

Improving Wellbore Strengthening Techniques by Altering the Wettability of Non-Aqueous Fluids Lost to Drilling Induced Fractures

Jonathan J. Brege, Chad F. Christian, Lirio Quintero, and David E. Clark, Baker Hughes, AADE

Copyright 2010, AADE

This paper was prepared for presentation at the 2010 AADE Fluids Conference and Exhibition held at the Hilton Houston North, Houston, Texas, April 6-7, 2010. This conference was sponsored by the Houston Chapter of the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individuals listed as authors of this work.

Abstract

Lost circulation events pose a major economic and safety risk. When drilling through depleted formations, where the pore pressure and fracture gradient window is narrow, drilling fluid losses typically occur by induced fracturing. There have been numerous publications concerning the need to use closure stress around the wellbore to effectively decrease drilling fluid losses. Using these techniques to mediate lost circulation with conventional water-based lost circulation material (LCM) can be extremely difficult when drilling with non-aqueous fluids (synthetic or oil-based drilling fluids). The reduced permeability of a non-aqueous fluid (NAF) filter cake prevents effective leak-off and support of the fracture to the maximum closure stress. The ability to alter the wettability and enhance the fluid loss of an NAF filter cake is paramount to improving LCM placement and ultimately strengthening of the wellbore.

A new approach to apply LCM in non-aqueous fluid has been developed. This technology will solubilize oil, water-wet the NAF filter cake and enhance the fluid leak-off of the LCM pills. The data presented demonstrates: (1) the ability of the fluid loss pill to alter the wettability of an NAF filter cake from oil-wet to water-wet and (2) the dramatically enhanced permeability and fluid loss of the altered NAF filter cake with an LCM pill.

Introduction

Drilling commonly requires the selection of a drilling fluid density that balances the need to provide an adequate hydrostatic pressure to prevent the influx of formation fluids without exceeding the fracture initiation pressure of the exposed formations in the open hole. However, pressure depletion changes the wellbore stress and can significantly reduce the fracture resistance of a formation. This creates a very narrow operating window between pore pressure and fracture pressure. This increases the risk for a well control issue, often resulting in massive fluid losses while drilling, running casing and cementing due to induced fracturing.

In the late 1980s a joint industry project (JIP), DEA-13, demonstrated that before borehole breakdown occurs, a stable fracture develops that can be sealed by drilling fluid solids bridging the fracture inlet.¹ Even when drilling fluids are injected, borehole breakdown was not observed until the well

pressure significantly exceeded the pressure where the tangential stress was equal to the tensile strength of the rock. Fundamentally, when the aperture of the fracture inlet is opened to a sufficient width such that the sized particles in the drilling fluid are no longer able to plug or bridge, the whole drilling fluid begins to enter the fracture and lost circulation occurs.

DEA-13 evaluated fractures with both water-based and oil-based drilling fluids. Interestingly, the fracture initiation pressures for both fluids were essentially the same, but the fracture propagation pressure (fracture extension) was much lower for oil-based fluids.^{2,3} Observations from the study concluded:

- Oil-based drilling fluids had lower propagation and reopening pressure than water-based fluids.
- High fluid loss water-based fluids “healed” fractures more effectively in permeable formations. The fracture healing mechanism is believed to be by “screen out” of the fracture tip.

Major losses commonly occur through fracture propagation, which by one estimate accounts for over 90% of lost returns expenditures.⁴ A common approach to addressing drilling-induced fracturing has been to develop preventative solutions, such as refining of hydraulic and geo-mechanical models, new field techniques and new lost circulation materials.^{5,6} Materials and techniques used include fibrous, flaky and granular materials; cross-linked polymer pills; gunk squeezes and cement squeezes. These products and methods have been used extensively. Often they only temporarily restore or partially restore circulation before losses reoccur as drilling proceeds. Drilling fluid losses can be more problematic in a reservoir, where mud losses, and many of the techniques used to mitigate, often result in extensive formation damage and ultimately reduced productivity.

Some success at managing lost circulation has been achieved when drilling depleted zones that have good permeability, especially with water-based muds (WBM). However, as DEA-13 highlights, NAF pose a more significant challenge.

Synthetic or oil-based muds have recognized benefits, such as a thin impermeable filter cake, enhanced lubricity, improved wellbore and shale stability and a tolerance to some contamination. Often NAF will contain a prescription of sized

lost circulation materials as a preventative, but if these conventional methods prove inadequate, reducing downhole losses could prove extremely difficult, unless the wettability and permeability of the NAF filter cake inside the fracture can be altered in accordance with the observations made in DEA-13.

