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# Improving Flat Rheology Properties of Organophilic Clay Based Non-Aqueous Drilling Fluids Systems

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## Abstract

The principle of "less is more" stems from the belief that simplicity and clarity lead to good designs. Since their introduction in the 1960s, non-aqueous fluids (NAFs) have traditionally included base oil, organophilic clay and lignite, lime, calcium chloride ($CaCl_2$) brine, emulsifier, and other additives. The organophilic clay component, critical for stability and preventing barite SAG, has limited the suitability of these fluids for drilling narrow margin wells due to their tendency to progressively gel over time, especially at lower temperatures. To overcome these limitations, a new NAF design has been developed, featuring a novel rheology modifier that enables the incorporation of additional organophilic clay, ultimately improving stability, viscosity, gel strength and barite SAG.

The fluid consists of just 7 components: base oil, emulsifier, organophilic clay, rheology modifier-component, CaCl2-brine (or alternative high-density divalent brine), fluid loss control agent and standard barite for density. Tests have demonstrated that this new fluid maintains low viscosity, non-progressive gels, and full mobility even after sitting static for up to 1 month at high temperatures and pressures, making it suitable for deepwater applications. Furthermore, the fluid's ability to retain full mobility during prolonged static periods, such as temporary well suspensions, ensures that it does not hinder flow through standalone screens (SAS) or slotted liners.

This paper presents a groundbreaking yet simple NAF formulation that is well-suited for drilling wells in deepwater as well as challenging narrow margin drilling scenarios.

## Introduction

Losses of drilling fluids during the well construction phase can occur during various operations, such as drilling, running casing or drilling assemblies to the bottom (tripping), and cementing. Typically, drilling losses are associated with the equivalent circulating density (ECD) surpassing the fracture gradient. In contrast, losses during tripping and cementing are influenced by a combination of ECD, the pressure required to disrupt the gel structure of the drilling fluid, and the equivalent static density at the time of the operation.

To mitigate drilling fluid losses, a novel rheological modifier has been employed to control the viscosity fluctuations of the drilling fluid system under downhole conditions. This method aims to reduce the uncertainties related to the behavior of drilling fluids and is commonly known as flat rheology or an apparent flat yield point (YP) drilling fluid system. [1, 2]

These flat rheology NAFs systems are developed using high-performance emulsifiers, a novel rheological modifier, and large quantities of organophilic clay. The findings in this study prove that a rheological profile achieved with organophilic clay additives can deliver excellent hole cleaning, lower ECD, elimination of barite SAG, reduced downhole fluid losses during cementing operations, casing runs, and drilling, and overall enhanced fluid-related drilling efficiency when compared to traditional and organophilic clay free drilling fluid systems. [3]

This paper outlines the techniques employed to attain a flat YP profile, details viscometer measurements conducted under downhole conditions of field drilling fluids and offers comparisons between the flat system and a traditional shear-thinning drilling fluid system.

### *Flat Rheology Definition*

Flat rheology, as identified in a review of a proprietary internal database and literature, pertains to specific rheological properties. These properties include the YP, 6-RPM Dial Reading, 3-RPM Dial Reading, 10-second Gel, 10-min Gel, and 30-min Gel, which exhibit relatively consistent values at temperatures of 40 °F (4.4 °C), 120 °F (50 °C), and 150 °F (66 °C), Table 1 provides detailed information on what constitutes a flat rheology fluid for the purposes of this study. The determination of flat rheology is carried out using a standard couette viscometer to measure the rheological properties before and after hot rolling at the specified temperatures.

### *The Evolution of Flat Rheology Drilling Fluids*

The evolution of flat rheology NAFs exemplifies the proverb that "necessity is the mother of invention." The pressing needs of the oilfield were highlighted by the emergence and swift advancement of deepwater drilling. Deepwater wells share common characteristics, including significant water depths, which are consistently above 1,000 feet, and low temperatures near the mud line, typically below 40° F (4.4° C). As water depth increases, the drilling window becomes abnormally narrow due to reduced overburden pressure. Additionally, the frigid water temperatures near the mudline exacerbate downhole fluid losses by cooling the drilling fluid, which significantly elevates fluid rheology and disturbs ECD. This issue is particularly pronounced during prolonged static periods of the fluid, such as during connections, tripping, running, and cementing casing. Consequently, interruptions in circulation often result in ECD surges, leading to the loss of entire mud volumes.

In the 1990s, the introduction of NAFs using synthetic based oils served as a pivotal technology for deepwater drilling in the Gulf of Mexico (GoM). Owing to their environmental and technical advantages, these fluids rapidly gained preference over other NAFs and water-based drilling fluids. The launch of second-generation NAFs further propelled the adoption of these advanced synthetic base oils in deepwater drilling, attributed to their lower viscosity, enhanced environmental profile, and reduced cost structure. [4, 5, 6]

By the late 1990s, certain limitations associated with the use of NAFs in deepwater drilling emerged, particularly concerning their viscosity and its effects on wellbore stability. These stability challenges frequently led to the loss of entire mud volumes during drilling, casing, and cementing operations [7]. The growing complexity and intricacy of deepwater wells amplify the risk of downhole fluid losses by promoting a higher propensity for dynamic barite SAG within the drilling fluid, which in turn requires more efficient hole cleaning practices. These demanding drilling environments can also raise ECDs and heighten the risk of exceeding the fracture threshold, leading to further downhole fluid losses.

A variety of ancillary fluid technologies have been developed to tackle this challenge, including wellbore strengthening technologies and micronized weight materials [8], to name a couple.

