URTeC: 2487

Performance of Friction Reducers in Iron-Rich Environments

S. Hazra[1], M. Van Domelen[2], W. Cutrer[2], N. Peregoy[3], P. Okullo*[3] and B. Darlington[3] ([1]DynaChem Research Center; [2]Downhole Chemical Solutions; [3]Ovintiv Inc)

This paper was prepared for presentation at the Unconventional Resources Technology Conference held in Austin, Texas, USA, 20-22 July 2020.

Abstract

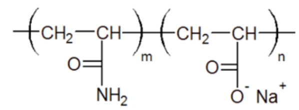
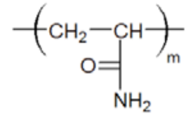
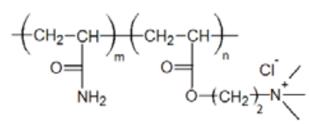
In certain wells where relatively high levels of iron are present, the use of polyacrylamide-based friction reducers (FR) for hydraulic fracturing completions can lead to poor performance and negative chemical interactions including the formation of unusual semi-solid accumulations. The accumulations, often referred to as “gummy bears” due to their rubbery texture, can form in surface and downhole equipment and can inhibit well production. This paper summarizes work performed to evaluate the performance of FRs in the presence of iron, identifies the specific causal factors for the formation of the accumulations, and provides practical solutions to mitigate the problems associated with the negative iron impact in order to improve overall well performance.

Iron can present itself during fracturing operations in different forms and from different possible sources including source water, tubulars, and within the rock formations themselves. To study the interactions between iron sources and anionic friction reducers, synthetic and field water sources were used to identify and quantify the negative effects that iron has on performance parameters for FRs and viscosifying friction reducers (VFR) such as friction reduction, viscosity development and the development of polymer accumulations. The second portion of this paper is given to identify methods to improve overall FR performance and to mitigate the risk of developing the accumulations in iron-rich environments. Field case histories are presented to support the results of this work.

Introduction

Over the years, the oil and gas industry has documented many of the detrimental effects that iron can have on well completion operations. Iron sulfide scale, for example, is the result of hydrogen sulfide and iron interacting with each other and can lead to problematic issues including loss of injectivity in water injection and disposal wells, plugging of artificial lift mandrels and perforations, reduced reservoir permeability, and other mechanisms that can limit overall well production (Nasr-El-Din et al, 2001).

In hydraulic fracturing operations, the presence of iron can also have negative effects on the performance of fracturing fluids. Many, if not most, of the polyacrylamide polymers used in fracturing operations are negatively charged (anionic) in nature. When positively charged ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), ferrous iron (Fe^{2+}), or ferric iron (Fe^{3+}) come into contact with the negatively charged polymer, the result is usually a reduction in the overall performance of the polymer.

Type of Polyacrylamide	Structure of Repeat Units
Anionic polyacrylamide (APAM)	
Neutral polyacrylamide (PAM)	
Cationic polyacrylamide (CPAM)	

Images collected from Polymer database (https://polymerdatabase.com/polymer%20classes/Polyacrylamide%20type.html)

Recently, research has been performed which describes the impact of various ions, including iron, on the friction reduction characteristics of FRs as well as the viscosity development of VFRs (Hazra et al. 2019). Hazra's study showed that iron (both Fe^{2+} and Fe^{3+}) had the most detrimental impact of all ions tested.

The presence of iron is also believed to be a factor behind the flowback of accumulations during well cleanup and early production after hydraulic fracturing operations. These accumulations often contain formation fines, hydrocarbons, frac sand and/or polymer from friction reducers used during the frac operations (Calvin et al, 2015). The accumulation problems occur in formations such as the Woodford Shale in Oklahoma. The Woodford is a silica-rich formation with high clay content, with mineralogy varying across the state (Foltz et al, 2016). Chert is abundant within the Woodford, and can be seen in Figure 1 as conchoidal, shell-shaped objects within the matrix. The mineral of specific concern for this study however is pyrite (FeS_2) and the Woodford is known to contain appreciable quantities of pyrite within the chert matrices. Table 1 shows an XRD analysis for the Woodford. Mineralogy varies within the Woodford from area to area, but pyrite content is often observed at around 2%.

Figure 1: Woodford Shale outcrop in Arbuckle Mountains - Southern Oklahoma.

Table 1: Example XRD Analysis from Woodford Shale.

	Woodford
Quartz(%)	67.0
Calcite, syn(%)	0.0
Feldspar(%)	10.0
Pyrite(%)	2.0
Total Non Clay	79.0
Smectite (%)	0.0
Illite (%)	17.0
Chlorite IIb-4(%)	1.0
Kaolinite-1A(%)	3.0
Total Clay	21.0

Pyrite in the formation can lead to the release of both ferrous and ferric iron sources. Specifically, Fe^{2+} can be released by oxidative dissolution of pyrite minerals according to the equation below in which ferrous iron and sulfate is released.

$$2FeS_2 + 7O_2 + 2H_2O \Rightarrow 2\ Fe^{2+} + 4\ SO_4^{2-} + 4H^+$$

(Pyrite + Oxygen + Water => Ferrous Iron + Sulfate + Acidity)

Another reaction that can occur is the conversion of ferrous iron to ferric iron as per the equation below. This reaction is pH dependent and proceeds very slowly at low pH values (between 2-3), and more rapidly at higher pH values of 5 or more.

$$4Fe^{2+} + O_2 + 4H^+ \Rightarrow 4\ Fe^{3+} + 2H_2O$$

(Ferrous Iron + Oxygen + Acidity => Ferric Iron + Water)

As we will show in the sections below, iron is one of the main contributing factors to poor FR performance and the formation of polymer accumulations.

Negative Impacts of Iron on FRs

In this study, a series of laboratory tests were performed to evaluate the negative impact of iron on the performance of both standard FRs as well as VFRs. VFR fluids are becoming increasingly more popular in hydraulic fracturing operations, and their benefits have been documented in industry publications (Van Domelen et al, 2017; Dahlgren et al, 2018; Poppel, 2020). We review the effect of iron on various FR properties in the section below.

Impairment of friction reducing properties

Hazra studied the effects of both ferrous (Fe^{2+}) and ferric (Fe^{3+}) iron on the friction reduction properties of an FR polymer in a laboratory flow loop. Figure 2 shows a plot of friction reduction percentage vs. time, using an FR at 0.5 gpt polymer loading. Prior to the addition of iron at time of 300 seconds, the FR shows excellent friction reduction of about 70%. However, when iron was introduced into the fluid in 100 mg/L increments, the performance of the FR drops significantly. The loss of FR performance could have significant consequences on the success of a hydraulic fracturing treatment, most likely resulting in higher than expected pumping pressures and/or a reduction of the maximum pump rate.

