells achieved their maximum production by the second month of production after refracturing and started to decrease during the third month of production post refracturing.
- Refracturing operations have proven to increase production in vertical, deviated, and horizontal wells.

- Of the 39 researched wells across the major shale plays, the highest production gain from refracturing is achieved in the Eagle Ford with a 174% increase from production before refracturing followed by Bakken (160%), Marcellus (133%), Barnett vertical wells (46%), Niobrara deviated wells (43%), Haynesville (34%), and Permian (32%).
- Based on the studied wells, refracturing treatment is a successful stimulation technique to restore high production gain over a short period of time.
- Although having the same perforation length and formation, most shale plays had high variability in terms of production from each well that was refractured, suggesting more factors contribute to the production gain of refracturing operations. Furthermore, it can be concluded that refracturing candidate selection is an important process to guarantee a successful refracturing treatment.

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SECTION

4. SUMMARY CONCLUSIONS

In this study, a data of 1200 wells were created from FracFocus database registry and further processed to study the refracturing activities in the major US shale plays in terms of treatment type and number of fracture operation per well. Of the 1200 studied wells, 39 refractured wells production data were diagnosed and analyzed to test the efficiency of refracturing treatment as a stimulation technique, the following conclusion were made based on the study:

- 1200 wells were refractured in the major shale plays in the United States
- Refrac candidate selection can be identified based on the following factors: cluster spacing, well spacing, proppant distribution, fracture reorientation, production response from initial fracture, and reservoir properties.
- In terms of treatment type, the most common treatment type is the Hybrid treatment, followed by, Slick Water Treatment, and Cross-Linked Gel treatment, respectively
- Niobrara shale play was the most active play in terms of refracturing activities between the years 2013 to 2020.
- The maximum production gain for the studied refractured wells were achieved by the second month after refracturing and started to decrease by the third month after refracturing

- Based on the production gain of the 39 studied refractured wells across the major US shale plays, refracturing stimulation is an efficient treatment technique to increase productivity over a short period of time
- The highest production gain from refracturing is achieved in the studied wells of the Eagle Ford play reaching a production gain of 174% increase from production pre-refracturing.

APPENDIX

DAILY AVERAGE PRODUCTION OF REFRACTURED WELLS

The figures below are used to show the daily average production of the refractured wells in BOE. To validate the production gain through refracturing, each figure includes a well from the selected wells for each shale play included in paper 2. The figures are used to study the trend of the production gain due to refracturing. For most of the refractured wells, the refracture gain was not sustained for a long period of time after the refracturing operation.

1. AVERAGE DAILY PRODUCTION OF HAYNESVILLE PLAY WELLS

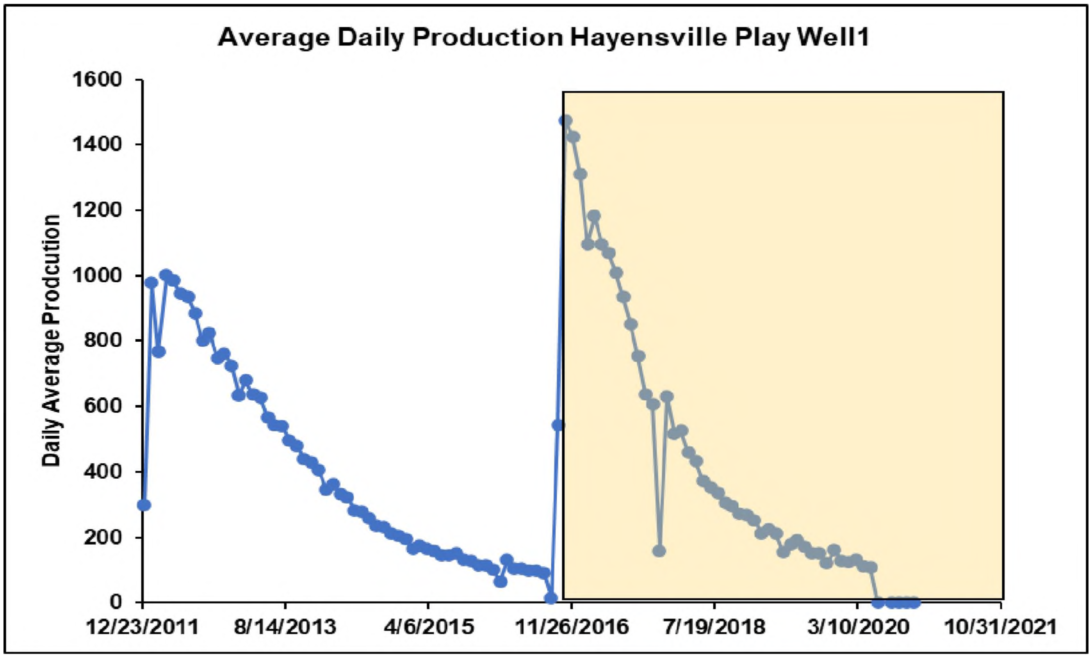

Figure A.1. Average Daily Production of a Refractured Well in the Haynesville Play

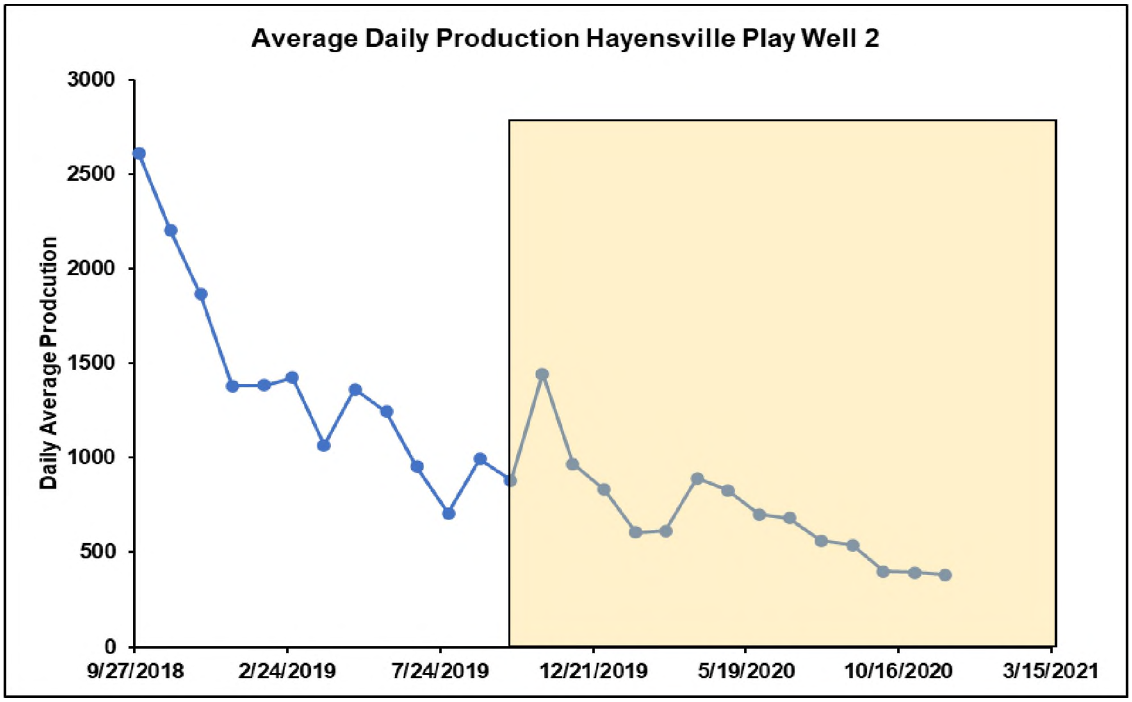

Figure A.2. Average Daily Production of a Refractured Well in the Haynesville Play

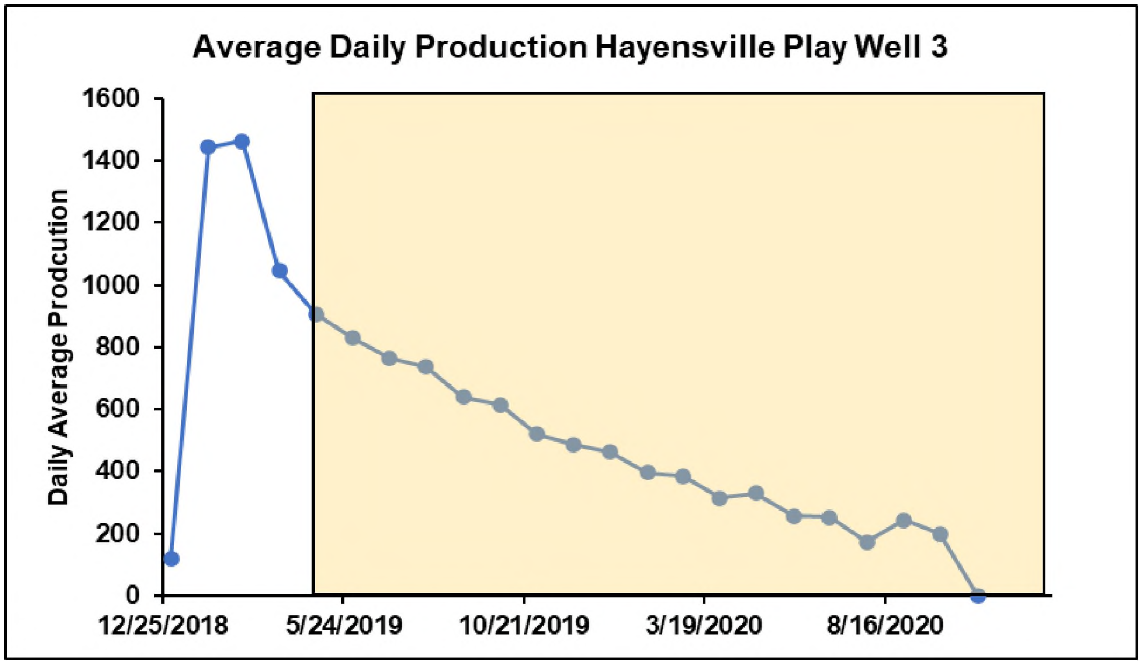

Figure A.3. Average Daily Production of a Refractured Well in the Haynesville Play

