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A New Approach to Deepwater Drilling Using SBM with Flat Rheology

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Abstract

Owing to its superior performance in achieving high penetration rates and enhanced wellbore stability, synthetic-based mud (SBM) frequently is used in deepwater drilling. Conventional SBMs, however, may generate high equivalent circulating densities (ECDs) that lead to mud losses that affect fluid cost and rig time significantly. Fluid rheology is one of the main contributing factors to these increased ECD's. Typically, SBM rheology increases rapidly with decreasing temperature in the riser, and decreases with increasing temperature at the bottom of the well. The rheology increase at low temperature may adversely elevate ECD, while a rheology decrease at high temperature may compromise hole cleaning efficiency and promote barite sag. Therefore, the main challenge in designing an SBM for deepwater drilling is to simultaneously balance fluid rheology for hole cleaning efficiency, ECD constraints, and barite support.

This paper describes a new approach in the design of SBM that has been shown to improve the balance of fluid rheology for hole cleaning and ECD management. The newly designed SBM exhibits a unique "flat" rheological profile characterized by a low-end rheology and yield point, along with gel strength readings that are virtually constant as a function of temperature and pressure. The flat rheology profile allows higher but constant rheological properties to be maintained for better hole cleaning and faster drilling without sacrificing ECD. The higher rheological properties also help to minimize any undesired barite sag tendency.

The authors will present the results of field trials that demonstrate the flat rheology can be easily achieved and maintained in the field. Consequently, the relatively high and flat rheological properties, better hole cleaning, improved ROP and barite sag tendency were observed without sacrificing ECD control. Lower mud losses were also encountered during drilling, running casing, and cementing.

Introduction

Synthetic-based mud (SBM) is preferred for deepwater drilling because of its superiority in achieving high penetration rates and maintaining desired wellbore stability. However, the rheological properties of conventional SBM are known to be both temperature/-pressure-dependent as well as temperature-sensitive, i.e., the rheology of SBM increases rapidly with decreasing temperature and decreases rapidly with increasing temperature. The magnitude of this rheological change can vary depending on the additives used as well as the type of synthetic base fluid.

In the deepwater environment, water temperature can dip below 40°F when the depth reaches 4,000 ft or greater. This low-temperature environment effectively cools down the drilling fluid, significantly increasing fluid rheology, which in turn impacts equivalent circulating density (ECD) and surge pressure. The narrow ECD windows often encountered in deepwater drilling operations make such rheological increases undesirable and sometimes intolerable, as they would lead to severe losses of SBM and significantly increase the fluid cost and rig time.

Although the loss of SBM can be curtailed with various precautionary measures, such as reducing fluid density, fluid viscosity, and flow rate, this may in turn create compromises in hole sections where the temperature is higher and fluid rheology is lower. Potential problems that could occur in these sections are insufficient hole cleaning, formation of cuttings bed, settling and sagging of barite. Therefore, effectively balancing fluid rheology, hole cleaning, ECD, and barite suspension simultaneously is the main component and challenge to most deepwater drilling operations.

Since fluid rheology is the denominator of all the issues, a redesign of SBM to minimize the temperature dependence of the rheological property was believed to be a promising approach to alleviating the difficulty routinely encountered in achieving the desired balance among all these issues.

This paper discusses the development of a new generation of SBM that can achieve the desired balance of fluid rheology and drilling performance without sacrificing ECD requirement. Field trial data from a deepwater operation are provided to validate the performance of this new generation of SBM.

Fluid Development

Conventional SBMs normally exhibit a temperature-dependent rheological profile, which is illustrated in **Fig. 1a**. Here, key rheological parameters, such as plastic viscosity, yield point, 10-min gel strength, and 6-rpm reading, are plotted against the temperature at which they were measured. All these properties are highly temperature-dependent, showing a pronounced decrease with increasing temperature.

Preliminary tests conducted in the early stage of the developmental project indicated the temperature-dependence of conventional SBM is not just a function of the physical behavior of the base fluid, but also could be affected by the type and amount of, as well as interactions among, organophilic clay, emulsifier package (emulsifier and wetting agent), rheology modifier, and drill solids. Among all these factors, emulsifier package, organophilic clay, and rheology modifier are most important contributing factors to the development of high rheology and high gel strengths at low temperatures. The significant increase in rheology of a SBM containing a conventional emulsifier package and rheology modifier in the presence of drill solids is illustrated in **Fig. 2.** Such increase is often encountered in actual drilling operations.

To minimize the undesirable rheological impact at low temperatures, new approaches were adopted for the development of the new SBM. These new approaches included:

1. The use of 100% olefin as the base fluid to minimize fluid thickening at low temperatures
2. The use of a new emulsifier and wetting agent to minimize interactions with drill solids
3. The use of a new rheology modifier to modify the rheology profiles so they become temperature-independent
4. The use of less organophilic clay to minimize low-temperature rheology
5. Monitoring rheological properties at temperatures between 40°F and 150°F to ensure temperature-independence.

After performing hundreds of tests to evaluate various combinations and chemistries of surfactant packages, organophilic clays, and rheology modifiers, a new generation of SBM with temperature- and pressure-independent rheological characters was developed. This new SBM showed similar values of low-end rheology, yield point, and gel strengths in the temperature range of 40°F - 150°F, thus denoting the "flat" rheological profile moniker (**Fig 1b**).

Since the rheological modification did not alter the physical nature of the synthetic base fluid, the plastic viscosity of the flat rheology SBM still shows a thickening with decreasing temperature. Modifying this rheological property is more complicated.

Despite the drastic contrast in rheology, the additives used to make up the flat-rheology SBM are of a similar type but utilizing slightly different chemistries than those in the conventional SBM. A comparison of the types of chemicals and additives used in these two systems is given in **Table 1**.

Once the base mud formulation was developed, the fluid system was evaluated further. In particular, tests such as contamination with drill solids, seawater, and cement were carried out to evaluate the stability of the system. In addition, the behavior of the fluid under temperature and pressure was measured using a Fann 70 viscometer. Furthermore, the impact of the rheological property of the new system on ECD was investigated using hydraulic models. The evaluation results are briefly discussed as follows.

The solids tolerance of the new flat-rheology SBM was evaluated by treating the fluid with increasing amounts of simulated drill solids. The rheological properties of the solids-contaminated fluids were measured at three temperatures – 40°F, 100°F and 150°F. The main objective was to determine if the new system was sensitive to solids contamination and if the flat-rheology profile would change drastically or unfavorably in the presence of drill solids.

