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The Revolution in Non-Aqueous Drilling Fluids

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Abstract

Since their introduction in the late 1930s, non-aqueous drilling fluids (NADF) have improved considerably, and for the last three decades NADF have generally been the preferred type of fluid for drilling through problem formations, thanks in part to the introduction of synthetic-based fluids twenty years ago. The revolution in NADF technology has not been without challenges, however, as the complexity of drilling operations has grown enormously, and environmental regulations have grown increasingly restrictive. In the past, when shallow vertical land wells were the norm, drillers focused on stabilizing shales and hole cleaning. Now, drilling often involves construction of wellbores that are long and deviated; deep and hot; through depleted or abnormally pressured zones; and in deep water. These new challenges have required that NADF be environmentally friendly, stable and possess desirable mud properties over broad ranges of temperature and pressure. Another challenge is that NADF are increasingly used for drilling reservoirs, where potential impairment in well productivity – including cleanup and completion – is of paramount importance.

New NADF have been and will continue to be developed to handle increasingly tough and complex drilling scenarios. Solutions to these challenges have included not only changes in base fluids, but also internal polar phases, surfactants, polymers and colloidal (and now sub-colloidal) additives. In this paper, we discuss changes in the composition and properties of NADF over the years that have enabled NADF to remain at the forefront of the drilling fluid industry.

Introduction

Oil-based drilling fluids or muds (OBM) have been in use for several decades. Properties of these fluids are described elsewhere.[1-4] OBM offer several advantages over water-based drilling fluids or muds (WBM), including stabilization of formation clays, high lubricity, less corrosion, potentially less formation damage, and the ability to handle very low and very high temperatures. Some of the earliest attempts used untreated field crude oil of uncertain composition to drill and complete producing formations.[4] Later, clay was added for viscosity to clean the hole, and a small amount of a fatty acid was thrown in to ensure oil wetting of drilled cuttings.[5] From these humble beginnings, non-aqueous drilling fluid (NADF) technology has advanced to "designer fluids," which typically consist of a well-characterized synthetic hydrocarbon as the base fluid or continuous phase for the NAF; polymers and perhaps organophilic clay for viscosity and fluid loss control; an internal polar phase of prescribed water activity; and surfactants to emulsify the polar phase as well as oil-wet drilled cuttings and weighting material.

On the other hand, OBM have posed significant challenges, including high initial cost; health, safety and environmental (HSE) concerns; incompatibility with elastomers; high potential for lost circulation; high sensitivity to pressure and temperature; inability to detect gas kicks; and undesirable effects on some logging tools. Many of these issues, however, have been addressed and even eliminated in the intervening years since the introduction of NADF.

In this paper we describe some of the progress that has been made to overcome these challenges.

Synthetic Fluids

In the drilling fluid industry, the term "oil" is used for liquids prepared from distillation of petroleum, whereas the term "synthetic" or "synthetic fluid" is reserved for non-aqueous liquids prepared from the reaction of fundamental organic building blocks, such as ethylene or methane. Arguably the revolution in NADF began in the early 1990s with the advent of synthetic-based drilling fluids (SBM). The primary driver was biodegradability of the residual NADF on drilled cuttings. Although OBM had shown significant improvements in HSE properties such as flash point and aromatic content, other HSE issues arose that were difficult or even impossible to solve using petroleum-derived hydrocarbons.

The primary concern was the fate of oily drilled cuttings, especially those discharged into the sea during offshore drilling operations. Sampling of cuttings mounds on the seafloor revealed that not only the mounds themselves, but vast areas around them, had become anoxic and were essentially devoid of life. A base fluid that would anaerobically biodegrade might solve this problem. The search for such fluids led to esters, in the belief that their "built-in oxygen" would enable these materials to biodegrade without the assistance of dissolved oxygen.

Vegetable and animal oils – many of them natural esters – were tried but failed to meet performance and/or HSE standards. However, an ester prepared from a natural fatty acid and an alcohol, showed much more promise, and it became the first commercial "synthetic" fluid. Other synthetic fluids soon followed, including acetals, alkylbenzenes and an assortment of aliphatic hydrocarbons derived from ethylene. Today the most commonly used synthetic fluid is an internal olefin with a carbon chain length of C_{16}-C_{18}.

