AADE-13-FTCE-16

Making Good HP/HT Invert Emulsion Drilling Fluids Great and Green

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Abstract

An efficient invert emulsion fluid (IEF) has key attributes for improved performance: enhanced low-end rheology to provide suspension for barite and drill cuttings; low plastic viscosity (PV) to limit equivalent circulating density (ECD); a high yield point (YP)-to-PV ratio for improved hole cleaning; fragile gels to negate surge and swab pressures; sag resistance; performance in high-pressure/high-temperature (HP/HT) conditions and environmentally friendly components. The newly developed IEF is essentially free of organoclay, low-gravity solids (LGS) and salt. This paper outlines its three-phase development.

First, a novel polymeric rheology modifier (RM) was developed that provided enhanced rheology to the clay-free IEF with a tau0 value of > 6 (yield stress parameter from the Herschel-Bulkley model), considered satisfactory for drilling. A high tau0 value is difficult to attain with available non-clay RMs.

Next, a new polymeric suspension agent (SA) was added, which provided sag resistance with small effect on overall rheology. Static ageing of 12.0-ppg fluids for 48 hours at 250°F and 72 hours at 150°F showed no oil separation and insignificant change in the bottom density. The absence of LGS resulted in lower PV than other IEFs.

Lastly, the internal-phase calcium-chloride brine was replaced with a biodegradable salt-free liquid. The so developed salt-free, clay-free and LGS-free IEF showed improved rheology and sag resistance at temperatures up to 300°F. The new IEF exhibited high YP, low PV, and fragile gels, and it performed well under HP/HT conditions.

Toxicity and biodegradability testing on the RM, SA and salt-free internal phase show that the fluids formulated with these additives can be used in regions with stringent environmental regulations.

Introduction

Over the last decade, organo-clay-free invert emulsion drilling fluids have become popular. Improved wellbore stability, high rate of penetration (ROP), fragile gels, reduction in downhole losses during drilling, and increased tolerance to contamination are some of the many benefits associated with organo-clay free IEFs.[1,2]

However, in the absence of organo-clay, 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 resistant to barite sag. The commonly occurring problems due to barite sag are mud weight gradient, stuck pipe, wellbore instability, lost circulation, differential sticking and well control difficulties. In the organo-clay-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 improves the yield point (YP) but at the same time 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.[3,4] Research on drilling fluids has concentrated on developing additives and systems that minimize sag in the IEF by controlling the rheology of the IEF.[5,6] 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.[5] Thus, it is desirable to develop sag-resistance in the IEF without significantly increasing its viscosity.

Also, though the IEFs provide excellent wellbore stability, they incorporate an aqueous solution of inorganic salt, such as calcium chloride to provide wellbore stability. The calcium chloride in water dissociates into positively-charged cations and negatively-charged anions. These ions bind water molecules which decreases the water activity of the aqueous salt solution. As the concentration of the salt increases, the water activity decreases further. While drilling through shale, the water activity of the IEF is maintained at a lower level than the water activity of the shale, creating an osmotic pressure which drives flow of water from the shale to the IEF, thereby preventing shale hydration.[7]

However, the use of inorganic salts to maintain water activity poses cuttings disposal challenges. Even when the treated oil-based cuttings are mixed with the soil for purpose of land farming, this mix still exhibits high electrical conductivity due to the presence of salts, rendering the mix unsuitable for agriculture. Since the inorganics are non-degradable[8,9,10], the cuttings can be treated to a point lower than toxic limits via dilution. However, this does not eliminate the problem.[11,12] Thus, there is a need to replace the internal inorganic salt solution phase with an internal phase which is biodegradable.

To eliminate the problem associated with using excessive LGS and non-biodegradable calcium chloride internal phase, a new organo-clay-free, LGS-free and salt-free IEF has been developed which employs a novel organic rheology modifier (RM), sag-control additive (SA) and a biodegradable hygroscopic internal phase (HL). The use of the rheology modifier and sag-control additive eliminates the use of excessive LGS needed to get optimal rheology in low to medium density organo-clay-free IEF, while the use of a biodegradable internal phase eliminates the problem of cuttings disposal associated with calcium chloride based internal phase.

