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Mechanical Specific Energy and Rig Sensor Data: A Novel Approach to Lubricant Evaluation

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Abstract

Rig sensor data, including mechanical specific energy trends, reveal a new approach to characterize lubricant performance in real-time. Traditional laboratory and field observation methods failed to distinguish sustained torque mitigation between different additives due to equipment limitations and variations between wells and drilling conditions.

The new approach leverages wellsite data sources and physics-based drilling concepts to identify lubricant contributions to drilling efficiency. Collaborative efforts between the operator and drilling fluids company identified new metrics for performance contributions not observed through traditional laboratory screening techniques.

The industry relies upon laboratory testing to assess lubricant performance at low torque conditions using instruments with limited accuracy. Once a lubricant is qualified for field trial, torque trends are monitored with additions for comparison. In many cases, the reduction in torque is then offset by increased weight on bit to increase rate of penetration, resulting in a return to elevated torque. A physics-based approach uses mechanical specific energy to capture the reduction in energy loss across the drilling system at a given drill rate. This method revealed that seemingly indistinguishable lubricant additives as observed in the lab produced dramatically different results in the field.

This paper compares traditional and new evaluation methods using wellsite data from a drilling campaign in the Permian Basin. The authors will discuss how a comprehensive approach to the drilling system can facilitate future evaluation of fluid additives or other equipment as potential limiters.

Introduction

Drilling torque remains a persistent challenge as well complexity and length continue to grow beyond the capacity of available equipment. Excess torque and mitigation methods are under constant scrutiny to maximize drilling performance and minimize associated costs. Lower torque offers many benefits:

- Higher rate of penetration
- Improved directional control and utilization of lower-cost mud motors for steering
- Extended lateral capability
- Increased pipe life
- Lower hard-banding replacement costs
- Reduced pipe inspection frequency

Optimizing current drilling systems provides savings without significant changes in drilling equipment and rig design. Improving lubricity of the drilling fluid is a primary method to generate these savings, but consistent and reliable evaluation techniques are lacking.

Lubricant Evaluation in the Laboratory

Laboratory lubricant evaluation includes compatibility testing and coefficient of friction reduction measurement. In select cases, the film strength is measured. The testing process is iterative, with candidate selection based upon performance comparisons between products. This requires repeat tests in high volume and limits the practicality of test conditions that reflect downhole drilling environments.

Compatibility Testing

Compatibility testing confirms the lubricant candidate does not induce adverse effects on the drilling fluid. The complex chemistry of fluid mixtures can lead to unpredictable results without upfront evaluation. Performance variables include base fluid composition, pH, temperature, salinity, hardness, and solids (Farnum, Toomes, and Offenbacher, 2023). In whole drilling fluid, rheology and fluid loss is measured to capture and dramatic changes in properties.

Incompatibility takes many forms, including dramatic thickening or thinning of drilling fluid and loss of fluid loss control. Two primary incompatibilities in water-based drilling fluids are cheesing, where the lubricant forms emulsified chunks, and greasing where oil-wet solids agglomerate (Figure 1 and Figure 2).

Figures 1 (left): Cheesing and Figure 2 (right): greasing from Farnum, Toomes, and Offenbacher (2023)

Lubricity Measurement and Limitations

There are many lubricity measurement devices. Every few years attempts are made to develop an improved and more reliable offering, but acceptance is limited for several reasons:

- New equipment provides different values than familiar devices. This limits broad adoption as there is no baseline or frame of reference relative to prior experience.
- Improved accuracy through torque sensors and temperature and pressure vessels increase cost and time to perform the test. This complicates testing through iteration where many samples are tested to screen suitable candidates.
- Even if many research centers adopt new equipment, only a few units may be manufactured. This increases unit cost, particularly when patents limit rights to manufacture and distribute equipment. Without broad acceptance, companies are reluctant to secure another device that may never become standard.
- The inventors of a new meter are its biggest advocates. They also likely work for a company that sells lubricants and has favorable results using their own products. Without additional devices to evaluate and outside acceptance (possibly from a company with competing interests), it is difficult to convert skeptics.
- The inconsistency of past efforts limits confidence that any new equipment will accurately reflect rigsite performance.

The most common device used to evaluate drilling fluid lubricants is a lubricity tester, where a block is pressed against a rotating ring to provide a numerical coefficient of friction value. The block and ring assembly are immersed in a fluid cup and torque is applied to capture the reading. Testing occurs at ambient pressure and temperature.

The lubricity tester has many limitations. Most lubricants water-based lubricants are water dispersible, but not completely water soluble. Without circulation, insoluble components float above the block and ring apparatus instead of reaching contact surfaces (Figure 3).

Figure 3: Dispersible lubricant floating on top of lubricity meter cup

Coefficient of friction is measured by converting electrical current, which can vary depending on the use of the machine and electrical supply. As the coefficient of friction is lower, the absolute value is less reliable. It is not uncommon to observe coefficients of friction as low as 0.02 in a brine lubricant that offers mediocre performance on a drilling rig. This can be a function of compatibility, but calibration uses a single data point of distilled water at 0.34±0.02 with a correction factor calculated above or below 0.34. There is no further calibration using a standard at lower values where error is potentially higher (Fann Instrument Company, 2009; OFI Testing Equipment, 2015).

Another common lubricity meter uses a rotating knurled bob and a block of steel or rock immersed in a circulating cup to gather coefficient of friction readings under ambient conditions. Torque measurements utilize a torque sensor. These improvements increase the cost of the equipment, and few labs have more than one. The authors use this device, but it has required multiple modifications and re-calibration to achieve insightful results.

To gather insight from a lubricity meter, the authors use the following methods:

- Test an untreated fluid as a baseline. Compare treated fluid in relationship to the baseline as a percent reduction.
- Test a range of concentrations and at least one sample before and after 16 hour dynamic ageing. Some products deplete rapidly and ageing can assist to identify this effect.
- Test for repeatability. The randomness of measurements, especially in invert emulsion systems, requires multiple data sets to confirm performance.
- Thoroughly clean the equipment between tests. In many round-robin tests, the last lubricant performs best simply because residual products from the other materials supplement performance.