Figure 3 shows the rheological profiles of the flat-rheology SBM after contamination with up to 10% by weight (35 lb/bbl) of simulated drill solids (OCMA clay).

The flat-rheology SBM showed a fairly normal response to the solids contamination, suggesting the system is not sensitive to solids contamination. This also suggests that the interactions among drill solids, rheology modifier and emulsifier were not excessive. In addition, the rheological profile of the new SBM was retained after the solids contamination, indicating no significant or adverse interactions between the rheology modifier and drill solids.

The tolerance to seawater and cement contamination was also found to be excellent for the new flat rheology SBM.

As a side project, fluids containing no organophilic clays were assessed as well. Although the clay-free fluids provide relatively low rheologies at low-temperatures, their lack of proper barite suspension at elevated temperature was considered a major obstacle. Lack of proper barite suspension also could lead to severe hole cleaning and barite sag problems under downhole conditions. Consequently, the clay-free approach was abandoned.

The flat-rheology character is not just temperature-independent; it also exists under temperature and pressure as indicated by Fann 70 measurements. This is the only SBM system that possesses this unique temperature/pressure-independent character.

Figure 4 shows a comparison of the yield point values of an ester-based SBM (I), an isomerized olefin-based SBM (II) and the flat-rheology SBM measured by Fann 70 with temperatures up to 250°F and pressures up to 15,000 psi. The flat-rheology SBM displayed similar yield point values across the wide temperature and pressure ranges, whereas temperature and/or pressure impacted the conventional SBM (II). The ester-based SBM (I) displayed extreme sensitivity to both temperature and pressure variations, *i.e.* 40° F / 0 psi vs. 40° F/3000 psi and 40° F/0 psi vs. 120° F/0 psi.

A proprietary hydraulic monitoring software package was used to evaluate and compare the impact of the flat-rheology profile on ECD with that of a conventional synthetic-based fluid. A deviated well geometry with a 60-degree angle was used as the model well. The density of both fluids was 13.0 lb/gal and the system were evaluated under identical simulated drilling conditions. The only variable introduced was the rheological property at different temperatures. The parameters used and the ECD results are given in **Table 2** and **Fig. 5a-b**.

The hydraulic modeling showed a reduction in ECD of about 0.2 lb/gal could be achieved with the flat-rheology SBM. Although both fluids showed similar rheological numbers at 150°F, the conventional SBM displayed the typical thickening at cold temperatures. In contrast, the flat-rheology SBM once again exhibited the unique temperature-independent rheology. The lower ECD was attributed to the flat-rheology profile of the new SBM.

In the field, a similar reduction in ECD as to that calculated was observed when the flat-rheology system was actually used. The downhole tool data also showed no ECD spikes when the pump was kicked on after connections. This was attributed to the relatively high, yet fragile, gel strengths that effectively helped to suspend cuttings and barite when the pump was not in operation. These observations indicate that the flat rheology approach is an effective option for dealing with ECD issues in deepwater drilling operations.

In fact, with its temperature/pressure-independent rheology, the flat rheology SBM can be run with higher rheological numbers to improve hole cleaning, enhance penetration rate, and aid in barite suspension without adversely affecting the ECD. This is a superior advantage over the conventional SBM, especially when dealing with high-angle, extended-reach wells that otherwise would be troublesome or impossible to drill using conventional systems.

The unique flat rheological profile of the new SBM likely is generated from the interaction of the rheology modifier and reactive solids such as organophilic clays. Although the exact mechanism involved is not known, it is believed the flattening effect is derived from the change of the molecular size and shape of the rheology modifier with temperature. Regardless the rationale for this thermal affect, the thickening and thinning ("flattening") phenomena is reversible with respect to decreasing and increasing temperatures.

Field Trial

At this writing, more than 10 deepwater wells have been drilled with the flat-rheology SBM. In these field trials, the mud weight varied from 9.0 lb/gal to 16.5 lb/gal. The geometric profile of the test wells varied from nearly vertical to more than 60º angles, with hole diameters ranging from 22 to 6½ inch. Maximum measured depth was close to 27,000 ft with a bottomhole circulating temperature higher than 200ºF. The results of the first two field trials are discussed to demonstrate the characters of the flat rheology SBM.

Well A

Two intervals were drilled in field trial well A, a vertical 17½-in. section and a 14-in. build section. The total footage was about 8,240 ft and mud weight ranged from 11.0 lb/gal to 12.6 lb/gal. A bi-center PDC bit was used to drill the first interval, and a drilling-underreaming bit was used for the second interval. Water depth in the area was more than 3,000 ft, and the average flow line temperature was about 60-65°F.

The initial mud volume was mixed at the mixing plant using a high-shear hopper. The mud was sheared with a shearing device before loading up to boat. **Table 3** shows the main components used to mix the 11.0-lb/gal mud.

Initial drilling commenced with a relatively low fluid rheology similar to the offset previously drilled with a conventional SBM. The new flat-rheology SBM showed no difficulties in displacing the existing water-based mud (WBM), drilling cement, and performing leak-off test.

At the start of drilling, the relatively low rheology delivered a low ECD; however, PWD measurements showed the ECD tended to increase gradually with increasing depths. Hydraulic modeling suggested the fluid rheology was insufficient for proper hole cleaning, especially for the drilling rate and rather large cuttings generated by the bi-center PDC bit.

Most of the cuttings observed were about 2 x 1 x 0.25-in. in dimension or larger. Some showed rounded edges indicating long downhole residence time and mechanical erosion (**Fig. 6**). Although high viscosity sweeps were pumped periodically, the enlarged rat hole below the casing made the sweeping less effective.

To improve hole cleaning, the carrying capacity and low-end rheology of the fluid was increased by treating the system with a small amount of viscosifier and organophilic clays. The yield point was brought up from the low to high 20s, while the 6-rpm reading was raised from low to mid teens. Once the required rheology was established, hole cleaning improved significantly and ECD leveled off without slowing down the pump or drilling rates.

Larger size cuttings that remained intact were observed at the shakers, indicating improved hole cleaning and short residence time (**Fig. 6**). The average penetration rate was kept at 150 ft/hr and instantaneous penetration rates as high as 300 ft/hr were not unusual.

The well was drilled to section TD without any lost circulation even though the rheology of the fluid was considerably higher than the offset well employing the conventional SBM.

