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Laboratory and Field Study of a Nanoparticle Lubricant in Aqueous Drilling Fluids in the Bakken formation of North Dakota

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Abstract

Drilling directional and extended-reach wells continues to gain popularity, high torque and drag become increasingly important issues. Oil-based muds (OBM) and synthetic-based muds (SBM) generally produce a lower coefficient of friction (CoF) than water-based muds (WBM) and brines. However, OBM and SBM's are limited by environmental concerns and high costs. WBM and brines generally give rise to high CoF between the drill string and the wellbore, which translates to high torque and drag and low rate of penetration (ROP). Based on a patented nanotechnology, a first commercial nano-lubricant was developed to provide effective lubrication in sodium and calcium chloride brines. Post extensive laboratory testing, the technology entered a field validation stage consisting of 9 horizontal wells in the Williston Basin of North Dakota. The key challenges drilling these wells was high torque and drag and limited ROP, resulting in high lubricant usage and excessive costs. In all field test cases, the same rig, bit, fluid system and crew were used. Real time drilling data was collected and analysed. Comparing test wells to offset wells, showed that the test wells laterals were drilled 20-50% faster with 4-13% lower torque and 14-25% higher ROP, whilst using 35-58% less lubricant. This all translated to lower NPT whilst allowing these 3-mile laterals to be drilled under 16,000 ft-lb of Torque. With over 120 wells treated to date these positive effects have been shown multiple times. Laboratory lubricity and tribology measurements were also shown to correlate well with field results.

Introduction

Drilling horizontal wells in the Williston basin shale plays show high torque and drag and are often limited by low ROP and high lubricant usage with drill bits lasting 15,000-21,000 feet. The Bakken formation is a relatively tight formation with low porosity and low permeability rock, from which oil flows with difficulty. The speed in which a well is drilled, measured as the well's depth divided by the number of days spent drilling is a direct reflection of drilling productivity and downtime seen as non-productive time or NPT. Drilling in North Dakota is concentrated in the Williston Basin, a hydrocarbon-rich depression spanning 150,000 square miles and reaching into Canada, Montana, and South Dakota (NDGS, n.d.). The vast proportion of wells drilled in North Dakota within the Williston Basin targeting the Bakken and Three Forks formations are located about 10,000 feet below ground. The Bakken and Three Forks are termed unconventional tight oil plays due to their low permeability and low porosity. While oil was first produced from the Bakken in 1955 (EERC, 2014), much of the oil present could not be economically extracted until recently. Bakken activity was flat during the early 2000s with no growth in the number of oil-producing wells. In 2005, the horizontal well "Nelson Farms 1-24H" was drilled by EOG Resources in the Ross Field. The success of this well is considered to be a turning point in that it showed how combining horizontal drilling and hydraulic fracturing could unlock the Bakken's once uneconomic hydrocarbons (EERC, 2014). In these systems, WBM or low solids brine are the preferred drilling fluid choice to drill parts of these horizontal wells mainly because of cost and environmental constraints. The typical brine used to drill these wells is saturated NaCl system. However, this system generally gives rise to higher coefficients of friction (CoF) resulting in higher torque and drag and lower ROP. To counter these challenges, lubricant is added to these water-based drilling fluids with a view of enhancing performance and reducing non-productive time (NPT). Common liquid lubricants deployed in the field in principle work as friction modifiers. Protective layers are formed either by chemical reaction of the lubricant additive with the metal surface or by strong absorption forces from the polar head of additives to the metal surfaces (Rudnick 2009). The key lubricant in these studies combines these common boundary layer properties with compatible nanoparticle technology which migrates into the surface asperities of the drill pipe and casing and by so doing greatly reduces surface roughness whilst enhancing and extending boundary layer lubrication. Some of the concomitant problems experienced in the field during the application of common lubricants in saturated brine systems include (a) foaming (b) "cheesing" or more accurately the saponification of fatty acid materials from the lubricant. Both problems can reduce the efficiency and effective lubricant concentration and may contribute to further cost. Hence, the nano-lubricant tested in this paper was not only developed to enhance lubrication performance but also to eliminate foaming and cheesing.