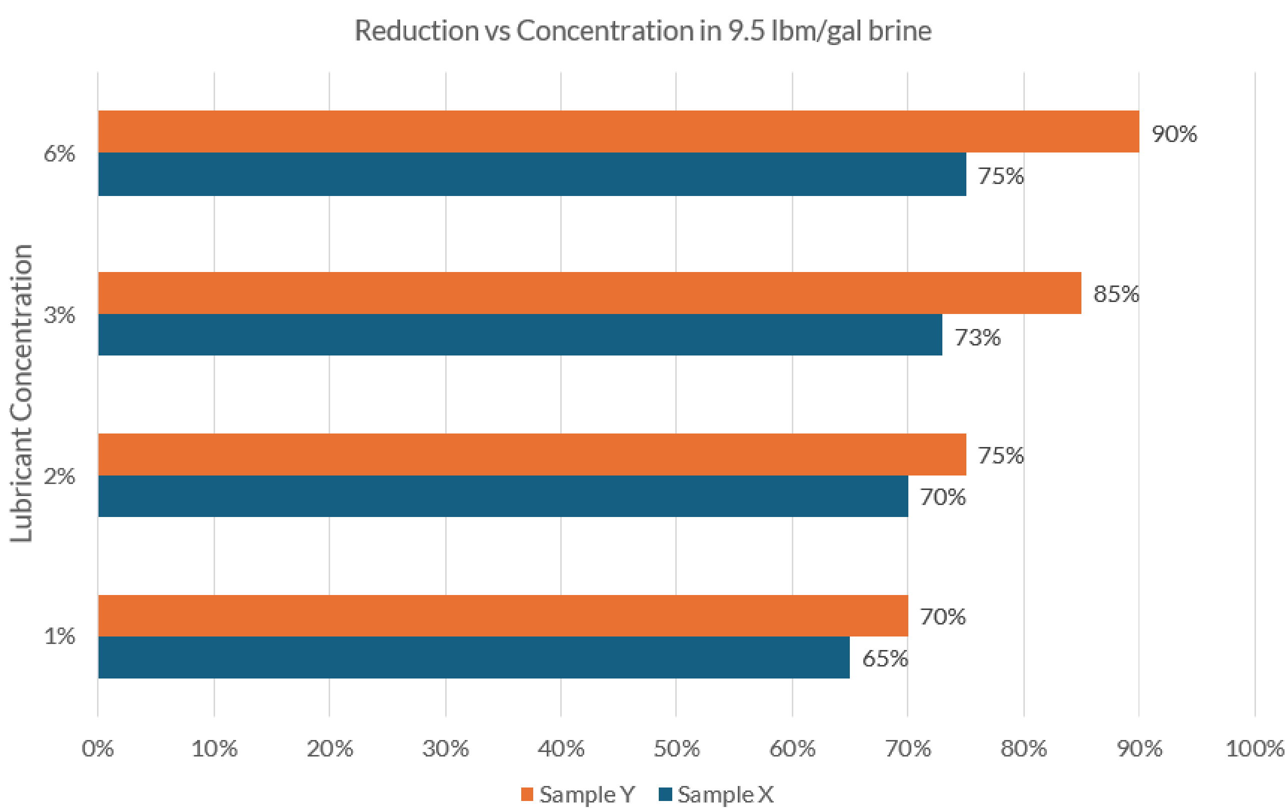


Figure 4: Comparison of lubricity to baseline fluid. The reduction is reported in as a percentage reduction to untreated base fluid.

This approach facilitates lubricant screening, but a key limitation is the coefficient of friction at maximum torque is far below rigsite values. Lubricity meters screen low performing products, but they fail to capture coefficient of friction data under the elevated torque conditions they are designed to mitigate. Multiple runs are required to confirm data quality. Multiple runs are required to verify data fidelity, which is a correlation instead of an absolute value.

Film Strength Measurement

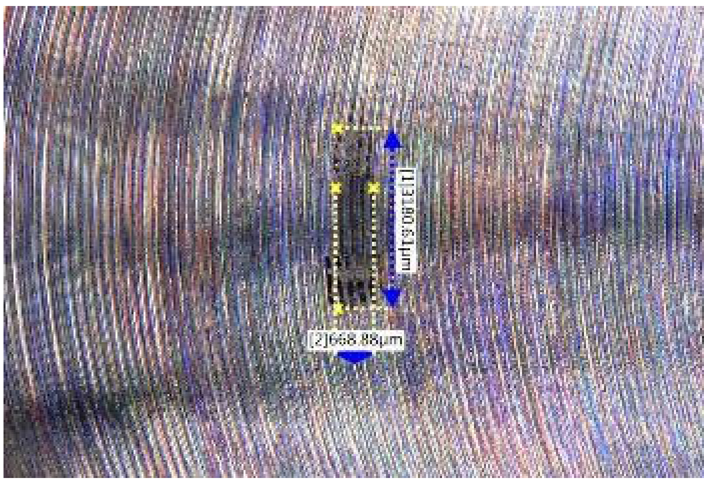
Extreme pressure additives are designed to improve the strength of the lubricating film. These additives can act as supplements to conventional lubricants or as a standalone product to prevent film failure and reduce metal-on-metal contact.

Many block and ring style lubricity testers are capable of performing extreme pressure tests by replacing a grooved ring and flat block with the traditional flat ring and curved block. There are slight procedure variations between the two major providers of extreme pressure testers that introduce some variance to results (Fann Instrument Company, 2009; OFI Testing Equipment, 2015). Multiple data points are required to confirm film strength trends, and the equipment requires skill and experience to capture reliable data.

In a film strength test, the neat lubricant is placed in the sample cup and torque is applied until the equipment seizes. One procedure calls for a repeat test with a new block surface using a load 50 in-lb below where seizure occurred. In either procedure, film strength is reported in psi as the torque divided by the scar width (Equation 1). Figures 5 and 6 show two different scar dimensions under an optical microscope. Each test requires a new ring and a new block surface.

Equation 1:

$$Film\ Strength\ (psi) = \frac{Torque\ Meter\ Reading\ (in - lb)}{Scar\ Width\ (0.01\ in)}$$



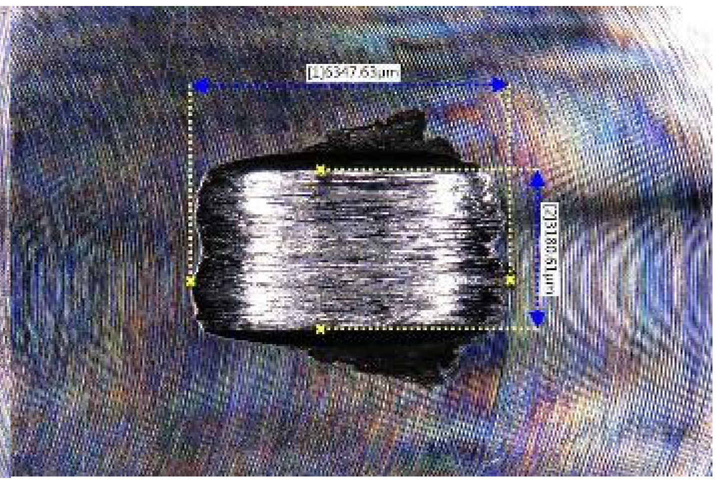


Figure 5 (left) : A high film strength lubricant shows a small scar width. Figure 6 (right): A lower film strength scar with galling.

High film strength materials require replacing the stock motor ½ horsepower motor with a 1 horsepower motor to achieve sufficient torque to reach the point of seizure. Because this is not a standard modification, many laboratories cannot measure the full spectrum of extreme pressure materials to evaluate film strength.

Measurement Issues

There are many shortcomings to laboratory evaluation, which contributes to the seemingly random performance of lubricant additives at the rigsite. Compatibility screening can identify potential issues, but it cannot capture all possible scenarios. There are occasions where lubricant addition rates impact performance or where improper treatment of contaminants causes cheesing and greasing despite acceptable lab results. Some lubricants perform well in testing, but do not provide sustained lubricity. The torque reduction benefit may last only as long as the first circulation with some lubricants.

In Figure 7, a field-proven lubricant Product X was compared with a new lubricant, Product Y, which includes extreme pressure additives to achieve high film strength. Both passed standard compatibility testing and progressed to coefficient of friction measurement. The results indicate that the lubricants provide very similar coefficient of friction reduction, particularly considering the lower absolute coefficient of friction and measurement error at low values. Based on this data, the cheapest lubricant would be selected.

Product Y was trialed for its film strength properties. At the rig, it actually demonstrated lower coefficient of friction while drilling – at lower concentrations than Product X.