2. AVERAGE DAILY PRODUCTION OF THE PERMIAN PLAY WELLS

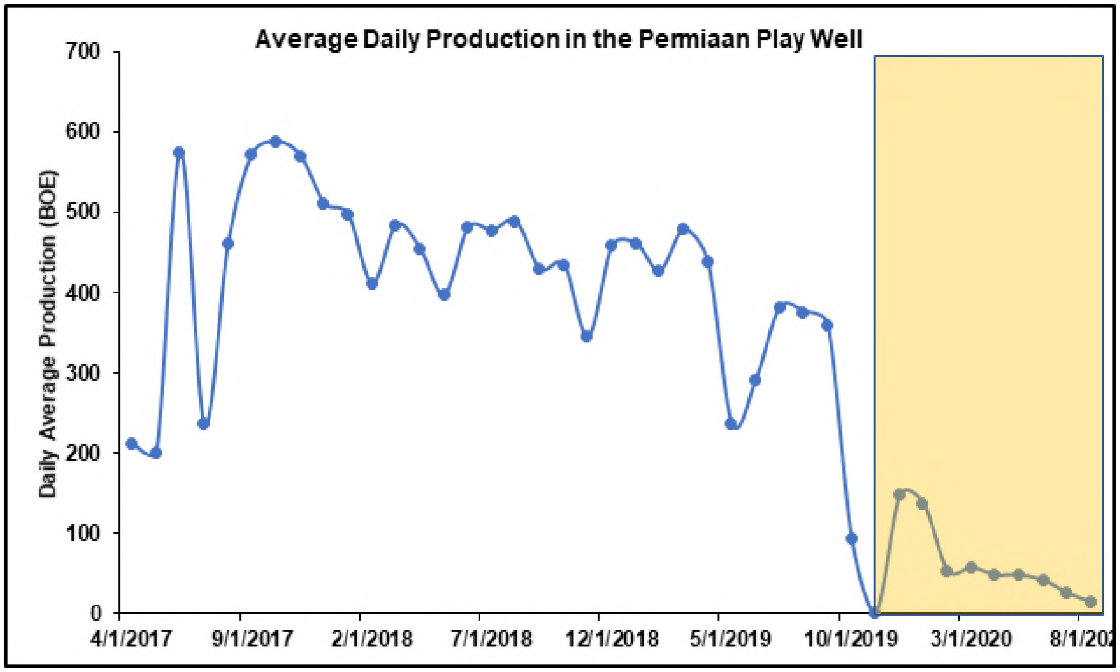

Figure A.4. Average Daily Production of a Refractured Well in the Permian Play

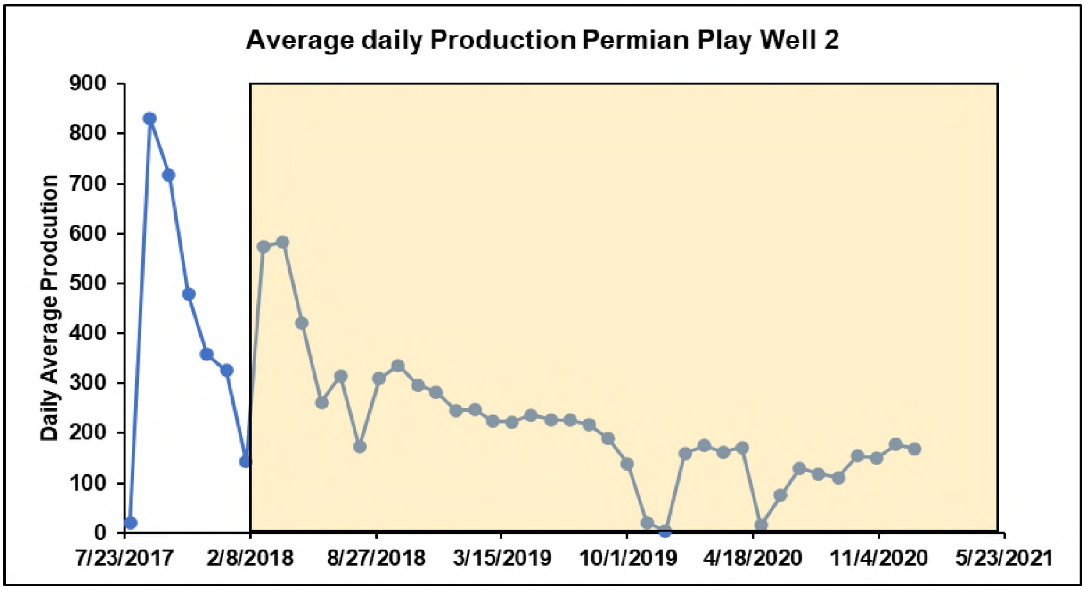

Figure A.5. Average Daily Production of a Refractured Well in the Permian Play

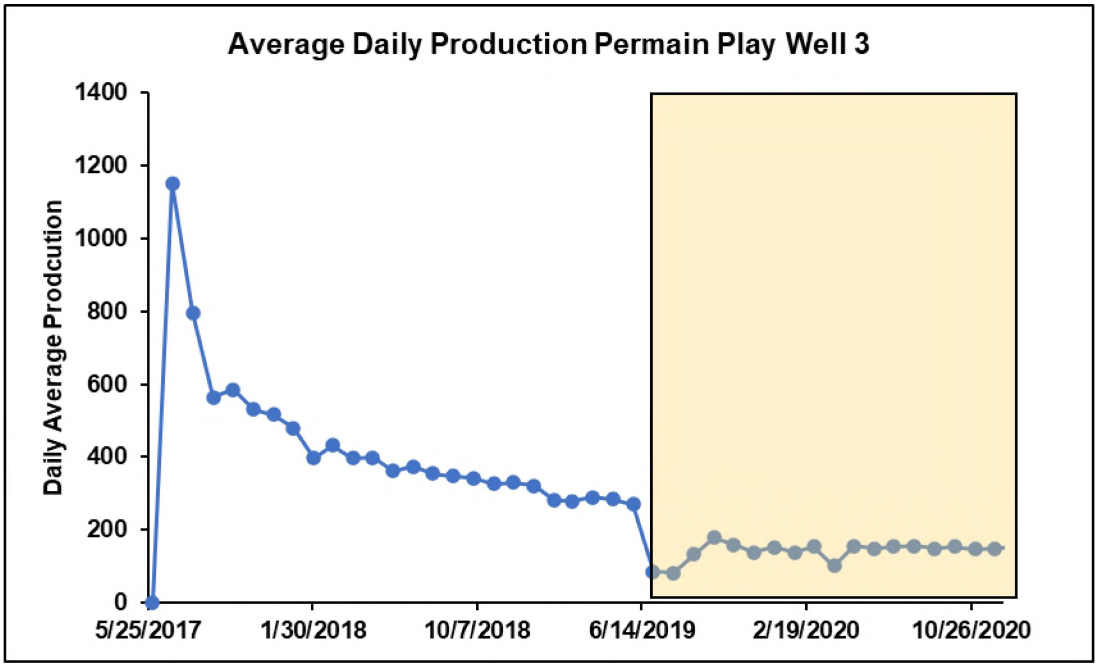

Figure A.6. Average Daily Production of a Refractured Well in the Permian Play

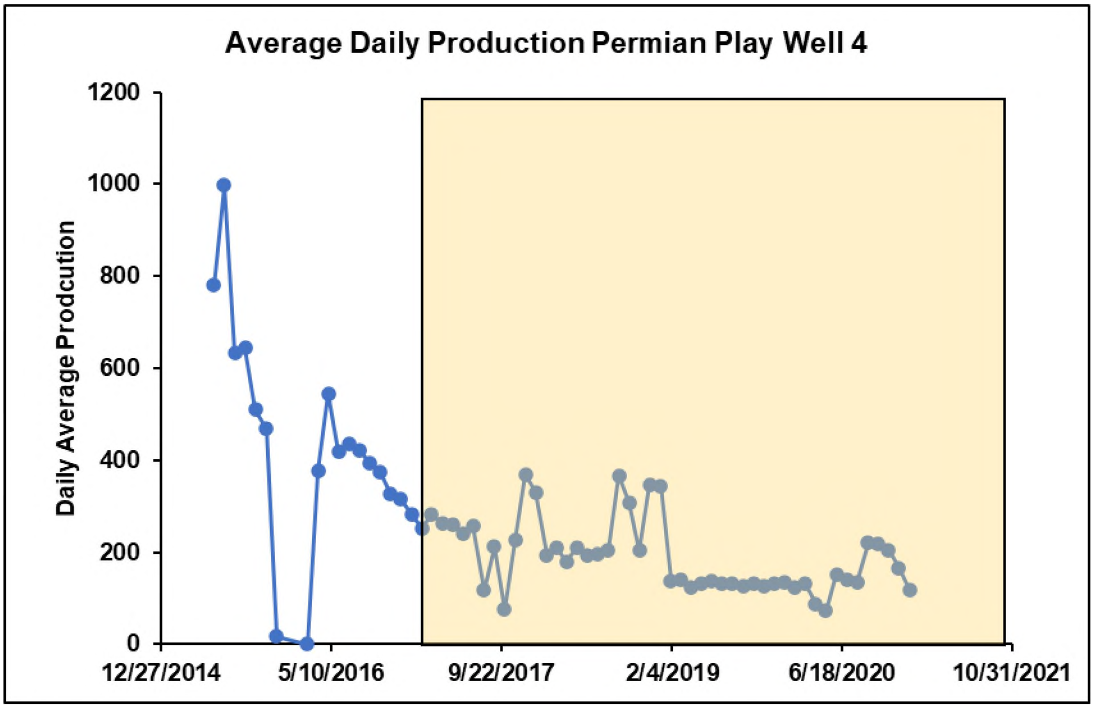

Figure A.7. Average Daily Production of a Refractured Well in the Permian Play

