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An Adaptable Water-Based Mud System for Multiple Applications While Drilling

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Abstract

Due to significant variations of the subsurface geology from the surface to the top of reservoir and requirement of different fluid characteristics for drilling various hole there is a need to use various mud systems. These may include a simple spud mud for surface hole section, an inhibitive drilling fluid for reactive shale section, a salt water-based mud for salt diapirs and salt formations, and a highly lubricating mud for deviated hole sections with high dogleg severity.To optimize each of these separate and distinct scenarios, there is a need to change the mud system while drilling to overcome the technical challenges associated with these formations and wellbore profiles. The change over from one mud system to another is typically done between casing points while constructing the well to overcome specific drilling challenges associated with next whole section.There is significant time and effort required to clean the mud circulation system adequately before a mud change over in order to avoid any contamination of the new mud system.This is especially true when displacing a water-based mud by an oil-based mud or an oil-based mud by a water-based mud.If this is not done properly, contamination of the new mud by the old mud could be a source of major problems due to partial or complete loss of functional ability of the new mud system.

An adaptable drilling mud system that can easily be transformed from a spud mud system to an inhibitive, or a high lubricating or a salt water mud can provide the industry a versatile fluid system with multiple hole section applications.This removes much of the NPT associated with mud changeover, reduces the mud cost as compared to mixing a totally new mud system and eliminates concerns regarding mud contamination as well as any disposal or recycling cost for the replaced system.

This paper describes a volcanic ash-based drilling mud that can be used as a spud mud to drill the surface hole, can easily be converted to an inhibitive mud system to drill reactive shale sections of a borehole, a salt water-based mud to drill the salt sections and also a high lubricating water-based drilling mud to reduce torque and drag problems in deviated and horizontal boreholes. The flexible and easily convertible nature of the base volcanic ash-based drilling mud has potential to reduce total drilling cost significantly as it eliminates a significant portion of non-productive drilling time associated with mud changeover, cleaning of mud circulation system, new mud preparation, incorporation of new mud in the circulation system and displacement of the old mud from the borehole by the new mud, etc.

Introduction

Drilling fluid is the first external foreign fluid that comes in contact with subsurface formations while drilling and thus needs special design considerations to prevent various mud related drilling problems such as shale-drilling fluid interactions, ECD effect of mud rheology, EMW effect of gel strength, sticking effect of mudcake, environmental impact of mud additives, reservoir damaging effect of drilling muds, degradation effect of drilling mud at HTHP conditions, etc [1-6]. It is a complex system that contains a fluid phase, a solid phase and a chemical phase. The fluid phase could be aqueous, non-aqueous or gaseous depending on the technical and environmental requirements. The aqueous fluid phase may be fresh water, sea water or salt water, the non-aqueous fluid phase could be diesel, mineral oil, synthetic oil or vegetable oil and the gaseous fluid phase could be air, nitrogen or foam with a set of functional requirements for trouble-free drilling operation. These base fluids are used with other mud additives to generate appropriate mud rheology, fluid density, mud activity, fluid loss control property, ability to reduce shale swelling, cuttings dispersion and borehole instability, torque and drag, formation damage, environmental impact especially to marine environment and also to improve thermal stability, acid gas tolerance, borehole cleaning and other functional capabilities [7-11]. Though the factors that guide the choice of a fluid base and the mud additives are complex, the selection of the additives must consider the technical requirements of various hole sections along with the environmental rules and regulations of the locality, region or the state to eliminate any short or long term environmental impact. As it is difficult to find water-based muds and mud additives that can fulfil the technical and environmental requirements of various hole sections of a borehole, several mud systems are usually required to drill a borehole from the surface to the bottom of a reservoir.

Most of the water-based drilling mud fulfils the environmental characteristics of all hole sections and thus could be used to drill from the surface to the bottom of a reservoir if they could fulfil the technical requirements of all the hole sections. Current experience shows, it is often impossible to fulfill all functional tasks that are essential in various hole sections using conventional water-based drilling muds due to their inadequate physical, chemical and thermal characteristics [12]. Hence, in spite of significant improvement of engineered mud design, no water-based mud system is available that is easily adaptable to overcome the technical challenges of various hole sections. That's why different mud systems with various mud additives are used for drilling various subsurface formations that contain different chemicals, salts and minerals to avoid drilling problems encounter while drilling different hole sections or subsurface formations [13-16].

Due to non-polar nature of the base oils used in formulating oil-based muds, they are essentially suitable for drilling all hole sections without major drilling problems. Borehole sections containing reactive shale, water dissolvable salt, gypsum, and anhydrite, sour gases can safely be drilled using OBMs due to their superior technical characteristics compared to WBM systems. Hence, OBMs could be used without any mud changeover. However, due to poor biodegradation characteristics and high toxicity and also the high cost, OBM is not applicable for multiple hole sections drilling. The short and long term detrimental effect of OBM on surrounding environments, eco-systems, habitats allows highly restricted use of oil-based muds. Due to unacceptable environmental characteristics of oil-based muds the environmental protecting agency (EPA) forced the drilling and operating companies to find an alternative to oil-based drilling mud to protect the global environment, especially sensitive marine environment and habitats. This opens the door for development of water-based drilling fluid system using suitable mud additives that can allow easy conversion of the mud system to respond to changing borehole environment without any detrimental effect on mud properties such as fluid consistency, rheology, fluid loss behavior, cuttings carrying capacity, mudcake quality, etc. and also the surrounding environment.