The second (14-in.) interval was drilled with a similar fluid rheology and no problems were encountered.

The typical rheological properties from each interval measured at different temperatures using a Fann 35A viscometer are shown in **Table 4**. The fluid demonstrated the flat profile of low-end rheology, yield point, and gel strengths throughout the operation. A plot of the key rheological properties measured at 70°F against well depths is shown in **Fig. 7**.

Well B

For field trial well B, a PDC bit and under-reamer rather than bi-center bits were used to drill the 17-in.,14-in., and 11½-in. sections. The total footage drilled was about 13,600 ft. Mud weight in this field trial varied from 11.0 lb/gal up to 13.2 lb/gal. A side track was drilled for geological reason. Maximum inclination of the wellbore reached 60º.

The rheology of the system was again maintained at a relatively high level for effective hole cleaning. Drilling of the 17-in. section was event-free and no drilling-induced lost circulation problems were encountered.

The relatively high rheology was slightly reduced for drilling the 14-in. and 11½-in. intervals. The well was drilled to TD without experiencing any problems or loss of whole mud to formation.

During the drilling operations, hydraulic modeling was carried out regularly. The actual sizes of cuttings generated were used as input to assess ECD and hole cleaning performance to ensure proper balance of fluid rheology, hole cleaning, and ECD management. Excellent agreement was observed between the predicted ECD values and the actual PWD values.

Rheological properties representative of the flat-rheology SBM used for each interval are shown in **Table 5**.

An extended logging run of 10 days was carried out at TD. The long period of logging at a 60-degree hole angle with a relatively high mud weight clearly tested the system's capacity for controlling barite sag. Density measurements collected from the flow line and PWD tool all showed minimum variations in mud weight throughout the whole well section, indicating little or no barite sag. In contrast, previous wells drilled with conventional SBM experienced varying degrees of barite sag under similar conditions.

Laboratory comparison of the performance of the barite sag control of the conventional and flat-rheology SBM was carried out using field mud samples. The flat-rheology SBM showed a tendency to stabilize barite sag more effectively than conventional SBM (**Fig. 8**) when tested in a sag flow loop. The ability to control and stabilize barite sag is critical for extended-reach operations.

Offset Well Comparison

When compared with offset wells of similar hole sizes but drilled with conventional SBM, the flat-rheology SBM in average had higher YP, flatter rheology profile, yet similar or lower ECD. The flat-rheology system also delivered faster or comparable penetration rates, less dilution volume, no pack-off's and back-reaming. The better performance of the flat-rheology SBM was attributed to its temperature/pressure-independent rheology, improved carrying capacity, and better hole cleaning. A comparison of the fluid performance of the field trial wells and offset wells is shown in **Table 6**.

The improved carrying capacity also minimized lost circulation problems caused by improper hole cleaning or barite sag. Compared with offset wells, the field trial wells did show less lost circulation problems particularly during drilling operation, indicating the approach used to design the fluid system was a valid approach.

Lost circulation problems encountered while running and cementing casing are affected by not just the rheology of the fluid but also by the type of tools used and the clearance between casings and open hole. On one section where no surge-protection tools were used when running casing, lost circulation did occur. However, when a surge-protection tool was used, the lost circulation was prevented on the next interval. Overall, the flat-rheology SBM system appreciably minimized the lost circulation problem with an average of 50% reduction during casing run and cementing.

A comparison of the losses of field trial wells and offset wells is shown in **Table 7**. On field trial Wells A & B, losses seemed to be somewhat evenly distributed between running and cementing casing. On the offset wells using conventional SBM, larger volumes were lost while cementing casing.

Conclusion

1. The new flat rheology SBM exhibits a unique rheological profile that is not significantly affected by temperature and pressure. This unique profile is beneficial to deepwater drilling where low-temperature and high-pressure conditions co-exist and exert adverse impacts on fluid performance.
2. The temperature/pressure-independent rheology gives rise to flat profiles of low-end rheology, yield point, and gel strength over a wide temperature range of 40°F – 250°F, with or without pressure.
3. The flat rheology can be easily established and maintained in the field for drilling operations.
4. The temperature-independent nature allows the overall rheology to be elevated for hole cleaning improvement without sacrificing ECD management.
5. The relatively high but flat and fragile gel structure provides excellent suspension quality for both cuttings and barite, and significantly

improves barite sag control.

6. The improved hole cleaning and enhanced barite sag control help to reduce and minimize pack-off, barite sag, and lost circulation problems that can hamper fluid performance and drilling operation.
7. The flat-rheology SBM is suitable for drilling deepwater extended-reach wells where rheology control, hole cleaning, ECD control, and barite sag prevention are demanding and critical to the success of the operation.
8. The flat-rheology SBM can appreciably minimize mud losses while running and cementing casing. Field trials showed the losses were on average 50% less than offset wells.

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Table 1 - Comparison of key components of Conventional SBM and Flat-Rheology SBM

Components	Conventional SBM	Flat-Rheology SBM
Organophilic Clay	Organophilic Bentonite Typically 4-6 lb/bbl	Similar but with 50% lower concentration
Emulsifier	Blend of surfactants	Modified to improve performance
Wetting Agent	Surfactant	Different chemistry with no adverse solids interactions
Fluid Loss Control	Polymer	Polymer
Rheology Modifier	Fatty Acid Based	Fatty Acid Based
Viscosifier	Polyamide	Polyamide

Table 2 - Parameters used to evaluate the ECD impact from conventional SBM and flat rheology SBM on a model well

(Notice the lower ECD obtained with the flat rheology SBM and its much flatter rheology profile when compared with the conventional SBM. The flat rheology SBM also showed non-progressive gel structures.)

	13.0 lb/gal Conventional SBM			13.0 lb/gal Flat-Rheology SBM		
Measured Depth (ft)	29,000					
Hole diameter (in.)	9⅞					
Flow rate (gal/min)	540					
ROP (ft/hr)	50					
Pipe rotation (rpm)	115					
Hole angle (deg)	60					
Rheology Temp. (°F)	40	75	150	40	100	150
600-rpm Reading	306	176	96	139	84	72
300-rpm Reading	192	108	60	83	55	49
200-rpm Reading	148	83	47	63	45	40
100-rpm Reading	101	55	32	41	34	31
6-rpm Reading	38	20	12	15	17	16
3-rpm Reading	35	18	11	14	15	15
PV (cP)	114	68	36	56	29	23
YP (lb/100 ft^2)	78	40	24	27	26	26
10-sec Gel (lb/100 ft^2)	35	21	16	22	20	21
10-min Gel (lb/100 ft^2)	57	37	22	35	35	31
30-min Gel (lb/100 ft^2)	-	-	-	36	-	33
ECD at TD (lb/gal)	**14.10**			**13.85**		

Table 3. Composition of the Flat-Rheology SBM used for field trial Well A

(The fluid was mixed at mixing plant and sheared once through a shearing unit before loading for transportation.)