Cost

The cost of non-aqueous fluids (NAF) that are used to construct NADF has always been higher than that of water. Indeed, when synthetic fluids were developed as replacements for oils in offshore operations to enable direct discharge of cuttings to the sea, the initial drilling fluid cost more than doubled. However, NADF are usually rented, so that the operator only pays for loss of residual fluid on cuttings, losses downhole (mainly through lost circulation) and rental of the fluid returned to the service company for reconditioning and re-use. Furthermore, use of synthetic-based NADF, often called SBM, does not require expensive collection, transportation and onshore disposal of cuttings. Thus, for drilling in reactive, deep and/or hot formations, which usually is more efficient with NADF than with WBMs, the net cost of using SBM is significantly less than WBMs, though their initial costs may still be higher.

HSE Issues

The move to synthetic fluids has had some additional benefits, including lower environmental impact (lower toxicity to marine life); lower pour points (easier to use in cold climates); and lower and more salutary vapor emissions (improved health and safety because of lower carcinogenicity, lower vapor pressures and higher flash points). Incorporating water into NADF to make invert emulsion fluids also has provided benefits in all these respects, along with reducing cost; generally the lower the ratio of Oil/Water (O/W) or Synthetic/Water (S/W), the greater these benefits.

A side benefit arises from the differences in composition of synthetics vs. oils. Oils may contain a plethora of compounds, depending on the source material and the distillation details, e.g. summer diesel (#2) contains more than 200 different types of compounds, and these can be quite variable. However, some mineral oils may contain basically only one type of compound, though the molecular weight distribution may be broad. Synthetic fluids typically contain essentially only one type of compound with a fairly narrow molecular weight distribution. Consequently, it is much easier, generally, to control and monitor synthetics than oils in drilling operations.

NADF have posed all kinds of HSE issues since they were first introduced. Flammability was of prime importance initially, inasmuch as flash points of crude and diesel oils were quite low. Adding water to the fluid helped considerably in this regard; it was found that O/W or S/W ratios lower than 80/20 did not support combustion. Decreasing the fraction of volatiles and aromatic content also was found to increase flash points, and as a bonus it also reduced hazards associated with handling the fluids. Environmental risks, however, have been the most difficult to manage, primarily because discharge regulations vary so much geographically and are continually changing.

Environmental regulations governing discharges generally deal with toxicity (acute and chronic) and biodegradability. Regulations imposed for discharge in the North Sea[6] are some of the strictest. Indeed, in the UK sector discharge of cuttings to the ocean is permitted only if the NAF on cuttings < 1 % w/w relative to dry cuttings; anticipating that all discharges will eventually be banned, operators have opted for zero discharge. Many countries in the Eastern Hemisphere defer to those regulations. In the Western hemisphere, the most common standards for offshore use and disposal are those for the Gulf of Mexico; here synthetics are permitted but strictly limited.[7] For land use, the regulations devised for Louisiana, USA[8] and Alberta, Canada[9] are modeled widely. Indeed, in some South American countries, an operator has a choice of following one or the other of those sets of regulations. And, of course, usually there are local restrictions that also must be overcome before a drilling fluid is allowed.

In Canada, compliance means passing a Microtox test (looking for metabolic changes in a chemiluminescent bacterium harvested from sea horses), and landfarming or spreading contaminated drilled cuttings requires that residual base fluid on cuttings <1% w/w relative to wet cuttings.

In the Gulf of Mexico, compliance requires that the base fluid contain <10 ppm polyaromatic hydrocarbons (PAH), creates no visible sheen on the surface of the water, passes kill tests with Mysid shrimp (for the water column) and Leptocheirus amphipod (for the sediment), and passes a bioaccumulation test. There are also limits on the maximum concentration of organics on cuttings. For SBM with C_{16}-C_{18} internal olefin base fluid, the limit of residual base fluid on cuttings is 6.9% (w/w relative to wet cuttings); for C_{12}-C_{14} ester base fluid, the limit is 9.4%. Regulatory bodies have determined that zero discharge requirements do not serve the public as well as permitting discharge of SBM with strict limits on the type of fluid and the concentration that may be discharged with cuttings. Accidental releases, especially from riser disconnects, occur infrequently, but here, too, the environment is thought to be damaged less by SBM than by OBM.