Materials and Methods

In this paper, a comprehensive study of fluid lubricity measurement is conducted using two instruments: (1) OFITE EP (Extreme Pressure) & Lubricity Tester; (2) Falex Pin & Vee Block Test Machine. The lubricity of various NaCl-based field brines and lab prepared WBMs were tested along with field-based lubricants for their effectiveness in improving fluid lubricity. We tested two WBM formulations to include (a) Bentonite Polymer; (b) KCl-PHPA systems. All systems were mixed in laboratory and dynamically aged (hot-rolled) at 150 °F for 16 hours. Field application consisted of drilling a whole pad comprising of four baseline wells and five test wells. The baseline wells were drilled using a commercial lubricant. The five test wells were drilled using the nanoparticle-based lubricant. In all the field test cases, the same rig, bit type, fluid system and crew were used. Real time Pason data was collected and the following parameters were analysed: on-bottom hours, convertible torque, ROP, hook load, weight on bit, lubricant usage and drilling time in the lateral section of the wells.

Table 1: Density of water-based drilling fluid used

Drilling fluid	**Density (lb/gal)**
North Dakota (NaCl) field brine	10.0
Bentonite-Polymer	10.7
KCl-PHPA	10.6

Lubricants

We tested several field lubricants denoted (A-E) and several variants of the nano-lubricant system. The lubricants were added to the baseline fluids at 3 vol% in both the lab and the field tests.

Lubricants/Fluid Compatibility Screening

Prior to any lubricity measurement being performed, it is critical that the lubricant system be evaluated for compatibility with the baseline fluids. As previously mentioned, incompatibilities such as "cheesing" or foaming can have an adverse effect on drilling operations. In the case of cheesing, key components of the lubricant are separated from the brine-lubricant system and become agglomerated where they can coat various components such as the production zone, sand screens and shakers (Knox & Jiang 2005). Compatibility was evaluated by mixing the lubricant at 3 vol% with the baseline fluid, which was mixed on Silverson L5M using a slotted screen for five minutes at 5000 rpm. Lubricants that did not exhibit compatibility issue were used in subsequent measurements.

Lubricity Measurement Techniques

In this study, two instruments were deployed to measure lubricity: (1) OFITE EP & Lubricity Tester; (2) Falex Pin & Vee Block Test Machine.

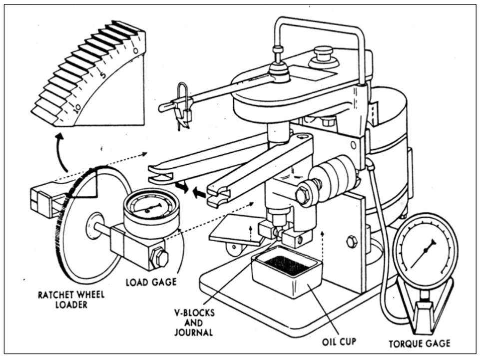
1. OFITE EP & Lubricity Tester

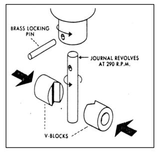
Lubricity testing using the OFITE lubricity meter was conducted at ambient conditions using a block on ring configuration at 60 rpm and 150 lb-in of applied torque (Model #112-00, OFI Testing Equipment, Inc.). Prior to lubricity measurements, the unit was conditioned in deionized water using both coarse and fine valve lapping compound to polish the block and ring surfaces to a standardized surface roughness. During lubricity measurements the block and ring were immersed into the fluid sample and the hardened steel block was pressed against a rotating hardened steel ring. Using the fixed applied torque setting and rotational speed, the instrument calculated a measure of the CoF. The unit was cleaned, and deionised water measurement was taken prior to measuring any fluid sample so as to ensure consistency and accurate comparison between the results. The lubricity tester measurements are only good for lab-based comparisons but are rarely correlated with field performance (Redburn et al; 2013).

Figure 1: OFITE EP & Lubricity Tester (model #112-00).

2. Falex Pin & Vee Block Test Machine

The Falex Pin & Vee Block Test Machine evaluates wear, friction and extreme pressure properties of materials and lubricants. The Falex unit allows us to look at higher loads & rotational speed. The equipment rotates a ¼ inch diameter test pin against two ½ inch diameter vee blocks. A four-line contact is established as an increasing load is applied through a mechanical gauge by a ratchet wheel and an eccentric arm. The system measures frictional torque and wear, temperature and the maximum pressure it will withstand before the lubricating properties fail and the shear pin snaps.