Notably, the flat rheology NAF technology represented a comprehensive drilling fluid system for deepwater drilling applications. This paper introduces a more straightforward fluid design that facilitates the incorporation of high concentrations of organophilic clays, effectively preventing gelation at lower temperatures while preserving a flat rheology profile.

## Considerations for Flat Rheology NAF Systems

The concepts of flat rheology and flat YP in relation to drilling fluids have emerged within the drilling industry in the last three decades. These ideas were developed in response to the need to mitigate drilling mud losses during the installation of casing and liners in deepwater wells. It was hypothesized that a drilling fluid exhibiting a "near" constant YP under both low and high temperatures, as well as under high pressure, would enhance the predictability of pressure responses during tripping operations, thereby reducing, or preventing downhole fluid losses.

This paper examines an idealized flat rheology drilling fluid system that can effectively minimize ECD in various drilling scenarios. However, the capacity to maintain a flat viscosity profile is subject to several uncontrollable factors, such as temperature, pressure, the interactions between rheological modifiers and drilled solids, variations in shear rate within the annulus, fluctuations in alkalinity, and changes in the concentration of rheological modifiers.

Table 2 provides a list of drilling fluid components utilized in the formulation of both conventional and flat rheology drilling fluid systems in this study and in the industry. Several components significantly affect the ability to achieve a flat viscosity profile, with the most impactful ones discussed in the following sections.

The initial step in creating a flat rheology drilling fluid system involves selecting the appropriate **base fluid**. A base fluid characterized by a low, consistent kinematic viscosity across varying temperatures will facilitate the attainment of key parameters, such as Bingham YP and viscometer readings at 6 and 3 RPM, at the lowest possible values, particularly at low temperatures and elevated pressures. [9]

Historically, **organophilic clays** have served as the primary viscosifiers in NAF systems. A range of organophilic clays is available, from relatively low-cost dry-processed bentonite to more expensive wet-processed hectorite clays. The effectiveness of these clay viscosifiers varies mainly in their ability to maintain viscosity at low shear rates and their stability under elevated temperature conditions. In a drilling fluid system that employs organophilic clay as the principal viscosifier, a reduction in viscosity is typically observed with increasing temperature when measured using a standard oilfield six-speed viscometer at atmospheric pressure. Therefore, to achieve a stable YP or low shear viscosity under atmospheric conditions as temperatures rise, it is crucial to supplement the use of organophilic clay with rheological modifiers. An increase in pressure will enhance the viscosity of a NAF system. [10]

Often, downhole pressure influences a system composed of organophilic clay and a compressible base fluid by raising the viscosity, thereby offsetting the viscosity reduction associated with higher temperatures. This effect is particularly noticeable at temperatures ranging from 40 °F (4.4 °C) to approximately 80 °F (26.7 °C). A conventional fluid formulated with organophilic clay typically exhibits relatively stable viscosity curves when assessed under downhole temperatures and pressures, apart from the cold riser.

It is feasible to develop a NAF that maintains a nearly constant YP and exhibits low RPM viscometer dial readings by utilizing organophilic clay and a **novel rheological modifier**, which demonstrate beneficial effects under different pressures and both low and elevated temperatures. The viscosity produced is influenced by the concentration of this rheological modifier.

### *The Matter of Clay*

The primary point of contention between service companies pertains to organophilic clays. One service company has consistently advocated for the removal of organophilic clay from formulations as a fundamental aspect of flat rheology NAFs. The purported advantages of this approach include diminished whole mud losses, reduced equivalent circulating densities (ECDs), and elevated, stable gel strengths that require minimal initiation pressure to break. [3]. All service companies reported these benefits within their respective systems.

The topic of barite SAG also sparked disagreement. Another service company conducted extensive research on both dynamic and static barite SAG and found that, in the absence of all organophilic clay, preventing barite SAG proved to be quite challenging. They noted that regardless of low shear viscosity and other rheological factors, reliance solely on polymeric or non-organophilic clays or oligomer modifiers did not resolve the issue of barite SAG. Furthermore, their findings indicated that the presence or absence of organophilic clays had minimal impact on the fundamental rheological characteristics of flat rheology NAF. The absence of organophilic clays seemingly affects gel behavior more significantly than overall rheology, and when viscosity is primarily dependent on organophilic clays at concentrations of 5-8 pound-per-barrel (lb/bbl), the cold temperature profile and temperature effects on rheology are negatively influenced. Consequently, the service company reduced their total organophilic clays loading to 1-3 lb/bbl within their system. [11]

Some developments in flat rheology NAFs have introduced new chemistries aimed at mitigating SAG and enhancing overall rheological stability. These innovations are based on glycol derivatives [12] and are incorporated into the latest generation of flat rheology NAF. Additionally, a novel chemistry has emerged that utilizes a polar hydrophobe to improve low shear performance without adversely affecting high shear viscosity [13]. While these products are distinctive, there is limited published information regarding their performance.

This work presents a simplified fluid formulation that enables the integration of elevated levels of organophilic clays, successfully averting gelation at lower temperatures while maintaining a flat rheological profile, thereby addressing issues raised in earlier published studies and prevailing assumptions.

## Methodology

This paper contains various test results which are detailed in the following sections.