Nearly three quarters of the earth is ocean with high prospect of hydrocarbon resources in addition to other valuable marine resources. According to Liesman reserves at depths approaching a mile or more now represent the biggest single new oil resources for the world communities [17]. For this reason, the industry attention is now on the vast offshore areas. This is reflected by the increasing drilling activities in the marine environment [9]. The exploration and exploitation of the shallow and deep water marine hydrocarbon basins demand the recovery of the hydrocarbon resources without damaging other marine resources. Hence, any current or future exploration and exploitation of oil and gas resources in the offshore areas, especially in the deep water environment need a technically superior but highly eco-friendly drilling mud system to protect the marine and coastal ecosystems and also the livelihood of the fishing and other coastal communities. Hence, the development of a highly flexible and eco-friendly water-based drilling mud with easily adaptable mud properties to fulfil the technical demands of various hole sections is highly desirable to be in the forefront of best drilling practices for economic and trouble-free drilling operation.

Fluid design to drill the pay zone must consider the formation damage potential of the mud in addition to other technical requirements. A drilling fluid causing unacceptable formation damage is not acceptable for the reservoir section. However, this nondamaging criterion is not important for various hole sections required to drill from the surface to the top of the pay zone. Hence, an easily adaptable drilling mud system that can be converted to various mud systems by adding one or two additional mud additives can allow continuous drilling operation from the surface to the top of the reservoir. This paper describes a novel water-based mud that can easily be adapted to meet the technical requirements of various hole sections for uninterrupted drilling operation without changing the mud system.

Base Mud Formulation

An intensive review of existing, new and other industry used additives were performed to identify several green natural and/or organic additives to design a base mud with desirable technical and environmental characteristics. Table 1 shows the "Base Mud" formulation using a locally available volcanic ash, a commercial viscosifier (XC Polymer) and a tree-based organic fluid loss additive cum viscosity enhancer (PHP). The Table also shows the formulation of a bentonite mud used for comparative assessment of SAVA mud properties and demonstrate the suitability of the SAVA mud as an alternative to bentonite-based drilling mud that frequently needs, chemical treatment, dilution and dumping due to poor contaminants tolerant characteristics such as mono and divalent salts, set and green cements, drill solids, acid gases, etc. The fresh water-based SAVA mud has technical properties better than the bentonite mud but has higher formulation cost compared to the bentonite mud cost. To evaluate the adaptability of the SAVA mud to various mud systems used for drilling different hole sections, additional additives were added to the base mud to fulfill the technical requirement of a particular hole section.

Table 1: Bentonite and Basic SAVA Mud Formulations

Pre-Hydrated Bentonite Formulation		Base SAVA Mud Formulation	
Fresh water (bbl)	0.97	Fresh water (bbl)	0.97
Soda Ash (ppb)	0.5	SAVA (ppb)	20
Caustic Soda (ppb)	0.5	XC Polymer (ppb)	2
Bentonite (ppb)	25	PHP (ppb)	2
-----	-----	Caustic Soda (ppb)	0.5

Adaptability& Suitability Evaluation Approach

The performance of the base SAVA mud was experimentally evaluated by comparing the fluid loss and rheological behavior of the base SAVA mud with respect to Bentonite mud properties which is used as a spud mud and/or surface hole drilling in all drilling operations. The suitability of transformation of the SAVA mud to an inhibitive mud for reactive shale drilling was evaluated by comparing fluid loss and rheological behaviorand also the inhibition potential with respect to an inhibitive KCl-Polymer mud at equal shale inhibitor concentrations in the mud systems (Table 2). Its suitability for trouble-free drilling operation in high torque and drag creating borehole environments were evaluated by incorporating several lubricants in the SAVA mud. The conversion of the SAVA mud to salt water-based mud was evaluated by incorporating 25 ppb NaCl in the mud. All the experimental results indicate that the newly developed Saudi Volcanic Ash-based drilling mud (SAVA Mud) is suitable for drilling multiple hole sections of a borehole due to its easy transformation to various mud systems to overcome the technical challenges associated with different hole sections. Figures 1-15 shows the result of the base mud along with the adapted muds designed to overcome the mud related drilling problems of various hole sections.

Table 2: Formulations of 78 pcf SAVA and KCl-Polymer mud with Barite and KCl-Polymer Mud with $CaCO_3$ as Weighting Agent using Required Water Volume

Mud Components	SAVA mud 78 pcf Barite	Mud Components	KCl Polymer 78 pcf with Barite	Mud Components	KCl Polymer 78 pcf with $CaCO_3$
	Amount				Amount
SAVA (g)	20	Caustic Soda (g)	0.75	XC Polymer (g)	1.25
XC (g)	2	XC Polymer (g)	1.25	Starch (g)	6
PHP (g)	2	KCl (g)	25	KCl (g)	25
KCl (g)	25	CaCO3 M (g)	20	CaCO3 Fine (g)	95
$CaCO_3$ Medium (g)	20	Barite (g)	75	CaCO3 Med. (g)	20
Barite (g)	65	B-54 (cc)	0.3 cc	Caustic (g)	0.75
Caustic (g)	0.75 (pH 10)	Starch (g)	6	B-54 (Biocide) (cc)	0.3
Defoamer (cc)	0.2				
Biocide (cc)	0.3				

Experimental Results & Discussion

The rheological, filtration and gel strength properties of the SAVA mud along with the mud systems used for comparative evaluation of the performance of the SAVA mud were measured using standard API test apparatus and procedures. The properties of the SAVA mud adapted to meet technical requirements of various hole sections were also measured using the same procedures. In addition to rheology and fluid loss behavior, the inhibition potential and the lubricating efficiencyof the adapted SAVA mud were also evaluated using standard test procedures. A detailed description of the test results along with a comprehensive discussion of the findings are given below.

Base SAVA Mud

Figure 1 shows the API and HTHP spurt loss values of the conventional Bentonite and the newly developed SAVA muds.SAVA mud shows no spurt loss in the API test. This indicates that the SAVA mud will cause no/negligible particulate invasion with an overbalance pressure of 100 psi. However, the SAVA mud shows spurt loss like the Bentonite mud at HTHP test condition (212°F and 500 psi pressure).Hence, their spurt loss behavior will be very similar in borehole environments with a bottom hole temperature that is equal to or less than 212°F. If the formulation cost is not a factor, the newly developed SAVA mud can be used to drill the surface hole section of a wellbore with performance similar to or better than the currently used bentonite mud. It may be mentioned that the SAVA mud has higher formulation cost than the bentonite mud. However, it is technically superior and more OHS friendly than the bentonite mud.

