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Low Plastic Viscosity Invert Emulsion Fluid System for HPHT Wells

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Abstract

Drilling high pressure high temperature (HPHT) wells can present issues with sagging and hole cleaning. Further, horizontal and extended reach drilling (ERD) wells require careful equivalent circulating density (ECD) management due to the high pump rates involved. Surge and swab pressures when breaking circulation or running casing can lead to mud losses in weak formations. Maintaining optimal mud rheology can help overcome these problems, but attaining optimal rheologies in low to medium density clay-free mineral oil-based fluids can be difficult. Adding organo-clays or low gravity solids (LGS) to boost rheology can lead to high ECDs and low rates of penetration (ROP)

The new HPHT organic rheology modifier (ORM) imparts optimal rheological properties to low density clay-free invert emulsion fluids (IEF). The IEF thus formulated exhibits enhanced low shear rheology (even at 9.0 ppg) with lower or similar plastic viscosity values when compared to the IEF formulated without the new HPHT rheology modifier. A good low shear rheology implies better hole cleaning and sag control. A low plastic viscosity (PV) implies lower ECD exerted at the bottom.

Adding the ORM imparts fragile gel characteristics to clay-free IEFs weighing 9.0 to 18.0 ppg. The rapid gel-to-flow transition helps minimize surge and swab pressures and reduce mud losses. The new HPHT rheology modifier also stabilizes the IEF and provides comparatively low fluid loss values. The need to add LGS to boost rheology is eliminated. Experimental data demonstrating the performance of the HTHP rheology modifier is presented.

Introduction

The high temperatures and pressures encountered while drilling deep wells make it challenging to maintain optimum rheological properties while drilling. The ability of a drilling fluid to suspend drill solids and weighting materials has commonly been associated with the rheology of the fluid. Increasing the fluid viscosity is often seen as an effective means of improving weighting materials and drill solids suspension in the fluid.

The most commonly used additive to viscosify an oil-based drilling fluid is organophilic clay. The use of organophilic clay in the drilling fluid, however, has some disadvantages. The utility of organophilic clay to viscosify the low aromatic, high paraffin oil muds which are considered safer to marine life than the traditional diesel oil-based fluids is limited. In the absence of heat and/or high shear mixing, excess organophilic clay is needed to provide viscosity to the mud prior to its equilibration in the drilling system. Also, the quaternary ammonium salts from which the clays are prepared are generally thought to be toxic to aquatic organisms. [1,2]

In addition, organophilic clays in HTHP conditions fail to provide sufficient viscosity to the fluid due to thermal thinning and thermal degradation, thereby destroying their viscosifying capacity.[1] In temperatures in excess of 350F, it is undesirable to use organophilic clays due to the continuous need to replenish clay and the build up of inert solids in the mud which results from the degraded organophilic clay. The build up of such solids along with the deliberate addition of low gravity solids to build up the viscosity of the fluid in HTHP conditions results in high plastic viscosity (PV) of the fluid. A high PV of the drilling fluid results in increased equivalent circulating density (ECD) caused by increased pump pressures needed for pumping such a fluid.[3] A fluid with a high PV also has a detrimental effect on the rate of penetration (ROP), as an increase in number of solids in the fluid slows down the penetration rate.[4]

A desirable IEF would be the one which not only has a low PV but shows good low shear viscosity (LSYP 5-15)[5] and a good yield point (YP). [6,7] An IEF with a good YP and low shear yield point (LSYP) demonstrates improved sag resistance[5] and cuttings carrying capacity respectively.[6,7] Okrajni and Azar have shown that maintaining a high YP/PV ratio improves cutting transport through the annulus in the laminar flow region.[6]

Apart from rheology, another parameter which also distinguishes a desirable drilling fluid in its suspension capability is its ability to form robust gels. Such a robust gel, though good for better suspension, needs to be fragile.[8] A “fragile gel” is easily disrupted or thinned, and liquefies or becomes less gel-like and more liquid-like under stress. The gels should be strong but fragile so that they not only help in suspension but can be easily disrupted by a mere pressure wave or a compression wave during drilling. Fragility of the gel is important in preventing induced fractures and fluid losses to the formation. Such rheological properties can provide low ECDs with greater suspension properties, eliminating the need for fine ground weighting agents while providing excellent hole cleaning. High fragile gel strengths also require lower surface pressures to break gels thereby eliminating the need to modify fluid rheology before running casing.

The ability to meet these drilling fluid requirements merits the development of an additive which not only provides the fluid with high low shear yield point but also imparts robustness as well as fragility to its gels in HTHP conditions. The organic rheology modifier (ORM) serves this purpose for invert emulsion fluids formulated with commonly used mineral oils. This additive increases the low shear yield point (LSYP) without significantly affecting the plastic viscosity (PV) of the fluid. In addition, it produces fragile gels in the IEF.

Methods and Materials

The test fluids were formulated with commercially available invert emulsifiers, lime, polymeric viscosifier, high-pressure high-temperature (HPHT) filtration control agent, HPHT invert emulsifier (as needed), barite, sized calcium carbonate (mean particle size 5 microns) and mineral base oils. BASE OIL I is mixed paraffin base oil, BASE OIL II is typical naphthenic oil with high content of cyclic alkanes and BASE OIL III is composed of normal alkanes.

The fluids were mixed in stainless steel mixing cups on a five-spindle multimixer model 9B having a rotational speed of 11500 RPM with sine-wave impeller blade No. 9B29X. The fluids were aged in HPHT stainless steel ageing cells and hot rolled in a Model 705ES Five Roller Oven at the desired temperature for 16 hours. The rheology of the fluids was determined at 120F on a 12-speed standard oilfield viscometer. The temperature was controlled with an electrically heated thermo cup. Rheological and HPHT fluid loss testing was performed as per API 13A recommendations. High temperature and pressure rheology measurements were performed on a commercially available HPHT viscometer. The mixing order of products, the concentrations and mixing time for the different density fluids are given in **Table 1**. The concentration of products used to formulate these fluids was estimated with a proprietary numerical simulator.

The rheology of the fluid was characterized in terms of PV, YP and LSYP of the invert emulsion drilling fluid. In this study the YP is obtained from the Bingham-Plastic rheological model when extrapolated to a shear rate of zero. The PV represents the viscosity of a fluid when extrapolated to infinite shear rate. 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. The yield stress or Tau0 is the stress that must be applied to a material to make it begin to flow (or yield), and it is calculated from viscometer dial readings measured at rates of 3, 6, 100, 200, 300 and 600 rpm. The extrapolation in this case may be performed by applying a curve fit to the Herschel-Bulkley rheological model. The Tau0 can be estimated reasonably by calculating the LSYP value from Equation 3.

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

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

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

The gels formed in the IEF were characterized by the 10-min gel strength, which represents dial reading inflection at 3 rpm on the viscometer, after keeping the IEF static for an interval of 10 min.

Fragile gel strength measurements were performed on a Brookfield viscometer. The procedure uses the Brookfield DV-II+ Programmable Viscometer to measure gel strengths with a vane spindle. The test allows for a more detailed description of the gel structure and uses much lower revolution speeds than the 12-speed standard oilfield viscometer. In a typically experiment, a 0.5 rpm shear is applied to break the gels formed at defined intervals of 10 and 30 min.

Results and Discussions

1: Performance of ORM in 9.0 ppg IEF

Initially a 9.0 ppg “base” fluid with 60:40 OWR and water phase salinity (WPS) of 200,000 ppm (200K) $CaCl_2$ was formulated with BASE OIL I. This “base” formulation contained no ORM additions. The fluids were then hot rolled at 250F followed by determining the rheology.

Figure 1 shows the comparative rheological performance of the ORM at concentrations of 1, 3 and 6 ppb with that of base formulation in 9 ppg IEF. It is observed that the fluid containing the ORM shows higher YP, 10-min gel strengths and LSYP values as compared with the base formulation. A slight increase in PV is observed at 1.0 ppb concentration though it remains fairly constant after further increase in the additive concentration. It was observed that at 6.0 ppb ORM, the PV increased by 38% whereas the YP, 10-min gel strength and LSYP increased by 250%, 320% and 200%, respectively, as compared to the base IEF. This demonstrates the performance of the ORM.