This paper presents a three-stage development of the novel LGS-free, salt-free IEF

1. Formulation of an LGS-based organo-clay-free IEF using RM
2. Formulation of an LGS-free organo-clay-free IEF using RM and SA
3. Formulation of LGS-free salt-free organo-clay-free IEF using RM, SA and HL.

The paper discusses the salt-free, LGS-free IEF in terms of fluid performance, shale stability, tolerance to contamination, tolerance to static ageing, HTHP rheology, fragile gel measurements and environmental impact.

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 oil used for the study was a naphthenic oil containing a high content of cyclic alkanes. The concentration of products required to formulate the IEFs were estimated with a proprietary numerical simulator

The flow of experiments 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 Instrument Company 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; oven Model 705ES from FANN Instrument.
3. After hot rolling, 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 mins and placed in HPHT SS cells. The cells were placed in an upright position and static aged in a mechanical convection oven with application of pressure as per API 13B-2; oven model MO1490SC-1 is available from Thermoelectron Corporation.
5. After static ageing, 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 ageing 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 mins. The rheology of the IEFs was then determined at 120^{o}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 tests were performed as per API 13B-2 recommendations. The HPHT rheology was determined on a commercially available HPHT rheometer.

The sag factor for the static aged IEFs was calculated as shown below (**Equation 1**):

$$SagFactor = \frac{SG_{bottom}}{SG_{bottom} + SG_{top}} \quad \text{.....................} 1$$

A sag factor greater than 0.53 implies that the fluid has potential to sag.[13]

The rheology of the fluid was characterized in terms of plastic viscosity (PV), yield point (YP), and low shear yield point (LSYP). The YP and PV are parameters from the Bingham Plastic (BP) rheology model. The YP is determined by extrapolating the BP model to a shear rate of zero, and 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 2** and **3** respectively. 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 proposed to deliver a sag-resistant IEF. The Tau0 can be estimated reasonably by calculating the LSYP value from **Equation 4.**

PV = (600 rpm reading) – (300 rpm reading) 2
YP = (300 rpm reading) – PV 3
LSYP = [2×(3 rpm reading)] – (6 rpm reading)........... 4

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 12-ppg IEFs were formulated at 70/30 OWR in the presence of polymeric rheology modifier, suspension agent and 60% w/w hygroscopic liquid sequentially to show the development of the final fluid. The mixing order, concentration and mixing time of the products are given in **Table 1**.

I. LGS based organo-clay free IEF with RM

The 12-ppg IEF was formulated with 5ppb RM, drilled solids and 250K WPS $CaCl_2$. The fluids were hot rolled at 250°F followed by static ageing at 250°F for 24hrs. Three fluids were prepared with increasing concentrations of drilled solids. The mud properties are given in **Table 2**. The fluid with 0ppb drilled solids designated as Fluid 1a was considered as the base fluid. Fluid 1b and 1c contained 10ppb and 20ppb drilled solids respectively.

Fluid 1a (base fluid) showed a YP of 11 and LSYP of 3. After static ageing barite sag was observed at the bottom of the ageing cell. Oil separation was quite high: 100ml with a sag factor of 0.68.

Fluid 1b was formulated with 10ppb drilled solids. The increase in PV, YP and LSYP was 26%, 18% and 0% respectively when compared to the base fluid. Oil separation was again high at 75ml with a sag factor of 0.68.

Fluid 1c was formulated with 20ppb drilled solids and the increase in PV, YP and LSYP was 40%, 62% and 167% respectively as compared to Fluid 1b. Static aging of this fluid at 250°F showed negligible oil separation with a sag factor of 0.5

The HPHT fluid loss for all the fluids was less than 2ml. The synergistic interaction of drilled solids and RM increased the overall rheology of the IEF with no barite sag, but addition of LGS increased the PV of the IEF which may lead to high ECD.

A novel suspension agent (SA) was developed as the next step to eliminate the need for any type of LGS in the IEF.

II. LGS-free organo-clay-free IEF with suspension agent (SA) and rheology modifier (RM)

The 12-ppg IEF was formulated with 3ppb SA, 3ppb RM and 250K WPS $CaCl_2$. The mud properties are shown in **Table 3 (Fluid 2)**. The 3ppb SA treated 12-ppg IEF was static aged for 24 hours at 250°F and then at 300°F.

