AADE-04-DF-HO-11

The Design and Application of "Fit-For-Purpose" Oil-Based Drilling Fluids For Technically Demanding North Sea Wells

Daryl Cullum, M-I SWACO

Abstract

All oil-based drilling fluids and associated additives are not created equal. The proper selection of base oil, emulsifier package, viscosifier, and fluid–loss-control agent can directly impact the effective performance and total cost of the drilling fluid and, more importantly, the probability of a successful application.

The engineering of invert emulsion drilling fluids can be tailored to meet specific technically demanding applications, including, but not limited to, extended reach drilling, low and/or high-temperature and high-density applications, proper management of equivalent circulating density (ECD) and deepwater applications. Often, a combination of these technical challenges can be encountered in a single well.

Product Selection

After a careful review of the technical specifications for a specific well, the first step to successfully designing a "fit-for-purpose" oil-based fluid is a careful review of the local environmental standards. A product that is ideally suited to meet a technical specification or challenge may be acceptable for use in one area while banned from use in another. This product ban may be implemented by a governing body or an operator internal decision. Once this review is completed and a final list of available products is determined, product selection can begin.

Base Fluid Selection – Base oil can be selected based on a variety of factors or properties among which are environmental restrictions, Health & Safety (H&S) considerations, availability, price, and physical properties. The importance of the base oil selection increases with increasing technical demands placed on the drilling fluid.

Two types of wells in which the choice of base fluid can directly impact the chance of success are extended-reach drilling (ERD) and narrow hydraulic window applications. In these types of wells, a base fluid with a lower kinematic viscosity is often selected due to the ability to formulate a fluid with a lower overall rheological profile which can result in a reduced equivalent circulating density (ECD) and the ability to obtain a higher circulation rate for improved hole cleaning. Quite often though, a reduction in the kinematic viscosity results in reduced flash points and increased vapors that can lead to an increase in H&S concerns. A compromise between technical demands and H&S is often required to select the proper base fluid. **Table 1** contains comparative properties of several base oils currently used in the North Sea.

Organophilic Clay Selection – The selection of organophilic clay can be based on a single technical specification or multiple specifications. The type of clay selected and the manufacturing process yields a variety of different organophilic clays for different applications. Wet-processed clay will contain higher clay content, exhibit higher efficiency, and have greater application flexibility in comparison to a dry processed clay.[1] A low-temperature vertical well may require dry–processed, low-cost montmorillonite clay to achieve required rheological properties while a highly deviated or ERD well may require a wet-processed montmorillonite clay, premium wet-processed montmorillonite clay, or a combination with other clays such as an attapulgite for reduced barite sag while a high-temperature application may require the use of a hectorite high-temperature clay.

A new product has been identified for use in high-temperature applications. The new product is a hectorite clay as previously used, but a new type of quaternary amine group attached to the clay to make it oil-soluble and increased the temperature stability of the product. The previously used high-temperature clay begins to thermally degrade at approximately 175ºC (347ºF) while the new product is stable to temperatures greater than 260ºC (500ºF).[1]

Emulsifier / Wetting Agent Selection – Selection of the emulsification package will have a direct impact on the final properties of the oil-based drilling fluid. The impact on the properties and their effect on the well must be taken into account when planning for various types of applications. Using a standard package without proper testing to qualify the emulsifier and wetting agent may also cause unexpected problems such as unacceptable formation damage.[2]

A conventional emulsification package may be acceptable for a low-temperature, low-risk application but may not be the proper choice for a technically demanding ERD well, high-temperature high-pressure (HTHP), or narrow hydraulic window application.

A new emulsification package with very low-dispersion characteristics has been designed and has been used to successfully drill a variety of wells including ERD, low–temperature high-angle and horizontal, through tubing rotary drilling (TTRD), narrow hydraulic window, and HTHP wells. In addition to meeting the technical challenges from these types of wells, return permeability testing conducted to date indicates that formation damage is minimized.

The use of the low-dispersion emulsification package produces a fluid with lower gel strengths than fluids formulated with a conventional emulsification package when both fluids have similar 6 and 3 rpm dial readings. The reduction in gel strength results in a lower ECD surge being placed on the wellbore to break circulation. This is a distinct advantage when drilling wells with a narrow hydraulic window. The reduction in gel strength has not resulted in an increase in incidents of barite sag in fact the opposite has occurred. Operators report a reduced tendency for barite sag to occur when using the low-dispersion package.

