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Base-Fluid Influence on Additive Compatibility in Non-Aqueous Drilling Fluids for High-Temperature Wells

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Abstract

The drive for deeper and longer wells continues to push the temperature limits of drilling operations in the U.S., particularly in the Eagle Ford and Haynesville basins, where it approaches and sometimes exceeds 400°F. Such extreme conditions accelerate additive degradation, increase fines generation and stress drilling fluid systems, impairing both fluid properties and drilling performance.

The adoption of gas-to-liquids (GTL) base fluids has been associated with improved fluid stability under elevated temperature conditions. This study presents a direct laboratory and field comparison of conventional diesel based OBMs with GTL based SBMs. Thermal stress tests up to 425 °F combined with HTHP rheological measurements shed a light on the HT fluid stability. It showed that GTL SBMs maintained a greater viscosity reserve and a better emulsifier stability.

New bench-scale methods were developed to further quantify the effect of non-polar synthetic base fluid especially on solid/fluid interactions. Findings suggest that GTL-based systems exhibit reduced fluid/solids interaction under the tested conditions, which improves cuttings integrity and solid removal efficiency. Field data from the Haynesville corroborate lab studies, demonstrating that lower dilution, improved emulsion stability and stable torque/drag occur when GTL SBMs are used. Above 350 °F, diesel-based OBMs require higher additive treatment to counteract volatility and maintain emulsion stability, while SBMs sustain emulsion robustness with lower incremental treatment.

This paper outlines screening protocols that connect laboratory metrics with field KPIs. In high-temperature applications, performance benefits can offset higher unit costs depending on operating conditions. The study also provides a balanced technical framework for fluid optimization up to 425 °F.

Introduction

Efficiency gains have been driving U.S. shale development in the last few years. The adaptation of new technology and drilling practices help combat the increasing challenges to drill deeper and longer lateral wells. Among all the US shale basins, the Haynesville stands out in terms of true vertical depth (TVD) and bottom hole temperature (BHT). The TVD is over 10,000 ft and approaches 20,000 ft in the western basin, and the BHT goes beyond 350 °F and reaching 400 °F in certain wells.

The high temperature exposes unique challenges to the drilling operation including the design and maintenance of the drilling fluid systems. As shown in Figure 1, the average TVD has increased over 100 ft each year while the lateral length has increased about 370 ft per year since 2021. On the other hand, the drilling performance is improving continuously with new records being made in the basin. One example is the first 4-mile lateral in the basin. The collaboration and adoption of new technologies were the driving force for the success. Among them, the use of synthetic drilling fluid is a key factor crossing the basin. The number of wells drilled with the synthetic system is also shown in Figure 1, which accounts for more than half of the total wells in 2024 and 2025.

The synthetic system is based on a Gas-to-Liquid (GTL) product and is referred to as GTL-SBM in this paper. GTL is manufactured from natural gas via the Fischer-Tropsch synthesis process and has a chemical composition of over 98% slightly branched iso-paraffins and n-paraffins. For comparison, diesel can have over 25% aromatics including a considerable amount of BTEX. As mentioned in the previous studies (Lu et al., 2025), the presence of aromatics causes health, safety and environmental concerns and more importantly impacts the fluid properties by accelerating the drill solid degradation. The effect is amplified at elevated temperatures. In addition to the solid degradation leading to excessive fine particles, the aromatics can adversely affect the additive compatibility when the temperature is reaching the thermal limit of the chemical reagents.

Non-aqueous drilling fluid (NADF) is the system of choice for lateral drilling due to the shale inhibition, fluid stability, and lubricity. Although it has been widely applied for decades, NADF still remains a complex and dynamic fluid system and requires more understanding, especially for the temperature range up to 350 °F and above. High temperature non-aqueous drilling fluid systems have been developed around the GTL base and utilized in the industry for instance, in the Gulf of Thailand, where the BHT often exceeds 400 °F; but the requirements in the Haynesville basin are more challenging for several reasons. The laterals add more stress as the fluid stays within the BHT range longer and requires more stable rheological properties. The increased penetration rate adds more low gravity solids. For example, the LGS is maintained at 5% offshore while it often exceeds 10% for US land. In addition, there is the use of downhole tools such as mud motors that pose additional requirements on fluid compatibility at high temperatures.

As shown in Figure 2, the combination of various additives and structures make up the non-aqueous drilling fluid system. Under high pressure high temperature, the additives undergo changes that often lead to detrimental degradation. There are brine droplets and a large number of solids – not only LGS but also a high amount of barite for the density requirements. To maintain the stability of all the interfaces, the emulsifiers/wetting agent play a critical role. Unfortunately, some of the chemicals show some degree of thermal degradation under these conditions for example hydrolysis of amidoamine (Growcock et al., 2011), which certainly affects the emulsion stability and dispersion of solids. Another important aspect of the behavior of solids includes organoclays. Depending on the type of the clay crystal structure, the microstructure can collapse and lead to decrease of viscosity. The degradation products of certain additives can also react with the fine solids and create undesired gel structure. As all the changes occur in the non-aqueous medium, the properties of the base fluid can inhibit or accelerate the reactions. Aromatic content has been reported to influence HTHP fluid behavior and is considered a contributing factor as demonstrated in a Fann 77 study (Jian et al., 2023). It is hypothesized that emulsifier degradation mechanisms may be moderated in lower-polarity base fluids.

Thermal exposure induces viscosity decreases in drilling fluid systems although the pressure can compensate for some of the losses. It is critical to quantify the rheological profiles under downhole conditions, from which the performance of the additives can be optimized to improve the drilling outcomes. The purpose of this study is to investigate the effect of base oil on the fluid properties and understand subsequent field performance under HT conditions in the Haynesville. Certainly, the role of additives cannot be ignored. The investigation also provides some guidance for HT fluid optimization up to 425 °F.

HTHP Fluid Properties

As operators are tapping into deeper formations and drilling longer laterals to maximize the return, it further stretches the resilience of the fluids used. When the mud weight increases from 15.0 to 17.0 ppg, it adds increased complexity to the NADF as the solids require more additives to disperse and stabilize in a crowded invert emulsion system. During circulation, the fluid is heated up continuously in the lateral while being chilled down on the surface. The drill solids are sheared for a longer time, which means more potential to generate fines. All the factors combined lead to the requirement for more robust additives and system for stability and maintenance.