After static ageing at 250°F for 24 hours, the SA treated 12-ppg IEF gave a sag factor of 0.5 without top oil separation. The rheology of SA treated 12-ppg 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 treated IEF resulted in greater emulsion stability and prevented barite from sagging.

Fluid 2 was then subjected to static ageing for 24 hours at 300°F. The static ageing at high temperature gave a sag factor of 0.501 and top oil separation of 2ml. The rheology of this IEF decreased a little 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 HPHT fluid loss obtained in all the fluids was less than 2ml. Thus the above fluid was formulated successfully in the absence of any LGS or organo-clay.

As the next step, the internal phase of the IEF – 250K WPS $CaCl_2$ – was to be replaced with an environmentally friendly, less toxic and more biodegradable alternative.

III. Salt-free, LGS-free, organo-clay-free IEF with 60% w/w hygroscopic liquid (HL), suspension agent (SA) and rheology modifier (RM)

To develop a more environmentally acceptable fluid it was imperative to replace the existing $CaCl_2$ internal phase with an alternative that had a better environmental profile. A hygroscopic liquid was chosen as an alternative. The biodegradation and toxicity values for the HL were compared with $CaCl_2$ and are shown in **Table 4**. The HL achieves 60% biodegradability in 10 days as compared to $CaCl_2$ which is not biodegradable. The toxicity values for different organism were higher for the $CaCl_2$ internal phase than the HL.

The formulation for this 12-ppg salt-free LGS-free organoclay-free IEF along with the mixing order and mixing time are given in Table 1 (Fluid 3).

This IEF was formulated using 60% w/w hygroscopic liquid (HL) as the internal phase, 5ppb SA and 3ppb RM. A 60% w/w HL concentration was chosen as a replacement for 250Kppm $CaCl_2$ solution since both the solutions show a similar water activity of 0.75.

The fluids, after hot rolling at 250°F, were subjected to static ageing at 250°F and at 300°F for 24hrs. It was observed that both the static aged fluids provided no oil separation or barite settling; A sag factor of 0.5 was obtained when these fluids were tested. The rheological properties of the IEF are given in **Table 5**. The PV, YP, LSYP and fluid loss values of this IEF remained almost consistent throughout the static ageing studies. Gel strengths at 10sec and 10min remained unchanged.

A. Performance of Salt free-LGS free organo-clay free IEF under HPHT

The performance of 12-ppg salt-free, LGS-free, organo-clay-free IEF was evaluated on a FANN® 75 HPHT rheometer under HPHT conditions (**Figure 1**). The test pressures varied from 1000-10,000 psi for a temperature range of 250°F to 300°F.

The PV varied from 26 to 22 across the pressure and temperature range whereas the YP and LSYP varied from 11 to 5 and 6 to 9 respectively. It is interesting to see that under HPHT conditions, the LSYP was similar to YP and at times higher. Since YP and LSYP are derived from different models, a low YP should not be construed as unsuitable for hole cleaning since under the same conditions of temperature and pressure the fluid had a sufficiently high LSYP to perform functions of hole cleaning and suspension. The PV of the fluid was low and almost constant under HPHT.

B. Contamination study

As the next step in the development, the IEF was subjected to contamination study. The contamination protocol is given below.

1. Hot roll the IEF at 250°F for 16 hrs.
2. Measure the HPHT fluid loss and the rheology.
3. Mix the IEF with the contaminants for 5 min.
4. Hot roll the IEF at 250°F for 4 hrs.
5. Measure the HPHT fluid loss and the rheology.

The contaminants used in the study were 40.0 ppb of artificial drilled solids, 10% seawater, a 2.0-ppg weight up with barite, and 5.0 ppb lime. The contamination testing results are presented in **Figure 2.**

(i) 5ppb lime: An overall decrease in rheological properties was observed after contaminating the fluid with 5ppb lime. The decrease in PV, YP and LSYP obtained were 13%, 31% and 40% respectively. However, these lower values can be treated easily with the RM and SA to restore the fluids close to its original values.

For all the other contaminants an increase in rheological properties were observed.