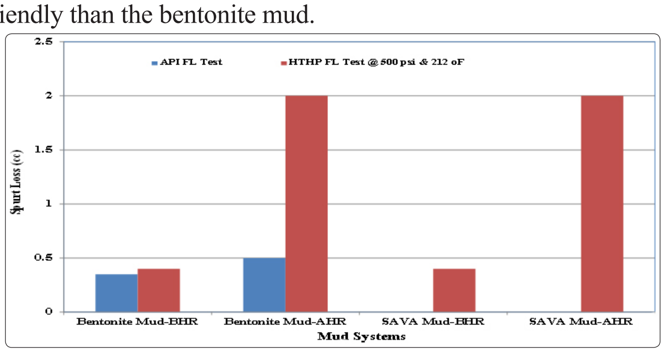

Figure 1: Comparison of API and HTHP Spurt Loss of Bentonite and SAVA Muds Before and after Hot Rolling

Figure 2 shows the API and HTHP fluid loss values of the conventional Bentonite mud and the newly developed SAVA muds.SAVA mud shows much lower fluid loss in the API test. The conventional Bentonite mud indicates more than 40% higher fluid loss than the SAVA mud. API fluid loss test conducted after hot rolling the muds at 212°F also indicates the same behavior. The HTHP fluid loss behavior of the Bentonite and the SAVA mud indicates 13 to 15% more fluid loss for the bentonite mud under the same test condition (212°F and 500 psi pressure). This demonstrates the somewhat superior fluid loss behavior of the SAVA mud compared to the conventional Bentonite mud. Hence, the base SAVA mud is a better alternative to the conventional bentonite mud if we disregard the cost of the SAVA mud. Previous studies of SAVA mud indicated high mono and divalent salt tolerance along with other mud contaminants encountered while drilling. Hence, the extra formulation cost of the SAVA mud may not be significant with respect to the overall economic benefits achievable due to superior mud properties. The frequent dumping and dilution associated with contaminated bentonite mud, mud related drilling problems associated with contaminated bentonite mud, the treatment cost of contaminated mud along with the negative impact of foul bentonite mud on ROP, hole cleaning, ECD and induced loss of circulation can increase the overall drilling cost significantly. Hence, the formulation cost of the SAVA mud may not be a real measure of its economic benefit.

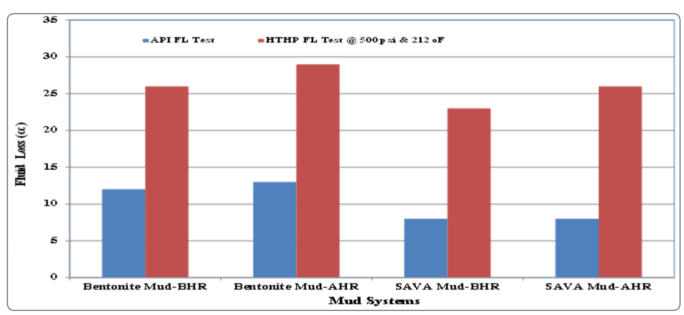

Figure 2: Comparison of API and HTHP Fluid Loss of Bentonite and SAVA Muds Before and after Hot Rolling

Figure 3 shows the API and HTHP mudcake thickness of the conventional Bentonite and the newly developed SAVA muds.SAVA mud shows much lower mud cake thickness in the API test both before and after hot rolling at 212°F. The conventional Bentonite mud indicates more than 60% higher mudcake thickness before hot rolling and greater than 160% mudcake thickness after hot rolling compared to the SAVA mud in API fluid loss test. The deposition of a thicker mudcake by the bentonite mud, especially after hot rolling at 212°F indicates a higher potential of differential sticking in the presence of a differential sticking prone high permeable zone. On the other hand, the deposition of a thinner mudcake by the SAVA mud indicates it's less likelihood in causing any differential sticking. This is another technical advantage of the SAVA mud.

The mud cake thickness measured at HTHP test condition also indicates much higher mudcake thickness for the Bentonite mud than the SAVA mud.Mudcake deposited by the Bentonite mud at HTHP test conditions indicates more than 200% higher thickness than the mudcake deposited by the SAVA mud at the same test conditions. This indicates that even at higher bottom hole temperature and mud overbalance pressure, the scope of differential sticking is very slim in the presence of SAVA mud. Due to superior mudcake characteristics, SAVA drilling mud has the potential to reduce mud related drilling problem significantly.

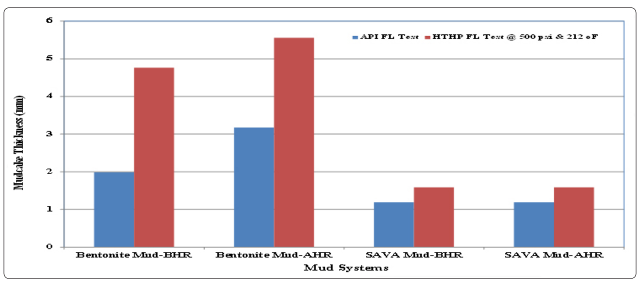

Figure 3: Comparison of API and HTHP Mudcake Thickness of Bentonite and SAVA Muds Before and after Hot Rolling

Figure 4 shows PV and YP values of the conventional Bentonite and the newly developed SAVA muds. SAVA mud shows lower PV values both before and after hot rolling at 212°F. Due to lower PV, the SAVA mud has better acceptance than the Bentonite mud as it will have a positive impact on reducing ECD effect and other mud related drilling problems The comparison of the YP value of the conventional Bentonite mud with the YP values of the SAVA mud indicates much lower YP values for the Bentonite mud compared to the SAVA mud. The low YP value of the bentonite mud can cause particle settlement easily, especially in deviated and horizontal wells. In case of weighted mud system, the low YP value can trigger dynamic barite sagging and thus can trigger a suite of mud related drilling problems. The high YP value of the SAVA mud will eliminate all settling and sagging problems and thus can reduce the mud related drilling problems significantly.