- Fluid density was measured using pressurized mud scales at a temperature of 70 °F (21.1 °C).
- Initial rheology and gel strengths were measured at both 40 °F (4.4 °C), 70 °F (21.1 °C), and 150 °F (66 °C) to determine the expected base fluid properties before exposure to wellbore temperature.
- Post-aging rheology and gel strengths were measured at temperatures of 40 °F (4.4 °C), 70 °F (21.1 °C), and 150 °F (66 °C) to demonstrate the stability of the fluid after extended exposure to wellbore temperature.
- Post-aging static filtration on API 12 (old 5µm) filter medium involved recording the spurt loss, 30 minutes, 1-hour, and 16-hour filtration volume to determine the incremental rate of fluid loss on a simulated porous zone.
- The static aging test recorded supernatant and SAG measurements at 16-hours, 3-Days, and 7-Days to evaluate the behavior of the fluid under static conditions over time at wellbore temperature.
- Results from additions of seawater, API standard evaluation base clay, and Class G cement were analyzed to measure the stability of the fluid to basic contaminants, including rheology, gel strengths, and filtration results.

## Results

Conventional NAFs, as outlined in Table 3, generally exhibit a rheological profile that is significantly affected by temperature, as illustrated in Tables 4, 5, and 6. Figures 1 and 2 present key rheological parameters, such as YP and 10-minute gel strength, plotted against their respective measurement temperatures. These characteristics reveal a pronounced sensitivity to temperature, showing a notable decrease as the temperature increases.

The tests conducted indicate that the temperature sensitivity of conventional NAFs cannot be solely explained by the physical properties of the base fluid; it is also likely influenced by the type and amount of organophilic clay, the emulsifier system, and rheology modifiers.

In contrast, flat rheology NAFs, as outlined in Table 3, exhibit a rheological profile that is less influenced by temperature, as shown in Tables 4, 5, and 6. Figures 1 and 2 again illustrate essential rheological parameters, including YP and 10-minute gel strength, plotted against the corresponding measurement temperatures. These properties demonstrate a minor dependence on temperatures.

The flat rheology NAF was subjected to contamination testing, which utilized 36.45 lb/bbl API standard evaluation base clay, 10% vol./vol. seawater, and 5 lb/bbl Class G cement. While the introduction of contaminants did influence the rheological characteristics of the fluid, the effect was minimal due to the adequate amounts of emulsifier and rheological modifier present, which also enabled the system to endure cement contamination with negligible impact on the fluid's rheological properties. The influence of contamination was more pronounced in the samples contaminated with API standard evaluation base clay than in those contaminated with seawater; however, this effect can be mitigated through dilution and/or the addition of further emulsifier and rheology modifier. The robustness of the system can be verified by referring to Figure 3.

The post-dynamic properties were assessed, including a 16-hour high-pressure high-temperature (HP/HT) fluid loss, see Table 7.

### *Significance of Pressure-Temperature Measurements in Flat Rheology Drilling Fluid Design*

Accurately predicting the downhole viscosity of a drilling fluid that includes compressible components can be challenging without adequate input data. Several complicating factors contribute to this difficulty, including:

- The specific type and concentration of additives incorporated into the drilling fluid for particular applications;

- The diverse chemistries available to achieve desired functionalities such as viscosity, filtration control, and emulsion stability, and;
- The distinct compressibility characteristics of various synthetic and oil-based fluids present in the market.

Drilling fluid manufacturers offer a range of organophilic clays, emulsifiers, fluid loss additives, rheology modifiers, and other products to formulate and sustain NAFs. The impact of these additives on viscosity under downhole conditions may vary significantly. Consequently, it becomes impossible to accurately model how viscosity will react to changes in temperature and pressure. Therefore, it is essential to directly measure the fluid's response to temperature variations under downhole conditions using a pressurized viscometer.

HP/HT rheology testing was performed on the base fluid using the FANN® iX-77™ Rheometer. This testing involved applying constant pressure while conducting temperature assessments at various stages. The pressure was held steady while the temperature was gradually increased from 40 °F (4.4 °C) to 280 °F (137.8 °C), beginning with an initial pressure of 15 psi. A consistent reduction in viscosity was noted as the temperature rose. It is important to highlight that the 6-RPM and 3-RPM Dial Readings remained largely unchanged despite fluctuations in pressure and temperature, see Table 8 and Figure 4.

This information can subsequently serve as critical input data for enhancing the accuracy of hydraulics and hole cleaning models. Figure 5 illustrates the ECD, and hole cleaning characteristics of the fluid analyzed in this study, further supporting the finding that the fluid exhibits outstanding hole cleaning efficiency and a low ECD/ESD (equivalent static density) both in the presence and absence of cuttings.

### *The Importance of Minimizing Viscosity and Weighting Material SAG*

Barite SAG, which refers to the separation of solid weighting materials, occurs when the solid constituents of the drilling fluid settle, resulting in variable densities that may lead to complications in drilling and wellbore integrity. The situation is further intensified when efforts are made to reduce the viscosity profile of the fluid to attain lower ECD profiles.

Flat rheology NAF was mixed and then placed in a static oven at bottomhole temperatures for durations of 16 hours, 3 days, and 7 days, see Table 9. To conduct the SAG test, 30 milliliters (mL) of fluid were extracted from the bottom of the cell using a 60-mL syringe. This fluid was then transferred into a beaker and subjected to a vacuum for at least 30 minutes to eliminate any excess gas. The density of the sample was subsequently compared to the initial mud weight to assess the increase in density. All fluids exhibited satisfactory performance, effectively suspending the barite with minimal SAG during the designated time intervals. This approach, which deviates from the standard three-layer SAG method and employs a more rigorous testing protocol, validates the enhanced SAG tendency of the system.

HP/HT SAG was conducted prior to dynamic aging at a pressure of 15,000 psi for a duration of 7 days and 1 month at the bottomhole temperature using standard three layer method. The fluid aged for 7 days displayed a barite SAG index of 0.5012 and the fluid aged for 30 days displayed a barite SAG index of 0.5177, see Table 10.