When synthetic esters were introduced, it was soon realized that they had some drawbacks. Not only were esters expensive (even those synthesized from natural products), but also they degraded at elevated temperatures, especially in the presence of alkaline materials like lime, and they generated high viscosities, which created excessive equivalent circulating densities. Consequently, the search for alternative synthetic fluids continued, and it finally alighted on ethylene-derived hydrocarbons. Although these olefinic products proved to be very successful offshore, they proved less so on land because of their cost and environmental issues.

In contrast to offshore operations, onshore drilling projects generally operate with much smaller budgets. The high cost of synthetics was a major stumbling block. Another impediment pertained to biodegradability and toxicity. Spreading and farming on land has been considered one of the best methods of managing NADF-laden cuttings. However, the synthetic esters, even those synthesized from natural products, were found to form toxic metabolites (intermediate products) during biodegradation when the cuttings were spread or landfarmed.[10] Further study revealed that the most readily biodegradable liquids which produced minimal side effects were aliphatic compounds, especially linear (also called "normal") paraffins. These are also more economical than either synthetic esters or olefins. Paraffins may be generated via distillation of petroleum or synthesized, e.g. via the Fischer-Tropsch reaction. If distilled from crude oil, the intermediate material must be further refined and hydrogenated; the liquid products – mineral oils – are mixed branched and linear paraffins.

Removal of NADF from cuttings to comply with regulatory limits of residual NAF on discharged cuttings has received considerable attention. Rigsite methods traditionally have involved disposal of the oily cuttings on site or elsewhere, and usually required some means to solidify or fixate them. However, since the fluid is not really removed from the cuttings, other methods have been investigated and used to actually remove the fluid from the cuttings one way or another. Removal methods have included washing with solvents (chlorocarbons and chlorofluorocarbons are the most common, but fairly exotic materials have also been used, e.g. supercritical CO_2); centrifugation of the fluid off the cuttings with rotating shakers; degradation by bacteria in a bioreactor; incineration and distillation, e.g. with a rotary kiln or a hammer mill; vermiculture with worms to digest the organics; biopiles to biodegrade the organics on cuttings spread on land; and modifying the drilling fluid itself so that all of the components can biodegrade or serve as soil amendments.[10]

In offshore operations, the concentration of NAF in the seabed sediment under deposited cuttings may decrease with time by re-suspension, bed transport, mixing, and bio-degradation. In many cases, sediment-dwelling micro-organisms are able to use the NAF as a source of nutrition. However, biodegradation of the NAF in the sediment may result in a decrease in sediment oxygen concentration. If the initial NAF concentration is sufficiently high, a sediment could become anoxic (oxygen depleted). Ideally, NAF should be biodegradable under both aerobic and anaerobic conditions.

Removal of NADF from cuttings may have secondary benefits, e.g. recovery of the NAF. Methods for removing and recovering the fluid for re-use – such as solvent extraction, centrifugation and distillation – have become popular. In the Gulf of Mexico, it is common to use rotating shakers (also called centrifugal driers) to help reduce the level of base fluid on cuttings to below the regulatory limit. On land, distillation is a popular choice. Both direct and indirect heating are used. An example of a direct heating device is the externally fired rotary kiln; indirect heating includes hammer mill and steam.

Finally, the oily cuttings problem can be addressed by removing the cuttings from the rig site. Transport to landfills or other onshore facilities was the standard years ago, but now cuttings re-injection either down the annulus of the well being drilled or into a dedicated disposal well is also common.

Each method of managing NADF-contaminated cuttings and other drilling wastes has costs and side effects, so a comprehensive cost/benefit analysis must always be made.

