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AADE 2009-NTCE-15-01: NEW INVERT EMULSION FLUID PRODUCES EXCEPTIONAL CORRELATION BETWEEN YIELD POINT, GEL STRENGTHS AND LOW-END DIAL READINGS – A CASE HISTORY

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Abstract

This paper describes a new invert emulsion drilling fluid that produces a closer rheological correlation in the low-end Fann dial readings, gel strengths and yield point. In the field, this fluid also has demonstrated the ability to maintain a closer relationship between all gel strengths for the duration of the drilling process.

The invert emulsion drilling fluid has been used throughout the mid-continent, northern plains region and into the Canadian Rockies where previous wells employed earlier generation conventional type inverts. The fluid is suitable for wells with angles up to 90°, mud weights from 8.6 to 17.0 lb/gal and formations depths from 4,000 to 21,053 ft.

The new chemistry utilized in the system employs a new one-drum additive that eliminates the need for the traditional primary and secondary emulsifiers and a wetting agent. The authors examine laboratory and field case histories that demonstrate the ability of the fluid to not only maintain a closer relationship in the rheological values, but also show how the fluid can reduce costs by increasing the water content of the fluid in the lower densities while still maintaining the desired rheological properties.

Introduction

Oil-based drilling fluids, also known as invert emulsion systems, were introduced in the mid 1930's. Scientific advancements over the years have resulted in the systems used widely today. While contemporary invert emulsion drilling fluids are perceived to deliver relatively trouble-free wells, a few drawbacks remain. Owing to the escalating cost of the base fluid, in 2007 a number of operators requested typical formulations be modified to reduce base oil content. Furthermore, the investigation also was to look at improving the rheological properties of the fluid, particularly the 6-rpm dial readings and the relationship to gel strengths, which would improve hole cleaning and reduce barite settlement and sag, respectively. Consequently, testing commenced in the laboratory on a single emulsifier package that exhibited strong good potential when compared to the traditional emulsification package.

What resulted was a new invert emulsion drilling system that was engineered to overcome the principle drawbacks observed with conventional inverts, in particular the wide spreads between the 6-rpm dial reading and the 10 and 30-min. gel strengths. Since its inception, the system has been applied in several locations in Africa and South America, but is being employed primarily in North America. Used specifically in the U.S. Mid-Continent, the system has proven very effective for drilling wells at angles from 0° to horizontal with density ranging from 8.6 to 17.1 lb/gal.

Formulation of the system starts with unique new chemistry packaged in a single drum that produces a formulation that effectively replaces the traditional emulsification and wetting package. This new chemistry provides the basis for increased solids and water tolerance while providing the desired rheological properties.

Since the basic formulation requires only base oil, brine water, the one-drum emulsifier, lime and organophilic clay, the system also has simplified engineering at the well site. Additives such as a secondary emulsifier and wetting agent are eliminated, and unless high-temperature, high-pressure (HTHP) filtration values of less than five are desired, fluid loss additives also are unnecessary.

For the purposes of this paper, the authors specifically will examine drilling applications in the Bakken shale area of North Dakota and the Arkoma and Anadarko basins in Southeastern Oklahoma, while first describing the development program.

Fluid Development

The research and development project was undertaken with the objective of formulating an improved invert emulsion fluid. Specifically, the project objectives were to provide a final fluid composition that could achieve the following:

- be readily engineered and understood
- be stable across a broad density range (9.0 – 18.0 lb/gal)
- be stable to high temperatures (450°F)
- be stable to contamination (cement, saltwater, drill solids)

In this context, stability meant the fluid should exhibit rheological and filtration properties that would be considered acceptable for drilling. The improved fluid would be benchmarked against existing invert emulsion systems in use and development testing would incorporate three basic fluids:

a) 9-lb/gal invert @ 70/30 oil/water ratio, tested at 150°F
b) 13-lb/gal invert @ 80/20 oil/water ratio, tested at 250°F
c) 10-lb/gal invert @ 85/15 oil/water ratio, tested at 400°F

Contamination testing with simulated drill solids was performed on each fluid: to 30 lb/bbl in Fluid A; to 120 lb/bbl in Fluid B and to 15 lb/bbl in Fluid C. Contamination testing with 15-lb/bbl cement and with 10% seawater also was carried out on Fluid B.