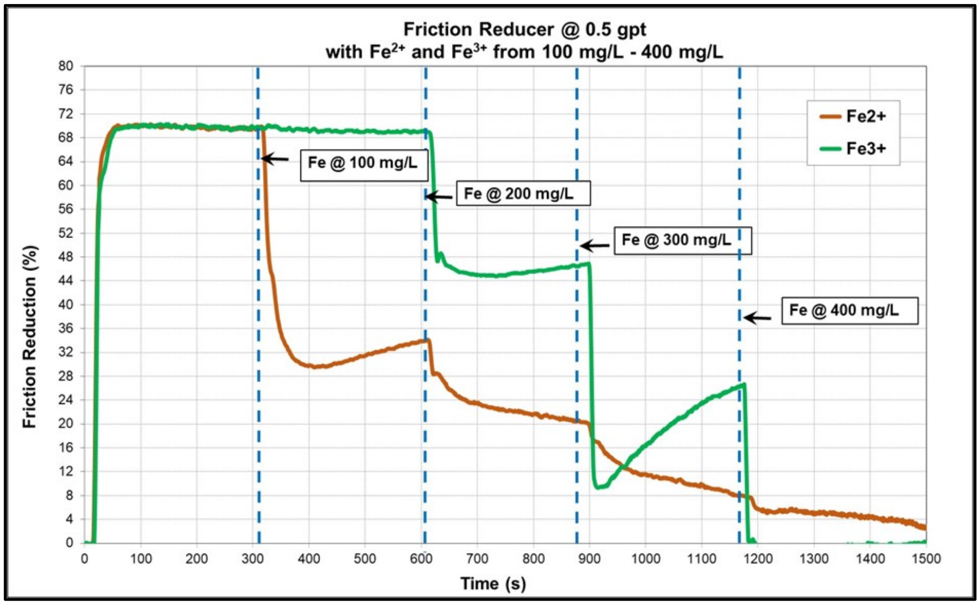
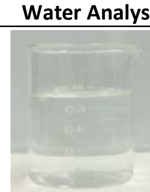


Figure 2: Effect of Fe^{2+} and Fe^{3+} on friction reduction properties of polyacrylamide friction reducer.

Produced waters from field operations are often analyzed for compatibility with friction reducers. Table 2 shows the results of water analyses on three different potential source waters that an operator was considering for their frac completions. Two of the waters were from fresh sources and the third was water produced from another well. The produced water contained very high Total Dissolved Solids (TDS) levels as well as a relatively high concentration of iron at 39 mg/L. Figure 3 shows the flow loop results for the three different water sources which clearly indicated that the produced water had a strong detrimental effect on the performance of the FR. In these situations, many operators will use a mixture of the fresh water with the produced water and are successful in placing their job designs as planned.

Table 2: Analyses of three potential frac source waters with two fresh waters and one produced water source.

Water Analysis Report			
			
General Information	**Water 1**	**Water 2**	**Water 3**
Water	Fresh	Fresh	Produced
Fluid appearance	Clear	Clear	Cloudy
Precipitate at bottom	None	None	Brown
Fluid color	Yellowish	Colorless	Yellow
Fluid Odor	None	None	Rusty
pH	8.39	8.19	5.57
Oxidation Reduction Potential	117 mV	169 mV	165 mV
specific gravity	1.006	1.000	1.138
Parameters	**Concentration (mg/L)**	**Concentration (mg/L)**	**Concentration (mg/L)**
Alkalinity (1) (as CaCO3 mg/L)	720	430	6,900
Total Hardness (1) (as CaCO3 mg/L)	570	890	52,200
Calcium (1) (as CaCO3 mg/L)	480	680	34,800
Magnesium (1) (as CaCO3 mg/L)	290	210	7,400
Manganese (2) (Mn)	0.4	0	10
Iron (2) (Fe)	0.05	0.01	39
Phosphate (3) (PO4)	5 - 15	5 - 15	15
Sulfate (2) (SO4)	7,000	50	400
Barium (2) (Ba)	2	0.01	300
Hydrogen Sulfide (4) (H2S)	0	0	0
Chloride (3) (Cl)	3,136	126	122,400
TDS (5) (as conductivity at 25C)	7,160	497	209,300

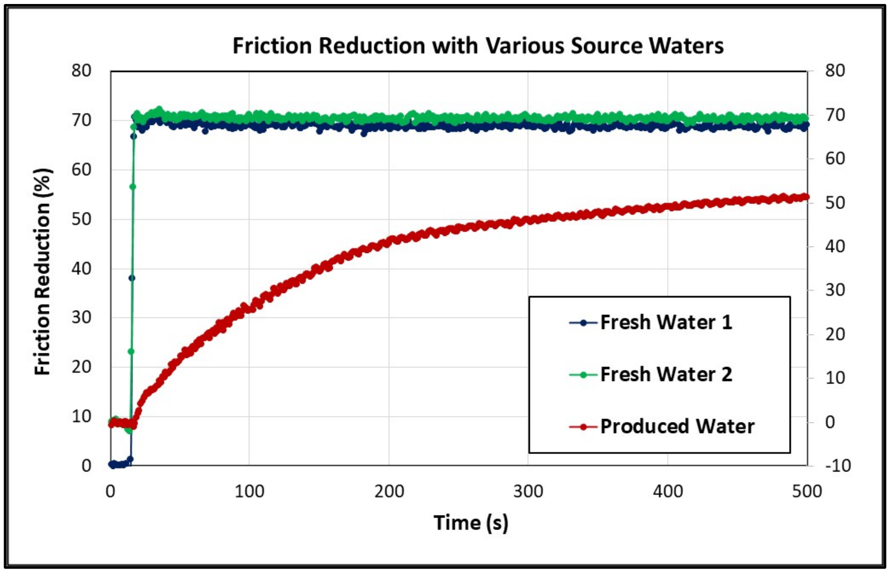


Figure 3: Flow loop friction reduction from three source waters, with poor performance exhibited by the FR in produced water.

Loss of Viscosity with VFRs

Another negative impact that iron can have on fracturing fluids is to hinder the viscosity development of viscosifying friction reducers. The viscoelastic properties of VFR systems are used by operators to help transport proppant deeper into the reservoir and allow for higher proppant concentrations to be placed, thereby reducing frac water requirements. Unfortunately, these advantageous fluid properties are hindered as a result of iron interacting with the VFR polymer. Figure 4 shows the viscosity profiles of a VFR system with and without 50 ppm of Fe^{3+} added. The reduction in viscosity caused by the iron, especially in the low shear rate range of 0 to 100 sec^{-1} (the range commonly accepted as normal shear rates in a hydraulic fracturing network), leads to a loss in proppant carrying capacity of the fluid.