Elastomer Compatibility

Early OBM caused deterioration of elastomers, e.g. in pumps, leading to premature sealing problems and even failure. The swelling and embrittlement of elastomers accompanying exposure to OBM is roughly associated with the aniline point, which itself is inversely related to the aromaticity of the base fluid. Typically, the lower the aromatic content, the higher the aniline point will be and the more compatible the fluid will be with elastomers. Higher aniline points, especially over 150°F (65°C), indicate that the fluid is not a good solvent either for aniline or for common elastomers.

Crude oils generally have aniline points below 150°F, diesel fuels are on the borderline, e.g. 142°F, and mineral oils are higher.[11] Regular mineral oils with significant aromatic content may give values of 150 to 170°F (65 to 77°C), whereas enhanced (low-toxicity) mineral oils – with <1% aromatic content – will typically generate values in excess of 160°F (70°C). Synthetic fluids generally have aniline points that range from 160 to 200°F (70 to 93°C). It should be noted, however, that some high-aniline-point base fluids, such as PAOs (polyalphaolefins), can solubilize plasticizers in the elastomers and cause embrittlement.

Aniline is hazardous to handle and get rid of. Compositional analysis via instrumental techniques (like proton and ^{13}C-NMR) does not pose such HSE concerns and has been found to correlate well with aniline point.[12]

Lost Circulation Potential

DEA 13 demonstrated that, although the risk of fracture initiation is essentially independent of the nature of the drilling fluid, fracture propagation occurs more readily with OBM (and presumably all NADF) than with WBMs.[13] Furthermore, induced fractures tend to heal in the presence of WBMs. Consequently, the risk of lost circulation through induced fractures is greater with NADF than with WBMs, and it is generally accepted that a wellbore can withstand a higher mud weight when drilled with WBM than with NADF.

Some studies suggest that increasing the low-shear-rate viscosity while increasing the shear-thinning profile of a drilling fluid can slow the rate of invasion of the fluid into fractures. A Yield-Power Law (Herschel Bulkley) fluid can be described by

$$\tau = \tau_y + K\gamma^n$$

where τ = shear stress, τ_y = true yield stress, K = Consistency Index, γ = shear rate and n = Power Law Index. A high value of K coupled with a low value of n can provide the required viscosity profile to reduce the rate of fluid invasion. Furthermore, if the fluid has a true yield stress, τ_y, it will actually stop. τ_y can be approximated by the Low-Shear Yield Point, or LSYP, which is defined as 2 x 3-rpm Fann Reading –

6-rpm Fann Reading.[14] Although it is easy to design WBMs with this property, it has been difficult to do so with NADF. Nevertheless, some progress has been made to create shear-thinning NADF with high low-shear-rate viscosity.

The conventional way of controlling lost circulation is through the use of particulates incorporated in the NADF formulation or in pills that can seal pores or fractures or even halt fracture propagation before it leads to lost circulation.

ECD management has advanced considerably since the early days and has become an objective in most drilling operations to minimize lost circulation and maintain hole stability. Because a major component of ECD is the viscosity profile of the NADF, a common fluid design objective is minimization of viscosity and changes in viscosity with changes in depth and drilling fluid density.

A recent innovation relies on replacement of organophilic clays with special polymers that generate a viscosity profile (especially at low shear rates) vs temperature that is opposite to that of the NAF alone; the sum of these is a viscosity that is relatively insensitive to temperature.[15] **Fig. 1** shows how this new fluid design can impact the temperature dependence of low-shear-rate viscosity, which has a direct bearing on ECD while circulating and tripping.

Another new technology development is micronization of the weighting material, usually barite or calcium carbonate. This reduces the effect of weighting material on viscosity of the NADF and helps to maintain an ECD that varies minimally with mud density.[16] **Fig. 2** shows how micronizing the weighting material can affect the viscosity profile of a NADF.

