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Improved Laboratory Methods for Understanding Lubricity, Torque and Drag in Non-Aqueous Drilling Fluids

Shawn Lu, SciDev; Don Van Slyke, Shell

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Abstract

Optimized pad design and advanced directional drilling technologies have pushed shale development to a new level. Not only the rate of penetration but also lateral lengths have improved significantly; however, progress is often limited by the difficulties arising from torque and drag, despite most laterals being drilled with non-aqueous muds that have higher lubricity than WBMs.

The rheological properties and nature of solids play an important role in determining the friction. The type of base oil can also have an impact as torque has been observed to decrease when switching from OBM to SBM. From a tribological perspective, the dynamic characteristic of the interface determines the overall friction or torque; however, current laboratory methods only provide limited data. For example, conventional lubricity meters only measure friction over a small surface area in a short period of time, without regard to the erosion of steel or the contact area between shale and steel.

A modified lubricity meter was used to measure carbon steel erosion, and a new experimental apparatus was built to study drag force with 4 inch diameter shale disks contacting steel in the presence of drilling fluids. In addition to fluid composition, the normal force was found to affect the friction coefficient. Laboratory drilling simulations were successfully carried out with shale core and PDC bit to provide a direct connection between base fluid type and ROP. The higher ROP with synthetic fluid was believed to be connected to lubricity and dynamic changes on the surfaces. The study brings a new aspect to light in the analysis of friction, torque and drag to help improve drilling performance with non-aqueous drilling fluids.

Introduction

Drilling efficiency has become a key driving force for oil and gas production in US post Covid. The adaptation of new horizonal drilling tools has enabled the industry to drill longer and more wells with the same number of rigs. Drilling wells is becoming a manufacturing assembly line where consistent and predictable performance is preferred while new records are being made. It makes non-aqueous drilling fluid (NADF) the perfect candidate in horizontal sections over aqueous fluids for its shale stability, consistency, and lubricity (Song et al., 2019).

It is known that excessive torque and drag can be critical limitations in horizontal drilling. Torque and drag are modeled with software and monitored on site. A critical parameter is the friction factor which is connected to the lubricity of the drilling fluid, although it is also affected by hole condition, well trajectory, pipe rotation and rate of penetration (Nour et al., 2022).

The friction coefficient or coefficient of friction (CoF) is calculated as the ratio between drag force and normal force or weight.

$$\mu = F/N$$

Where:

μ=friction coefficient

F= frictional force (drag force)

N= normal force (weight)

The coefficient is a dimensionless number that is measured in a lubricity tester. Torque is applied with leverage. It is the twisting force that causes rotation, as with rotating the drill pipe and bit. The unit is Newton·meter or $lb_f \cdot in$. Drag is the resistance of an object in a fluid environment. Examples of when drag is important in well construction are tripping pipe, running casing, sliding pipe while drilling with a mud motor, and reciprocating pipe to clean the wellbore. The term friction factor is often used interchangeably with the coefficient of friction, but it can also be a term to describe the inverse of lubricity. Lubricity is generally meant to describe the reduction of friction between two solid objects rubbing against each other in the presence of fluid (e.g. drilling base oil or mud). In modeling or calculations, friction factors are often determined based on the fluid types without considering fluid composition, including base fluid chemistry, dispersed particles such as drill solids, additives, and emulsion.

NADF is used for most of the extended reach and horizontal well drilling. In the US, diesel-based muds (DOBMs) still dominate the market due to the availability and low up front base oil cost, although synthetic-based muds (SBMs) are gaining more attention because of several advantages including low toxicity, improved HSE profile and better options for cuttings disposal. In addition to environmental benefits SBMs provide improved drilling rates, better wellbore stability, reduced torque and drag, and better cuttings integrity (Sabeh et al., 2023). The improved performance of SBM over DOBM cannot be explained from the traditional lubricity perspective.

When lubricants are added to fresh water or brines, the measured steel-on-steel coefficient of friction can be reduced to the range around 0.1, which is close to that of non-aqueous fluids such as diesel or synthetic base oil (0.07 to 0.13). However, when the same lubricants are added to water-based mud, the CoF often is higher than fresh water or brine with the same lubricants. On the contrary, the CoF of SBM is often closer to that of the base oil used, with the difference caused by the presence of solids and emulsion. The interaction between base fluid and the solid surfaces of drill solids, mud additives and pipe/wellbore interface probably plays a more important role in determining the overall friction coefficient in SBM than in WBM, as was reported in a recent study (Sayindla et al., 2017).

The main laboratory test to measure drilling fluid lubricity utilizes the EP lubricity tester. It is a great tool to compare various lubricants in water or brine but does not have sufficient accuracy among fluids that all have a relatively low CoF. Plus, the test results do not reflect the field performance due to the test equipment limitation. For example, the contact area affects the results while the contact area between the ring and block in the lubricity test is exceedingly small. (Zhou et al., 2020).

It is generally understood that DOBM can provide sufficient lubrication for drilling horizontal wells. It is certainly true in comparison to WBMs; however, diesel may become a limiting factor for drilling longer wells due to the aromatic content. One study showed that additives added to OBM reduce friction and wear. The chemical additives have a hydrophobic tail and a polar head group (Humood et al., 2019). It was indicated that the interaction between fluids and solids during drilling is a factor in lubricity and subsequent torque and drag.

The comparison of SBM to DOBM in standard laboratory tests is not conclusive enough to make quality field recommendations due to the equipment limitations and the need to eliminate variables that mask interpretation.

The base oils compared in this study include a synthetic Gas-to-Liquid (GTL) product and diesel. GTL is manufactured from natural gas via the Fischer-Tropsch synthesis process and has a chemical composition of over 99% slightly branched iso-paraffins and n-paraffins, while diesel has over 15% aromatics including a considerable amount of BTEX.

In this study, a new in-house apparatus was built to directly measure the friction force between a 4” core disk and a metal surface covered with non-aqueous drilling fluid. The large contact area provides more realistic measurement, and the linear drag motion better simulates a tripping or casing-run scenario in the field. The results are compared to conventional lubricity measurement.

In addition, the cuttings recovered from field drilling fluids under similar conditions were examined to provide further evidence of the difference in solids impact between SBM and DOBM.

Lastly, a novel drilling simulator was modified and employed to measure torque and ROP at various weights on bit (WOB) and revolutions per minute (RPM), using a PDC microbit drilling through Wolfcamp core in the presence of fluid circulation and cuttings removal. The data obtained were used to calculate the mechanical specific energy (MSE) as it is an important parameter to understand drilling efficiency. The ROP is inversely proportional to the MSE during drilling with the same conditions including the same fluids. As described previously (Dupriest et al., 2005), ROP increases with WOB but it can reach a plateau. By designing the parameters or using a better performing fluid, the drilling envelope (Flounder region) can be expanded.