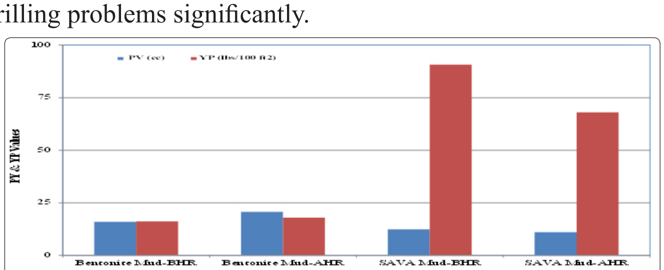

Figure 4: Comparisons of PV&YP of Bentonite and SAVA Muds Before and after Hot Rolling

Figure 5 shows the 10 secs and 10 min gel strength of the conventional Bentonite and the newly developed SAVA muds. SAVA mud shows 10 secs and 10 min gel strength very close to each other and thus indicate a pseudo fragile gel character. Hence, the initiation of recirculation after a static period of non-circulation will be much easier in the presence of SAVA mud. The conventional Bentonite mud shows big difference between the 10 secs and 10 min gel strength and thus indicates a progressive gel characteristic. Hence, higher pump pressure will be required to restart the circulation after a static period of non-circulation. Due to higher pressure requirement in initiating the circulation, there is a greater scope of induced loss of circulation in the presence of Bentonite mud system. The circulation initiation pressure of bentonite mud could be a critical factor in creating induced loss of circulation in wellbore with narrow mud weight window. From OHS point of view, the absence of any cristobalite in the Saudi volcanic ash used to formulate the SAVA mud, it is highly OHS friendly to mud engineers and rig crews. It may be mention that bentonite may contain some cristobalite which is carcinogenic in nature.

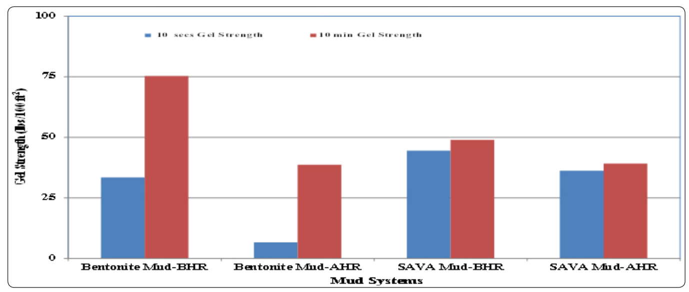

Figure 5: Comparison of 10/10 Gel Strength of Bentonite and SAVA Muds Before and after Hot Rolling

Transformation to an Inhibitive Mud System

Shale inhibition potential of the base SAVA mud was evaluated after converting it into an inhibitive SAVA mud to use as an alternative to inhibitive KCl-Polymer mud that is frequently used in drilling reactive shale sections of a wellbore. To compare the inhibition potential of the adaptable SAVA Basemud (inhibitive SAVA mud), a KCl-Polymer mud with same concentration of KCl salt and the shale inhibitor saltex was used. Figure 6 shows the shale cuttings dispersion test results for these muds along with water and 5% KCl salt containing water. The shale dispersion test results with water have the lowest %recovery due to severe shale-water interaction. The 5% KCl salt containing water gave the 2nd lowest shale recovery due to the inhibition effect of K+ ions arising due to the dissociation of KCl salt in the water phase.

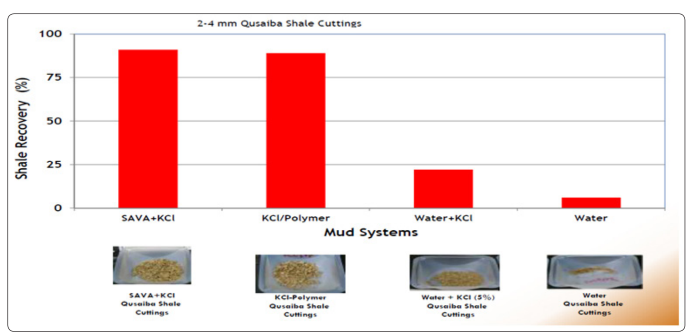

Figure 6: Comparisons of Inhibition Potential KCl-Polymer and SAVA Muds

The inhibitive SAVA and KCl-Polymer mud gave nearly similar shale recovery after the dispersion test. This demonstrates that the basic SAVA mud can easily be converted to an inhibitive mud system by simply adding and mixing KCl salt and shale inhibitor saltex in the mud system. It further indicates that if the SAVA base mud is used as the spud mud, it can easily be converted to an inhibitive mud if a hole section with a reactive shale is encountered. The direct conversion of the initial SAVA mud to an inhibitive mud system will eliminate the mud changeover or mud conditioning time to switch from a spud mud to an inhibitive mud system. Moreover, due to slight adaptation of an existing mud to transform it from a non-inhibitive mud to an inhibitive mud will eliminate any contamination effect associated with switching from one mud system to another mud system. It will also eliminate the NPT associated with disposal of the existing mud and the cleaning of the circulation system to remove the leftover of the existing mud from the mud tanks, suction and discharge lines, mud pumps, etc. From economic point of view, this will save the NPT cost associated with old mud disposal, circulation system cleaning, new mud preparation and displacement of the old mud from the wellbore. Similar inhibition potential of the SAVA mud like the KCl-Polymer mud demonstrates the suitability of the SAVA mud as a better alternative for continuous drilling operation and to be in the fore front of advanced drilling practices.