(ii) 40ppb drilled solids: Contaminating the fluid with 40ppb drilled solids provided an increase of 27%, 31% and 60% respectively in PV, YP and LSYP.

(iii) 2-ppg weigh up: Weighting up the fluid with 2ppg showed an increase of 24%, 25% and 20% in PV, YP and LSYP respectively.

(iv) 10% sea water: The salt-free, LGS-free IEF contaminated with 10% sea water exhibited an increase of 3%, 50% and 60% respectively in PV, YP and LSYP.

For all the contaminants, the HPHT fluid loss at 250°F was minimal, about 2ml

C. Fragile gel character

A "fragile" gel is easily disrupted or thinned, and liquefies or becomes less gel-like and more liquid-like under stress. These fragile gels are easily disrupted with a pressure wave or a compression wave during drilling, helping to prevent induced fractures that initiate fluid loss to the formation especially due to surge and swab pressures. These fragile gels require lower surface pressures to break gels thereby eliminating the need to modify fluid rheology before running casing.

Brookfield measurements to determine fragile gel values were performed for the 12-ppg salt-free, LGS-free organo-clay free IEF. Steps in this experiment on the Brookfield viscometer are as follows:

1. The fluid is first stirred at 100 rpm to break any gel structure formed
2. The gel peaks are measured at a shear rate of ½ rpm (viscosity is recorded once per second) after 10-second, 10-minute, and 30-min static intervals.
3. Following the gel peaks, the fluid viscosity is measured at the same shear rate before stirring again at 100 rpm to break up the gel

The viscosity versus time profiles for the fluid are shown in **Figure 3**. A gel peak of greater than 5 viscosity units after a 30-min interval is usually taken as the presence of fragile gels. The height of the gel peak is proportional to the amount of gel formed—the higher the peak the more gel build up. In Figure 3, after the 30-min gel peak (about 10 viscosity units) the viscosity curves falls down rapidly with application of shear rate of ½ rpm and then viscosity curve levels off. This indicates lesser resistance of the fluid to the stress and lower pressure required to move the fluid. It can be concluded that the salt-free, LGS-free IEF demonstrated fragile gel character.

D. Shale Stability Studies.

One of the fundamental concerns while drilling is the prevention of shale erosion. The shale-erosion test is used to measure the dispersive effect that a mud will have on a specific type of shale. Typically, 30 gm of oven-dried shale cuttings, sized between US#5 and US#10, are hot rolled with the drilling fluid at 150°F for 16 hrs. These shale cuttings are then screened through US#10 and then washed, dried, and weighed to obtain the percent erosion of the shale. The initial moisture content is taken into account when calculating percent erosion (**Equation 5**):

$$\%\,Shale\,Erosion = \left[100 - \frac{Weight\,of\,the\,retained\,shale\,cuttings}{Original\ weight\ of\ the\ cuttings}\right]\times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots 5$$

Shale-erosion studies were performed on London clay outcrop cuttings with 12.0-ppg salt-free, LGS-free, organo-clay-free IEF formulated with HL at 60% w/w internal phase concentrations. The XRD composition of the London clay outcrop cuttings is shown in **Table 6**.

The 12.0-ppg salt-free IEF formulated with 60% w/w HL concentration showed a shale erosion value of 0.9%. A low shale-erosion value of 0.9% shows that the salt-free IEF with 60% w/w HL internal phase concentration demonstrates good shale stability.

E. Environmental performance of RM and SA

Both the RM and SA additives were subjected to biodegradability and eco-toxicity studies. The biodegradability and eco-toxicity data for RM and SA is given in **Table 7**. The RM and SA were subjected to marine biodegradation assessment by the BODIS method where biodegradation was recorded every week, up to 35 and 45 days respectively. The eco-toxicity studies of RM and SA were performed in the presence of marine juvenile fish *Cyprinodon variegatus*, marine copepod *Acartia Tonsa* and marine algae *Skeletonema costatum* in seawater. The test methods for *Cyprinodon* *variegatus* fish are consistent with OECD 203 guideline for marine testing of offshore chemicals. The test methods for copepods *Acartia Tonsa* are consistent with ISO 14669:1999(E) guideline for marine testing of offshore chemicals while the test methods for algae *Skeletonema costatum* were consistent with ISO 10253:2006, OECD guideline as adapted for marine testing of offshore chemicals.