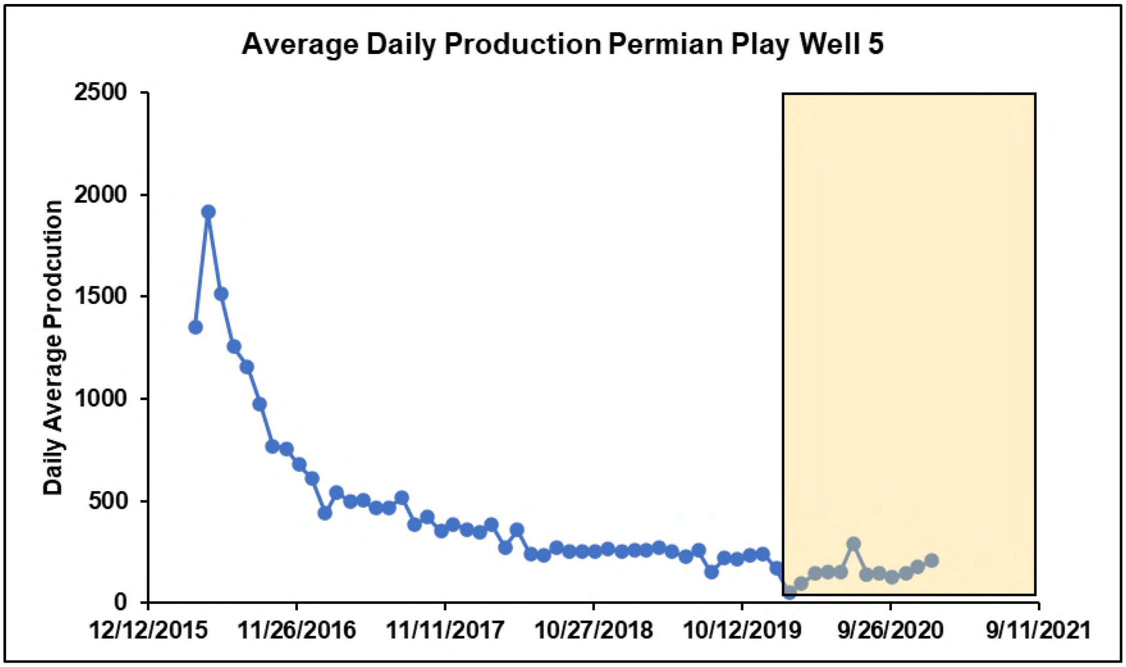

Figure A.8. Average Daily Production of a Refractured Well in the Permian Play

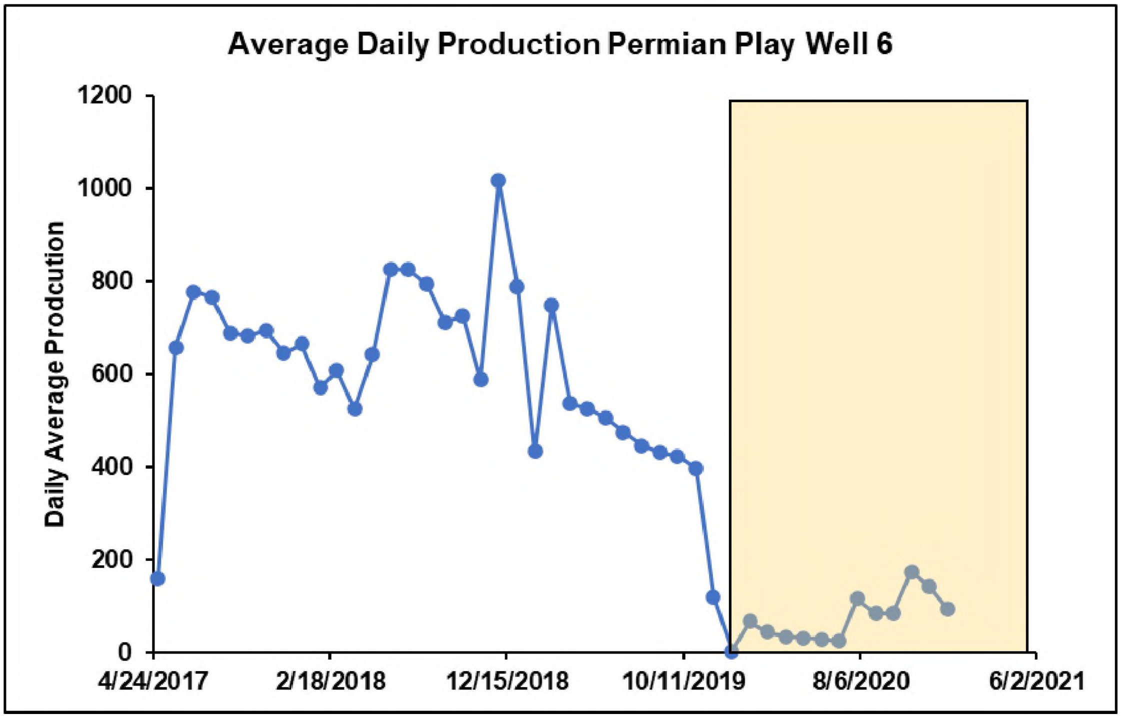

Figure A.9. Average Daily Production of a Refractured Well in the Permian Play

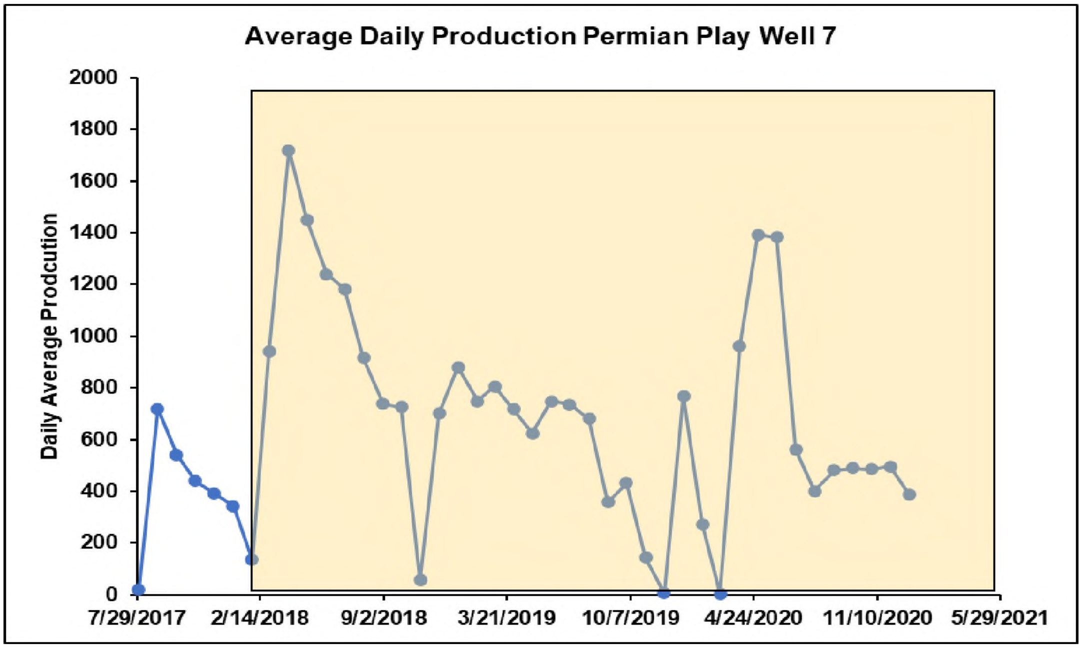

Figure A.10. Average Daily Production of a Refractured Well in the Permian Play

3. AVERAGE DAILY PRODUCTION OF THE NIOBRARA PLAY WELLS (DEVIATED WELLS)

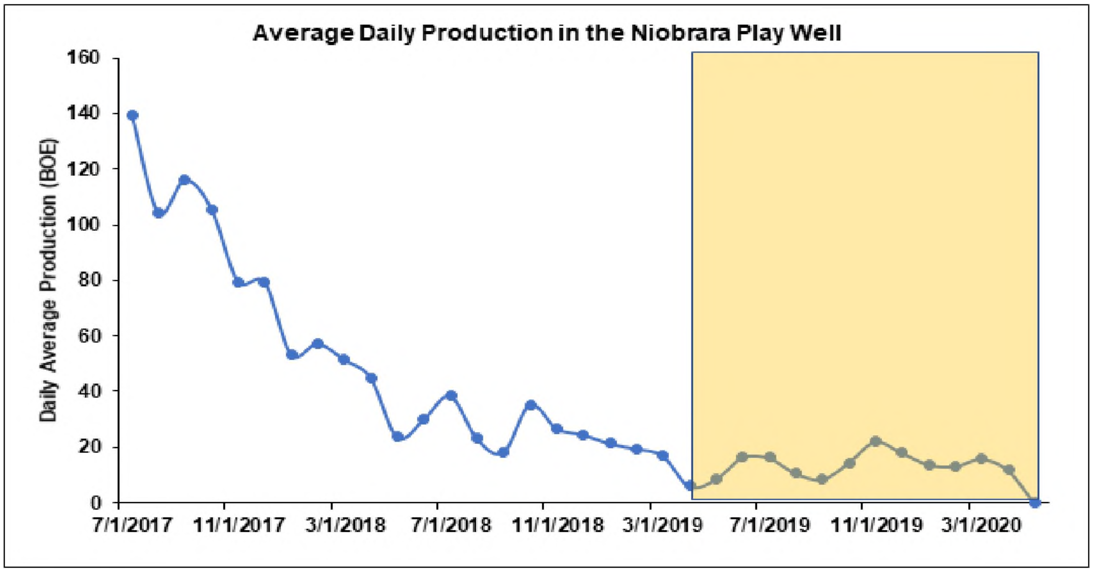

Figure A.11. Average Daily Production of a Refractured Well in the Niobrara Play