Questions were raised about the compatibility of the inhibitive SAVA mud with traditional weighting additives such as barite and calcium carbonate to subdue high formation pressure while drilling. Hence, a comparative evaluation of the filtration and rheological behavior of 78 pcf weighted SAVA and KCl-polymer muds was done. Figures7 shows the API fluid loss test parameters of the 78 pcf barite and calcium carbonate weighted KCl-Polymer mud along with the 78 pcf barite weighted SAVA mud. All the muds showAPI fluid loss behavior well below the API recommended fluid loss value. The barite and calcium carbonate weighted KCl-Polymer mud show spurt losses before and after hot rolling at 212°F. But the SAVA mud shows no spurt loss before hot rolling. It only shows slight spurt loss after hot rolling at 212°F temperature for 16 hours. SAVA mud shows slightly higher API fluid loss compared to KCl-Polymer mud. However, the muds show deposition of a very thin mudcake in API test under 100 psi overbalance pressure. The low pressure and low temperature (25°C) API test parameters indicate nearly similar behavior of the weighted KCl-Polymer and weighted SAVA mud. Hence, they are expected to show equivalent performance in a borehole environment with 212°F or less bottom hole temperature.

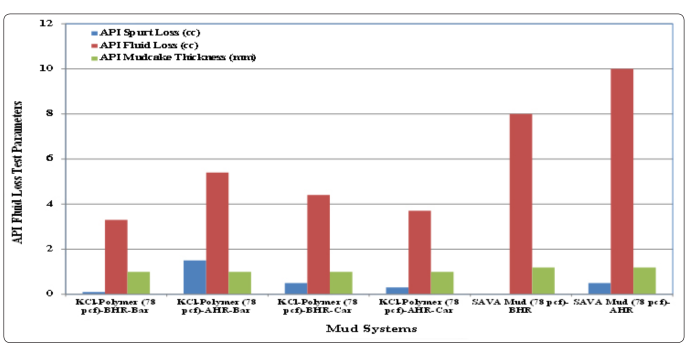

Figure 7: Comparison of API Fluid Loss Test Parameters of 78 pcf KCl-Polymer and SAVA Muds Before and after Hot Rolling

Figure 8 shows the HTHP fluid loss test parameters of the 78 pcf barite weighted and 78 pcf calcium carbonate weighted KCl-Polymer mud along with the 78 pcf barite weighted SAVA mud tested at 212°F and 500 psi. The barite and calcium carbonate weighted KCl-Polymer mud produced more spurt loss before hot rolling than the barite weighted SAVA mud. Analyses of HTHP fluid loss behavior of the 78 pcf barite and calcium carbonate weighted KCl-Polymer and the SAVA muds after hot rolling indicate higher HTHP spurt and fluid loss for the KCl-Polymer mud.Hence, the SAVA mud is expected to demonstrate better performance than the $CaCO_3$ and barite weighted KCl-Polymer mud at bottom hole conditions with similar temperature and overbalance pressure.

The analyses of deposited mudcake thickness (see Figure 8) show that the weighted KCl-Polymer mud created thicker mudcake than the weighted SAVA mud. The formation of a thin mudcake at HTHP conditions in the presence of weighted SAVA mud indicates its superior performance than the KCl-Polymer mud. The possibility of causing differential sticking problem in a high permeable zone is less in the presence of SAVA mud due to the deposition of a thin mudcake. On the other hand, the scope of differential sticking is higher in the presence of weighted KCl-Polymer mud due to the formation of a thicker mudcake at HTHP conditions. As deposited mudcake thickness is one of the major factors in causing differential sticking, a drilling mud with the ability to deposit a thin mudcake is highly desirable for differential sticking prone zones. Hence, SAVA mud has a technical advantage over the KCl-Polymer mud for high permeable formations causing differential sticking. The overall HTHP test parameters indicate superior behavior for SAVA mud compared to the weighted KCl-Polymer mud and thus indicate higher technical benefits and better drilling efficiency in the presence of SAVA mud.

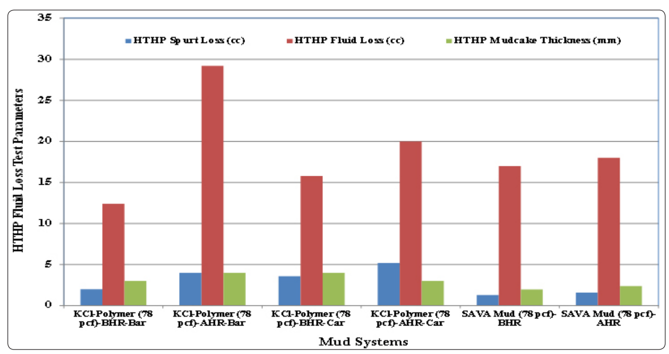

Figure 8: Comparison of HTHP Fluid Loss Test Parameters of 78 pcf KCl-Polymer and SAVA Muds Before and after Hot Rolling

Figure 9 shows the PV & YP values of the 78 pcf Barite weighted and 78 pcf calcium carbonate weighted KCl-Polymer mud along with the 78 pcf barite weighted SAVA mud before and after hot rolling at 212°F for 16 hours.The barite weighted KCl-Polymer and SAVA muds have low and nearly similar PVvalues before and after hot rolling at 212°F. Drilling muds with low PV value is desirable to minimize ECD effect and other mud related drilling problems. Also no change of PVvalues at down hole conditions eliminates the dumping and dilution of drilling mud to maintain PV as low as possible and avoid any detrimental effect on mud rheology, hole cleaning and drilling efficiency.

The $CaCO_3$ weighted KCl-Polymer has higher PV than the barite weighted SAVA mud, especially after hot rolling the mud system.It has more than 30% higher PV value than the SAVA mud after hot rolling and about 25% higher PV value before hot rolling at 212°F for 16 hours. SAVA mud, on the other hand, shows no change or slight decrease in the PV values after hot rolling. The no/negligible temperature effect of the SAVA mud PV indicates a flat PV mud system up to a bottom hole temperature of 212°F. The lower PV value of the SAVA mud along with its no/negligible alteration after hot rolling indicate no detrimental effect on rig hydraulics both at surface and down hole conditions. All these positive attributes of the SAVA mud indicate that it is a water-based mud with superior mud properties than barite and $CaCO_3$ weighted KCl-Polymer mud.

