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An Effective Way to Prevent Sag in Low Gravity Solids Free Invert Emulsion Fluids

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Abstract

Invert emulsion fluid (IEF) systems that are not built with organophilic clay have been successful in the fluids industry at addressing issues of barite sag and reservoir productivity. While 'clay-free' IEFs provide robust properties in the context of ongoing operations, they require additional materials in the form of low gravity solids (LGS) like sized calcium carbonate or clay type materials to bolster the rheological properties and suspension character of the system. This results in increase of plastic viscosity of the fluid and thereby resulting in a lower rate of penetration (ROP) and an increase in equivalent circulating density (ECD). In the absence of LGS, the loss of suspension can cause sag and a higher density gradient along the fluid column leading to fracturing of the formation.

This paper presents a solution for barite sag in an LGS free IEF (free of fine sized calcium carbonate or clay type material) formulated with a novel suspension agent (SA). The additive has been shown to prevent barite sag in 9ppg, 12ppg and 16ppg clay free IEFs of different base oils. The fluids when static aged at 250°F and 300°F for 24 hrs and 48 hours resulted in less than 5 ml top oil separation. Even extended periods of aging for 72 hrs at 150°F showed less than 5 ml oil separation without barite sag. High temperature high pressure rheology testing demonstrates a flat rheology for 9ppg and 12ppg IEFs containing this additive. Contamination testing on IEFs formulated with this additive showed tolerance to contaminants in terms of rheology and HPHT filtrate loss. Static aging these contaminated IEFs confirms improved sag behavior for these SA based IEFs. The SA is expected to be North Sea compliant with a biodegradability of greater than 71.4% in 42 days and LC_{50} on aquatic organisms > 10 g/L. Experimental data demonstrating the environmental impact, sag control and rheological performance is presented and corroborated with IEFs formulated without the SA.

Introduction

The benefits of using high performance organoclay free invert emulsion fluids (IEFs) are well-known. High rate of penetration (ROP), reduction in downhole losses during drilling, and increased tolerance to contamination are some of the many benefits associated with organoclay free IEFs.[1,2] However, in the absence of organoclay, it is difficult to obtain optimal rheology for low to medium density IEFs formulated with mineral oils. For successful drilling, the IEF is expected to have optimal rheology and be sag resistant. The commonly occurring problems due to barite sag are mud weight gradient, stuck pipe, wellbore instability, lost circulation, differential sticking and well control difficulties. Barite sag in IEF can be resolved by imparting the IEF a viscoelastic gel behaviour[3,4] or by increasing its low-shear rheology.[5,6] The low shear rheology is characterized by the low shear yield point (LSYP) with expected value in the range 7-15 lb/100ft^2 [7,8] for a sag resistant IEF. In the organoclay free IEF, low-gravity solids (clay-type materials and micronized calcium carbonate) are added which interact with the polymeric rheology modifiers to improve the rheology of this IEF. The addition of LGS though improves the yield point (YP) and increases the plastic viscosity (PV). A high PV may lead to high ECD; in addition, a high volume percentage of LGS results in low ROP.[9,10]

Research on drilling fluids has concentrated on developing additives and systems that minimize sag in the IEF by controlling the rheology of the IEF.[7,8] However this approach delivers high viscosity fluids, thus high ECD. Another approach to minimize sag uses weighting agents with fine particle size, because small particles tend to settle slowly in the fluid. But this increases the particle-particle interactions, leading to high PV.[7] It is desirable develop an additive that provides resistance to sag in the IEF without significantly increasing its viscosity.

The development of a novel suspension agent (SA) is described which provides a sag-resistant organoclay-free and LGS-free IEF. The SA provided sag control in IEFs with very low rheology (e.g., 12ppg IEF with PV of 16 cP and LSYP of 2 lb/100ft^2). The SA provided a sag resistant IEF in the most common base oils used to drill wells. The SA had a good environmental profile with a biodegradation of 71.4% in 42 days and LC_{50} > 10g / L for the subject organisms.

Methods and Materials

The invert emulsion fluids were formulated with commercially available invert emulsifiers, lime, rheology modifiers, high-pressure high-temperature (HPHT) filtration control agent, and with commonly used base oils. The base oils used for the study were BASE OIL I which is a naphthenic oil containing a high content of cyclic alkanes, BASE OIL II contains major portion of aliphatic hydrocarbons with minor portion of aromatic hydrocarbons and BASE OIL III which is a mixed paraffin base oil composed of normal alkanes. The composition of these base oils is given in **Table 1.** The concentration of products required to formulate the

IEFs were estimated with a proprietary numerical simulator

The experimental procedure for this study is shown below.

1. The fluids were mixed in stainless steel mixing cups on a five spindle multimixer model 9B available from Fann instruments at 11500 rpm using sine-wave impeller blade No. 9B29X.
2. The fluids were then aged in HPHT stainless steel (SS) cells in a hot rolling oven at 250°F for 16 hours (Fann Model 705ES roller oven).
3. After the hot roll the IEFs in the cells were inspected for oil separation and barite settling. Only the IEFs without oil separation or barite settling were considered for further study.
4. The IEFs were then mixed on the multimixer for 5 min and placed in HPHT SS cells. The cells were placed in an upright position and static aged in a mechanical convection oven by applying 100 psi pressure for desired temperature and duration (Thermoelectron Model MO1490SC-1).
5. After static aging, the cells were inspected for top oil separation which was determined in units of volume by drawing the separated base oil with a syringe.
6. The sag performance of the fluid was assessed by determining the sag factor. The specific gravity of the top (SG_{top}) and bottom (SG_{bottom}) portion of the IEF in the aging cell were determined by drawing 10 ml aliquots and measuring their weights on an analytical balance.
7. After the sag factor determinations, the IEFs were mixed on the multimixer for 5 min. The rheology of the IEFs was then determined at 120°F on a 12-speed standard oilfield viscometer. The temperature of the fluid was controlled in an electrically heated thermo cup.
8. Then the fluid loss was determined on a 175 ml capacity HPHT filter press cell.