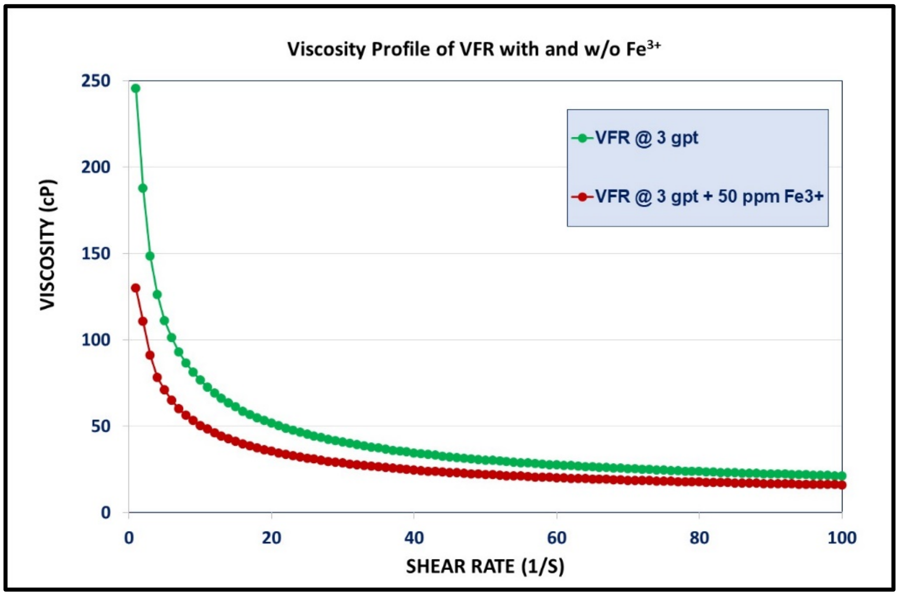


Figure 4: Viscosity profiles of VFR system with and without the addition of Fe^{3+}.

Formation of Accumulations (ie: "Gummy bears")

As we have described above, the presence of iron in contact with a friction reducer can lead to lower levels of friction reduction as well as lower viscosities of VFR systems. A third and perhaps most severe interaction that can occur is the formation of semi-solid accumulations. In Oklahoma, accumulations were widely reported when operators began to use PA friction reducers in formations such as the Woodford. Figure 5 shows an example of an accumulation mass taken from a well completed in the Woodford following a fracturing treatment using a PA FR. These accumulations can lead to many issues including plugging of separators, chokes at surface, tubing, casing and other downhole equipment. Many operators attributed these problems to the fact that the Woodford is known to have appreciable concentrations of pyrite, a source of iron in the formation mineralogy. Some operators have switched their frac fluid systems back to guar-based fluids to mitigate this problem, however this option is not ideal as guars are known to leave residue damage in the fracture, potentially reducing well productivity. Thus, many operators desire a solution which will allow for anionically charged FRs to be used for frac operations in these types of formations.

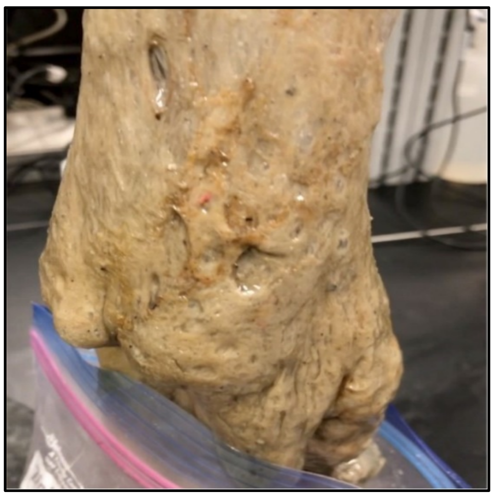


Figure 5: Polymer accumulation after frac operation with standard industry FR.

To demonstrate this problem in a laboratory setting, Figure 6 shows a photograph of a standard industry anionic FR mixed in fresh water with and without the addition of 50 ppm of ferric chloride ($FeCl_3$). When the iron source is added to the fluid (right-hand side of Figure 6), a nearly instantaneous development of the accumulation material was noted. So how can the interaction problems between iron and FRs be mitigated? As we will describe in the next section of this paper, factors such as polymer molecular weight, formation fines control, the use of breakers, and iron-blocking additives can all play a role in the mitigation of this problem.

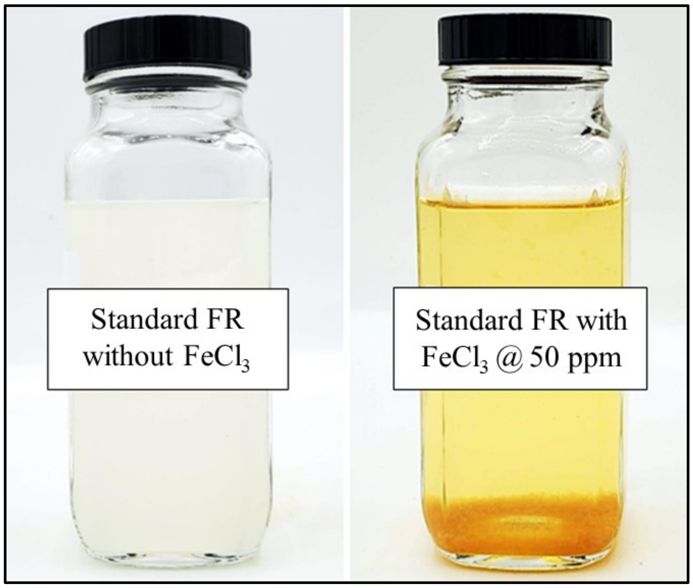


Figure 6: Standard FR shows negative interaction when iron is introduced.

Prevention and Mitigation Methods

We have described some of the negative impacts that iron can have on the performance of polyacrylamide friction reducers. In this section, we offer potential solutions and mitigation factors for these issues based on laboratory testing and field applications.