2. Performance of ORM IEFs of different densities

To assess the performance of ORM at different mud weights, ORM was tested in 10.0 ppg (OWR 60:40, 250K ppm WPS), 12.0 ppg (OWR 70:30, 200K ppm WPS) and 18.0 ppg (OWR 90:10, 300K ppm WPS) fluids hot rolled at 250F, 350F and 375F respectively. The 10.0 ppg fluid was formulated with BASE OIL III (**Figure 2**) whereas the 12.0 ppg and 18.0 ppg fluids were formulated with BASE OIL I. (**Figures 3 and 4**). It was observed in the 10.0 ppg and 12.0 ppg IEF that the PV increased by 30% and 13% only on comparison with the respective base formulations. However, for the 10.0 ppg and 12.0 ppg IEF the YP, 10 min-gel strength and LSYP increased by roughly 300% and 200% compared to the respective base formulations. For the 18.0 ppg fluids an increase in 10 min-gel strengths were observed with reduced the HTHP filtrate loss to a considerable extent. Thus, the ORM was able to provide enhanced rheology and emulsion stability.

3: Performance of ORM under high pressure high temperature conditions in 9.0 ppg and 12.0 ppg IEF

The 9.0 ppg IEF containing 3.0 ppb ORM was formulated with 200K ppm WPS in BASE OIL I and hot rolled at 250F. The performance of the ORM in the fluid was further evaluated with a HPHT viscometer using simulated downhole conditions. The pressures were varied from 1000-10,000 psi at 250F and 1000-6000 psi at 325F. Higher YP **(Figure 5b)** and LSYP **(Figure 5c)** values were obtained for fluid containing 3.0 ppb of ORM as compared to the corresponding base formulation under identical HPHT test conditions. The YP and LSYP values were higher across a range of temperature and pressures as compared to those obtained for the base formulation. Though the ORM formulation had higher YP and LSYP than the base formulation the PV (**Figure 5a)** of both the fluids were similar.

The 12.0 ppg IEF with 2.0 ppb ORM was formulated with 70:30 OWR, 200K ppm WPS in BASE OIL I and hot rolled at 350F. **Figure 6** shows the performance of the 2.0 ppb ORM in 12.0 ppg IEF under HTHP conditions. It can be observed that the fluid containing the ORM shows appreciable YP and LSYP values over a varied temperature-pressure range. The results in both the 9.0 ppg and 12.0 ppg IEF demonstrate that the additive can help achieve the desired YP and LSYP in low to medium mud weight IEF in HTHP conditions with little contribution to the PV.

4: Performance of ORM in different mineral oils for 9.0 ppg IEF

Figure 7 depicts the performance of 3.0 ppb ORM in invert emulsion fluids with different commercially available mineral oils as identified above: BASE OIL I, BASE OIL II and BASE OIL III. Each formulation had a mud weight of 9.0 ppg with OWR of 60:40 and 200K ppm WPS. The IEFs were hot rolled at 250F. HPHT filtrate loss obtained were less than 2.0 ml for all the base oils investigated. Among all the mineral oils investigated, the highest YP and LSYP with lowest PV were observed for BASE OIL III. It is usually difficult to achieve high YP and LSYP in low density invert emulsion fluids formulated with mineral oils, the data in Figure 7 shows the effectiveness of ORM as a rheology modifier in a variety of commercially available mineral oil based invert emulsion drilling fluids.

5: Performance of ORM at higher temperatures.

The effect of temperature on the performance of the ORM was investigated in 9.0 ppg BASE OIL I based IEF at 300F and 325F hot roll temperatures. The effect of the hot roll temperatures on the YP and LSYP of the fluids containing 3.0 ppb ORM are shown in **Figures 8 and 9** respectively. It was observed that the YP and LSYP of the IEFs increased by 125% or higher whereas the PV increased by roughly 20% compared to the respective base formulation. This demonstrates the thermal stability of the ORM when subjected to HPHT conditions.

6. Performance of ORM in the absence of low gravity solids

The addition of low gravity solids (LGS) in a low density clay-free IEF helps in increasing the low shear viscosity of the system. However, this also increases the PV of the system which may lead to higher ECD values. The commonly used LGS include finely sized calcium carbonate with a mean particle size of 5 microns, and an inorganic rheology modifier. The performance of ORM in the presence and absence of LGS is shown in **Figure 10**, for a 9.0 ppg BASE OIL I, IEF system hot rolled at 250F.

Similar LSYP, 10-min gel strengths and YP values were observed in the presence and absence of LGS. Thus, in the presence of the ORM the use of LGS is effectively eliminated in the invert emulsion fluids.

7. Ability of ORM to impart fragile gels to IEF

Fragile gels were measured for 9.0 ppg and 18.0 ppg IEFs (hot rolled at 250F and 375F respectively) as depicted in **Figures 11 and 12** respectively. When the fluids are at rest or static (as when drilling has stopped in the wellbore), the curves are flat or relatively flat (see area at about 50-65 minutes elapsed time for example). When shear stress is resumed (as in drilling), the curves move up straight vertically or generally vertically (see area at about 68 to about 80 elapsed minutes for example), with the height of the curve being proportional to the amount of gel formed—the higher the curve the more gel built up. The curves then fall down and level out or begin to level out, with the faster rate at which the horizontal line forms (and the closer the horizontal line approximates true horizontal) indicating the lesser resistance of the fluid to the stress and the lower the pressure required to move the fluid.[9] Figure 11 shows that even a low mud weight drilling fluid with the ORM demonstrates "fragile gel" behavior relative to the base fluid. Figure 12 which shows "fragile gel" behavior of a 18.0 ppg clay-free drilling fluid demonstrates that even at high mud weights, a clay-free IEF with the ORM shows fragile gel strength. The testing shows that both the low and higher mud weight clay-free IEFs build higher gel strength which breaks easily.

8: Contamination testing of ORM in 9.0 ppg BASE OIL I systems

Contamination studies were performed on 9.0 ppg IEFs with OWR 60:40 and WPS 200K ppm, formulated with BASE OIL I at 250F. The contamination testing was performed on fluids having a 3.0 ppb ORM concentration. The contaminants include 40.0 ppb of artificial drilled solids, 10% seawater, 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 rheological and the filtration properties of the IEF.

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

The results of contamination studies are presented in

Figure 13a and 13b. It can be observed that 5.0 ppb lime and 2 ppg weight up with barite resulted in small changes in the PV, YP and LSYP of the fluids which did not warrant treatment. The contamination with 40.0 ppb drilled solids and 10% sea water resulted in 100% and 60% increase in the YP and the LSYP of these fluids respectively. However this was easily treated with the addition of 0.7 ppb and 0.4 ppb concentrations of a conventional polymeric thinner which caused decrease in the YP and the LSYP. But the PV remained similar to that of the contaminated fluids. The filtration properties of the contaminated fluids remained unaffected.

Static ageing studies

Static ageing studies were performed on 9.0 ppg IEF with BASE OIL I having OWR 60:40 and WPS 200K ppm. The formulated 9.0 ppg IEFs with 3.0 ppb of ORM were initially hot rolled at 250F for a time period of 16 hours. After 16 hours of hot rolling the IEFs were then mixed for about 5 minutes on a multimixer and were subsequently static aged at 250F for 16, 48 and 56 hours.

The static aged IEFs were then tested for the top oil separation which is a measure of the emulsion stability. It is calculated as a percentage of the height of the separated oil at the top to the total height of the aged IEF in the ageing cell. In all the aged IEFs, less than 2% top oil separation was observed implying that the IEFs were stable. In addition, the static aged IEFs for 16, 48 and 56 hours showed an insignificant change in their rheological and filtration properties as shown in **Figure 14**. This shows that the ORM was able to perform without adversely affecting the fluid even when static aged for long durations**.**

10: Ecotoxicological studies of ORM

The ORM was subjected to ecotoxicity studies. It exhibited a 48-hr LC_{50} of >10g/L and a 96-hr NOEC of 10g/L to the marine juvenile fish ***Cyprinodon variegatus*** in the seawater phase. The test methods for fish are consistent with OECD 203 guideline for marine testing of offshore chemicals.

For the tests involving marine copepod ***Acartia Tonsa***, ORM exhibited a 24-hr LC_{50} and 48-hr LC_{50} of >10g/L and a 48-hr NOEC of 10g/L in the seawater phase. The test methods for copepods were consistent with ISO 14669:1999(E) guideline for marine testing of offshore chemicals.

ORM exhibited a 24-hr density EC_{50} of >30mg/L, 48-hr density EC_{50} of 7.5mg/L, a 72-hr density EC_{50} of 12.9mg/L and a 72-hr density NOEC of 5.0mg/L to the marine algae ***Skeletonema costatum*** in the seawater phase. The 72-hr cell count EC_{50} was 14.5mg/L and the 72-hr cell count NOEC was 10.0mg/L. The test methods for algae were consistent with ISO 10253 guideline as adapted for marine testing of offshore chemicals.

