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Increased Deepwater Drilling Performance Using Constant Rheology Synthetic-based Mud

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Abstract

Synthetic-based muds (SBM) are considered the "fluid-of-choice" in deepwater operations due to their ability to deliver well objectives while minimizing risk and costs. Key benefits derived from use of SBM include gas hydrate suppression, high rates-of-penetration (ROP), wellbore stability, and torque and drag reduction and lower overall well costs. However, a high frequency of lost circulation events and high unit costs can sometimes offset the technical benefits derived from use of SBM. Downhole temperature and pressure conditions in deepwater operations are such that the fluid becomes more viscous, due to cooler temperatures, when it remains static. The cooling increases pressures required to initiate and maintain circulation after static periods. Afterwards, lost circulation events often occur due to the increased surge and circulating (ECD) pressures arising from the cooled, viscous SBM.

A new SBM, exhibiting a constant rheological profile over a broad range of temperatures and pressures, has recently been developed specifically for deepwater operations. Unlike conventional SBM, the fluid exhibits a "constant rheology" profile under the temperature and pressure conditions encountered in deepwater operations. With its constant rheological and gel strength profiles, surge pressures and ECD are minimized in the wellbore, reducing the frequency and severity of lost circulation events. The innovative SBM is fully compliant with Gulf of Mexico environmental requirements for cuttings discharge. This paper provides key design criteria for a constant rheology SBM (CR-SBM), accompanied by field results detailing improved deepwater drilling performance derived through its use.

Introduction

SBM are the preferred drilling fluid for deepwater operations because of consistent performance in allowing operators to meet project objectives while managing well costs. The status-quo of using conventional SBM in deepwater operations would remain in place were it not for the frequent and recurring problems of downhole losses associated with SBM.

Losses of SBM during wellbore construction often occur when drilling, tripping, running pipe and cementing. Drilling losses are usually related to the equivalent circulating density (ECD) exceeding the fracture gradient. Tripping and cementing losses are related to surge pressures arising from SBM gel structure and the equivalent static density at the time of the operation.

Downhole temperatures and pressures encountered in deepwater operations create a unique challenge in managing static and dynamic pressures. Temperatures encountered in deepwater operations decrease dramatically from the surface to the mud line, where temperatures can decrease from ambient to 40° F (4° C) at water depths of 2,000 feet. This temperature reduction across the length of the riser effectively cools the drilling fluid, raising its viscosity, resulting in increased down hole pressures and lost circulation potential. This potential for losses is increased with conventional SBM when the mud column has been static and the temperature profile has reverted close to the geothermal gradient.

The margin between fracture gradient and pore pressures is typically narrow, particularly in Gulf of Mexico (GoM) deepwater operations. The temperature dependency and resulting pressure increases arising from conventional SBM often exceed this pressure window, resulting in a lost circulation event. In severe lost circulation events, the economic benefits derived from using SBM are reduced or lost.

The preferred method of managing pressure fluctuations in conventional SBM is to control the temperature and pressure dependency of SBM viscosity and gel strengths. In essence, the key design criterion for the newly designed SBM was to exhibit a near constant rheology over the temperatures and pressures encountered in deepwater operations.

History & Development of Constant Rheology SBM

The ideal drilling fluid for deepwater operations is one that satisfies all technical, performance and environmental goals, while also managing costs and non-productive time (NPT). The "best-case" SBM is one that allows operators to realize the benefits derived from use of this fluid, while managing or eliminating lost circulation events in deepwater operations.

The main challenge in achieving these objectives is to minimize the dependency of fluid viscosity and gel strengths on temperatures and pressures encountered in deepwater wells. BP identified the need to develop a new type of SBM, one that would allow operators to realize the benefits of conventional SBM while also managing the problem of lost circulation frequently encountered through their use. BP initiated a collaborative project with their 3 primary drilling fluid service providers for deepwater operations aimed at developing constant rheology systems. The project plan was divided into phases with clearly defined goals, objectives and deliverables from each phase.

The outcome of this initiative was a new family of constant rheology SBM that were developed, field-tested and commercially introduced in GoM deepwater drilling operations. Improved deepwater performance has been reported using this new family of SBM.[1,2,3] Key target performance enhancements from these systems were:

- Reduced surge pressures
- Reduced circulating pressure (ECD)
- Reduction in down hole mud losses

Phase I Fluid Testing

In 2001 BP commissioned testing of non-aqueous fluids (NAF) used in Gulf of Mexico deepwater operations. The first phase of this study involved benchmarking the rheological properties of conventional invert-emulsion drilling fluids from ongoing deepwater operations. Those rheological parameters viewed as important in affecting downhole mud losses were identified and used to develop the test matrix at different temperature and pressure combinations. This testing was performed at an independent laboratory using a viscometer capable of measuring fluid viscosity and gel strengths at temperatures and pressures encountered in deepwater operations.