Pin & Vee Block Configuration

Figure 2: Falex Pin on Vee Block Tribometer

The Falex test parameters used during this testing were as follows: (1) 290±10 rpm; (2) Temperature 49±3 °C; (3) Load 300-4500 lb.

Results and Discussion

It's important to note that there is flexibility in the formulation of the nano-lubricant which enables performance optimization when brine composition varies between various field samples.

Lubricant Compatibility Comparison

Figure 3 shows the commercial lubricant A in field brine (left), commercial lubricant B in field brine (middle) and the nano-lubricant in field brine (right). After shearing at 5000 rpm for 5 minutes using a Silverson mixer, the lubricant A showed a great amount of foaming and the lubricant B showed a small amount of cheesing, whereas the nano-lubricant showed no foaming and no cheesing. With very mild mixing the nano-lubricant is easily dispersed in field brine.

Figure 3: 3 vol% Lube A (left), 3 vol% Lube B (middle) and 3 vol% nano-lubricant (right) in a NaCl field brine.

Figure 4: Polymer WBM control (left) and with 3 vol% nano-lubricant (right).

Figure 4 shows the nano-lubricant is compatible with the polymer based WBM system.

Laboratory Lubricity Test Results

1. Effect of Nano-lubricant in North Dakota Brines

The following tests (figures 5-9) were conducted using the OFITE lubricity tester.

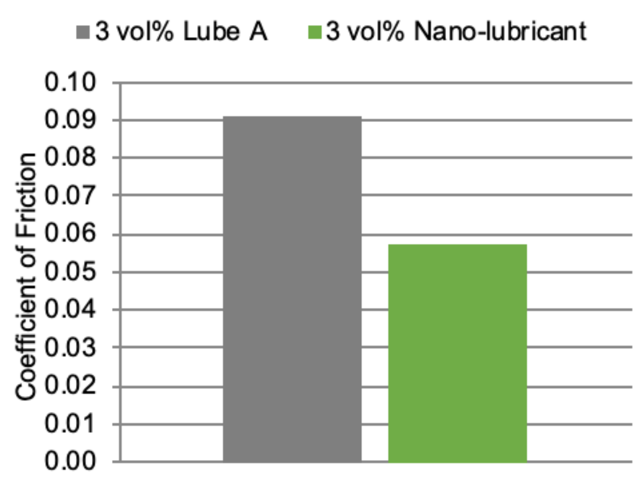


Figure 5: Lubricant testing of unfiltered North Dakota NaCl field brine

Setting against a common field lubricant A in unfiltered North Dakota field brine, the nano-lubricant showed an improvement in the reduction of the CoF by 37%.

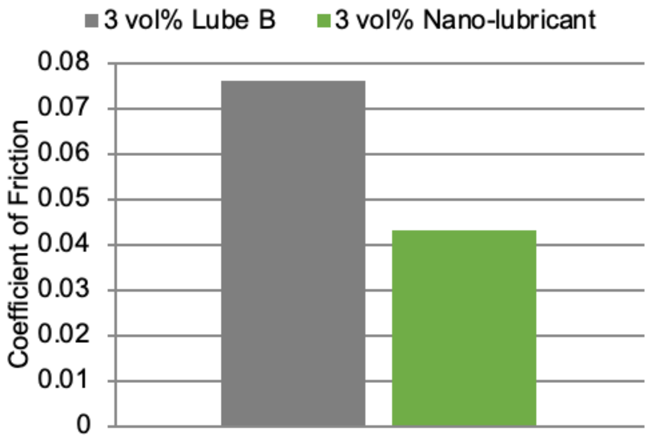


Figure 6: Lubricant testing of filtered North Dakota NaCl field brine.

Figure 6 shows the same test in filtered brine and highlights the impact of solids. A trend we have noticed in testing many lubricants is that solid material has less of an impact on nano-lubricant than it has on conventional lubricants. This may be related to the extremely small size of the nanoparticles in the lubricant that can penetrate the asperities of the contact surfaces regardless of solids content. The nano-lubricant shows an improvement in the reduction of CoF by 43% set against commercial lubricant B.