Due to higher PV value of $CaCO_3$ weighted KCl-Polymer mud compared to the SAVA mud, there will be a higher effect on ECD, surge and swabbing pressure and induced loss of circulation. The high PV of the KCl-Polymer mud will also have a detrimental effect on ROP and thus the drilling efficiency. Hence, the $CaCO_3$ weighted KCl-Polymer mud is expected to demonstrate lower performance than the SAVA mud at bottom hole condition. The possibility of causing ECD induced drilling problem is higher for the $CaCO_3$ weighted drilling mud than the weighted SAVA mud. In conclusion it can be said that the PV values measured after hot rolling indicate superior performance of the weighted SAVA mud compared to the weighted KCl-Polymer mud.

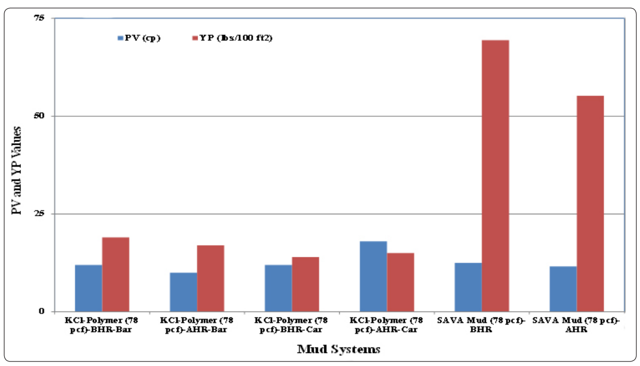

Figure 9: Comparison of PV&YP of 78 pcf KCl-Polymer and SAVA Muds Before and after Hot Rolling

The analyses of YP values (see Figure 9) indicate a low YP value both for the barite and $CaCO_3$ weighted KCl-Polymer mud systems. Due to lower YP value, there is a high possibility of dynamic sagging of weighting materials during the period of mud circulation. The tendency of barite sagging will be even higher in deviated, horizontal and extended reach wells. Other than the weighting material sagging, the low YP will cause settling of drilling cuttings even during the period of mud circulation. In case of deviated and horizontal wells, the settling of drill cuttings at the low side of the wellbore can create a cutting bed. This can cause mechanical pipe sticking, higher ECD, lower hole cleaning efficiency and other mud related drilling problems. The high YP value of the SAVA mud will avoid the settling of drilling cuttings totally and thus can reduce the scope of various mud related drilling problems. As too high YP value also has an effect on ECD, the value of YP should be kept within an optimum range to fulfill all functional tasks without any detrimental effect.

Figure 10 shows the 10 secs and 10 min gel strength of the 78 pcf Barite weighted and78 pcf calcium carbonate weighted KCl-Polymer mud along with the 78 pcf barite weighted SAVA mud before and after hot rolling at 212°F for 16 hours. The barite and $CaCO_3$ weighted KCl-Polymer muds show less than 6lbs. /100 ft2 gel strength for 10 secs and 10 minutes (see Figure 10) for tests conducted before and after hot rolling at 212°F. The low gel strength of the mud will have a detrimental effect on mud performance due to its inability to keep drilling cuttings in suspension during the period of non-circulation. The easy settling of drilling cuttings will create hole pack-off and cuttings bed formation, especially in deviated, horizontal and extended reach wells. The settling of drill cuttings can also cause poor hole cleaning and mechanical pipe sticking problem. The low gel strength of the weighted KCl-Polymer muds can cause sagging of weighting materials leading to a variation in mud density along the mud column. This can trigger a kick and well control problem at shallow depth and an induced loss circulation problem at the deep horizon.

The weighted SAVA mud indicates far superior 10 secs and 10 min gel strength compared to the weighted KCl-Polymer mud and thus demonstrates its superior functional ability to keep drilling cuttings in suspended condition along the stable and homogeneous mud column during the period of non-circulation. Even though, there is a decrease in the gel strength of the SAVA mud after hot rolling, the 10 secs and 10 min gel strength is more than 15 lbs/100 ft2, which is nearly 3 times higher than the gel strength of the weighted KCl-Polymer mud. Hence, the hole pack-off, cuttings bed formation and mechanical pipe sticking will be a rare event in the presence of the weighted SAVA mud. Moreover, the superior gel strength characteristics of the weighted SAVA mud will prevent the sagging of any weighting materials in deviated wellbore. The prevention of weighting material sagging will allow maintaining same mud density along the mud column and thus expected to eliminate kick and well control problems at shallow depth and induced loss circulation at deeper horizon.

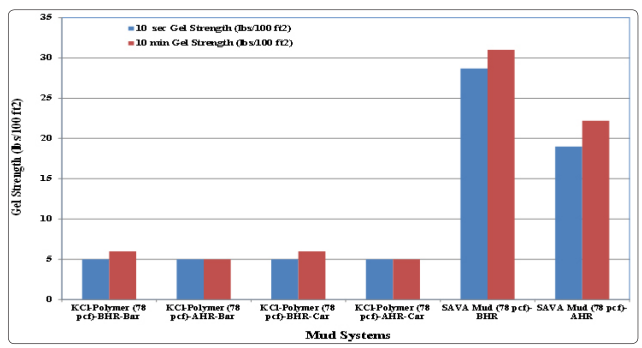

Figure 10: Comparison of 10/10 Gel Strength of 78 pcf KCl-Polymer and SAVA Muds Before and after Hot Rolling