Each drilling fluids company submitted a 12.0 lb/gal NAF composed of a mineral (MOBM), synthetic (SBM) or ester-based (EBM) external phase for rheological tests performed on a Model 70 HPHT viscometer. The laboratory conducted viscosity measurements on each NAF at temperatures ranging from 32°F (0°C) to 212°F (100°C) at ambient pressure and 2,500 psig.

Results of the HPHT viscosity testing are presented in Figures 1- 3 as a plot of yield point (YP) versus temperature and pressure. In general, the mineral oil-based NAF exhibited the most constant YP profile, while ester-based fluids had the greatest variation in YP over the temperature range and pressures tested. This initial evaluation provided a "snapshot" of the rheological properties of conventional NAF being used in BP's Gulf of Mexico deepwater operation at that time. A key deliverable of Phase I of this study was achieved in that baseline rheological profiles were now available and could be used in future work targeted towards delivering a CR-SBM.

Phase II Fluid Testing

The next phase of this study began in 2002 when BP commissioned a second evaluation of these key rheological properties. This analysis was an extension of the work in Phase I, occurring after each service company was tasked with modifying the conventional systems in order to achieve a more constant rheological profile. In Phase II, each service company submitted a 12.0 lb/gal mineral oil, synthetic, and ester-based formulations to the outside laboratory for evaluation. Unlike samples evaluated in Phase I, these samples were contaminated with 10 lb/bbl simulated drill solids to more closely simulate field conditions. Phase II HPHT viscosity testing was conducted at temperatures ranging from 32°F (0°C) to 212°F (100°C) and at ambient pressure, 2500 psig, and 5,000 psig.

Improvements in delivering a constant rheological profile are shown when comparing Figures 4-6 (Phase II) to Figures 1-3 (Phase I). These data clearly show measurable gains in reducing the dependency of YP on temperature in Phase II tests. Again, the mineral oil base fluid exhibited the most constant YP profile over the temperatures and pressures tested, while the synthetic and ester based fluids showed significant improvement in their YP profile compared to the initial testing.

The first two phases of this project were very successful in that they: 1) delivered data showing that NAF in use in 2001 exhibited large variation in key rheological properties as a function of temperature and pressure, 2) established a basis of comparison for three types of NAF in use at that time and, most importantly, 3) demonstrated the feasibility of modifying the rheological behavior to achieve a CR-SBM for deepwater operations. Having provided "proof-of-concept", BP then commissioned each drilling fluid service provider to develop a next generation CR-SBM, one that would exhibit near constant rheological properties under deepwater conditions. These constant rheology SBM systems exhibit a more uniform rheological profile compared to a conventional SBM over the broad range of temperatures and pressures encountered in deepwater operations while also maintaining compliance with GoM environmental requirements for cuttings discharge.

Fluid Design–New Constant Rheology SBM

This paper provides an overview of the design process, development and field testing of one of the CR-SBM systems developed as an outcome of the BP study. The CR-SBM presented in this paper was the third system to be field tested by BP and case history data on the first field test is presented in this paper. Second and third field tests of the CR-SBM for BP in the Gulf of Mexico are underway at the time of preparing this paper.

The design team for the CR-SBM set aggressive goals to meet clearly defined performance and environmental criteria, initially targeting field tests with BP in Gulf of Mexico deepwater operations. Key rheological parameters, primarily gel strengths, 6 & 3 rpm readings and yield point (YP) were targeted to remain "constant" in this new SBM at a range of temperatures and pressures. Specific design criteria of the CR-SBM presented in this paper were:

- GoM compliant internal olefin external phase, with calcium chloride in the internal phase
- Rheological properties (gel strengths, YP, 6 & 3 rpm reading) nearly independent of temperature and pressure conditions

- Conform to Gulf of Mexico environmental regulatory guidelines
- Optimize product mix to deliver performance in areas of hole cleaning and barite sag management

Initial development work was carried out using an internal olefin base fluid at a density of 12.0 lb/gal. The design team evaluated each component to determine the product mix required to meet project objectives. An olefin base fluid was selected in lieu of other available base fluids, particularly esters, with consideration to product compatibility, environmental acceptance and temperature stability. The researchers were able to engineer the system in such a way that the same emulsifier package found in the conventional SBM was also compatible with the CR-SBM. This was a tremendous breakthrough in that the majority of components found in the conventional SBM were compatible with the CR-SBM, with exceptions being those of the viscosifier package.