To illustrate the difference in obtainable gel strengths, a comparison of properties is contained in **Table 2**. The table contains representative properties from two HTHP wells one of which used a conventional emulsifier package while the second well used the low-dispersion package. Both fluids have similar 6- and 3-rpm dial readings at both 50°C (122ºF) and 80ºC (176ºF) when measured using a conventional 6-speed rheometer, similar density, and identical oil to water ratio (OWR). The advantage in using the low-dispersion package is readily apparent in the reduced gel strengths. The fluid utilizing the low-dispersion package realized a 45% reduction in the 10-min gel strength at 50ºC and a 31% reduction when measured at 80ºC.

Fluid–Loss-Control (FLC) Selection – A variety of FLC materials are available. Among the available products are polymeric, amine-treated lignite, gilsonite, sulfonated asphalt, and fatty acids. The products can be used alone or in combination as selected by the technical specifications for a particular application. Most products will deliver acceptable fluid-loss control at temperatures less than 149ºC (300ºF). Recent HTHP wells drilled in Norwegian and Danish offshore applications have been designed for bottomhole static temperature of 175º to 200ºC (350º to 400ºF).

Pre-planning and laboratory testing for a HTHP well with a static bottomhole temperature of 175ºC (350ºF) helped identify a new high-melting-point FLC product for use in HTHP applications. The melting point of the new product is > 232ºC (450ºF). Previous 2.04-sg (17.0-lb/gal) fluid formulations used in laboratory testing for this application included the low-dispersion emulsification package and a combination of polymeric and standard gilsonite to obtain HTHP fluid-loss control when measured at 175ºC. To compare the effectiveness of the high-melting-point product to standard gilsonite, two laboratory formulations were prepared on high-speed mixers and dynamically aged for 16 hours at 175ºC. Identical concentrations of FLC materials were used in both formulations. The high-melting-point product reduced the HTHP fluid loss from 11 mL/30 min with the standard gilsonite to 4 mL/30 min with very little impact on the rheological properties. The results from this testing is contained in **Table 3**.

In pre-planning for a different HTHP application, the high-melting-point product in combination with the low-dispersion emulsification package was tested in 2.15-sg (17.9-lb/gal) laboratory formulations static aged for 16 hr and for 5 days (120 hr) at 200ºC (392ºF). The HTHP fluid loss when measured at 190ºC (374ºF) after static aging was 2.8 mL/30 min after 16 hours and after 5 days.

Field Results

To date 21 wells have been successfully drilled utilizing the low-dispersion emulsification package. These wells have included low-temperature/high-inclination, low-temperature/horizontal, TTRD, ERD, and HTHP applications. Of these 21 wells, 20 have been formulated with a linear alkane base oil.

Low-Temperature Applications – The first use of the low-dispersion package in combination with a premium wet-processed organophilic clay in a linear alkane base oil occurred in November 2002. The choice of the low-dispersion system was based on hydraulic simulations conducted using hydraulics modelling software packages from the service company and the operator. Both hydraulic modelling software predicted that the new fluid would provide a reduced ECD for a narrow hydraulic window application when compared to the fluid used on offset wells.[3] Since the first successful application, the operator has continued to use the low-dispersion system in an additional 9 low-temperature applications. The low-temperature wells have ranged in density from 1.55 to 1.82 sg (12.9 to 15.16 lb/gal) and hole sizes ranging from 9.875 in. to 6 in. with inclinations 72 to 108 degrees.

The combination of base fluid, organophilic clay, and emulsification package for these applications were based on laboratory work indicating reduced barite sag tendencies, reduced rheological profile, and reduced gel strength structure. The laboratory work was verified with these 10 field applications. A comparison between the rheological properties obtained with the new combination in these field applications and the convention combination is illustrated in **Fig. 1** and **Fig. 2**. These graphs illustrate the reduction in high-shear-rate viscosity that is obtainable with the new combination while maintaining elevated low-shear viscosity.

Fig. 1 compares two field fluids with very similar drilled solids content and similar 600 rpm, 100 rpm, 6 rpm and 3 rpm dial readings from a 6-speed rheometer measured at 50ºC. The fluid utilizing the new combination had an OWR of 75:25 with a density of 1.74 sg (14.5 lb/gal) to obtain these properties. To obtain the same properties with a fluid utilizing a conventional package, the selected fluid had an OWR of 80:20 and a density of 1.58 sg (13.17 lb/gal)

Fig. 2 shows two field fluids with identical density of 1.68 sg (14.0 lb/gal) and very similar drilled solids content and OWR, 72:28 with the conventional package and 73:27 with the new combination. The fluid utilizing the new combination has a reduced 600- and 100-rpm dial reading while the 6- and 3-rpm dial readings are equivalent. With the reduction in high-shear-rate viscosity, a reduction in system pressure loss is realized while maintaining equivalent low-shear-rate viscosity.