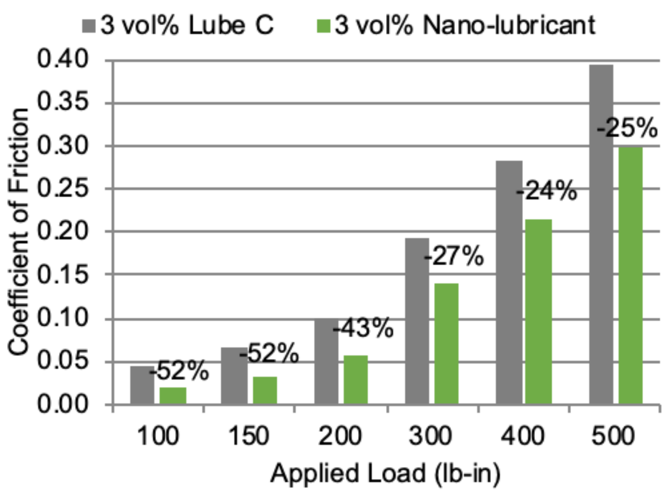


Figure 7: Lubricity at various loads in Louisiana NaCl field brine.

Figure 7 evaluates the CoF between commercial lubricant C and nano-lubricant in the field brine from Louisiana when subjected to a progressively increasing applied load up to 500 lb-in, in increments of 100 lb-in. From 100 to 200 lb-in of applied torque, there is little difference in the rate of change of CoF in both systems. However, over 200 lb-in, the rate of change of CoF in lube C begins to increase at a higher rate which suggests a gradual breakdown in the lubricant's ability to maintain a coherent lubrication film.

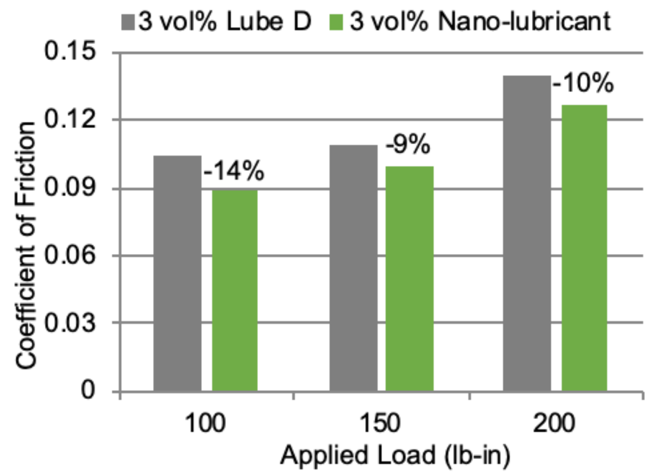


Figure 8: Lubricant testing of Bentonite-Polymer WBM

Figure 8 shows a comparison of CoF between the commercial lubricant D and nano-lubricant in a bentonite-polymer WBM under a progressively increasing applied load. As in previous cases, the nano-lubricant creates a lower CoF than the common commercial lubricant.

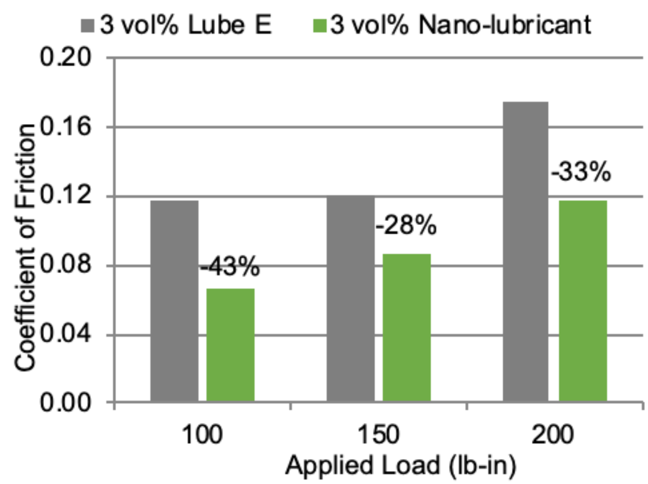


Figure 9: Lubricant testing of KCl-PHPA WBM.

Figure 9 shows a CoF comparison between commercial lubricant E in KCl-PHPA WBM and nano-lubricant in the same system. Under various applied load, lubricant E is beginning to degrade at 200 lb-in, whereas the nano-lubricant gave relatively consistent results across this load range.