The rheological and HPHT fluid loss testing was performed as per API 13B-2 recommendations. High temperature high pressure rheology was determined on a commercially available HPHT rheometer.

The sag factor, for the static aged IEFs was calculated with the formula:

$$SagFactor = \frac{SG_{bottom}}{SG_{bottom} + SG_{top}}$$

A sag factor greater than 0.53, implies that the fluid has potential to sag.[11]

The rheology of the fluid was characterized in terms of PV, YP, and LSYP. The YP and PV are parameters from the Bingham Plastic rheology (BP) model. The YP is determined by extrapolating the BP model to a shear rate of zero; it represents the stress required to move the fluid. The YP is expressed in the units of lb/100ft^2. The YP indicates the cuttings carrying capacity of the IEF through the annulus or in simple terms the IEFs hole cleaning ability. A YP of 10-25 is considered good for drilling. The PV represents the viscosity of a fluid when extrapolated to infinite shear rate, expressed in units of centipoise (cP). The PV indicates the type and concentration of the solids in the IEF, and a low PV is preferred. Both PV and YP are calculated using 300 revolutions per minute (rpm) and 600-rpm shear rate readings on a standard oilfield viscometer as given in Equations 1 and 2 below.

The yield stress or Tau0 is a parameter from the Herschel Buckley (HB) rheology model which is the equivalent of the YP in the BP model. The Tau0 is determined by fitting the HB model to the shear stress vs shear rate curve, which is the dial readings plotted against the corresponding rpm determined on the standard oil field viscometer. The Tau0 is expressed in the similar units as the YP. The Tau0 indicates the susceptibility of the IEF to barite sag: a high Tau0 is expected to deliver a sag resistant IEF. The Tau0 can be estimated reasonably by calculating the LSYP value from Equation 3.

$$PV = (600\text{ rpm reading}) - (300\text{ rpm reading})$$
(Equation 1)

$$YP = (300\text{ rpm reading}) - PV$$
(Equation 2)

$$LSYP = [2\times(3\text{ rpm reading})] - (6\text{ rpm reading})$$
(Equation 3)

The gels formed in the IEF were characterized by the 10 sec / 10 min gel strength which represents the highest dial reading at 3 rpm on the viscometer, after keeping the IEF static for an interval of 10sec / 10 min. The gel strengths indicate suspension ability of the IEF for cut drill solids and barite particles when drilling stops.

Results and Discussions

The performance of the SA was tested at three densities: 9ppg, 12ppg and 16ppg. The IEFs were formulated in the absence of LGS, with BASE OIL I and at 250K WPS, unless specified. The 9ppg, 12ppg and 16ppg IEFs were formulated at OWRs 60/40, 70/30 and 80/20 respectively. The mixing order, concentration and mixing time of the products for the different density fluids are given in **Table 2**. In this study a concentration of 3ppb SA was used in the IEFs. The IEFs formulated in the absence of the SA are the "base" formulations.

I. Performance of SA in 9ppg Organoclay-free and LGS- free IEF

The performance of SA was first tested in a low density 9ppg IEF. Both the base and SA based 9ppg IEF were static aged at 250°F for 24 hours. Static aging the base 9ppg IEF (**Table 3**) gave a sag factor of 0.6 with a top oil separation of 80ml. Static aging the SA based 9ppg IEF (Fluid 1, Table 3) gave sag factor of 0.5 without top oil separation. The results were intriguing since the concentration of barite in the 9ppg IEF is around 40-45 ppb, which implies the barite available to sag is less.

The rheology and gel strengths for the 9ppg IEF were determined which are given in Table 3**.** The base IEF had a low rheology with YP and LSYP of 5 and 0 respectively. The gel strengths at 10 sec and 10 min were 1 and 2 respectively. The base with such low rheology was expected to sag in the static aging studies. This may imply that the low rheology resulted in emulsion destabilization leading to a high volume of top oil separation and to barite sag.

The SA based 9ppg IEF demonstrated higher rheology than the base. The YP and LSYP were 10 and 3 respectively. The 10 sec and 10 min gel strengths were 5 and 10 respectively. The higher rheology imparted greater emulsion stability and prevented barite from Sagging. However review of the literature suggested an LSYP from 7 to 15 was required to prevent barite from sagging.[7] Despite the low LSYP of 3 to 4 the 9ppg IEF did not sag even after 24 hours of static aging.

The 24 hour static aged IEF was then static aged for extended 72 hours at 150^{o}F. In addition a fresh SA based 9ppg IEF was formulated and static aged for 48 hours at 250^{o}F. Both the 72 hour and 48 hour static aged fluids showed similar rheology to the 24 hour static aged fluid. The 48 hours static aged fluid gave sag factor of 0.5 without oil separation. The extended 72 hours static aged fluid gave a sag factor of 0.51 and 4 ml oil separation, which is an agreeable performance as specified in the Methods and Materials section. The results demonstrate the performance of SA in preventing barite sag and emulsion destabilization in low density LGS-free IEF when subjected to extended durations of static aging.