The importance of organophilic clay in managing dynamic barite sag is well documented in the literature; therefore, the team felt it important that high-quality organophilic clay was used in the viscosifier package. This novel organophilic clay, new to the GoM deepwater arena, was the first step in achieving constant rheology, at levels sufficient to deliver performance for hole cleaning and barite sag.

Barite sag is the density variation observed in directional wells observed when circulating bottoms up after operations where the drilling fluid has been exposed to near static conditions. A significant amount of work has been undertaken to investigate and understand the mechanisms of dynamic barite sag, and to provide direct and indirect well-site tests to manage the problem. It is well understood that appropriate control of low shear rate viscosity is fundamental to managing the problem and that organophilic clays are the most effective viscosity control additives to manage the problem.[4,5]

The second key development was the identification of a polymeric viscosifier specifically designed to perform in combination with the organophilic clay. Having established the compatibility of the other constituents of the system with the new viscosifier package, the team then began a rigorous program of optimizing the product mix and concentrations. This testing was conducted over a range of densities expected to be encountered in deepwater operations, ranging from 9.7 lb/gal and upwards to 12.0 lb/gal.

The CR-SBM presented in this paper is unique in the sense that near constant profile of these key rheological properties was achieved while using organophilic clay and without the use of special emulsifiers. It is a simplistic system in that a constant rheological profile has been achieved using the same base fluid and emulsifier package found in conventional SBM.

The three service companies initially involved in this BP-sponsored initiative all were successful in developing and field testing constant rheology systems, however, each took a different route to develop a CR-SBM system.

Verification work on the newly designed system was performed at the outside laboratory used in Phases I and II of this project. Here, conventional and constant rheology SBM were submitted for HPHT rheology testing for comparison of the fluids viscosity and gel strengths from 40˚F (4˚C) to 200˚F (93˚C) and at ambient pressure and 5000 psig. The results of these tests are presented in Figures 7 through 10, which show a reduced dependency on YP and gel strength to temperature with the CR-SBM compared to conventional SBM.

Environmental Criteria

Environmental compliance is mandatory for any drilling fluid system designed for discharge into the Gulf of Mexico (GoM). The NPDES General Permit for GoM discharge dictates adherence to environmental criteria for dischargeable fluids, including oil-on-cuttings, formation oil contamination, free oil, sediment toxicity and monthly toxicity compliance.

Individual products and additives used to formulate SBM must adhere to the same criteria as the whole fluid. The most crucial of these criteria when designing fluids that use new components is the sediment toxicity test.

The new CR-SBM is formulated utilizing products that fully satisfy stringent Gulf of Mexico environmental criteria according to the EPA General Permit for SBM in the Gulf of Mexico (Region 6 GMG 290000). Sediment toxicity testing was performed on both the CR-SBM whole mud and new components in the viscosifier package to ensure compliance. The permit specifies that the fluid toxicity ratio should not exceed 1.0. Due to the inherent variability of the test, samples of the new fluid were tested in duplicate. The CR-SBM was tested alongside a standard reference mud, as well as a conventional SBM. Test results show the CR-SBM fluid to have a toxicity ratio of 0.726 and therefore be environmentally compliant for GoM discharge. Results also indicated a reduced level of toxicity compared to a conventional SBM (Figure 11).

Two sedimentary toxicity Tests were conducted on the “organic polymer”. One sample tested the organic polymer “neat” and the other contained a 50:50 blend of the polymer and the synthetic base fluid. Results of these tests indicated the “organic polymer” to be environmentally compliant for GoM discharge as shown in Figure 12.

Case History

The new CR-SBM fluid was selected for use on a re-entry well in the Green Canyon field of the GoM. The hole geometry consisted of 18” casing set at a depth of 9,039 feet (2,755 meters). Software modeling was performed using both steady-state and dynamic hydraulics software. Both models dissect the wellbore into grids and analyze the fluid density and pressure based upon local temperature and pressure conditions within each grid. The simulations were set up to compare conventional SBM to the new CR-SBM with respect to ECD, SPP, pressure spikes and tripping speeds. The only variables in these cases were the HPHT viscosity readings of the SBM and CR-SBM being evaluated. This type of analysis provided for side-by-side comparison of the results. This pre-drill hydraulics modeling indicated that surge pressures when running casing could be reduced in each of the hole sections using the CR-SBM compared to conventional SBM as shown in Figures 13 and 14. These simulations were consistent with expectations of the benefits of the system with respect to surge pressure reduction.