Tribology Test Results

Having evaluated numerous field lubricants using the OFITE lubricity tester, we decided to extend this round of testing using standardized tribological test methods so as to better understand the wear, friction and extreme pressure properties of these systems. To conduct these tests, we selected the premium commercial lubricant (Lube A) and nano-lubricant. Standardized test ASTM D3233-19 (ASTM, 2019) was performed on the Falex Pin & Vee Block Test Machine. After a 300 lb break-in run for five minutes, the load was continuously ramped until failure (signaling the end of the load carrying capacity) occurs. The results shown below in Figure 10 clearly indicate that the CoF of the nano-lubricant has a smaller and more consistent CoF amplitude than lube A, inferring that the nano-lubricant would be more consistent during field operations.

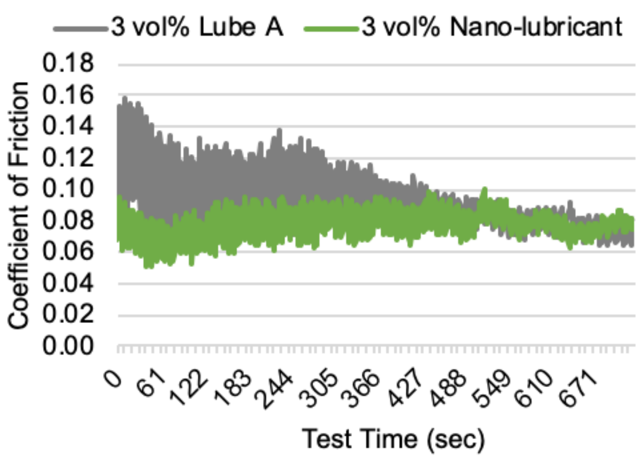


Figure 10: Tribology test using Falex Pin & Vee Block Test Machine in unfiltered North Dakota NaCl field brine.

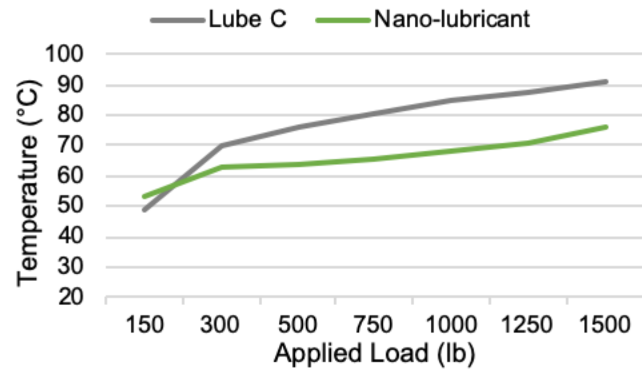


Figure 11: Lubricant temperature during Pin & Vee Block testing in unfiltered North Dakota NaCl field brine.

During the tribology test shown in Figure 10, we also measured the temperature of the lubricant at the same time. It is clear from Figure 11 that the nano-lubricant system is running at about 20 °C cooler than lube A. This is most likely due to the ability of the nanoparticles to dissipate frictional heat energy in the lubricant due to the massive specific surface area.

Field Trial

1. Field Trial Methods

As previously mentioned, in order to minimize differences between well pads, a new well pad was chosen for all test cases. This pad consisted of 9 wells in total, with four baseline wells and five test wells. The tests were focused on the lateral section of the wells. The baseline wells were drilled using the common commercial field lubricant and the test wells were drilled using the nano-lubricant. The key challenges normally experienced with these wells in the lateral section is high torque and drag, low ROP and high lubricant usage. The field trial test method for these wells was as follows: When drilling into the lateral section, pump the lubricant at about 3 vol% per sweep. Lubricant injection rate was maintained at 0.3-0.5 gallon/min to the active tank. Real time Pason data was collected and the following parameters were analyzed: on-bottom hours, convertible torque, ROP, lubricant usage, hook load, weight on bit and drilling time in the lateral section of the wells. Figure 12 shows the typical well schematic of the test wells in the Bakken formation. The general field test conditions are as follows: (1) horizontal wells; (2) average TD 21000 ft; (3) average lateral section 10000 ft; (4) average brine density 10 ppg.