Table 4 is representative properties from one of the 10 low-temperature wells. The rheological properties are measured at 28º, 50º, and 80ºC (82º, 122º, and 176ºF). Across the range of temperatures, the yield point remains flat while the gel strengths are low and the 30-min gel strength is non-progressive. This type of rheological profile has allowed the operator to successfully drill the first 10 low-temperature applications and continues to utilize the system for this type of highly deviated technically demanding well.

TTRD Applications – There have been 5 TTRD sections drilled utilizing the low-dispersion emulsification package in combination with a premium wet-processed organophilic clay in a linear alkane base oil. In each application, a 5⅞-in. openhole was drilled for an average length of 785.8 meters (2578 ft). The length of open holes ranged from 268 to 1250 meters (879 to 4101 ft) with inclinations ranging from 58 to 115 degrees.

The density of the fluids ranged from 1.59 to 1.72 sg (13.25 to 14.33 lb/gal). The well utilizing the 1.72-sg fluid was drilled from ~3550 to 4000 meters (~11,647 to 13,123 ft) with a 600-L/min (158.5-gal/min) flow rate, 220 to 250 bar (3,191 to 3,626 psi) total system pressure loss, 35 – 40 rpm, and an ECD of 1.81 to 1.855 sg (15.08 to 15.46 lb/gal). **Table 5** contains average properties of the 1.72 sg fluid.

ERD Applications – The low-dispersion emulsification package in combination with a premium wet-processed organophilic clay in a linear alkane base oil has been utilized to drill 2 ERD applications.

This combination was selected to drill the first well to achieve higher flow rates with reduced system pressure loss in the upper intervals, to improve hole cleaning, and to reduce or eliminate instances of barite sag throughout the well. The fluid was used to drill 16.75-, 12.92, and 8.5-in. intervals to a measured depth (MD) of 7,230 m (23,720 ft) with a true vertical depth (TVD) of 2,773 m (9,098 ft). In comparison to offset wells, the 16.75-in. interval was drilled in record time with the highest rate of penetration ever recorded in the field. In addition a reduction of 20% in the total system pressure loss was realized. This reduction in system pressure loss allowed the operator to successfully drill to interval total depth without a reduction in flow rate due to increasing system pressure loss exceeding maximum allowable as had been experienced in previous wells. A 10% reduction in system pressure loss was realized in the 12.25-in. section and equivalent or slightly reduced pressures were observed in the 8.5-in. section. While sag was not totally eliminated, it was greatly reduced. The only reported incident occurred in the 8.5-in. interval and then only after leaving the well static for 6 days while logging and running 7-in. liner. While circulating the 1.6-sg (13.3-lb/gal) fluid after the liner was in place, a minimum density of 1.56 sg (13.0 lb/gal) was recorded.

Table 6 contains typical values for each interval drilled in this ERD application.

Table 7 contains 6-speed rheometer and high-temperature, high-pressure (HTHP) rheometer properties. With a bottomhole static temperature of 89ºC (192ºF), the maximum testing temperature used in the HTHP rheometer testing was 100ºC (212ºF). The results from the HTHP rheometer testing indicate a fluid with very stable rheological properties with little on no change in the 6 and 3-rpm dial readings or the Yield Point with increasing temperature and pressure.

The second ERD application was a 9.5-in. interval drilled from 6605 to 8084 m MD (21,670 to 26,522 ft), then a geological sidetrack drilled from 7,591 to 8263 m MD (24,905 to 27,109 ft) with a TVD of 2,977 m (9767 ft) and a maximum inclination of 94 degrees. The fluid performed as expected with properties similar to the first ERD well.

HTHP Applications – One HTHP well has been drilled in the Norwegian sector and two wells have been drilled in the Danish sector.

The first well drilled in the Danish sector utilizing the new products was planned as a vertical HTHP well but the final bottom hole static temperature was 143ºC (290ºF) instead of the maximum possible 175ºC (347ºF). The fluid was formulated with linear alkane base oil in conjunction with the new hectorite clay, low-dispersion package, and the high-melting-point FLC material.