Component	Concentration
Organophilic clays (lb/bbl)	2.0-3.0
Emulsifier (lb/bbl)	7.0
Wetting Agent (lb/bbl)	2.0
Rheology Modifier (lb/bbl)	2.0
Viscosifier (lb/bbl)	0.4
Fluid Loss Control (lb/bbl)	0.5
Internal phase	20% CaCl2
Mud Weight (lb/gal)	11.0
Synthetic/Water Ratio	70/30

Table 4 - Rheological properties of Flat-Rheology SBM system used in field trial well A.
(The large diameter sections required high rheology for good hole cleaning, which was achievable and maintainable because of the temperature-independent nature of the system.)

	17½-in. Section 11.1 lb/gal Mud Wt.				14-in. Section 12.6 lb/gal Mud Wt.			
Rheology Temp. (°F)	*40*	*69*	*94*	*150*	*42*	*70*	*137*	*150*
600-rpm Reading	168	107	87	57	196	135	84	73
300-rpm Reading	103	68	56	40	110	79	55	49
200-rpm Reading	78	53	44	33	82	59	44	38
100-rpm Reading	52	38	31	25	54	40	33	28
6-rpm Reading	18	15	15	15	18	16	15	14
3-rpm Reading	16	14	14	14	16	14	14	14
PV (cP)	65	39	31	17	86	56	29	24
YP (lb/100 ft^2)	25	29	26	23	24	23	26	25
10-sec Gel (lb/100 ft^2)	20	17	17	18	23	20	22	21
10-min Gel (lb/100 ft^2)	32	33	26	28	38	33	32	32

Table 5. Key rheological properties, HTHP fluid loss, and electrical stability of flat rheology SBM used on field trial well B.
(The properties are representative of each section indicated.
A total footage of 13,600 ft was drilled before the well was side tracked.)

	17-in. Section 11.2 lb/gal Mud Wt.				14-in. Section 12.5 lb/gal Mud Wt.				11½-in. Section 13.2 lb/gal Mud Wt.			
Rheology Temp. (°F)	*42F*	*70F*	*97F*	*150F*	*40F*	*70F*	*120F*	*150F*	*42F*	*68F*	*150F*	*175F*
6-rpm Reading	21	23	21	23	18	16	17	17	17	15	14	15
PV (cP)	54	31	21	15	79	45	21	17	69	49	22	19
YP (lb/100 ft^2)	31	32	33	33	27	25	26	26	23	21	22	22
10-min Gel (lb/100 ft^2)	37	34	35	36	35	32	33	30	30	30	28	27
HTHP at 200°F (mL)	4.6				4.8				2.8			
ES at 120°F (v)	480				500				510			

Table 6. Comparison of the field performance of Flat-Rheology SBM with Conventional SBM used in offset wells

(The new flat rheology SBM showed less ECD increase while giving a faster ROP.)

	Hole size (in.)	Flow Rate gal/min	ΔECD (lb/gal)	ROP (ft/hr)	Footage (ft)
Conventional SBM	17½	1240	0.65-1.3	40.6	3760
Flat Rheology SBM	17½	1270	0.37	66.7	3400
Flat Rheology SBM	17	1300	0.28-0.41	80.9	3640
Conventional SBM	14¾	850	0.41	56.2	4046
Conventional SBM	14¾	1086	0.6	87.4	6028
Flat Rheology SBM	14	1200	0.5-0.66	88.6	3987
Conventional SBM	12¼	680	0.67	83.4	7800
Conventional SBM	12¼	728	0.7	51.6	8230
Flat Rheology SBM	11½	770	0.5	69.1	5842
Flat Rheology SBM	11½	770	0.51	87.2	6798

ΔECD = PWD – Mud Wt

ROP = total footage/drilling hours

Table 7. Comparison of the Losses encountered while running and cementing casings using Conventional SBM and Flat-Rheology SBM.

(A 50% reduction of losses was observed with the flat rheology SBM.)

	13⅝-in. Casing Set in 17-17.5-inch Hole	**11¾-in. Casing Set in 14-inch Hole**	**8⅝-in. Casing Set in 11½-inch Hole**
Conventional SBM	>2000 bbl	>1100 bbl	>1500 bbl
Flat Rheology SBM	1100 bbl	650 bbl	850 bbl

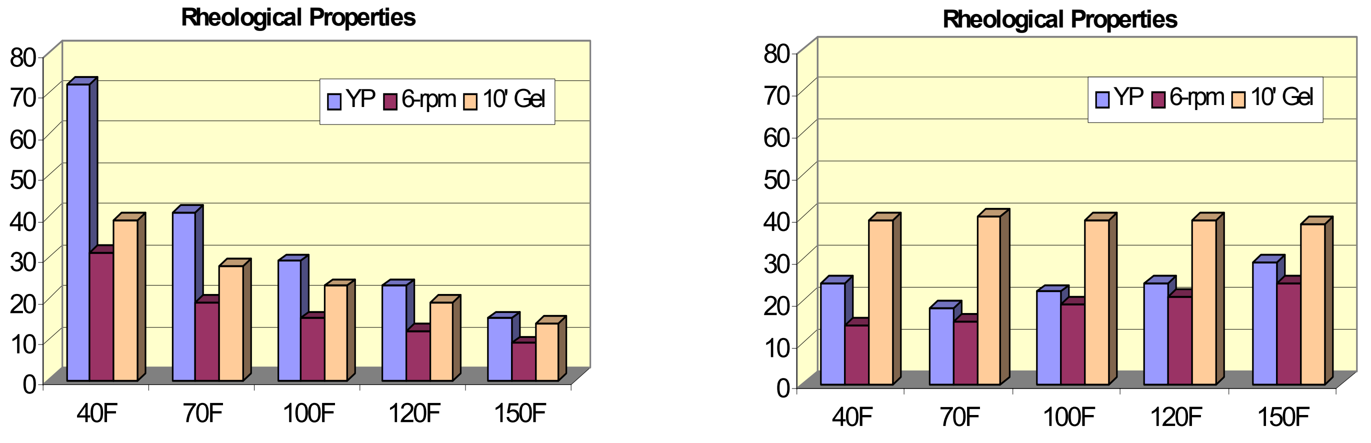


Chart A - Conventional SBM

Chart B - "Flat" Rheology SBM

Fig. 1 - Profile of yield point, 10-minute gel strength and 6-rpm reading of a 13.8-lb/gal conventional SBM (Chart A) and the new “Flat” Rheology SBM (Chart B) in the temperature range between 40°F and 150°F.

