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Building a Better Pack Using a Solid-Free Non-Aqueous Carrier Fluid for α-β wave gravel packs

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Abstract

The operational practice of drilling wells with a non-aqueous fluid (NAF) followed by traditional completion brine carrier fluid concerns the operators when the borehole section has interbedded shales. Also, a large number of production wells in sandstone reservoirs require sand control due to the poorly consolidated formations, and open-hole gravel pack (OHGP) is still a popular sand control method.

Significant progress has been made in the development of fluid systems for gravel packing with either water-based or oil-based fluid. However, drilling of build-up and horizontal sections in a single step, followed by alpha-beta wave gravel pack, is still a challenge that requires a Newtonian NAF fluid.

In order to guarantee superior wellbore stability, lubricity, and shale inhibition in those long sections, a new type of non-aqueous fluids with internal phase brine were developed for use as a carrier medium to perform alpha-beta wave gravel packs. These fluids are designed to provide Newtonian behavior, minimum viscosity, proper gravel wetting and minimum formation damage.

This article presents the results on the optimization of the low shear rheological behavior of the non-aqueous gravel carrier fluid. Selected carrier fluids formulations were evaluated for use as a gravel pack carrier fluid in a large-scale acrylic flow loop. The results showed that a proper alpha-beta wave gravel deposition is obtained with the designed NAF that have minimal viscosity variation at low shear rate.

Introduction

Drilling build-up and horizontal sections in a single step is an attractive design approach aimed at cost reduction and increased performance efficiency in offshore field development, including the reentry of old wells in mature fields – infill drilling. Constructing the well using a solid-free synthetic fluid can reduce total rig time, in addition to saving casing costs.

Most of the production wells in sandstone reservoirs require some sort of sand control, either mechanical, chemical, or both types of methods, for stabilization of the formation due to poor consolidation. The unconsolidated formations of deepwater wells often require sand control during the producing life of the well. Operators generally have two options for openhole completions, stand alone screens (SAS) or gravel packing.[1] OHGP is still the most popular solution for sand control in offshore deepwater reservoirs.[2] The petroleum industry has developed a number of fluid systems for a successful OHGP using water-based drill-in fluid (DIF) and gravel carrier fluid, or a synthetic DIF and water based gravel carrier fluid.[3,4,5] In addition, some efforts have been made to develop an oil-based carrier fluid.[6,7,8,9]

The petroleum industry has made efforts to develop high performance water-based fluids; however, the use of synthetic fluids guarantees superior wellbore stability, lubricity, inhibition, and drilling performance.

One important situation, where DIF shale inhibition is critical, is in the drilling of horizontal sections, where the reservoir zone contains interlayers of reactive shales. Displacing of synthetic DIF for water-based gravel carrier fluids is a complex operation, due to the potential for fluid interaction, formation damage and problems of offshore logistics. In this scenario, the entire wellbore is displaced to brine before running the gravel pack assembly and resultant gravel pack.

Another challenge faced is providing a reliable sand control technique in the horizontal section with operational safety and minimum formation damage.

This article proposes a new approach, in which synthetic fluids are used for all steps of the well construction (drilling and completion). Using a solid-free invert emulsion synthetic fluid as the carrier medium to pack the gravel in a conventional alpha-beta wave deposition technique eliminates the need for introduction of a water-based gravel pack fluid. This approach would be useful in the two instances previously mentioned.

The goal was to optimize the synthetic fluid to provide Newtonian behavior, especially at low-shear rate, minimum viscosity for a given density, compatibility with the drilling fluid, minimum formation damage, wellbore stability, and gravel wettability to ensure proper placement.

Experiments were conducted using a large-scale acrylic flow loop to evaluate the performance of the synthetic fluid as a gravel carrier medium for horizontal gravel packing operations. Alpha wave deposition heights and packing qualities were measured for different proppant materials and densities. The resultant fluid formulation has densities ranging from 9.0 to 10.2 lb/gal, and guarantees proper alpha-beta wave gravel deposition and minimal formation damage.

Fluid Development

For gravel-pack applications, a solid-free invert emulsion carrier fluid was required that would be compatible with the paraffin-based DIF that would be used for drilling the horizontal section.

The required specifications of the designed invert emulsion carrier fluid are:

- The carrier fluid should exhibit near-Newtonian behavior with zero or near-zero values for yield point, low rpm oil field viscometer readings and gel strength.
- The carrier fluid should remain stable, with no brine breakout, for 48-hours during static testing.

Formulation of an invert carrier with these desired characteristics requires the proper choice of base oil and surfactant package. Laboratory testing determined that low kinematic viscosity paraffins and mineral oils were most appropriate for this application, particularly for providing minimal viscosity and near-Newtonian behavior. A surfactant package consisting of an emulsifier and wetting agent was also developed to optimize fluid performance. Use of this blend of surfactants is critical in maintaining fluid stability at temperature, achieving near-Newtonian rheological behavior, and desirable wetting of the gravel. Care must also be taken to utilize the proper ratio and total concentration of emulsifier and wetting agent to obtain the required fluid properties.

Solids-free invert emulsion carrier fluids using paraffin base oil were designed with densities of 9.0, 9.5, 10, and 10.5 lb/gal. Calcium bromide and calcium chloride brines were used as internal phases in the invert emulsion formulations.

The following test matrix includes the most critical laboratory testing steps for evaluation of these carrier fluid formulations:

1. Rheological evaluation using a Fann 35A viscometer and RFS-III rheometer.
2. Long term emulsion stability under static conditions for 48-hrs at 200°F.
3. Fluid properties of the carrier fluid contaminated with
    a. 3% low-gravity solids (Rev-Dust)
    b. Formation water
    c. conditioned oil-based drilling fluid.
4. Effect of emulsifier and wetting agent concentrations on rheological properties.
5. Maintenance of near-Newtonian rheological behavior during gravel pack operations.
6. Settling conditions of 20/40 sand in the invert carrier fluid.
7. Evaluation of the impact of filtrate invasion after displacement to solids-free invert
    a. Quantify filtrate invasion after displacement to solids-free invert
    b. Determine if the solids-free filtrate reduce the permeability of the sandstone (formation damage test).