Experimental Setup

Modified EP Lubricity Test

The EP lubricity meter is a commonly used instrument in lubricant evaluation in brine, water, and water base mud. It is also used in measuring lubricity of NADFs. The procedure is simple and easy to follow although the measurement has limitations. Prior to conducting the test, the meter is calibrated with water so that the friction coefficient reads within a targeted range. If the friction coefficient is too high due to oxidation, rust or abrasion, then it is recommended that the metal surface is smoothed with 200-300 fine grade sandpaper until the desired 0.34 ± 0.02 friction coefficient baseline for water is obtained. If it is too low, then the ring and block must be cleaned to remove film or residue from a previous test. The use of water for calibration instead of a standard calibration oil points to the instrument being less suitable for comparing different NADFs.

The area of contact during testing is less than 0.2 square inches. The recommended procedure is to apply 150 lb_f·in of normal force with the ring rotating at 60 rpm. The parameters do not necessarily represent the drilling conditions especially in NADFs. The equivalent pressure is approximately 600 psi at the contact surface. This is a more suitable pressure for testing the performance of engine oils or automotive lubricants in service (which the instrument was originally designed for) than the pressure of drill pipe laying on steel casing or open hole, which is typically orders of magnitude lower. Pressure differentials over 500 psi are encountered with differential pipe sticking (i.e. stuck pipe) and the hydraulic fracturing of shale, but not during the normal processes of drilling, tripping, casing running, and reciprocating pipe.

New Torque/Drag Apparatus

An in-house apparatus was built to measure torque/drag between metal/metal or metal/rock but with a large contact surface area. Core disks were used to better simulate the drilling or tripping actions in the field. A 4” core plug was cut from a slab into 1” thick disks. One of two adjacent disks were used for each fluid to ensure that the minerology was nearly identical. Weights were stacked on top of the core disks to mimic the pressure between drill pipe and shale downhole. Synthetic oil, diesel oil, SBM or DOBM were placed in the metal tray to a depth of 0.5 inches so that the contact area was fully submerged in the fluid. In addition to neat base oils, mud samples from the field were used in the study to incorporate the effects of drill solids, additives and emulsion.

Dynamic Drilling Simulator

Grace Instruments has developed the M2200 Drilling Simulator to mimic the field drilling process. In rate of penetration measurement, the drilling is conducted with a mini PDC bit. When rotating, the bit can drill through a core plug while measuring distance drilled vs time with variable or constant weight on bit. There is a metal holder that keeps the core in place to prevent movement of the core. The core/holder assembly is placed in a metal cell filled with drilling fluid. For this study, the metal cell was replaced by a clear acrylic cell to provide visual observation and enable fluid circulation to move cuttings out of the borehole while drilling. Weight on bit, torque, and distance over time are digitally recorded through the test run. ROP and other parameters are then calculated.

Results and Discussion

Torque and drag during drilling are affected by multiple factors including operational parameters such as well trajectory, weight on bit, pipe rotation and drilling fluid properties including viscosity and solids content. The friction coefficient is used to directly estimate the torque and drag but it is hard to accurately determine, although it is becoming more critical for long lateral drilling.

There are often gaps between lab results and field predictions. For example, WBMs with selected lubricants can show lower coefficients of friction than NADFs in the standard lubricity test but it is well established in the industry that NADFs provide a better friction factor and overall drilling performance than aqueous-based fluids. It was demonstrated in the OGS Drilling Simulation study that a more in-gauge hole was drilled with OBM than with WBM (Simpson et al., 1989). Due to the gaps, there is less understanding of how the types and properties of NADFs affect the torque and drag. In many models, a friction factor that is both assumed and fixed is used although in reality the fluids can perform differently in the field. The goal of the study is to provide quantitative tests and analyses with the aim to bridge the gap between laboratory measurement and field performance. The end benefit is to enable the drilling of even longer laterals.

The dynamic interface governs the friction and thus the torque/drag and subsequently the ROP, as demonstrated in Figure 1. Drilling fluids with solids are always present at the junction between the metal/metal or metal/formation. The existence of solids and surface roughness make it a non-linear process as explained in a previous study (Zhou et al., 2017). The normal load, fluid viscosity and solid properties all affect the friction coefficient, which helps to explain the gaps. One of the focuses of the study is to look at the effect of solid surfaces including metal and formation on the prediction of torque and drag in the field.

Modified EP Lubricity Measurement

The first set of experiments were conducted with a typical EP lubricity meter but with a modified procedure. The motor speed was increased from 60 rpm to 200 rpm while the normal force was reduced from 150 lb_f·in to 100 lb_f·in. The testing period was extended from 5 minutes to 70 minutes. The measurements were made with synthetic and diesel base oils. The two base oils produce very different results, as shown in Figure 2. Diesel shows a steady friction coefficient with a slight decrease over the period, while the synthetic base oil shows a pattern of changes. As pointed out in the plot, a standard lubricity measurement only takes a reading for 5 minutes. For example, if the measurement was taken between 2 and 7 minutes it would show a much different comparative result than if it was taken after 25 minutes.

To understand the difference and the dynamic aspects, a modified carbon steel block was used to replace the standard high strength steel block as shown in Figure 3. Carbon steel is more representative of the typical drill pipe and casing than high strength steel. The same carbon steel block was used for both the synthetic oil and diesel runs to eliminate any variation in metallurgy. A deeper gouge was carved into the block in diesel than in the synthetic base oil, representing a 50% increase in erosion of the carbon steel block for diesel after completion of the 70-minute test. The weight loss can be directly related to drill pipe erosion and thus the life span. It is also correlatable with the increasing friction factor. Interestingly, the color changes in the base oils are noticeably different. Metal residues or reaction products in diesel result in a much darker color than with the synthetic sample. The phenomenon indicates a chemical reaction or adsorption on the metal surface as the aromatic content in diesel may dominate the formation of a surface layer and/or oxidation products.

New drag force measurement

As discussed above, the standard EP test employs a very limited contact area, and most solids are squeezed out due to the constant movement while in the field there is nowhere for the solids to go in downhole conditions. In addition to the area limitation, the pressure and force applied are out of the field ranges. The average drill pipe/casing weighs from 10 to 60 lbs/ft. If we assume one inch width of contact area, the pressure at the contact area is between 1 and 5 psi during drilling operations in horizontal holes. Certainly, pipe rotation and well angles make it more complicated to predict but the order of magnitude should be in the range of estimation.