When benchmarking the existing fluid systems, researchers noted in at least one case the gel strengths became elevated when contaminated with high solids, thus requiring treatment with an additional wetting agent. This behavior was identified as the result of excess polymerized natural organic acids that were present in the primary emulsifier. In another benchmark case, the HTHP fluid loss became elevated at the higher temperature, requiring treatment with an additional emulsifier and fluid-loss-control additive. The root cause of this behavior was linked to a poor balance and over-reaction of natural organic acids in both primary and secondary emulsifiers.

The initial fluid development focused heavily on development of a new, single-component emulsifier comprising a careful blend of natural organic acids that were reacted with organic alkali under optimized temperature conditions. The result was an emulsifier that exhibited optimized performance with respect to both rheology and filtration under a wide range of oil-water ratios (OWR) and solids (density), and was thermally stable to a temperature exceeding 450°F. Likewise, measured gel strengths were low and flat, even at high levels of contamination, while an acceptable level of fluid-loss control was maintained up to 400°F with no additional additives required. The ability to utilize only one product over a broad density range, and with little observed effect from contamination, greatly simplified the engineering of this unique system.

Field Trial 1 – Arkoma Basin

The first field trial was undertaken in February 2008 in the Woodford shale play of Oklahoma's Arkoma Basin. The typical drilling program entails setting 13⅜-in. surface casing at 300 ft to 400 ft, followed by 9⅝-in. intermediate casing about 200 ft into the Atoka shale. Afterwards, the wells are drilled vertically with an 8¾-in. bit into the Woodford shale (between 7,800 ft to 11,000 ft). Once the shale is penetrated, directional tools are employed and the well kicks off horizontally where it it drilled anywhere from 3,000 to 5,000 ft.

Typically, invert emulsion drilling fluids are used from below the 9⅝-in. casing through the curve and into the production interval. In the targeted area, fluid density typically ranges from 8.0 – 8.8 lb/gal to assuage lost-circulation concerns arising from the under-pressured fractured shales. The rheological properties required to drill the curve and lateral, center on elevated 3- and 6-rpm dial readings with gel strengths that correlate closely to the low-end rheometer reading. This helps minimize losses to the formation caused by excessive pressure surges after drillpipe connections while also ensuring good hole-cleaning characteristics. In addition to proper rheological properties, attention also must focus on excessive low-gravity solids (LGS) loading as a result of limited use of solids-control equipment and poor cuttings removal efficiencies when incorporating lost circulation material (LCM).

Prior to the field trial, extensive laboratory testing was performed to develop a formulation that would have the suitable recommended properties. Table 1 lists the typical mud properties for the Arkoma Basin.

Table 1 – Typical Mud Properties for Drilling in the Arkoma Basin

Mud weight, lb/gal	8.0 – 8.8
OWR	85/15
Water phase salinity, mg/L	>250,000
6-rpm dial reading	10-12
Electrical stability, v	500 – 800
HTHP Fluid Loss @ 250°F, mL/30 min	8-12

The new invert system was mixed in the mud plant and delivered to location with an OWR of 80:20 and a density of 7.9 lb/bbl. The system was displaced in the wellbore at 3,400 ft after the 9⅝-in. casing was set. Drilling commenced with an 8¾-in. bit with initial penetration rates of 190 to 270 ft/hr and flow rates of 730 – 750 gal/min, which required the shaker screens be redressed from 105 to 80-mesh to handle the flow and cuttings load. After the first day of drilling the electrical stability climbed to 762 v from an initial reading of 330 v.

The well was drilled vertically to approximately 5,900 ft. While drilling the curve section, mud treatments were initiated to elevate the low-end rheology profile, which would enhance hole cleaning in the lateral section. At the kick-off point, heavy rain contaminated the uncovered mud pits reducing the OWR to 70:30. Because of the water influx and clay yield, a higher than desired – 27 lb/100 ft² – yield point was observed, which increased viscosity dramatically. Gel strengths, likewise, increased from 8, 9, and 10 to 16, 18 and 21, on the 10-sec/10-min/30-min gels, respectively. Eventually, the OWR was returned to 80/20 for density proposes, which also dropped the gel strengths back to the original properties (Table 2). Directional drilling continued until reaching a horizontal inclination at approximately 7,000 ft and the lateral section continued to 9,528 ft TD. Within this interval, bit trips were non-eventful with no excessive torque or drag observed. The primary formations drilled were shale, 300 ft of sandstone and 200 ft of limestone in the Wapanucka formation.