II. Performance of SA in 12ppg Organoclay-free and LGS-free IEF

The performance of the SA was then tested in medium density 12ppg IEF. The 3ppb SA based 12ppg IEF and its base were static aged for 24 hours at 250^{o}F. On static aging the base IEF gave a sag factor of 0.68 with top oil separation of 100 ml (**Table 4**). On static aging, the SA based 12ppg IEF gave a sag factor of 0.505 without top oil separation (Fluid 3, Table 4). It should be noted that the base formulation has two commercially available organic rheology modifiers which total to 6ppb concentration. It was believed that at high volume % of solids the organic rheology modifiers synergistically interact with the solids to deliver a stable sag free IEF without top oil separation; however it was not so.

The rheology and the gel strengths of the 12ppg IEF were then determined as given in Table 4. The base IEF had a low YP and LSYP of 6 and 1 respectively. The gel strengths at 10 sec and 10 min were 3 and 4 respectively, which was also low. The rheology of the 12ppg base IEF was similar to the rheology of the 9ppg base IEF. Thus the base was expected to destabilize its emulsion and sag.

The rheology of SA based 12ppg IEF was higher with the YP and LSYP being 14 and 5 respectively. The gel strengths at 10 sec and 10 min were 5 and 16 respectively. The higher rheology of the SA based IEF resulted in greater emulsion stability and prevented barite from sagging. However the LSYP was still lower than 7; in the 9ppg IEF it could be reasoned that the IEF had a low concentration of barite but 12ppg IEF had a barite concentration of 220 ppb and still did not sag.

Fresh SA based 12ppg IEFs were then static aged at 250^{o}F and 150^{o}F for 48 (Fluid 4, Table 4) and 72 (Fluid 5, Table 4) hours respectively. The 48 hour and 72 hour static aged IEF gave sag factor of 0.5 with negligible oil separation of 1 and 4 ml respectively. The rheology of these static aged IEFs were similar to the 24 hour static aged IEF though the gel strength at 10 min was 10 which was less than gel strength for the 24 hour static aged IEF which was 16 (Fluid 3, Table 4).

The 48 hour static aged IEF (Fluid 4, Table 4) was then subjected to extended static aging for 24 hours at 300^{o}F. The extended static aging at high temperature gave a sag factor of 0.505 and top oil separation of 1ml. The rheology of this IEF decreased slightly with the YP and LSYP of 12 and 3 respectively. The gel strength at 10 min though decreased to 7. This decrease in rheology however did not result in top oil separation or barite sag. The extended aged 12ppg IEF had rheology very similar to the 48 hour static aged 9ppg IEF (Fluid 2, Table 3). This aged 12ppg IEF still did not sag, considering the high amount of barite in 12ppg IEF.

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III. Performance of SA in Organoclay-free and LGS-free 16ppg IEF

The performance of SA was then tested in a high density 16ppg IEF which had a lower volume percentage of the internal brine phase. Both the base and SA based 16ppg IEF were static aged at 250^{o}F for 24 hours. On static aging the base 16ppg IEF (**Table 5**) gave a sag factor of 0.76 with a top oil separation of 110 ml. The SA based 16ppg IEF (Fluid 6, Table 5) gave sag factor of 0.5 with top oil separation of 1ml. The high volume % of solids and the presence of 6ppb rheology modifiers did not prevent the barite from sagging in the 16ppg base IEF. The literature indicates that at high mud weights a hindered effect comes into play that provides resistance to the falling barite particle thereby preventing sag.[3,7] But none of the above factors helped the barite from sagging.

The rheology and gel strengths for the 16ppg IEF were determined which are given in Table 5. The base IEF had a low rheology with YP and LSYP of 9 and 2 respectively. The gel strengths at 10 sec and 10 min were 3 and 3 respectively. The base with such low rheology was expected to sag in the static aging studies.

The SA based 16ppg IEF demonstrated higher rheology than the base. The YP and LSYP were 19 and 6 respectively. The 10 sec and 10 min gel strengths were 9 and 21 respectively. The higher rheology imparted greater emulsion stability and prevented barite sag. Again it should be noted that the LSYP was less than 7 which is required to prevent the barite from sag, considering that the concentration of barite in the 16 ppg IEF is around 450 ppb.

The 24 hour static aged IEF was then subjected to extended static aging for more 72 hours at 150^{o}F. In addition a fresh SA based 16 ppg IEF was formulated and static aged for 48 hours at 250^{o}F (**Fluid 7, Table 5**). Both the extended 72 hour and 48 hour static aged IEF gave sag factor of 0.5 with top oil separation of 4 ml and 3 ml respectively. The rheologies of both the static aged IEFs were similar to the 24 hour static aged IEF. The results demonstrate the performance of SA in preventing barite sag and emulsion destabilization in high density LGS free IEF.