All fluids evaluated in this report comply with the SAG specifications, ensuring adherence to the required operational standards.

## Conclusions

For more than two decades, flat rheology NAFs have significantly influenced the use of NAFs in drilling operations. Originally designed for the deepwater sector, these fluids have proven to be highly effective in various other drilling contexts. Ongoing research and development efforts are concentrated on understanding downhole behavior and properties that can most effectively reduce non-productive time (NPT) and enhance operational efficiency. It is evident that the initial emphasis on reducing cold-temperature viscosity has been shifted towards exploring downhole behavior, where these systems demonstrate their advantages.

The introduction of our new rheology modifier has enabled a more streamlined fluid design, which allows for the effective integration of high concentrations of organophilic clays. This advancement successfully prevents gelation at lower temperatures while maintaining a consistent rheology profile. Consequently, we have challenged the long-held belief, spanning over two decades, that only formulations devoid of organophilic clays can achieve such characteristics.

The newly formulated flat rheology NAF exhibits a unique rheological profile that remains largely stable despite fluctuations in temperature and pressure in spite of the high concentrations of organophilic clays. This feature is particularly beneficial for deepwater drilling operations, where the coexistence of low temperatures and high pressures can adversely affect fluid performance. The rheological characteristics that are independent of temperature and pressure ensure consistent low-end rheological properties, YP, and gel strength across a wide temperature range of 40°F (4.4 °C) to 280 °F (137.8 °C), irrespective of pressure conditions.

Implementing and sustaining this flat rheology in field drilling operations is uncomplicated. The temperature-independent nature allows for an enhancement of overall rheology, which aids in improved hole cleaning without jeopardizing ECD management.

The relatively low yet stable and delicate gel structure provides excellent suspension capabilities for both cuttings and barite, significantly improving control over barite SAG. These advancements play a crucial role in reducing pack-off, barite SAG, and lost circulation challenges, which can negatively impact fluid performance and drilling efficiency.

The flat-rheology NAF is particularly advantageous for drilling extended-reach wells in deepwater and narrow margin environments, where effective control of rheology, hole cleaning, ECD management, and barite SAG prevention are vital for successful operations.

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## Nomenclature

*AHR = After Hot Rolling*
*ASA= After Static Aging*
*ECD = Equivalent Circulating Density*
*ESD = Equivalent Static Density*

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**Table 1:** Flat Rheology Profile Guidelines

| Properties | Description |
|---|---|
| Yield Point | The ratio between the yield point at different temperatures should not exceed 1.5. |
| 6-RPM Dial Reading | The difference between the maximum measured value and the minimum measured value should be < 5. |
| 3-RPM Dial Reading | The difference between the maximum measured value and the minimum measured value should be < 5. |
| 10-min Gel Strength | The difference between the maximum measured value and the minimum measured value should be < 5. |
| 30-min Gel Strength | The 30-minute gel strength should not exceed 2-times the 6-RPM Dial Reading. |

**Table 2**: Typical Components of NAF

| Component | Conventional NAF Systems | Flat Rheology NAF System |
|---|---|---|
| Base Fluid | ✓ | ✓ |
| Primary Emulsifier | ✓ | ✓ |
| Organophilic Clay | High | High |
| $CaCl_2$ Brine | ✓ | ✓ |
| Lime | ✓ | ✓ |
| Fluid Loss Control | ✓ | ✓ |
| Bridging Material | ✓ | ✓ |
| Novel Rheological Modifier | X | ✓ |
| Conventional Rheological Modifier | ✓ | X |
| Weight Material (Barite, $CaCO_3$, etc) | ✓ | ✓ |

**Table 3:** 15.5 lb/gal NAF – Base Fluid Formulation

| Products | Units | Conventional NAF System Formulation 1 | Flat Rheology NAF System Formulation 2 |
|---|---|---|---|
| Synthetic Based Oil | lb/bbl | 147.24 | 142.44 |
| Primary Emulsifier | lb/bbl | 14 | 14 |
| Organophillic Clay | lb/bbl | 8.5 | 8.5 |
| Lime Hydrate | lb/bbl | 2 | 2 |
| Polymeric Fluid Loss Control | lb/bbl | 4 | 4 |
| Water | lb/bbl | 31.51 | 31.51 |
| 96% calcium chloride | lb/bbl | 11.09 | 11.09 |
| Ultra Fine Barite | lb/bbl | 431.24 | 430.48 |
| Rheology Modifier | lb/bbl | - | 7 |

**Table 4:** 15.5 lb/gal NAF – Initial Viscosity

<table>
<tr><th>Properties</th><th>Units</th><th>Formulation 1</th><th>Formulation 2</th></tr>
<tr><td>Mud Weight</td><td>lb/gal</td><td colspan="2">15.50</td></tr>
<tr><td>Oil-to-Water Ratio</td><td>--</td><td colspan="2">85:15</td></tr>
<tr><td>Water Phase Salinity</td><td>% wt.</td><td colspan="2">25.0</td></tr>
<tr><td>Electrical Stability @ 120°F</td><td>volts</td><td>1437</td><td>1424</td></tr>
</table>