The large contact area in the new in-house drag force apparatus provides more realistic measurement, and the linear drag motion better simulates a tripping or casing-running scenario. The diagram in Figure 4 shows the design of the apparatus. When the core disks along with the cap and weights are pulled forward along the steel channel at a constant rate, the meter reads the force and feeds the data to a computer software program.

One data set is shown in Figure 5 as a comparison between synthetic oil and diesel. Although the average drag forces are similar between synthetic oil and diesel, a much larger spiking is observed with diesel. The difference is attributed to the chemistry of the base oils that leads to a different surface interaction.

It is known that suspended solids play a role in torque and drag. SBM and DOBM field samples were used to better mimic torque and drag during drilling. Both mud samples were obtained at around the same time from approximately the same measured depth from the same formation and shale basin. The rheological properties and mud densities were similar. The weights stacked above the core disks in the test were the same for both muds to assure the effect of pressure did not change. The contact pressure was calculated based on the weight load and the contact area. As 4” diameter core disks were used, the contact area was estimated to be 12.5 sq.in., which is 70 times larger than that of the EP lubricity meter. In the experiments, the disk was left static in NADF for 2 days with weights generating 1.7 psi pressure. During the 2 days, the apparatus was covered to eliminate base oil evaporation. A higher drag force was recorded and reported as the first point of each curve, which means the maximum force needed to initiate the movement of the disk. This static friction coefficient may be related to the field operation after a pause in drilling operations.

The comparative results are shown in Figure 6. It is seen that the friction coefficients are higher than those measured in the standard EP lubricity tests but closer to the friction factors employed in the field estimation for NADFs. In other words, the low friction coefficient (< 0.15) from the EP lubricity meter may not be accurate for the field torque and drag calculations. SBM shows a lower friction coefficient in the low pressure range than DOBM. The average drag force over the course of the test is lower in SBM than DOBM predicting higher lubricity during drilling and running casing. Interestingly, SBM and DOBM showed an opposite response to pressure increases. In the range over 4-5 psi, the two fluids have a similar friction coefficient as it increases in SBM and decreases in DOBM.

Drilled cuttings characterization

To better understand the effect on torque and drag, SBM and DOBM cuttings from the same drilling operation where the mud samples were obtained were characterized. The cuttings were washed with solvent to remove the drilling fluids and then dried. The processed cuttings are shown in Figure 7 a. Visually, DOBM cuttings are darker in color than the SBM cuttings. Interestingly, the diesel oil after erosion testing in the modified EP lubricity test with the carbon steel block had also noticeably changed to a much darker color by the end of the test. Based on the cuttings recovered, the mud concentrations on cuttings were calculated and converted to the units of bbls mud on cuttings per bbl drilled cuttings. DOBM mud on cuttings was 0.72 bbls/bbl, while it was only 0.52 bbls/bbl for the SBM.

The processed cuttings were characterized by sieve analysis and the sub 230 mesh particles were measured with a Malvern Mastersizer 3000. The cumulative particle size distribution is shown in Figure 7 b. SBM cuttings showed a large particle size in the range between 100 to 1000 microns, which is related to cuttings removal by shale shakers in the field. It can affect the torque and drag during drilling as cuttings are transported by fluid movement.

The +5 mesh cuttings after processing were also selected for microscopic observations. The photos are shown in Figure 8. DOBM cuttings are shown on the top row and SBM cuttings are on the bottom row. The first two photos on the left side are dry cuttings after being rinsed by solvent. The rest are cuttings after being rinsed by solvent, dried and then soaked in fresh water or xylene for seven weeks. In general, the surfaces of DOBM cuttings were smoother while the SBM cuttings surfaces were more jagged and more sensitive to new fluid exposure in case of fresh water or xylene. There are also more cracks and light-colored quartz/feldspar particles in the SBM cuttings compared to the DOBM cuttings. In other words, there is less alteration of shale in SBM compared to DOBM.

The characteristic of the solid surface may play an important role in determining lubricity and torque/drag. Depending on the pressure at the interface, the stickiness and roughness of the solids trapped can affect the overall friction. Due to the interaction and motions during drilling, the drill solids degrade further and become finer solids; however, the chemistry of the base oil may alter the solid degradation. It was demonstrated in a previous study comparing shale organic matter interaction in non-aqueous drilling fluids (Lu et. al., 2023). Synthetic base oil is less polar than diesel thus penetrates more slowly into drilled cuttings. SBM is also thinner in viscosity than DOBM. These two factors help explain the lower mud on cuttings ratio.

Drilling simulation

The understanding and prediction of torque and drag are important for field operations as excessive torque and drag can cause drilling issues. Certainly, the overall drilling performance is affected by many other factors including weight on bit, type of bit and formation conditions. A comprehensive way to compare SBM to DOBM is to evaluate the drilling performance while drilling with the fluid through shale. The Grace 2200 Drilling Simulator was utilized in the study to quantify the correlation between those parameters and the type of drilling fluid. The instrument setup is shown in Figure 9.

The simulator is designed with a realistic wellbore chamber and can monitor ROP on actual core samples with a polycrystalline diamond (PDC) microbit. The core samples can vary to match various formations. In this study, Wolfcamp shale core plugs from the Permian Basin were obtained from a commercial supply to assure consistency for comparison. The core plug is 1.5” diameter and 1” thick. In other words, the maximum drilling depth is 1”. The diameter of the bit is 1”, which determines the hole size.

In a standard setup, a core plug is placed in the core holder, which sits on the top of a piston. The pressure that pushes the piston upward represents the weight on bit. The PDC bit is attached to a shaft driven by a motor with a maximum torque of 120 $\mathrm{lb_f}$·in. During a test, the chamber is filled with drilling fluid so that the drill bit and core plug are fully immersed in the fluid. The depth of the bit is tracked as the drilling depth. The ROP can be calculated by measuring the depth versus time. Computer software controls and records all the pertinent data.

The drilling simulator setup was improved during the study based on the observations made. Fins were added to the shaft just above drill bit to aid fluid movement during drilling and push drilled cuttings away from the top of the bit. Another important implementation was the use of a circulation system with a clear chamber for better visualization. Two ports were added to the chamber with a return nozzle pointing directly toward the core holder. The idea is to simulate the fluid circulation system in the field. During a run, an external pump circulates the fluid out of the clear chamber into an external reservoir containing a screen to remove solid particles entrained in the fluid. After solids removal, the fluid is returned back to the chamber. The addition of the screen is designed to mimic the shale shaker in the field.