North Sea regulations require an offshore chemical to show a LC_{50} value of >10mg/L. ORM, thus, an additive which is North Sea compliant since the LC_{50} value obtained after subjecting ORM to each of the toxicity tests is greater than 10mg/L.

Conclusions

1. The ORM can provide the necessary low end rheology and yield point without significantly affecting the PV for clay free invert emulsion fluids in HTHP conditions.
2. The ORM was able to perform in the base oils commonly used for drilling and imparted enhanced rheology for low to high density (9.0-18.0 ppg) clay free mineral oil IEF systems.
3. The product can also effectively eliminate the use of low gravity solids needed to boost low end rheology for the low density clay free system.
4. The effect of contamination on the rheology of the fluid containing ORM was minimal and the fluids were easily treated by conventional polymeric thinners to restore desired rheological properties.
5. After static ageing of the fluid containing the ORM, the fluid showed minimal changes in the rheological and filtration properties.
6. Fluids formulated with the ORM also showed excellent control on the fluid loss for the high mud weight systems.
7. The ORM was able to impart fragile gels to mineral oil based invert emulsion fluids for low to high density IEF (9.0-18.000 ppg) necessary for the lower ECD in the wellbore while drilling.
8. Ecotoxicity studies show that the product has potential application in the 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
ORM =Organic rheology modifier
NOEC = No observed effect concentration
LC_{50} *= lethal concentration, median*
OECD = Organisation for Economic Co-operation and Development

References

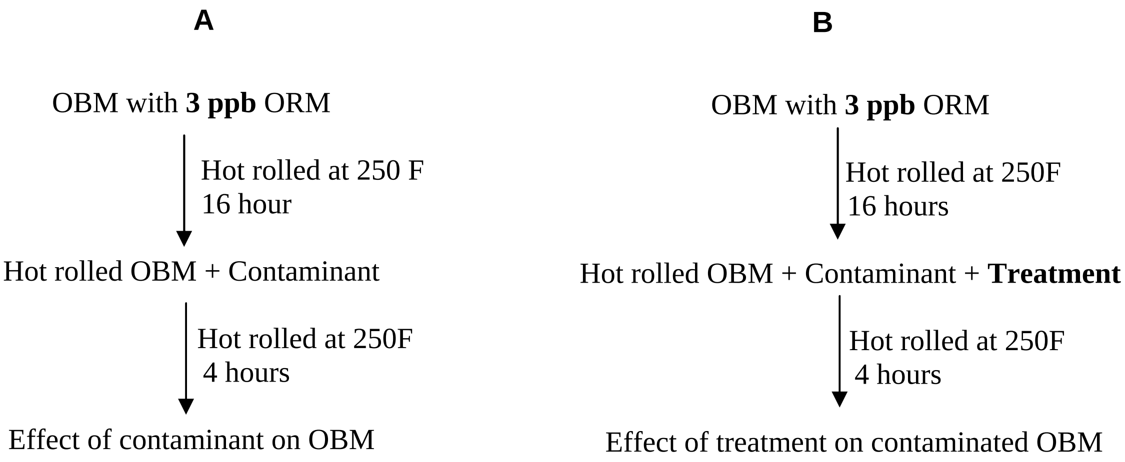
1. Portnoy, R.C. et al.: “Novel Polymeric Oil Mud Viscosifier for High Temperature Drilling.” IADC/SPE 14795, IADC/SPE Drilling Conference and Exhibition, Dallas, February 10-12, 1986.
2. Patel, A.D. and Salandanan, C.S.: “Thermally Stable Polymeric

Gellant for Oil-Base Drilling Fluids." SPE 13560, SPE International Symposium on Oilfield and Geothermal Chemistry, Phoenix, April 9-11, 1985.
3. 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.
4. Beck, F.E. et al.: "The Effect of Rheology on Rate of Penetration." SPE/IADC 29368, SPE/IADC Drilling Conference and Exhibition, Amsterdam, February 28 – March 2, 1995.
5. Bern, P.A. et al.: "The Influence of Drilling Variables on Barite Sag." SPE 36670, SPE Annual Technical Conference and Exhibition, Denver, October 6-9, 1996.
6. Okrajni, S.S. and Azar, J.J.: "The Effects of Mud Rheology on Annular Hole Cleaning in Directional Wells." *SPEDE*, (August 1986) 297-308.
7. Becker, T.E., Azar, J.J. and Okrajni, S.S.: "Correlations of Mud Rheological Properties with Current Transport Performance in Directional Drilling." *SPEDE*, (Mar 1991) 16-24.
8. 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.
9. Kirsner, J. et al.: "Method of formulating and using a drilling mud with fragile gels." US patent 7278485, 2004.

Table 1: Test formulations of 9.0 / 10.0 / 12.0 / 18.0 ppg fluids

Products	**Concentration ppb**	**Time min**
BASE OIL	As required	
Invert emulsifier, ppb	8/8/9/14	2
HTHP Invert emulsifier, ppb	-/-/1/2	2
Lime, ppb	3/1.5/3/3	2
Polymeric viscosifier, ppb	3	2
Filtration control agent, ppb	1.5/1.5/3/-	5
HPHT filtration control agent, ppb	-/-/-/3	5
ORM, ppb	1-6	5
$CaCl_2$ solution, ppb	As required	2
Inorganic rheology modifier, ppb	5/-/5/-	5
Drilled solids, ppb	20	5
Barite, ppb	As required	10
Sized $CaCO_3$ (D50 = 5 microns), ppb	20/-/50/-	10