| Rheology Temperature | °F | 40 | 70 | 150 | 40 | 70 | 150 |
|---|---|---|---|---|---|---|---|
| 600 RPM | D.R. | 355 | 248 | 127 | 242 | 176 | 92 |
| 300 RPM | D.R. | 227 | 162 | 85 | 137 | 102 | 57 |
| 200 RPM | D.R. | 180 | 130 | 67 | 99 | 75 | 44 |
| 100 RPM | D.R. | 124 | 94 | 48 | 58 | 45 | 30 |
| 6 RPM | D.R. | 55 | 44 | 21 | 11 | 11 | 11 |
| 3 RPM | D.R. | 50 | 40 | 19 | 9 | 9 | 9 |
| Plastic Viscosity | cP | 128 | 86 | 42 | 105 | 74 | 35 |
| Yield Point | lb/100 $ft^2$ | 99 | 76 | 43 | 32 | 28 | 22 |
| 10 Second Gel | lb/100 $ft^2$ | 44 | 39 | 18 | 10 | 9 | 10 |
| 10 Minute Gel | lb/100 $ft^2$ | 45 | 40 | 19 | 12 | 11 | 11 |
| 30 Minute Gel | lb/100 $ft^2$ | | - | - | 12 | 11 | 11 |

**Table 5:** 15.5 lb/gal NAF – Post Hot Roll Viscosity

| Properties | Units | Formulation 1 | | | Formulation 2 | | |
|---|---|---|---|---|---|---|---|
| Electrical Stability @ 120°F | volts | 1602 | | | 1069 | | |
| **Rheology Temperature** | **°F** | **40** | **70** | **150** | **40** | **70** | **150** |
| 600 RPM | D.R. | 417 | 290 | 123 | 240 | 177 | 86 |
| 300 RPM | D.R. | 267 | 190 | 81 | 134 | 103 | 53 |
| 200 RPM | D.R. | 210 | 152 | 65 | 98 | 75 | 41 |
| 100 RPM | D.R. | 146 | 107 | 46 | 58 | 46 | 27 |
| 6 RPM | D.R. | 62 | 46 | 19 | 12 | 11 | 10 |
| 3 RPM | D.R. | 58 | 42 | 17 | 10 | 9 | 9 |
| Plastic Viscosity | cP | 150 | 100 | 42 | 106 | 74 | 33 |
| Yield Point | lb/100 $ft^2$ | 117 | 90 | 39 | 28 | 29 | 20 |
| 10 Second Gel | lb/100 $ft^2$ | 54 | 40 | 17 | 10 | 10 | 9 |
| 10 Minute Gel | lb/100 $ft^2$ | 60 | 43 | 18 | 11 | 10 | 10 |
| 30 Minute Gel | lb/100 $ft^2$ | - | - | - | 11 | 11 | 11 |

**Table 6:** 15.5 lb/gal NAF – Post Static Aging Viscosity after 7 Days

| Properties | Units | Formulation 1 | | | Formulation 2 | | |
|---|---|---|---|---|---|---|---|
| Electrical Stability @ 120°F | volts | 1697 | | | 1069 | | |
| **Rheology Temperature** | **°F** | **40** | **70** | **150** | **40** | **70** | **150** |
| 600 RPM | D.R. | 456 | 302 | 124 | 255 | 180 | 86 |
| 300 RPM | D.R. | 308 | 202 | 85 | 147 | 106 | 53 |
| 200 RPM | D.R. | 253 | 164 | 69 | 109 | 78 | 41 |
| 100 RPM | D.R. | 185 | 121 | 51 | 66 | 48 | 28 |
| 6 RPM | D.R. | 95 | 59 | 24 | 14 | 12 | 10 |
| 3 RPM | D.R. | 87 | 57 | 22 | 11 | 10 | 9 |
| Plastic Viscosity | cP | 148 | 100 | 39 | 109 | 74 | 33 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Yield Point | lb/100 $ft^2$ | 160 | 102 | 46 | 39 | 32 | 20 |
| 10 Second Gel | lb/100 $ft^2$ | 85 | 54 | 21 | 11 | 10 | 9 |
| 10 Minute Gel | lb/100 $ft^2$ | 91 | 55 | 22 | 13 | 11 | 10 |
| 30 Minute Gel | lb/100 $ft^2$ | - | - | - | 13 | 12 | 10 |

**Table 7:** 15.5 lb/gal Flat Rheology NAF – Filtration Tests Results

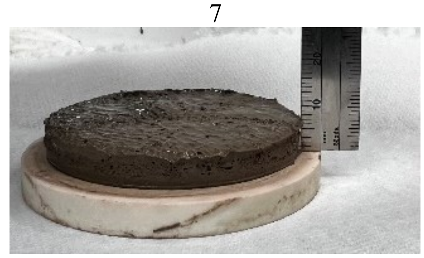
| **Properties** | **Units** | **AHR @ 260 °F** |
|---|---|---|
| HP/HT @ 260°F, 5µm disk, Spurt (Actual) | mL | trace |
| HP/HT @ 260°F, 5µm disk, (Actual) | mL/30 min | 1.6 |
| HP/HT @ 260°F, 5µm disk, (Actual) | mL/60 min | 2.5 |
| HP/HT @ 260°F, 5µm disk, (Actual) | mL/16-hr | 12.4 |
| Water in Filtrate, 5µm disk | mL/30 min | none |
| Filtercake Thickness | 1/32 inch<br>16-hr | 7<br> |