The desired objectives of using the CR-SBM on this well included:

- Maintenance of environmental compliance for Gulf of Mexico discharge
- Reduction in pressure spikes when initiating circulation after connections and trips
- Reduction in surge pressures when running casing to eliminate or reduce whole mud losses compared to similar offsets
- Elimination of mud-related Non-productive time (NPT)

The well was temporarily abandoned and contained conventional SBM that had been used in drilling the original hole interval, along with several cement plugs. This system was used to drill the cement plugs and to clean debris from the hole. Afterwards, this system was displaced with the CR-SBM, which was then used to drill the remainder of the hole interval. The drilling program had planned to drill four (4) intervals with the CR-SBM to a total depth of 22,584 feet.

The 16.5” x 19” section was drilled and casing was set within the salt. When drilling, the interval pressures during pump initiation were recorded, indicating that pump initiation pressures were approximately 300 psi less compared to conventional SBM under similar conditions on offset wells. Additionally, the pressure required to initiate circulation was generally 50 psi higher than before making the connection as shown in Figure 15, suggesting very little increase in gel strength development while making the connection.

Due to a recurring problem with loop currents, the well was temporarily abandoned prior to drilling the 12.25” section. Operations were temporarily suspended for 30 days between the two intervals that were drilled, waiting on loop currents to diminish. Upon resumption of operations, the properties of the fluid left in the hole were stable, as shown in the stability of gel strength measurements of the system (Figure 16). Generally, low initiation pressures allowed operations to quickly resume without problems, NPT or down hole losses. Additionally, the incremental circulating density averaged less than 0.25 lb/gal throughout the interval, which was significantly lower than what was predicted (>0.5 lb/gal) based on offset well data drilled with conventional SBM (Figure 17).

The hole interval was drilled without mud-related problems or NPT and the system met all expectations in terms of performance when drilling, running casing and cementing. Down hole losses were limited to 60 barrels lost in the salt, compared to 2,800 barrels of conventional SBM lost on the nearest offset well using conventional SBM. Additionally, there were no barite sag or hole cleaning incidents reported.

Pressure management benefits of the system allowed the drilling team to trip to bottom, eliminating the need to stage-in the hole, thereby reducing NPT and rig-related costs.

The development and field test process allowed the team to fully evaluate the benefits derived from the CR-SBM. Field data clearly showed that these benefits include, but are not limited to:

- ❖ Reduced surge pressures
- ❖ Reduced circulating pressure (ECD)
- ❖ Reduced circulation initiation pressures
- ❖ Reduction in down hole mud losses
- ❖ Optimized hole cleaning
- ❖ Improved barite sag management
- ❖ Control of well bore breathing (ballooning)
- ❖ Reduced non-productive time

Conclusions

- ❖ A new family of CR-SBM has been developed, field tested and commercially introduced through a BP-supported initiative to reduce downhole losses of SBM.
- ❖ CR-SBM exhibit near constant rheological properties, primarily gel strengths, yield point and 6/3 rpm readings and are not significantly affected by temperature and pressure
- ❖ CR-SBM can be formulated using many of the components currently available in conventional SBM, differing primarily in the rheological package
- ❖ Benefits of CR-SBM include reduced dynamic and static pressures, leading to the reduction in down hole mud losses when drilling, running casing and cementing
- ❖ Additional benefits from use of CR-SBM include reduction in mud-related NPT and well costs

Acknowledgments

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Nomenclature

SBM = *Synthetic-based Mud*
ROP = *Rates-of-Penetration*
ECD = *Equivalent Circulating Density, lbs/gal*
CR-SBM = *Constant Rheology SBM*
F = *Temperature, degrees Fahrenheit*
C = *Temperature, degrees Celsius*
NPT = *Non-productive Time*
Lbs/gal = *Density, pounds per gallon*
NAF = *Non-aqueous Fluid*
MOBM = *Mineral-oil based Mud*
EBM = *Ester-based Mud*
HPHT = *High Pressure / High Temperature*
Psig = *Pressure, pounds per inch^2 (gauge)*
YP = *Yield Point, lbf/100 ft^2*
Lb/bbl = *Concentration, pounds per oilfield barrel*

GoM = Gulf of Mexico
NPDES = National Pollution Discharge Elimination System
SPP = Standpipe Pressure, psi
Gals/min= Flow rates, gallons per minute
SPP = Stand-pipe Pressure, psi

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Figure 1
Mineral Oil Based Fluids
Yield Point vs Temperature Phase 1