IV. Performance of SA in the Absence of Viscosifiers in 12ppg and 16ppg Organoclay-free and LGS-free 16ppg IEF

The studies in previous sections show that even at LSYP lower than 7 the entire SA based IEFs showed no sagging tendency or > 10ml top oil separation. So to test the role of rheology in the SA based IEF, both 12ppg and 16ppg IEF were formulated in the absence of rheology modifiers (**Table 6**). It also implies that these IEF will have more tendencies to sag due to the high volume percentage of the solids. The SA based 12ppg and 16ppg IEFs were static aged at 250^{o}F for 24 hours. On static aging the 12ppg and 16ppg IEF gave sag factor of 0.506 and 0.51 respectively whereas the top oil separation was 5ml and 7ml respectively. This demonstrated that the commercially available rheology modifiers had little role in preventing barite sag or top oil separation. The SA independently provided sag control.

The analysis of the rheology of these 12ppg and 16ppg IEFs was more intriguing as shown in **Table 7** (Fluids 8 and 9). The SA based 12ppg IEF had YP and LSYP of 5 and 2 respectively whereas the 16ppg IEF had YP and LSYP of 4 and 1 respectively. Both these fluids were certainly expected to sag since the YP and LSYP of both these IEFs were similar to or lower than the respective base IEF (Table 4 and 5) which had sagged with a high volume of top oil separation.

On closer analysis it was observed that the 10 min gel strengths of the SA based 12ppg (Fluid 8, Table 7) and 16ppg IEF (Fluid 9, Table 7) was 10, which was similar to or higher than the 10 min gel strengths of the non sagging SA based IEF in this study.

One may conclude that sufficient gels are needed to prevent the barite from sagging and to prevent top oil separation. Also this study shows that low YP and LSYP do not imply that the barite will sag. These concepts were further analyzed in the section on testing of SA in different base oils.

A closer look shows that the SA based 12ppg and 16 ppg IEF had very low PV of 16 and 25 respectively which is not typical of IEF of these densities. Even in the presence of the rheology modifiers the PV of the 12ppg and 16ppg IEF were approximately 20 and 35 respectively which are also considered low. The presence of SA in the IEF negated the requirements of LGS in the IEF, resulting in low a PV of IEF; additionally it provides a sag resistant fluid with no top oil separation.

V. Performance of SA in HPHT Conditions

In this section the rheologies of the 9ppg (**Figure 1**) and 12ppg (**Figure 2**) IEFs were tested on Fann 75 HPHT rheometer under downhole conditions. The pressures were varied from 1000-10,000 psi for a temperature range of 250°F to 325°F. For the 9ppg IEF the PV values varied from 11 to 19 across the pressure and temperature range whereas the YP and the LSYP varied from 9 to 15 and 5 to 8 respectively. For the 12ppg IEF the PV varied from 15 to 22 across the pressure and temperature range whereas the YP and LSYP varied from 4 to 12 and 5 to 9 respectively. The YP and LSYP values were within the range of expected drilling fluid rheology. Comparison between the two IEFs shows that at both the densities, 3ppb SA imparted similar rheology.

The HPHT rheology data show that these IEFs under pressure and temperature exhibit higher rheology than at 120^{o}F under ambient pressure. Usually a decrease in the rheology of the IEF is observed under HPHT conditions when compared to rheology at 120^{o}F. Thus, the SA based IEFs can perform the functions of hole cleaning and suspension under high pressure and high temperature in addition to its role in controlling barite sag.

VI. Performance of SA in Different Base Oils

For an additive to be used universally it is expected to perform in the most commonly available base oils. Thus, for this study the commonly available base oils designated as BASE OIL II and BASE OIL III were used. The composition of these base oils are given in Table 1. The base 12ppg IEF for BASE OIL II was formulated, as the rheology modifiers are known to perform better in this base oil. It was expected that the base IEF formulated with BASE OIL II would show high rheology that can prevent barite from sagging and prevent top oil separation. However, the results were intriguing, since static aging this base IEF for 24 hours at 250^{o}F gave a sag factor of 0.68 with a top oil separation of 80 ml **(Table 8)**.

The rheology of the static aged base IEF was even more intriguing since it had YP and LSYP of 25 and 7, respectively. The gel strengths at 10 sec and 10 min were 9 and 15, respectively. The high gel strength at 10 min was not able to prevent the barite from Sagging nor was it able to prevent top oil separation. On the contrary, the SA based 12ppg IEFs which did not sag (Fluids 3-5 and 8) had lower 10 min gel strengths than the 12ppg base IEF formulated with BASE OIL II. The results clearly demonstrate that it is more than just high gel strengths that are required to prevent barite sag.

The SA based 12ppg IEF formulated with BASE OIL II on static aging for 24 hours at 250^{o}F gave top oil separation of 0.5 with a top oil separation of 3 ml (Fluid 10, Table 8). The rheology of this BASE OIL II IEF was higher than the rheology of the IEF formulated with BASE OIL I. The BASE OIL II IEF had YP and LSYP of 32 and 8, respectively. The gel strengths at 10 sec and 10 min were 10 and 25 respectively. This fluid was then further static aged at 150^{o}F for 60 hours which gave a sag factor of 0.505 and top oil separation of 12 ml. The YP and LSYP of this IEF were 38 and 9 respectively.

Another SA based 12ppg IEF was formulated with BASE OIL III (Fluid 11, Table 8). Static aging this IEF for 24 hours at 250^{o}F gave a sag factor of 0.5 with top oil separation of 2 ml. The rheology of this BASE OIL III IEF was also higher than the rheology of the IEF formulated with BASE OIL I.