Effects of Pressure and Temperature

Well depth affects the density of NADF much more than that of WBMs. NAF are considerably more compressible than aqueous fluids, so that the density of NAF (and consequently NADF, too) rises rapidly with increasing pressure; however, density decreases with increasing temperature. There is no remedy for this, other than to have an accurate and comprehensive database. Fortunately, these data are available and are usually incorporated into hydraulics programs to ensure accurate calculations of wellbore pressure and fluid dynamics.

The rheology of NADF can also vary considerably with pressure and temperature, which is problematic when drilling deepwater wells or deep holes. The viscosity of NAF (and NADF) can increase several-fold upon decreasing the fluid temperature from ambient to seabed conditions (~ 40°F in the Gulf of Mexico). Similarly, it can drop several-fold upon increasing the temperature from ambient to bottomhole conditions. Such a swing in viscosity can have strong impacts on ECD, wellbore stability and suspension properties. Fortunately, the NADF innovations described in the previous section, namely technologies to reduce the dependence of viscosity on temperature and mud density, have reduced the risks of drilling deepwater, depleted and deviated wells and reduced non-productive time.

Another issue is thermal stability. While NADF are generally able to withstand temperatures at least 100°F higher than WBMs, typically they have not been used at temperatures much in excess of 350°F. [Note: In the drilling industry High-Pressure, High-Temperature (HPHT) wells reach bottomhole pressures and temperatures in excess of 10,000 psi and 350°F.] As fields mature and the industry pushes to greater depths to find oil, bottomhole pressures and temperatures are exceeding these limits regularly. Indeed, the push into geothermal drilling has carried this quest to temperatures in excess of 500°F. Historically diesel OBM treated with special clays have been able to push up to 500°F for short times. Now SBM are being asked to go to this temperature and beyond and remain stable for long periods of time.

Not only does the base fluid have to be stable at elevated temperatures, so do all of the additives that control key properties like viscosity, fluid loss, emulsion stability and wettability. The surfactants responsible for emulsion stability and wettability are critical. Most of the amido-amine surfactants used in invert emulsion drilling fluid formulations hydrolyze at elevated temperatures and at the high pH used in drilling fluid formulations. This chemical instability, along with functional limitations of amido-amines at high temperature, renders them ineffective for HPHT applications.

Recently we developed a new surfactant that can be used in invert emulsion fluid formulations for applications in excess of 550°F. This surfactant, based on polyether carboxylic acid chemistry, is largely non-ionic and has no hydrolyzable functionality; as a result, it is chemically and functionally stable to high temperature. The HPHT fluid formulation utilizing this surfactant and a nano-particulate viscosifier, is given in **Table 1a**. This fluid was heat-aged at 570°F for 16 hr. The viscosity profile at 150°F and electrical stability at 80°F were measured after heat-aging. The results, shown in **Table 1b**, were considered acceptable. Fluid loss at 300°F after heat-aging was 40 mL/30 min. Had this fluid been formulated with a conventional amido-amine surfactant and an organophilic clay viscosifier, it would have become water-wet and looked like cottage cheese; the viscosity would not have been measureable, its electrical stability nil and fluid loss uncontrolled.

Gas Kick Detection

Hydrocarbon gases tend to be more soluble in NADF than in WBMs, so that release of formation gas as the fluid is circulated out of the hole is delayed. Symptoms of a gas kick include the following:[17]

- Increase in circulation rate
- Sudden change in drilling rate
- Change in pump pressure
- Reduction in drillpipe weight
- Reduction in mud weight
- Change in mud texture (becomes fluffy)

With WBMs, influx of formation gas leads to a relatively rapid expression of these symptoms, and steps can be taken quickly to manage the gas kick. With NADF, on the other hand, the delay in release of gas delays onset of these symptoms and hinders quick recognition and action to control the gas kick, thus increasing the risk of a blow-out.

One way to deal with this problem is to monitor the volume of NADF. Although gas coming into the NADF may dissolve, it will still cause some increase in the volume of the NADF. The rate of mud pit gain can be inputted into rate-of-swelling models to estimate the rate of influx of the gas and determine whether a gas kick may indeed be imminent.[18]

Another effective solution is managed pressure drilling, using techniques such as constant bottomhole pressure and pressurized mud-cap drilling. The latter also appears to be particularly effective for controlling sour gas.