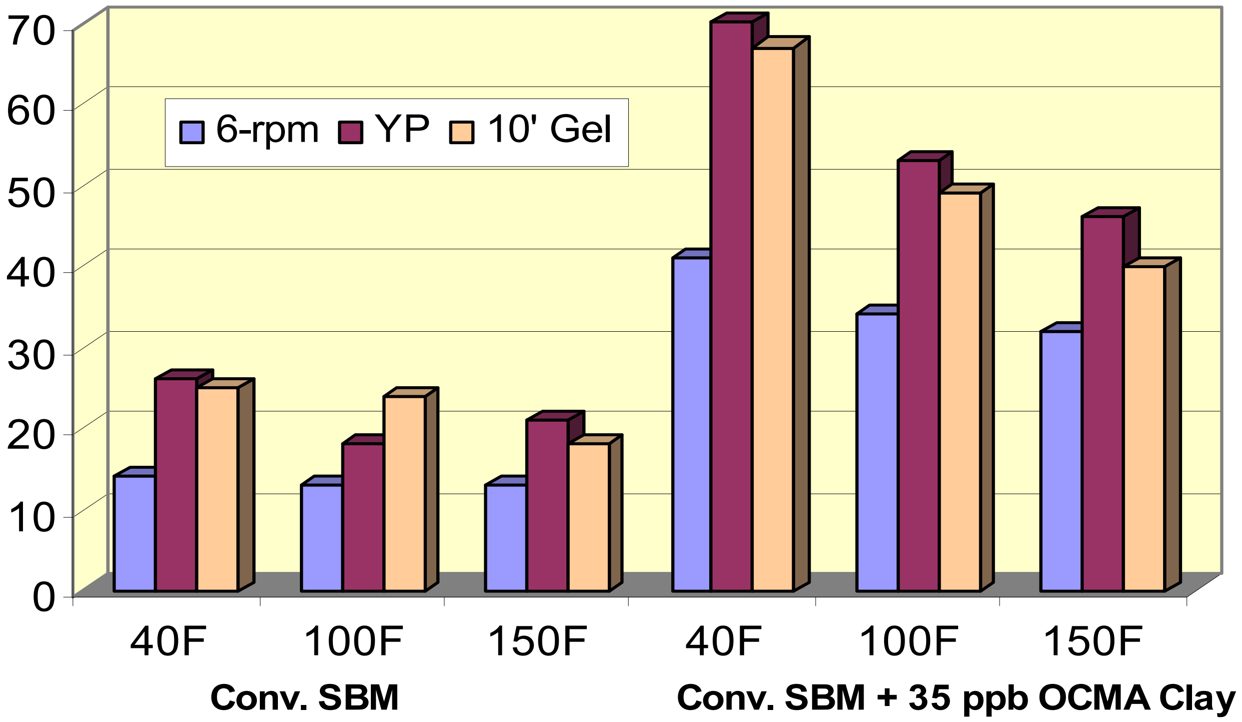


Fig. 2 - A demonstration of the effect of drill solids (35-lb/bbl OCMA clay) on the rheology profile of conventional SBM at various temperatures. A significant increase in low-temperature rheology after the incorporation of drill solids can occur in actual drilling operations.

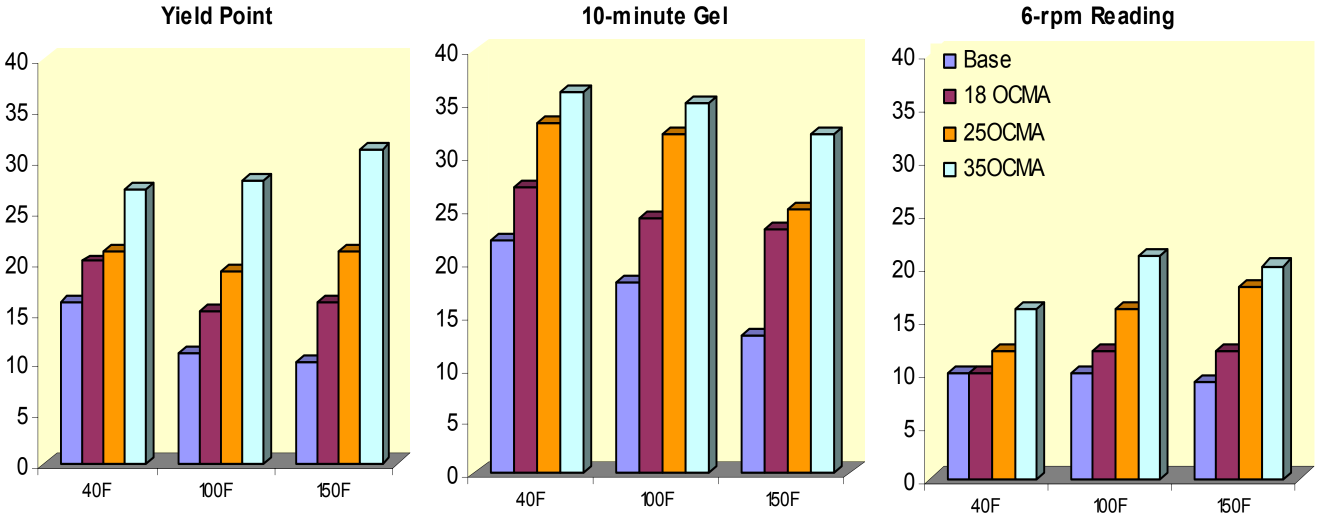


Fig. 3 - Effects of various amounts of drill solids (OCMA Clay) on flat-rheology SBM. The fluid system shows good solids tolerance as well as retention of the flat rheology profile in the presence of drill solids. As expected, the overall rheological properties increased proportionally with increasing amounts of contamination, but the key profiles remained relatively flat.