A spotting fluid was developed to increase the permeability of an NAF filter cake by altering the wettability of NAF lost into a fracture from oil-wet to water-wet. By altering the wettability of the NAF:

- The permeability of the filter cake will be greatly enhanced going from an NAF filter cake to a WBM filter cake.
- Converting the filter cake and water-wetting the formation will promote fracture healing.
- The fracture propagation pressure should increase as the wettability is changed to water-wet.

A similar technology with a different application has proven quite successful in cleaning NAF in several other applications, including clean-up of NAF filter cakes for enhanced productivity.⁷⁻¹⁰

Spacer Development

When lost circulation is encountered, a slurrified solids laden fluid is pumped into the loss zone and pressure is applied. The fracture(s) propagate until the fracture closure stress (FCS) exceeds the propagation stress. Much like in production fracturing, an immobile mass will prop open the fracture to the maximum closure stress, providing additional formation integrity and resistance to further hydrostatic fracturing of the depleted zone when drilling commences.

When drilling with NAF, a very robust and impermeable filter cake is built on the formation and inside fractures where losses have occurred. During the course of drilling, powerful emulsifiers and wetting agents oil-wet and create a very lubricious rock surface. A treatment is needed to alter the wettability of the NAF filter cake and render the fracture faces water-wet to improve the effectiveness of most water-based LCM pills. A patented approach can be used to water-wet the NAF cake in these wellbore fractures.¹¹ The spotting fluid in **Table 1** is formulated with calcium chloride brine or seawater and a surface active additive package (SAAP). A common water-based LCM pill is used in conjunction with the spotting fluid. The spotting fluid for the purpose of these tests is described in **Table 2**.

Testing Protocol

A lab protocol has been developed to evaluate treatments for enhancing wettability of fractures that includes a high-pressure/high-temperature (HP/HT) leak-off test and a wettability test. To complete each of the following tests, a NAF filter cake was built in a double-ended HP/HT cell on a 35- μ m ceramic disk for 30 minutes with 500 psid at the desired testing temperature. This is to simulate the filter cake on the fracture faces. Then, 100 mL of the high fluid loss water-wetting spotting fluid is carefully added to the cell in a

manner such that the filter cake is not disturbed. The cell is closed and placed back into the heater jacket. Pressure (normally 100 psid to simulate pressure loss at the fracture tip) is applied and both valve stems opened. A computer program monitors the fluid loss with time. The rate of filtration aids in determining when the treatment fluid has statically infiltrated the filter cake and complete leak-off has occurred. Once all of the filtrate from the high fluid loss spotting fluid is collected (without letting the filter cake dehydrate), the cell is removed from the heating jacket, cooled and carefully depressurized. A LCM pill is carefully added, trying not to disturb the simulated filter cake. The HP/HT cell is closed and placed back into the heater jacket. Pressure is applied (as much as 1000 psid) to the cell and both valves are opened. Leak-off is monitored versus time in a similar fashion as previously described. Once complete fluid loss occurs, if it occurs, the cell is closed, removed from the heating jacket and cooled. After cooling the cell, it is carefully depressurized, opened and an immobile mass is ideally observed. The wettability of the original NAF filter cake is determined and a plot is constructed relating volume of filtrate collected as a function of time.

Results and Discussion

Simulating Downhole Conditions

In this laboratory test the high fluid loss spotting fluid is allowed to soak on a filter cake under static conditions. Fluid motion and changes to the filter cake can only occur as the soak solution penetrates the filter cake through a mechanism of diffusion. Although not necessary to achieve the oil cake removal, hesitation squeezing will enhance the ability of the spotting fluid to water-wet and improve the permeability of the NAF filter cake in the fracture to water-based LCM pills.