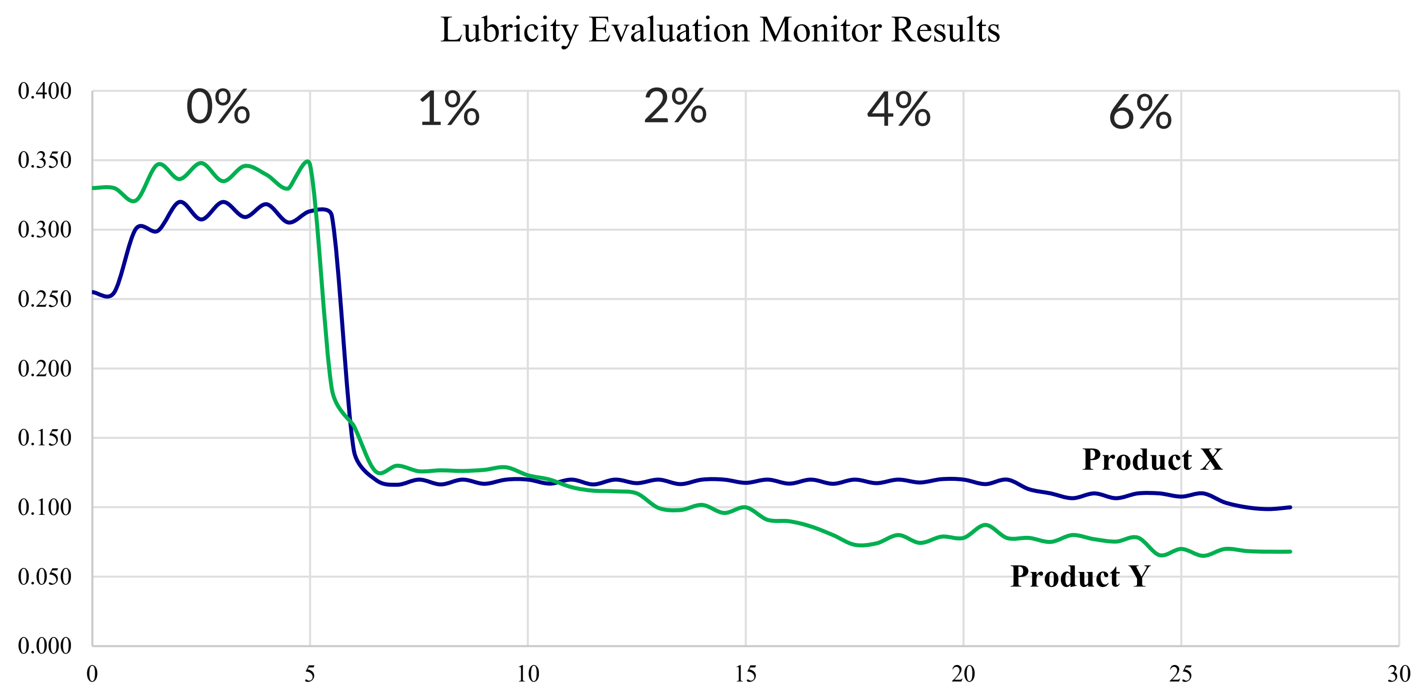


Figure 7: Laboratory lubricity meter comparison between products

During a trial, lubricant performance measurement typically include spreadsheets or isolated observations of torque readouts. When a lubricant lowers torque, the driller raises the weight on bit to increase rate of penetration. In turn, torque increases again, but this may or may not be noted as part of the overall evaluation. This reduces lubricants to qualitative and anecdotal observations when quantitative data sets are available in real time from rig sensor data that can be normalized and contextualized to well conditions (Table 1).

Table 1: Summary of common rigsite lubricant evaluation methods

Method	Issue
Monitoring torque trends	- Torque increases with increased weight on bit to elevate ROP - Difficult to capture sustained lubricity contribution of lubricant - Well-to-well comparison depends on wellbore quality
ROP	- Selective data harvesting risk - Limited context relative to drilling objectives (control drilling for tools)
Drill partial interval and add lubricant at scheduled time	- Requires drilling part of interval unassisted

Limiter Redesign and Drilling Systems

The value proposition of a drilling fluid lubricant is its contribution to drilling efficiency. Product cost is only offset by lower costs elsewhere through faster drilling processes and subsequent time savings. A wholistic view of drilling efficiency and its relationship to a lubricant provides the opportunity to measure the impact of the lubricant to the overall system, and to optimize treatment levels.

Mechanical specific energy (MSE) is the calculation of energy to drill a volume of rock. The equations are detailed numerous papers and vary based upon the presence of a drilling motor. Equations 2 and 3 provide simplified representations of each calculation. The total MSE is a function of axial and rotational energy at surface divided by rock volume. Downhole MSE is the axial and rotational energy at the bit divided by rock volume (Dupriest et al, 2023).

Equation 2: Total MSE

$$MSE_{total} = \frac{Energy_{axial,surf} + Energy_{rot,surf}}{Volume_{rock}}$$

Equation 3: Downhole MSE

$$MSE_{downhole} = \frac{Energy_{axial,bit} + Energy_{rot,bit}}{Volume_{rock}}$$

MSE calculations require some assumptions based on data available. To improve MSE analysis across the industry, an ad hoc MSE Standardization Committee released standardized calculations for MSE in 2023 (Dupriest et al). This facilitates consistent comparisons across electronic data recorders, which output MSE values alongside other drilling data sets in real time.

MSE analysis provides a real-time method to observe and potentially resolve a number of drilling issues. Elevated MSE compared to trends seen during a drill off test reveal inefficiencies in the system. Decreases in MSE suggest improved efficiency (less energy to drill a rock volume).

Bit efficiency is optimized when rate of penetration increases in a linear trend relative to weight on bit. The founder point is where dysfunction leads to a break from this linear trend. Limiter redesign is strategy of extending the founder point and maximizing drilling performance (Figure 8).

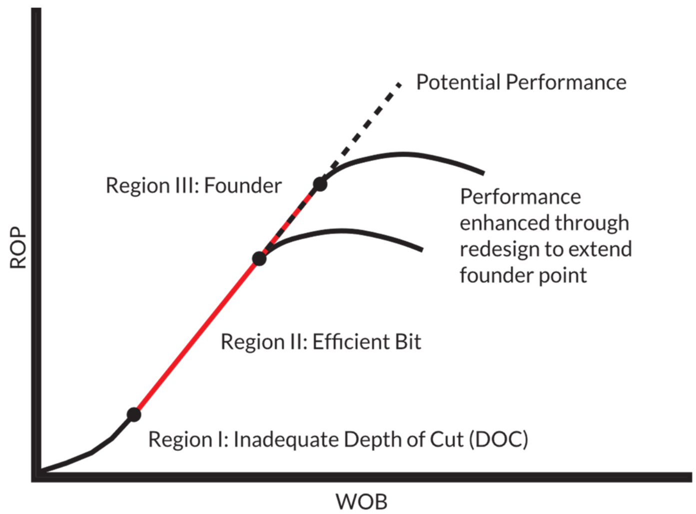


Figure 8: Drilloff curve – adapted from Dupriest and Koderitz (2005)

Issues such as balling and vibration are identified in real time and adjustments made. In some cases, the limiter may require changes to equipment. When efficiency returns, MSE drops and the linear trend of increased ROP with weight on bit continues. With drilling dysfunction addressed, MSE trends can be used to evaluate other system factors, including lubricant performance.