The starting point for technical qualifications is a standard laboratory test. As a continuation to the previous study (Lu et al. 2025) , the temperature is extended to 425 °F. Various additive packages were selected and evaluated in a standard fluid formulation at 16.8 ppg. The dosage of organoclay, emulsifier, and wetting agent were kept constant. Fluid properties were measured after hot rolling at 425 °F. HTHP rheological measurements were also conducted to quantify the downhole performance. One noticeable observation is the impact of each fluid component is amplified. Inefficiency of any single additive can break down the system or potentially cause downhole issues. Emulsifier, wetting agent and organoclay are considered the backbone of the fluid system as they heavily influence the emulsion stability and fluid viscosity. In the study, HT grade organoclays are used and fixed. The variabilities are mainly the base fluid and emulsifier packages. In addition, drill cutting samples from Haynesville were processed and used as drill solids in the test matrix at 55 ppb.

Figure 3 shows the effect of hot rolling on fluid properties including PV, YP and ES at 425 °F. The values reported are the changes after hot rolling, which were seen to be significant. In addition to the differing emulsifier packages, the fluids were formulated with GTL base oil or diesel, with or without drill solids. The change in PV is moderate as the solids are predominantly inert barite. YP drops dramatically after hot rolling, indicating a major change in the chemical forces in the system, which is also reflected in the drops in ES. Fluid package 1 behaved marginally better than package 2 with less changes after hot rolling although the increase in PV may indicate sufficient wetting capacity. The thermal degradation is expected to be the primary reason for drops in emulsion stability and YP. Interestingly, GTL-SBMs show less changes in comparison to DOBMs. The positive impact on YP means a more stable fluid under downhole condition and may also indicate inhibited or retarded thermal degradation in GTL.

The impact of each factor including temperature (425 °F), base oil type, fluid package and LGS are summarized in Table 1. The values are reported as the difference in PV, YP and ES when the results are separated into two groups by the parameters shown in parentheses. For instance, by changing the base oil from diesel to GTL, the drop in YP with GTL-SBM is 11 less than that with DOBM. Based on the analysis, it can be concluded that the hot rolling (425 °F) definitely has the largest impact on the fluid properties. Changing to GTL impacts the fluid properties more positively than the variation of the emulsifier package. The presence of LGS shows a minimum impact on the fluid properties; however, 55 ppb is only 6 vol% equivalent and the LGS percentage in the field can be higher. The effect of LGS is expected to be more pronounced when the concentrations of emulsifier/wetting agent are not sufficient.

It is also worth noting the step impact of temperature increase to 425 °F when compared to the previous study at 350 °F. (Lu et al., 2025) The average drop in ES is 669 V while it was only 358 V for the fluids hot rolled at 350°F. The same trend was observed for yield point (YP). The average drop is 20 after hot rolling at 425 °F while it was only 1.5 after 350 °F. The data indicates a step-change response above approximately 350 °F within the tested temperature range. Potentially, every 25 °F increase causes a step change. For laboratory investigation, hot rolling the selected fluids at various temperatures may be desired to systematically improve or optimize the formulations and provide a quantitative guideline for field maintenance.

In addition, the effect of other variables was also observed to be amplified in the 425 °F study such as water phase salinity. The salinity can affect the interfacial tension and thus the emulsion stability. It probably also plays a role in emulsifiers' behavior especially TOFA based. The details will be considered for publication in the future. As the temperature pushes the additives to the thermal limits, all the variables need to be considered when designing a fluid formulation or developing field maintenance strategies.

Shear Degradation

As reported previously, aromatics in diesel are expected to accelerate the thermal effect on the fluid system as the small polar molecules penetrate the solids deeper and quicker. It causes degradation of LGS and thus creates more fines and surface area, which in turn consumes more additives. At elevated temperatures beyond 350 °F, it can be more critical. It is also believed that the possible hydrolysis of certain emulsifier molecules is slowed in a more non-polar GTL fluid. The large decrease in ES reading in diesel mud not only indicates a weaker emulsion, but also the possible presence of water wet components in the oil phase due to the hydrolysis reaction. In addition, it is speculated that aromatic molecules can act as solvents to adversely remove the organic coating on organoclay and thus interrupt the gel structure.

A laboratory shear degradation test was performed to quantify the solid degradation. A selected core sample from the Haynesville formation was crushed and sieved. 20-mesh particles were collected and added to 525 mls (1.5 lab barrels) of lab prepared fluids. Both GTL-SBM and DOBM were used. The 9 ppg fluid formulations were identical except for the base oil. The fluids containing 75 grams of 20-mesh solids were sheared with a Hamilton Beach mixer at low speed for 1 hour. The fluid samples were then run through sieves from 10 to 100 mesh. The recovered solids were washed and dried. The test setup and recovered solids are shown in Figure 4. The cumulative solids recovery is reported in Figure 5. The result shows a quantitative change with the solids in the fluids after 1 hour of shear at 13,000 rpm. The estimated linear velocity falls within the order of magnitude of field circulation rates. 90% of 20 mesh solids broke down in DOBM while only 70% broke down in GTL-SBM. 46% of solids recovered were over 150 microns (20-100 mesh) in GTL-SBM while it was only 28% in DOBM. In other words, the rest became sub-150 micron (greater than 100 mesh) fine solids. A higher degradation means less removal efficiency over the shale shaker and an increase in LGS, which eventually need to be treated with additives. The increase in YP of DOBM after shearing is 50% more than that of GTL-SBM, which is attributed to the increase of fine solids. The shear tests were carried out at ambient temperature, so the degradation is expected to be more at downhole conditions. Certainly, other factors such as formation minerology, fluid formulation and pumping rate all affect the solids degradation but the results demonstrate a relative difference between base fluids under controlled laboratory shear conditions. It also speaks for the fluid strategy in the basin – the use of GTL in addition to dilution to keep LGS low.

Lubricity Measurement

The non-polarity of GTL not only helps preserve the downhole fluid properties but also improves the lubricity, which is critical for high temperature wells. As studied previously (Lu et al., 2024), there is a limitation to the conventional laboratory methods for coefficient of friction (CoF) measurements and an in-house friction tester was developed to focus on the lubricity of non-aqueous fluid for horizontal wells. The improvement is the use of a 4" diameter disk to have a large contact interface and also a low normal load or surface pressure to mimic the downhole condition when tripping or running casing in laterals.