This second Danish HTHP application was also a vertical application with a maximum bottomhole static temperature of 154ºC (309ºF), density of 1.92 sg (16.0 lb/gal), and a final depth of 4,966 m (16,292 ft). The fluid from the first well was used in this application and performed as expected from the experience gained in the first well.

The fluid used in the Norwegian sector was formulated with a low-toxicity mineral oil, base oil "D" in **Table 1**, in conjunction with the new hectorite clay, low-dispersion emulsifier package, and the high-melting-point FLC material. The fluid was used to drill a vertical well to 4,986 m (16,358 ft) with a density range of 1.66 to 2.05 sg (13.8 to 17.1 lb/gal) and a final bottomhole static temperature of 180ºC (356ºF). The fluid performed as predicted from the extensive laboratory testing conducted prior to drilling the well.

The new high-melting-point FLC material maintained HTHP fluid-loss control at less than 5 mL/30 min when measured at both 180º and 190ºC (356º and 375ºF) with an average fluid loss between 2.0 and 3.5 mL. The range of HTHP fluid loss measurements are contained in **Fig. 3**.

The combination of new hectorite clay and low-dispersion emulsifier produced a fluid with very low and non-progressive gel strengths. The gel strength technical specification for this well was a 10-sec gel strength >10 lb/100 ft^2 and a 10-min gel strength <20 lb/100 ft^2 with a non-progressive 30-min gel strength. This gel strength specification was accomplished. Gel strengths measured at 50ºC (122ºF) are contained in **Fig. 4**.

Conclusions

Proper pre-planning for technically demanding wells can directly impact total cost and increase the probability of a successful application.

Environmental and H&S restrictions may limit available options to satisfy technical specifications. These restrictions must be identified in the pre-planning.

A new high-temperature organophilic clay has been identified. The hectorite clay product can viscosify in HTHP applications to 260ºC (500ºF).

A new low-dispersion emulsifier package has been developed to provide a flat rheological profile with a low, non-progressive gel structure. The package has successfully been used to drill 21 technically demanding low-temperature, high-angle and horizontal, ERD, TTRD, narrow hydraulic window, and HTHP wells.

A new HTHP fluid-loss control product has been identified. The high melting point of the product, greater than 232ºC (450ºF), has allowed the product to be successfully used in a HTHP well with a static bottom hole temperature of 180ºC (356ºF).

Acknowledgments

The author thanks M-I Norge for permission to publish this work, the M-I Norge laboratory staff for their endless patience and hard work, and Mary Dimataris and Jim Redden for their assistance in the preparation of this paper.

References

1. Elementis Specialties: "Rheology and Additives for Drilling Fluids," (presentation).
2. Eilertsen, T., Haga, M. and Svoboda, C.: "Unique Drilling Fluid for Åsgard Development in the North Sea," *Petroleum Engineer International* (Aug 1998) 65.
3. Taugbøl, K., *et al.*: "Reformulating an Oil-Based Drilling Fluid with Especially Selected Chemicals Lead to Development of a Low-Viscosity, High-Sag Stability Drilling Fluid," SPE 87139, IADC/SPE Drilling Conference, Dallas, March 2 – 4, 2004.

Table 1 – Comparative properties of commonly used base oils in the North Sea. Typical Values*

BASE OIL PROPERTIES	LTMO "A"	LTMO "B"	LTMO "C"	LTMO "D"	Linear Alkane
Density @ 15° C / 59° F, s.g. (lb/gal)	0.814 (6.78)	0.820 (6.83)	0.799 (6.66)	0.811 (6.61)	0.765 (6.38)
Kinematic Viscosity @ 25° C / 77° F, cSt	5.00	3.20	2.09	3.20	2.87
Kinematic Viscosity @ 40° C / 104° F, cSt	3.50	2.38	1.62	2.28	1.76
Pour Point, ASTM D 97, °C (°F)	– 27 (–17)	–24 (–11)	–35 (–31)	–51 (–60)	–8 (18)
Flash Point, ASTM D 93, °C (°F)	118 (244)	102 (216)	76 (169)	101 (214)	94 (201)

*** If there is a range of typical values the lowest typical value was used**

Table 2 – Average Rheological Properties from HTHP Wells Conventional Emulsification Package and Low-Dispersion Emulsification Package.