The BASE OIL III IEF had YP and LSYP of 25 and 7 respectively. The gel strengths at 10 sec and 10 min were 10 and 19, respectively. This IEF was then further static aged at 150°F for 60 hours which gave a sag factor of 0.505 with top oil separation of 10 ml. The rheology of the 60 hour static aged IEF increased, with the YP and LSYP of 38 and 5, respectively. The gel strengths also increased with 10 sec and 10 min gel strengths of 18 and 24, respectively.

As discussed previously that high gel strengths were not the only reason for a good sag factor. This was clearly demonstrated on 60 hour extended static aging of the BASE OIL III IEF which gave high gel strengths than the 24 hour static aged IEF. The extended static aged IEF had a higher sag factor and more volume of top oil separation when compared to the 24 hour static aged IEF.

It is proposed that the prolonged emulsion stability is imperative to improved sag resistance. Though a fluid can show high gel strengths at any time especially after it has experienced shear, it is imperative that the high gel strengths are maintained for longer durations. For the high gel strengths to be maintained for longer durations, prolonged emulsion stability is required. All the sagging fluids showed top oil separation which means that the emulsion destabilized over time. Thus, the SA was able to provide emulsion stability and structure that held the barite in place, the presence of this emulsion structure provided sufficient gel strengths to prevent barite from sagging. These results demonstrate the effectiveness of the SA in the commonly available base oils.

VII. Contamination Study of 12ppg Organoclay-free and LGS-free IEF

Tolerance to contamination is the primary requisite of any good drilling fluid. The contaminants used for the testing included the following:

- 40.0 ppb of artificial drilled solids
- 10% v/v seawater increment
- 2.0 ppg weight up with barite and
- 5.0 ppb lime.

The contamination study was divided into two parts as shown in **Testing Scheme I**:

Part A: Effect of the contaminant on the rheology, filtration and sag factor values of the IEF.

Part B: Effect of treatment on the contaminated IEF to restore its rheology and filtration values within ~20% of its original values (uncontaminated state).

The effect of contaminants on the 12 ppg IEFs are given in **Table 9**. The contamination of 12ppg IEF with 5ppb lime resulted in negligible change in the overall rheology of the IEF which did not warrant any treatment.

The contamination with 10% v/v seawater and 2ppg barite weight up increased the YP of the contaminated IEF from 13 to 20 and 17 respectively whereas the LSYP increased from 3 to 4 and 5 respectively. The gel strengths at 10 min increased from 10 to 12 and 14, respectively. Since the rheological parameters are within the range of the specifications desired of a typical drilling fluid, it did not warrant any treatment.

The contamination of the 12ppg IEF with 40pp drilled solids however increased the YP and LSYP from 13 and 3 to 30 and 12, respectively. The gel strengths at 10 min increased from 10 to 33. The contaminated fluid was then treated with 0.5ppb conventional thinner which brought down the YP and LSYP to 10 and 5 respectively. The gel strength at 10 min however was down to 28. An analysis of these results suggests that the SA interacts synergistically with the low gravity solids to improve the overall rheology of the IEF**.**

The contaminants had no effect on the HPHT fluid loss of the SA based 12ppg IEF. This implies that SA improved the emulsion stability of the IEF, keeping the fluid loss under control.

The contaminated fluids were then static aged for 24 hours at 250°F. All the contaminated fluids gave a sag factor of 0.5 without top oil separation. Thus SA based IEFs did not show tendency for barite sag or for top oil separation.

VIII. Biodegradability and Eco-toxicity Studies of SA

To check the applicability of SA in environmentally stringent regulations, SA was subjected to biodegradation and eco-toxicity studies. The SA was assessed for marine biodegradation by the BODIS method where the biodegradation was recorded every week, up to 42 days. The eco-toxicity study of SA was performed with marine juvenile fish *Cyprinodon variegatus* in seawater with OECD 203 guidelines for marine testing of offshore chemicals. The results are given in **Table 10**. The results demonstrate the good environmental profile of the novel sag control additive with potential applications in the North Sea.

Conclusions:

1. Stable organoclay-free and LGS-free IEFs were formulated with the SA at 250°F.
2. The SA based IEFs show no tendency to sag or for top oil separation for extended hours (48-72 hours) of static aging at temperatures of 150°F and 250°F.
3. The SA based IEFs were sag resistant at very low rheology with YP of 5 and LSYP of 1 for rheology measurements at 120°F.
4. The SA performed in IEF with densities from 9-16ppg and in commonly available base oils.
5. The SA performed independently of the commercially available rheology modifiers in providing suspension to the IEF.
6. The SA based IEFs were tolerant to the effect of contaminants. Any deviations from the desired range were easily treated with conventional additives.
7. HPHT rheology studies of 9ppg and 12ppg SA based IEFs show consistent YP and LSYP across a temperature and pressure range
8. Eco-toxicity studies shows that the product has potential applications in North Sea.

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Nomenclature:

YP = Yield point
LSYP = Low shear yield point
PV = Plastic viscosity
IEF = Invert emulsion fluids
ppg = Pounds per gallon
ppb = Pounds per barrel
LGS = Low gravity solids
ECD = Equivalent circulating density
OWR = Oil water ratio
WPS = Water phase salinity
SA =Suspension agent
RM1 =Rheology modifier 1
RM2 =Rheology modifier 2
LC_{50} *= Lethal dose required to kill 50% of the organisms*
NOEC = No observed effect concentration
LC50 = lethal concentration, median
EC50 = Effective concentration, median

References

1.Mowrey, C. and Cameron, C.: "Achieving the Drilling Performance Benefits of a Clay-Free System in a Variety of Commonly-used Base Fluids." AADE-06-DF-HO-07, AADE Drilling Fluids Technical Conference, Houston, April 11-12, 2006.