Effectiveness of Logging Tools

The performance of some logging tools, particularly those that depend upon establishment of an electrical circuit at the borehole wall, can be affected by having an electrically insulating drilling fluid in the wellbore. Resistivity and Spontaneous Potential are directly affected. Conductive NADF have been developed using novel surfactant chemistry,[19] but difficulty controlling standard mud properties over a broad range of temperatures and pressures has precluded their adoption by the industry. Instead, logging tools themselves have been modified to enable measurements through non-conductive media.[20] For example, imaging tools have been developed using an array of electrodes that are spaced so closely that electrical current can penetrate through the drilling fluid, thus generating a resistivity profile of the wellbore.

Another issue that has been addressed with appropriate surfactant chemistry is the inability to log CO_2 accurately in formations where this gas is prevalent. Drilling fluids, including NADF, are generally formulated to be alkaline. NADF are no exception, and excess lime is a ubiquitous component of NADF. Lime serves multiple purposes, including scavenging CO_2/H_2S that may seep into the drilling fluid and reacting with surfactants to generate more efficient emulsifiers and/or wetting agents. However, if quantifying release of CO_2 is the objective of a logging operation, lime is not desirable. Consequently, a lime-free NADF was invented to enable accurate logging of CO_2. Without the lime, formation CO_2 could be measured accurately.[21]

Novel Products

NADF have been at the center of various discoveries and inventions, many of them focused on surfactant chemistry. Electrically conductive NADF were invented to enable conventional logging tools to measure the wellbore's electrical properties. Although these fluids were phased out a few years ago in favor of logging tools that could overcome the nonconductive nature of this fluid in the wellbore, the surfactant chemistry that was involved was quite innovative.

Low-alkalinity drilling fluids (see previous section), which employ emulsifiers and wetting agents that do not require lime to be efficient, are still being used.

As mentioned earlier, incorporation of novel products such as surfactants based on polyether carboxylic acid (rather than amido-amine) chemistry and nano-particulate viscosifiers have enabled NADF to be used at extremely high temperatures, such as those encountered in geothermal applications.

Another innovation is invert emulsion NADF with non-conductive internal (polar) phases. Environmental regulations in some parts of the world stipulate a very low upper limit for the concentration of salts in the mud. Other than eliminating the internal phase, i.e. using all-oil or all-synthetic NADF, there are few choices. The internal phase must be polar, yet possess a water activity similar to that provided by 15 to 25 wt% $CaCl_2$. Such fluids have indeed been developed.[22] Typically they are aqueous solutions of alcohols instead of salts, and different surfactant chemistries are necessary to provide emulsion stability.

Another important development has been reversible drilling fluids.[23] These are fluids whose continuous phase can be altered from oil or synthetic to water or brine and vice versa. This concept is drawn in **Fig. 3**. Applications include more efficient cementation of casing and elimination of NADF-laden drilled cuttings. One may use the oil/synthetic version of the fluid to drill the well, displace it with aqueous fluid, convert the residual drilling fluid in the filter cake on the wellbore to WBM and remove it with conventional effective cleaning techniques before cementing. Cement bond logs measured with a reversible mud acidified to the WBM state show the cement to be firmly bonded to casing, whereas conventional OBM shows no bond strength at all (**Table 2**). Drilled cuttings can be treated in a similar fashion, thereby eliminating the NAF on the cuttings. Again, it was the invention of a novel class of surfactants that permitted development of reversible muds.

Summary

New findings and innovations in NAF technology have greatly enhanced the effectiveness and utility of NAF for drilling operations. Without compromising the operational advantages that NAF have over WBMs, many of the issues which have previously limited utilization of NAF have been addressed, including:

- high initial cost
- health, safety and environmental (HSE) concerns
- incompatibility with elastomers
- high potential for lost circulation
- variability in properties with pressure and temperature
- inability to detect gas kicks
- incompatibility with some logging tools

As field operations evolve and demand better performance under more extreme conditions, we will continue re-inventing NADF. Novel polymer and nano technologies, along with new surfactant chemistries, will be critical for this revolution.