Rig Sensor Data and Drilling Systems

MSE trends will vary by rock strength. Drilling vertically, the bit encounters many different layers, but in horizontal drilling the MSE trend offers greater consistency. Logan (2015) discusses MSE to optimize fracture placement based upon variations in rock strength, demonstrating a lateral is not one single section of uniform material. The data shows that rock strength varies, but it remains within a range where trending is possible.

MSE also provides insight into drilling as a system. When dysfunction occurs, a lubricant is unlikely to overcome issues with whirl or balling. Failure to capture and address dysfunction prior to lubricant addition risks attributing poor lubricant performance to other drilling issues.

Case Histories

The following case histories are part of a detailed lubricant evaluation. Electronic data recorder data was correlated to lubricant addition timing, concentrations, and the drilling system response to these additions. The study includes multiple wells with the same parameters for comparison.

Conventional Lubricant Evaluation Method

Traditional lubricant performance evaluation at the rig site often includes monitoring of torque relative to lubricant concentration. As torque is reduced a driller will increase weight-on-bit and/or rotate the drill string faster, causing torque to increase – resulting in a net increase in rate of penetration. Figure 9 illustrates ROP, torque, and WOB, while drilling a Dean target formation (7 ⅞” open hole with 5 ½” drill pipe and an average 8.8 lb/gal mud weight). The lubricant concentration was raised to 2% v/v at approximately 13,600 ft MD, where torque continued to climb while ROP increased.

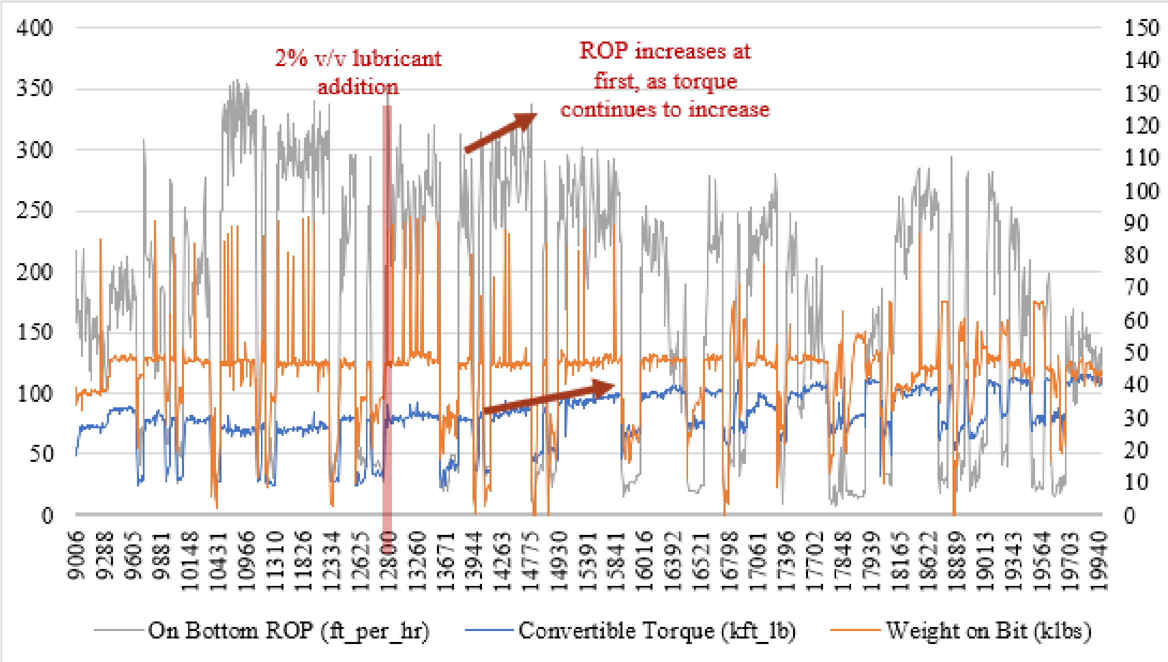


Figure 9: Lubricant addition while drilling 2-mil lateral, resulting in ROP increase with increasing torque and flat WOB.

2-mile Lateral Lubricant Evaluation

Two lubricants, Lubricant A and Lubricant B, were selected for analysis. Lubricant A is a new formulation with superior film strength intended to retain lubricity under high torque conditions. Lubricant B is a conventional lubricant with proven performance on hundreds of wells in the Permian Basin.

The lubricants were applied on two similar 2-mile horizontal wells in Martin County in the Midland Basin. The mud system utilized an 8.6-8.9 lb/gal unviscosified cut brine with inhibitors and pH modifiers to mitigate corrosion risk. A viscosified sweep regimen was utilized to assist in cuttings conveyance.

Table 3 provides well details and corresponding average on-bottom drilling metrics. Drilling data shows lower torque, higher ROP, and lower MSE (Figure 10 and Figure 11). Lubricant A utilized an average concentration of 1.6% v/v while Lubricant B required an average concentration of 1.4% v/v. Both wells incurred significant downhole losses throughout drilling – making lubricant concentration tracking challenging. Maximum lubricant concentration is also provided.

Across the lateral section, Lubricant A resulted in a 31% increase in average ROP, 28% decrease in average torque, and a 31% lower average MSE compared to Lubricant B. Data indicates that a higher film strength as seen in Lubricant A contributes to improved drilling results.

Table 3: Lubricant comparison results on two similar Dean target formation wells in Martin County

Well Parameter	Well #2568 (Lubricant A)	Well #2562 (Lubricant B)
Avg. Mud Weight, lb/gal	8.6	8.7
Target Formation	Dean	Dean
Open Hole Diameter, in.	7 ⅞	7 ⅞
Drill Pipe Diameter, in.	5 ½	5 ½
Approx. Lateral Section Length	2mi	2mi
TD MD / TVD, ft	19,843 / 8,662	19,969 / 8,707
*Avg. Lubricant Concentration, % v/v	1.6	1.4
Avg ROP, ft/hr	217.23	165.92
Avg Torque, kft-lb	21.45	29.84
Avg MSE, kpsi	36.71	53.56
Avg ROP-to-MSE, ft/hr/kpsi	6.25	3.64