The data captured from runs with neat synthetic oil and diesel are shown in Figures 10 a) and b). WOB, torque, and drilling depth are plotted as a function a time. It is observed that the torque increases with drilling depth as the bit penetrates further, similarly to in the field. The cuttings generated can possibly increase the torque as well. WOB is increased in steps during the tests to simulate the increase in WOB while drilling in the field.

ROP was calculated based on the drilling depth vs. time and plotted as a function of WOB for synthetic oil and neat diesel. The results are shown in Figure 11 a. Under the same drilling parameters, synthetic oil yielded a higher drilling rate than diesel with the Wolfcamp cores. The dotted lines represent the classic drilling curves where in the first region ROP is very low due to inadequate depth of cut. In the second region, ROP increases steadily when the bit is efficiently cutting the rock. When the WOB reaches certain values, the curve enters the Flounder region and ROP does not increase or may decrease due to insufficient torque generated by the WOB to maintain the rock cutting action by the bit.

In addition to neat base oils, drilling simulations were run with 9.0 ppg non-aqueous drilling fluid based on synthetic oil or diesel. To compare the impact of the base oils, the SBMs were prepared with the otherwise identical formulation and additives. The results are shown in Figure 11 b. With neat base oil and formulated SBMs, synthetic base oil showed an extended Flounder region and higher ROP than diesel with the same weight on bit. Synthetic base oil provided a significant increase in ROP over diesel in drilling Wolfcamp shale. The increase in ROP with synthetic was less with the 9 ppg SBMs most likely due to the dampening effects of solids and other components. Overall, the ROP improvement with synthetic oil can be attributed to the non-polarity.

The high aromatic content in diesel leads to a different dynamic process when exposed to the formation or solid surface. It was directly observed during and after the drilling simulation runs as shown in Figure 12. The cuttings generated in diesel are noticeably darker, finer and wetter than those generated in synthetic oil, which indicates that the formation reacts differently when it is cut by the PDC bit. The darker color for shale cuttings in diesel during the simulation is in line with the darker color for diesel after the EP lubricity tests with carbon steel and with the condition of the cuttings examined from the field. The cutting process can fundamentally affect the ROP. The finer, wetter cuttings with diesel could be an indicator of the bit having more difficulty cutting the shale rock. In addition, the cuttings can stay in the fluid if not removed effectively by shale shakers and thus adversely affect the fluid properties.

Lastly, the lab simulation results need to be connected to field drilling performance. One important aspect is the mechanical specific energy (MSE), which is calculated from WOB, bit area, RPM, torque, and ROP. The equation used is shown below (Dupriest et al., 2005). A scaling factor is added to properly use the laboratory data as the efficiency is lower than in the field due to the size of the bit and core plug. This factor is 0.1 for the drilling simulations.

$$MSE = \frac{WOB}{A_b} + f \cdot \frac{120\pi \cdot RPM \cdot T}{A_b \cdot ROP}$$

Where:

MSE, Mechanical specific energy, (psi)
WOB, Weight on bit, (lbs)
T, Torque, ($\mathrm{lb_f}$·ft)
A_b, Bit area, (inch^2)

ROP, Rate of penetration, (ft/hr)
RPM, Rotational speed, (revolutions/min)
f, Scaling factor

MSE is a direct indication of drilling efficiency and is proportional to the energy required to remove a unit amount of rock. As the energy input is fixed, the amount of energy transferred to the bit during drilling determines the overall efficiency. The drilling fluid used plays an important role in the energy transfer process. MSE can be used to optimize the overall drilling efficiency in addition to improving fluid properties and reducing torque and drag. MSE was calculated from the drilling simulation data and is presented in Figure 13. For a given ROP, the average MSE with synthetic oil was lower than with neat diesel, indicating improved drilling performance. The MSE approach can also be used to optimize fluid formulations with the same base oil.

Conclusions

The study provides a new insight into the lubricity, torque, drag, and ROP measurement in NADF and helps explain the gap between lab data and field performance. The comparison between synthetic base oil and diesel yields a quantitative understanding on how to improve the fluid and subsequently the drilling performance.

- The EP lubricity measurement has a much higher contact pressure than in the field, which causes more surface damage and may not represent the downhole scenario. The procedure was modified to better mimic the field parameters to understand the difference between synthetic fluid and diesel.
- A newly designed apparatus provided a practical simulation of drag force with base oil and field mud samples. The results showed a clear effect of contact area, contact pressure and fluid type.
- The characterization of drilled cuttings from SBM and DOBM showed a different solid/fluid interaction due to the chemistry of base oils.
- The Grace 2200 Drilling Simulator was modified to quantitatively measure the ROP in relationship with the base oil types. The relationship between weight on bit, torque and drilling depth provided an improved understanding of fluid impact on drilling efficiency.
- The combined understanding of torque/drag force and drilling rate provides insight into the performance of synthetic fluid compared to diesel.

Acknowledgments

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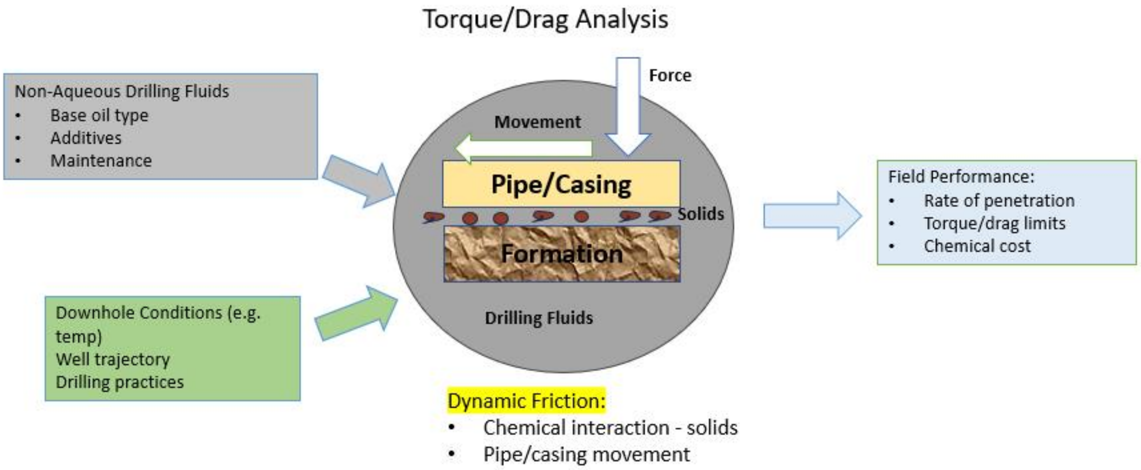