Evaluation of a Water-Wetting Spotting Fluid

There are many different NAF formulations, fluid types, and densities that may be used during the course of drilling. We have chosen four common fluids (NAF #1, NAF #2, NAF #3, NAF #4) for the evaluation of the spotting fluid in this paper. This demonstrates results of the water-wetting spotting fluid tested on several different NAF densities and formulations under various temperature and pressure conditions. The generic formulation for an 11-lb/gal NAF that was evaluated is shown in **Table 3**. The spotting fluid treatment was tested on each of these muds at 150°F with 100 psi differential and the results of the HP/HT filtration tests are shown in **Fig. 1a**. The spotting fluid effectively infiltrated the NAF filter cake of all the various formulated muds at 100 psi and led to an acceptable leak-off rate. At the conclusion of each of the treatments conducted in **Fig. 1a**, the filter cakes were removed and inspected for destruction. Shown in **Fig. 2a and 2b** is the NAF #2 filter cake before and after it has been treated with the spotting fluid. Notice the obvious change in appearance of the filter cake after treating with the water-wetting spotting fluid.

To gain a better understanding of the wettability of the

residual solids and leak-off ability of an LCM into the formation, another test was performed to measure the rate of fluid loss of an LCM pill after treating the NAF filter cake with the water-wetting spotting fluid. After the spotting fluid reacted with the filter cake, the LCM is placed in the cell and pressurized with 1000 psi differential until complete carrier fluid loss occurs, **Fig. 1b**. Clearly the residual solids are water-wet after treating with the water-wetting spotting fluid, creating an ideal water permeable surface for carrier fluid loss of the LCM. The immobile mass that is created after treating an NAF filter cake with the spotting fluid and an LCM pill is shown in **Fig. 3a**. Investigation of what was an NAF filter cake shows that the solids are water-wet, **Fig. 3b** (the residual solids on the filter cake are placed in water and readily disperse. A control experiment was conducted to simulate the fracture faces with only an LCM pill (no water-wetting spotting fluid). In **Fig. 1b** it is clear that without the spotting fluid, no fluid loss of the LCM occurs, an immobile mass would not be created and circulation losses would continue once drilling commenced. The water-wetting spotting fluid is necessary to alter the wettability of an NAF filter cake to water so that an LCM may be successfully applied.

Spotting Fluid Compared to Acid Treatment

It has been noticed that acid treatments can penetrate oil-based filter cake containing a high percentage of acid soluble components. Given the relative low cost and abundant availability of acids, the performance of an acid versus the water-wetting spotting fluid to improve an NAF-containing fracture for an LCM pill is of interest. As shown in **Fig. 4a**, both an acid and the spotting fluid penetrate and breakthrough the NAF #3 filter cake at 150°F with 500 psid of pressure. The filtration rates of the two are comparable. However, penetrating a filter cake without water-wetting is not sufficient to have a successful LCM leak-off and placement. To determine the significance of the wettability of the solids, the loss circulation material was placed in the cell after each of the treatments (water-wetting spotting fluid or acid) and pressurized to 1,000 psid at 150°F. The leak-off rate is shown in **Fig. 4b**. The filter cake that was treated with the spotting fluid allows for complete LCM fluid loss in less than 30 minutes, which forms an immobile mass that is ideal to preventing further losses. The filter cake treated with only acid does not exhibit complete fluid loss. This would **not** allow for an immobile mass to be created in the fracture or water-wet the formation to promote fracture healing and whole mud losses would continue.

Even though acid is able to penetrate a filter cake with calcium carbonate, it is unable to render it water-wet, **Fig. 5a**. The solids remain oil-wet, adhering to the walls or falling as an oil-wet clump to the bottom of the beaker. They do not disperse, even when they are vigorously agitated. In comparison, the residual solids that were analyzed after the spotting fluid are water-wet and easily disperse, **Fig. 5b**. This is the optimum condition to allow a water-based carrier fluid to exhibit leak-off through the filter cake. It is clear that to

have a successful treatment, the water-wetting spotting fluid must *penetrate and water-wet* the formation faces to promote fracture healing and placement of the immobile mass into the fracture.

Spotting Fluid Treatment at Various Temperatures

Lost circulation events can be encountered at any temperature. To determine the range of temperature at which the spotting treatment is effective, several temperatures were tested, **Fig. 6a**. A clear correlation exists between the breakthrough time and the temperature. As the temperature increases, the time needed for breakthrough decreases. The spotting treatment is effective to above 300°F. Despite a rather large variation in spotting fluid treatment breakthrough times for the different temperatures, all of the LCM filtration rates are similar, **Fig. 6b**. This shows that the rate of fluid loss of the LCM is not dependent on the time it takes for the spotting fluid to perform. The success of the LCM is only dependent on the permeability and water-wetness of the residual filter cake solids.