Polyacrylamide Molecular Weight

Polyacrylamides come in different molecular forms and are used in many different industries including water treatment, soil conditioning, paper processing, and of course oil and gas. Depending upon the application, the properties of the PA can be modified to achieve the performance criteria. The molecular weight (MW) of a PA has a strong influence on the rheological properties of the fluid. As the molecular weight of the polymer increases, the resistance to flow and thus the viscosity increase. At the same time, the stability of the PA increases with higher MWs making them harder to break and clean up. For hydraulic fracturing applications, PAs used for friction reducers and VFRs generally range from about $5x10^6$ g/mole to about $30x10^6$ g/mole. Given the above, laboratory testing on FRs and VFRs should include not only friction reduction and viscosity tests, but also regain fracture conductivity tests to ensure that proper breaking and cleanup of the polymer is observed. It is also reasonable to believe that high MW FRs and VFRs could be more problematic with regards to developing polymer accumulations, although further work in this area is needed.

Acid Spearheads

A common practice within the industry is to incorporate a small acid stage at the beginning of many fracturing treatments. Acid “spearheads” are used to help improve early injectivity and achieve maximum pump rate more rapidly into a formation by dissolving rock material near the perforations and helping to reduce near wellbore entry friction. The effectiveness of acid spearheads can vary significantly; in some cases reducing pressure significantly while in others not resulting in improved injectivity. Due to the unique mineralogy of the Woodford and the known sensitivity of friction reducers interacting with cations such as iron in the matrix, studies were performed to evaluate the solubility of the Woodford rock matrix in the presence of acid. Figure 7 shows the results of the acid solubility tests which showed a significant release of magnesium, iron and aluminum after allowing Woodford cuttings to soak in 15% HCl acid for 24 hours at 200 deg F. Inductively coupled plasma (ICP) analyses yielded the results in Figure 7 with an overall solubility of 38.35%. Given these results, the use of acid spearheads has been minimized for Woodford completions in order to reduce the risk of iron-polymer interactions. If an acid spearhead is performed, it is recommended to pump a spacer of water between the acid and the FR laden steps of the pump schedule.

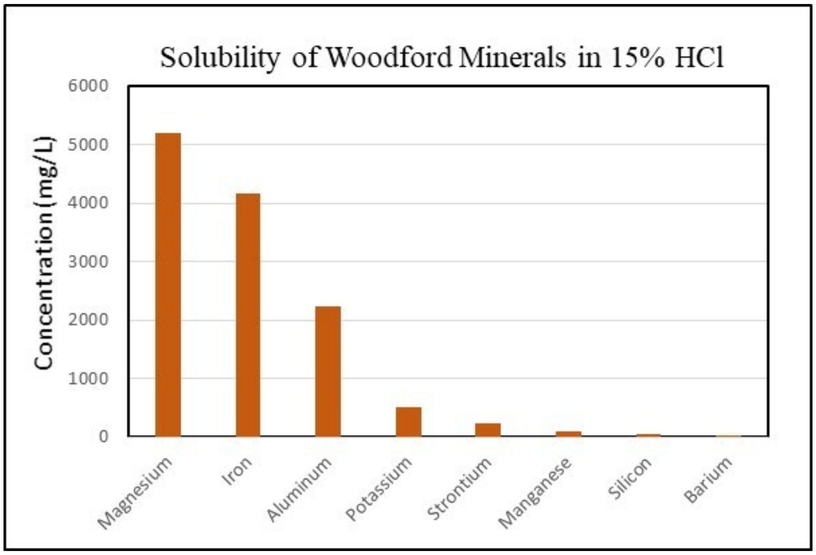


Figure 7: ICP analysis showing elements and concentrations in solution after soaking Woodford cuttings in HCl acid for 24 hours at 200 deg F.

Clay Control

Another mitigating factor towards the prevention of the accumulations evaluated in this study included the use of a clay control product due to the presence of high concentrations of illite in the Woodford. Illite is known to easily free itself from a rock matrix and migrate as fine clay particles within the fracturing fluid. Figure 8 shows results after hot roll testing was performed on Woodford formation cuttings samples. The sample on the left had no clay control additive while the sample on the right contained 1 gpt of a polymeric clay control additive. Hot roll testing is conducted by physically rolling the formation cuttings in the fracturing fluid system for 16 hours at expected bottomhole temperature. By reducing the amount of formation fines material released during the fracturing process, the extent and severity of polymer accumulation is likely to be reduced.

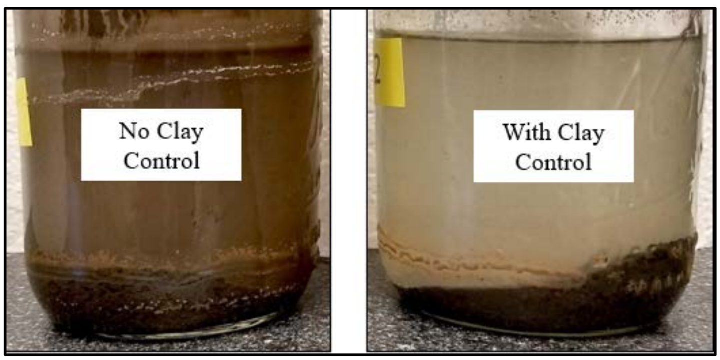


Figure 8: Photos of Hot Roll test samples after 16 hours at 180 deg F, without and with clay control, using Woodford Formation cuttings.

Chemical Breakers

Any process or phenomenon resulting in breakdown of molecular structure of polymers is referred to as degradation (Sheng, 2013). Polymer degradation can be broadly classified into three categories – chemical, mechanical and biological (Sorbie, 1991). Chemical degradation represents both oxidative degradation (thermal degradation) and natural hydrolysis of the polymer molecules (Ferrerira & Moreno 2017). Degradation also depends on the molecular structure of the polymer (Ryles 1988). Thus, all polymers do not degrade in the same way and under similar circumstances. The effects of the ions present in water on polyacrylamide can be classified as oxidative degradation. In the process of oxidative degradation, the element that has been most abundantly studied is ferrous iron (Fe^{2+}). In the presence of Fe^{2+}, polymers tend to lose viscosity and degrade at a much faster rate. As explained by Fenton (1984) and Levitt, et al. (2011b), the mechanism involved in the degradation of organic compounds in presence of ferrous iron involves conversion of ferrous iron to ferric iron (Fe^{3+}) in the reducing environment downhole.

Pertaining to the prevention/mitigation of polymer accumulations, three different advantages were believed to have been achieved using an oxidizing breaker during this work:

1. Reduction of VFR viscosity – the breaker is proven to reduce overall viscosity of the fluid system.

2. Breakdown of polymer molecular structure – Table 3 shows the molecular weight of the VFR system used on this project, with and without the addition of breaker. The VFR has a relatively low MW of $7\text{x}10^6$ g/mole without breaker and drops to around $1\text{x}10^6$ g/mole with breaker. Degrading the polymer structure in this manner very likely helps to reduce the formation of viscous accumulations.