Drilling fluid field samples were obtained from the Haynesville and used to study the CoF between a core sample and metal base. 3 normal loads were used to compare the friction force or CoF between GTL-SBM and DOBM. The core disk is sliding at a constant speed around 1 inch/second, which is 300 ft/hour and in the range of tripping or casing run speed in the field. The results are shown in Figure 6. It is not straight forward to analyze the results as there are multiple factors and the interface changes constantly during sliding.

From the Stribeck friction model, the scenario is in the hydrodynamic regime as the CoF decreases with pressure increase but it only explains the overall trend. The high amount of solids in the fluids and the rough surface of the core disk certainly make it complicated. When the pressure increases to 10 or 20 psi, the CoF readings are more steady, indicating less change at the interface. The spikes or noise is an indication of the interactions between the core disk and metal base. The average CoF in GTL-SBM is around 0.3 with 10 or 20 psi, while it is close to 0.4 for DOBM. In addition, it shows a steady increase towards the end of the test for DOBM. The CoF yielded is close to the friction factors used to model the friction force in the field. Wellbore trajectories can outweigh the fluid effect when micro-doglegs are present in the laterals. Certainly, other drilling practices also affect the friction such as hole cleaning. Cutting bed formation is more detrimental in long laterals as it dominates the friction, which can be minimized by fluids with a stable and consistent downhole profile especially in the temperature range beyond 350 °F.

Drilling Simulation with Hayesville Cores

To further investigate the connection between base oil type and overall drilling performance, the Grace 2200 Drilling Simulator was employed to simulate the drilling process in the Haynesville. GTL-SBM and DOBM at 16.8 ppg were prepared in the laboratory. A core slab obtained from the Haynesville was used to make plugs with consistent minerology and desired dimensions to fit the instrument. The simulations were carried out at ambient temperature and the results are shown in Figure 7. Torque, drilling depth and fluid temperature increase are plotted against time. Identical parameters were used in both runs.

The torque readings are in the similar range in both fluids; however, DOBM registered more spikes and also showed a higher temperature increase, which all point to a higher friction. As the fluids are not circulated a high rate, the friction is mainly from the bit/core interface, where the role of the base fluid is more critical than the overall fluid properties. The difference is also reflected in the average drilling speed. The ROP was calculated based on the slope of drilling depth vs. time. Under controlled ambient-temperature laboratory conditions, GTL-SBM exhibited higher drilling rates relative to DOBM. Furthermore, a more rapid decline in ROP was observed in DOBM with the drilling depth. These results are intended for comparative analysis only and are not predictive of field ROP.

The key characteristic of the Haynesville is the high BHT, which is not reflected in the simulation in order to the keep the parameters simple and obtain a head to head comparison as the overall drilling performance is determined by many other factors. The results provide a base for analyzing or comparing the performance in the field. As discussed above, the non-polarity of GTL is expected to be more compatible with formation solids and thus reflected in the drilling performance. The attribution is more profound in the Haynesville formation temperature ranges.

Field Performance – Haynesville Data

A first set of drilling data from 31 Haynesville wells was obtained. To achieve a fair comparison, the wells are selected from one operator with a close range of total depth (TD) and curve + lateral length. The location of the wells are in the same approximate area. The wells are divided into two groups based on the base fluid type and the overall performance is summarized in Figure 8. Besides the average TD and curve+ lateral length, casing run speed, trip speed, number of trips in the laterals and total drilling days in the laterals are also presented. The curve and lateral lengths are in the 2-mile range with TD in the 4-mile range. The trip speed only refers to the last trip for each well after reaching TD. Casing run is the 5" production casing. The average number of extra trips in the laterals are also reported in addition to total lateral drilling days.

Incremental benefits were observed in the wells drilled with GTL-SBM vs. DOBM. The combined performance enhancement results in more than 3 days of savings in rig time, which means a significant cost reduction. The improvement in average ROP is not only from the instantaneous drilling speed but also the reduction in undesirable trips in the laterals, which are often related to downhole tool issues caused by the temperature. One of the key components is elastomers, which deteriorate under temperature and the presence of non-aqueous fluids. The lower polarity of GTL-based fluids is consistent with reduced elastomer interaction reported in prior studies. It helps maintain the tool efficiency and also extend the lifetime.

The hook load of two selected wells from the data set are plotted in Figure 9 to compare the friction during casing runs. The curves show a typical behavior as the load increases proportionally to length in the vertical section and decreases in the lateral. The decrease in the lateral is partially due to the friction. The casing was 5.5" 23# P110-E and the mud weight was 15.5 ppg. The effective weight is estimated to be 17.5 lb/ft, while the slope in the plots is approximately 19.3 lb/ft. The side force and fluid movement can explain the difference. In the lateral sections, the casing weight is offset by the support of the wellbore and serves as the normal force for friction of the casing, which decreases the hook load as shown. The slopes were extrapolated and determined to be -3.0 lb/ft in case of DOBM and -2.2 lb/ft in case of GTL-SBM, which are 0.17 and 0.13 if converted to friction factors using the effective casing weight.

Drilling Additives

A second set of Haynesville data was used to analyze the impact of base oil types on additive consumption. It comprises 22 wells drilled with GTL-SBM and 22 wells with DOBM. The results are reported in Figure 10 as the comparison of the average of 4 parameters between GTL-SBM and DOBM wells. Production section length, average production section per day, average emulsifier cost per barrel of dilution and average wetting agent cost per barrel of dilution are listed. Despite the production sections being 15% longer on average in GTL-SBM wells, the average footage per day was slightly higher. More interestingly, decreases in emulsifier and wetting agent cost were observed. With each barrel of base oil dilution, the emulsifier consumption in GTL-SBM wells was 88% of that in DOBM. The decrease in wetting agents was more significant. The consumption in GTL-SBM wells was only 68% of that in DOBM.

Certainly, the additive consumption can be affected by the overall fluid maintenance strategies especially the requirements on LGS, which dictate the dilution strategy. Although the unit cost of GTL can offset some of the savings in additives, GTL-SBM reduced the production section drilling days and thus the overall cost. The cost saving was even more when on-site disposal was used.

Cutting Disposal

Base-fluid chemistry can influence cuttings handling and waste management logistics in non-aqueous drilling operations. In many of the evaluated wells, diesel-based OBM cuttings required off-site disposal, adding trucking and disposal complexity during extended lateral drilling. By comparison, GTL-based synthetic fluids provided greater flexibility under certain operator waste management programs, allowing cuttings to be managed on location rather than transported off site. While practices vary by operator and jurisdiction, the observed reduction in disposal logistics represents an operational benefit of GTL-based systems.