*Average lubricant concentration while drilling throughout the lateral section

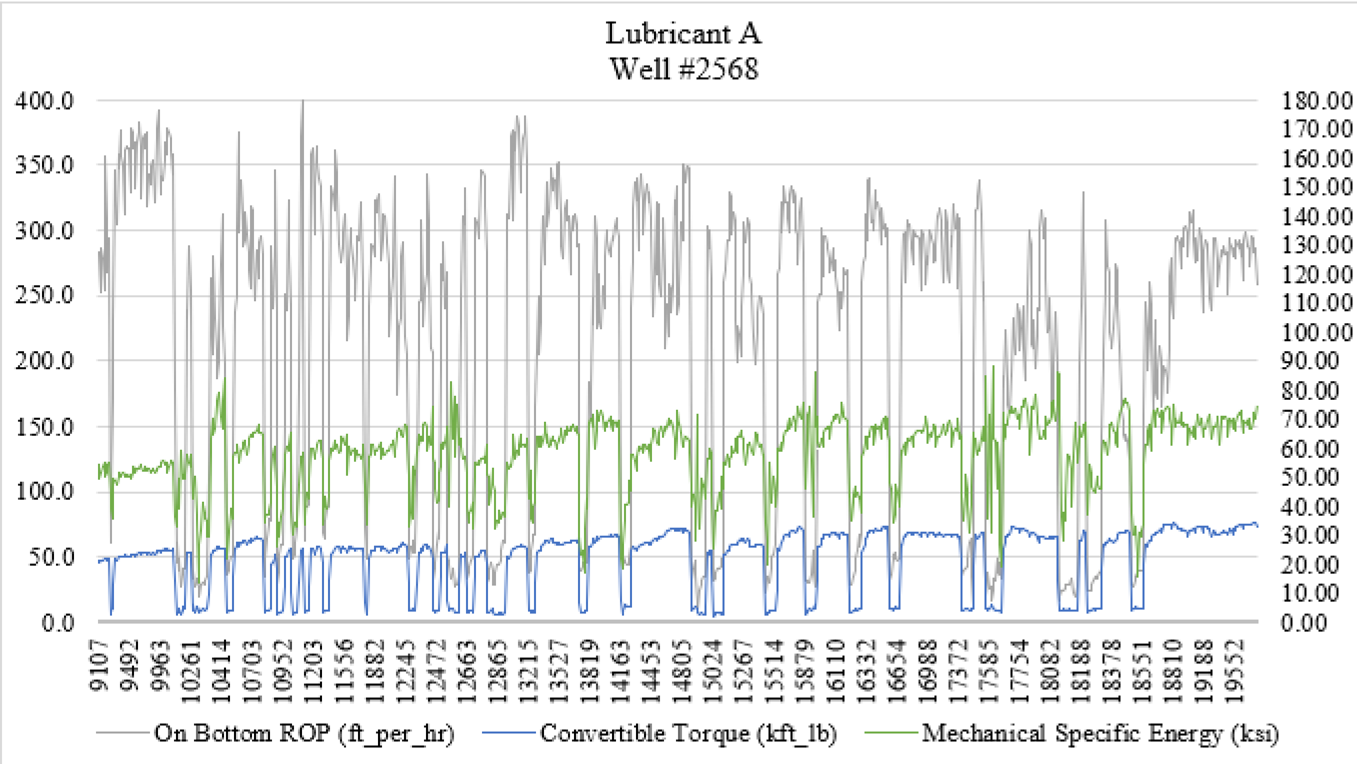


Figure 10: Drilling parameters utilizing Lubricant A on a 2-mile Dean target lateral well

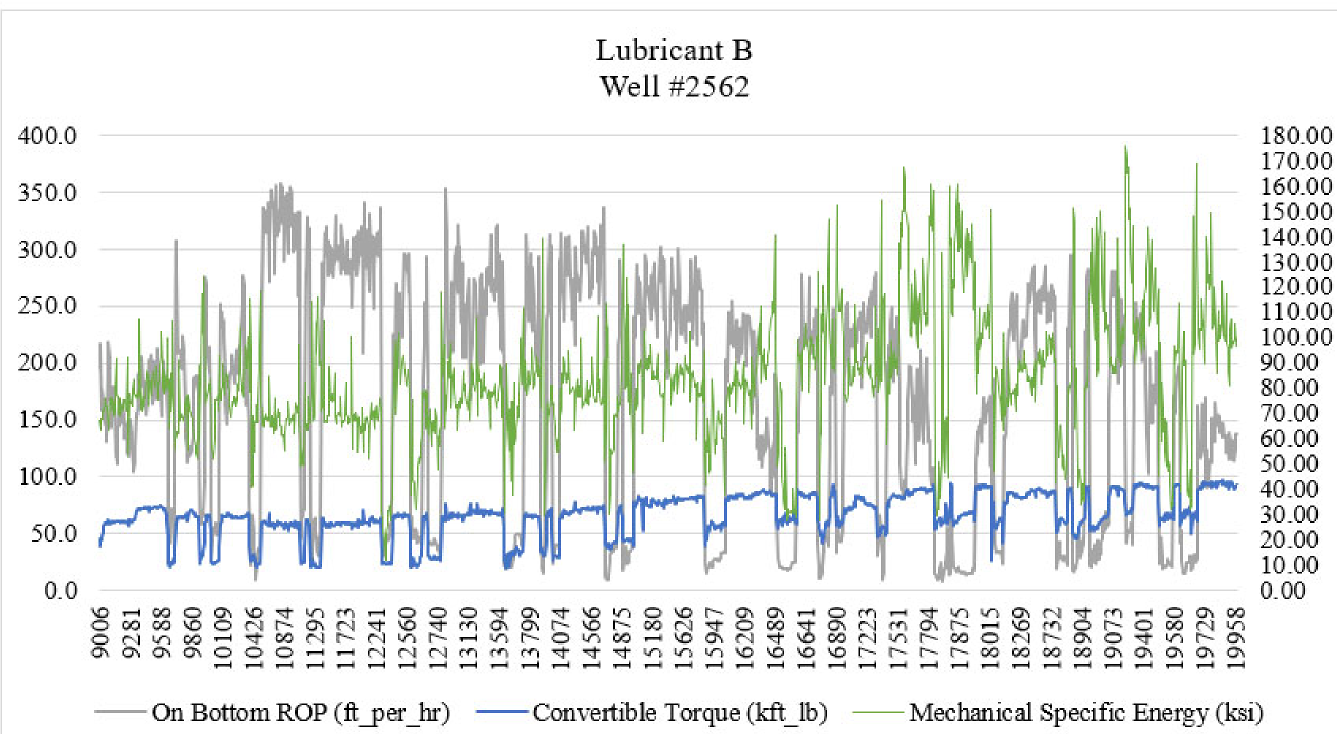


Figure 11: Drilling parameters utilizing Lubricant B on a 2-mile Dean target lateral well

MSE is a proven metric to quantify drilling efficiency and identify drilling dysfunction. Coupling MSE with rate of penetration in a ROP-to-MSE ratio can provide a quick and more reliable evaluation for ongoing drilling operations (Hassan 2020). A higher ROP-to-

MSE ratio indicates faster drilling at a lower amount of energy.

The two wells ROP-to-MSE ratios are displayed in Figure 12. Well #2568 utilizing Lubricant A resulted in an average 6.25 ROP:MSE across the lateral vs. an average 3.64 ROP:MSE on Well# 2562 utilizing Lubricant B.