Figure 1 – Torque/Drag analysis in drilling operations

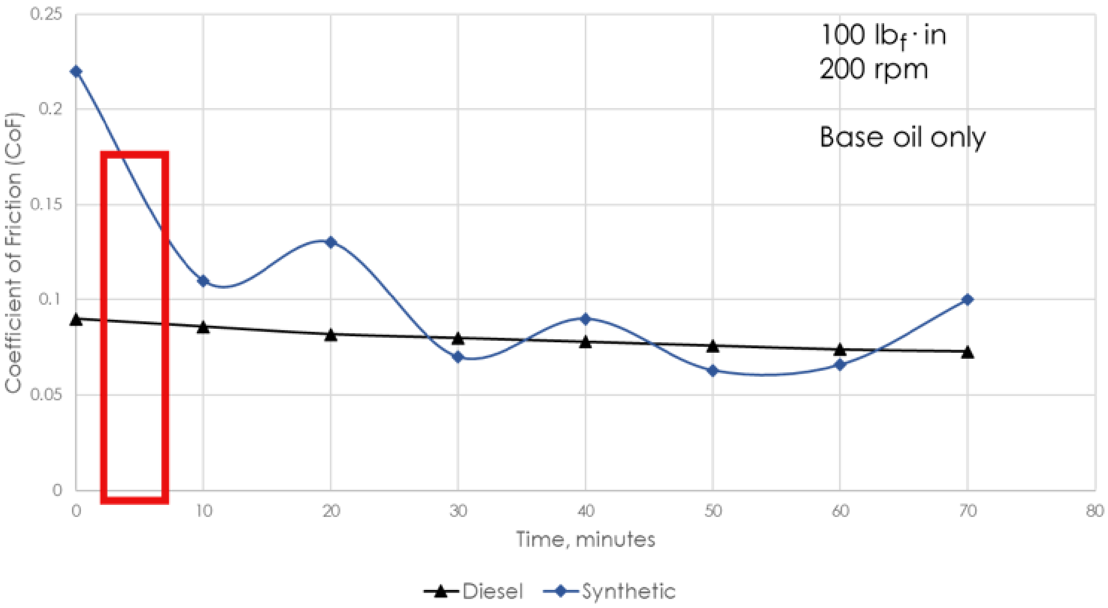


Figure 2 – EP lubricity measurement with extended run time

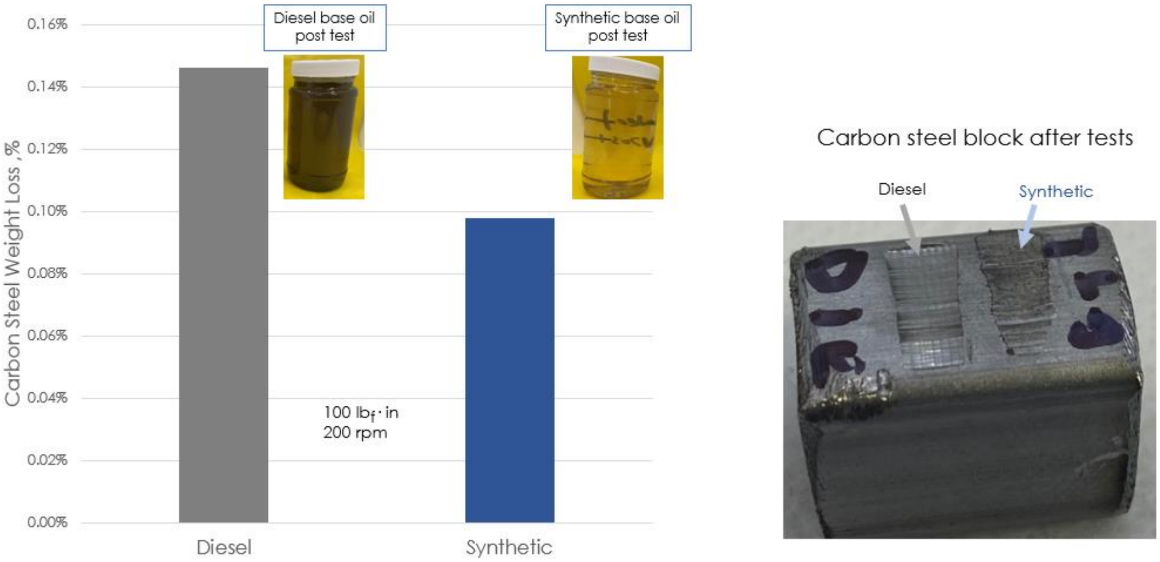


Figure 3 – Weight loss with carbon steel block in modified EP meter

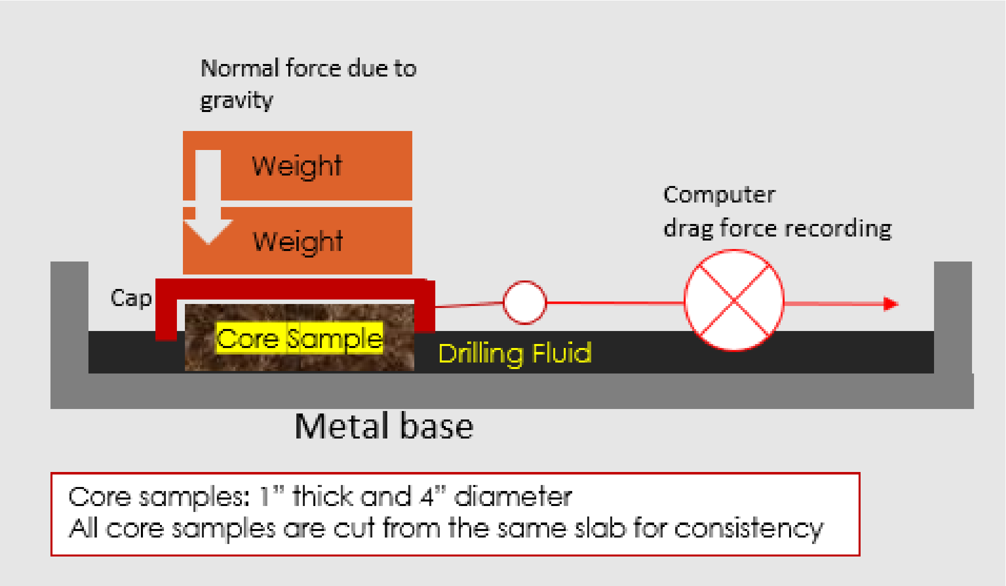
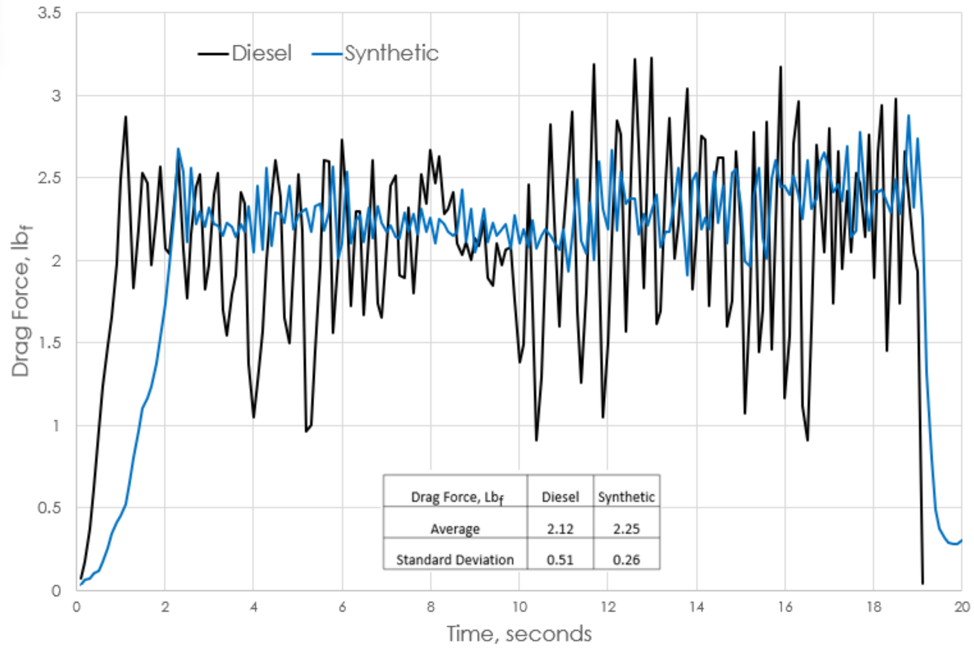