Table 3: Molecular weight of VFR polymer with and without breaker.

	Molecular Weight (gram/mole)
VFR Without Breaker	$6.9\text{x}10^6$
VFR With Breaker	$1.3\text{x}10^6$

3. Degradation of polymer accumulations before they become problematic – Figure 9 shows the results of bottle tests in which a VFR system, mixed in a produced water, showed tendencies for polymer accumulations to form. With the addition of the breaker, these accumulations quickly dissipated.

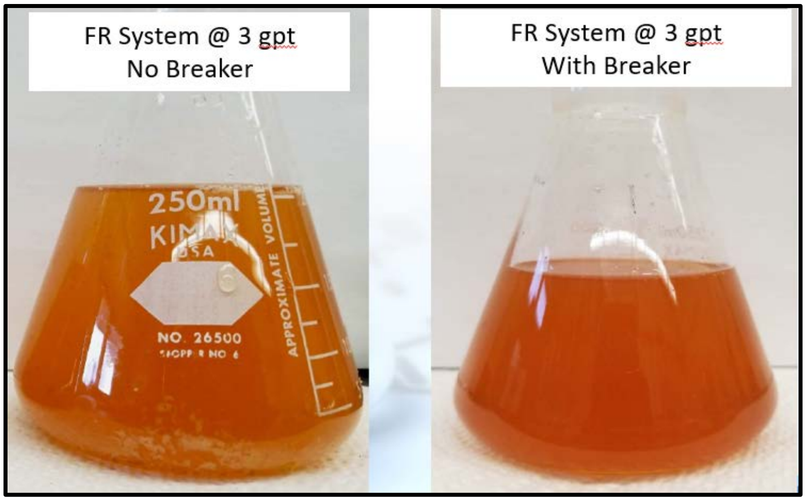


Figure 9: FR system (in produced water) without breaker showing tendency for polymer accumulations (left photo), and reduced tendency with breaker (right photo).

Further research (Sun 1999, Ramsden 1986) into peroxides shows that the presence of iron can reduce the effectiveness of the peroxide and therefore higher concentrations of the breaker are required in iron-rich environments. Laboratory testing performed during this study verified the need for higher breaker loadings as well, and this conclusion was adopted into practice by Ovintiv. Details are included in the case history section.

Performance Booster

To help control the negative interactions that iron and other cations have with anionic friction reducers, a booster product was tested extensively in both the lab and field operations. The booster product is an anionically charged additive that acts as a “sacrificial surfactant” designed to react with cations such as iron, calcium and magnesium in the frac source water. By tying up these cations, the interaction between the cations and anionic FRs is reduced thereby allowing FRs to work as expected. Figure 10 shows a plot of friction reduction percentage from the flow loop using a Permian Basin produced water source with and without the booster. The water showed about 98,000 TDS, with total hardness of 9800 mg/L and iron content of 20 mg/L. With this relatively high level of both hardness and iron, even a normally high performing FR (run at 1 gpt) does not perform well in this water. Figure 10 (red curve) shows only about 28% total friction reduction without the booster. Using the booster, a significant improvement in the friction reduction performance was achieved at 0.5 and 1 gpt loading (green curves).

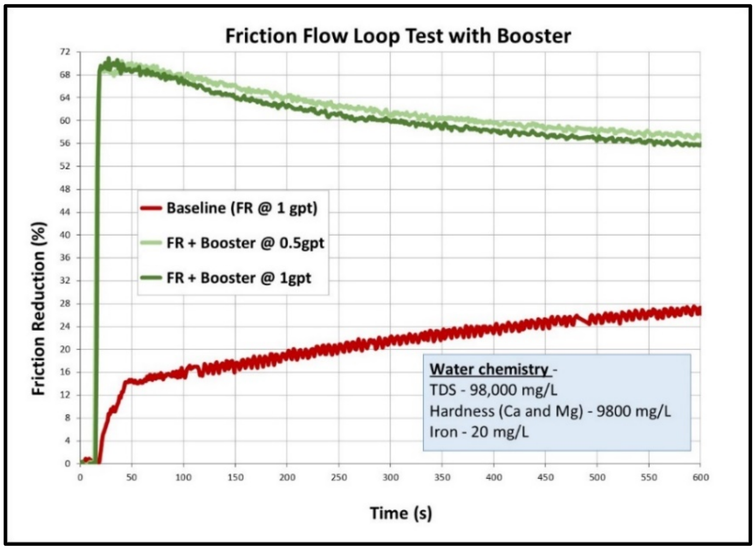


Figure 10: Performance of FR in high TDS water with and without booster.

The booster also performed well with regards to the viscosity development of the VFR system. If we refer back to Figure 4, we remember that the viscosity profile of the VFR system was degraded due to the presence of iron. Figure 11, however, shows that the booster almost completely prevented any deterioration of the VFR's viscosity due to the presence of iron. The two viscosity curves (original viscosity before iron was added, and the curve with the addition of the booster) lie nearly on top of each other, showing that the booster was effective at mitigating the negative effects of the iron. When applying the booster, the best results occur when it is added before the polymer encounters the frac source water. In field operations, this can be accomplished by adding the booster to the frac water before the blender, and then delivering the FR either at the blender or missile.

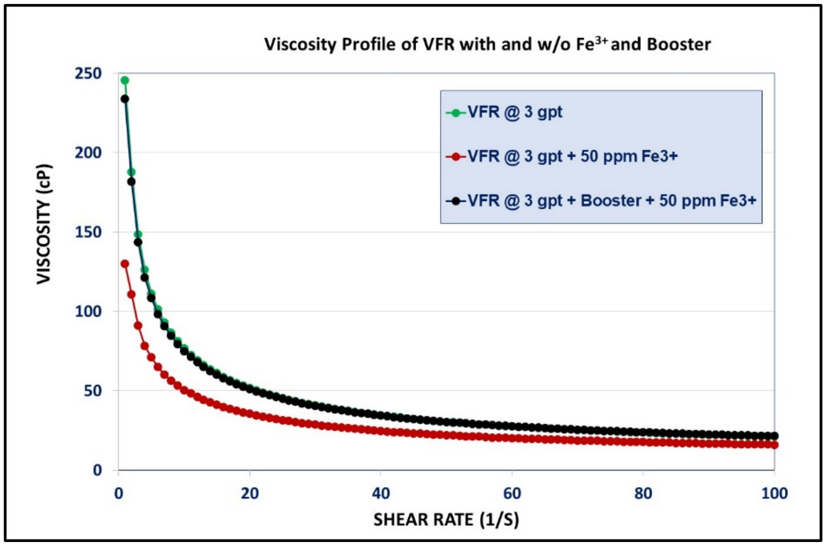


Figure 11: Viscosity profile of VFR system showing no detrimental effects from iron when booster is used.