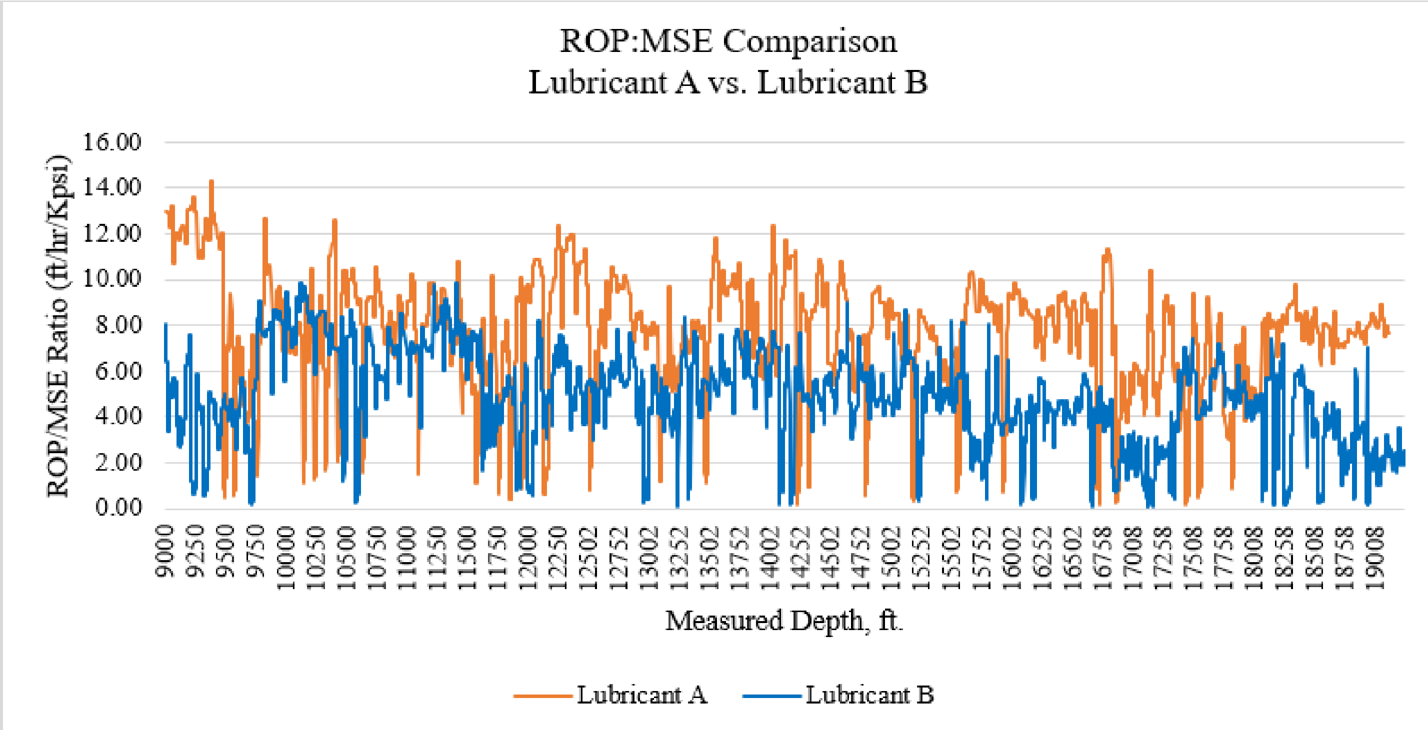


Figure 12: ROP-to-MSE comparison of Lubricant A vs. Lubricant B. A higher ROP-to-MSE ratio suggests faster drilling with lower energy required.

Torque values were analyzed across similar four (4) similar 2-to-2.5-mile lateral wells. All wells targeted the Dean formation, drilling a 7 ⅞” open hole with 5 ½” drill pipe, utilizing an unviscosified cut brine system with an average mud weight of 8.6 – 8.7 lb/gal.

Torque values plotted in Figure 13 show wells utilizing Lubricant A with lower average torque versus wells utilizing Lubricant B. Wells utilizing Lubricant A required a maximum concentration of 1.0 and 2.0% v/v lubricant – with average torque values across the lateral of 26.14 and 27.92 kft-lb.

Wells utilizing Lubricant B required 3.2 and 4.0% v/v lubricant – with average torque values across the lateral of vs. 31.88 and 30.87 kft-lb.

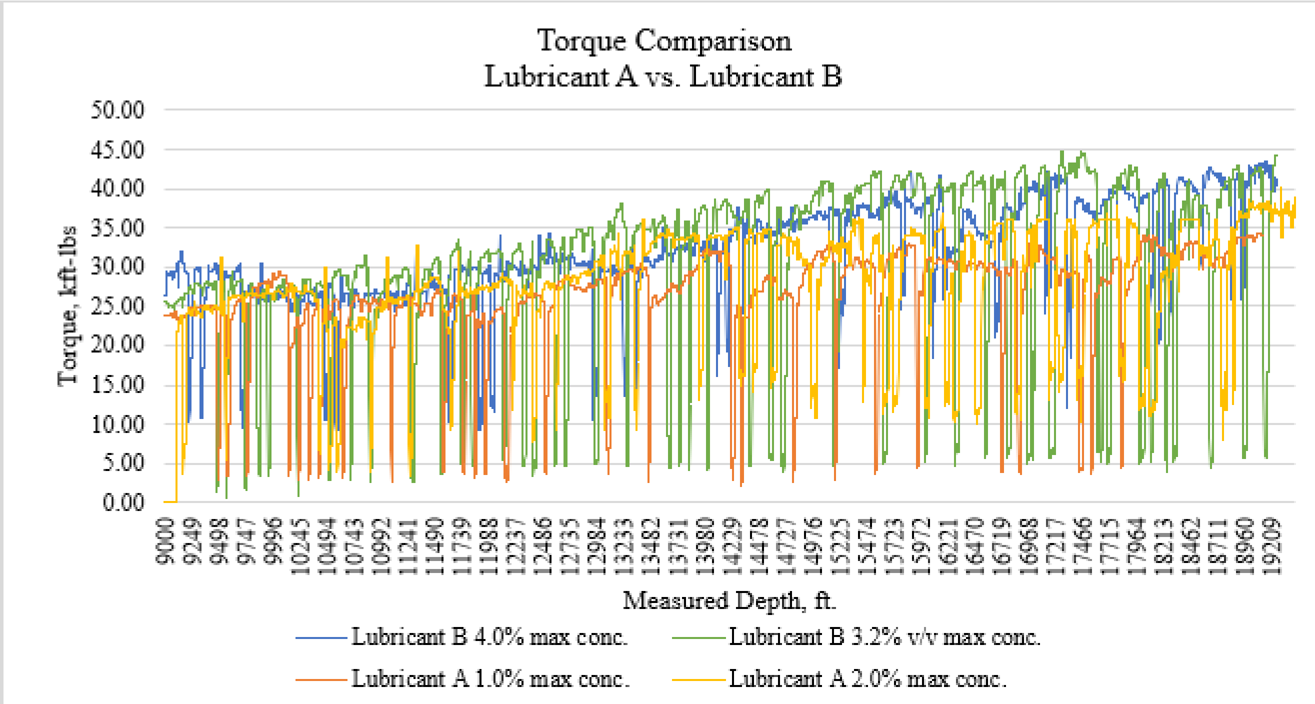


Figure 13: Torque comparison of Lubricant A vs. Lubricant B plotted across four (4) similar 2-mile Dean target lateral wells

3 Mile Lateral Lubricant Evaluation

Another lubricant performance analysis comparing Lubricant A vs. Lubricant B was conducted on two 3-mile lateral wells, both targeting the Jo Mill producing formation. Among the on-bottom drilling parameters tracked are torque vs. depth (Figure 14), ROP vs. Depth (Figure 15), Torque vs. MSE (Figure 16), and Torque vs. RPM (Figure 17).

Table 4 shows Lubricant A providing 5.9% lower average torque, 4.97% higher ROP, and 13% lower MSE. Figure 17 reveals Lubricant A providing lower MSE (drilling efficiency) versus Lubricant B, at elevated torque levels.