Table 2 – Changes in Fluid Properties Before and After Rain Contamination and Readjustment

Fluid Properties	Initial properties	After incorporation of Rain Water	Readjustment of OWR
Density, lb/gal	7.9	8.5	8.4
PV, cP	9	18	15
YP, lb/100 ft²	10	27	17
6-rpm dial reading	8	17	11
3-rpm dial reading	7	15	10
10-sec gel	8	16	11
10-min gel	9	18	14
30-min gel	10	21	16
OWR	80/20	70/30	79/21

While drilling the lateral section, flow rates were reduced to 400 – 500 gal/min, allowing for the shakers to be screened up to 105-mesh screens. The maximum low-gravity solids reached 6.7% by volume.

While drilling the lateral, only organophilic clay, lime, the one-drum emulsifier and calcium chloride were required for maintaining the system. The mud exhibited excellent tolerance to both solids and excessive water influx, while yield point and gel strengths remained manageable, with the gels low and non-progressive. Mud losses during the production interval were minimal and excellent cuttings integrity was noted while drilling the lateral. By the end of the well, HTHP fluid loss ranged from 10 mL initially to 7.6 mL without the addition of any fluid-loss reducers. Drilling fluids costs were within budget, and the operator deemed the well a success.

When the mud costs were compared against offset wells drilled with conventional inverts, total mud costs were lowered by 8%. In comparison to the offset wells, rheological profiles were well within expected ranges, while gel strengths trended lower. A post-well summary showed a 5,736 ft of 8¾-in. lateral section drilled, cased and cemented in 17 days. When comparing the new invert to conventional inverts in similar wells, the new system showed improved drilling performance and solids tolerance while minimizing fluids costs.

Field Trial 2 – Anadarko Basin

The new emulsifier also was employed in Oklahoma's Anadarko Basin for an operator employing an alternative water-phase salt in its conventional invert emulsion systems. This system utilizes calcium ammonium nitrate deca-hydrate in the water phase to lower the activity of the fluid, while the absence of chlorides eliminates the associated environmental consequences. As the operator already had a conventional invert fluid on location, lab testing was performed to ascertain the viability of converting the fluid onsite from the conventional system to the new one-drum emulsifier fluid. Laboratory testing indicated complete compatibility with the existing system, which subsequently was converted on the fly by simply allowing for depletion of the old emulsifiers and wetting agent and subsequent additions of the new one-drum emulsifier.

Typically, these wells are drilled with water-based fluid through the second intermediate casing string anywhere from 14,500 to 16,500 ft depending on the formation, which usually comprises the Morrow Shale. An 8½-in. hole is drilled to a TD of 20,000 – 21,000 ft utilizing a weighted invert emulsion fluid; typically the wells are vertical to slightly deviated with some adjustments needed to maintain targets. Managing the equivalent circulating density (ECD) is critical in completing these wells as is well control and the ability to decrease the likelihood of loss of circulation due to poor mud rheology. As these wells exhibit extreme pressure and elevated temperatures, the functionality and chemical stability of any drilling fluid system selected is put to the test.

After displacement, the conventional system was run for the first four days, but on the fifth day the operator elected to convert to the new invert fluid system. Just prior to the conversion, properties were typical of inverts run in the basin. After only seven days of drilling, the converted system exhibited rheological properties correlating closely with those observed in the first field trial. The fluid showed a three-point differential between the 6-rpm dial reading and the 30-minute gel, where previous to the conversion the 6-rpm to 30-minute gel spread was 14 points (Table 3).