Conclusions

One of the technology shifts in the Haynesville basin is the adoption of GTL synthetic based drilling fluids to help combat the high temperature high pressure downhole conditions. The fluid system has been used to drill a large portion of the wells in the basin and has resulted in cost savings with reduction in lateral time and waste disposal. The field performance is in line with the laboratory results that show the pure chemical composition and high non-polarity help maintain the additive compatibility although the challenges remain to provide the desired fluids when BHT is approaching 400 °F.

- Laboratory formulations tested at 425 °F show an exponential drop in fluid properties. The thermal effects push the additives beyond the limits and cause potential degradation. The non-polar GTL fluid shows a positive impact in alleviating the temperature effect and thus preserving the fluid properties.

- Shear degradation tests demonstrate the rapid degradation of drill solids in the fluid during circulation and the aromatics in diesel accelerate the process. The solid/aromatic interaction can adversely affect the friction and thus rate of penetration.

- Lubricity measurements and drilling simulations provide quantitative comparisons between GTL-SBM and DOBM with high density fluids and Haynesville shale. They connect the fluid properties to the overall drilling performance. The non-polarity of GTL-SBM improves the friction, torque, and ROP.

- Haynesville field drilling data were obtained to evaluate the impact of base oil. GTL-SBM showed improved drilling performance and reduced the lateral drilling days.

- A 2nd Haynesville dataset showed a decrease in emulsifier and wetting agent consumption per barrel of dilution.

- GTL-SBM provides a flexibility for on-site waste disposal rather than transporting off-site.

Certainly, a close collaboration among all the technology providers is the best way to combat the high temperature challenges. The base fluid is the building block for NADF and GTL base fluid provides an edge for enhanced performance to combat the high temperature challenge, although the overall performance can be affected by the formulation and maintenance practices including dilution rate. The study also provides a guideline for further HT fluid development.

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Nomenclature

PV= Plastic Viscosity
YP = Yield Point
LGS = Low Gravity Solid
GTL-SBM = Synthetic Based Mud made with GTL
DOBM = Diesel Based Mud

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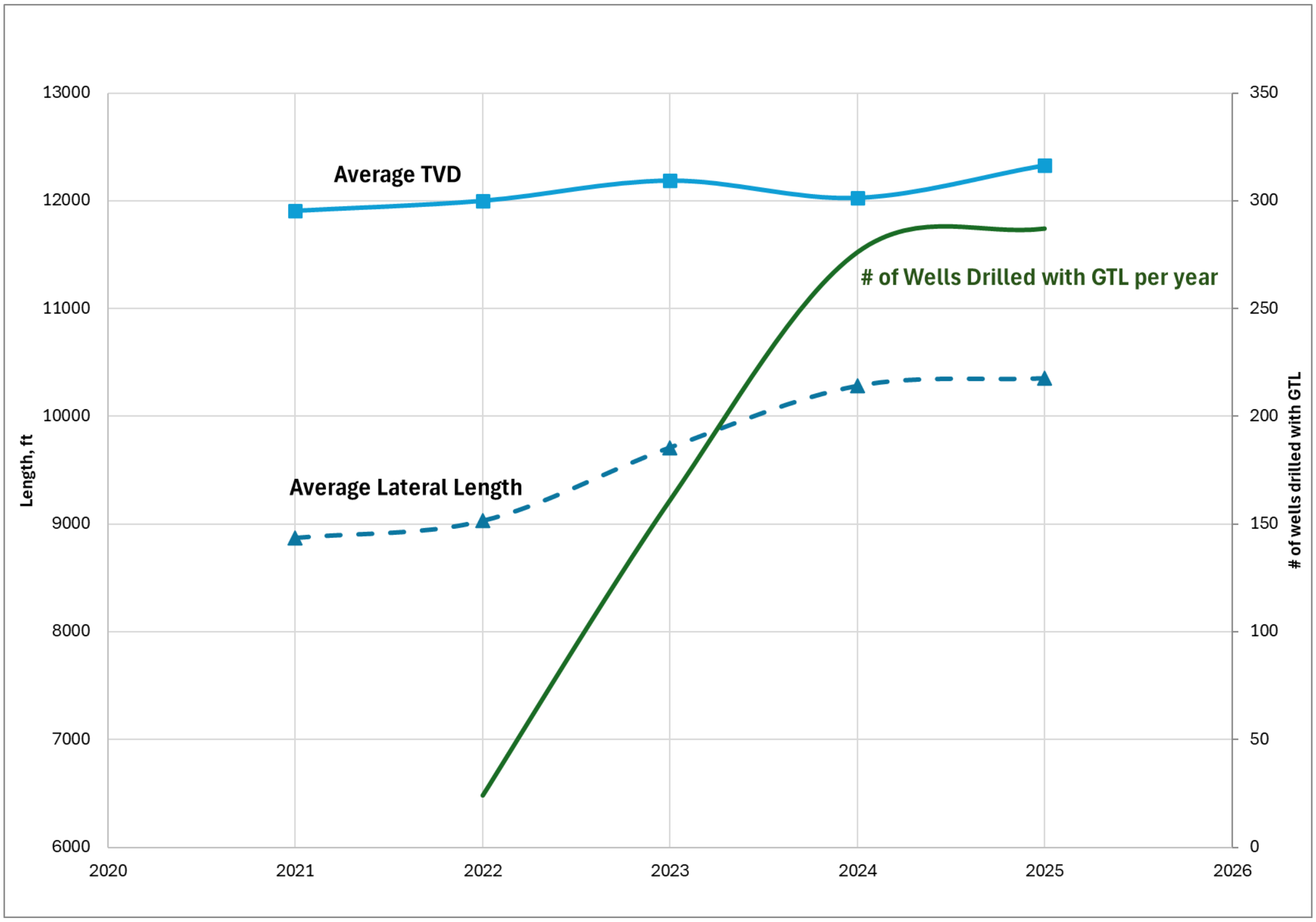

Figure 1 - Haynesville average true vertical depth (TVD), lateral length, and the number of wells drilled with GTL synthetic fluids