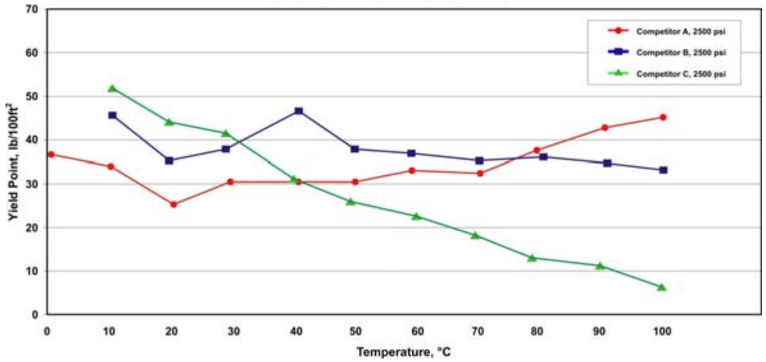


Figure 2
Synthetic Based Fluids
Yield Point vs Temperature Phase 1

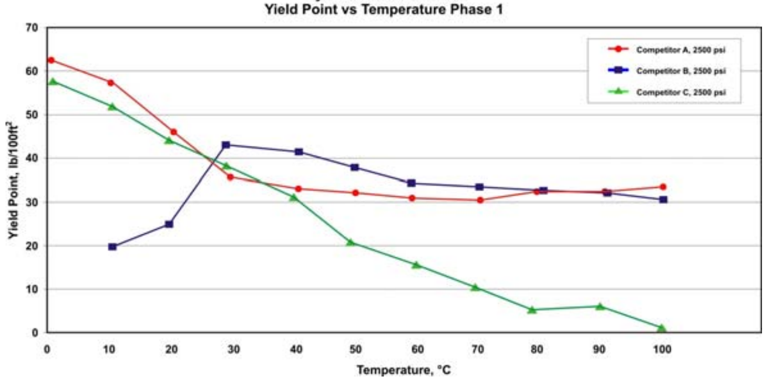


Figure 3
Ester Based Fluids
Yield Point vs Temperature Phase 1

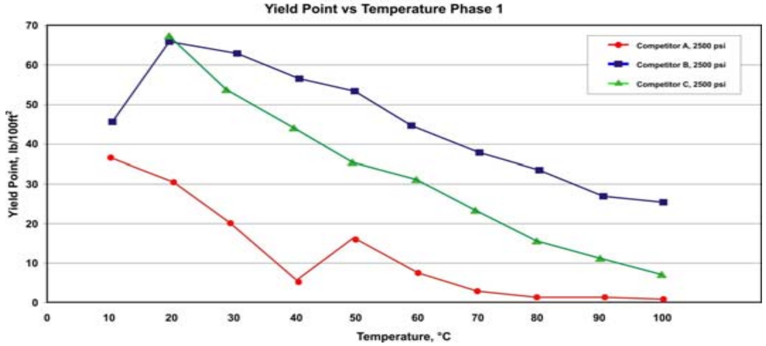


Figure 4
Mineral Oil Based Fluids
Yield Point vs Temperature Phase II

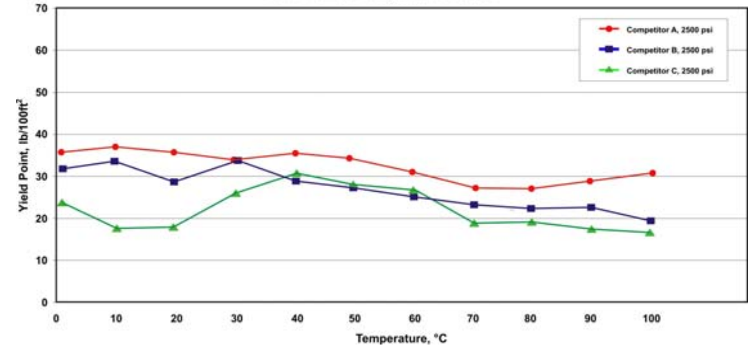


Figure 5
Synthetic Based Fluids
Yield Point vs Temperature Phase II

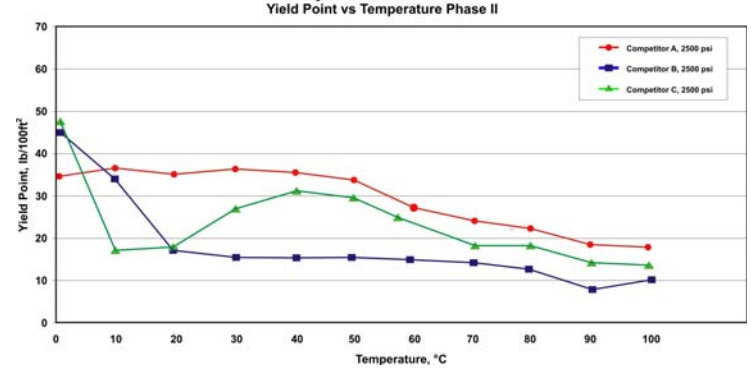