Fluid Formulations Evaluation

The solids-free invert emulsion fluids formulated with densities between 9.0 and 10.5 lb/gal are described in Table 1. The fluids were mixed with oil/brine ratios between 49/51 and 62/38 using calcium chloride or calcium bromide brine to achieve the desired density. After mixing, these fluids were then hot-rolled at 150°F and static aged at 200°F for 48 hours, after which the Fann 35 viscometer measurements and electrical stability were evaluated. The data collected for these fluids, exhibited in **Table 1**, indicated that the fluid formulations had near zero yield point, 3-rpm reading, and gel strengths after 150°F hot-rolling for 16 hours. The rheological properties exhibited minimal changes when the samples were static aged for 48 hours compared to the results determined after hot-roll. The near-Newtonian behavior observed in these fluids was verified by measuring the low shear rate viscosity of the fluids, which exhibited minimum variation with shear rate measured as low as 0.3 seconds^{-1}. **Figure 1** details the viscosities measured over a wide shear rate range for the 9.5 lb/gal invert carrier. These results satisfied the specified requirement for use of the invert emulsion carrier fluids in gravel pack operations.

Fluid Contamination Tests

Table 2 shows the properties of the 9.0 and 10.5 lb/gal invert carrier fluids after contamination with 3% Rev-Dust to simulate the incorporation of low-gravity solids into the fluid. The contaminated fluid exhibits rheological properties similar to the solids-free fluid, indicating that the solids-free formulation has adequate wetting agent to minimize the effect of the introduction of low gravity solids into the fluid. A slight increase in the plastic viscosity and a minor reduction in electrical stability were observed. As expected, the vast majority of the Rev-Dust was found to have settled out in the heat cup during the measurement of the gel strengths, consistent with the objectives of this fluid.

The rheological properties were also determined for solids-free fluids contaminated with: (1) 5% and 10% of the 10.5 lb/gal highly-viscous synthetic drilling fluid; and (2) 5% and 10% of formation water. The composition of the formation water used is described in **Table 3.**

The rheological properties determined after the 9.0 and 10.5 lb/gal invert carrier fluids were contaminated with 5 and 10% highly-viscous synthetic drilling fluid are shown in **Table 4**. Relative to the data gathered for the uncontaminated fluids shown in **Table 1** after 150°F hot-rolling for 16 hours, the rheological properties determined for the contaminated fluids change very little.

Table 5 exhibits the effect of contaminating the 9.0 and 10.5 lb/gal invert carrier fluids with 5 and 10% formation water. Compared with the results obtained for the uncontaminated fluid, a slight variation is noted in the plastic viscosity, gel strength, and electrical stability. These results indicate that the fluids contain enough excess emulsifier to properly tolerate an influx of formation water into the carrier fluid.

The results shown in **Tables 4** and **5** indicate that contamination with drilling fluid and formation water does not affect the rheological properties of the carrier fluid.

Optimization of Emulsifier / Wetting Agent Package

Use of appropriate amounts of emulsifier and wetting agent are integral to successfully formulating an invert gravel carrier with near-Newtonian low shear rate rheological properties. An excess of emulsifier or deficiency of wetting agent can cause large increases in the fluid viscosity at low shear rates, resulting in suboptimal pack performance. Deficiency in the emulsifier loading can result in fluid instability and improper oil-wetting of the gravel. In order to evaluate these effects and define an optimal range of emulsifier and wetting agent concentrations, several fluids were prepared by fixing the loading of emulsifier and varying the amount of wetting agent and by fixing the amount of emulsifier and varying the concentration of wetting agent. Standard measurements of the rheological properties were made using a viscometer, while the low shear rate properties were measured using a Rheometric Scientific RFS3 rheometer.

The effect of increasing loadings of emulsifier was evaluated compared to the ratio of emulsifier to wetting agent employed in previous testing. This 9.5 lb/gal formulation was presented in **Table 1**. The standard rheological properties for this series of tests are presented in **Table 6**. A reduction in the emulsifier loading from the baseline concentration results in reasonable properties, including a reduction in the plastic viscosity. Increases in the emulsifier content from the baseline loading results in elevated plastic viscosity and increases in the 6- and 3-rpm readings and gel strengths.

The low shear rate rheological properties were also determined for this set of fluids to evaluate the effect of the concentration of emulsifier as shown in **Figure 2**. Reduction of the emulsifier content by 33% results in a largely insignificant decrease in the low shear rate rheological properties. By increasing the loading of emulsifier, the low shear rate properties show elevated compared to the baseline formulation near-Newtonian behavior at an increase of 33% emulsifier. At a 50% increase in emulsifier, the desired Newtonian behavior is lost. These results and the desire for good fluid stability led to the adoption of the baseline concentration of emulsifier as ideal for this carrier.

The optimal concentration of wetting agent was also determined for this fluid using the 9.5 lb/gal carrier formulation from **Table 1** as the baseline. The standard rheological properties measured for this fluid are described in **Table 7**. As the concentration of wetting agent is increased from the baseline, little change is noted in the properties. A 50% decrease in the concentration of wetting agent, however, leads to an elevated plastic viscosity at 100°F.

The low shear rate rheological properties determined for fluids incorporating various amounts of wetting agent are presented in **Figure 3**. The concentration of wetting agent employed exhibits the opposite trend compared to that of the emulsifier loading in terms of the low shear rate rheological properties. Non-Newtonian behavior is noted when the wetting agent is reduced below the baseline concentration. An increase of 50% led to similar results compared to the baseline, though further increases resulted in an increase in the viscosity at low shear rates.