Testing Scheme I: Contamination studies for the 9.0 ppg oil based IEF



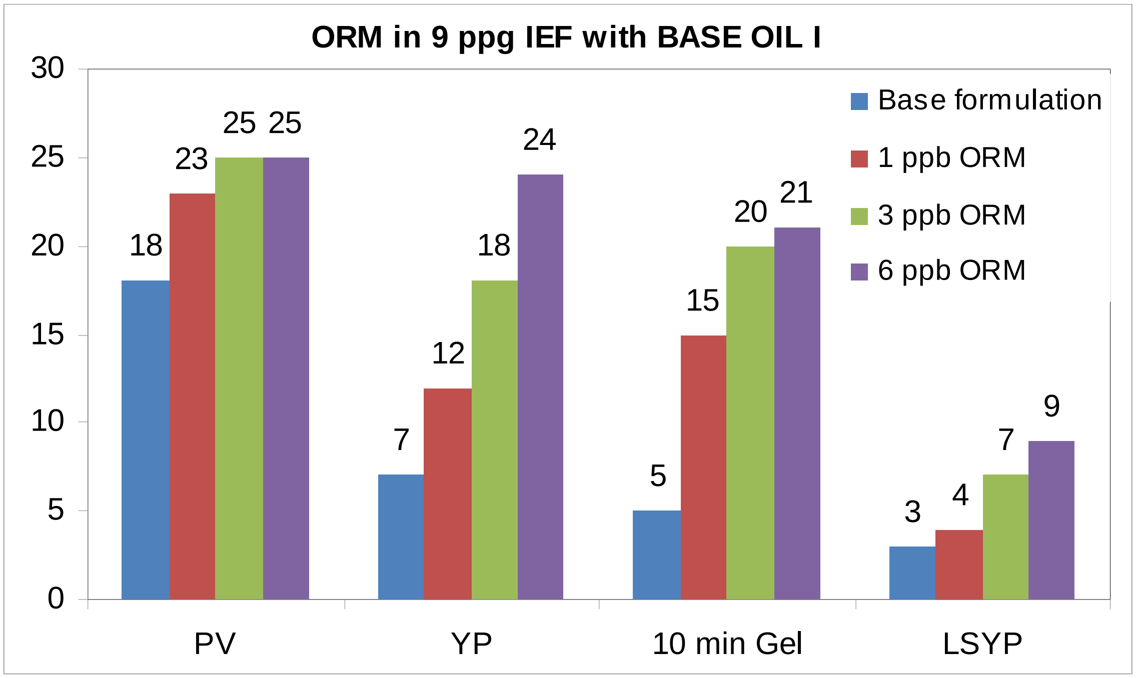


Figure 1: Effect of ORM on rheology of 9.0 ppg IEF with BASE OIL I

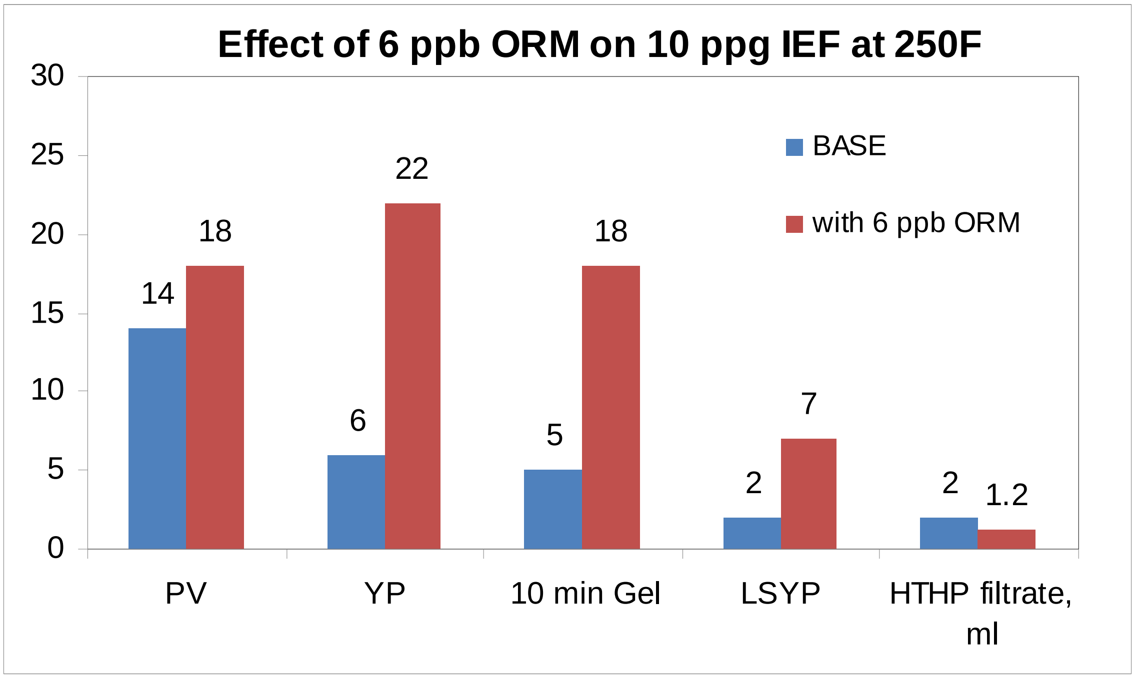


Figure 2: Performance of ORM in BASE OIL III based 10.0 ppg IEF at 250F

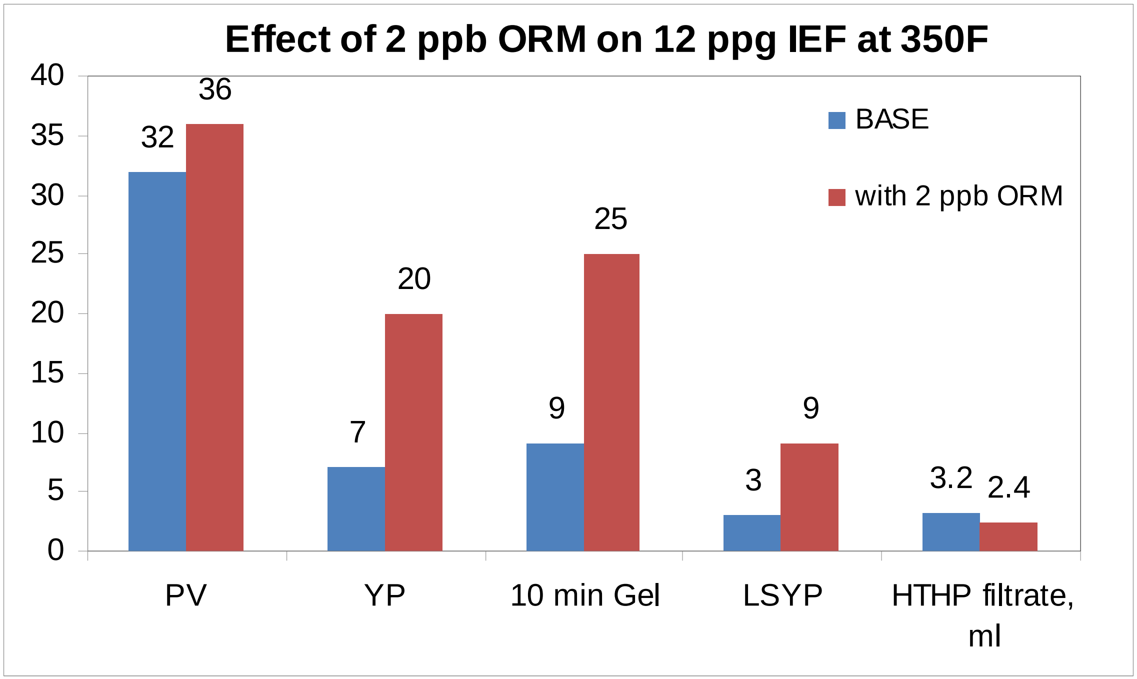


Figure 3: Performance of ORM in BASE OIL I based 12.0 ppg IEF at 350F

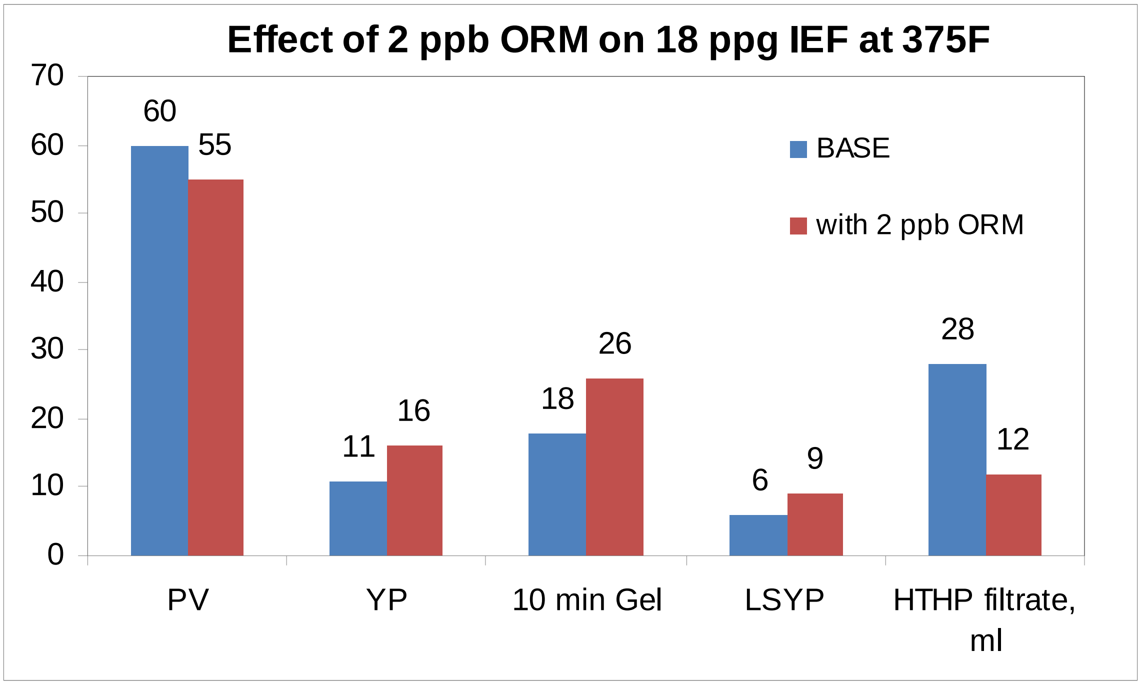


Figure 4: Performance of ORM in BASE OIL I based 18.0 ppg IEF at 375F

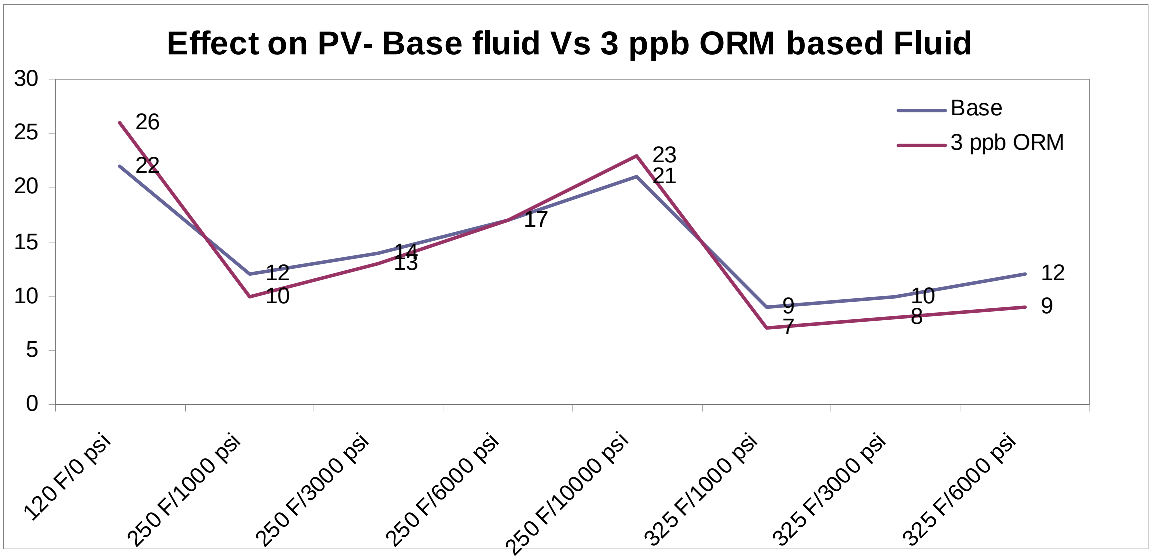