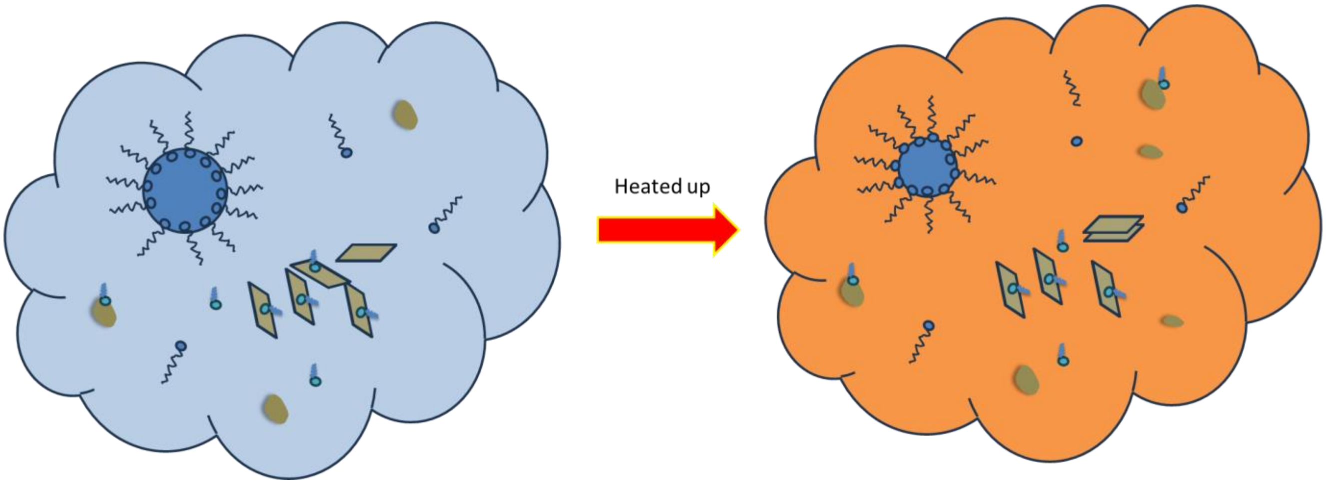

Figure 2 - Thermal effect on non-aqueous drilling fluid system

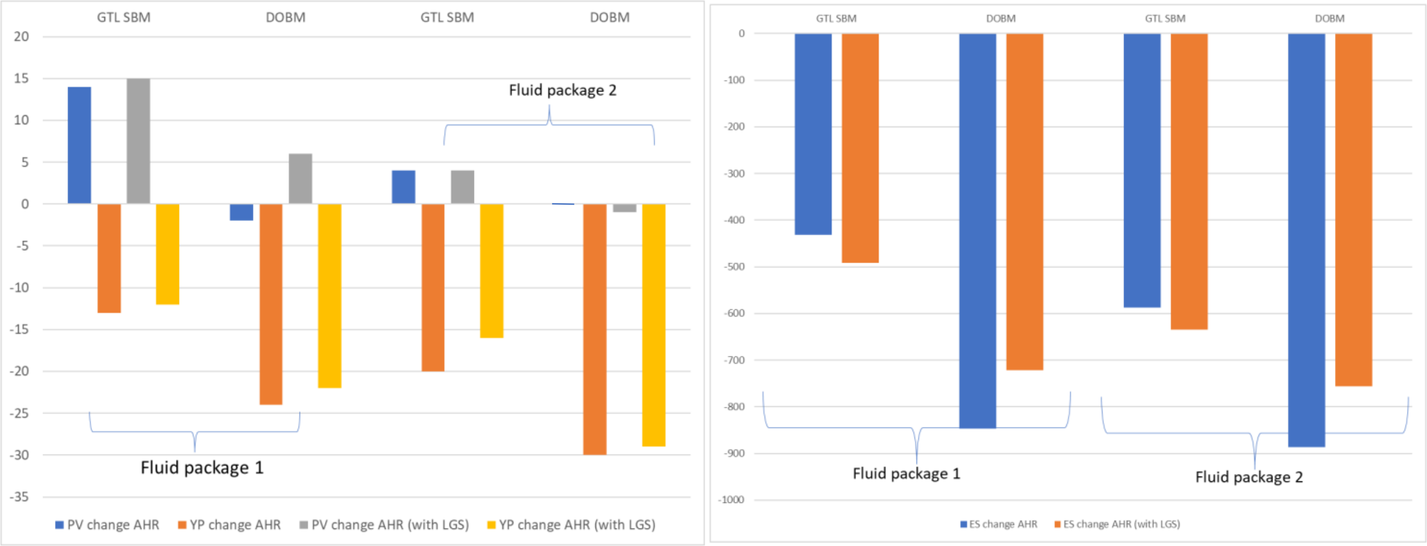

Figure 3 - Fluid property changes after hot rolling lab muds at 425 °F

Table 1 – Impact of hot rolling, base oil type, fluid package and LGS on fluid properties when exposed to 425 °F

	Temperature (AHR over BHR)	Base Oil (GTL over Diesel)	Fluid package (1 over 2)	LGS (0 over 55 ppb)
PV	5	8.5	18.5	2
YP	-20.5	11	6	2
ES	-669	267	93.5	-38