Table 3 – Comparison of Fluid Properties

Fluid Properties	Conventional Invert Day 4	7 Days into Conversion
Density, lb/gal	12.5	12.6
PV, cP	22	19
YP, lb/100 ft^2	15	17
6-rpm dial reading	10	11
3-rpm dial reading	9	10
10-sec gel	10	12
10-min gel	18	12
30-min gel	24	14
OWR	87/13	89/11
HTHP fluid loss @ 250°F, mL	10.0	9.6
ES, v	566	812

Drilling progressed to TD at 20,500 ft without any fluid-related issues. Between Day 7 and the reaching of TD on Day 37, the fluid was weighted up to 15.0 lb/gal and later to 16.8 lb/gal, which was necessitated by a gas influx, before attaining a final density of 17.0 lb/gal at TD. Fluid properties for the various mud weights are listed in Table 4. Once again, the 6-rpm to 30-minute gel strength spread was 3 until reaching TD where the spread increased to 7 because of the addition of a thinning agent for cementing the casing. Once conversion took place, the only additives to go into the fluid system were the one-drum emulsifier, lime, organophilic clay, an alternative salt, bridging agents and 1 lb/bbl of gilsonite for HTHP fluid-loss control. The bottomhole temperature was logged at 290°F and the well was drilled in total of 78 days compared against the offset that was drilled in 90 days (Fig. 1).

Table 4 – Fluid Properties During Weight Up

Fluid Properties	Weight up to 15.2 lb/gal	Weight up to 16.7 lb/gal	Weight up to 17.0 lb/gal
Density, lb/gal	15.2	16.7	17
PV, cP	32	46	45
YP, lb/100 ft^2	23	23	16
6-rpm dial reading	15	14	8
3-rpm dial reading	14	13	6
10-sec gel	15	15	7
10-min gel	17	17	14
30-min gel	18	17	15
OWR	87	87	87
HTHP fluid loss @ 250°F, mL	13	13	13
ES, v	833	794	605

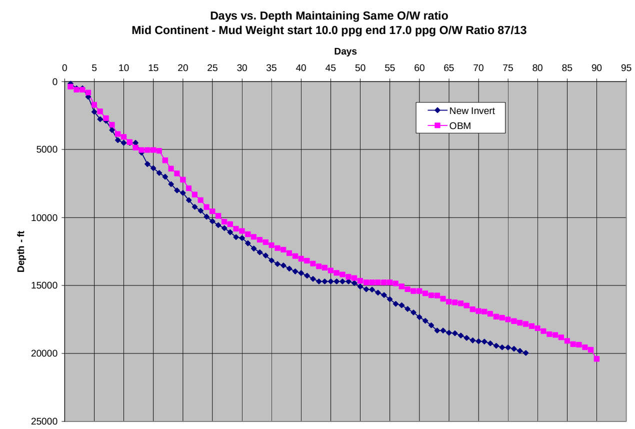

Fig. 1 – Comparison of drilling days vs depth.

Field Trial 3 - Williston Basin

The Bakken oil formation encompasses some 25,000 square miles in North Dakota, Montana, Saskatchewan and Manitoba, with about two-thirds located in Western North Dakota's Williston Basin. The key to the historical success of the basin can be attributed to horizontal/directional drilling. Oil is found approximately two miles below the surface and operators traditionally drill 5,000 to 10,000-ft lateral sections to maximize production. Historically, some of the common problems/issues center on drilling the sensitive shale and hygroscopic salt formations that create problems with differential sticking, hole cleaning and water/crude influx. Until recently, conventional invert systems were the primary drilling fluid systems used in the basin.

In addition to providing all the advantages of the conventional diesel-based system, the new invert emulsion fluid enhances rheological properties, such as delivering stable gel strengths, high tolerance to solids and water contamination, excellent HTHP fluid loss and good thermal stability, while adding value to the entire project by reducing base oil content. . The new invert system has been shown to drill successfully with a 70:30 OWR as compared to the tradition invert at 80:20 OWR, thus adding substantial savings and value to the operator.