Figure 4 - Design of in-house apparatus for torque/drag study



Drag Force, Lbf	Diesel	Synthetic
Average	2.12	2.25
Standard Deviation	0.51	0.26

Figure 5 - Drag force measurement with base oils

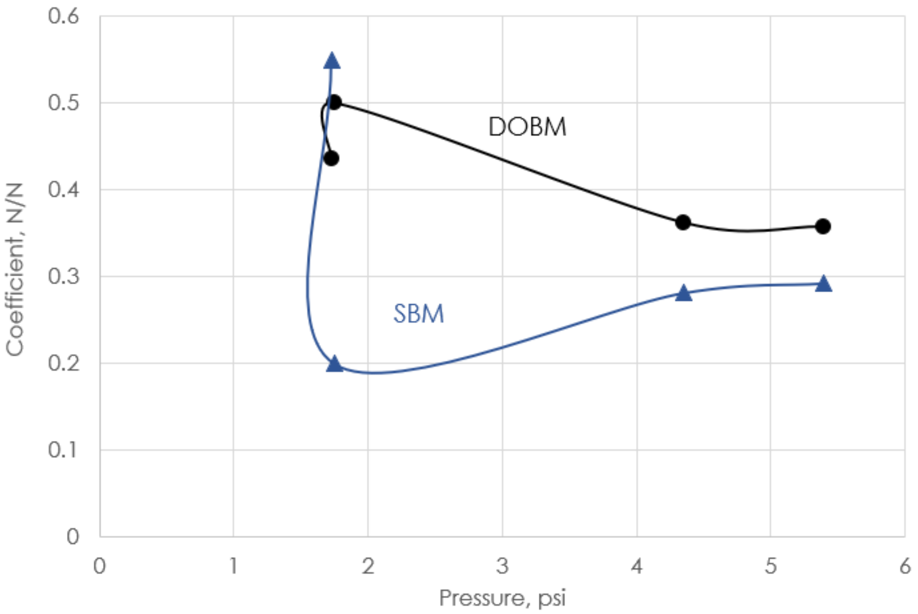
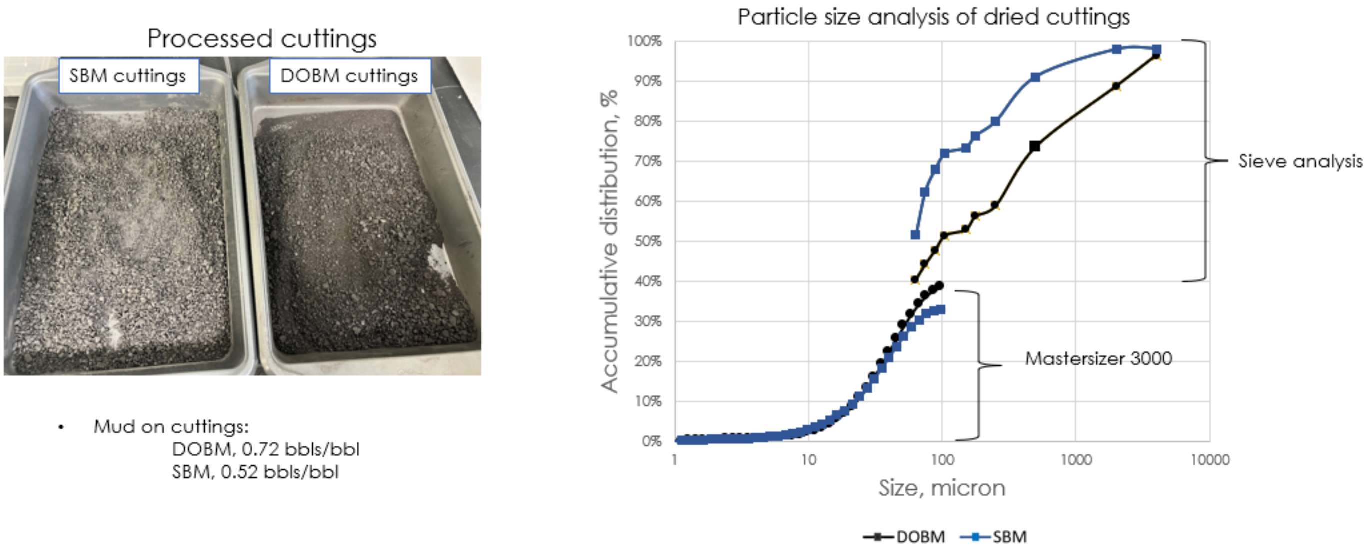