PROPERTIES	Conventional Fatty Acid Emulsifer Pkg.	Reduced Dispersion Emulsifer Pkg.
Base Oil Selection	**LTMO "A"**	**LTMO "D"**
Density, s.g. (lb/gal)	**1.90 (15.8)**	**1.85 (15.4)**
Average 6-rpm @ 50°C / 122°F, dial reading	**10.1**	**9.5**
Average 3-rpm @ 50°C / 122°F, dial reading	**9.0**	**8.5**
Average 10-sec Gel @ 50°C / 122°F, lb/100 ft^2	**12.5**	**10.0**
Average 10-min Gel @ 50°C / 122°F, lb/100 ft^2	**23.5**	**13.0**
Average 6-rpm @ 80°C / 176°F, dial reading	**8.5**	**8.0**
Average 3-rpm @ 80°C / 176°F, dial reading	**7.5**	**7.0**
Average 10-sec. Gel @ 80°C / 176°F, lb/100 ft^2	**10.0**	**8.2**
Average 10-min Gel @ 80°C / 176°F, lb/100 ft^2	**16.5**	**11.4**
Average Oil:Water Ratio	**83:17**	**83:17**

Table 3 – HTHP Filtrate Comparison

	Standard Gilsonite		New FLC Product	
	Initial	Aged	Initial	Aged
Density, sg (lb/gal)	2.04 (17.0)	2.04 (17.0)	2.04 (17.0)	2.04 (17.0)
Test Temperature, ºC / ºF	50 / 122	50 / 122	50 / 122	50 / 122
600-rpm Reading	123	115	124	118
300-rpm Reading	77	69	77	70
200-rpm Reading	59	53	59	53
100-rpm Reading	40	37	40	34
6-rpm Reading	15	15	16	12
3-rpm Reading	14	14	14	11
Plastic Viscosity, cP	46	46	47	48
Yield Point, lb/100 ft^2	31	23	30	22
10-sec Gel, lb/100 ft^2	16	16	16	15
10-min Gel, lb/100 ft^2		21		27
HTHP Filtrate, mL/30 min		11.0		4.0

Table 4 – Flat rheological properties and low non-progressives gel strengths obtainable with fluid containing low-dispersion emulsifier, premium clay, and linear alkane base oil measured at different 3 different temperatures

Test Temperature, °C / °F	28 / 82	50 / 122	80 / 176
Density, sg (lb/gal)	1.68 (14.0)	1.68 (14.0)	1.68 (14.0)
Oil/Water Ratio	77/23	77/23	77/23
% Low Gravity Solids	4.97	4.97	4.97
600-rpm Reading	108	78	55
300-rpm Reading	65	49	37
200-rpm Reading	50	38	28
100-rpm Reading	33	26	20
60-rpm Reading	25	20	16
30-rpm Reading	19	15	13
6-rpm Reading	11	9	8
3-rpm Reading	9	8	7
Plastic Viscosity, cP	43	29	18
Yield Point, lb/100 ft^2	22	20	19
10-sec Gel, lb/100 ft^2	13	11	9
10-min Gel, lb/100 ft^2	18	14	13
30-min Gel, lb/100 ft^2		16	

Table 5 – Average properties of fluid used in one of five TTRD applications.	
Average 1.72-sg TTRD Properties	
Oil/Water Ratio	80/20
% Low Gravity Solids	6.3
Test Temperature, ºC / ºF	50 / 122
600-rpm Reading	84.5
300-rpm Reading	53.9
200-rpm Reading	41.8
100-rpm Reading	29.6
60-rpm Reading	24
30-rpm Reading	18.4
6-rpm Reading	12.4
3-rpm Reading	10.8
Plastic Viscosity, cP	30.6
Yield Point, lb/100 ft^2	23.3
10-sec Gel, lb/100 ft^2	14.4
10-min Gel, lb/100 ft^2	21

Table 6 – Typical fluid properties from three intervals 7,230 m (23,720 ft) ERD well.			
Interval Size (in.)	16.75	12.92	8.5
Inclincation, degrees	74.85	75.00	91.78
Density, sg (lb/gal)	1.48 (12.3)	1.55 (12.9)	1.59 (13.25)
Oil/Water Ratio	72/28	77/23	78/22
% Low Gravity Solids	3	7.2	5.7
Test Temperature, °C /°F	50 / 122	50 / 122	50 / 122
600-rpm Reading	77	80	93
300-rpm Reading	49	49	58
200-rpm Reading	38	38	43
100-rpm Reading	27	26	26
6-rpm Reading	12	11	11
3-rpm Reading	11	10	10
Plastic Viscosity, cP	28	31	35
Yield Point, lb/100 ft^2	21	18	23
10-sec Gel, lb/100 ft^2	14	12	12
10-min Gel, lb/100 ft^2	16	18	18