Spotting Fluid Treatment at Various Differential Pressures

In addition to the role of temperature in the spotting fluid breakthrough, the applied differential pressure can also have an effect. Shown in **Fig. 7a** is a field-NAF treated at 150°F with different amounts of differential pressure. As the applied pressure is increased, the time needed for breakthrough is drastically decreased. Increasing the pressure from 100 psid to 250 psid reduces the breakthrough time by more than half. This can be crucial when difficult-to-treat muds are encountered that would normally exhibit slow penetration rates. By increasing the applied pressure, the filter cake can be infiltrated quicker, thus allowing for a faster treatment.

The LCM rate of filtration at different pressures is shown in **Fig. 7b**. Despite the large variation in filter cake breakthrough times, all of the LCM filtration rates are similar. This indicates that increasing the applied pressure reduces the breakthrough time **WITHOUT** compromising the water-wetting ability of the spotting fluid. This is further supported by **Fig. 8** where the filter cake destructed at 500 psid is completely water-wet and the subsequent LCM filtration rate test yields an immobile mass. The penetrating rate of the spotting fluid, and thus the application of the LCM pill, can be managed by controlling the applied pressure.

The Effect of Concentration and Contamination

Any fluid used downhole has the risk of being contaminated either by NAF dilution or formation fluids. It is possible that contaminants or dilution could have an effect on the performance of the spotting fluid. To better understand the effect of dilution, a study was conducted where the SAAP concentration was varied when treating an NAF #1 at 150°F with 100 psid. In **Fig. 9a**, it is clear that the SAAP is a very robust formulation and even at the low concentration of 20% SAAP, the spotting fluid is still able to cause breakthrough in a timely fashion. The LCM filtration rate data in **Fig. 9b**

shows that all three concentrations of SAAP in the FCS treatment provided sufficient water-wetting of the filter cake. Complete LCM carrier fluid loss easily occurred in less than 30 minutes and a solid LCM cake is still formed even at 20% SAAP (Fig. 9b inset). When the spotting fluid is contaminated with 50 vol% NAF or LCM pill, it is still able to penetrate the NAF filter cake, **Fig. 10**.

Conclusions

The spotting fluid treatment was successfully developed to enhance the effectiveness of a water-based LCM pill. The tests conducted prove the concept that the spotting fluid can penetrate and alter the wettability of an NAF filter cake from oil-wet to water-wet to allow carrier fluid loss and successful application of a water-based LCM pill. The following conclusions were drawn from the work conducted:

- The spotting fluid proved to be an effective treatment in applications where NAF #1, NAF #2, NAF #3 or NAF #4 is used.
- Acid treatment is NOT sufficient for penetrating and water-wetting an NAF filter cake to give successful LCM carrier fluid loss.
- For a given NAF, increasing the pressure of the system can decrease the time needed for the spotting fluid to cause breakthrough without compromising water-wetness.
- Even when contaminated or diluted, the new spotting fluid successfully alters the wettability of the NAF filter cake.

Acknowledgments

The authors thank the management of Baker Hughes for their support and permission to publish these results.

References

1. Black, A.D. "Investigation of Lost Circulation Problems with Oil Base Drilling Fluids," DRL Reports: Phase I - May 1986.
2. Morita, N., Black, A.D., Fuh, G-H. "Theory of Lost Circulation Pressure," SPE 20409, SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, September 23-26, 1990.
3. Onyia, E.C. "An Analysis of Experimental Data on Lost-Circulation Problems During Drilling with Oil-Based Mud," SPE 22581, SPE Annual Technical Conference and Exhibition, Dallas, Texas, October 6-9, 1991.
4. Dupriest, F. E. "Fracture Closure Stress (FCS) and Lost Returns Practices," SPE /IADC 92192, SPE/IADC Drilling Conference, Amsterdam, The Netherlands, February 23-25, 2005.
5. Ivan, C.D., Bruton, J.R., Thiercelin, M., Bedel, J-P. "Making a Case for Rethinking Lost Circulation Treatments in Induced Fractures," SPE 77353, SPE Annual Conference and Exhibition, San Antonio, Texas, September 29 – October 2, 2002.
6. Whitfill, D.L., Hemphill, T. "All Lost-Circulation Materials and Systems Are Not Created Equal," SPE 84319, SPE Annual Conference and Exhibition, Denver, Colorado, October 5-8, 2003.
7. Quintero, L., Jones, T. A., and Clark, D. E. "One-Step Acid Removal of an Invert Emulsion", SPE 86556, SPE 6th European Formation Damage Conference, Scheveningen, The Netherlands, May 25-27, 2005.
8. Laviox, F., Leschi, P., Aubry, E., Quintero, L., Le Prat, X., Jones, T. "First Application of Novel Microemulsion Technology for Sand Control Remediation Operations – A Successful Case History from the Rosa Field, a Deepwater Development Project in Angola", SPE 107341, SPE European Formation Damage Conference, Scheveningen, The Netherlands, May 30 – June 1, 2007.
9. Quintero, L., Jones, T., Clark, D.E., Torres, C., and Christian, C. "Single-phase Microemulsion Technology for Cleaning Oil or Synthetic-Based Mud", AADE-07-NTCE-18, AADE National Technical Conference and Exhibition, Houston, Texas, April 10-12, 2007.
10. Bustin, B., Phillips, J., Al-Otabi, M., Bin Moqbil, K., Christian, C.F., Torres, C., White, C. "Improved Wellbore Clean-up – Successful Case Histories in Saudi Arabia from Development to Field Implementation," SPE 08088, SPE Saudi Arabia Section Technical Symposium, Al-Khobar, Kingdom of Saudi Arabia, May 10-12, 2008.
11. Jones, et al. U.S. Pat. No. 7,134,496