Figure 6
Ester Based Fluids
Yield Point vs Temperature Phase II

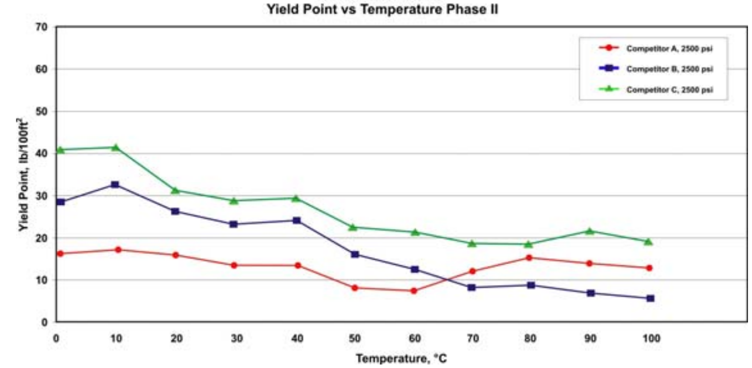


Figure 7
Camparison of Conventional and Constant Rheology SBM
Yield Point vs Temperature, Ambient Pressure

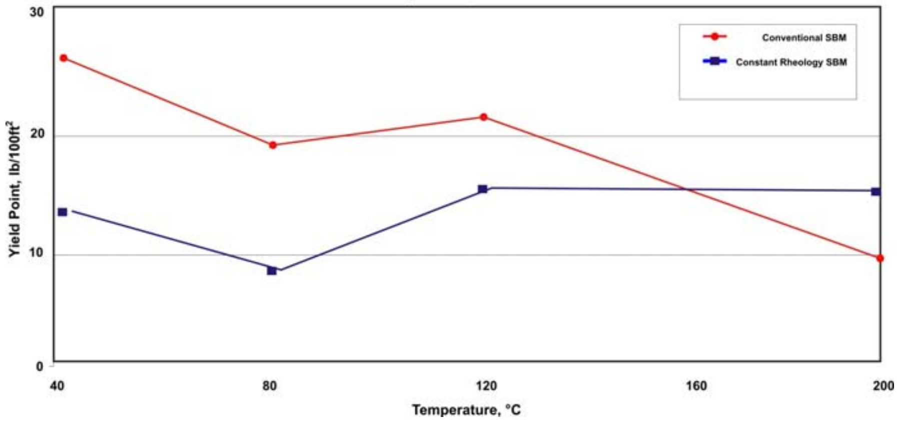


Figure 9
10-Minute Gels vs Temperature at Atmospheric Pressure - Fann Model 70

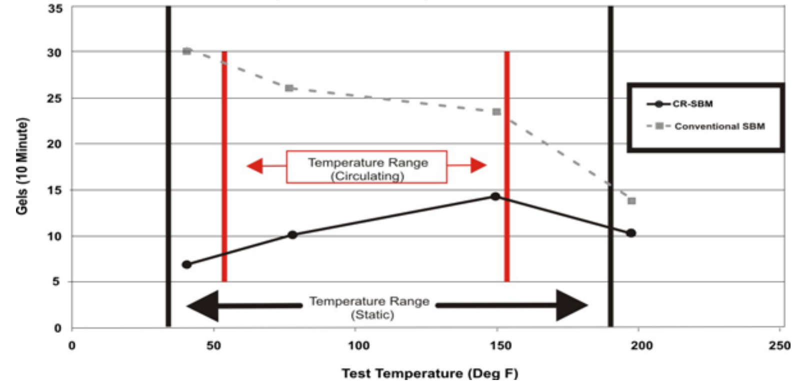


Figure 8
Comparison of Conventional and Constant Rheology SBM
Yield Point vs Temperature, 5000 psig