2. Basic Test Well Schematic

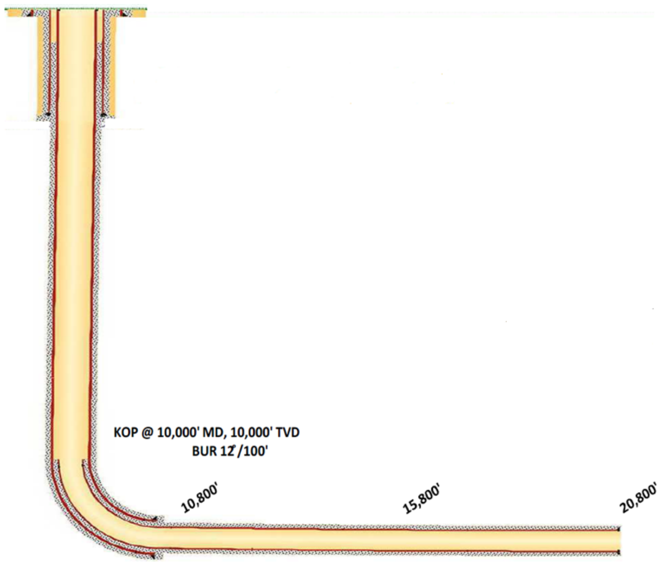


Figure 12: Well schematic of the field test wells in Bakken formation.

3. Test Results in Field Trial

The field results are interpreted from the data exported from PASON. As indicated in Figure 13, the four control wells had an average ROP of 260 ft/hour, the average ROP of the five test wells is 297 ft/hour. In general, nano-lubricant can increase the ROP by 14%, up to 25% for test wells.

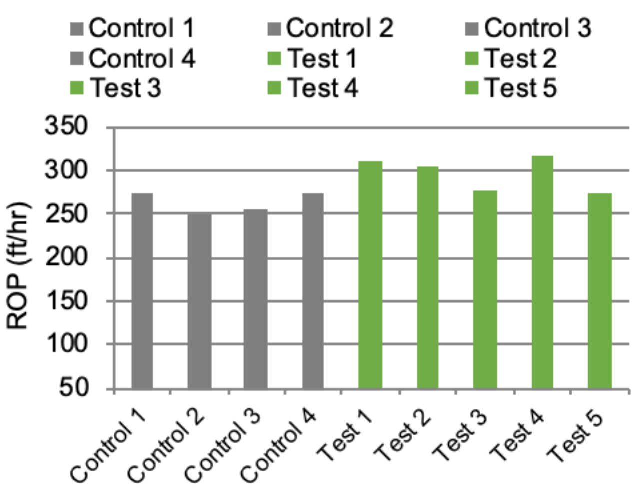


Figure 13: Rate of penetration in control and test wells during a field trial of nano-lubricant in North Dakota.

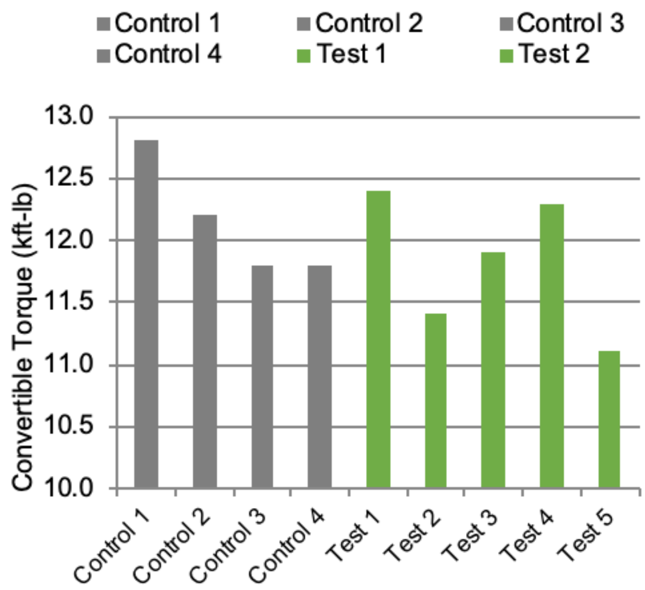


Figure 14: Convertible torque in control and test well during a field trial of nano-lubricant in North Dakota.