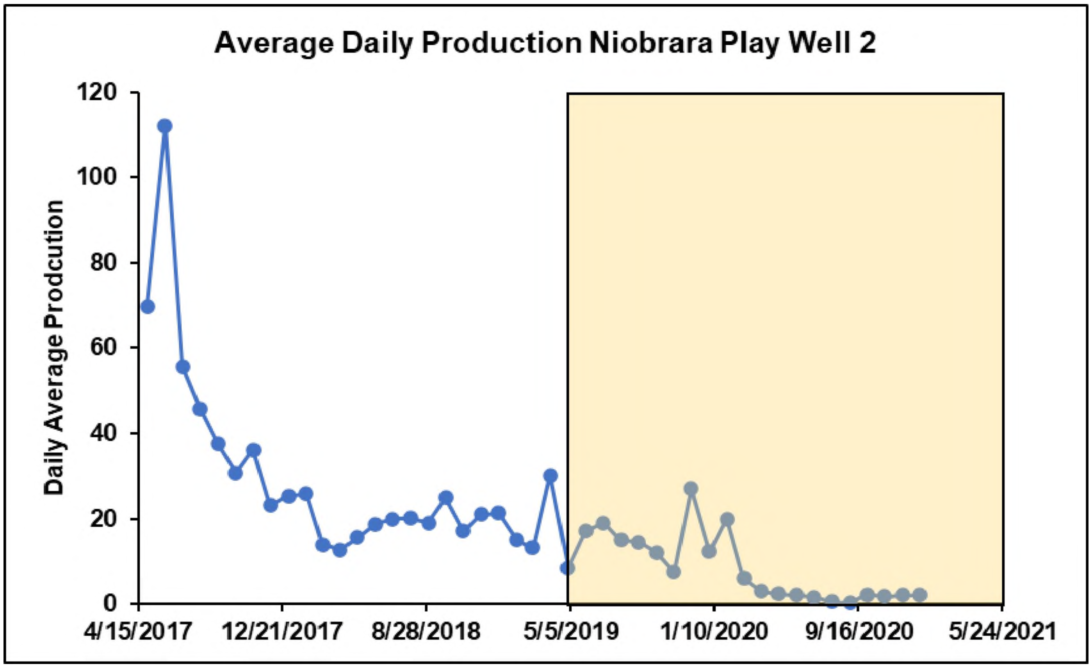

Figure A.12. Average Daily Production of a Refractured Well in the Niobrara Play

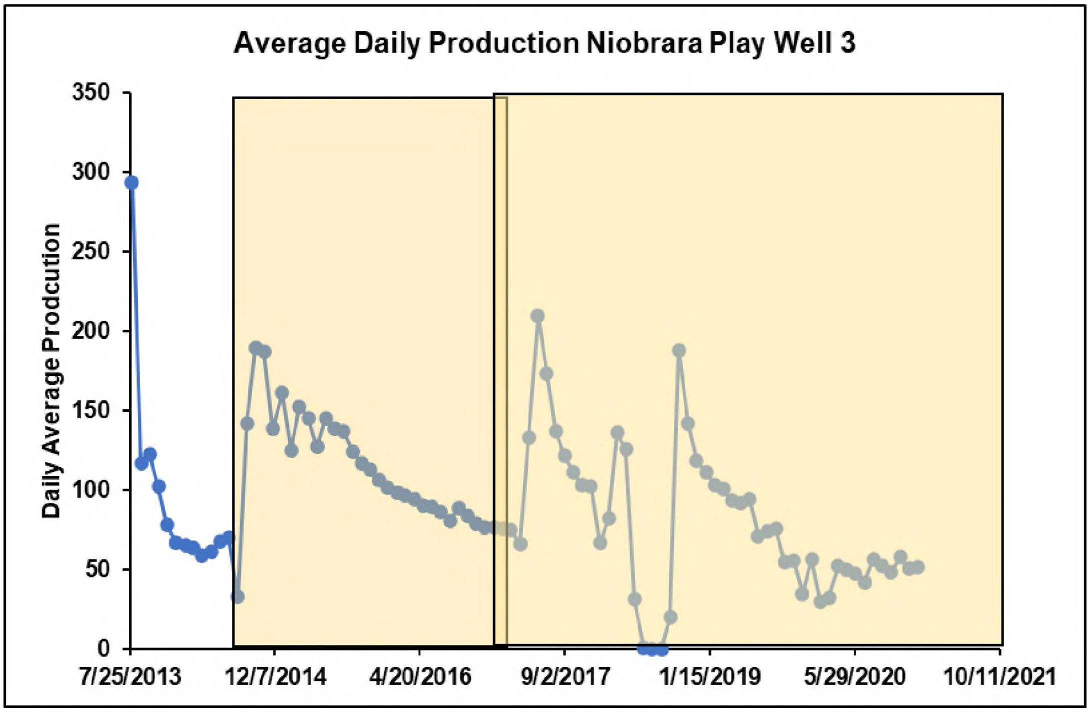

Figure A.13. Average Daily Production of a Refractured Well in the Niobrara Play

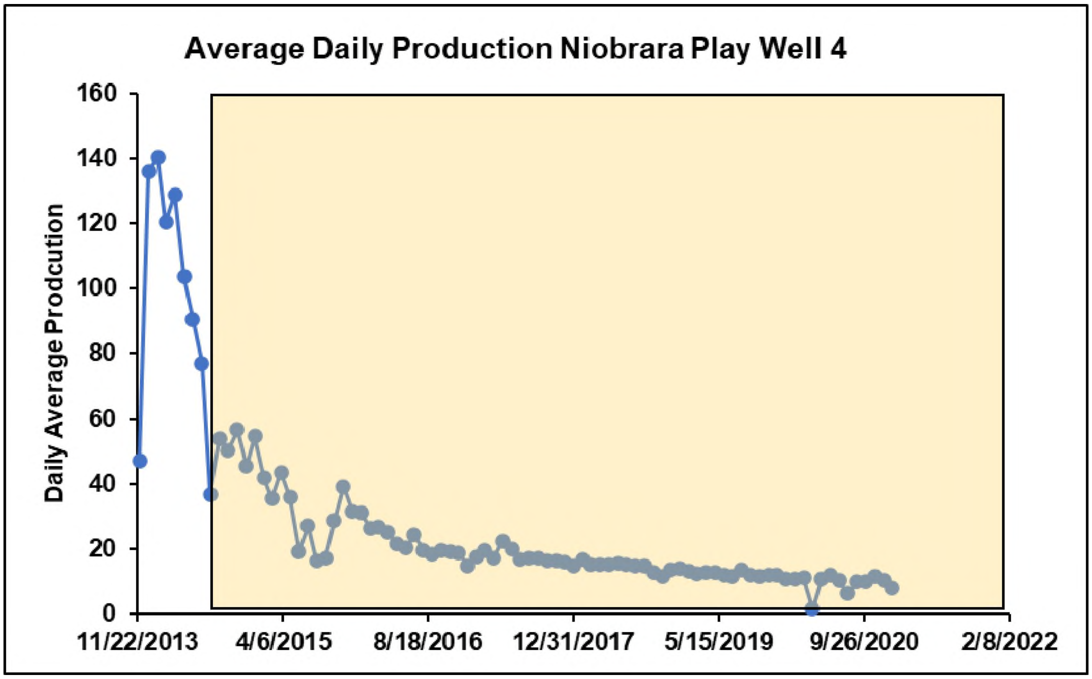

Figure A.14. Average Daily Production of a Refractured Well in the Niobrara Play

4. AVERAGE DAILY PRODUCTION OF THE EAGLE FORD PLAY WELLS

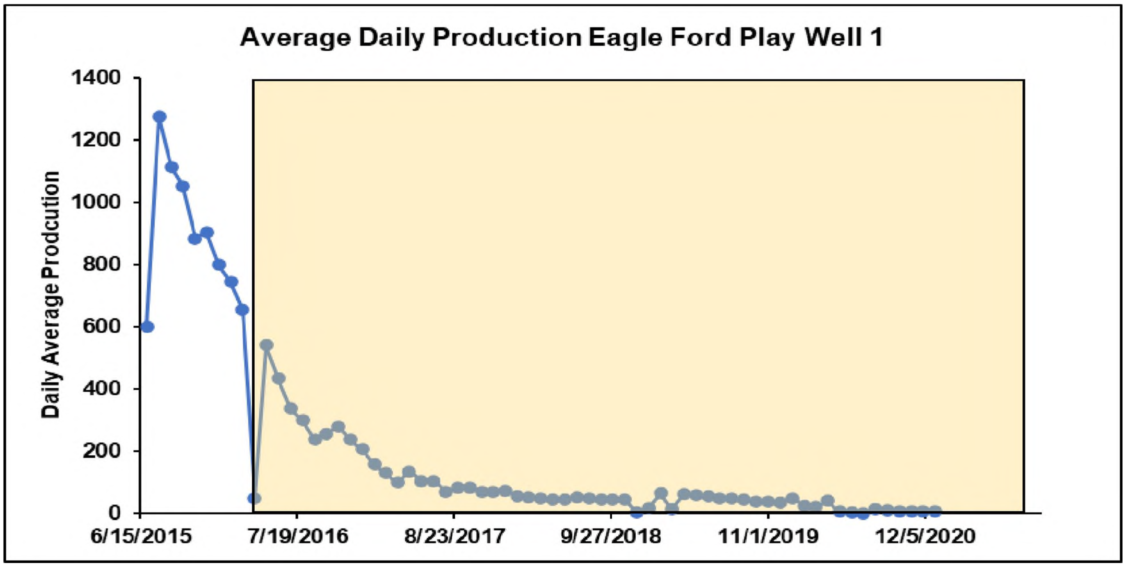

Figure A.15. Average Daily Production of a Refractured Well in the Eagle Ford Play