Tables

Table 1. Composition of the spotting fluid treatment

Product	(vol %)
Brine	70
SAAP	30

Table 2. Formulation of the lost circulation material pill

Product	Quantity
Sea water, bbl	0.7376
Attapulgite clay, lb/bbl	18
KCl, lb/bbl	36
Walnut shells, lb/bbl	70
Sized CaCO ₃ , lb/bbl	32

Table 3. NAF formulation

Properties	
Density, lb/gal	11
Product	
Quantity	
Base oil, bbl	0.5349
Organophilic clay, lb/bbl	10
Lime, lb/bbl	4
Emulsifier, lb/bbl	8
Wetting agent, lb/bbl	4
Water, bbl/bbl	0.2427
CaCl ₂ , lb/bbl	22.02
Barite, lb/bbl	85.71 – 110.71
Simulated drill solids, lb/bbl	36
Calcium carbonate, lb.bbl	0 - 25

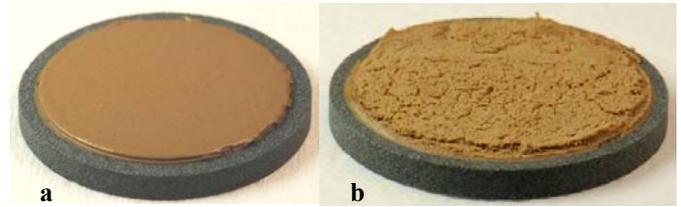


Fig. 2. The NAF #2 filter cake before (a) and after (b) the spotting fluid treatment shown in Fig. 1a

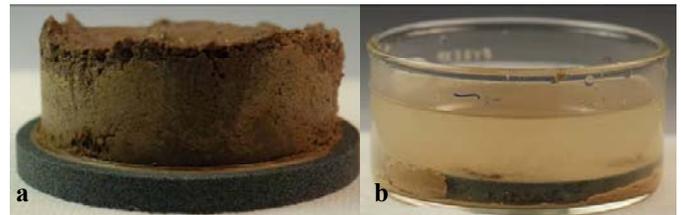


Fig. 3. The immobile mass created after LCM carrier fluid loss (a) and the wettability of the residual solid on the ceramic disk after the spotting fluid treatment (b)