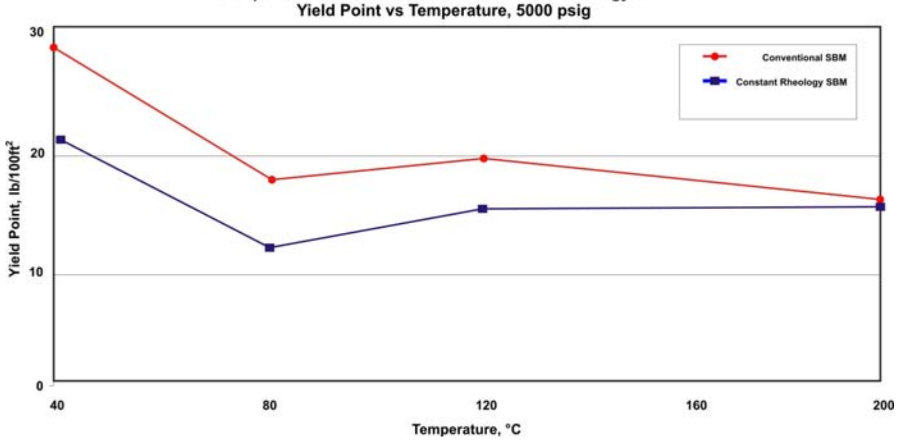


Figure 10
10-Minute Gels vs Temperature at 5000 psig - Fann Model 70

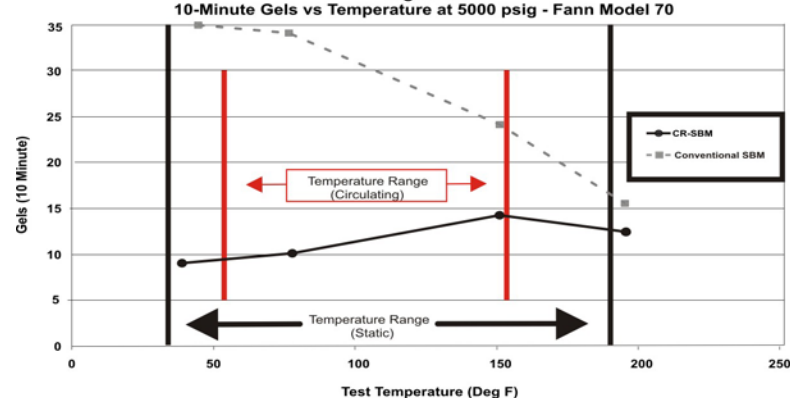


Figure 11
Leptocheirus Testing
Lc50 (mL/Kg)