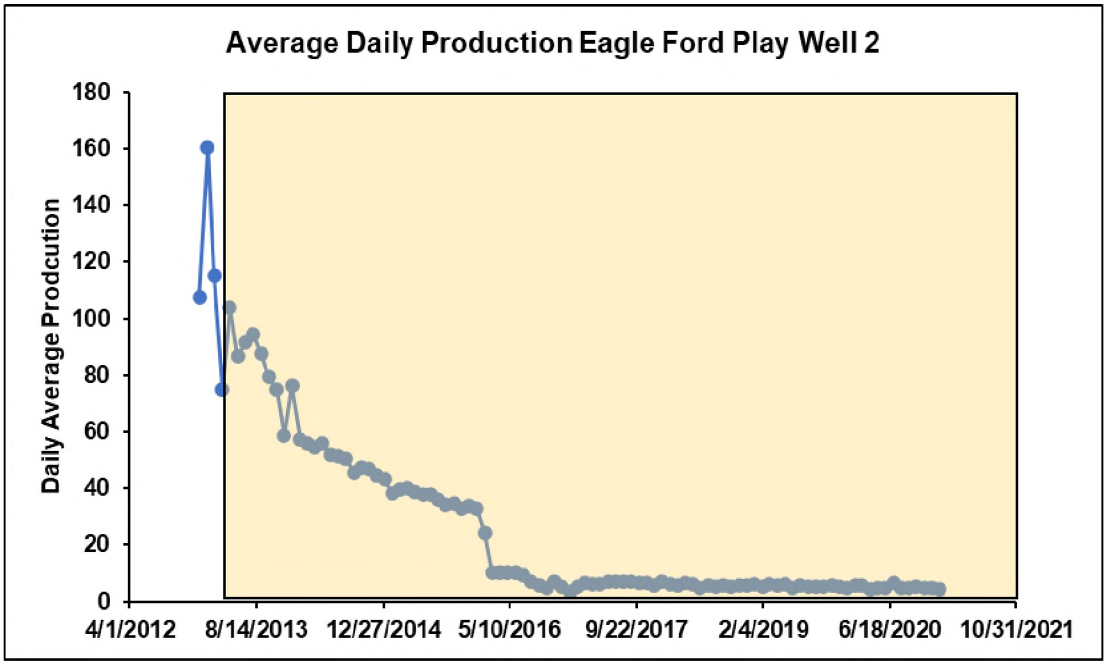

Figure A.16. Average Daily Production of a Refractured Well in the Eagle Ford Play

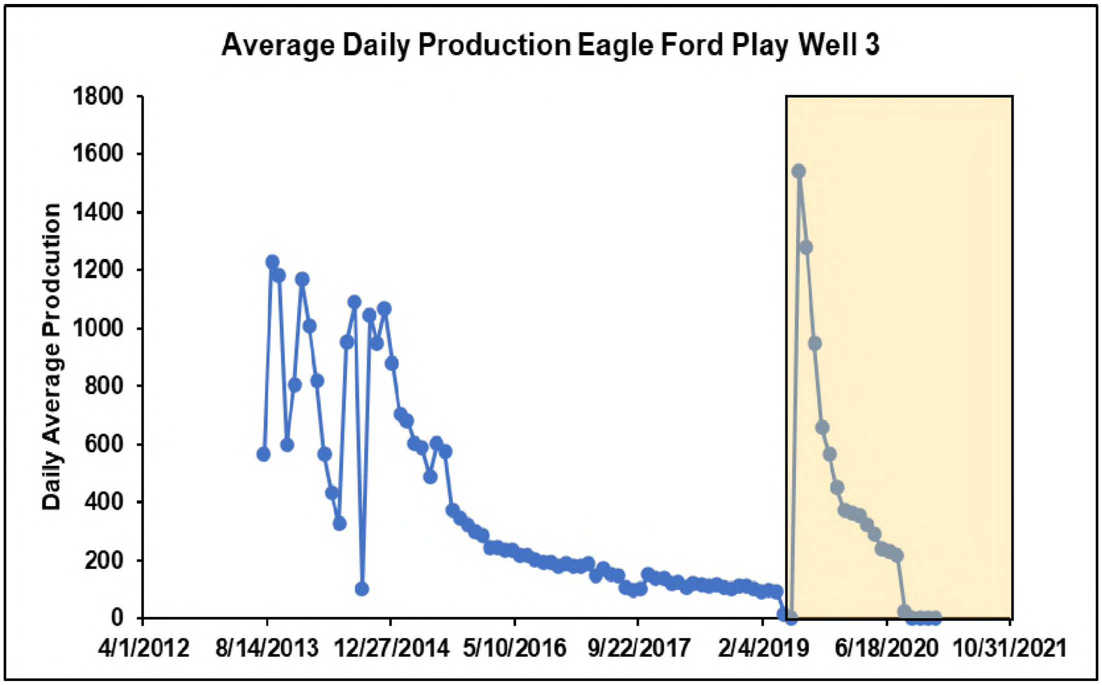

Figure A.17. Average Daily Production of a Refractured Well in the Eagle Ford Play

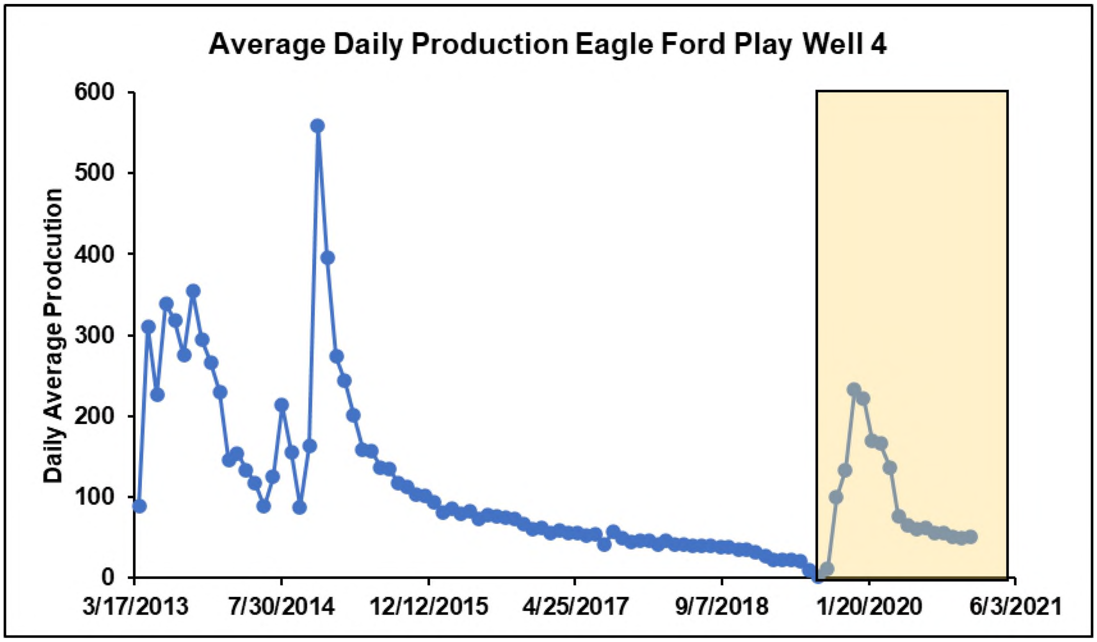

Figure A.18. Average Daily Production of a Refractured Well in the Eagle Ford Play