Figures

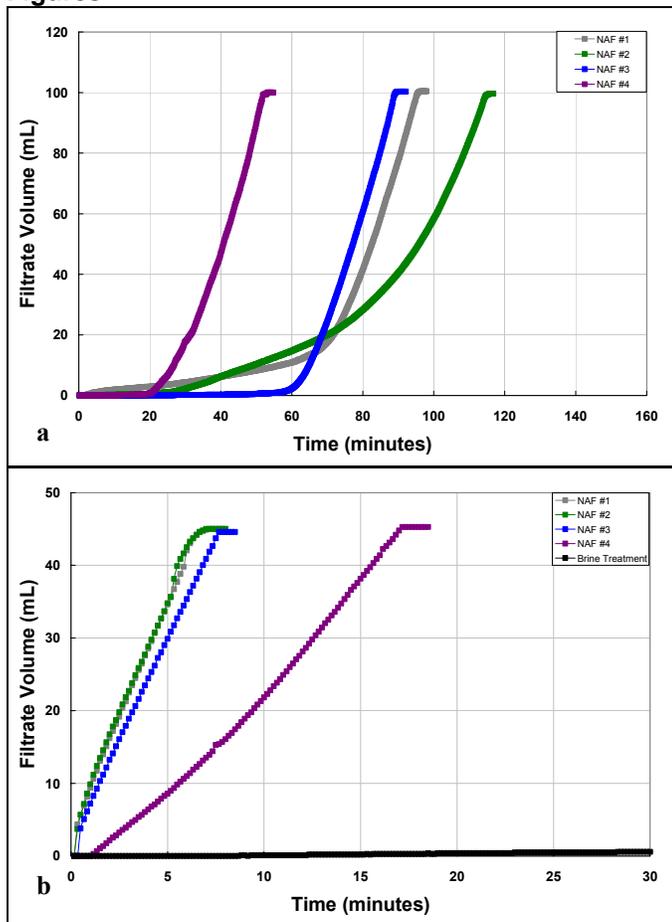


Fig. 1. The spotting fluid treatment on four different types of NAF at 150°F with 100 psid (a) and the LCM filtration rate test at 150°F with 1000 psid (b)

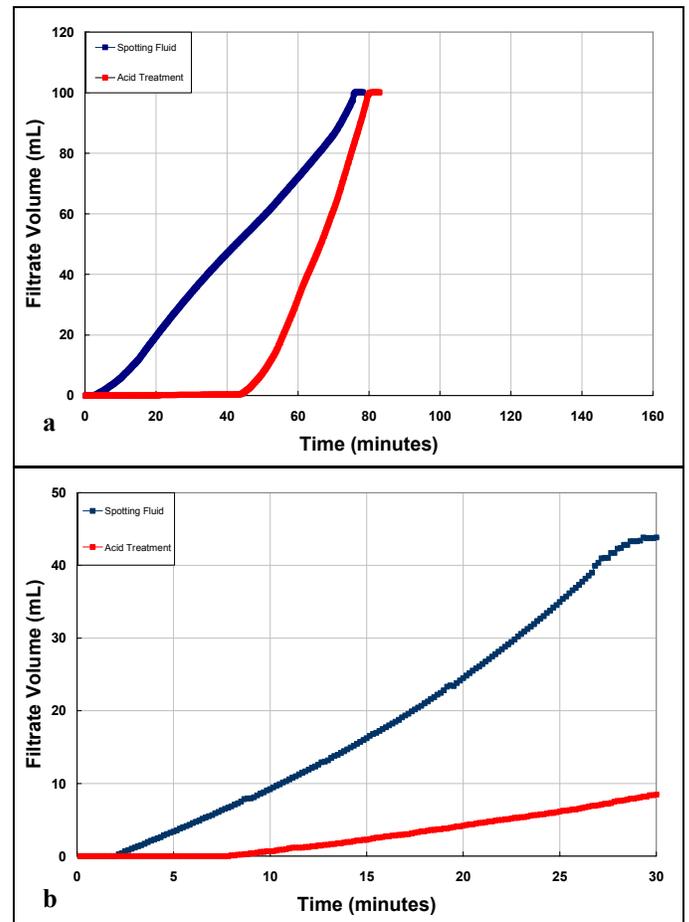


Fig. 4. The spotting fluid treatment and acid treatment on a filter cake at 150°F with 100 psid (a) and the LCM filtration rate test at 150°F with 1000 psid (b)

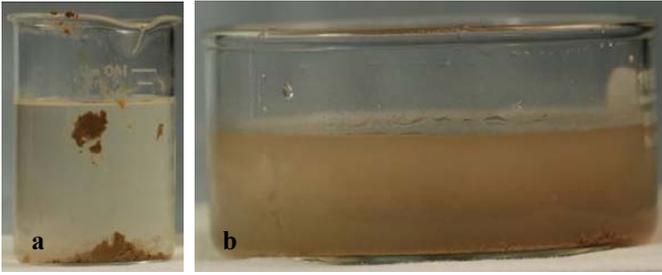


Fig. 5. The residual filter cake solids after the acid treatment (a) and the spotting fluid treatment (b)