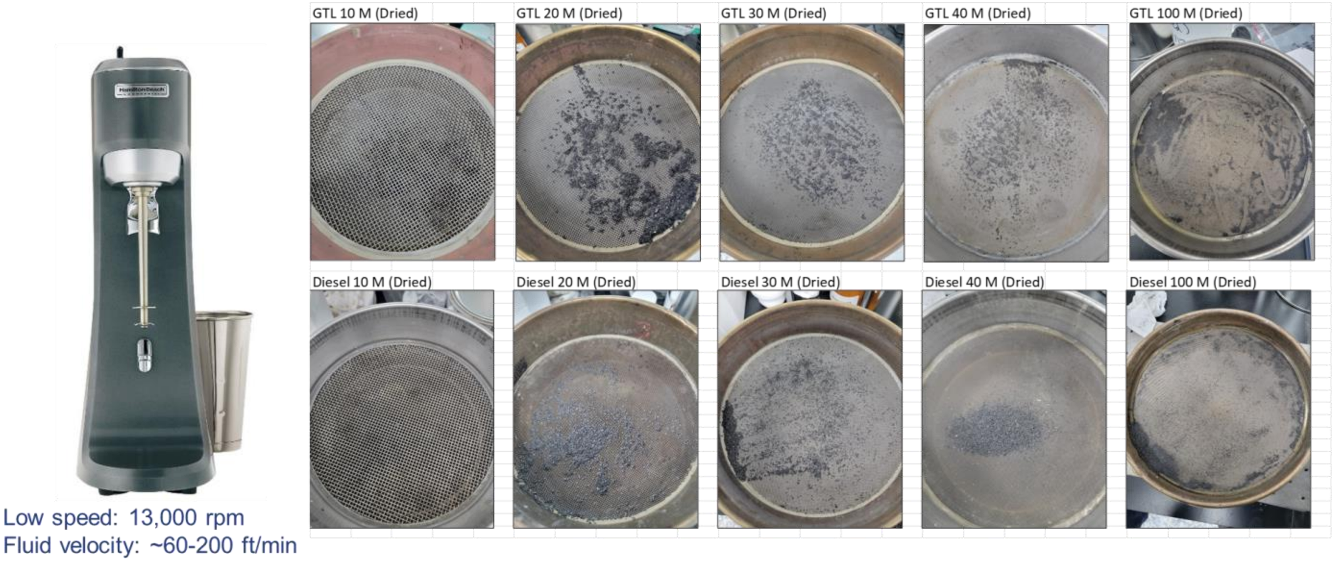

Figure 4 - Shear degradation test with 10 mesh solids

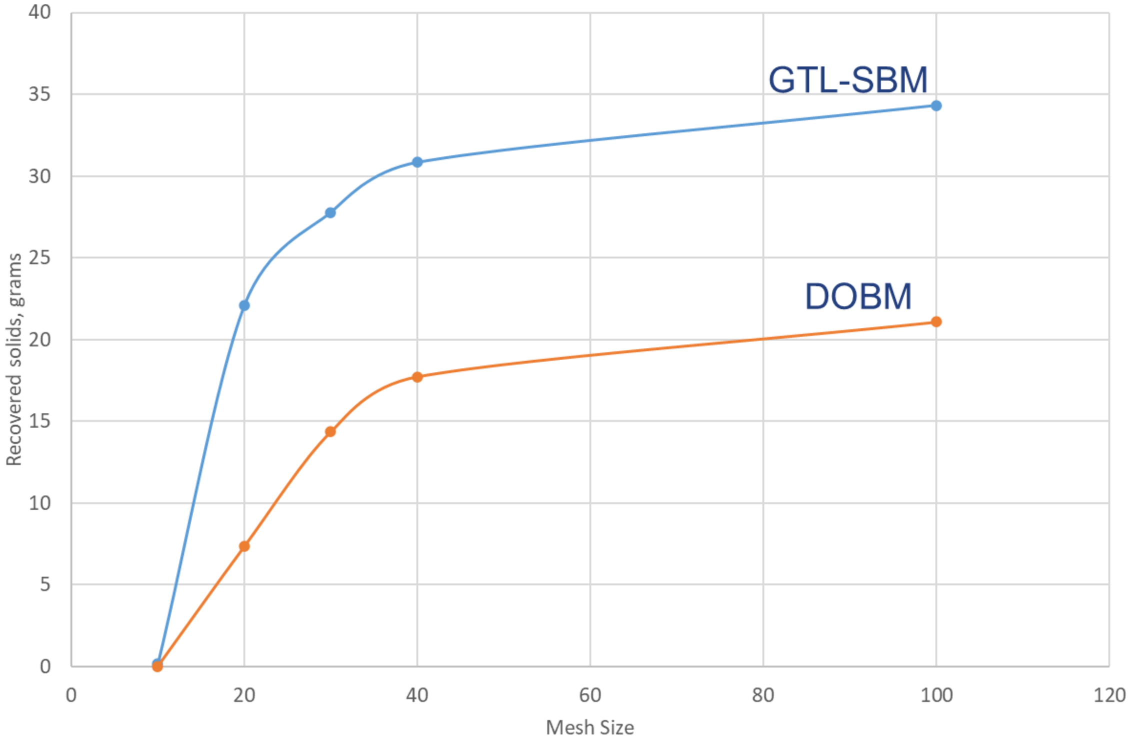

Figure 5 - Cumulative recovered solids from shear degradation test

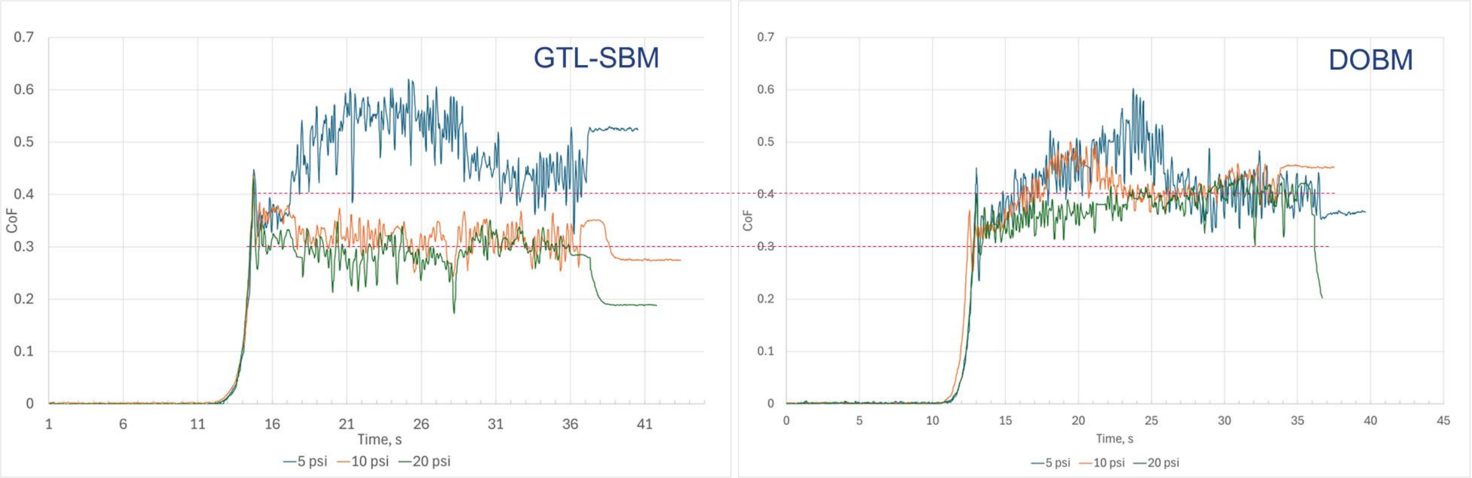

Figure 6 - Lubricity comparison between GTL–SBM and DOBM with in-house friction tester