Effect of Proppant Loading on Carrier Fluids Properties

During gravel pack operations, the carrier is expected to be recycled many times over, with fresh proppant infused into the fluid. In order to properly oil wet the gravel, some amount of wetting agent will adsorb to the surface of the particles. Depletion of the wetting agent eventually results in non-Newtonian behavior at low shear rates. To remediate this effect, additional wetting agent must be incorporated into the invert carrier.

To evaluate this effect, a 9.6 lb/gal invert emulsion carrier fluid was prepared and dosed with various amounts of 20/40 pack sand and hot-rolled at 100°F. These results are shown in **Figure 4**. Newtonian behavior is maintained at low shear rates until 10 ppa 20/40 pack sand has been incorporated into the carrier. At this point the low shear rate viscosity begins to increase greatly, suggesting the fluid will begin to function poorly. Addition of wetting agent is necessary to restore near-Newtonian behavior. Since large increases in the wetting agent concentration can lead to undesirable low shear rate rheological properties, the fluid cannot simply be initially prepared with a large concentration of wetting agent. To maintain an amount of active wetting agent in the carrier appropriate for ideal gravel placement, small amounts of wetting agent should be added periodically to ensure maintenance of the desired low shear rate rheological properties.

Settling of the Proppant in the Carrier Fluid

The sand settling was evaluated by mixing specific proportions of 20/40 sand with the 10.5 lb/gal solids-free invert carrier fluid. The sample was shaken vigorously until the gravel was dispersed in the IEGPF, and then quickly transferred to a 500-mL graduated cylinder. The settling rate of the gravel was then determined as a function of time by recording the volume of free fluid and sand/IEGPF slurry.

Figure 5 shows how the sand fully settles after less than 100 seconds, reaching the final sand volume of 225 mL.

Several additional tests were performed using smaller amounts of fluid and sand to determine the difference in the packing of sand when different carrier fluids were employed. These tests compared the height of the sand after complete settling had occurred using IEGPF, base oil, and water as the carrier fluid. Appropriate amounts of carrier fluid and 20/40 sand were introduced into a vial and shaken vigorously. After the sand settled, the heights were compared to a sample of dry 20/40 sand placed in a vial. Little difference was observed between the heights of the settled sand, indicating the use of the IEGPF carrier does not significantly affect the packing of the sand compared to using a low-viscosity aqueous or base oil carrier

Formation Damage Evaluation

A return permeability test, using a standard Hassler Permeameter with 500 psi differential pressure and 200°F, was carried out to evaluate the impact of filtrate invasion by the solids-free invert emulsion on formation damage. The test was performed using 2.8 Darcy Berea sandstone and a 10.5 lb/gal solids-free invert emulsion fluid, which flowed through the core because no filter cake existed. The results of the test show a permeability return of 95%, indicating no potential damage to the sandstone formation (see **Figure 6**).

A return permeability test was also made in a Sandpack permeameter using a 9.4 lb/gal IEGPF. The procedure includes the deposition of a filter cake prior to the placement of the invert emulsion carrier fluid for gravel pack. Results presented in **Table 8** show a return of permeability of 100%. Also important were the low break-through pressures required to initiate return flow (0.5 psi).

Filtration Tests

A modified procedure of static and dynamic filtration tests was used to determine the filtration invasion after displacement of the synthetic drill-in fluid by the invert emulsion carrier fluid. The modified procedure included the deposition of a paraffin DIF filter cake on a 10-micron ceramic disk for 16-hours, followed by the placement of the invert emulsion carrier fluid on top of the filter cake for 2 hours. The tests were carried out at 160°F and 500 psi differential pressure and 160°F.

Figure 7 details the results gathered when the modified procedure was performed under static conditions. At 160°F and 500 psi differential, the mud-off volume was 15.2 mL. After contacting the cake with the invert carrier for 2 hours, an additional 1.2 mL of filtrate was collected. Under dynamic conditions, the mud-off volume was 18.2 mL, and an additional filtrate of 3.0 mL of filtrate was collected after contacting the cake with the invert carrier for 2 hours.

These results indicate that the invert emulsion carrier fluid did not disturb the filter cake and consequently, no increase in filtrate invasion should be expected from the displacement of the drill-in fluid by the invert emulsion carrier fluid.

Gravel Pack Tests in Flow Loop

The next objective was to evaluate the gravel pack quality and pressures obtained with invert emulsion carrier fluids in a flow loop. Different proppants and carrier fluid densities were tested in series of flow loop trials.

Test facility - 30 ft Gravel Pack Simulator

The Gravel Pack Simulator reproduces field conditions during gravel packing operations. The 30 ft. long, transparent acrylic casing of the simulator allows visual inspection of the gravel pack assembly, as well as observation of perforation filling, and any voids or bridging during the pumping process (**Figures 8, 9 & 10**). Production can also be simulated. In the flow loop, there are 18 ft. of perforations with a variable shot density from 12 SPF downwards. Fluid leak-off into the perforations can be varied over the interval as required. Wellbore deviation can be set at any value from horizontal to vertical (inclusive). For the testing reported, the wellbore was horizontal, and all of the perforations were closed (i.e., 100% returns were simulated).

Phase 1 of Gravel Pack Tests

The first phase of the evaluation of invert emulsion fluid in the gravel pack simulator involved four tests with the conditions described in **Table 9**. These tests were designed to evaluate the likelihood of an alpha-beta wave packing sequence occurring with this oil-based fluid. In addition, information was sought concerning how the gravel/proppant density affects pack quality, as well as the effect that blank pipe sections may have on void formation.