Figure 14 shows how the nano-lubricant reduces the convertible torque during the drilling process. On average test wells showed 4%, up to 13% lower torque than the baseline wells.

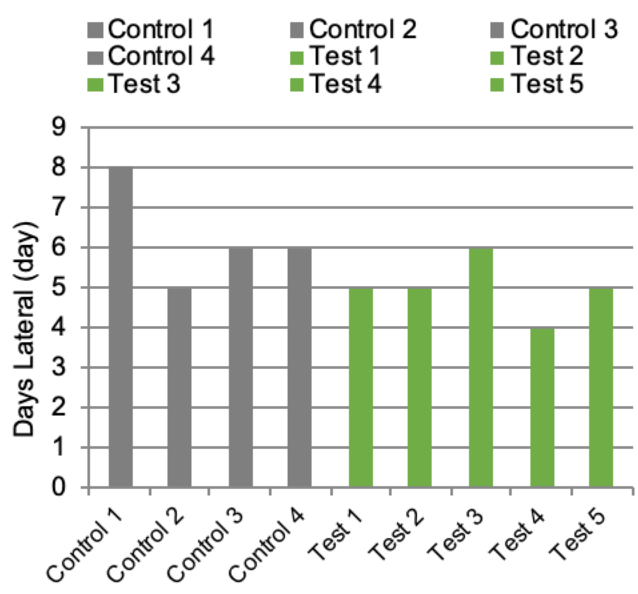


Figure 15: Days drilling the lateral section of the control and test wells during field trial of nano-lubricant in North Dakota.

Higher ROP leads to faster drilling in lateral section. Figure 15 shows that time spent in drilling the lateral section of the nano-lubricant test wells are generally 20% to 50% shorter than those wells using the common field lubricant, and therefore a great savings for the operators.

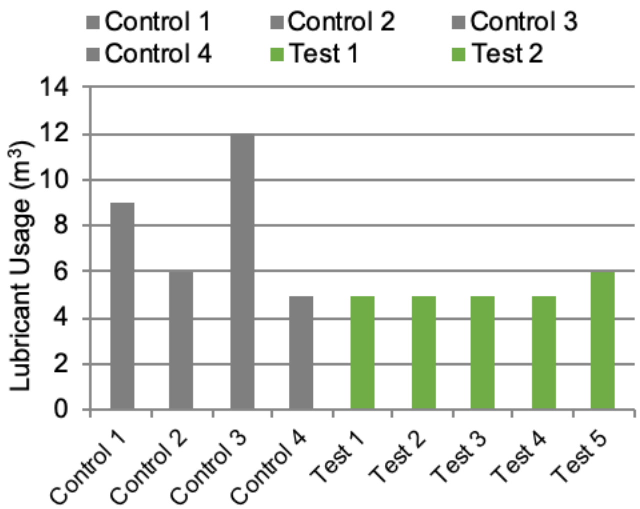


Figure 16: Lubricant usage in control and test wells during a field trial of nano-lubricant in North Dakota.

Figure 16 shows that on average, lubricant usage in the nano-lubricant test wells was 35-58% less than the common field lubricant and therefore a considerable savings to the operator.

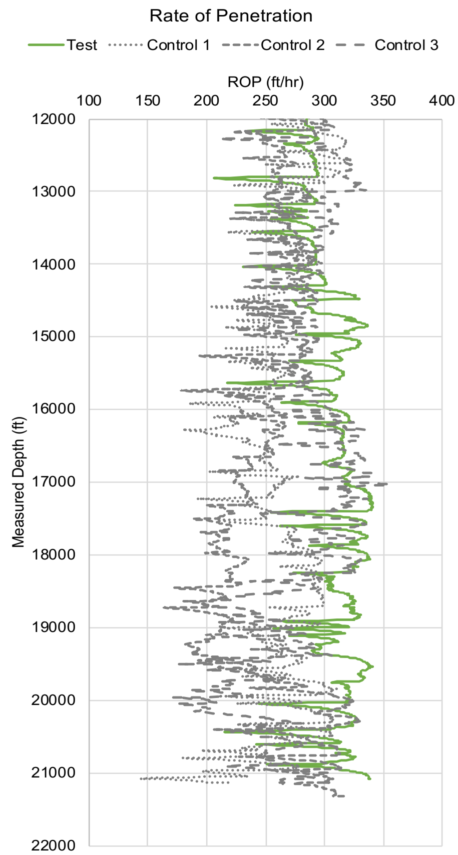


Figure 17: Comparison of ROP vs depth in control and test wells during a field trial of nano-lubricant in North Dakota.