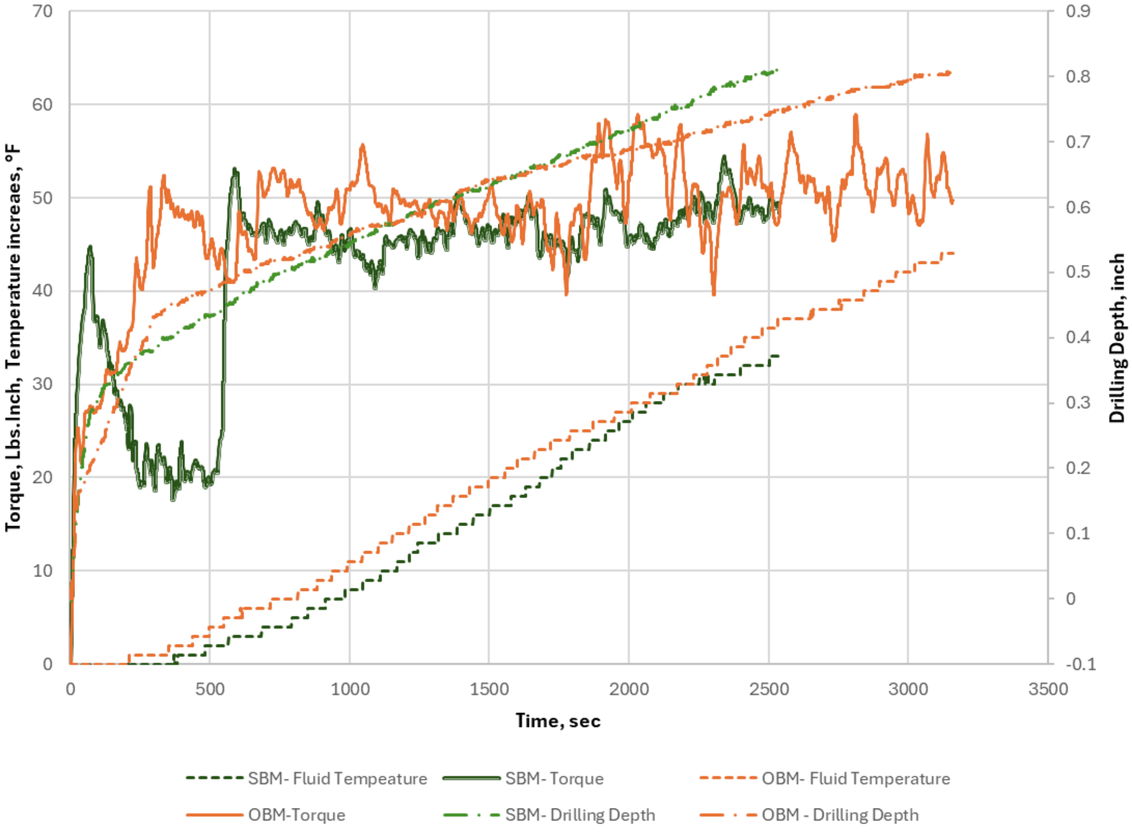

Figure 7 - Drilling simulation with Grace 2200 simulator

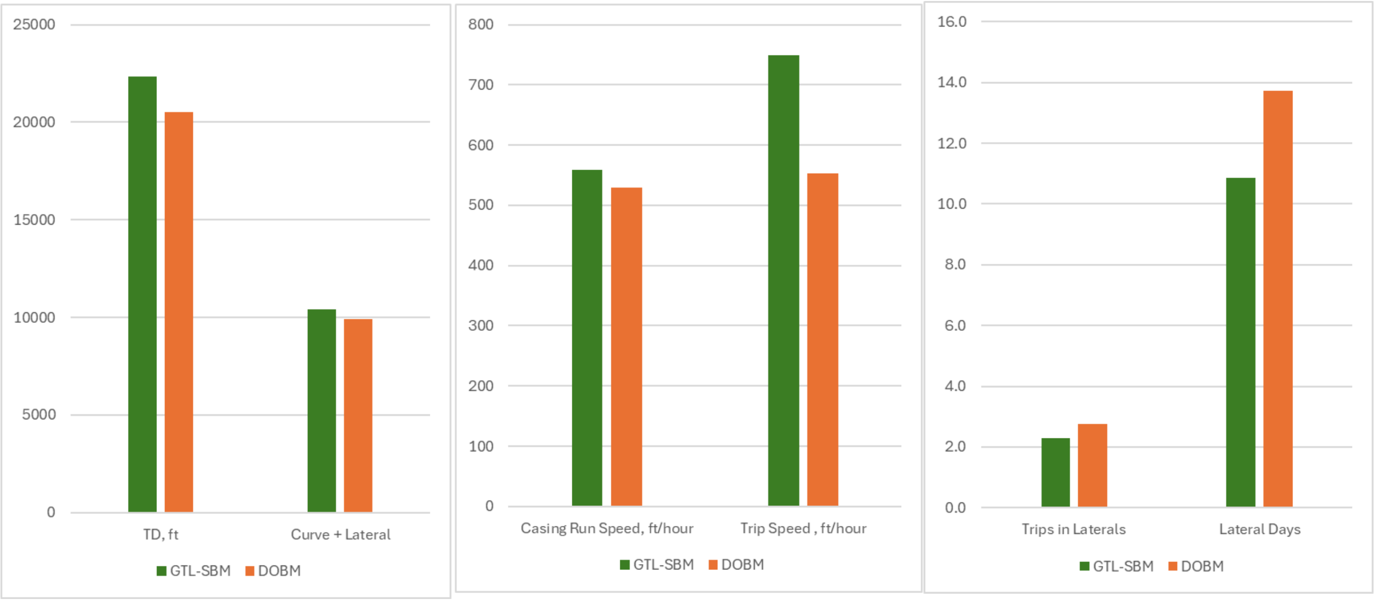

Figure 8 - Drilling performance comparison between GTL-SBM and DOBM