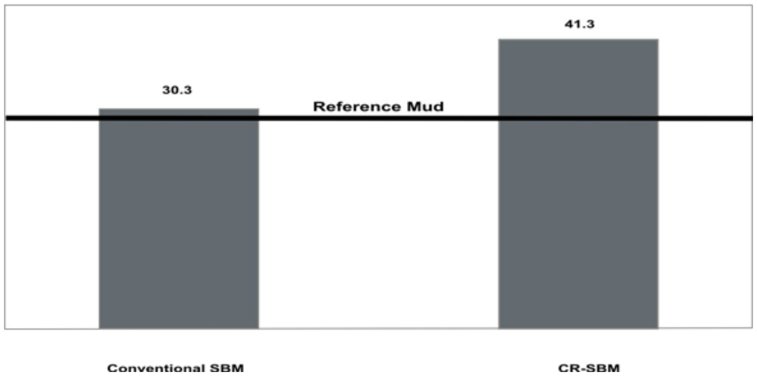


Figure 13
Surge Pressure Comparison
CR-SBM vs SBM

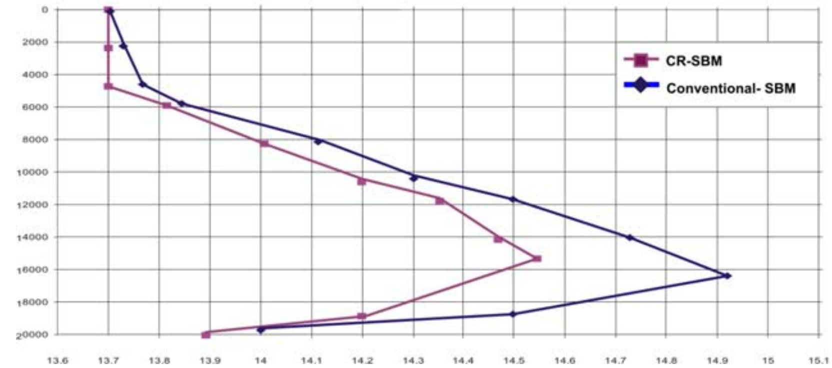


Figure 12
Leptocheirus Testing

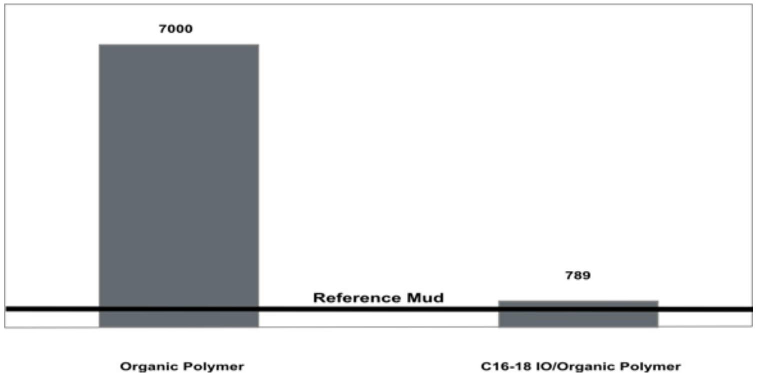


Figure 14
Surge Pressure Comparison
CR-SBM vs SBM

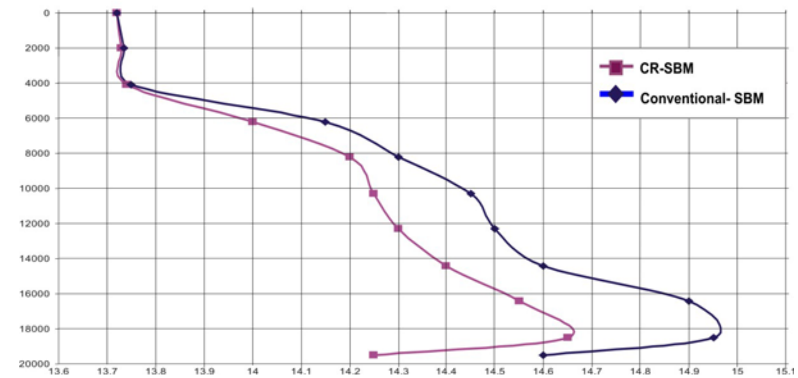
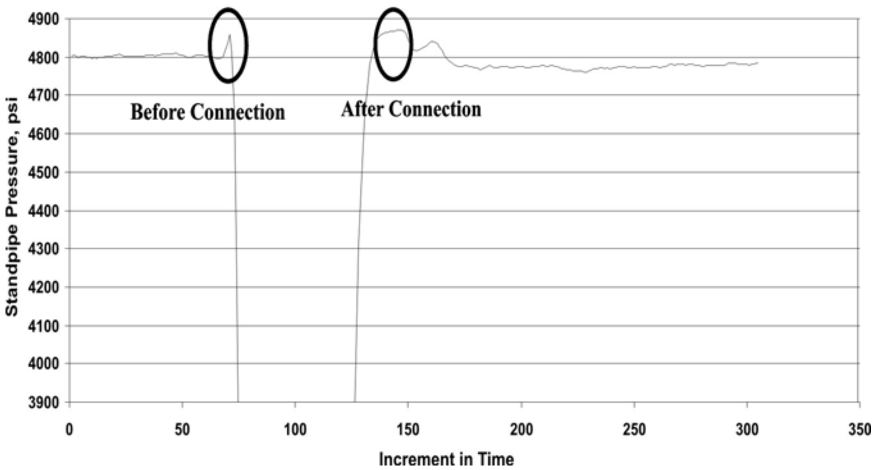


Figure 15
Circulation Initiation Pressure



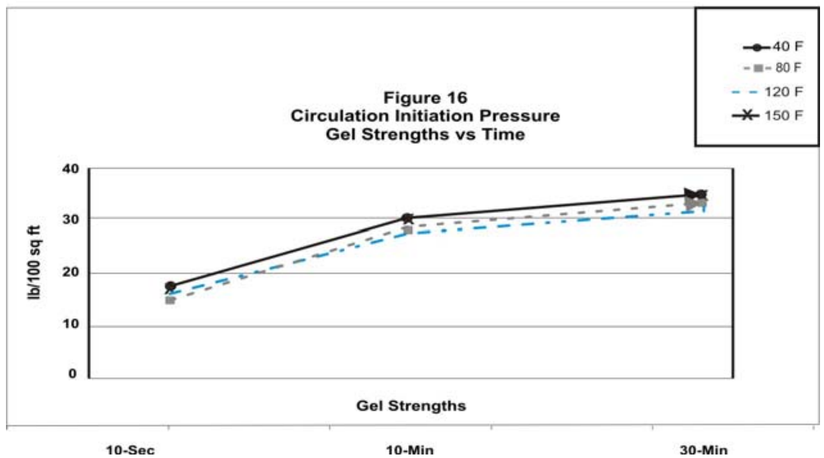


Figure 17
Incremental Circulating Density ,lb/gal