A final benefit of the booster is to mitigate the formation of polymer accumulations. Figure 12 shows bottle tests in which a VFR was added to a water sample containing 50 ppm $FeCl_3$, one sample without the booster and the other sample with the booster. The sample without the booster shows some potential for polymer accumulations while the sample with the booster was uniform and homogeneous.

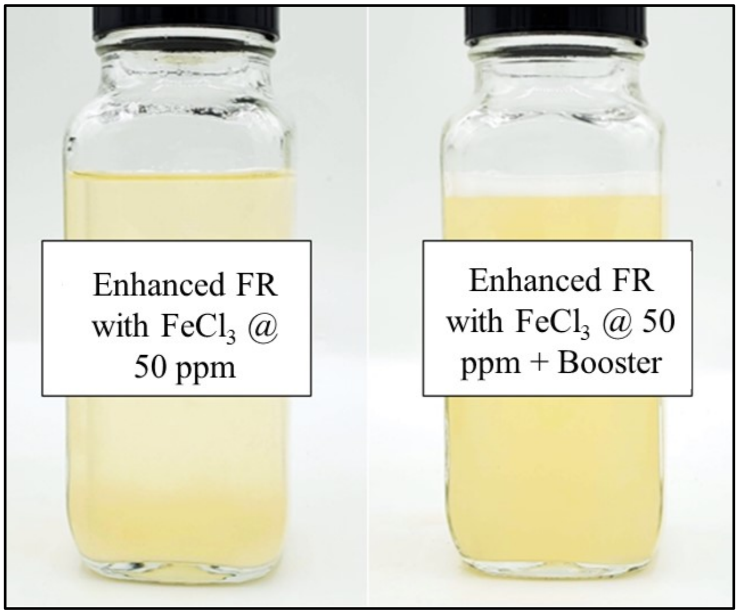


Figure 12: Booster effect on mitigating the formation of polymer accumulations.

Summary of Prevention Methods for Polymer Accumulations

We summarize below the approaches that can help prevent the formation of polymer accumulations when using friction reducers in the presence of iron. Some or all of these prevention methods were incorporated in field operations to achieve successful results and will be described in the case history section below.

- Lab testing prior to the start of a project will help to identify the optimum fracturing fluid system in iron-rich environments. The tests performed during this study included XRD and source water analyses, flow loop, rheology and hot roll tests. These tests are relatively simple and inexpensive to perform.
- Avoid pumping acid spearheads (unless necessary) to prevent the release of iron and other ions into solution. If an acid spearhead is required, pump a water spacer between the acid and the subsequent FR laden steps.
- The use of a clay control product minimizes the risk of fines attaching to potential polymer accumulations, particularly when sloughing clays such as illite are present in the matrix.
- Testing showed that the use of an oxidizing breaker helped not only to break the backbone of the PA polymer and reduce molecular weight, but also to break down the early formation of polymer accumulations. Breaker concentrations may need to be increased due to breaker spending on iron.
- A performance booster chemical can provide advantages by interacting with cations in the fracturing fluid. The advantages include better friction reduction properties, enhanced viscosity with VFR systems, and prevention of polymer accumulations.

Case History from the Woodford Formation, Oklahoma

Ovintiv has approximately 360,000 net acres held by production in the Anadarko Basin, primarily in the black oil window of the STACK and SCOOP (the Sooner Trend of the Anadarko Basin, mostly in Canadian and Kingfisher counties, and the South Central Oklahoma Oil Province). The Woodford Shale in the SCOOP region is one of the thickest, best quality resource shale reservoirs in the United States and many of Ovintiv's Woodford developments take place in the SCOOP.

This case study compares two different multi-well completions on pads located southwest of Oklahoma City in eastern Grady and western McClain counties (Figure 13). The first pad (referred to as Pad A) was completed prior to Encana's acquisition in 2019 and consists of seven wells, with five Woodford wells and two Caney wells. The Caney wells are omitted from this analysis. The second pad (referred to as Pad B) consists of five Woodford wells including a parent well completed in 2017 and four child wells completed by Ovintiv in early 2020. The parent well on Pad B is also omitted from this analysis. Figure 13 shows a map of the pad locations and the location of the well in which XRD data is presented below.

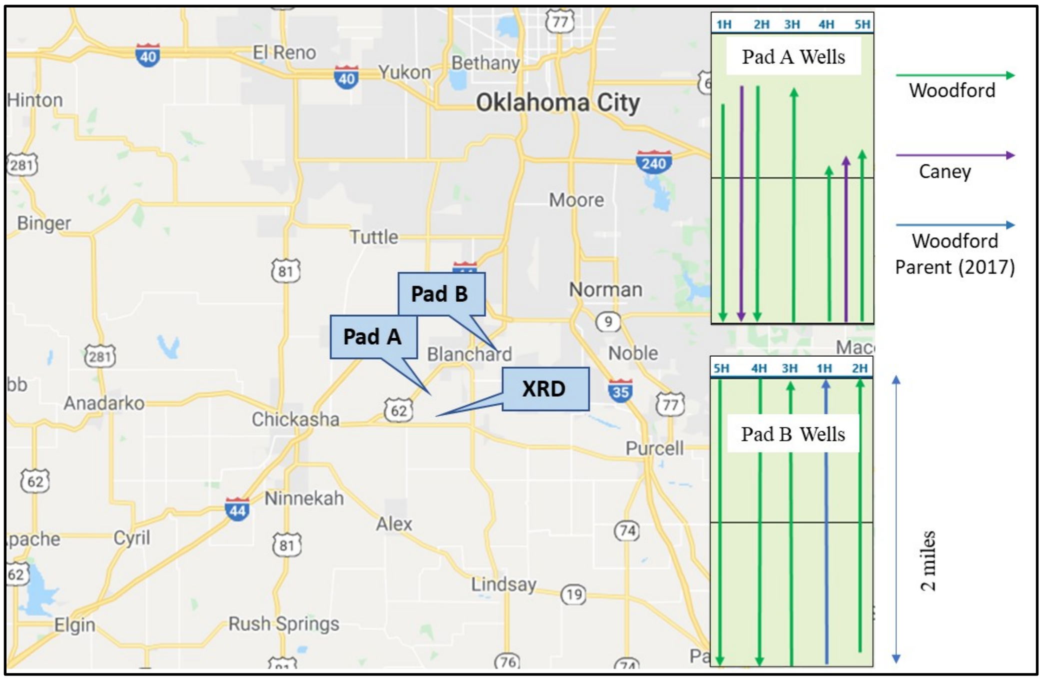


Figure 13: Locations of Pads A and B, and well location in which XRD data was extracted.