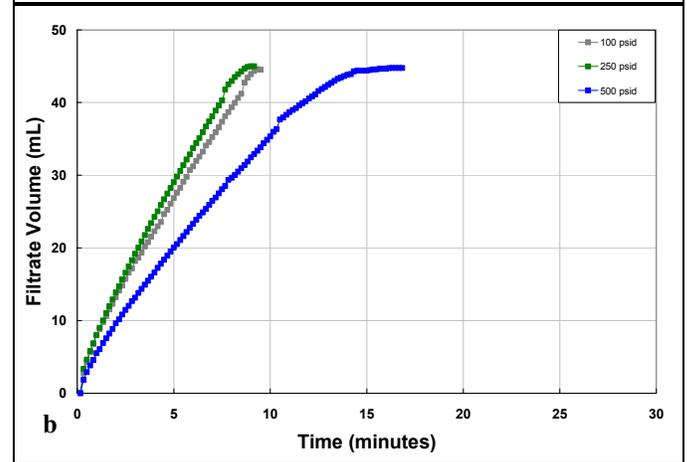
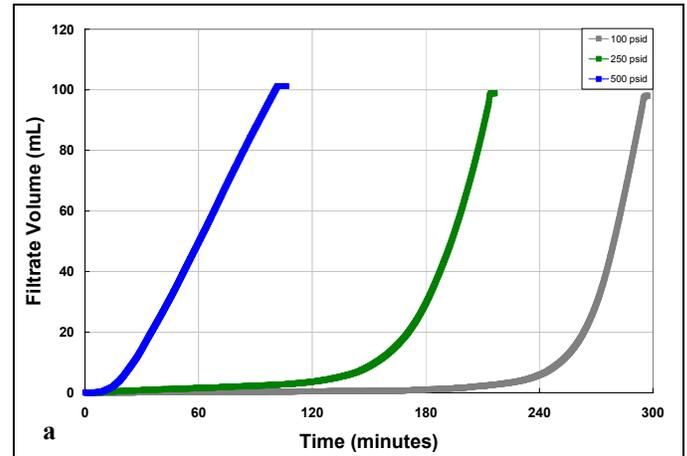


Fig. 7. The spotting fluid treatment on a field-NAF filter cake at 150°F at various pressures (a) and the LCM filtration rate test of each of these tests at 1000 psid (b)

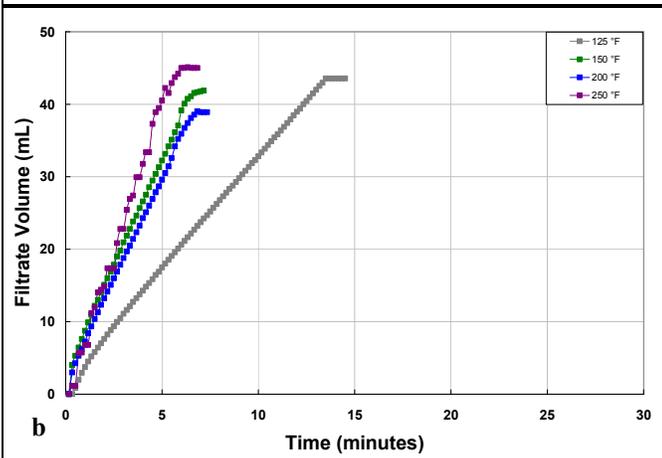
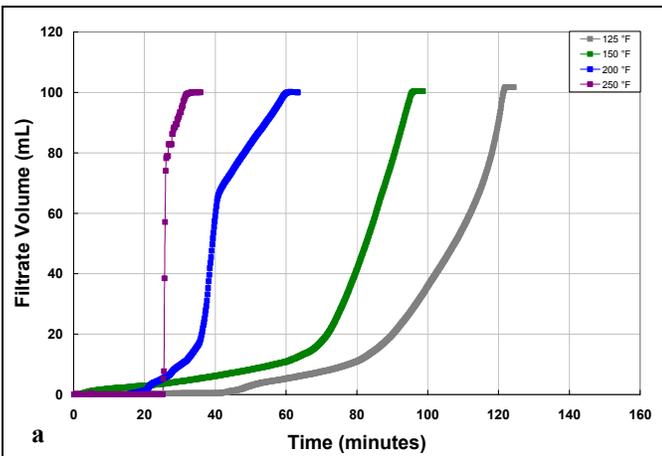


Fig. 6. The spotting fluid treatment on NAF #1 filter cake at various temperatures with 100 psid (a) and the LCM filtration rate test of each of these tests at 1000 psid (b)