During the initial laboratory investigation, the system had been tested extensively with different combinations of organophilic clays and different OWRs. (Table 5). The results were applicable to the Williston Basin field trial. Here, operators typically drill surface intervals with fresh water, set 9⅞-in. casing at 2,000 ft and drill an 8¾-in. intermediate interval and the vertical and building curve for lateral landing at 11,000 MD/10,500 ft TVD, using an oil-based mud (OBM) with NaCl brine as the internal phase. The horizontal section typically is drilled with NaCl brine with periodic high viscosity and lube sweeps/pills. Some of important fluid properties required while drilling the intermediate section of a Bakken well are low HTHP fluid loss (<8 mL), no water in filtrate, flat gel strengths, good solids control (LGS <5%), YP between 12 to 15 for good hole cleaning and strong emulsion (ES).

The information learned from the extensive lab testing was applied in the Williston basin field trial. Initially, only one rig was selected for this trial, but after the successful application, the new invert system was incorporated on the operator's other three rigs. As of this writing, 40 wells have been drilled in the basin using the new system. Moreover, the improved cost savings and drilling performance prompted four other operators to successfully drill their Bakken formation wells with the new invert system OBM system.

Table 5 – Formulations for Williston Basin

Fluid Formulation	1	2	3	4
Low-sulfur diesel, lb/bbl	0.683	0.683	0.646	0.689
Organoclay, lb/bbl	6	0	0	0
Alternate organoclay, lb/bbl	0	6	0	0
Premium organoclay, lb/bbl	0	0	3	3
Lime, lb/bbl	3.5	3.5	3.5	3.5
One-drum emulsifier, lb/bbl	5.5	5.5	5.5	5.5
Water, bbl	0.171	0.171	0.215	0.172
NaCl, lb/bbl*	16.87	16.87	21.27	17.01
Barite, lb/bbl	102.04	102.04	99.03	105.65
Gilsonite, lb/bbl	5	5		
Simulated drilled solids, lb/bbl	20	20	20	20
*NaCl brine is 9.7 lb/gal (22%/wt)				
Mud Properties	**1**	**Lab 2**	**Lab 3**	**4**
Heat Aging Temp, °F	150	150	150	150
Heat Aging Hours	16	16	16	16
Static/Rolling	Rolling	Rolling	Rolling	Rolling
Mud Weight, lb/gal	10	10	10	10
Rheo Temp, °F	150	150	150	150
600-rpm dial reading	48	50	47	37
300-rpm dial reading	31	32	32	24
200-rpm dial reading	24	24	25	18
100-rpm dial reading	18	16	19	12
6-rpm dial reading	10	10	10	6
3-rpm dial reading	9	9	10	5
PV, cP	17	18	15	13
YP, lb/100 ft²	14	14	17	11
10-sec Gel	10	10	10	8
10-min Gel	14	14	15	10
ES, v @ 120°F	971	1110	558	780
HTHP @ 250°F, mL	4	4	6	9.6
OWR	80/20	80/20	75/25	80/20

Formulation

The system used in the Williston Basin employed diesel as the primary base oil of the new invert fluid system, with NaCl brine as the internal phase. Basin operators traditionally use NaCl brine instead of $CaCl_2$, because of the inexpensive and easy availability of produced water (NaCl) in the basin, which the flexibility of the system permits. During drilling of the 40 wells, various oil-water ratios ranging from 70:30 to 75:25 were successfully used.

Field trial formulations were identically as those in the lab tests. The one-drum emulsifier/wetting agent was the primary emulsifier for this system and used at the 5.5-lb/bbl treatment level, while organophilic clay was the primary viscosifier (3 lb/bbl). Lime concentration was maintained around 6 lb/bbl on the average throughout the drilling operation. The HTHP fluid loss also was managed by manipulating the one-drum additive concentrations, while electrical stability was maintained between 450 and 600 volts.

Both the conventional invert and the new one-drum system were pre-treated with calcium carbonate, a medium fibrous-type LCM and a proprietary oil-wet granular LCM to control subsurface seepage losses. The new system required no additional fluid-loss agents, such as gilsonite, which are usually required by the traditional invert drilling fluid system. It is also noteworthy that all the LCM agents used were non-damaging to the formation and environmentally acceptable.

Maintenance

During drilling operations, a daily treatment of the viscosifier at 3 lb/bbl, lime at 6 lb/bbl and the one-drum additive at 8 lb/bbl was made for every new barrel of volume built. The OWR was controlled closely and managed at 70:30 with no additional base oil added to the system.