Table 4: Well profile & select on-bottom drilling parameters on two similar Jo Mill target formation wells in Martin County

Well Parameter	Well #3774 (Lubricant A)	Well #4671 (Lubricant B)
Avg. Mud Weight, lb/gal	8.9	8.6
Target Formation	Jo Mill	Jo Mill
Open Hole Diameter, in.	8 ½	8 ¾
Drill Pipe Diameter, in.	5 ½	5 ½
Lateral Section Lenth	3 mi	3 mi
TD MD / TVD, ft	23,820 / 7,740	24,525 / 8,339
*Avg. Lubricant Concentration, % v/v	1.8	1.7
Avg ROP, ft/hr	213.1	203
Avg Torque, kft-lb	33.1	35.2
Avg MSE, kpsi	42.2	48.6

*Average lubricant concentration while drilling throughout the lateral section

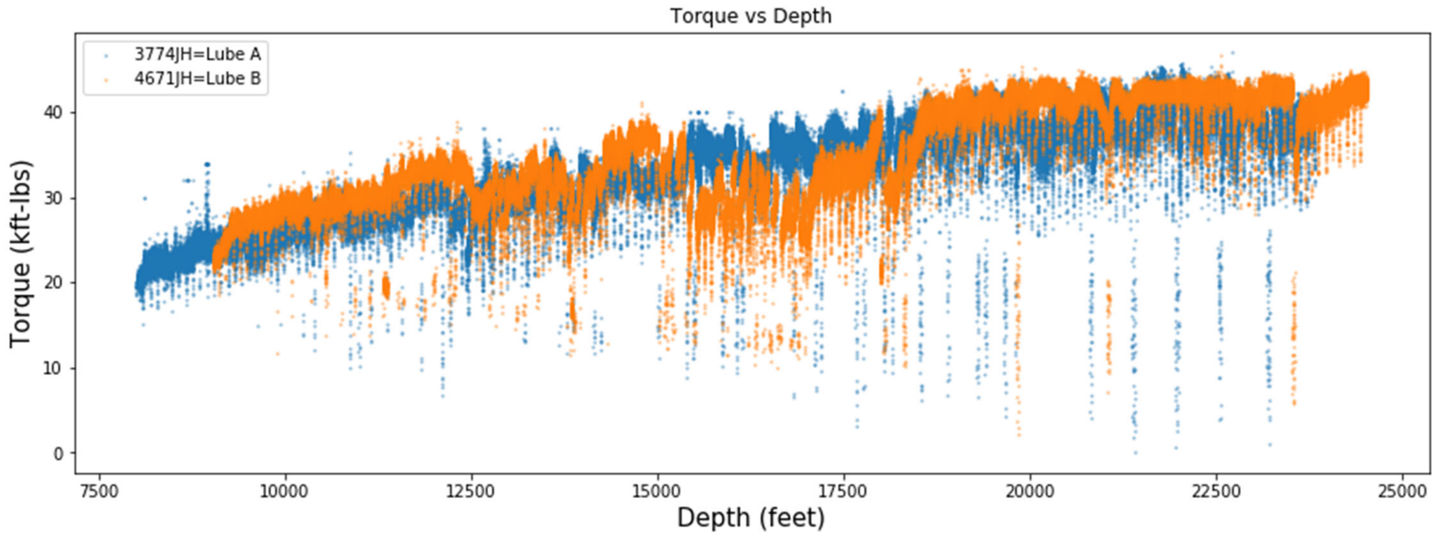


Figure 14: Lubricant A provides lower torque values across the lateral section vs. Lubricant B

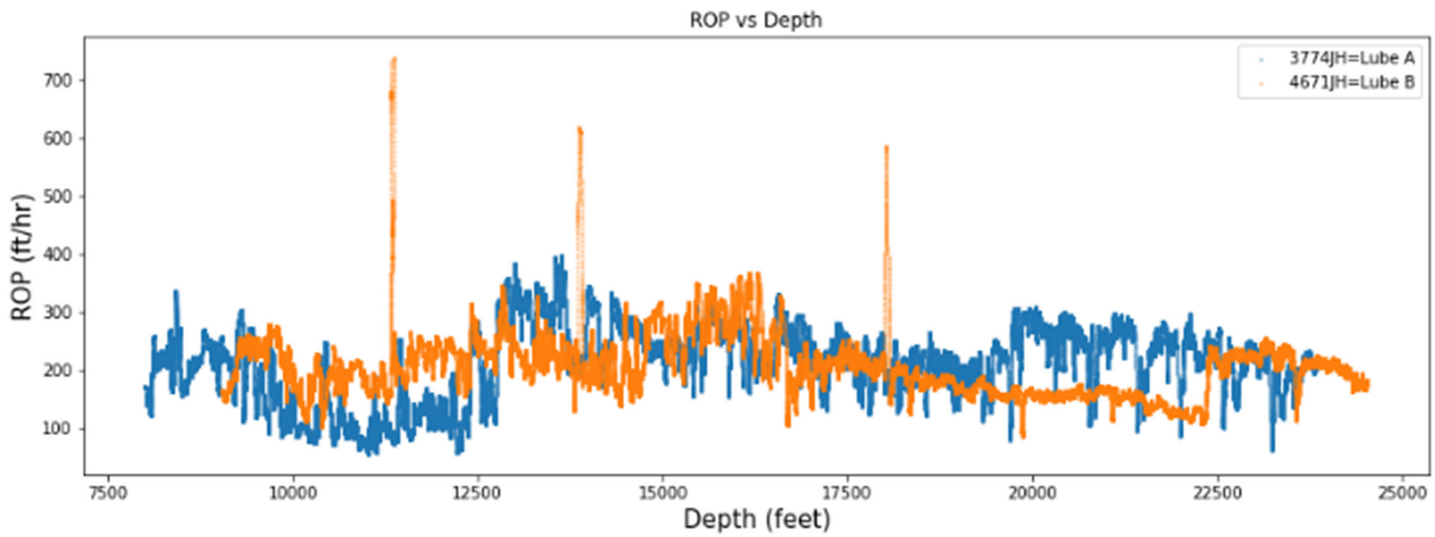


Figure 15: Lubricant A provides higher average ROP values across the lateral section vs. Lubricant B