2.Kirsner, J. et al.: "Method of formulating and using a drilling mud with fragile gels." US patent 7278485, 2004.

3. Saasen, A., Liu, D. and Marken, C.D. "Prediction of Barite Sag Potential of Drilling Fluids from Rheological Measurements", SPE/IADC 29410, SPE/IADC Conference, Amsterdam, Feb. 28-March 2, 1995.

4. Saasen, A., et. al.: "Monitoring of Barite Sag Important in Deviated Drilling," *OGJ*, Aug 1991.

5. Dye, W., et. al.: "Correlation of Ultra-Low Shear rate Viscosity and Dynamic Barite Sag in Invert-Emulsion Fluids," SPE 56636, SPE ATCE, Houston, 3-6 Oct 1999.

6. Kenny, P. and Hemphill, T.: "Hole-Cleaning Capabilities of an Ester-based Drilling Fluid System", *SPE Drlg & Comp*., March 1996.

7. Bern, P.A. Zamora, M. Slater, K.S. and Hearn, P.J.: "The influence of Drilling Variables on Barite Sag", SPE 36670, SPE Annual Technical Conference and Exhibition, Denver, Colorado, U.SA, 6-9 October 1996.

8. Bern, P.A. et. al.: "Barite Sag: Measurement, Modeling, and Management" SPE 62051, IADC/SPE Asia Pacific Drilling Technology Conference, Jakarta, 7–9 September.

9. Nicora, L.F. et al.: "High-Density Invert-Emulsion System with Very Low Solids Content to Drill ERD and HPHT Wells." SPE 65000, SPE International Symposium on Oilfield Chemistry, Houston, February 13-16, 2001.

10. Beck, F.E. et al.: "The Effect of Rheology on Rate of Penetration. "SPE/lADC 29368, SPE/lADC Drilling Conference and Exhibition, Amsterdam, February 28 – March 2, 1995.

11. Maxey,J.: "Rheological Analysis of Static and Dynamic Sag in Drilling Fluids", ANNUAL TRANSACTIONS OF THE NORDIC RHEOLOGY SOCIETY, VOL. 15, 200

12. Okrajni, S.S. and Azar, J.J.: "The Effects of Mud Rheology on Annular Hole Cleaning in Directional Wells." *SPEDE*, (August 1986) 297-308.

Table 1: Composition of base oils

Base Oil	% Cyclic alkanes	% Normal Alkanes	% Branched Alkanes	% Aromatic
BASE OIL I	33	24	43	-
BASE OIL II	34	7.8	33.5	24.7
BASE OIL III	17	14	69	-

Table 2: Mixing order, concentration and mixing time of products

Products	Time min	Mud weight 9ppg	Mud weight 12ppg	Mud weight 16ppg
Oil water ratio (OWR)		60/40	70/30	80/20
Water phase salinity (WPS) in ppm of $CaCl_2$		250,000	250,000	250,000
BASE OIL I		As required	As required	As required
Invert emulsifier, ppb	2	8	10	15
Lime, ppb	2	1.5	1.5	1.5
RM1, ppb	2	3	3	3
Filtration control agent, ppb	5	2	2	2
SA, ppb	5	3	3	3
$CaCl_2$ solution, ppb	2	As required	As required	As required
Barite, ppb	10	As required	As required	As required
RM2, ppb	1	3	3	3

Table 3: Performance of SA in 9ppg LGS-free IEF hot rolled at 250°F

9 ppg 60/40 OWR	Base	Base + 3ppb SA		
	Static aging @250°F, 24 hrs	Fluid 1 Static aging @250°F, 24hrs	Fluid 1 Extended static aging @150°F, 72hrs	Fluid 2 Static aging @250°F 48hrs
600 rpm	29	46	48	48
300 rpm	17	28	30	30
200 rpm	12	22	24	24
100 rpm	8	15	17	17
6 rpm	2	4	5	5
3 rpm	1	4	4	4
PV	12	18	18	18
YP	5	10	12	12
LSYP	0	4	3	3
Gel strength 10sec/10min	1/2	5/10	5/10	5/10
Oil separation, ml	80	0	4	0
Sag factor	0.60	0.50	0.51	0.50

Table 4: Performance of SA in 12ppg LGS-free IEF hot rolled at 250°F

12 ppg 70/30 OWR	Base	Base + 3ppb SA			
	Static aging @250°F, 24 hrs	Fluid 3 Static aging @250°F, 24hrs	Fluid 4 Static aging @250°F, 48hrs	Fluid 5 Static aging @150°F, 72hrs	Fluid 4 extended Static aging @300°F, 24hrs
600 rpm	34	58	55	55	50
300 rpm	20	36	35	35	31
200 rpm	15	28	27	27	23
100 rpm	10	18	19	19	16
6 rpm	3	5	5	5	5
3 rpm	2	5	4	4	4
PV	14	22	20	20	19
YP	6	14	15	15	12
LSYP	1	5	3	3	3
Gel strength 10sec/10min	3/4	5/16	5/10	5/10	5/7
Oil separation, ml	100	0	1	4	1
Sag factor	0.68	0.505	0.500	0.500	0.505