Table 7 – Rheological properties from fluid used in ERD well.						
	6-Speed Rheometer	**High Temperature / High Pressure Viscometer**				
Pressure, psi	0	14.7	2000	4000	4000	6000
Temperature, ºC/ºF	50 / 122	50 / 122	50 / 122	50 / 122	100 / 212	100 / 212
600-rpm Reading	85	78	83	98	61	67
300-rpm Reading	53	48	51	60	39	43
200-rpm Reading	41	38	40	46	32	35
100-rpm Reading	28	27	28	32	24	25
6-rpm Reading	11	12	12	12	11	12
3-rpm Reading	10	10	11	11	10	11
Plastic Viscosity, cP	32	30	32	38	22	24
Yield Point, lb/100 ft^2	21	18	19	22	17	19
10 Second Gel, lb/100 ft^2	13	12	12	13	11	11
10 Minute Gel, lb/100 ft^2	18	13	17	19	13	13

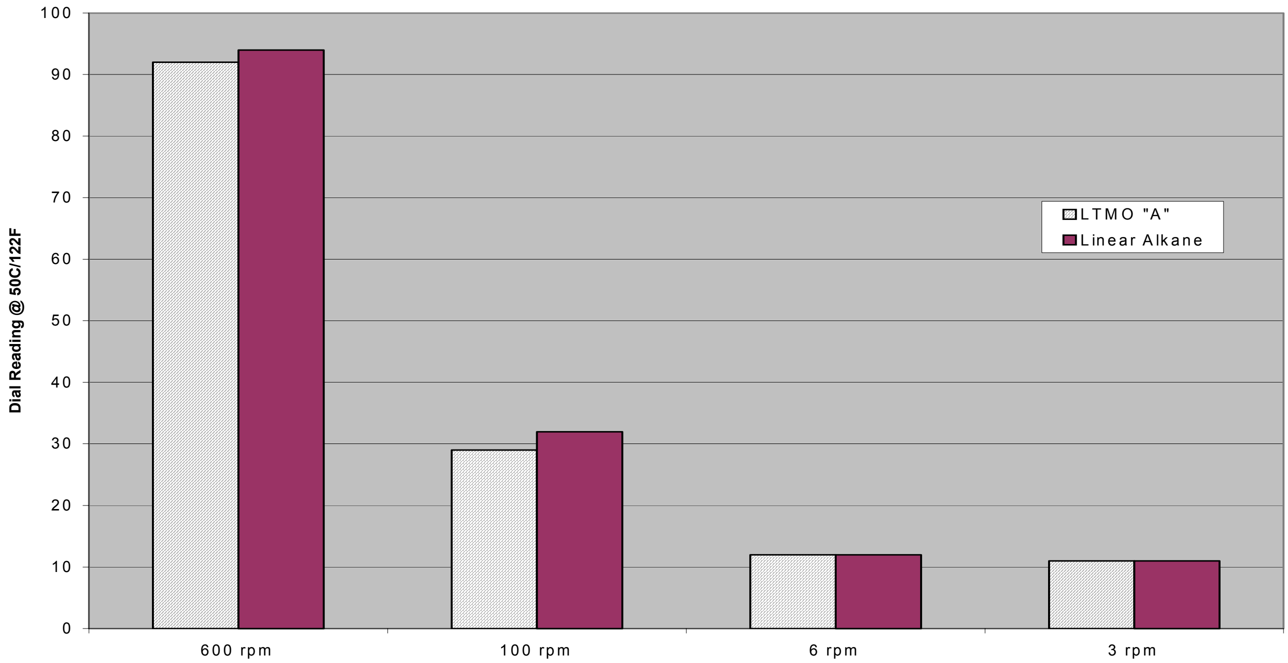

Fig. 1 – Similar rheological properties obtainable with low-dispersion emulsifier package in combination with a linear alkane base oil with an OWR of 75:25 and a density of 1.74 sg (14.5 lb/gal) compared to a conventional system with an OWR of 80:20 and a density of 1.58 sg (13.17 lb/gal).