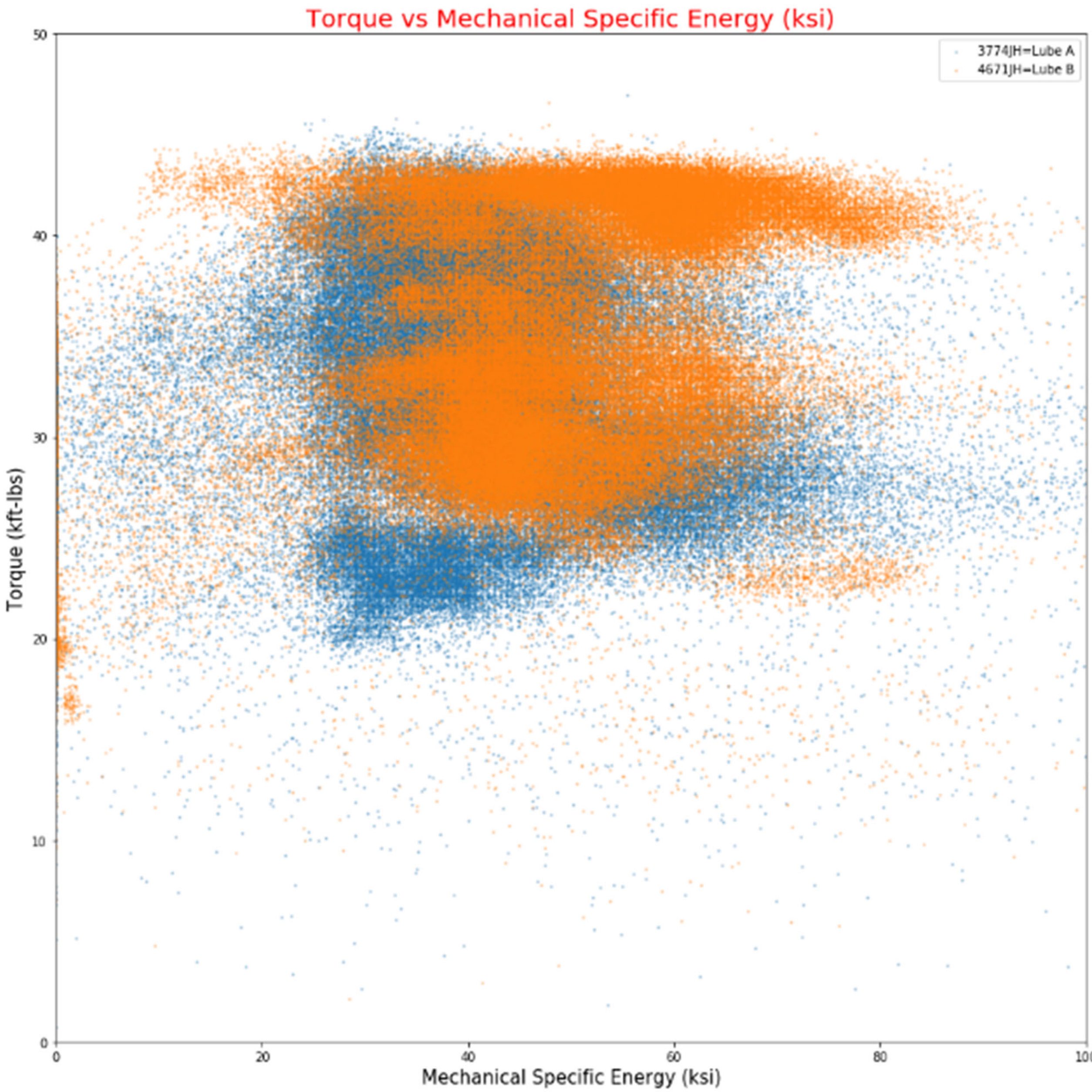


Figure 16: Lubricant A provides lower MSE values at higher torque versus Lubricant B

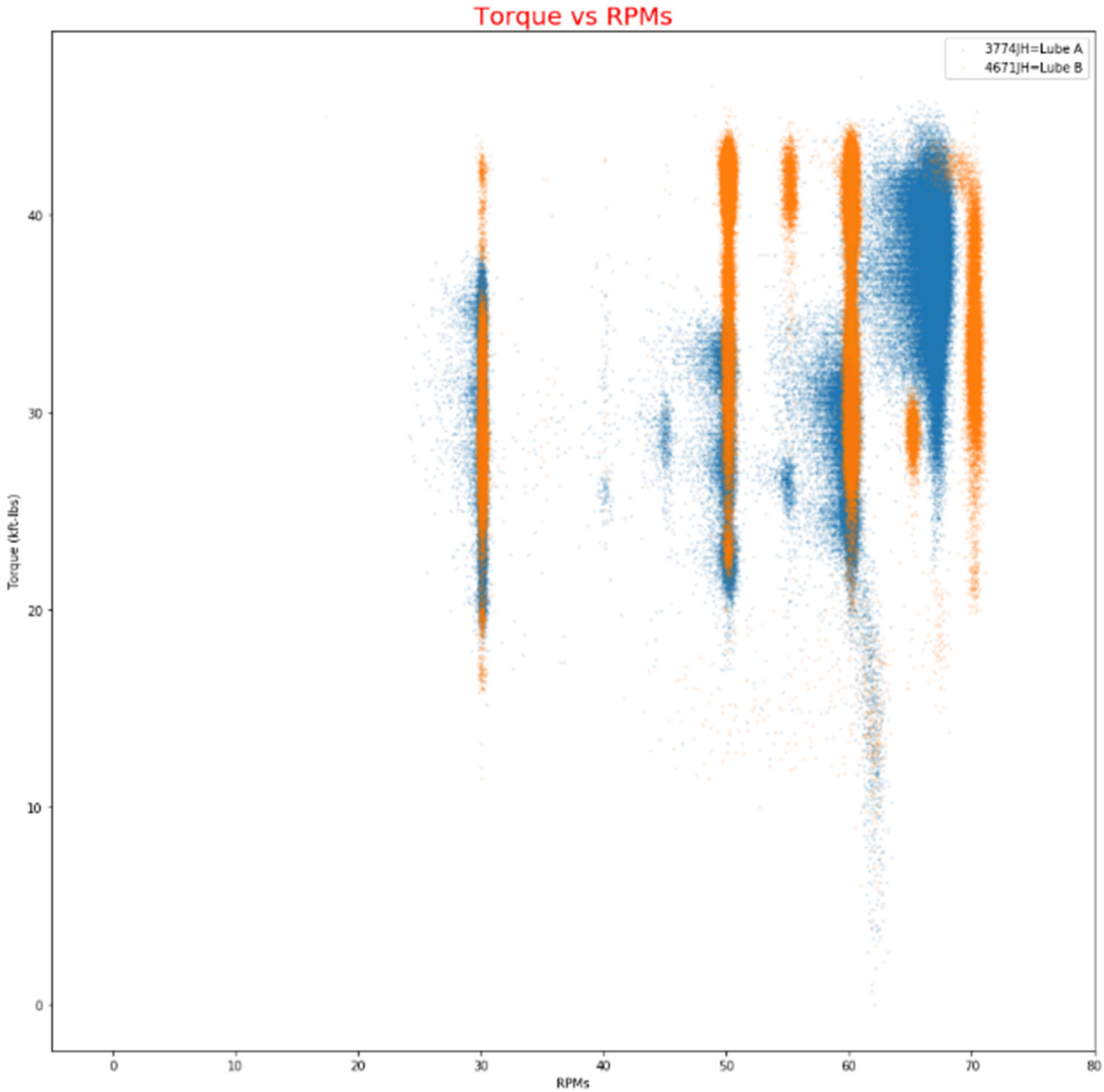


Figure 17: Lubricant A provides lower torque values at higher RPMs versus Lubricant B

Drill Pipe Wear Analysis

Drill pipe wear analysis is being conducted at the time this paper is being written. It is surmised that lower overall sustained torque provides additional savings via drill pipe longevity. The analysis compares Lubricant A vs. Lubricant B across select drill strings to determine if higher film strength lubricants reduce metal loss. A positive outcome may result in a follow-up publication.

Conclusions

- Laboratory equipment used for lubricant evaluation is limited by side-force availability. Rig sensors offer more reliability to distinguish lubricant performance where load force is orders of magnitude higher.
- MSE reveals dysfunction that may not be torque related. Addressing dysfunction avoids mis-attributing drilling issues with lubricant performance.
- MSE and ROP-to-MSE trends offer a superior approach to traditional lubricant evaluation. The value and impact appear alongside other relevant drilling data for greater context and insight not captured in basic torque sensor monitoring.

Nomenclature

$Energy_{axial,bit}$ = *Axial energy at the bit*

$Energy_{axial,surf}$	= *Axial energy at surface*
$Energy_{rot,bit}$	= *Rotational energy at the bit*
$Energy_{rot,surf}$	= *Rotational energy at surface*
$MSE_{downhole}$	= *Downhole MSE*
MSE_{total}	= *Total MSE*
$Volume_{Rock}$	= *Volume of rock drilled*

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