Conversion to Salt Water-based Mud

If salt formations or formation with salt stringers or brine influxes are encountered while drilling, then the conventional water-based mud rarely works due to the interactions of some mud additives with the cations and anions arising due to the dissociation of the salts. The incorporation of salts can cause severe flocculation of some mud additives such as bentonite leading to excessive thickening of drilling mud. This often requires frequent dumping and dilution of the salt intolerant mud system to restore the filtration, rheological and thixotropic properties of the mud and addition of new volume of water or mud to restore the programmed mud volume required for drilling. In some cases, the dumping and dilution method of mud treatment is not feasible due to technical and economic reasons. In that case change over to an OBM system or a salt tolerant water-based mud is the only solution. The NPT associated with the mud changeover, cost of the old mud that has been disposed and the new mud used to replace the old mud can increase the mud management cost significantly along with the overall drilling cost. Due to easy transformation of the SAVA mud to sea water, salt water or saturated salt water-based mud, it eliminates the need of dumping and dilution and/or a mud change over. It also eliminates all the technical challenges associated with poor salt tolerant water-based muds.

Figures 11-13 provide a comparison of the API fluid loss, rheological and gel strength properties of a fresh water SAVA mud with a salt water SAVA mud prepared by adding 25 ppb NaCl to the fresh water SAVA mud. Analyses of the API fluid loss test results shown in Figure 11 indicate nearly similar spurt loss and fluid loss behavior along with the deposited mudcake characteristics. The results further indicate that contrary to the conventional water-based mud, the SAVA mud is expected to demonstrate better performance after brine contamination due to a positive impact on deposited mudcake thickness.

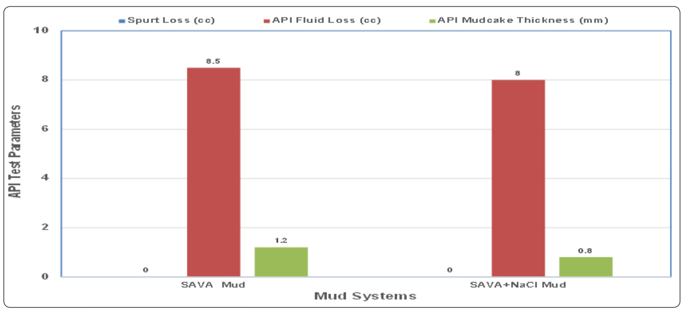

Figure 11: Comparison of API Test Parameters of Fresh Water and Salt Water-based SAVA Mud

Figure 12 shows the rheological parameters PV and YP of the fresh water and converted salt water SAVA mud. The data indicate no detrimental effect that is unacceptable to fulfil the functional tasks of a drilling fluid while making a borehole. In spite of incorporation of 25 ppb NaCl in the fresh water SAVA mud to convert it to a salt water mud, the PV remains below 20. There is slight increase in the YP due to the electrolytic effect of the salt. However, it is still within the acceptable operating range. Moreover, the YP can be kept within the desirable range by controlling the concentration of XC and the PHP in the mud.

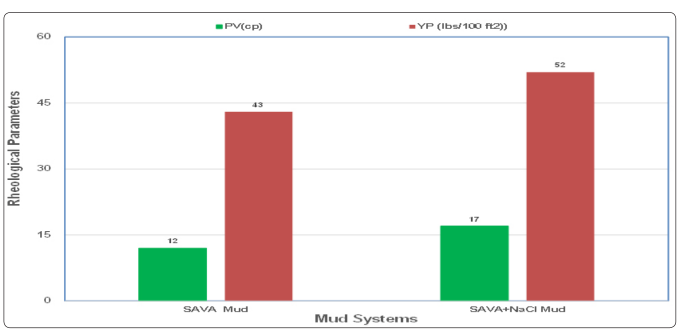

Figure 12: Comparison of Rheological Parameters of Fresh Water and Salt Water-based SAVA Mud

Figure 13 shows the 10 secs and 10 minutes gel strength parameters of the fresh water and converted salt water SAVA mud. The data indicate no detrimental effect on the thixotropic behavior of the SAVA mud due to its conversion to a salt water mud. There is slight increase in the 10 secs and 10 minutes gel strength due to the electrolytic effect of the salt. However, it is within the acceptable operating range that is required to fulfil the functional tasks during the period of non-circulation. The gel strength data further indicate that the converted salt water SAVA mud maintains the pseudo-fragile gel characteristics like the original fresh water-based SAVA mud. This again demonstrates the high adaptability of the originally formulated fresh water SAVA mud to a salt water mud to meet the technical requirements of hole sections containing salt formations or high salt content in the formations.

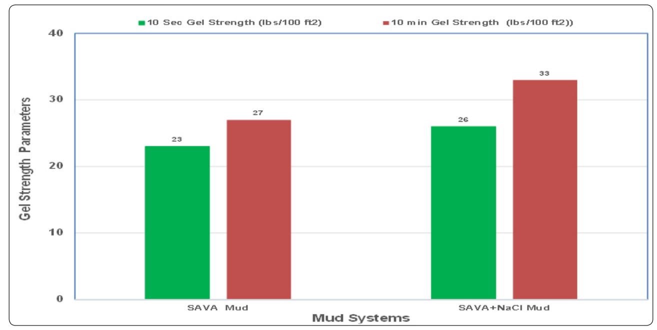

Figure 13: Comparison of Gel Strength Parameters of Fresh Water and Salt Water-based SAVA Mud

Finally, it can be concluded that the highly adaptable fresh water-based SAVA mud can easily be converted to salt water or saturated salt water mud if the borehole section requires a salt water mud without changing to a new salt tolerant mud system. Due to high tolerant of the SAVA mud to other salts such as monovalent NaCl and KCl and divalent $CaCl_2$ and $MgCl_2$, it can easily be prepared using sea water in an offshore drilling rig.