Figure 5a: Effect of ORM on PV of 9.0 ppg IEF under high temperature and high pressure conditions

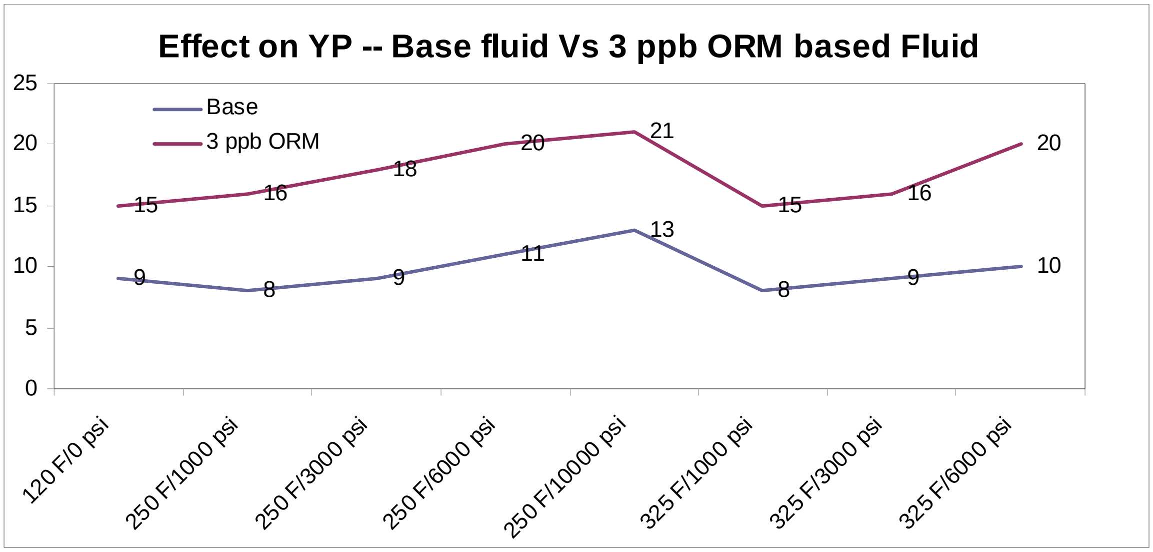


Figure 5b: Effect of ORM on YP of 9.0. ppg IEF under high temperature and high pressure conditions

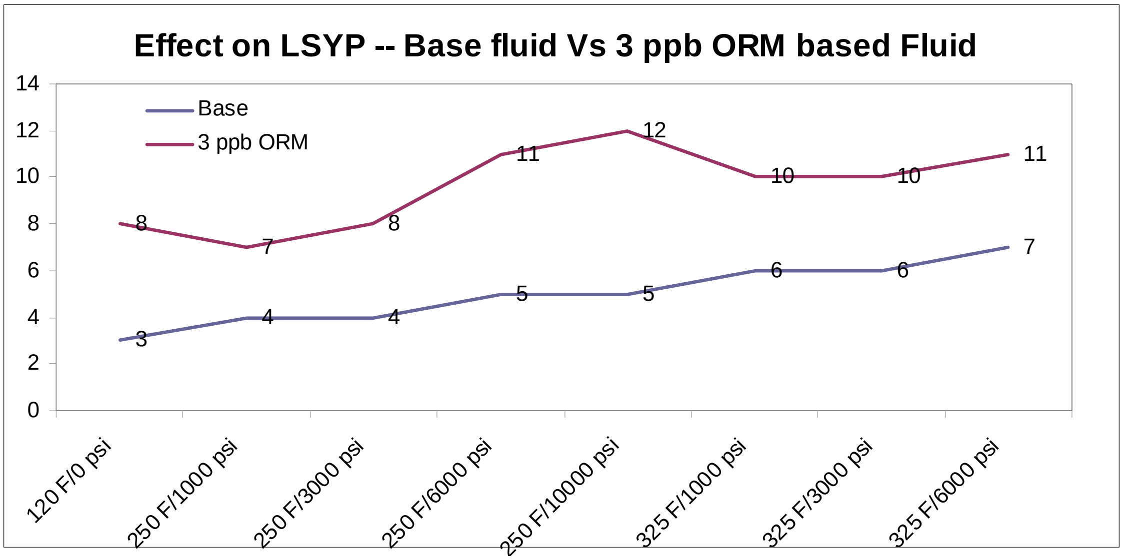


Figure 5c: Effect of ORM on LSYP of 9.0 ppg IEF under high temperature and high pressure conditions

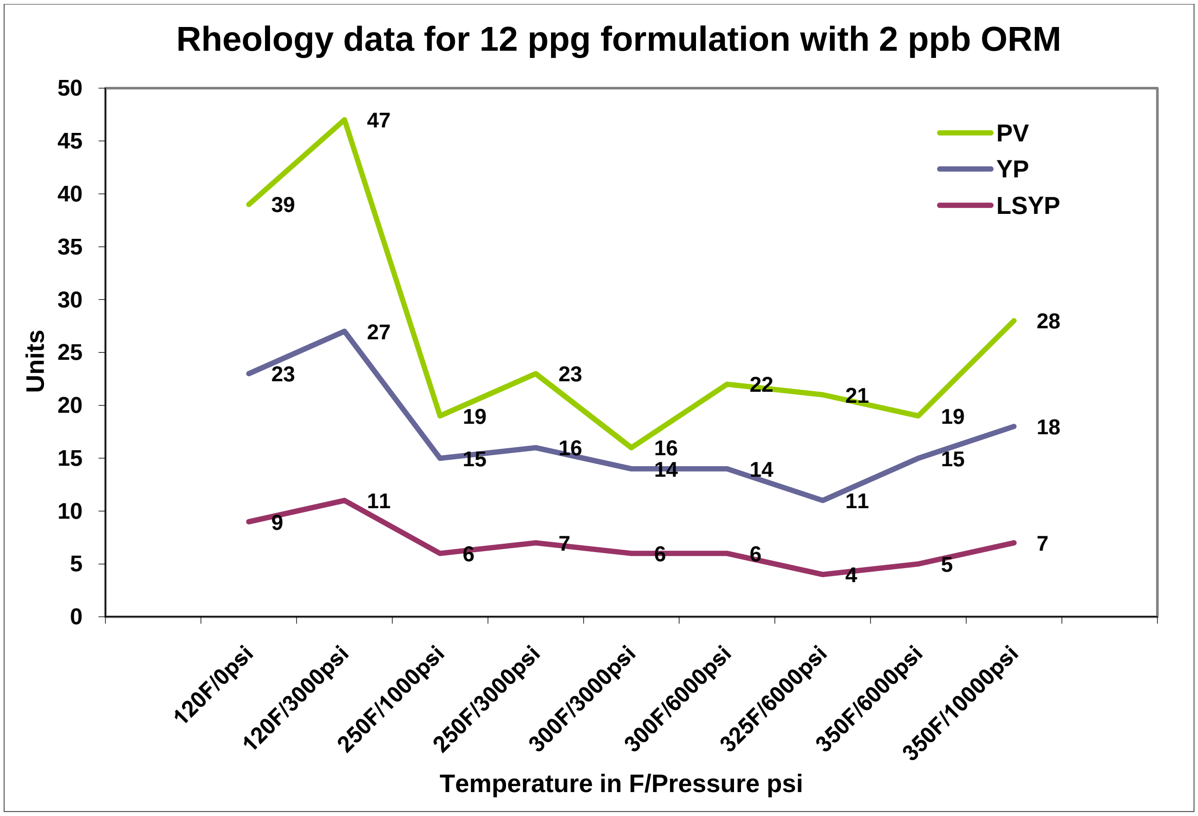


Figure 6: Effect of ORM on PV, YP and LSYP of 12.0 ppg IEF under high temperature and high pressure conditions