The first three of these tests were carried out with a 10.2 lb/gal solid-free invert-emulsion fluid at temperature of approximately 100°F. **Table 10** shows the rheological properties of the carrier fluids measured before and after each test. In addition to the measured data, videos of each test were recorded. Test #4 was performed with 9.36 lb/gal NaCl as a carrier fluid. This test allows direct comparison between the IEGPF tests and water packing.

The data recorded during the testing was obtained manually and through electronic data acquisition. Dune heights were measured by marking the equilibrium height at referenced locations. The tests were made with a volume fraction of gravel or proppant in carrier fluid of 0.043. **Table 11** summarizes the results of these measurements.

Figure 11 shows the pressures recorded during Test 1, as follows: inlet pressure (dark blue), wash pipe inlet (pink), pump pressure (yellow) and flow rate (light blue). This chart illustrates the stability and good control of flow rates and, consequently, normal pressure curves. Similar behavior was obtained in the other tests. An estimate of proppant/gravel placed was carried out for each test, except Test 1: 100% for Test 2 (bauxite), 76% for Test 3 (resin coated) and 92% for Test 4 (sand and water as the carrier fluid).

This series of tests shows that an alpha-beta wave packing sequence is maintained for this fluid. However, this fluid does not seem to pack blank pipe sections as well as water. Part of the reason for this observation was related to the testing configuration, namely absolutely no leakoff. Typically during water pack tests, some fluid is allowed to leakoff to the perforations. This is assumed to be reasonable since it is rare that zero leakoff is observed in the field. This small amount of leakoff will provide an additional fluid flow path over the blank pipe section during beta-wave placement. We have found that even minimal flow will cause gravel to be carried between 5 and 10 feet along the top of the alpha wave previously placed across the blank pipe. However, without any leakoff, all of the flow had to pass through a sand pack, which was not as easily done with this 13 cP fluid as it is with water. It has been noted that the increased permeability of bauxite assisted this process, resulting in a significantly smaller void remaining at the conclusion of pumping.

While a minor benefit was obtained through the use of resin-coated sand, the high density bauxite provided the best packing efficiency. The alpha-wave was much more stable, and appeared to behave in a manner more similar to water packing than did natural gravel pack sand. It has been observed that when packing with natural sand, the viscosity of the IEGPF was such that the initial packing was nearly a toe-to-heel (as demonstrated by a very low initial alpha-wave). This would be similar to the packing mechanism when using a gelled fluid. However, by the end of the test, a secondary alpha-wave had been deposited, and the pack was completed in a manner closer to that of a water pack. Nevertheless, the void left over the blank pipe section was the largest during this test.

Phase 2 of Gravel Pack Tests

A second set of tests was performed to evaluate packing quality in the following situations:

- 9.4 lb/gal IEGPF with a $CaBr_2$ brine as internal phase; proppants: sand and bauxite at 1 and 3 ppa. This fluid closely resembles several application requirements in the Campos basin, offshore Brazil.
- 9.0 lb/gal IEGPF with a $CaCl_2$ brine as internal phase. In this case, the objective was the definition of minimum weight limits for the fluid in order to broaden its range of application.

Tables 12 and 13 show the performed test matrix, as well as the results obtained for gravel compaction and fluid properties. The tests performed with the 9.4 lb/gal fluid containing $CaBr_2$ were all considered successful with normal alpha-beta wave deposition and increasing compaction values from the sand to the bauxite, regardless of their feed concentration.

On the other hand, the first test performed with the 9.0 lb/gal fluid containing $CaCl_2$ and using bauxite as proppant, showed low definition in the alpha-wave deposition process. The test was considered inadequate. This was initially attributed to the higher absolute viscosity of the fluid (19 cP) when compared with 11 cP for the 9.4 lb/gal fluid. The 9.0 lb/gal fluid was then diluted with paraffin until viscosity reached 15 cP. The resultant fluid density was 8.9 lb/gal.

The gravel pack tests with 8.9 lb/gal were performed at lower pump rates (2 and 1 bpm); however, the alpha-wave depositions were not successful. The next strategy was to confirm viscosity values (assure Newtonian behavior) at the low shear rates which are representative of the alpha-wave sedimentation mechanism. Low shear rate viscosity determinations were then made to quantify viscosities at shear rates as low as 0.01 seconds^{-1}. The results illustrated in **Figure 12** confirm the hypothesis of non-Newtonian behavior for the fluids containing $CaCl_2$ brine. Further testing indicated that this behavior resulted from utilization of an excess concentration of emulsifier. Compared to the testing performed for fluids incorporating calcium bromide brine as the internal phase (see **Figure 2**), the baseline loading of emulsifier judged optimal for calcium chloride containing fluids was roughly one-third less. To achieve desirable low shear rate rheological properties for calcium chloride fluids, an adjusted ratio and total loading of emulsifier and wetting agent is required. The fluids with $CaBr_2$ brines showed the expected Newtonian behavior at low shear rates.

Two additional gravel packing tests were performed at lower flow rates, in order to try to visualize alpha-wave deposition. This test was made at 2 bpm and a premature screen-out was observed, as expected, at the 1 bpm test.

Final Remarks and Conclusions

- The extensive lab and gravel pack placement experimentation program performed allowed validation of the concept of using invert emulsions containing $CaBr_2$ brines as gravel pack carrier fluids. Fluid with densities between 9.4 and 10.2 lb/gal were successfully tested.
- Although tests performed with bauxite showed superior gravel placement, all proppants achieved satisfactory results. The pumping of 3 ppa proppant concentration seemed to be an interesting alternative for the reduction of operational time and of fluid volume requirements.
- Tests performed with the 9.0 lb/gal IEGPF with calcium chloride brine showed poor alpha-wave deposition due to the non-Newtonian behavior at low shear rates of the fluid formulation. The types of brine and surfactant concentration are important parameters that affect the low shear rate viscosity.
- The extension of the concept for fluids designed with densities in the range of 9 lb/gal is certainly possible, but still requires some future lab effort.
- The strategy for implementation of this technology in the field includes the following steps:
  1. Perform three gravel pack operations in wells with conventional designs, utilizing the IEGP fluid containing $CaBr_2$
  2. With the operational success of the conventional well designs, perform gravel pack operations with the proposed fluid in wells where the buildup and reservoir sections have been drilled in a single phase (new development wells or re-entry wells).