Table 5: Performance of SA in 16ppg LGS-free IEF hot rolled at 250°F

16 ppg 80/20 OWR	Base	Base + 3ppb SA		
	Static aging @250°F, 24 hrs	Fluid 6 extended Static aging @150°F, 72hrs	Fluid 6 Static aging @250°F, 24hrs	Fluid 7 Static aging @250°F, 48hrs
600 rpm	55	88	91	91
300 rpm	32	54	55	55
200 rpm	24	42	42	42
100 rpm	15	28	28	28
6 rpm	3	7	8	8
3 rpm	3	6	7	7
PV	23	34	36	36
YP	9	20	19	19
LSYP	2	5	6	6
Gel strength 10sec/10min	3/3	8/17	9/21	9/21
Oil separation, ml	110	4	1	3
Sag factor	0.760	0.500	0.500	0.500

Table 6: Mixing order of products and concentration (ppb): 12ppg and 16ppg LGS-free IEF without viscosifiers

Products	Time min	Mud weight 12ppg	Mud weight 16ppg
BASE OIL I		151	137
Invert emulsifier, ppb	2	10	15
Lime, ppb	2	1.5	1.5
RM1, ppb	-	-	-
Filtration control agent, ppb	5	2	2
SA, ppb	5	3	3
$CaCl_2$ solution, ppb	2	114	62.2
Barite, ppb	10	222	452.3
RM2, ppb	-	-	-

Table 7: Performance of SA in the absence of RM1 and RM2 in 12ppg and 16ppg LGS- free IEF hot rolled at 250°F

Static aging @250°F 24 hrs	Fluid 8 12 ppg 70/30 OWR	Fluid 9 16 ppg 80/20 OWR
600 rpm	37	54
300 rpm	21	29
200 rpm	14	22
100 rpm	9	14
6 rpm	2	3
3 rpm	2	2
PV	16	25
YP	5	4
LSYP	2	1
Gel strength 10sec/10min	3/9	3/10
Oil separation, ml	5	7
Sag factor	0.506	0.51

Table 8: Performance of SA in 12ppg LGS-free IEF of different base oils at 250°F

12 ppg 70/30 OWR	Base oil II (Base)	Base oil II + 3ppb SA		Base oil III + 3ppb SA	
	Static aging @250°F, 24hrs	Fluid 10 Static aging @250°F, 24hrs	Fluid 10 extended static aging @ 150°F, 60hrs	Fluid 11 Static aging @250°F, 24hrs	Fluid 11 extended static aging @150°F, 60hrs
600 rpm	71	96	110	81	98
300 rpm	48	64	74	53	68
200 rpm	38	49	59	43	54
100 rpm	27	34	42	31	39
6 rpm	9	10	15	11	19
3 rpm	8	9	12	9	12
PV	23	32	36	28	30
YP	25	32	38	25	38
LSYP	7	8	9	7	5
Gel strength 10sec/10min	9/15	10/25	-	10/19	18/24
Oil separation, ml	80	3	12	2	10
Sag factor	0.68	0.5	0.505	0.5	0.505

Table 9: Performance of SA in the presence of different contaminants hot rolled at 250°F

12 ppg 70/30 OWR	**Fluid 1**	**Fluid 2**	**Fluid 3**	**Fluid 4**	**Fluid 5**	**Fluid 6**
	Uncontaminated Fluid	**Fluid 1+ 5ppb lime**	**Fluid 1+ 10% v/v Sea water**	**Fluid 1+ 2ppg Barite weigh up**	**Fluid 1+ 40ppb Drilled solids**	**Fluid 5+ 0.5ppb thinner**
600 rpm	55	52	66	69	90	80
300 rpm	34	30	43	43	60	45
200 rpm	25	23	34	34	48	34
100 rpm	17	15	24	24	34	21
6 rpm	5	4	6	7	14	7
3 rpm	4	3	5	6	13	6
PV	21	22	23	26	30	35
YP	13	8	20	17	30	10
LSYP	3	2	4	5	12	5
GELS 10 sec	5	4	7	7	20	10
GELS 10 min	10	9	12	14	33	28
HTHP, ml/30min (250°F)	2.0	2.0	2.0	2.0	1.8	2.0
Sag factor (250F, 16hr)	-	0.5	0.5	0.5	-	0.5
Oil separation, ml	-	0	0	0	-	0

Table 10: Biodegradability and Eco-Toxicity data Of SA

Tests		
Biodegradation	28 days	38.2%
	42 days	71.4%
Cyprinodon variegatus	48-hr LC50	>10g/l
	96-hr LC50	>10g/l
	96-hr NOEC	10g/l