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Nomenclature

Aniline Point	=	*Temperature below which a 50% v/v mixture of aniline and a non-aqueous fluid of interest becomes cloudy*
ECD	=	*Equivalent Circulating Density*
γ	=	*Shear Rate*
HSE	=	*Health, Safety and Environment*
K	=	*Consistency Index*
n	=	*Power Law Index*
NADF	=	*Non-Aqueous Drilling Fluid*
NAF	=	*Non-Aqueous Fluid (Base Fluid)*
OBM or SBM	=	*Oil- or Synthetic-Based Drilling Fluid*
O/W or S/W	=	*Volumetric ratio of Oil/Water or Synthetic/Water in a drilling fluid*
ppb	=	*lbm/bbl*
PAH	=	*Polyaromatic hydrocarbons*
PAO	=	*Polyalphaolefin*
ROP	=	*Rate of Penetration*
τ	=	*Shear Stress*
τ_y	=	*Yield Stress*
WBM	=	*Water-Based Drilling Fluid*

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Table 1a. HPHT NADF Formulation

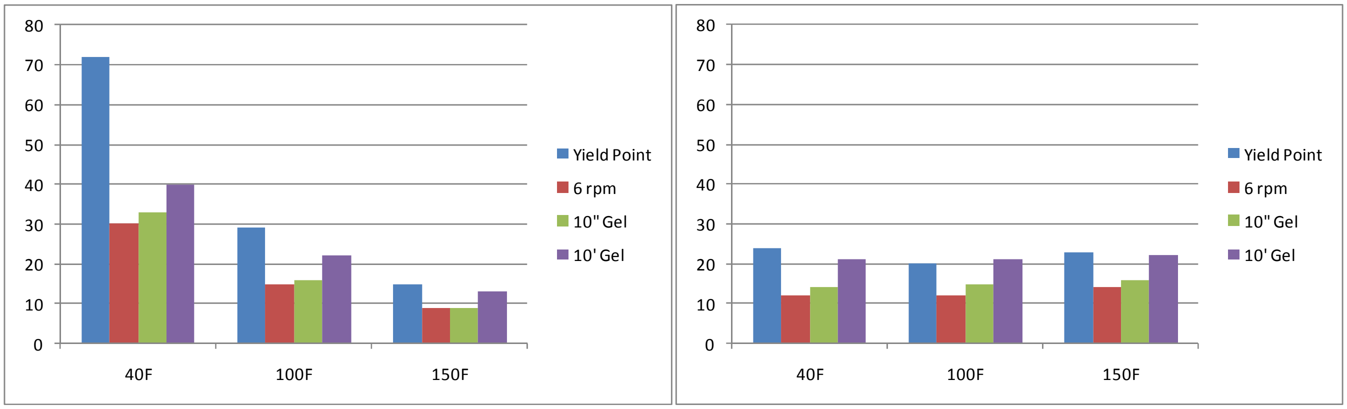
Product	Concentration (ppb)
Low-Tox Mineral Oil	129
Organophilic Clay	1
Lime	10
Polyether carboxylic acid emulsifier	25
Oil-Wetting Agent	5
Tap Water	41
95% $CaCl_2$	8.3
Non-Asphaltic Fluid Loss Additive	10
Nanoparticulate Viscosifier	12
OCMA Clay	15
Barite	383

Table 1b. Standard Mud Properties of HPHT NADF

Viscosity Profile at 150 °F	Unit	After Hot-Rolling 570 °F, 16 hr
600 rpm	deg	134
300 rpm	deg	84
200 rpm	deg	66
100 rpm	deg	44
6 rpm	deg	16
3 rpm	deg	13
Gel Strength, 10 sec	$lb/100\ ft^2$	19
Gel Strength, 10 min	$lb/100\ ft^2$	31
Apparent Viscosity	cP	67
Plastic Viscosity	cP	50
Yield Point	$lb/100\ ft^2$	34
Electrical Stability at 80 °F	V	310