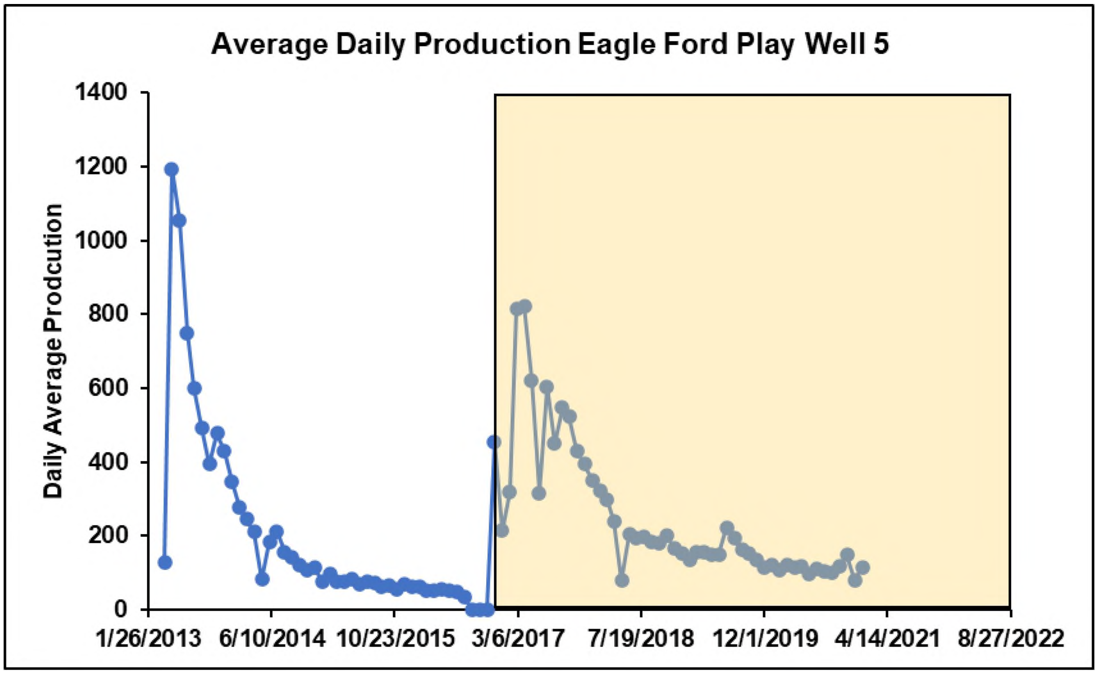

Figure A.19. Average Daily Production of a Refractured Well in the Eagle Ford Play

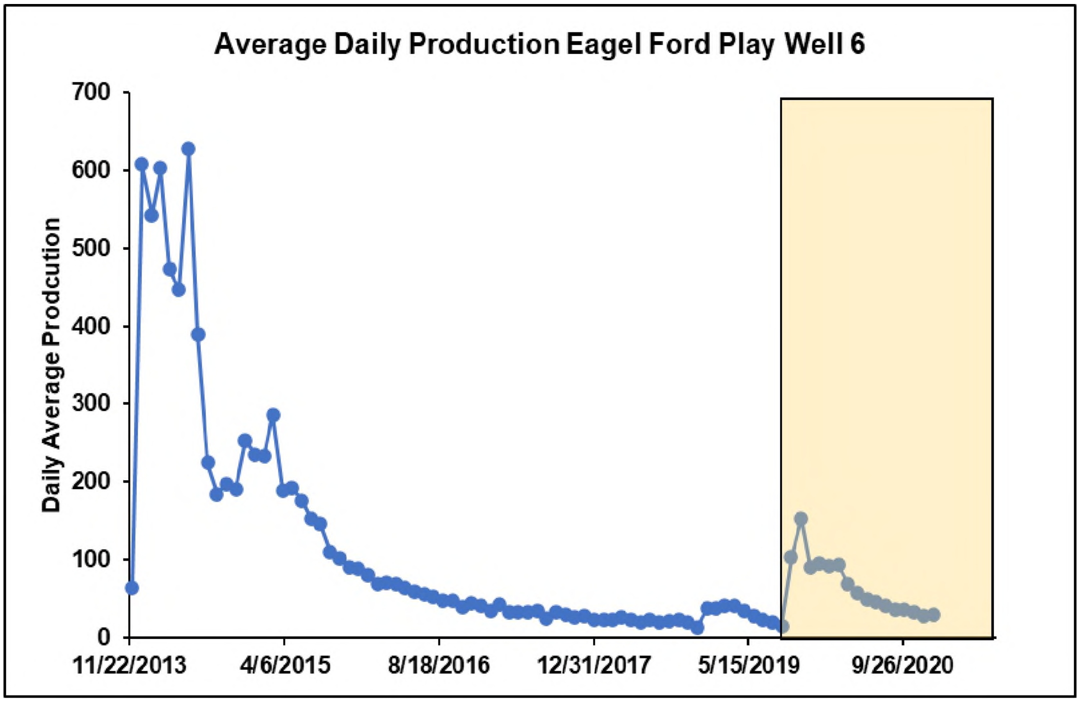

Figure A.20. Average Daily Production of a Refractured Well in the Eagle Ford Play

5. AVERAGE DAILY PRODUCTION OF THE MARCELLUS PLAY WELLS

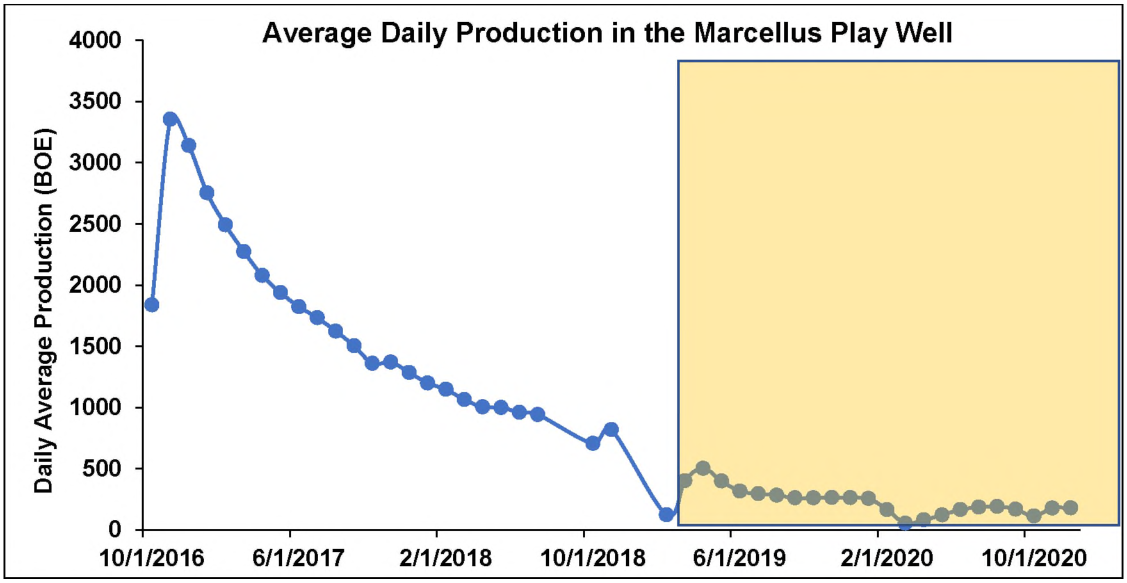

Figure A.21. Average Daily Production of a Refractured Well in the Marcellus Play

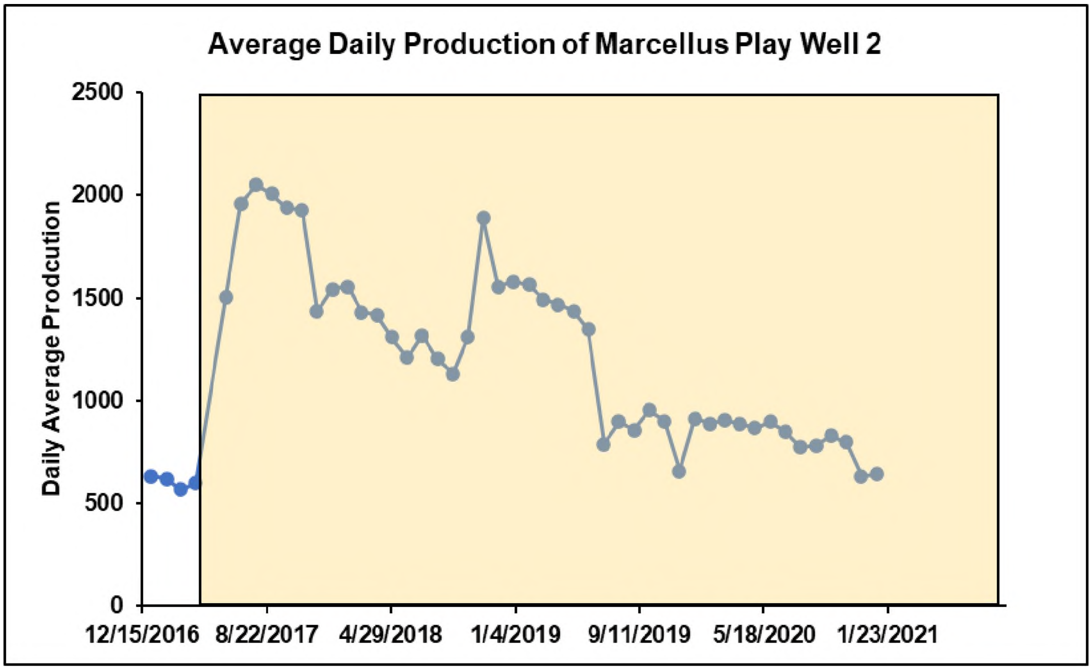

Figure A.22. Average Daily Production of a Refractured Well in the Marcellus Play