**Table 8:** 15.5 lb/gal Flat Rheology NAF - Post Hot Roll HP/HT Viscosity Data

| **Temperature, °F** | **Pressure, psi** | **RPM, Dial Reading** | | | | | | **Plastic Viscosity, cP** | **Yield Point, lb/100ft²** |
|---|---|---|---|---|---|---|---|---|---|
| | | **600** | **300** | **200** | **100** | **6** | **3** | | |
| 40 | 15 | 252 | 142 | 102 | 61 | 12 | 9 | 110 | 32 |
| | 2,500 | 273 | 153 | 109 | 63 | 12 | 8 | 120 | 33 |
| | 5,500 | 346 | 192 | 136 | 78 | 13 | 10 | 97 | 38 |
| 120 | 15 | 124 | 77 | 59 | 39 | 12 | 10 | 47 | 30 |
| | 10,000 | 203 | 119 | 87 | 54 | 12 | 9 | 84 | 35 |
| 150 | 15 | 86 | 53 | 41 | 27 | 10 | 9 | 33 | 20 |
| | 10,000 | 156 | 92 | 68 | 43 | 10 | 8 | 64 | 28 |
| | 15,000 | 201 | 117 | 85 | 52 | 11 | 8 | 84 | 33 |
| 200 | 20,000 | 183 | 107 | 79 | 48 | 10 | 8 | 76 | 31 |
| 280 | 20,000 | 121 | 74 | 55 | 35 | 8 | 6 | 47 | 27 |
| | 25,000 | 148 | 88 | 66 | 41 | 9 | 7 | 60 | 28 |

**Table 9:** 15.5 lb/gal Flat Rheology NAF - Static SAG results Using Bottom 30-mL

| Properties Static Aging @ 260 °F | Units | 16-Hour | 3-Day | 7-Day |
|---|---|---|---|---|
| Supernatant | mL | 0 | trace | trace |
| Starting Density | lb/gal | 15.46 | 15.46 | 15.46 |
| Bottom Density | lb/gal | 15.68 | 15.84 | 16.75 |
| SAG (Bottom Density – Starting Density) | lb/gal | 0.22 | 0.38 | 1.25 |

**Table 10:** 15.5 lb/gal Flat Rheology NAF - HP/HT Static SAG results using 3-layer method

| Properties Static Aging @ 260 °F and 15,000psi | Units | 7-Day | 30-Day |
|---|---|---|---|
| Supernatant | mL | 0 | 0 |
| Starting Density | lb/gal | 15.50 | 15.50 |
| Top Density | lb/gal | 15.52 | 15.22 |
| Bottom Density | lb/gal | 15.60 | 16.34 |
| SAG Index<br>Bottom Density / (Top Density + Bottom Density) | -- | 0.5012 | 0.5177 |