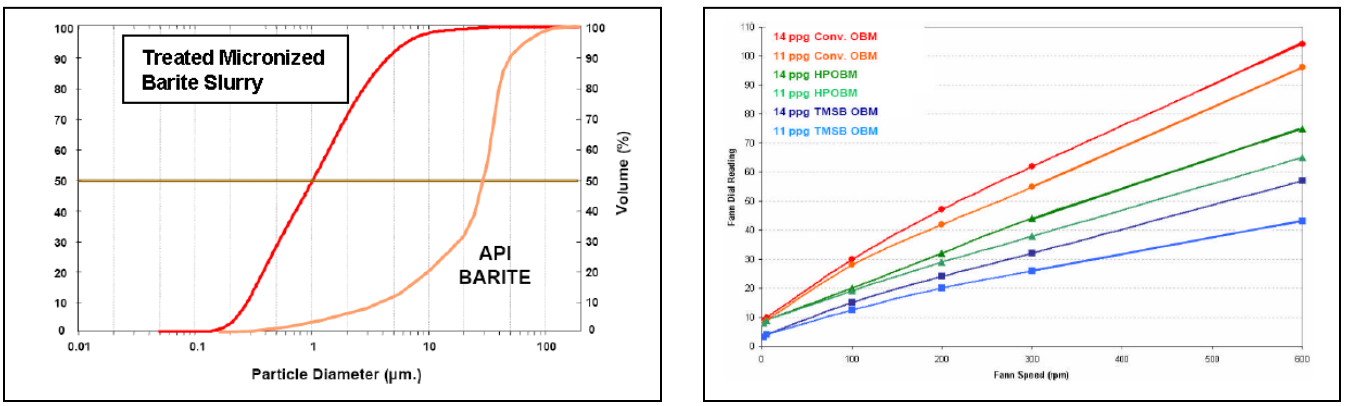
Table 2. Cement Shear Bond Test with Acidified Reversible Drilling Fluid [23]

Conditions	Shear Bond Strength (psi)	
	Conventional NADF	Reversible Drilling Fluid
Baseline with dry pipes	428	
No wash	0	0
5% Acid, 2-min wash	0	9
15% Acid-water, 2-min wash	0	95
15% Acid-water, 10-min wash	0	183



(a) Conventional Synthetic-Based NADF (b) Temperature-Independent Synthetic-Based NADF

Figure 1. Re-design of NADF produces viscosity profile that is relatively independent of temperature[15]



(a) Micronized barite is orders of magnitude smaller than API Barite (b) Viscosity profiles of TMSB OBM (with micronized barite) and conventionally weighted OBM

Figure 2. NADF weighted with micronized barite has much lower viscosity than conventionally weighted NADF[16]

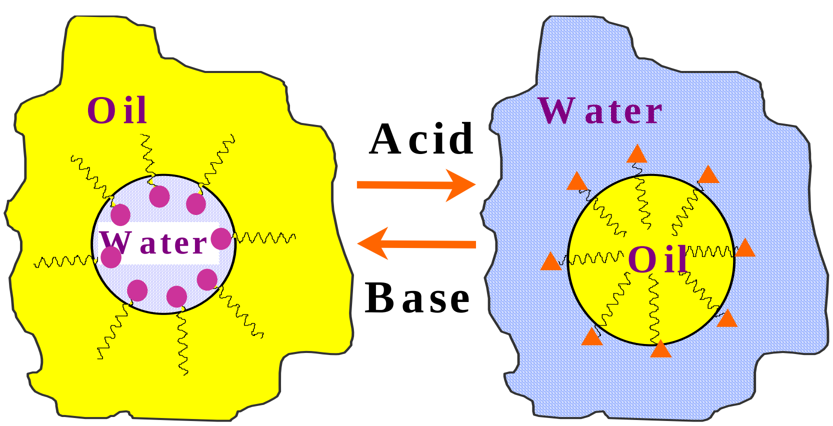


Figure 3. Reversible drilling fluid switches from NADF to WBM with change in pH[23]