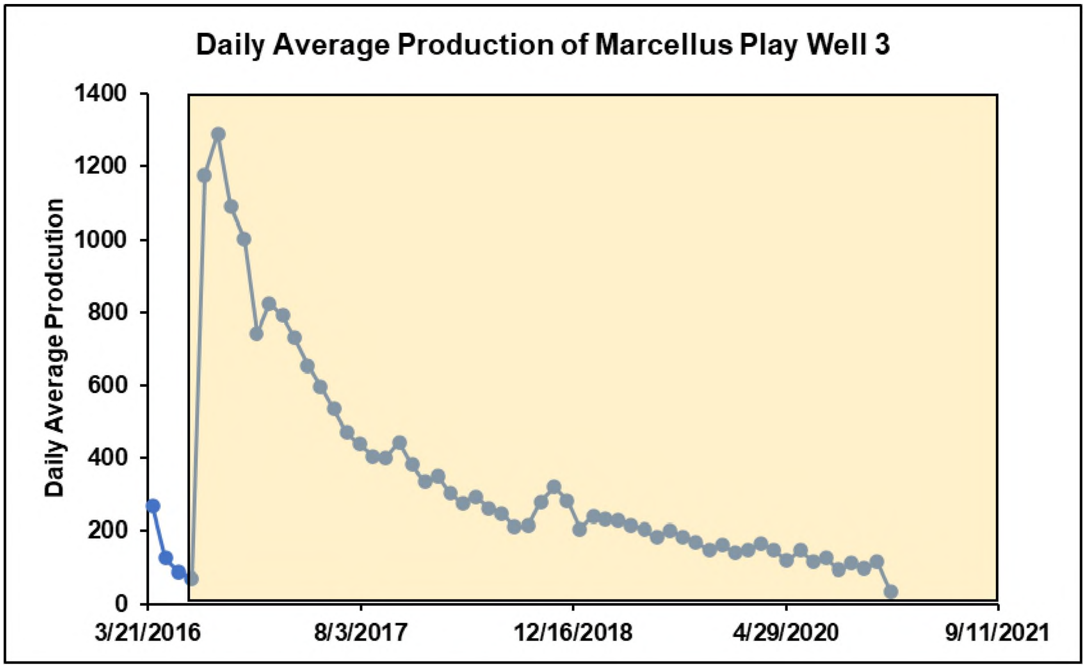

Figure A.23. Average Daily Production of a Refractured Well in the Marcellus Play