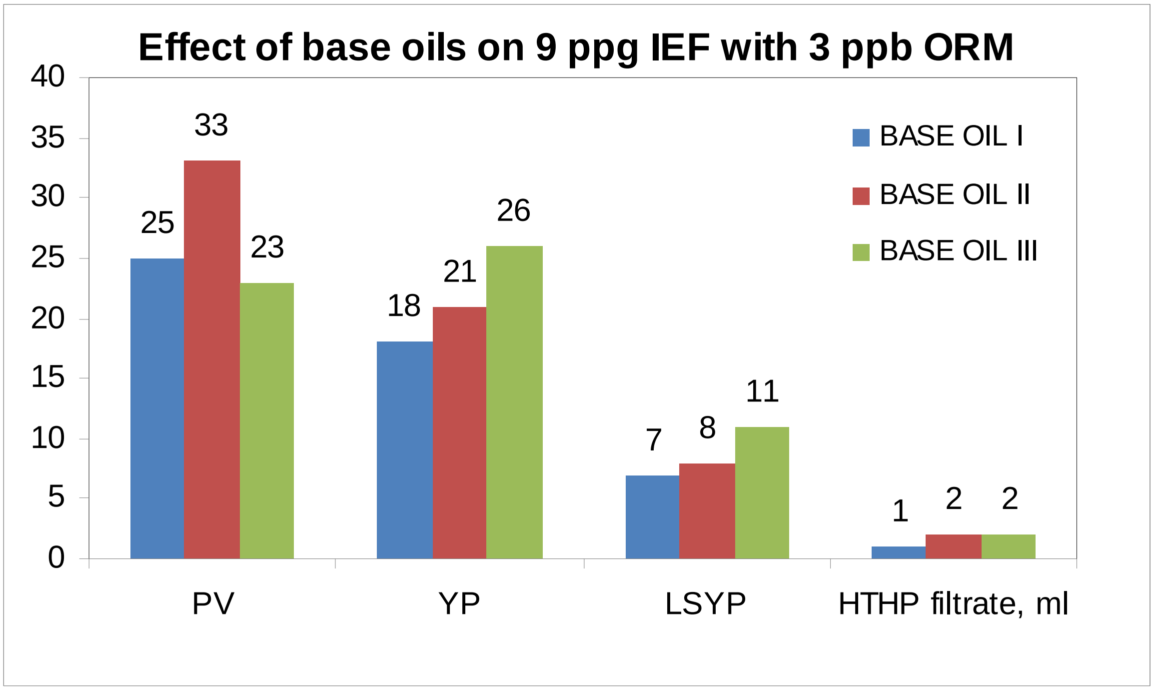


Figure 7: Performance of ORM in different mineral oils for 9.0 ppg INNOVERT® IEF

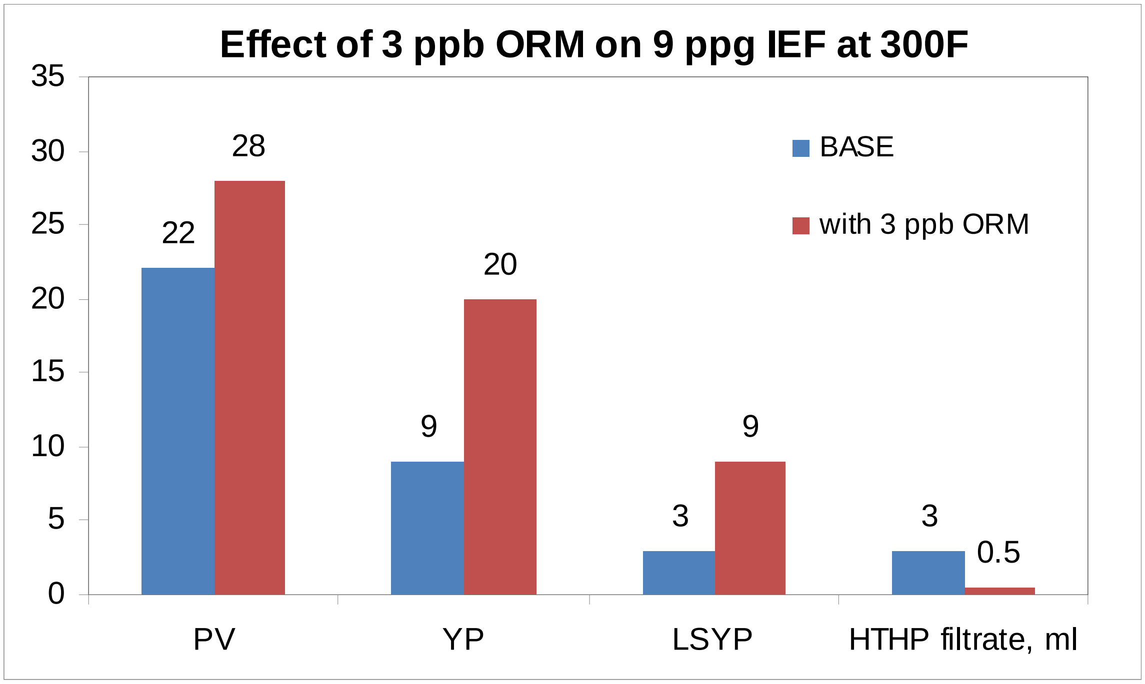


Figure 8: Performance of ORM in BASE OIL I based 9.0 ppg IEF at 300F

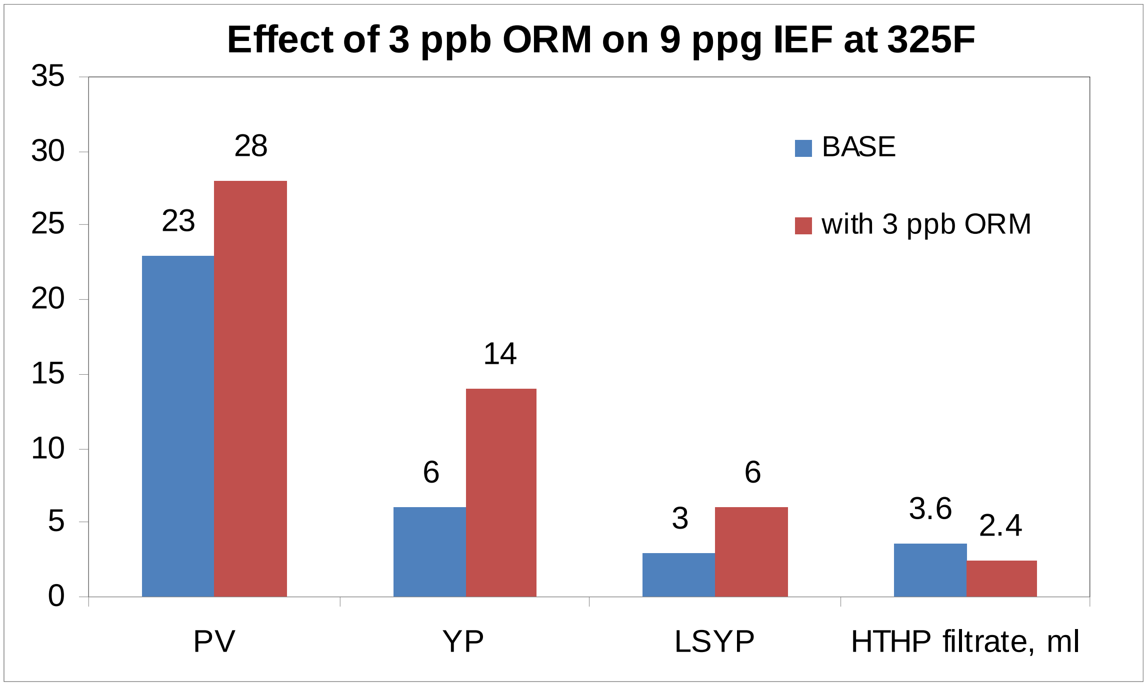


Figure 9: Performance of ORM in BASE OIL I based 9.0 ppg IEF at 325F

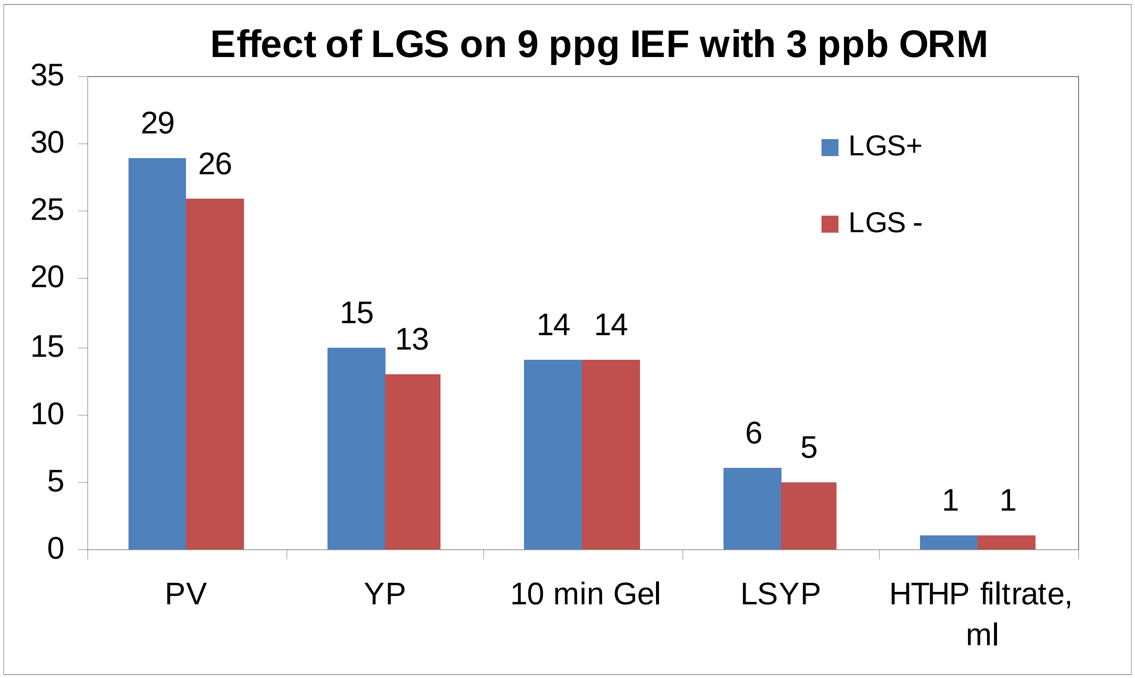


Figure 10: Performance of ORM in BASE OIL I based 9.0 ppg IEF in the presence and absence of LGS at 250F