Figure 6 - Coefficient of friction of field muds measured by in-house apparatus



- Mud on cuttings:
  DOBM, 0.72 bbls/bbl
  SBM, 0.52 bbls/bbl

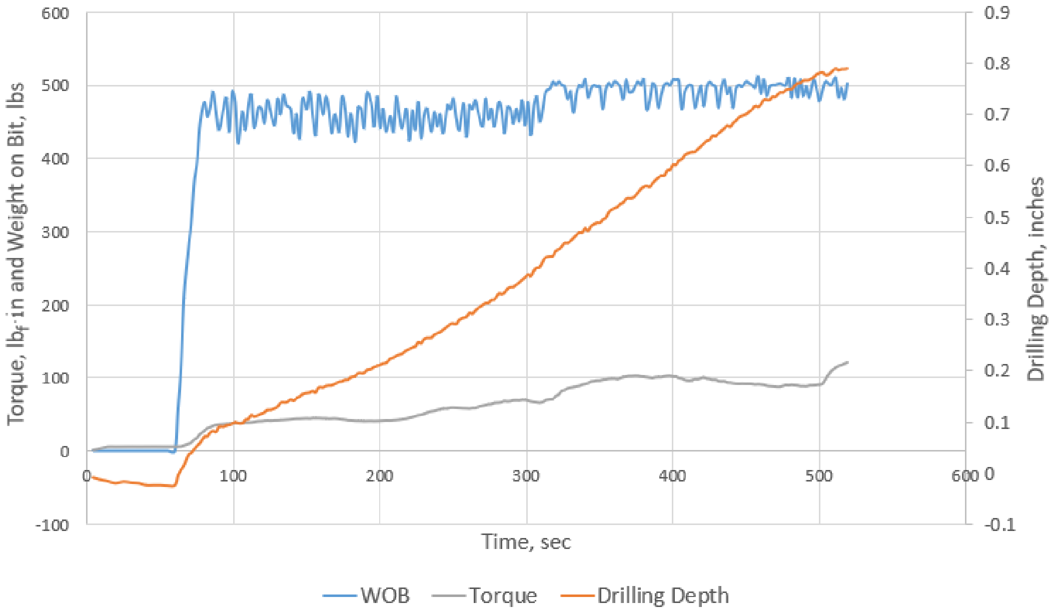
Figure 7 – Drilled cuttings from the field and particle size analysis

DOBM cuttings before and after being exposed to soaking fluids

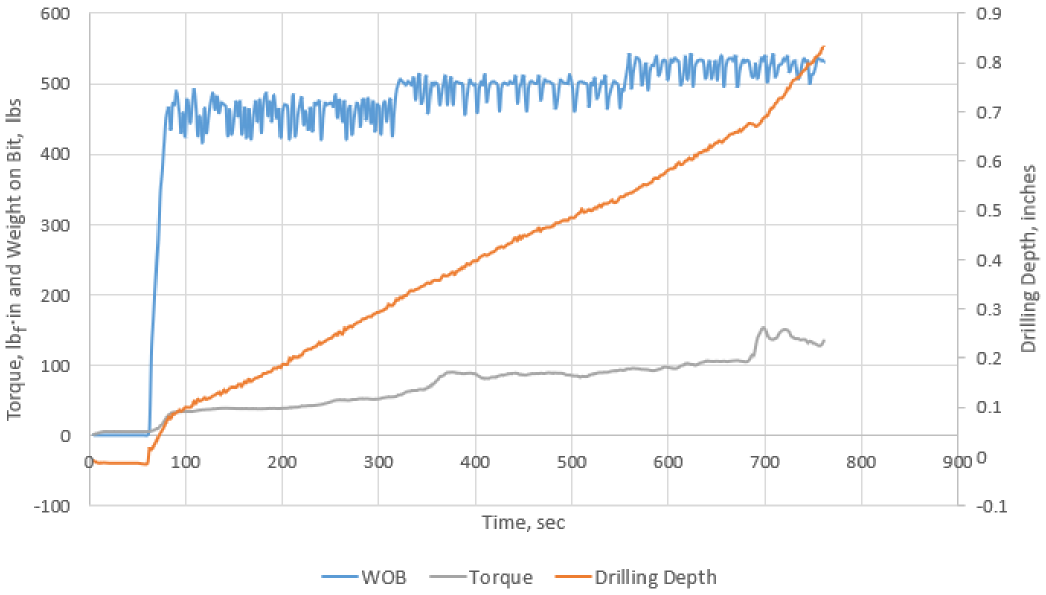
SBM cuttings before and after being exposed to soaking fluids