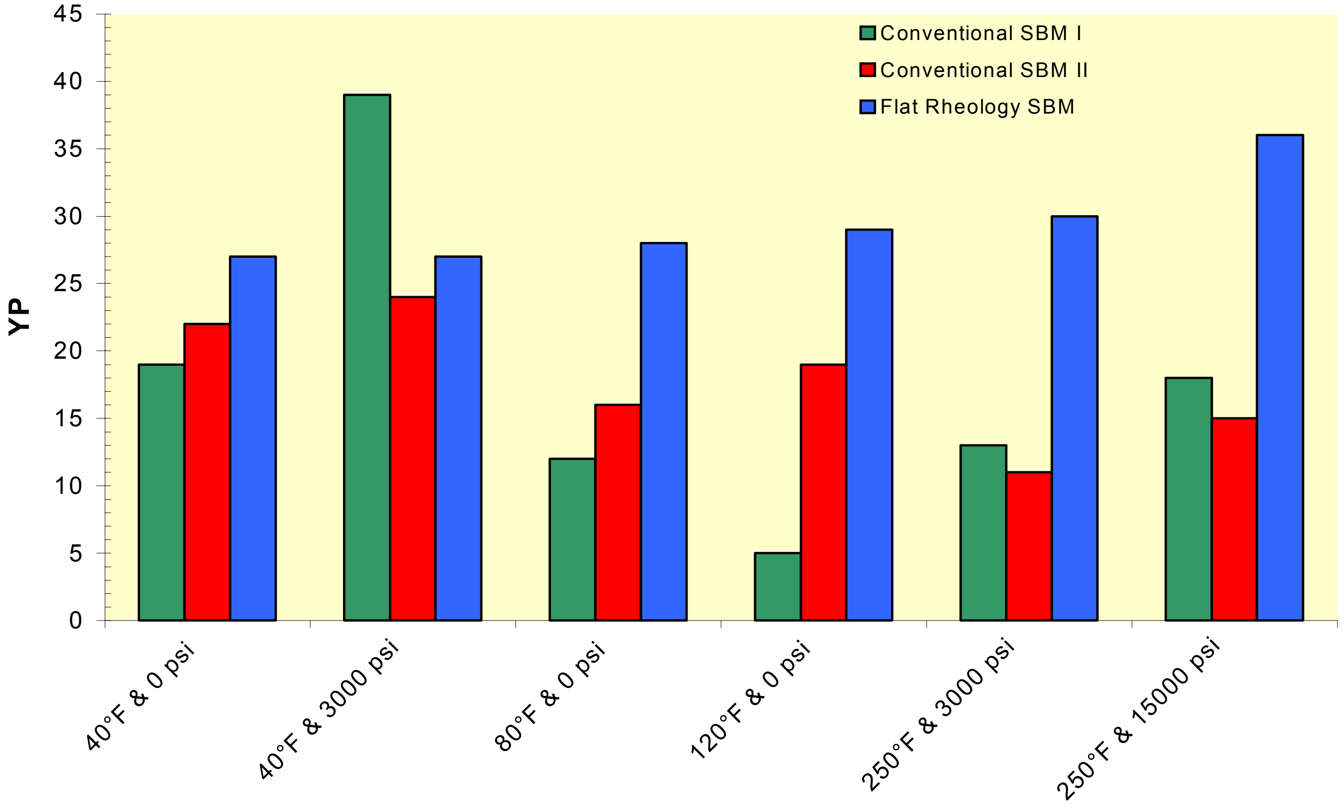


Fig. 4 - A comparison of the yield point of two conventional SBMs and the new flat-rheology SBM measured under temperature and pressure using Fann 70 viscometer. The conventional SBM I and II show the distinct effects of temperature and pressure on the rheological property, whereas the flat-rheology SBM shows almost constant yield point over the wide range of temperature and pressure.