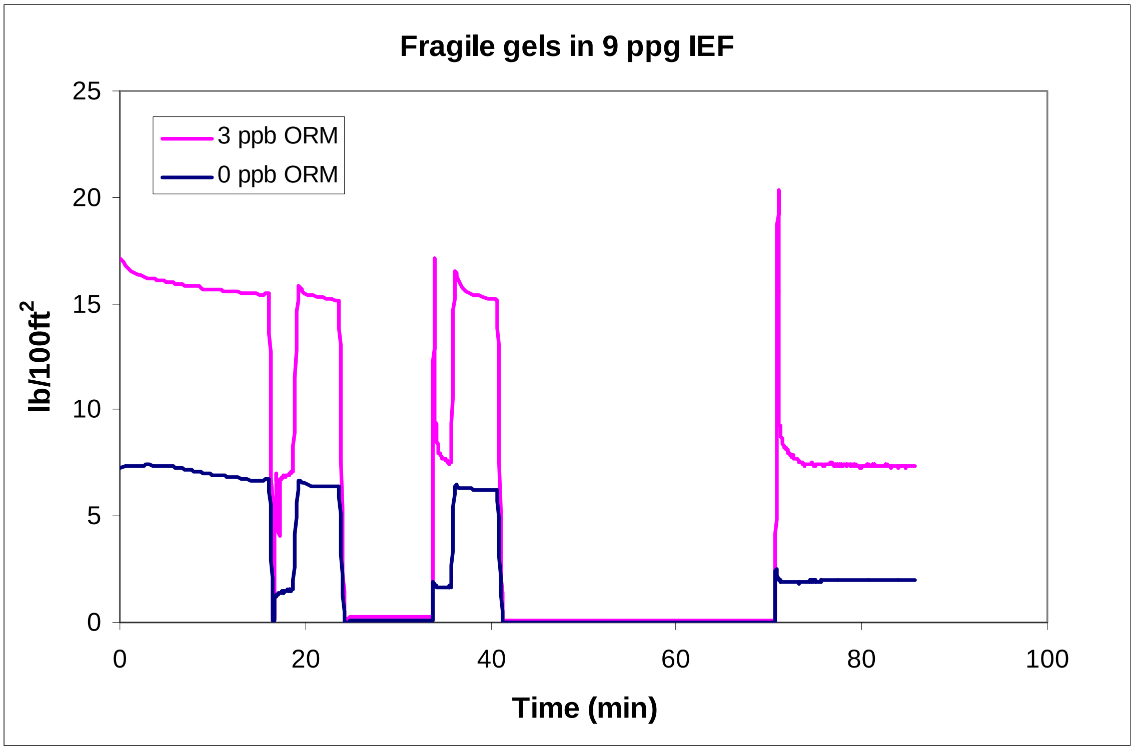


Figure 11: Fragile gels in 9.0 ppg IEF with 3.0 ppb ORM

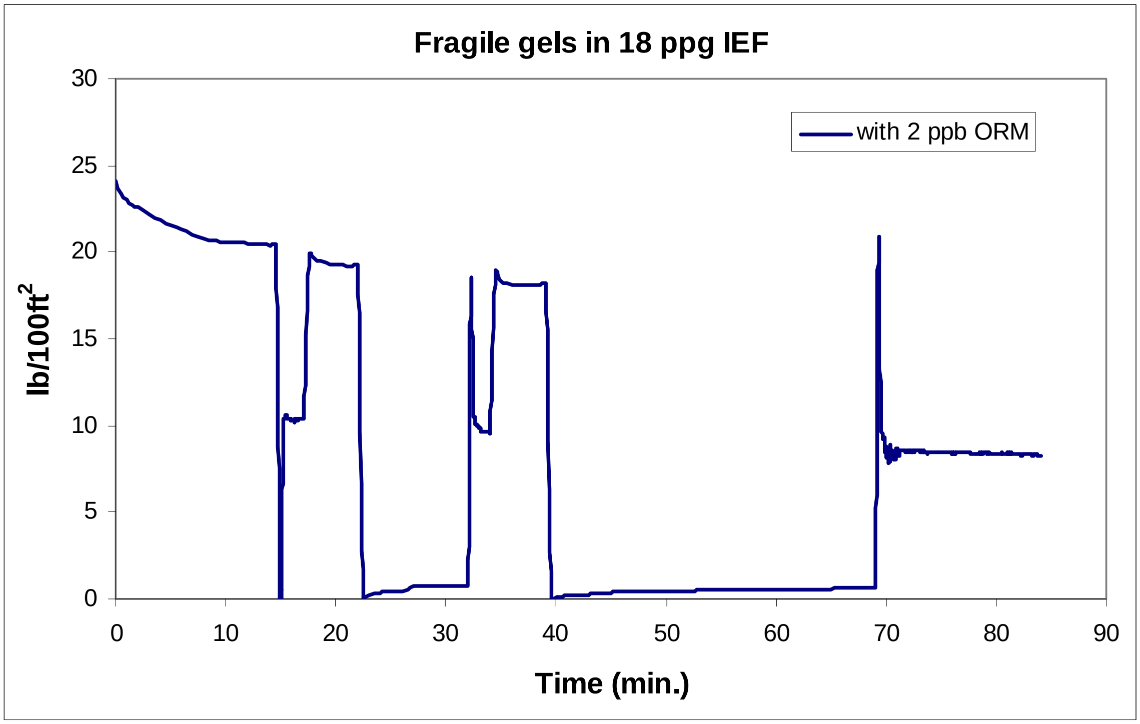


Figure 12: Fragile gels in 18.0 ppg IEF with 2.0 ppb ORM

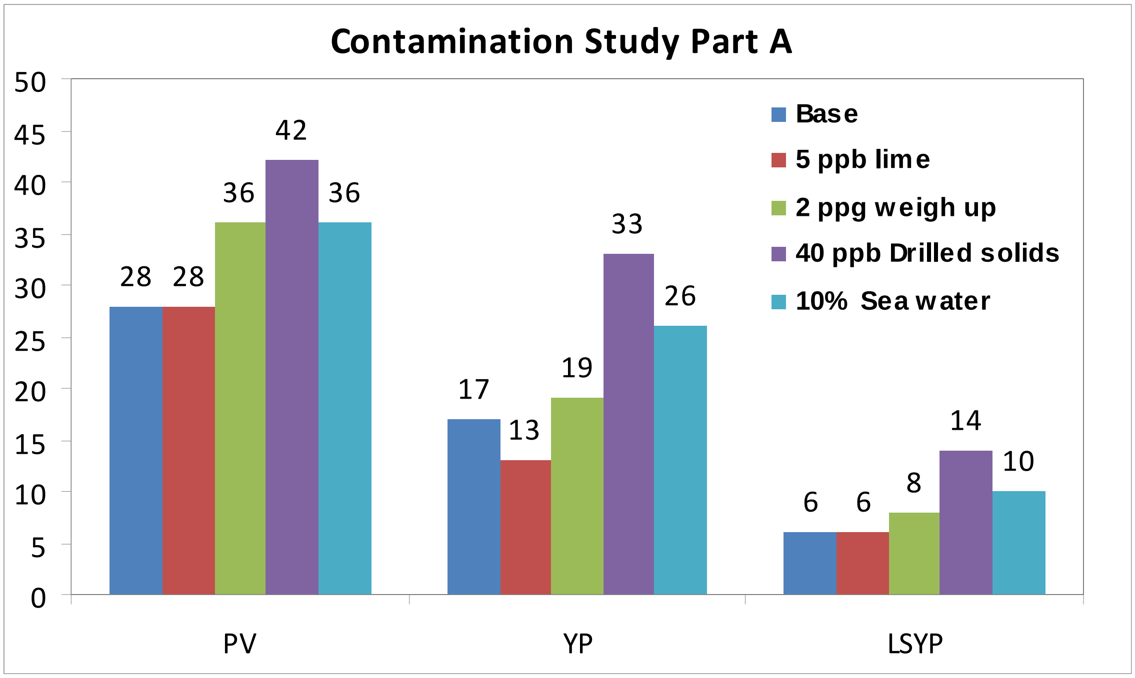


Figure 13(a): Effect of contaminants in 9.0 ppg IEF with BASE OIL I at 250F