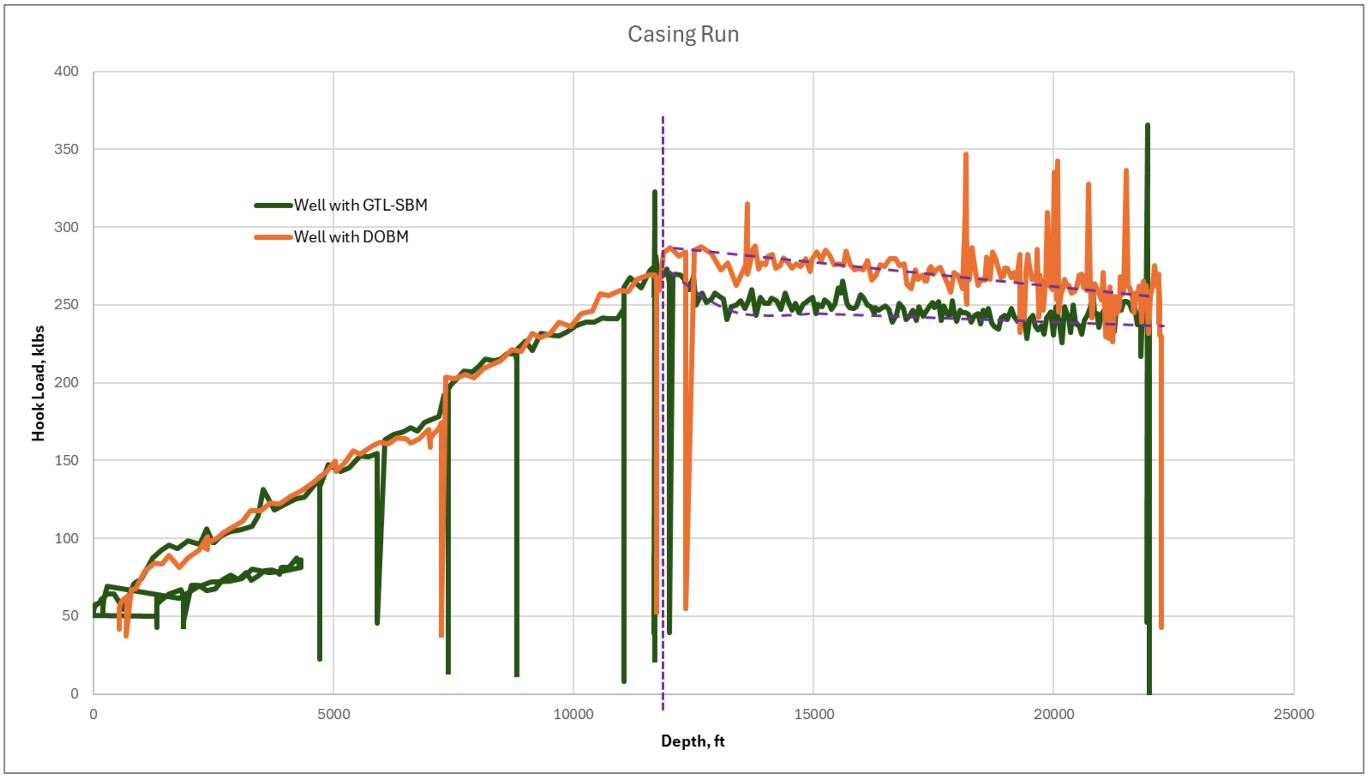

Figure 9 - Hook load during casing run in two Haynesville wells

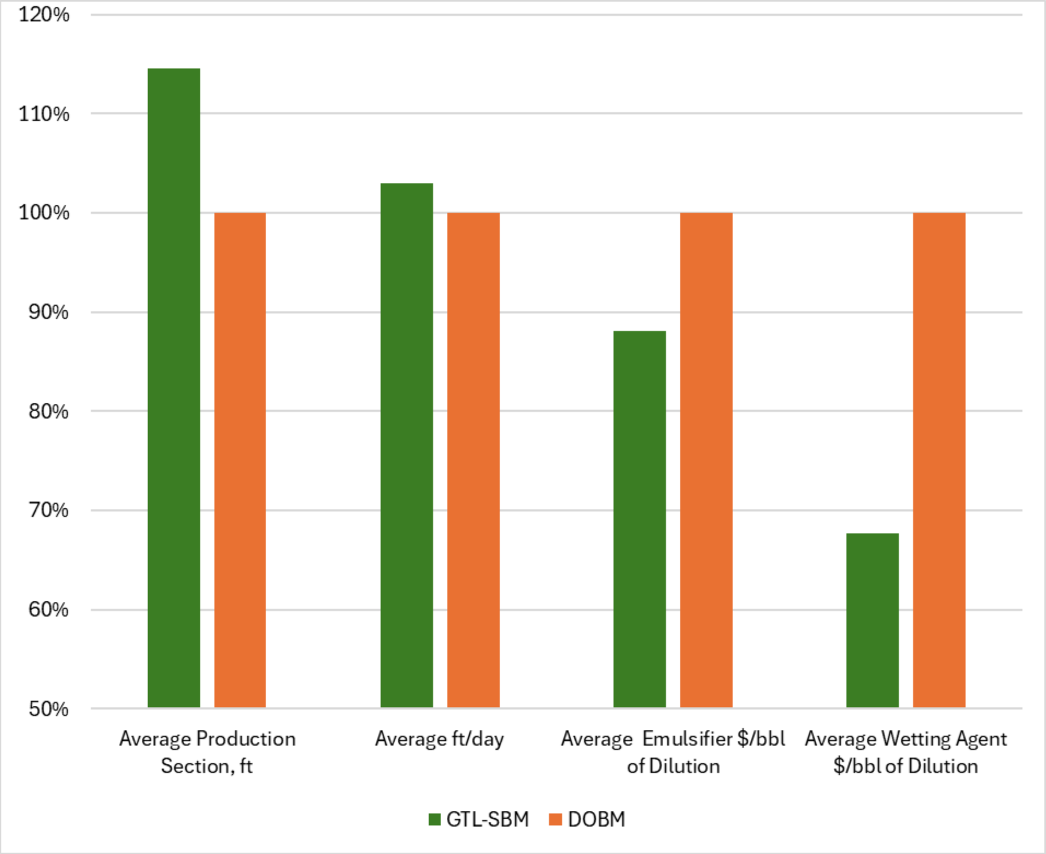

Figure 10 – Comparison of additive cost from a 44-well data set (DOBM is the baseline)