Transformation to High Lubricity WBM

In case of a vertical hole with high dogleg severity or a deviated borehole, the conventional water-based mud creates excessive torque and drag with a significant drop in drilling efficiency due to high coefficient of friction (COF). Drilling fluids with high COF can cause excessive torque and drag problems, drill string twist-off, pipe sticking, low ROR, etc. Hence, it is sometimes necessary to switch to a highly lubricating oil-based mud system. If the existing water-based mud can be converted to a high lubricating mud with a COF value similar to or better than a typical OBM system, then there is no need to change the mud system.

The adaptability of the original SAVA mud to a high lubricating mud system was evaluated by adding several lubricants to the base SAVA mud. The base mud has a high COF value like all other water-based muds. The commercial lubricants evaluated to convert the original SAVA mud to high lubricating mud are Lube 167, ME Lube and Radiagreen that are frequently used in the oil and gas fields. In addition to the commercial lubricants, we also tested two EXPEC ARC developed green lubricants ARC Ecolube and ARC Green. These two lubricants are eco-friendly like the Radiagreen lubricant. Evaluation of fluid loss and rheological behavior of the mud before and after adding the lubricants indicated no detrimental effect on SAVA mud properties.

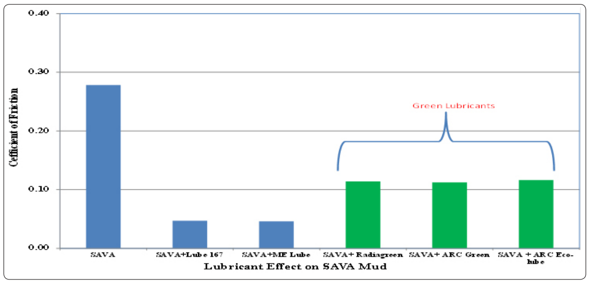

Figure 14: Evaluations of Various Lubricant Effects on SAVA Mud Coefficient of Friction (COF)

Figure 14 shows the coefficient of friction (COF) of the original SAVA mud along with the COFs of SAVA mud after converting to a high lubricating water-based mud by adding various lubricants to the mud system. The original SAVA mud has a high COF value of 0.28 and thus can create severe torque and drag problem in wells having high dog leg severity and also in deviated, horizontal and extended reach wells. However, the experimental data shown in Figure 14 indicate that the COF value of the SAVA mud can be reduced significantly by adding ecofriendly Radiagreen, ARC Ecolube and ARC Green lubricants. The data further indicate that the COF value of the SAVA mud can be reduced dramatically using Lube 167 and ME lube that is similar or better than the COF value of good quality OBM systems (see Figure 15). Addition of these two lubricants to the original SAVA mud can knock down the COF value of the SAVA mud to a level that is far below the COF of high performance water-based and conventional oil-based muds. The results confirm that the SAVA mud can easily be converted to a high lubricating water-based mud with a COF value less than oil-based muds to overcome the specific drilling challenges of certain hole sections.

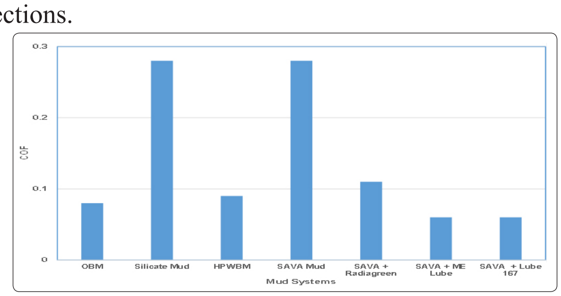

Figure 15: Comparisons of Original and Lubricant Containing SAVA Mud COFs with Published COFs of OBM, HPWBM and Silicate Muds

Conclusions

1. The rheological, filtration and thixotropic properties of the original fresh water SAVA mud demonstrate its suitability to use as a water-based mud system for making a borehole into the earth's crust.
2. Superior technical properties of SAVA mud compared to the bentonite mud indicate that it is a better alternative to bentonite mud if the formulation cost can be reduced to level close to the bentonite mud.
3. The experimental results of the original mud and the adapted SAVA mud systems indicate that the newly developed eco-friendly water-based mud is suitable for drilling various hole section of a borehole by adding one or two additional additives to the original mud.
4. Comparative analyses of the performance of the adapted mud systems with several water-based muds used in drilling different hole sections indicate the suitability of the new mud for uninterrupted drilling operation without mud changeover
5. The highly flexible and easily adaptable eco-friendly Saudi Volcanic Ash-based drilling fluid is expected to play an important role to be in the forefront of best drilling practices.
6. Due to the absence of any cristobalite in the Saudi Volcanic ash composition, the SAVA mud is not only eco-friendly but also OHS friendly for mud engineers and rig crews.
7. In spite of higher formulation cost of the SAVA mud compared to bentonite mud, it could be a cost effective drilling mud due to overall economic benefits associated with several operational advantages over salt intolerant water-based muds.
8. SAVA mud eliminates the need of treatment, dumping and dilution due to high tolerant to salts and other contaminants thus expected to reduce the mud management cost significantly.
9. Fresh water SAVA mud can easily be converted to a salt water-based mud by simply adding and mixing the required amount of salt in the mud system for trouble free drilling operations while encountering salt diaper, salt formations or formation with high brine fluxes.
10. Due to high mono and divalent salt tolerant capacity of SAVA mud components, the mud can easily be prepared using sea water. This will allow the offshore rig site preparation of the mud using sea water.
11. If a reactive shale section is encountered while drilling, the SAVA mud can easily be converted to an inhibitive mud system by adding KCl salt and a suitable shale inhibitor.
12. Comparative assessment of the inhibition potential of SAVA and KCl-Polymer muds with similar type and amount of shale inhibitors in the mud formulations demonstrated similar performance for both mud systems.
13. In case of high torque and drag problem in a vertical well with high dogleg severity or in a deviated borehole, SAVA mud can easily be converted to a high lubricity water-based mud to mitigate the torque and drag problems.
14. Several commercial lubricants available in the market can knock down the COF of SAVA mud to level that is well below the COF of high performance water-based and also oil-based muds.

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