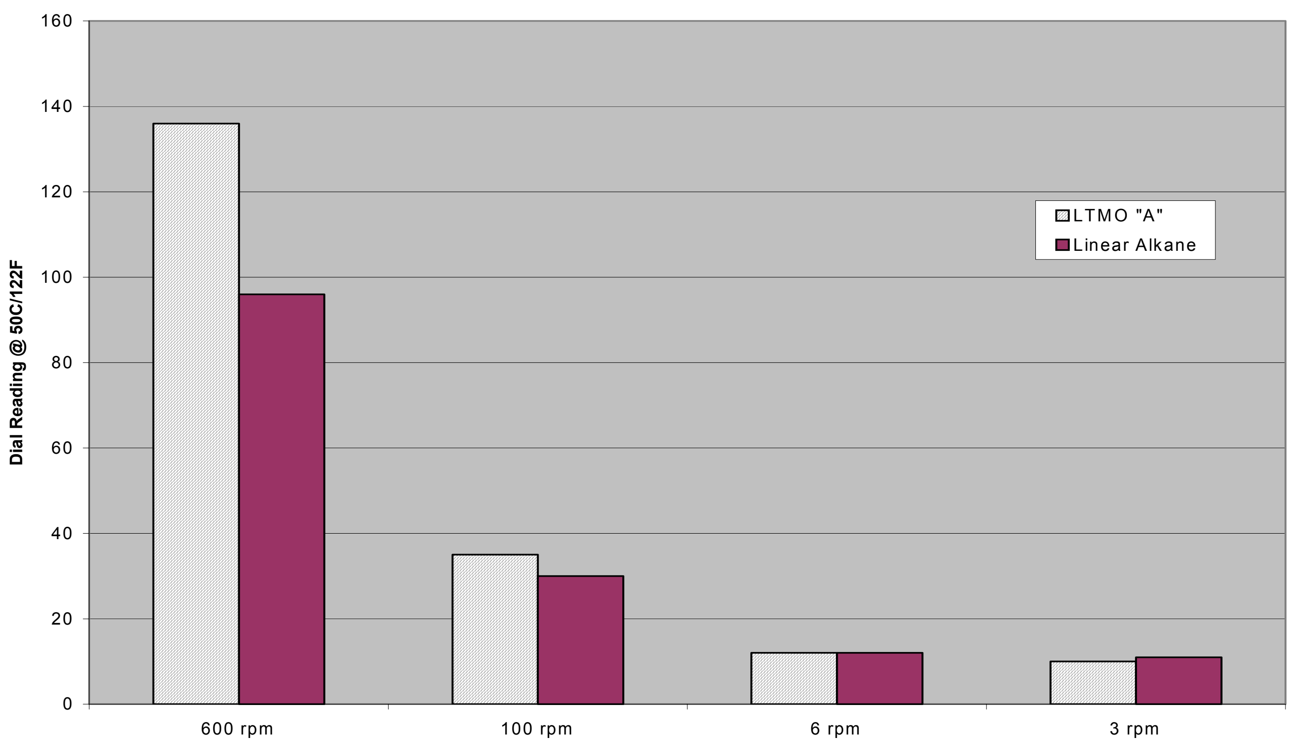

Fig. 2 – Reduction in rheological properties obtainable with low-dispersion emulsifier package in combination with linear alkane base oil in comparison to fluid using conventional package. Both fluids have identical density of 1.68 sg (14.0 lb/gal) and similar OWR.