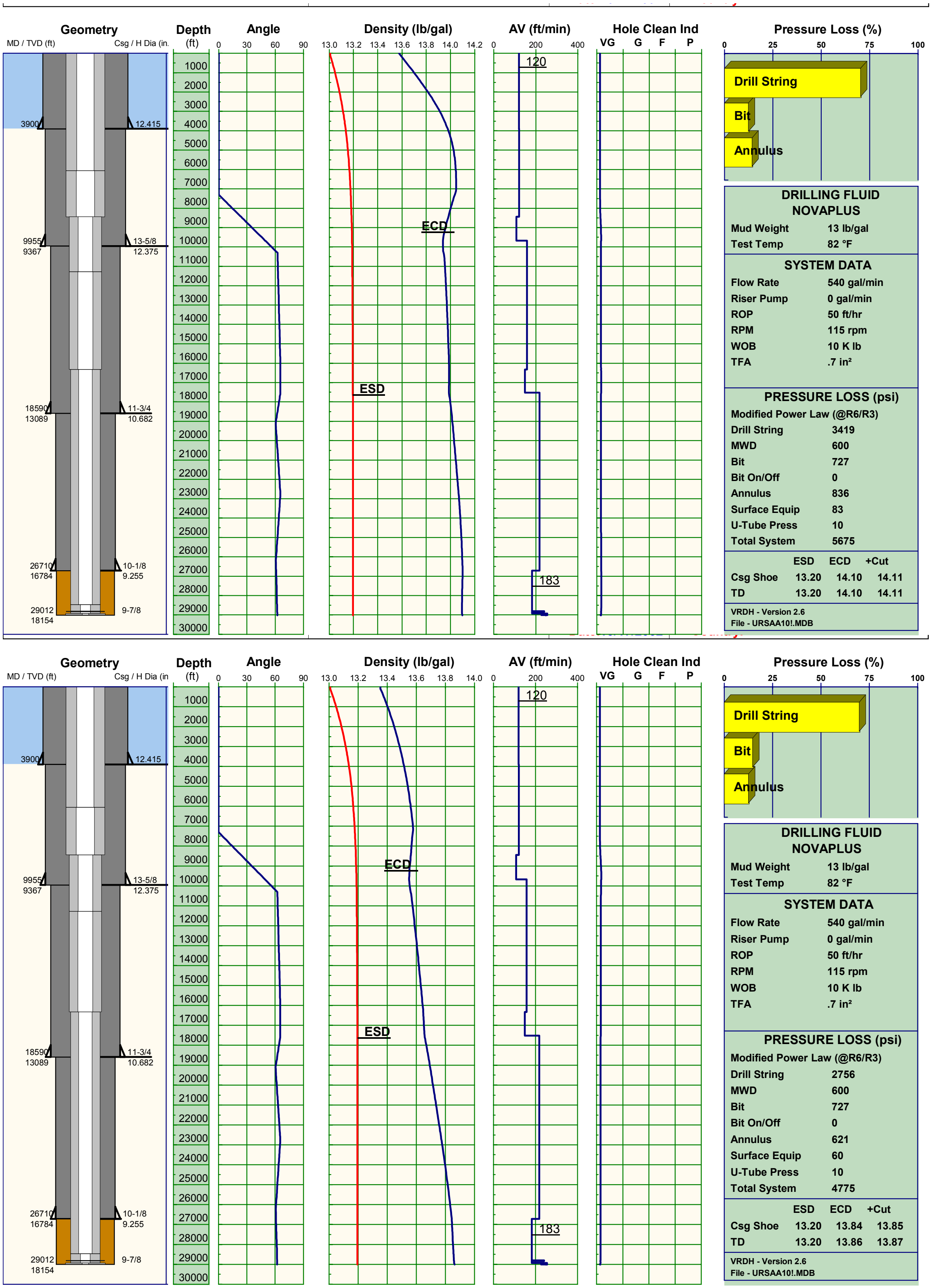


Fig. 5a (top):

DRILLING FLUID
NOVAPLUS

Mud Weight	13 lb/gal
Test Temp	82 °F

SYSTEM DATA

Flow Rate	540 gal/min
Riser Pump	0 gal/min
ROP	50 ft/hr
RPM	115 rpm
WOB	10 K lb
TFA	.7 in²

PRESSURE LOSS (psi)
Modified Power Law (@R6/R3)

Drill String	3419
MWD	600
Bit	727
Bit On/Off	0
Annulus	836
Surface Equip	83
U-Tube Press	10
Total System	5675

	ESD	ECD	+Cut
Csg Shoe	13.20	14.10	14.11
TD	13.20	14.10	14.11

VRDH - Version 2.6
File - URSAA10!.MDB

Fig. 5b (bottom):

DRILLING FLUID
NOVAPLUS

Mud Weight	13 lb/gal
Test Temp	82 °F

SYSTEM DATA

Flow Rate	540 gal/min
Riser Pump	0 gal/min
ROP	50 ft/hr
RPM	115 rpm
WOB	10 K lb
TFA	.7 in²

PRESSURE LOSS (psi)
Modified Power Law (@R6/R3)

Drill String	2756
MWD	600
Bit	727
Bit On/Off	0
Annulus	621
Surface Equip	60
U-Tube Press	10
Total System	4775

	ESD	ECD	+Cut
Csg Shoe	13.20	13.84	13.85
TD	13.20	13.86	13.87

VRDH - Version 2.6
File - URSAA10!.MDB

Fig. 5a and 5b - ECD modeling of conventional SBM (top) and flat-rheology SBM (bottom) using an extended-reach model well. The latter gives a lower ECD at TD due to its unique flat rheological properties at both low and high temperatures. See Table 2 for modeling parameters and fluid properties.

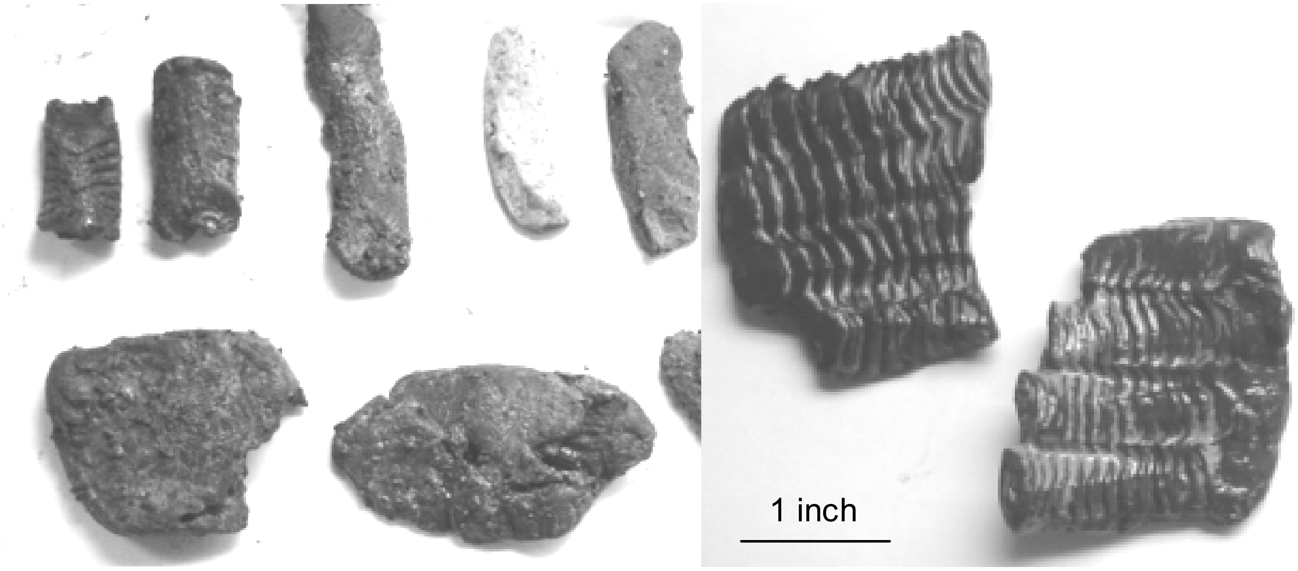


Fig. 6 - Typical cuttings generated during the field trial of flat-rheology SBM on Well A. The rounded and smaller cuttings on the left were carried to the surface with a YP of 20-22; however, much larger and intact cuttings on the right were carried to the surface when the yield point was increased to 28-30. ECD rapidly reduced and leveled off after all the cuttings have been effectively circulated out with the higher rheology. Both pictures have the same scale.