Figure 17 shows how the average nano-lubricant test well performed consistently better than the baseline wells.

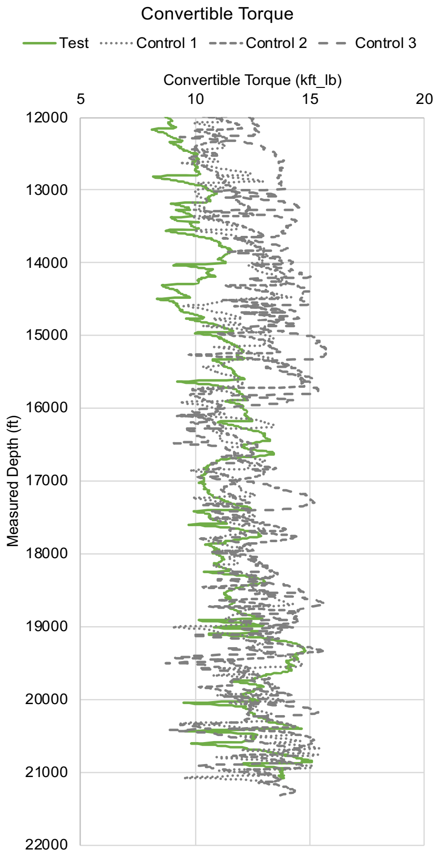


Figure 18: Comparison of convertible torque vs depth in control and test wells during a field trial of nano-lubricant in North Dakota.

Figure 18 shows how the average test well performs consistently better than the baseline wells for convertible torque.

Figure 19 shows how on average the nano-lubricant wells had fewer trips and therefore less non-productive time (NPT). Additionally, no foaming, cheesing or product separation was experienced during field trial operations.

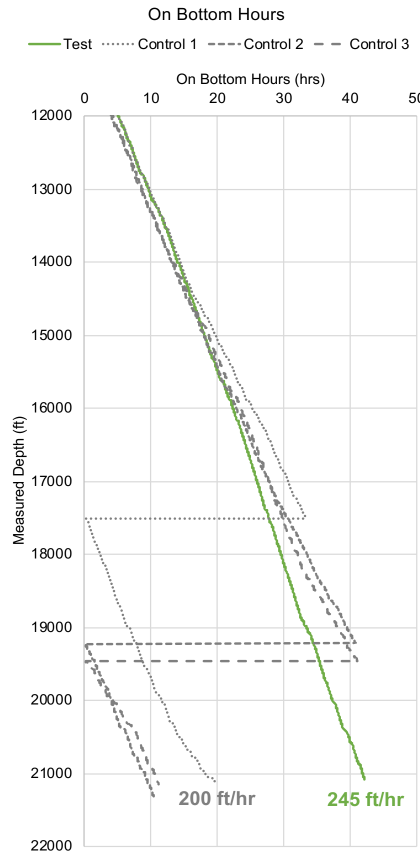


Figure 19: Comparison of on-bottom hours vs depth in control and test wells during a field trial of nano-lubricant in North Dakota.

Conclusions

1. The nano-lubricant evaluated in this study was wholly compatible with the North Dakota field brine and showed no cheesing, foaming or instability behaviour.
2. The laboratory results show that nano-lubricant out-performs the common commercial field lubricants by demonstrating significantly lower coefficient of friction using either OFITE EP & Lubricity Tester or Falex Pin & Vee Block Test Machine.
3. Analysis on tribology tests also identified that the nano-lubricant under study was 20 °C cooler under the same test conditions.
4. Field testing of the nano-lubricant system demonstrated the following improvement over the common field lubricant:
   - 14-25% higher ROP
   - 4-13% lower drilling torque
   - 20-50% faster lateral drilling
   - 35-58% lower lubricant usage.

Acknowledgments

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Nomenclature

ROP = Rate of penetration
NPT = Non - productive time
CoF = Coefficient of friction
OBM = Oil-based mud
SBM = Synthetic-based mud
WBM = Water-based mud

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