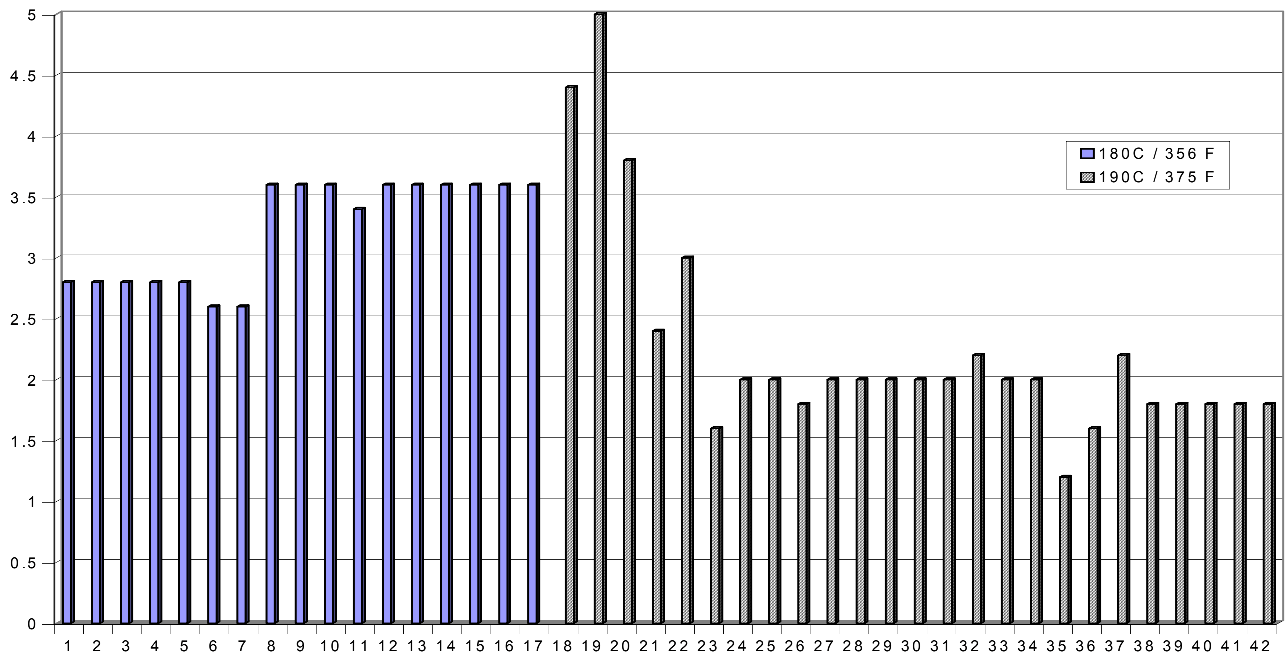

Fig. 3 – HTHP filtrate values measured at 180º and 190ºC from Norwegian HTHP well.

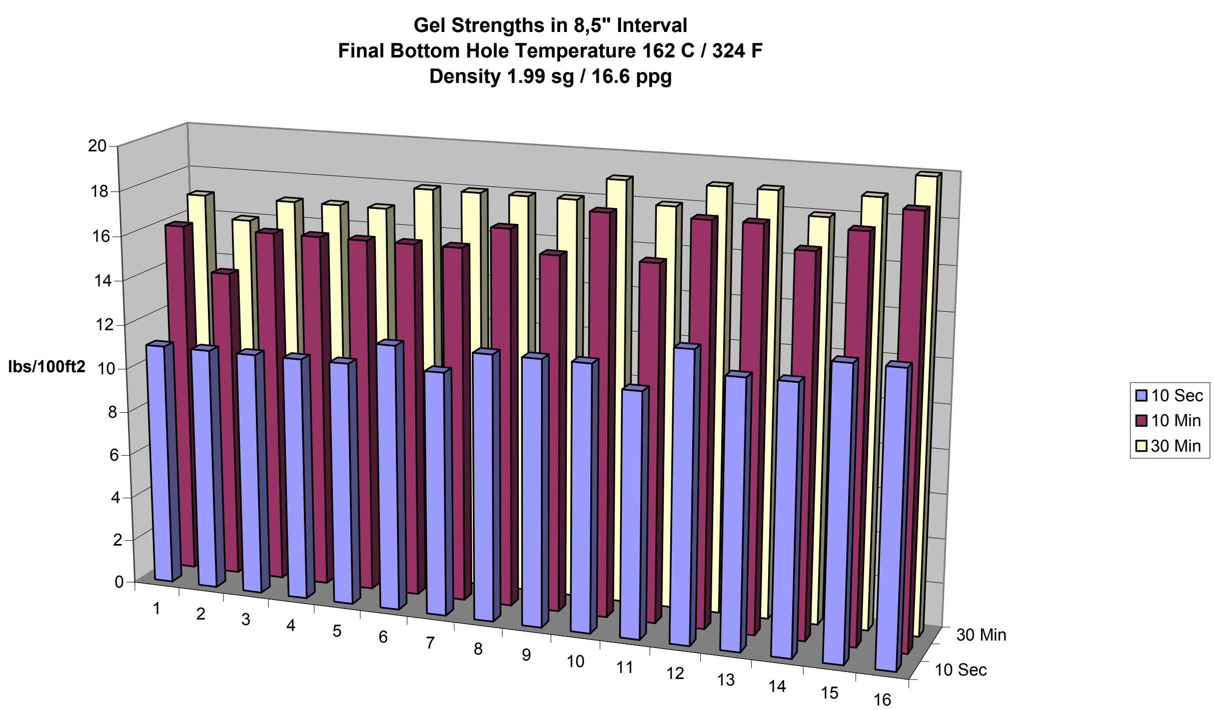

Fig. 4 – Measured gel strengths at 50ºC from Norwegian HTHP well.