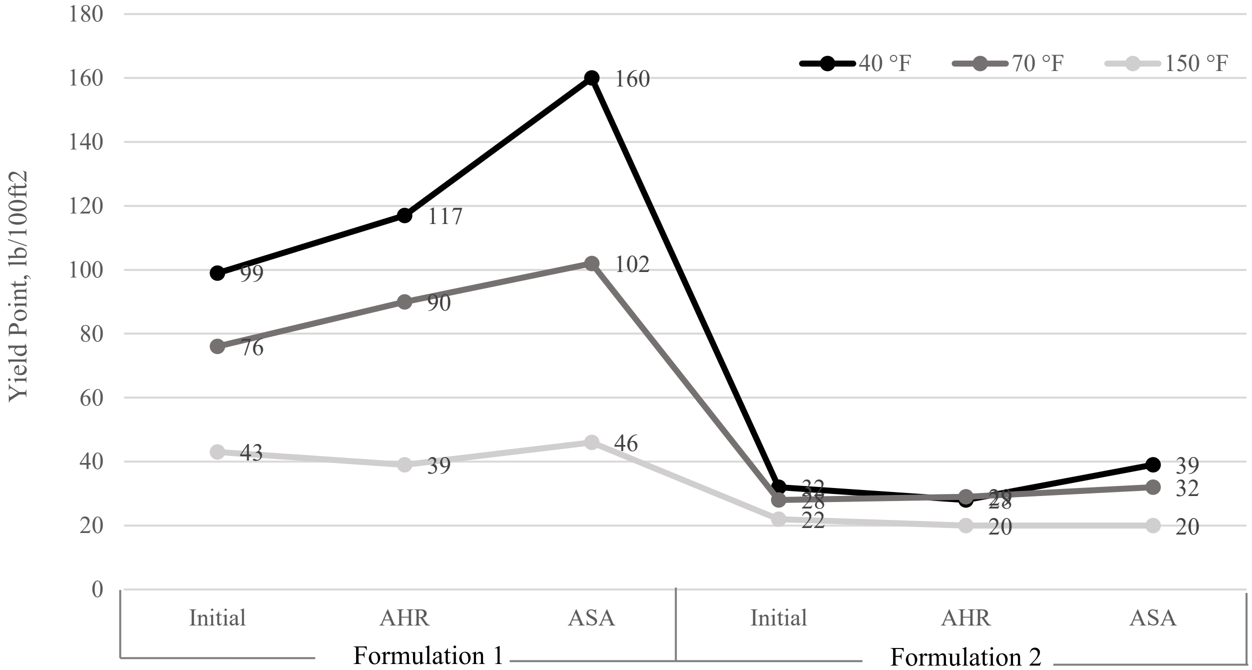



**Figure 1:** Rheology modifier impact on the YP of a 15.5 lb/gal NAF at various temperatures.

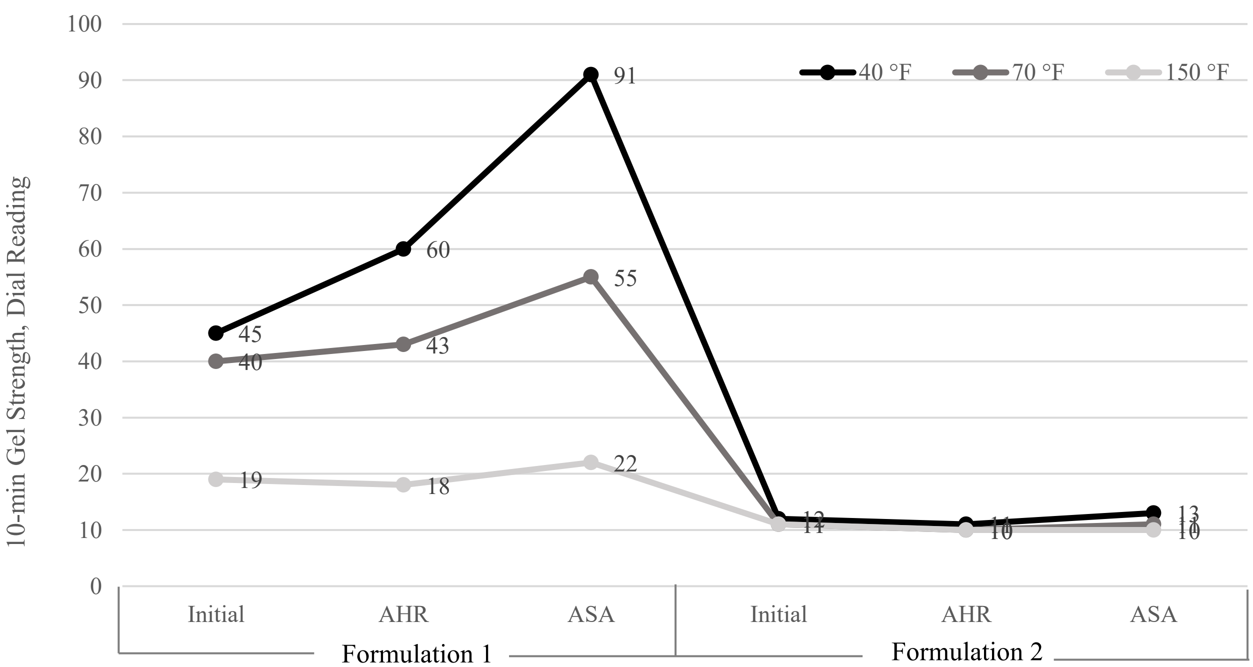



**Figure 2:** Rheology modifier impact on the 10-min Gel Strength of a 15.5 lb/gal NAF at various temperatures.

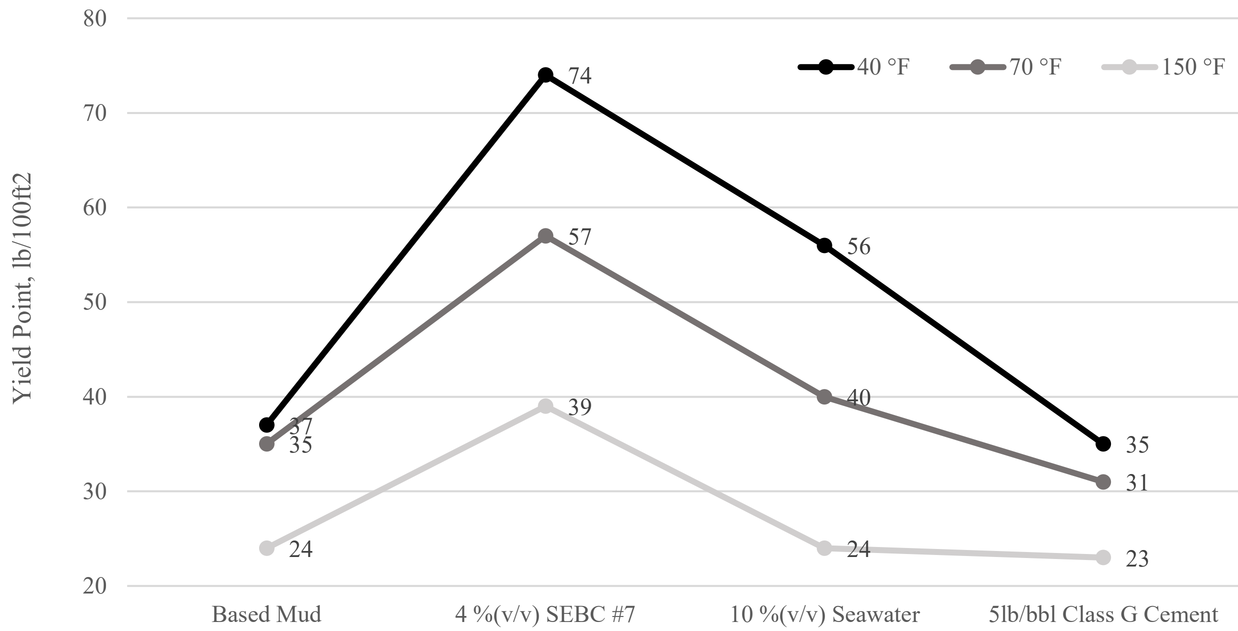