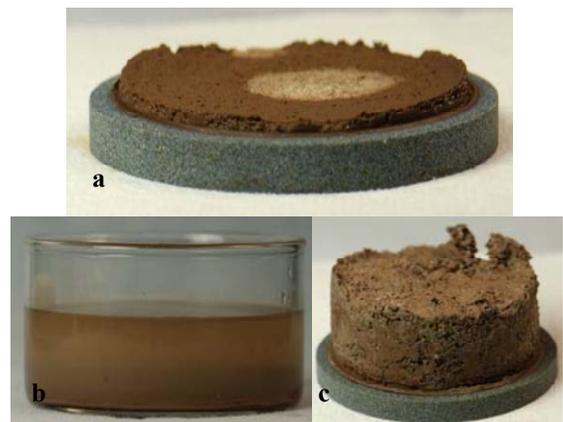


Fig. 8. The destructed field-NAF filter cake after the spotting fluid treatment at 500 psid (a), the residual solids on the ceramic disk placed in water showing the wettability (b) and the LCM cake formed after the LCM filtration rate test (c)

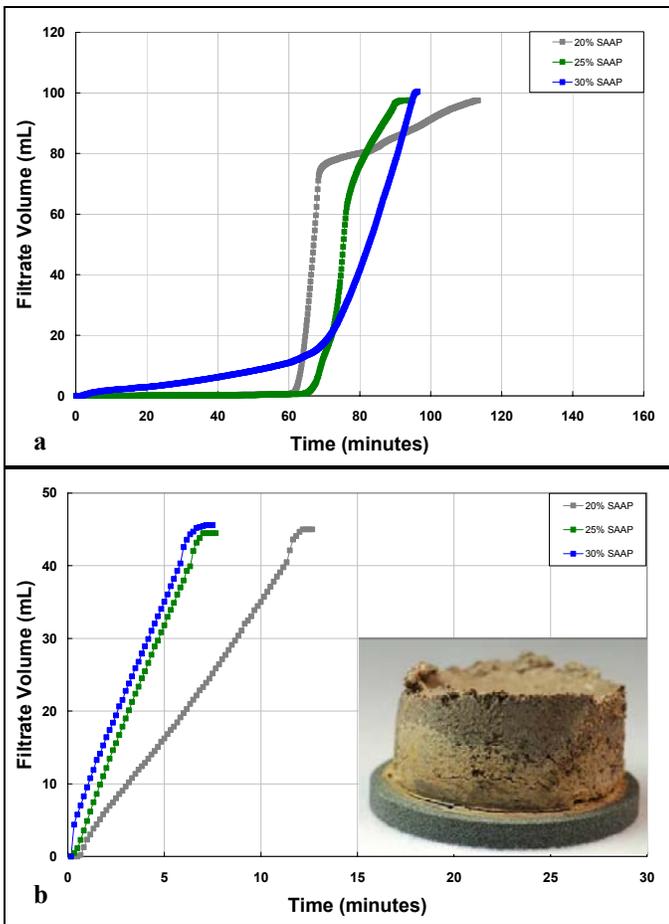


Fig. 9. The spotting fluid filtration rate test with varying concentrations of the SAAP at 150°F with 100 psid (a) and the LCM filtration rate test at 1,000 psid with the inset showing the LCM cake formed (b)

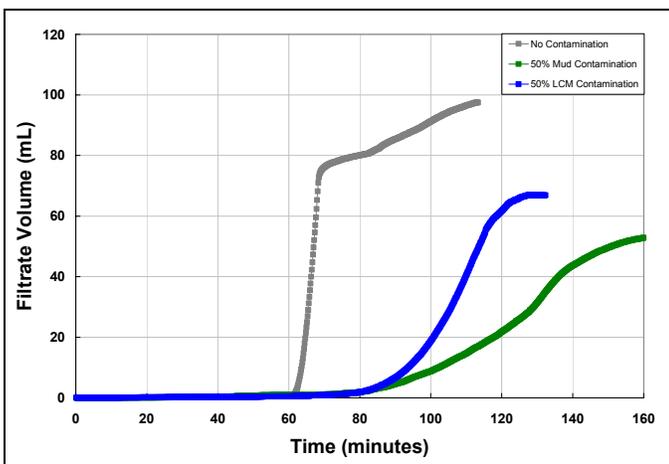


Fig. 10. The filtration rate of the spotting fluid with and without contamination on an NAF #1 filter cake at 150°F and 100 psid