North Sea regulations require an offshore chemical to show a LC50 value of >10mg/L and a biodegradability of >60% to be classified as Yellow – suitable to use in North Sea. Therefore the RM and SA additives are North Sea compliant since they not only show an LC50 value greater than 10mg/L for each of the toxicity tests but also show biodegradability in excess of 60%.

Conclusions

1. The polymeric rheology modifier (RM) imparted enhanced yield point, low shear yield point and gel strengths to the clay-free invert emulsion fluids without significantly affecting its plastic viscosity.
2. Stable LGS-free IEFs were formulated with a novel suspension agent (SA) and a novel organic rheology modifier (RM), with minimal oil separation and a sag factor close to 0.5
3. A stable salt free, LGS-free, organo-clay-free IEF was prepared with aqueous hygroscopic liquid (HL), a suspension agent (SA) and a polymeric rheology modifier (RM). Static aging of this fluid at 300°F provided no oil separation and a sag factor close to 0.5. The formulated fluid showed excellent fluid loss control.
4. Salt-free, LGS-free IEF showed consistent YP and LSYP values at HPHT conditions across a range of temperatures and pressures.
5. The salt-free, LGS-free, organo-clay-free IEF showed tolerance to contaminants. Deviations from the original properties can be restored with conventional thinners or RM and SA.
6. The salt-free, LGS-free, organo-clay-free IEF demonstrated fragile gels.
7. The salt-free, LGS-free, organo-clay-free IEF demonstrated good shale stability.
8. Environmental studies show that the IEF formulated with RM, SA and HL can be used in regions with stringent environmental regulations.

Acknowledgements

The authors would like to thank the management of Halliburton for permission to present the work. We would also like to thank the Technical Paper Review Board of Halliburton for reviewing this manuscript.

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*
RM =*Organic rheology modifier*
SA =*Suspension agent*
HL =*Hygroscopic liquid*
NOEC = *No observed effect concentration*
LC_{50} = *Lethal dose required to kill 50% of the organisms*

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Table 1: Mixing order, concentration and mixing time of products

12-ppg 70/30 OWR	Mixing Time, min	Fluid 1a/1b/1c	Fluid 2	Fluid 3
Base oil, ppb		As required	As required	As required
Invert emulsifier, ppb	2	10	10	10
Lime, ppb	2	1.5	1.5	0.75
Invert Viscosifier, ppb	2	3	3	3
Filtration control agent, ppb	5	2	2	4
SA, ppb	5	-	3	5
Water phase salinity (WPS) in ppm of $CaCl_2$	5	250,000	250,000	-
60% w/w HL, ppb	5	-	-	As required
Drilled Solids, ppb	5	0/10/20	-	-
Barite, ppb	10	As required	As required	As required
RM, ppb	2	5	3	3
Hot roll temperature 250°F for 16 hours				

Table 2: Performance of RM in 12-ppg IEF; 70/30 OWR; Static aged @ 250°F for 24 hrs.

Enhanced Rheology with RM			
12ppg 70/30 OWR	**Fluid 1a**	**Fluid 1b**	**Fluid 1c**
600 rpm	41	51	75
300 rpm	26	32	48
200 rpm	20	24	37
100 rpm	14	16	25
6 rpm	5	5	8
3 rpm	4	4	8
PV	15	19	27
YP	11	13	21
LSYP	3	3	8
Gels 10 sec/10 min	5/5	6/10	11/23
HTHP fluid loss, ml/30min	2	2	1.6
Bottom Mud weight, ppg	14.5	14.3	12.0
Sag factor	0.68	0.68	0.501
Oil separation, ml	100	75	0.5

Table 3: Performance of SA in 12-ppg IEF; 70/30 OWR

LGS free IEF with SA and RM			
12-ppg 70/30 OWR	**Fluid 2**	**Fluid 2 Static aged @250°F, 24hrs**	**Fluid 2 Static aged @300°F, 24hrs**
600 rpm	55	58	50
300 rpm	34	36	31
200 rpm	25	28	23
100 rpm	17	18	16
6 rpm	5	5	5
3 rpm	4	5	4
PV	21	22	19
YP	13	14	12
LSYP	3	5	3
Gels 10 sec/10 min	5/10	5/16	5/7
HTHP fluid loss, ml/30min	2	2	1.6
Bottom Mud weight, ppg		12.0	12.0
Sag factor		0.5	0.501
Oil separation, ml		1	2