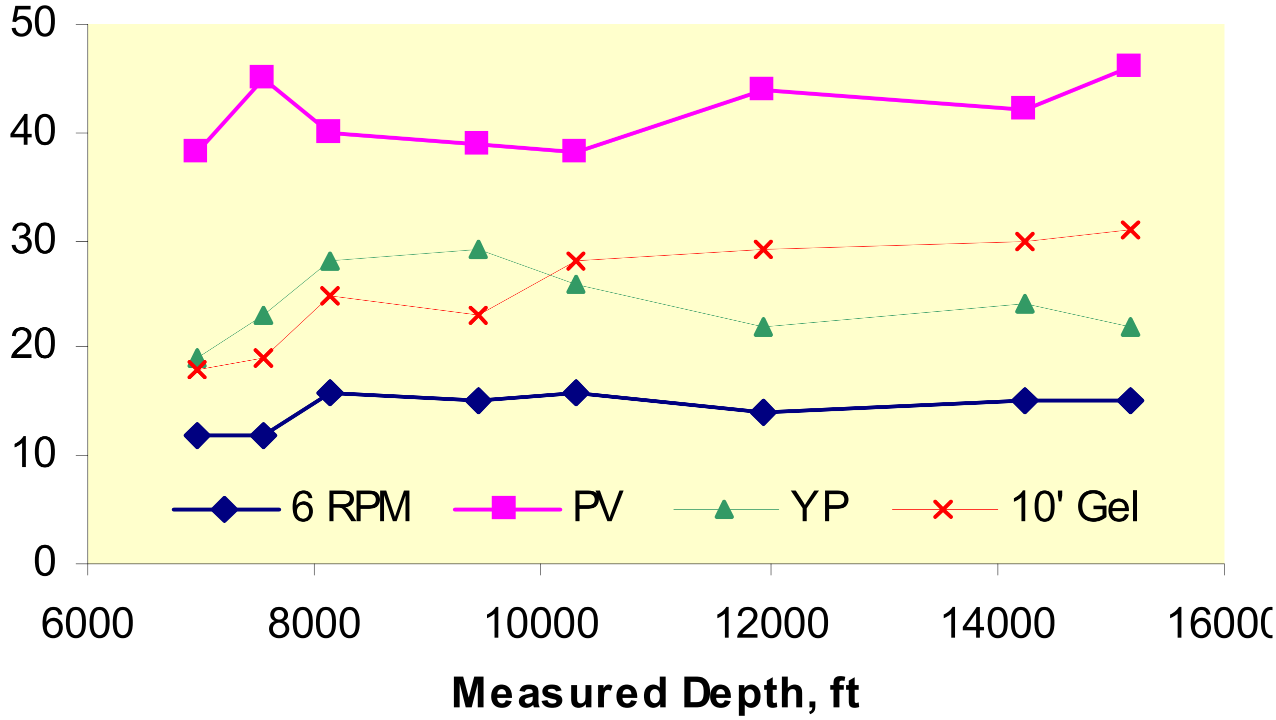
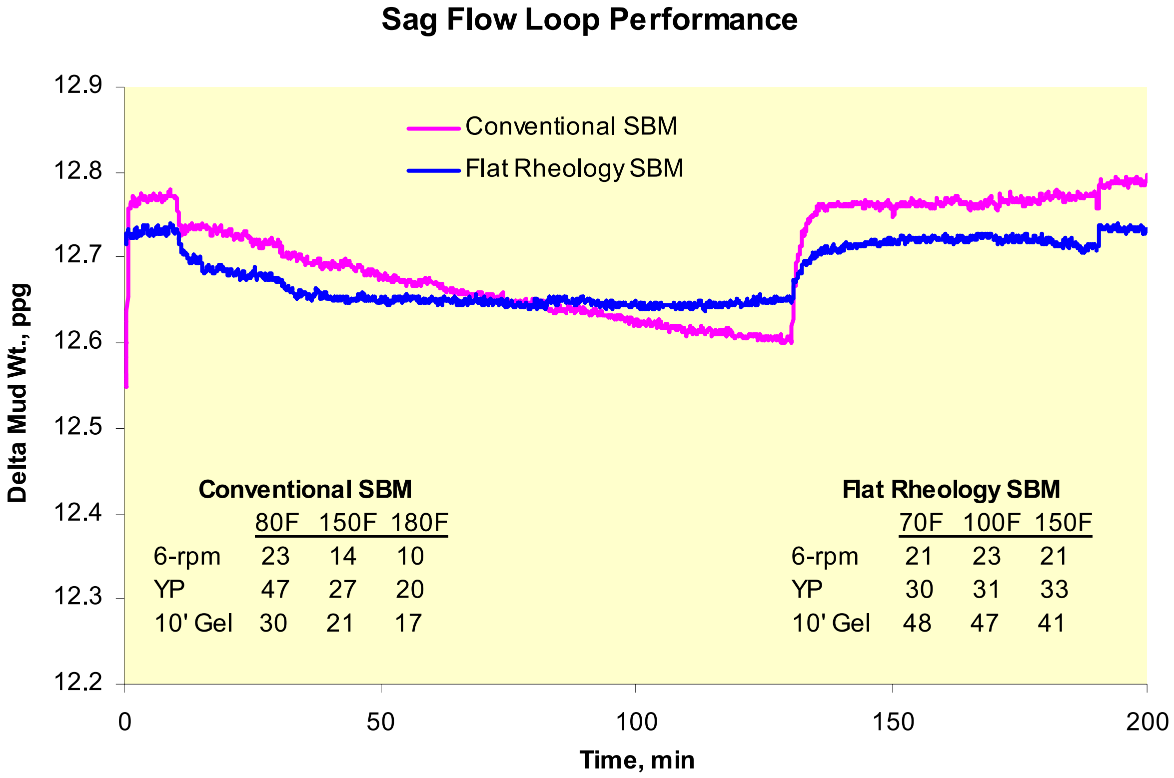


Fig. 7 - Rheological properties of the flat-rheology SBM measured at flow line temperature (65~70°F) during field trial on Well A. The yield point of the system was slightly reduced when drilling the second (14-in.) interval.



Conventional SBM

	80F	150F	180F
6-rpm	23	14	10
YP	47	27	20
10' Gel	30	21	17

Flat Rheology SBM

	70F	100F	150F
6-rpm	21	23	21
YP	30	31	33
10' Gel	48	47	41

Fig. 8 - A comparison of the sag flow-loop performance to evaluate the barite sag prevention of conventional SBM and flat-rheology SBM in a simulated wellbore with inclination that was maintained at 60-degree during the test. Barite sag, as indicated by the mud weight drop, occurred when the flow rate was maintained at a minimal of 25 ft/min for an extended period of time. The flat-rheology SBM shows a stabilized mud weight drop suggesting no further mud weight variation under sustained condition. However, the conventional SBM shows a constant mud weight drop which could continue on for an extended period of time before it would eventually stabilize. The flat-rheology SBM can provide better barite sag control under demanding situations.