**Figure 3:** 15.5lb/gal Flat Rheology NAF contamination impact on yield point

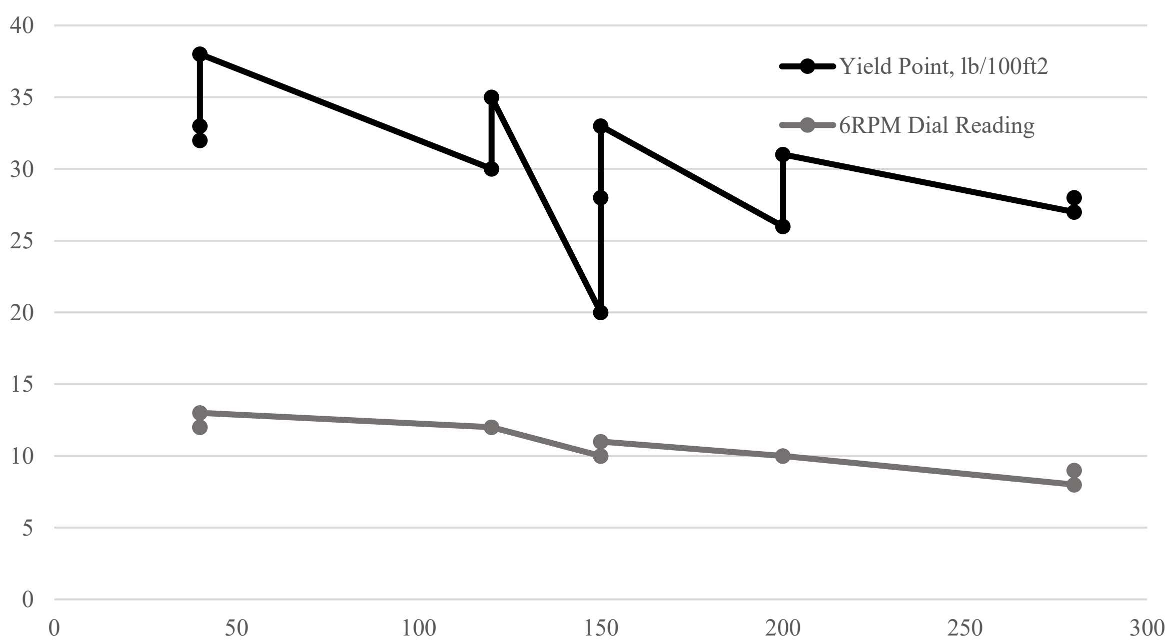



**Figure 4:** 15.5 lb/gal Flat Rheology NAF Post Hot Roll HP/HT Viscosity Data

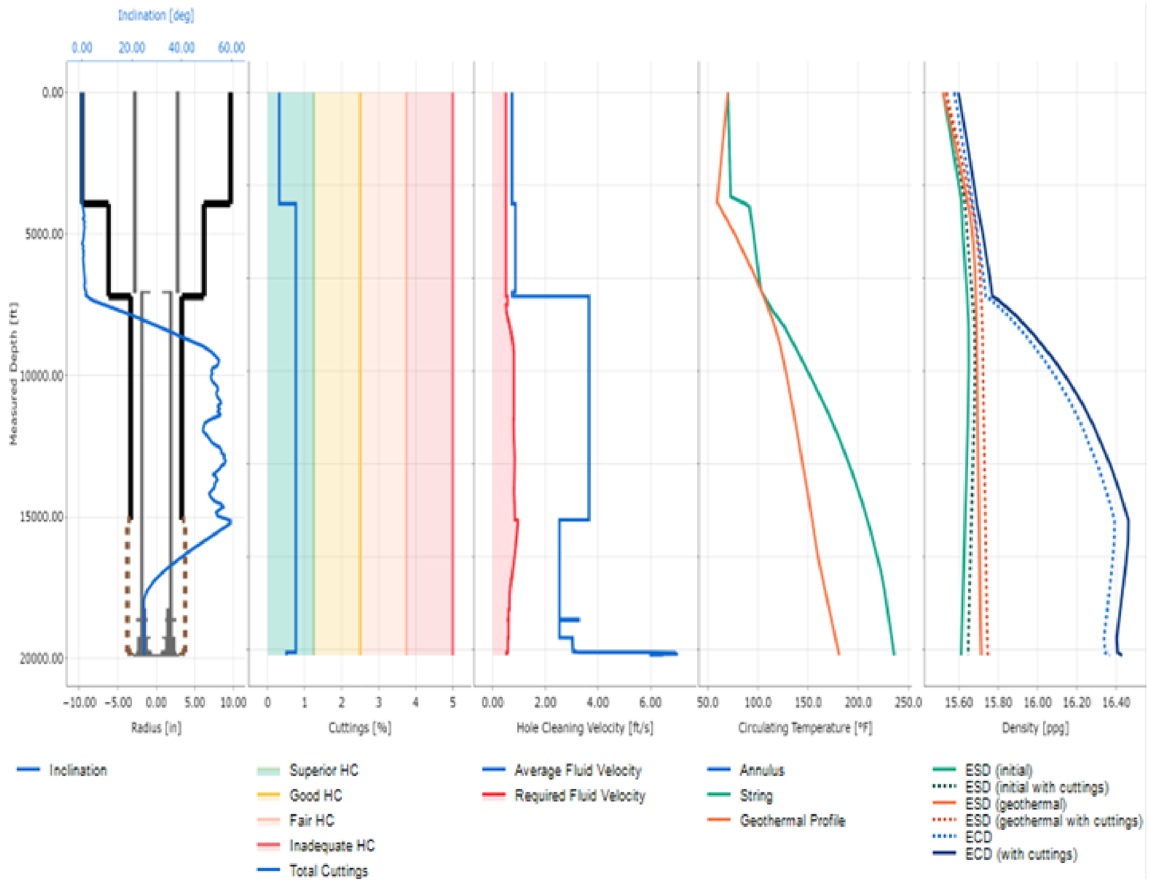



**Figure 5:** 15.5 lb/gal Flat Rheology NAF Hydraulics Simulation