Table 4 summarizes the key completion parameters for the Woodford wells on both pads. All completions used approximately the same volume of water per foot of interval completed. The Pad B wells were longer than the Pad A wells and incorporated more frac stages, more proppant placed, and 7% more proppant on a volume per foot basis on average (2,280 lb/ft for Pad B wells compared to 2,130 lb/ft for Pad A wells).

Table 4: Key completion parameters for Pads A and B in the Woodford wells. Caney wells in Pad A, and parent well in Pad B have been omitted.

Pad	Well #	Total Proppant (lb)	Total Fluid (gals)	# of Stages	Gross Interval (ft)	Proppant (lb/ft)	Fluid (gal/ft)
A	1	16,831,963	357,235	38	7,729	2,238	1,995
	2	16,967,883	357,803	38	7,791	2,178	1,929
	3	16,135,901	372,673	39	7,939	2,085	2,023
	4	12,144,999	284,471	27	5,431	2,344	2,306
	5	10,238,442	250,592	28	5,680	1,803	1,853
B	2	17,814,290	424,669	44	9,024	2,023	2,025
	3	24,338,566	468,572	49	9,705	2,619	2,117
	4	24,247,154	458,831	49	9,726	2,493	1,981
	5	20,187,443	465,215	51	10,166	1,986	1,922

Figure 14 shows an XRD analysis of the key mineralogical components of the Woodford matrix from the nearby well indicated in Figure 13. The large majority (over 90%) of the clays in the matrix were illites, with a relatively high average pyrite content of about 3%. Also, overall carbonate content was very low and consisted primarily of dolomite.

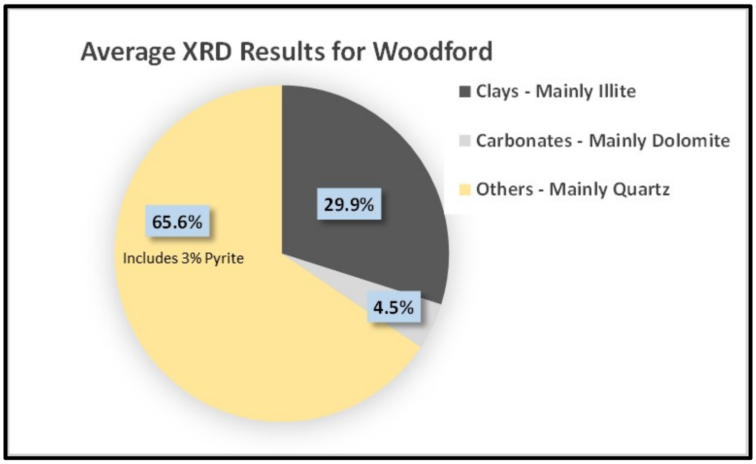


Figure 14: XRD Results for Woodford Formation in offset well.

Prior to self-sourcing frac fluid systems in this area, problems were sometimes experienced related to polymer accumulations discovered in the tubing and separators following frac completions. Figure 15 shows photos of accumulation material which were recovered from wells completed in the Woodford in this area. It is believed that these issues were a result of the polyacrylamide-based FR system being used at that time interacting with an iron-rich environment caused (at least) in part by significant pyrite concentrations found in the mineralogy of the Woodford in this area. Other potential contributing factors to the occurrence of polymer accumulations included:

- Significant concentrations of migrating clays in the form of illite were present in the matrix.
- Acid spearheads were routinely used on previous completions, potentially contributing to the release of iron into the system through interaction with tubulars and pyrite.
- Fracture driven interactions (FDI), or frac hits, had occurred on several occasions during completions on offset wells. Polymer accumulation issues were commonly observed after an FDI had occurred.

Figure 15: Polymer accumulations taken from a Woodford well completed in the project area.

With an objective to improve well performance and to mitigate the polymer accumulation issues, an extensive laboratory testing program was commenced using the principles and methods described previously in this paper. Of particular concern were the high pyrite contents which could interfere with the anionic VFR system and the high illite concentrations which could stabilize polymer accumulations.

A summary of the final fluid system developed for this project is given below:

- Fresh source water – from various ponds depending upon location of pad
- Low to moderate molecular weight polyacrylamide VFR polymer
- No acid spearheads
- Clay control additive
- Oxidizing breaker – run at ½ the VFR loading

Execution of the frac operations on Pad B wells took place in early 2020 with no issues encountered during the frac treatments and, perhaps more importantly, no indications of polymer accumulations observed during well cleanup and flowback operations. Positive production results were also observed from the Pad B wells, as shown in Figure 16. The chart shows daily oil production rates from both the Pad A and Pad B wells for the first 70-90 days of being online. For a more accurate comparison, the production rates have been normalized to the well lateral lengths. After 60 days, the average well production for the Pad B wells was 750 bopd compared to the average production from the Pad A wells of 335 bopd. While a portion of the improved well production in the Pad B wells can probably be attributed to slightly higher proppant volumes placed, the enhanced well deliverability results are encouraging.

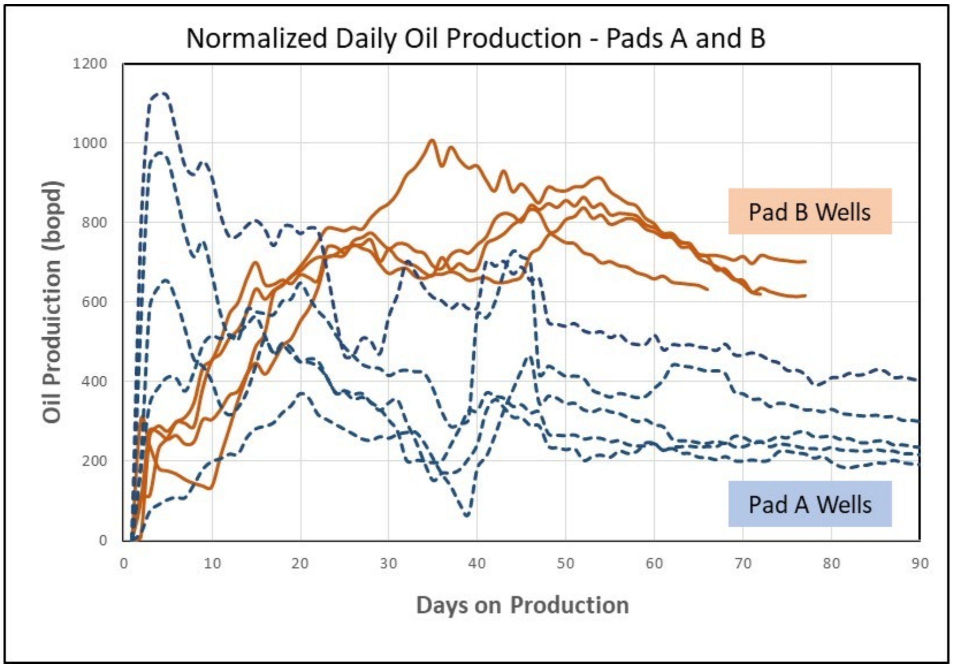


Figure 16: Daily oil production from Pads A and B, normalized to lateral length. Pad B wells used the new fluid design methodology.