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Nomenclature

IEGPF	=	*Invert emulsion gravel pack fluid*
OHGP	=	*open-hole gravel pack*
DIF	=	*drill-in fluid*
WBM	=	*Water Based Mud*
OBM	=	*Oil Based Mud*
$CaBr_2$	=	*calcium bromide*
CaCl2	=	*calcium chloride*
NaCl	=	*sodium chloride*
bpm	=	*barrels por minute*

ppa	=	*pounds per gallon added*
Palpa wave	=	*casing pressure at conclusion of alpha wave*
Pbeta wave	=	*casing pressure at conclusion of beta wave*
lb/bbl	=	*pounds per barrel*
lb/gal	=	*pounds per gallon*
ft	=	*feet*
°F	=	*temperature in Fahrenheit*
°C	=	*temperature in Celsius*
SPF	=	*shots per foot*

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SI Metric Conversion factors

ft. x 3.048	E – 01 = m
bbl x 1.589 873	E 01 = m^3
lbf/100 ft.^{2} x 4.788 026	E – 01 = Pa
lb/gal x 1/198 264	E +02 = Kg/m^3
lb/bbl x 2.853 010	E +00 = Kg/m^3
cP x 1.0	E - 03 = Pa s
mL x 1.0	E+00 = cm^3
psi x 6.894 757	E+00 = kPa
mD x 9.869 233	E -16 = m^2
micron x 1.0*	E -06 = m
GPM x 4.381 264	E - 08 = m^3/s
ppa x 1.198 264	E +02 = kg/m^3
°F (100°F -32)/1.8	= °C
bpm x 6.289	=m^3/min

Tables

Table 1 Fluid formulations and properties

	Fluid density, lb/gal			
	9.0	**9.5**	**10.0**	**10.5**
n-paraffin, bbl	0.487	0.585	0.519	0.455
Emulsifier/wetting agent, lb/bbl	10	10	10	10
11.6 lb/gal $CaCl_2$, bbl	0.482	-	-	-
14.2 lb/gal $CaBr_2$, bbl	-	0.384	0.449	0.514
Oil/brine ratio	52/48	62/38	55/45	49/51
Properties at 120°F after hot-rolling for 16 hours at 150°F				
Plastic viscosity, cP	13	8	11	18
Yield point, lb/100 ft^2	0	0	0	1
3-rpm reading	0	0	0	0
10-sec gel, lb/100 ft^2	0	0	0	0
10-min gel, lb/100 ft^2	0.5	0	0	0
Electrical stability, volts	280	360	340	340
Properties at 120°F after static aging for 48 hrs at 200°F				
Plastic viscosity, cP	12	7	11	18
Yield point, lb/100 ft^2	1	1	0	1
3-rpm reading	0	0	0	0
10-sec gel, lb/100 ft^2	0	0	0	0
10-min gel, lb/100 ft^2	0.5	0	0	0
Electrical stability, volts	230	200	200	220

Table 2 Contamination tests of 9.0 lb/gal and 10.5 lb/gal solids-free invert emulsion with Rev-Dust

	9.0 lb/gal		10.5 lb/gal	
	IEGPF	**IEGPF w/ Rev-Dust**	**IEGPF**	**IEGPF w/ Rev-Dust**
n-paraffin, bbl	0.487	0.487	0.455	0.455
Emulsifier/wetting agent, lb/bbl	10	10	10	10
11.6 lb/gal $CaCl_2$, bbl	0.482	0.482	-	-
14.2 lb/gal $CaBr_2$, bbl	-	-	0.514	0.514
Rev-Dust, %	-	3	-	3
Oil/brine ratio	52/48	52/48	49/51	49/51
Properties at 120°F , after 16 hrs dynamic aging at 150°F				
Plastic viscosity, cP	13	16	18	22
Yield point, lb/100 ft^2	0	1	1	1
3-rpm reading	0	0	0	0
10-sec gel, lb/100 ft^2	0	0.5	0	0
10-min gel, lb/100 ft^2	0.5	0.5	0	1
Electrical stability, volts	280	240	340	270

Table 3 Composition of formation water

Components	Concentration, mg/L
NaCl	82,500
Ca^{++}	7,425
K^{+}	175
Mg^{++}	1,254
$HCO3^{-}$	658,9
$SO4^{=}$	350

Table 4 Contamination tests of 9.0 lb/gal and 10.5 lb/gal IEGPF with synthetic DIF

Properties at 120°F	DIF	9.0 lb/gal		10.5 lb/gal	
		DIF/ IEGPF		DIF/ IEGPF	
		5/95	10/90	5/95	10/90
Plastic viscosity, cP	25	14	14	18	18
Yield point, lb/100 ft^2	39	0	1	1	1
6-rpm reading	23	0	0	0	0
3-rpm reading	21	0	0	0	0
10-sec gel, lb/100 ft^2	22	0.5	0.5	0	0
10-min gel, lb/100 ft^2	23	0.5	0.5	0	0
Electrical stability, volts	630	300	320	340	360

Table 5 Contamination tests of 9.0 lb/gal and 10.5 lb/gal IEGPF with formation water

Properties at 120°F	9.0 lb/gal			10.5 lb/gal		
	Formation water/ IEGPF			Formation water/ IEGPF		
	0/100	5/95	10/90	0/100	5/95	10/90
Plastic viscosity, cP	13	15	18	18	21	21
Yield point, lb/100 ft^2	0	1	0	1	1	1
6-rpm reading	0	0	0	0	0	0
3-rpm reading	0	0	0	0	0	0
10-sec gel, lb/100 ft^2	0	0	0	0	0.5	0.5
10-min gel, lb/100 ft^2	0.5	0.5	0.5	0	1	1
Electrical stability, volts	280	280	240	340	400	440