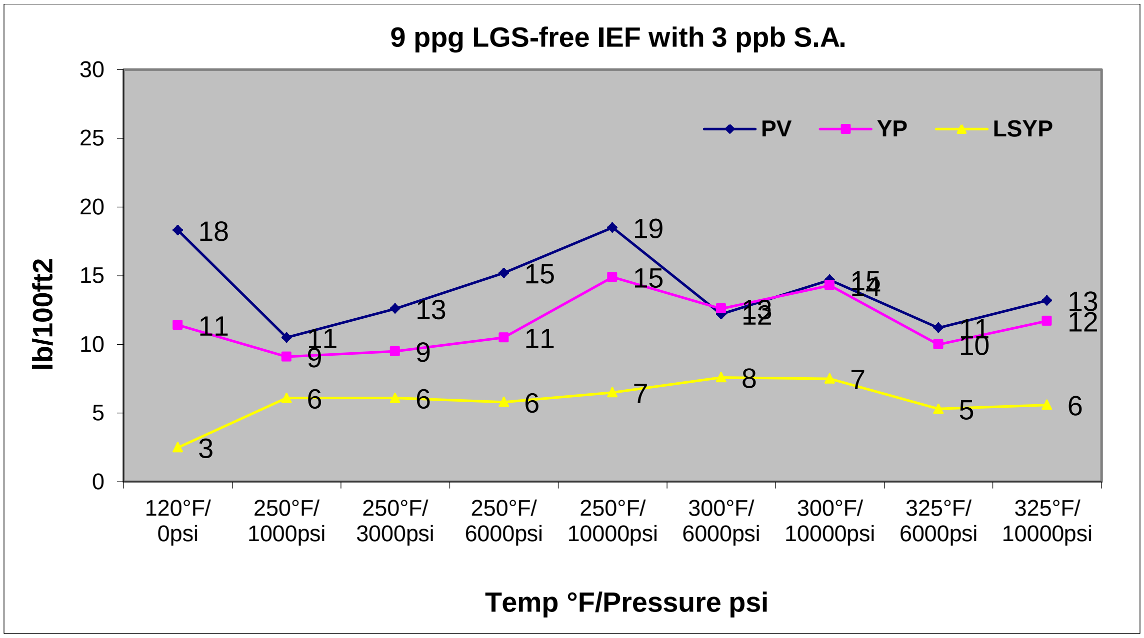


Figure 1: Performance of 9ppg LGS-free IEF with 3ppb SA at HPHT

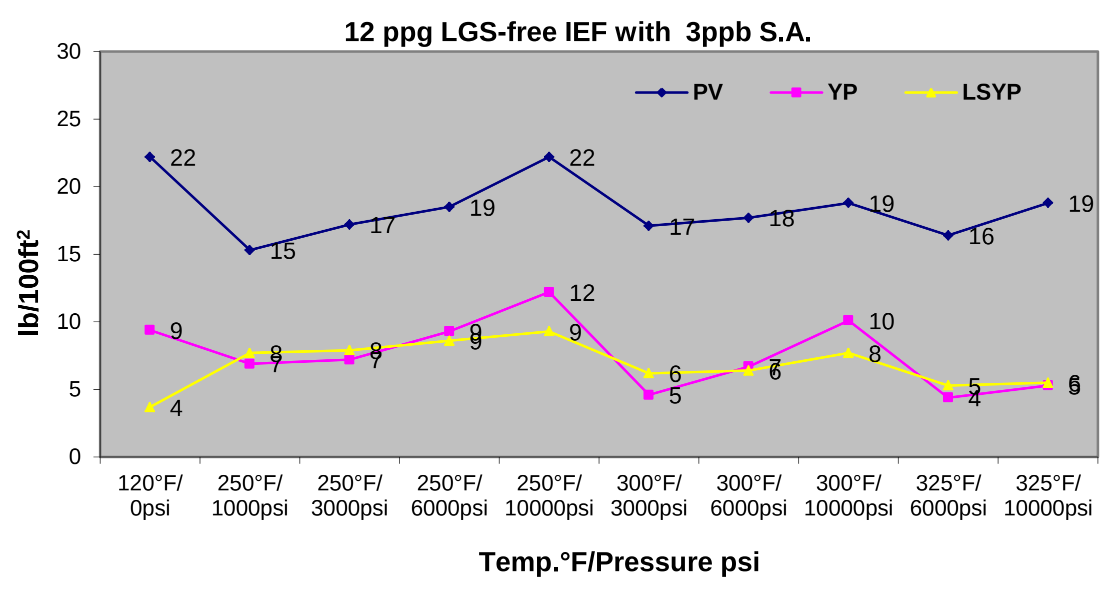
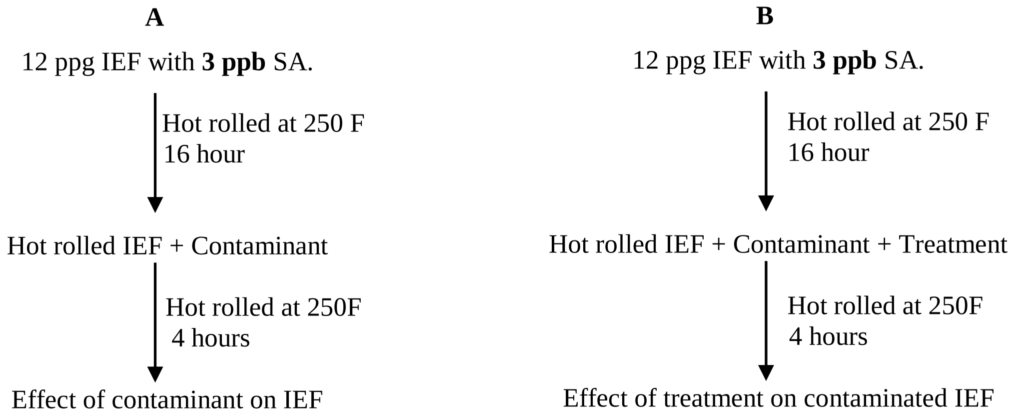


Figure 2: Performance of 12ppg LGS-free IEF with 3ppb SA at HPHT



Testing Scheme I: Testing scheme for contamination study of 12ppg LGS-free IEF