Figure 8 - Morphology of DOBM and SBM cuttings

Figure 9 - Drilling simulation setup with a PDC bit

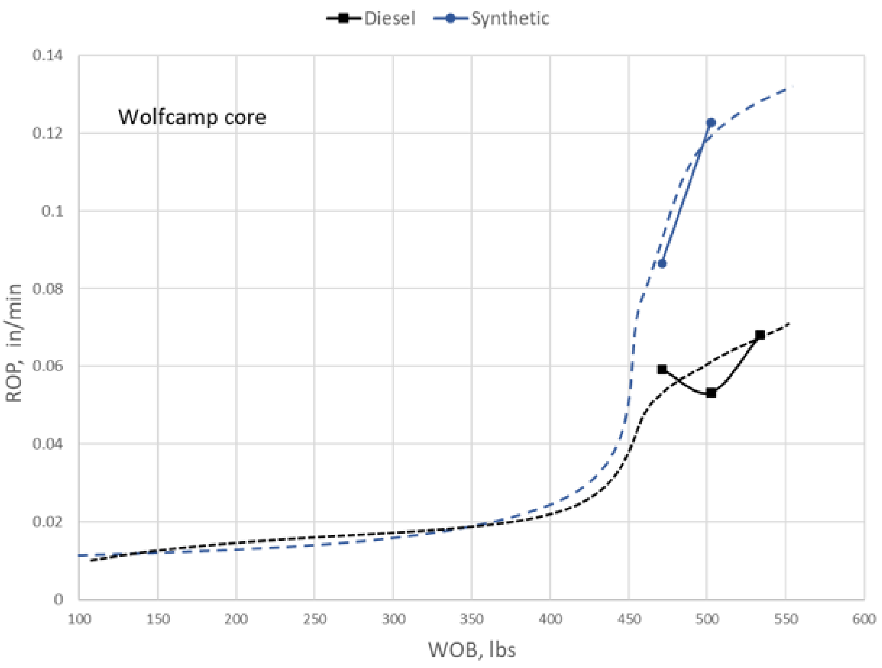


a) Drilling simulation with synthetic base fluid

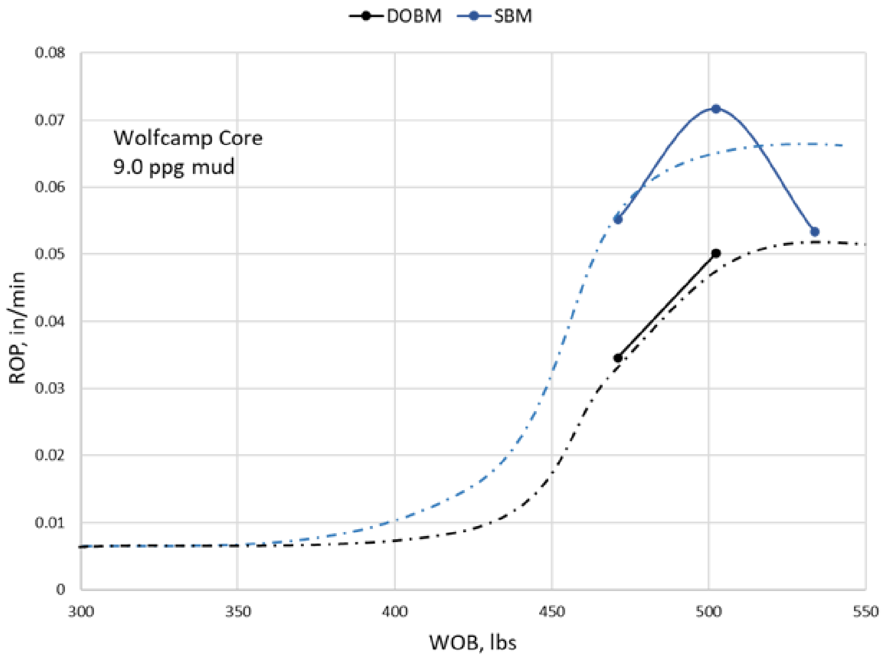


b) Drilling simulation with diesel

Figure 10 - Drilling simulation results with Wolfcamp cores



a. Comparison between neat diesel and synthetic oil



b. Comparison between 9.0 ppg DOBM and SBM

Figure 11 - Drilling rate comparison between diesel synthetic fluids

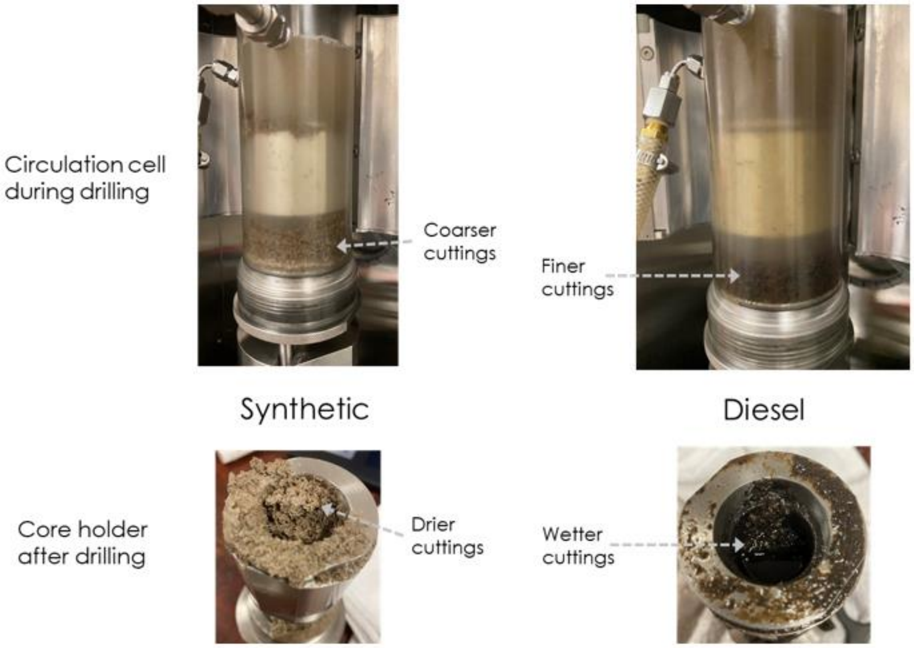


Figure 12 – Cuttings during and after drilling simulation

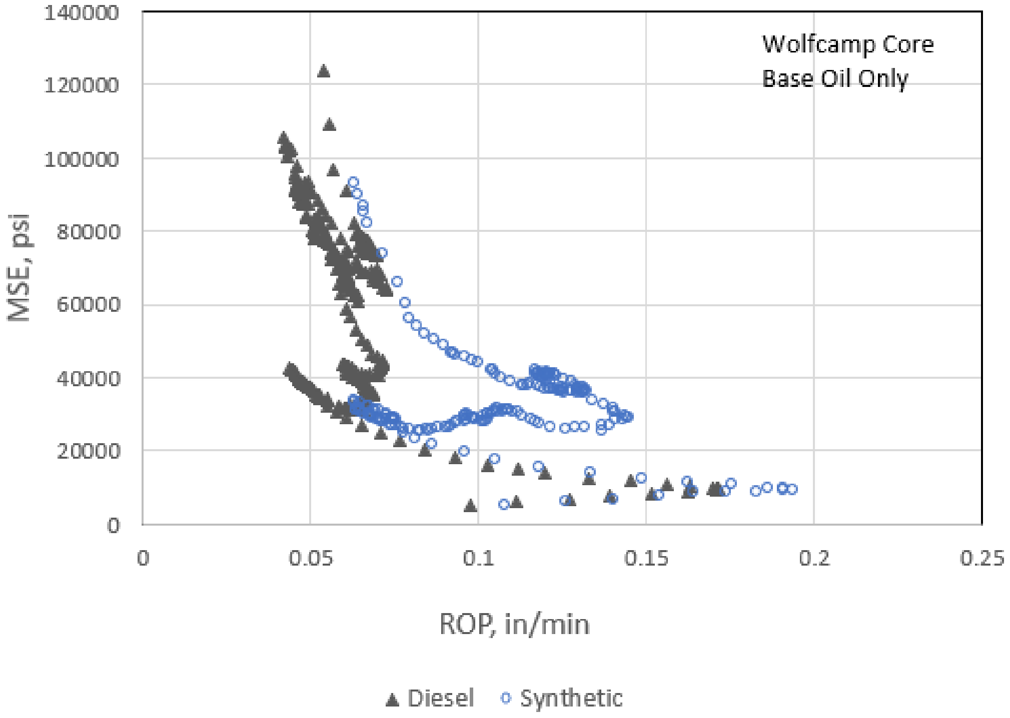


Figure 13 - Analysis of mechanical specific energy (MSE)