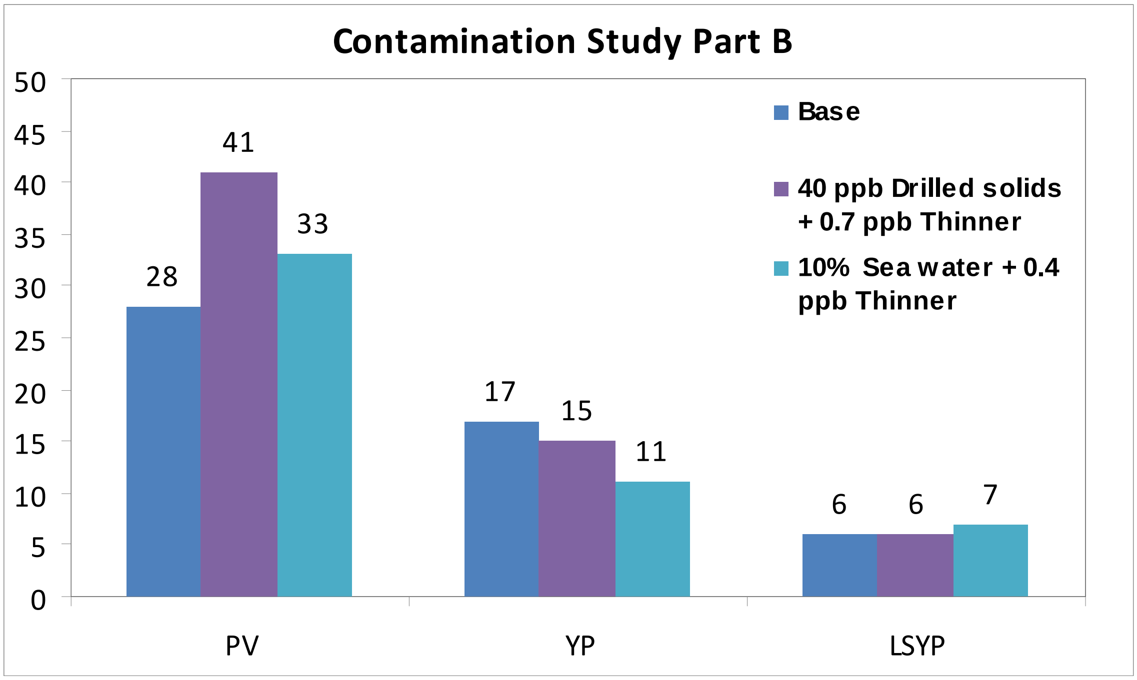


Figure 13(b): Effect of the treatments on the contaminated 9.0 ppg IEF with BASE OIL I at 250F

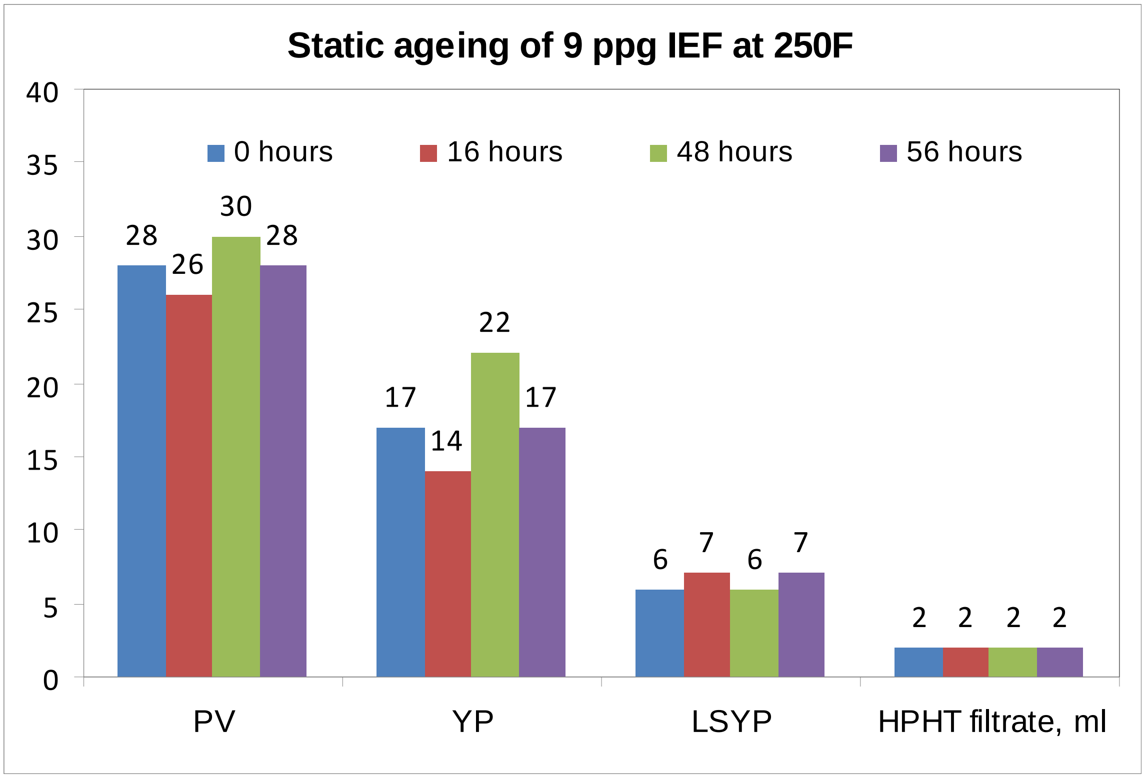


Figure 14: Static ageing studies of 9.0 ppg IEF with BASE OIL I at 250F