Ovintiv continues to use this frac fluid formulation and methodology on their Woodford wells, and have observed positive production results such as the ones described above on many wells completed in the SCOOP and STACK.

Conclusions

The results of this study provide the foundation for mitigating adverse chemical interactions and improving the performance of friction reducers in iron-rich environments. This study showed that polymeric accumulations are formed mainly due to the interaction of ions, specifically iron, present in the water and rock formations with polyacrylamide-based friction reducers and viscosifying friction reducers (VFR). A stepwise approach was used to identify the mechanisms involved and the appropriate chemistry required to both prevent and remove these types of accumulations. This approach involves using a fresh frac water source when feasible, a clay control product when fines are present in the formation mineralogy and a breaker to assist with prevention/removal of any accumulations formed. Using this methodology, the accumulations were not formed both at room temperature or after applying temperature and shear in most of the tests. In the tests where accumulations were formed, the breaker was effective at dispersing the accumulations. In addition, an FR booster product designed to interact with cations such as iron, magnesium and calcium was also shown to improve the overall performance of the FR with respect to friction reduction and viscosity development of FRs and VFRs.

This research enabled a higher level of confidence that fracturing operations can be carried out using polyacrylamide-based FR and VFR fluid systems in iron-rich environments. Positive well production results were observed during field applications of this process. This paper showed a comparison of two sets of wells completed in the Woodford Formation in close proximity to each other. After experiencing polymer accumulation issues and less than favorable production results, a new methodology and fluid formulation was developed and applied in the second set of wells and yielded much better well deliverability with no fluid incompatibility issues.

By understanding rock mineralogy and potential iron sources, along with their impact on fracturing fluids, a fluid system can be designed using appropriate additives to help mitigate the formation of polymer accumulations and improve overall well deliverability. The testing and application methods described in this paper can be applied in any iron-rich unconventional play in which friction reducers are being used.

Acknowledgements
The authors would like to thank the managements of Ovintiv Inc. and Downhole Chemical Solutions for their permission to publish this paper. Thanks also goes out to the many operations personnel within Ovintiv and DCS involved in day to day execution of completion operations in a safe and responsible manner.

References

Nasr-El-Din, H.A. and Al-Humaidan, A.Y. (2001, January 30). “Iron Sulfide Scale: Formation, Removal and Prevention”. SPE International Symposium on Oilfield Scale, Aberdeen, United Kingdom. SPE-68315-MS

Hazra, S., Madrid, V., Luzan, T., Van Domelen, M. and Copeland, C. (2019, April 9). “Correlating the Performance of Friction Reducers with Source Water Chemistry”. SPE Oklahoma City Oil and Gas Symposium, Oklahoma City, OK. SPE-195199-MS

Calvin, J., Grieser, B., and Benkley, J. (2015, March 1). “Identification and Remediation of Produced Solids Accumulation Occurring After Massive Hydraulic Water Fracs”. SPE Oklahoma City Oil and Gas Symposium, Oklahoma City, OK. SPE-195199-MS

Foltz, K. Snider, A. and Puckette, J. (2016, February). “Composition and Mechanical Properties of the Woodford Shale, Northern Oklahoma”. Search and Discovery Article #51220 Adapted from Oral Presentation at AAPG Mid-Continent Section Meeting, Tulsa, OK.

Van Domelen, M., Cutrer, W., Collins, S. and Ruegamer, M. (2017, March 27). “Applications of Viscosity-Building Friction Reducers as Fracturing Fluids”. SPE Oklahoma City Oil and Gas Symposium. Oklahoma City, OK. SPE-185084-MS

Dahlgren, K., Green, B., Williams, B., Inscore, J., Van Domelen, M., & Fenton, A. (2018, January 23) “Case Studies of High Viscosity Friction Reducers HVFR in the STACK Play”. SPE Hydraulic Fracturing Conference and Exhibition, The Woodlands, TX. SPE-189893-MS

Poppel, B. (2020, February 4) “Fighting the Fear: Overcoming Preconceived Notions of Low Polymer Cross-Linked Gels and High Viscosity Polyacrylamides in Unconventional Fracturing”. SPE Hydraulic Fracturing Conference and Exhibition, The Woodlands, TX. SPE-199760-MS

Sheng, J.J., 2013. Modern Chemical Enhanced Oil Recovery.

Sorbie, K.S., 1991. Polymer-Improved Oil Recovery. *Blakie.*

Ferreira, V. H. S. & Monero, R. B. Z. L. (2017). Polyacrylamide Mechanical Degradation and Stability in the Presence of Iron. OTC-27953-MS.

Ryles, R.G., 1988. Chemical Stability Limits of Water-Soluble Polymers Used in Oil Recovery Process. SPE Reserv. Eng. 3, 23-34. Doi:10.2118/13585-PA.

Fenton, H.J.H., 1894. LXXIII. – Oxidation of tartaric acid in presence of iron. J. Chem. Soc., Trans. 65, 899-910. Doi: 10.1039/CT8946500899.

Levitt D.B., Slaughter, W., Pope, G., Jouenne, S., 2011. The effect of redox potential and metal solubility on oxidative polymer degradation. SPE Reserv. Eval. Eng. 14, 287-298. Doi: 10.2118/129890-PA

Sun, Y., Fenster, M., Yu, A. et al. (1999) "The Effect of Metal Ions on the Reaction of Hydrogen Peroxide with Kraft Lignin Model Compounds". Canadian Journal of Chemistry. http://www.lib.ncsu.edu/resolver/1840.2/293

Ramsden, D. K. and McKay, K. (1986) "Degradation of polyacrylamide in aqueous solution induced by chemically generated hydroxyl radicals: Part I-Fenton's reagent". Polymer Degradation and Stability. Volume 14, Issue 3.