Table 4: Eco toxicity and Biodegradability studies of HL

Biodegradation and Toxicity profile of $CaCl_2$ and HL				
	Biodegradation (Method OECD 301)	**Toxicity against Rats LD50**	**Aquatic Toxicity (Fish) LC50**	**Invertebrate toxicity (Daphnia Magna) LC50**
$CaCl_2$	Non-biodegradable	1g/kg	0.1g/kg	0.76–3g/kg
HL	60% in 10 days	12.6g/kg	5g/kg	15.3g/kg

Table 5: Performance of 60% w/w HL in 12-ppg IEF; 70/30 OWR

Salt free-LGS free IEF with 60% w/w HL, SA and RM			
12-ppg 70/30 OWR	**Fluid 3**	**Fluid 3 Static aged @250°F, 24hrs**	**Fluid 3 Static aged @300°F, 24hrs**
600 rpm	90	79	81
300 rpm	53	48	50
200 rpm	40	37	40
100 rpm	26	24	28

Salt free-LGS free IEF with 60% w/w HL, SA and RM			
12-ppg 70/30 OWR	**Fluid 3**	**Fluid 3 Static aged @250°F, 24hrs**	**Fluid 3 Static aged @300°F, 24hrs**
6 rpm	7	7	10
3 rpm	6	6	9
PV	37	31	31
YP	16	17	19
LSYP	5	5	8
Gels 10 sec/10 min	8/19	8/20	10/21
HTHP fluid loss, ml/30min	2	2	1.6
Bottom Mud weight, ppg		12.0	12.0
Sag factor		0.5	0.501
Oil separation, ml		1	2

TABLE 6: XRD OF London clay outcrop cuttings

London Clay	
Quartz, wt %	26.00
Smectite, wt %	20.00
Illite, wt %	49.00
Kaolin, wt %	1.00
Chlorite, wt %	2.00

Table 7: Eco toxicity and Biodegradability studies of RM and SA

Tests		**RM**	**SA**
Biodegradation		66.5% (28days)	38.2% (28days)
		82.1% (35 days)	71.4% (42 days)
Skeletonema	72-hr EC_{50}	23mg/l	6.6g/l
	72-hr EC_{90}	29mg/l	>10g/l
	72-hr NOEC	15mg/l	5g/l
Acartia Tonsa	24-hr LC_{50}	>10g/l	>10g/l
	48-hr LC_{90}		
	48-hr NOEC		
Cyprinodon variegatus	48-hr LC_{50}	>10g/l	>10g/l
	96-hr LC_{50}		
	96-hr NOEC		

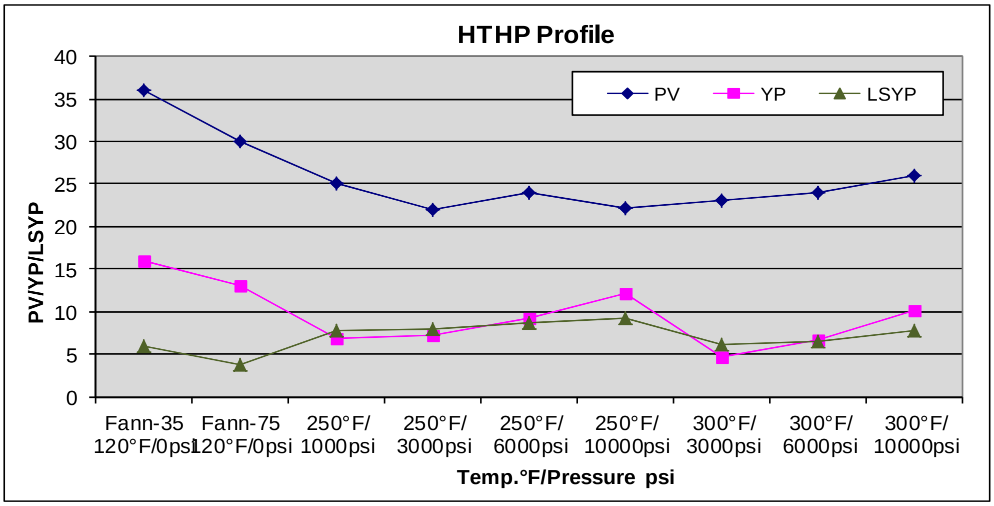

Figure 1: Performance of 12-ppg salt-free, LGS-free, organo-clay-free IEF in HPHT