6. AVERAGE DAILY PRODUCTION OF THE BARNETT PLAY WELLS (VERTICAL WELLS)

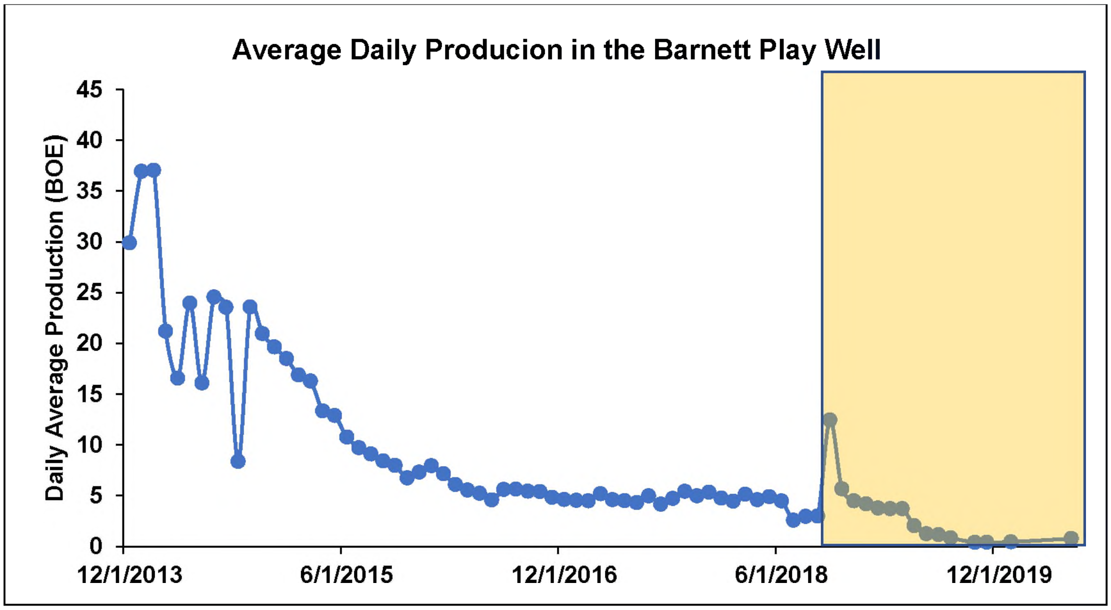

Figure A.24. Average Daily Production of a Refractured Well in the Barnett Play

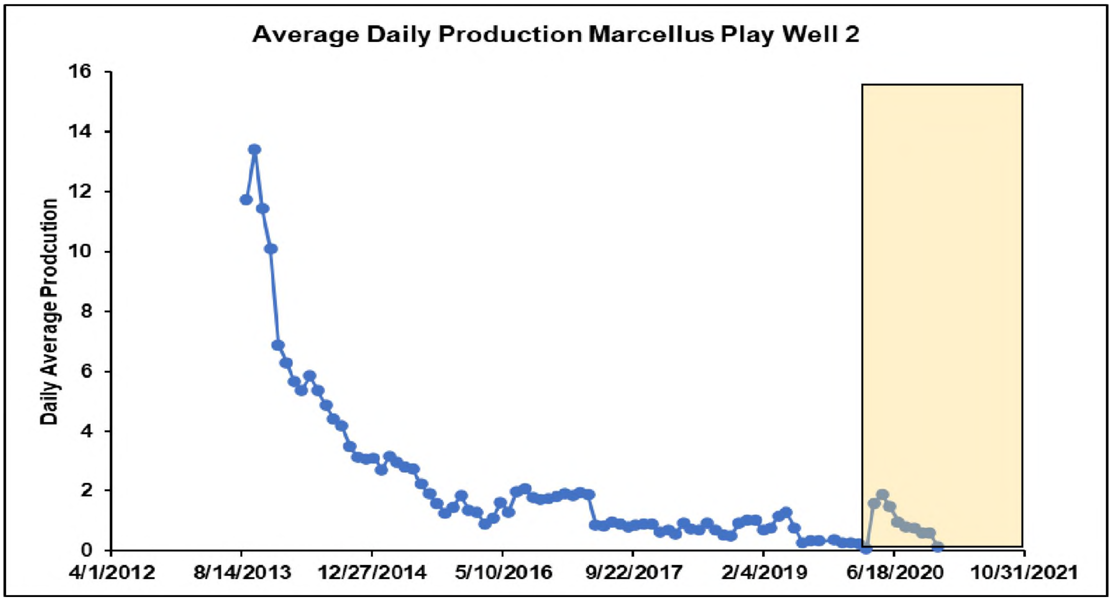

Figure A.25. Average Daily Production of a Refractured Well in the Barnett Play

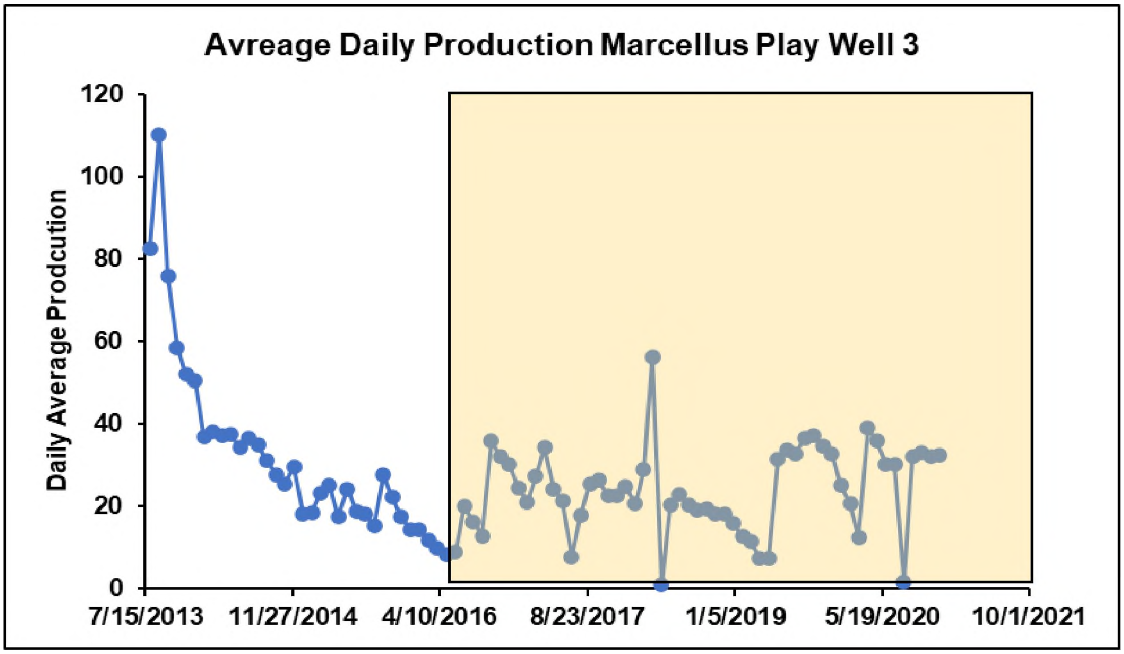

Figure A.26. Average Daily Production of a Refractured Well in the Barnett Play

7. AVERAGE DAILY PRODUCTION OF THE BARNETT PLAY WELLS (VERTICAL WELLS)

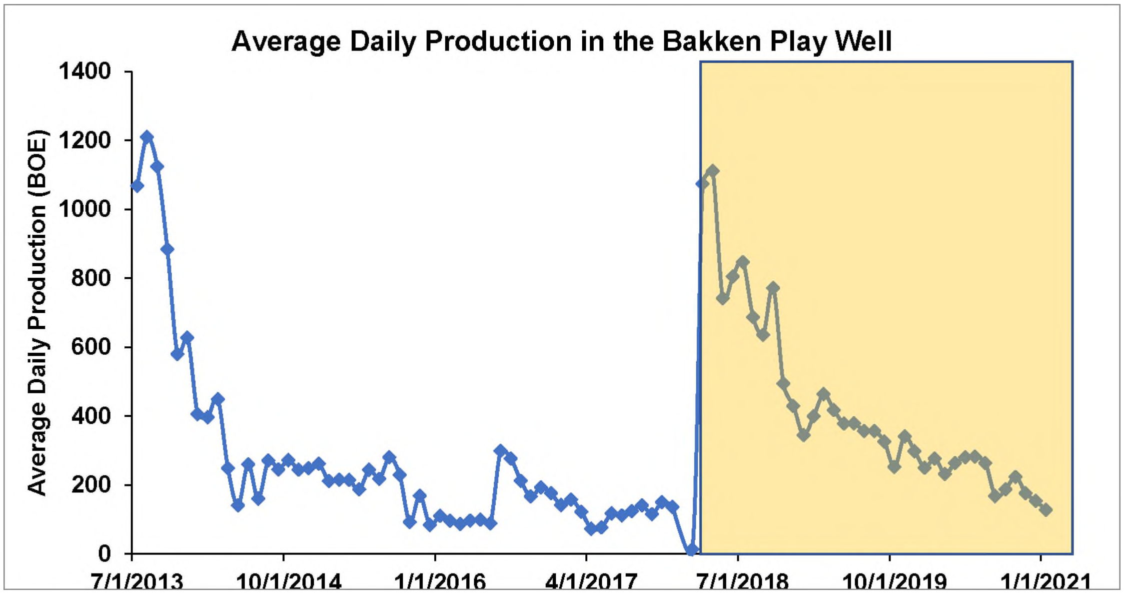

Figure A.27. Average Daily Production of a Refractured Well in the Bakken Play

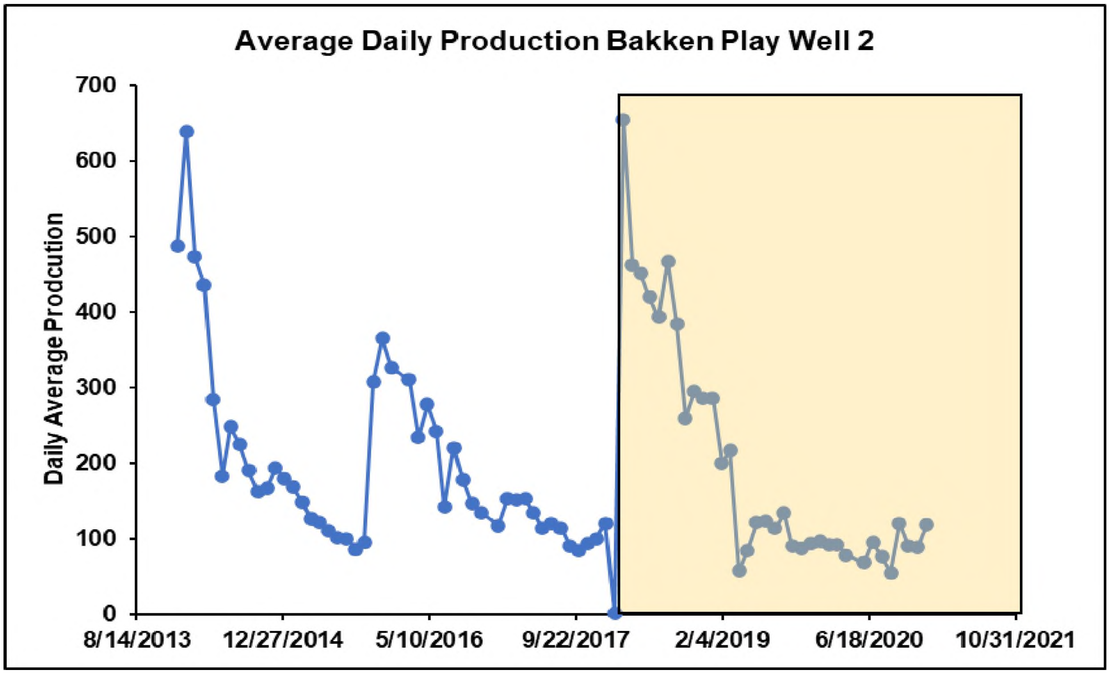

Figure A.28. Average Daily Production of a Refractured Well in the Bakken Play

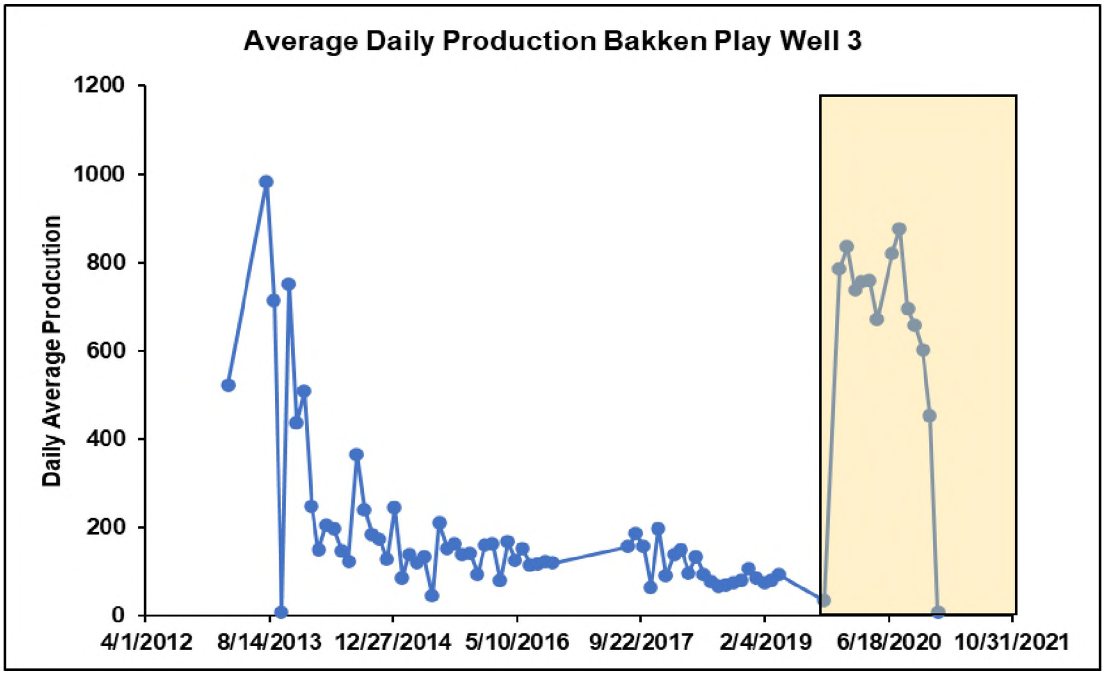

Figure A.29. Average Daily Production of a Refractured Well in the Bakken Play

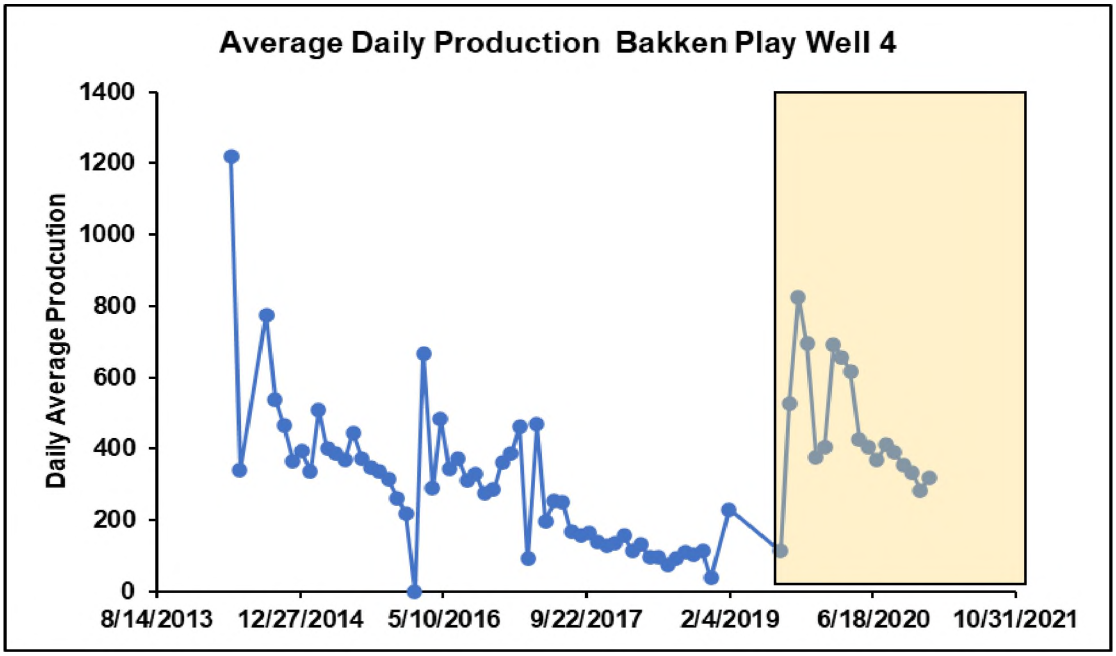

Figure A.30. Average Daily Production of a Refractured Well in the Bakken Play

VITA

Faisal Omran Shammam was born in Tripoli, Libya on. He graduated high school from Jamal AbdelNaser High School in June 2010. After one year, he entered Tripoli University, and later transferred to the American University in Cairo where he received his Bachelor of Science in Petroleum Engineering in June 2018. While pursuing his bachelor's degree, he worked as an intern engineer for different oil companies in Libya and Egypt including Schlumberger, Halliburton, and Arabian Gulf Oil Company in Libya. In January 2020, he joined Missouri University of Science and Technology to pursue his master`s degree in Petroleum Engineering. During his studies at Missouri S&T, he worked as a graduate teaching assistant and received his Master of Science in Petroleum Engineering in May 2021.