The new invert system was not affected by most contaminates, such as water and solids, but the alkalinity (P_{om}) must be maintained around 2 to 3, while excess lime of around 2 to 3.5 lb/bbl is recommended as H_2S and CO_2 gas have been tested in the basin.

The majority of the wells drilled for one operator in the basin during 2008-2009 employed the new invert system.

Primarily, the intermediate section is drilled using OBM with sodium chloride (NaCl) as an internal phase. Over the 40-well period, the system has successfully reduced base oil usage by 228 bbl with an average interval drilling cost/ft reduced by 20%. The well discussed in this paper was drilled in 7.23 days with minimum subsurface losses. Only 388 bbl of base oil (diesel) was used for fluid dilution and volume building and OWR was maintained consistently around 75:25 throughout the interval (mud weight from 9.6 – 10.6 lb/gal).

Cost & Environmental Savings

Due to its close relationship between the 6-rpm reading and the 30-minute gel strength, the system helped deliver a gauge hole as shown in the caliper logs. For this well, 8,692 ft of hole was drilled using the new one-drum invert system at a cost of \$3.73/ft; the average for all 40 wells using the new invert system is \$5.92/ft compared to \$6.43/ft with the earlier conventional invert systems (Fig. 2).

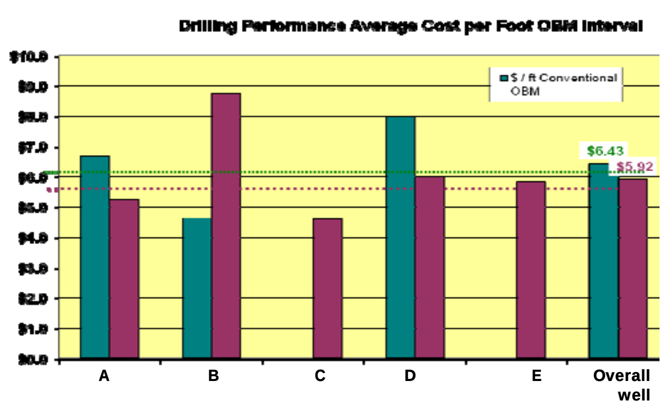

Fig. 2 – Comparison of drilling performance per interval by rig. (green is conventional invert, red is new one-drum system).

On the average, 228 bbl less base oil was used per well as compared to the conventional OBM system. At the same time, average drilling days were reduced from 9.09 to 7.55 days (Fig. 3), thus adding substantial value to the operator.

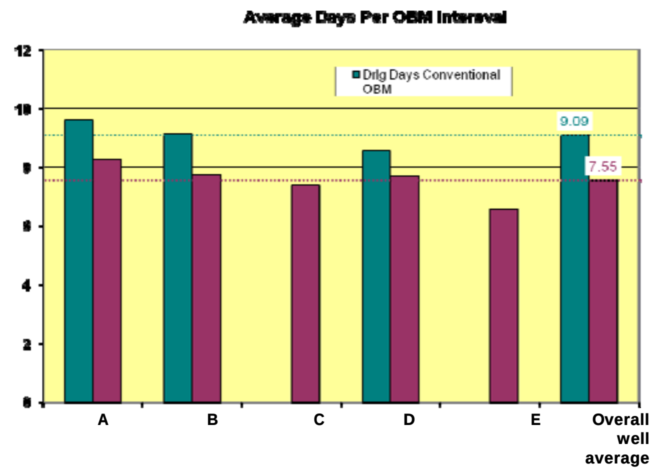

Fig. 3 – Comparison of average drilling days per interval by rig. (green is conventional invert, red is new one-drum system).

Both the reduction in base oil and the reduced drilling time represent savings in the overall carbon footprint of the drilling program.

Conclusions

The new one-drum invert emulsion fluid system has been proven in the field and provides the following benefits:

- Lower the relationship between the 6-rpm reading and the 10-minute and 30-minute gel strengths improving the hole cleaning and reduce the barite sag potential of the drilling fluid.
- Ability to reduce not only fluid-related costs, but also overall well cost by reducing the number of drilling days.
- Maintain the desired rheological profile with the ability to withstand increased loading of low-gravity solids.
- Allows for increased water content with the desired rheological profile

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