Table 6 Effect of emulsifier dosing

Property at 100°F	-33%	Baseline	+33%	+50%
Plastic viscosity, cP	9	12	17	17
Yield point, lb/100 ft^2	1	0	2	1
6-rpm reading	0	0	0.5	0.5
3-rpm reading	0	0	0.5	0.5
10-sec gel, lb/100 ft^2	0	0	0.5	0.5
10-min gel, lb/100 ft^2	0	0	0.5	1
Electrical stability, volts	230	270	260	280

Table 7 Effect of emulsifier dosing

Property at 100°F	-50%	Baseline	+50%	+100%
Plastic viscosity, cP	15	12	10	11
Yield point, lb/100 ft^2	1	0	1	1
6-rpm reading	0	0	0	0
3-rpm reading	0	0	0	0
10-sec gel, lb/100 ft^2	0	0	0	0
10-min gel, lb/100 ft^2	0	0	0	0
Electrical stability, volts	230	270	300	280

Table 8 Sandpack test with 9.4 lb/gal IEGPF

Test conditions and resutls	
Temperature, °F	160
Diferential pressure, psi	500
Initial permeability, mD	448.5
Final permeability, mD	450.5
Return permeability, %	**100**
Breakout pressure, psi	**0.5**

Table 9 Test matrix of 10.2 lb/gal IEGPF evaluation in the Gravel Pack Simulator

Test #	Flowrate (bpm)	Mix Ratio (ppa)	Carrier fluid	Gravel/proppant type
1	3	1	10.2 lb/gal IEGPF	20/40 gravel sand
2	3	1	10.2 lb/gal IEGPF	20/40 bauxite
3	3	1	10.2 lb/gal IEGPF	20/40 resin coated
4	3	1	9.36 lb/gal NaCl brine	20/40 gravel sand

Table 10 Properties of fluids tested in flow loop

	Test 1: 20/40 GP sand	Test 2: bauxite	Test 3: resin coated
n-paraffin, bbl	0.5112	0.5112	0.5112
emulsifier/wetting agent, lb/bbl	10	10	10
14.2 lb/gal $CaBr_2$, bbl	0.4576	0.4576	0.4576
Rheological Properties at 100°F			
	Initial/ after test	Initial/ after test	Initial/ after test
Plastic viscosity, cP	17/17	17/17	18/18
Yield point, lb/100 ft^2	0/1	1/0	0/0
3 rpm reading	0/0	0/0	0/0
10-sec gel, lb/100 ft^2	0/1	0/0	0/0
10-min gel, lb/100 ft^2	0.5/0.5	0/0	0/0

Table 11 Summary of alpha-beta wave results using 10.2 lb/gal IEGPF

Test	Flow rate, bpm	Mix ration, ppa	Final dune/hole ratio	Palpha/ Pbeta, psi	Observations
1	3	1	0.521	49/66	Multiple alpha waves, small void on top of blank section
2	3	1.344	0.69	51/68	Two alpha waves, small void on top of blank section
3	3	0.974	0.635	51/69	Two alpha waves, small void on top of blank section
4	3.2	1	0.77	40/60	One alpha waves, small void on top of blank section

Table 12 Matrix of tests in the gravel pack simulator using 9.4 ppg IEGPF

	Test 1	Test 2	Test 3	Test 4
Plastic viscosity, cP	11	11	11	11
O/W ratio	49/51	49/51	49/51	49/51
Proppant type	Bauxite 20/40	Bauxite 20/40	Gravel 20/40	Gravel 20/40
Proppant SG	3.56	3.56	2.56	2.56
Specific gravity abs, ppg	29.65	29.65	21.32	21.32
Bulk density, lb/gal	18.19	18.19	14.1	14.1
Mix ratio, ppa	3	1	3	1
Pump rate, bpm	3.5	3	3	3
Volume of proppant in simulator 1	**21.85**	**22.11**	**20.84**	**25.83**
volume in simulator	24.80	24.80	24.80	24.80
Packing efficiency, %	**88.1**	**89.2**	**84.0**	**104.2**

Table 13 Matrix of tests in the gravel pack simulator using 9.0 ppg IEGPF

	Test 5	Test 6	Test 7	Test 8
Fluid density, lb/gal	9.0	8.9	8.9	8.9
Plastic viscosity, cP	19	15(*)	15(*)	15(*)
O/W ratio	49/51	42/58	42/58	42/58
Proppant type	Bauxite 20/40	Bauxite 20/40	Gravel 20/40	Gravel 20/40
Proppant SG	3.56	3.56	2.56	2.56
Specific gravity abs, ppg	29.65	29.65	21.32	21.32
Density bulk, lb/gal	18.19	18.19	14.1	14.1
Mix ratio, ppa	3	1	1	1
Pump rate, bpm	3.5	3	3	3
Volume of proppant in simulator 1	**17.85**	**20.71**	**27,13**	**30.98**
volume in simulator	24.80	24.80	24.80	24.80
Packing efficiency, %	**72.0**	**83.5**	**109.4**	**124.9**