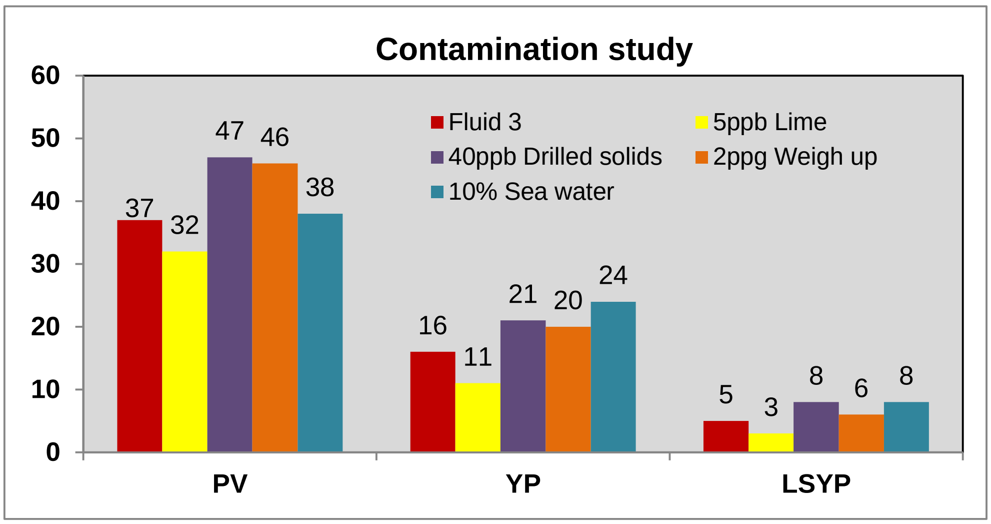

Figure 2: Contamination study of 12-ppg salt-free, LGS-free, organo-clay-free IEF

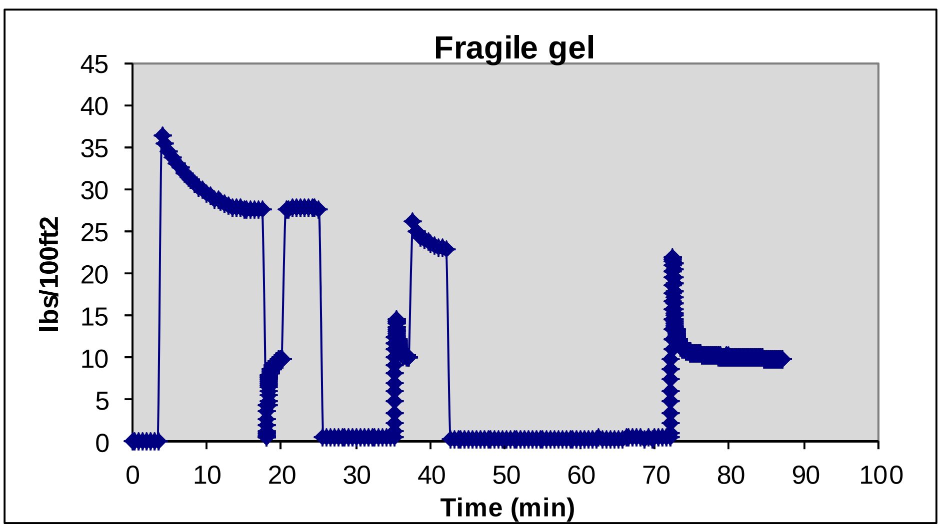

Figure 3: Fragile gel character of 12-ppg salt-free, LGS-free, organo-clay-free IEF