Figures

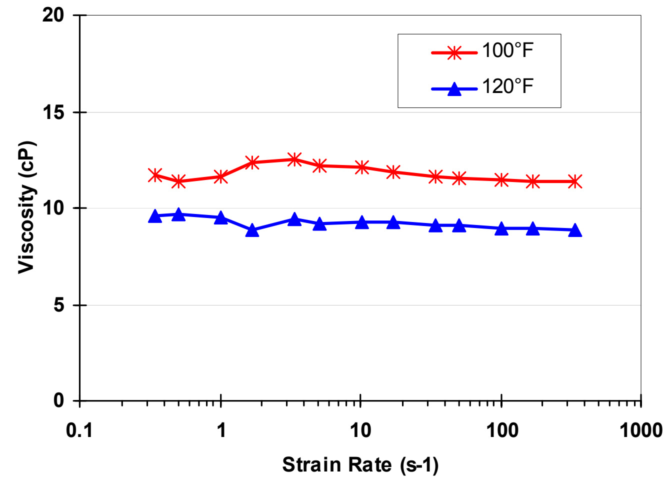

Figure 1 Low shear rate viscosity of 9.5 lb/gal IEGPF

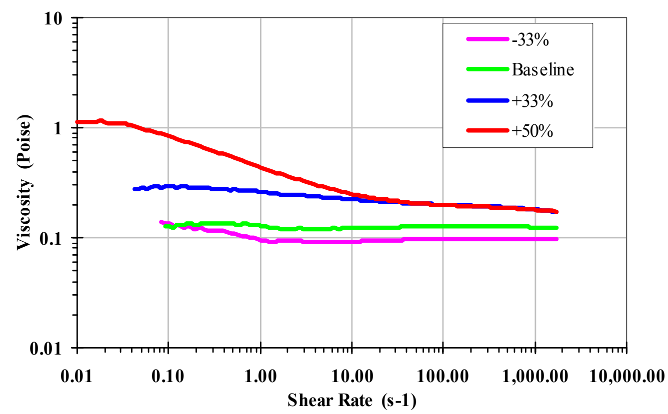

Figure 2 Effect of emulsifier loading on LSRV

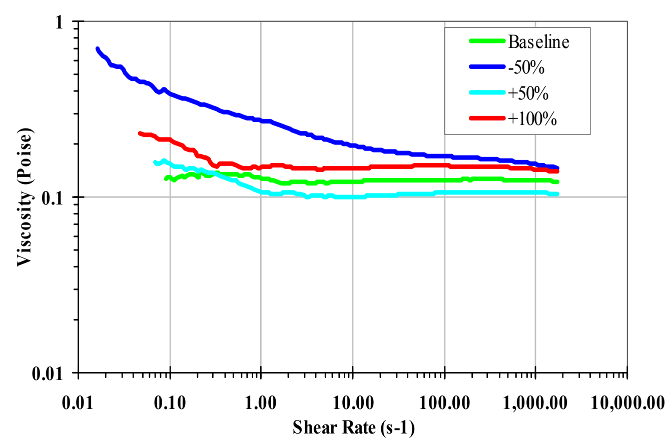

Figure 3 Effect of wetting agent loading on LSRV

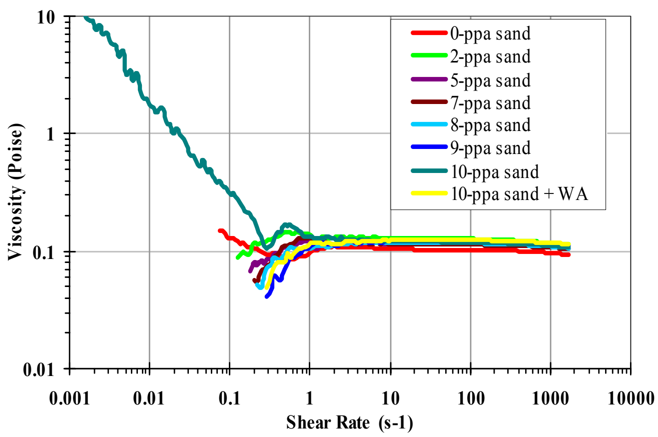

Figure 4 Effect of proppant loading on LSRV

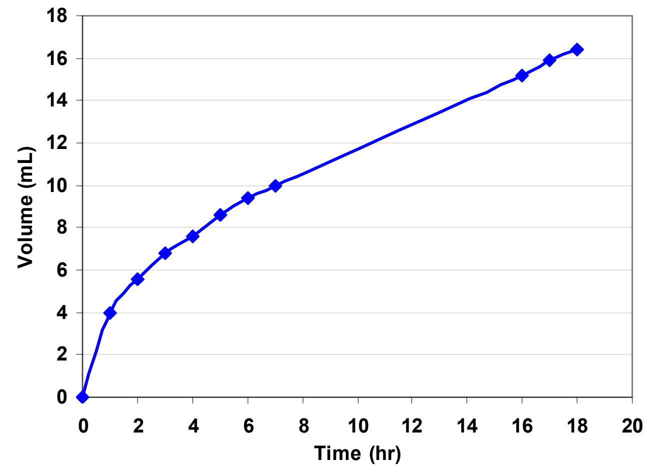

Figure 7 Effect of IEGPF on static filtration

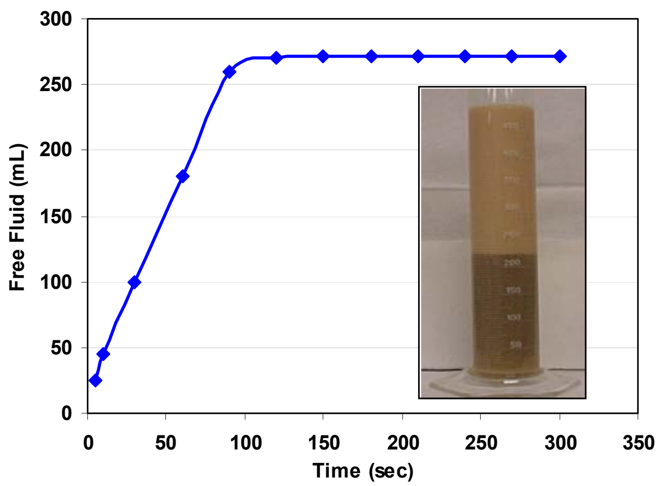

Figure 5 Settling of 20/40 sand in 10.5 lb/gal IEGPF

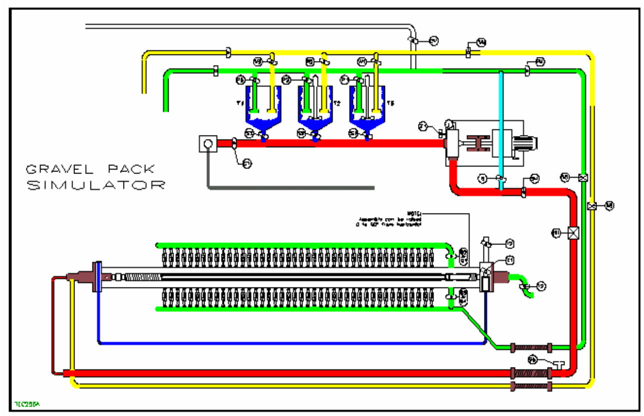

Figure 8 Detail of the Gravel Pack Simulator

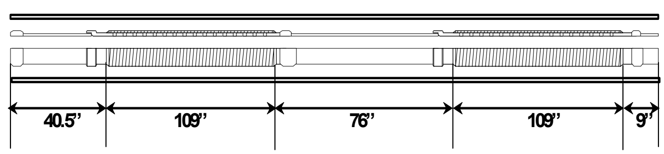

Figure 9 Detail of the Gravel Pack Screen

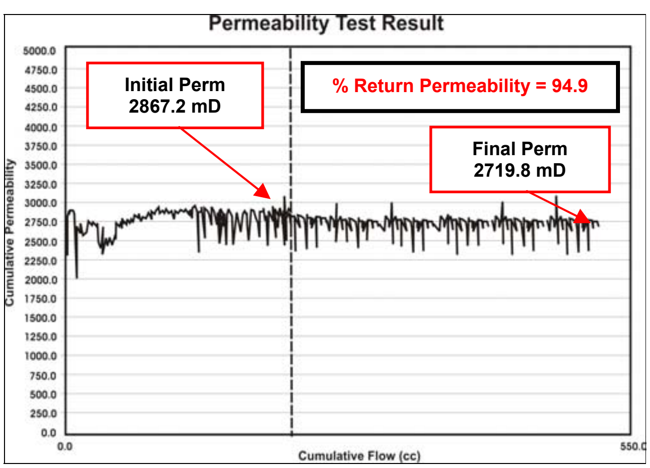

Figure 6 Return permeability test

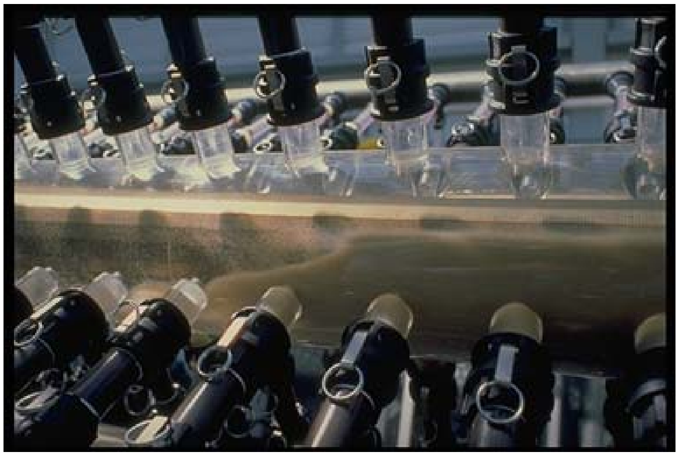

Figure 10 Detail of the Gravel Pack Simulator

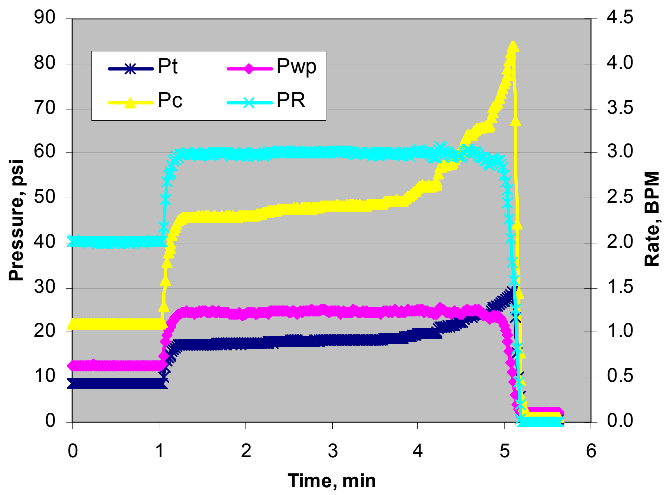

Figure 11 Pressures recorded during Test 1

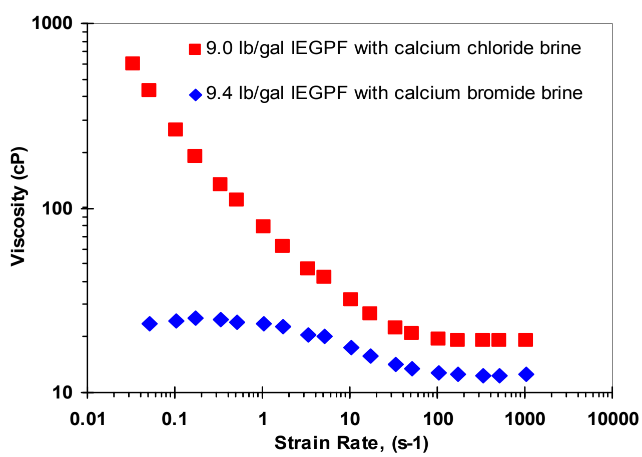

Figure 12 Non-Newtonian behavior of IEGPF with calcium chloride brine