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Highly Inhibitive Water-Based Fluid System Provides Superior Chemical Stabilization of Reactive Shale Formations

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Abstract

A new highly inhibitive water-base fluid system has been developed for drilling applications in highly reactive and dispersive shale formations. The system significantly reduces the clay dispersion and hydration compared to existing glycol and other inhibitive systems. The laboratory finding shows lower risk of accretion and other problems related to cuttings agglomeration. The system components are newly developed and are designed to perform specific functions to achieve higher performance in highly reactive shale formations. The new system is environmentally friendly compared to currently available inhibitive mud systems.

The new system consists of four basic components; the shale inhibitor, encapsulator, anti-accretion agent and fluid loss control agent. This fluid can be formulated with fresh water, seawater or salts, providing flexibility for a variety of drilling environments.

The paper compares the performance of previous high performance water-base mud systems with the newly developed system. The paper also discusses generically the unique chemistry of the newly developed system components, system formulations and applications.

Introduction

Invert emulsion drilling fluids have been used for a number of years primarily because of their drilling performance advantages over water-base muds. Oil-base muds (OBM) offer superior shale stability, excellent lubricity, high ROP and less risk of stuck pipe. However, the application of water-base muds is traditionally based on concerns associated with the use of OBMs, such as environmental compliance, logistical problems in remote locations, gas solubility in fluids, and the cost associated with makeup of fluid and anticipated lost circulation risk. Over the past two decades, environmental regulations and concerns have increasingly restricted the use of OBM worldwide. These increasing environmental demands have resulted in a keen interest in the development of highly inhibitive, high-performance water-base drilling fluid system, which would have similar drilling advantages to OBMs.

The search for inhibitive water-base mud systems, which perform like OBM, has been a continuous endeavor in the drilling industry. During the past several years many approaches have been taken,[1-7] such as cationic polymer mud systems, glycol-based muds, polymer/salt systems, silicate muds, calcium ion treated muds and other relatively high-concentration brine systems. However, these approaches have not been completely successful in inhibiting the hydration of highly reactive systems and have various limitations. For example, cationic polymer systems are almost as inhibitive as an OBM; however, the cost of running the system, toxicity of cationic polymers, and their incompatibility with other anionic drilling fluid additives has resulted in only limited success in the field. Highly concentrated brine systems have limitations on mud formulations and mud properties. While silicate muds have good inhibitive properties, they also have problems related to human health and environmental issues due to the high pH, logistic problems and mud formulation limitations. Some of the anionic and non-ionic polymer systems, e.g., natural and biopolymers, and PHPA-based systems have been used with varying degrees of success. However, these systems are considered less effective than the cationic or other salt systems for reactive shale formations. Moreover, these polymer systems have limitations of thermal stability and mud formulations.

These approaches have not been completely successful in inhibiting highly reactive water sensitive shales and alleviating resulting problems, such as accretion and stuck pipe. The newly developed high-performance water-base mud addresses these issues.

High-Performance Water-Base Mud (HPWBM)

Key Features:

- Highly inhibitive system
- Significant reduction in clay dispersion and hydration compared to existing state of the art inhibitive systems.
- Lower risk of accretion and cuttings agglomeration related problems.
- Environmentally friendly
- Viable alternative to OBM and silicate fluids.

Shale Inhibition

A new environmentally safe shale-inhibitive additive exhibits excellent shale inhibiting characteristics in the high-performance water-base mud. The newly developed shale inhibitor is an amine-based multi-functional molecule, which is completely water-soluble and has low toxicity. A 96-hour LC_{50} of >500,000 was obtained in a bioassay test. The bioassay was carried out at 3% level in generic mud #7 using *Mysidodsis bahia* specs. In addition to its excellent shale-inhibition properties and low-toxicity, it is compatible with other common drilling fluid additives used in WBM. The newly developed shale inhibitor has no hydrolyzable functionality and therefore it is stable to high temperatures even in high pH systems.

The unique molecular structure of the shale inhibitor is theorized to function by making a perfect fit between clay plates and binding the plates together thereby greatly diminishing the clay's tendency to imbibe water from an aqueous environment. The molecular modeling and x-ray diffraction studies of the newly developed shale inhibitor were carried out using a shale inhibitor-water mixture with a model montmorillonite clay layer using a combination of Monte Carlo and molecular dynamics methods. The studies show evidence that the newly developed shale inhibitor may inhibit shale swelling by a mechanism different from the polyglycols. The suggested mechanism involves specific binding of the amine groups of the shale inhibitor rather than entropically driven exclusion of water from the interlayer space. This mechanism may involve a neutral amine molecular binding to the clay via metal cations, or an amine molecule in the protonated ammonium form binds in place of the metal cations in an ion exchange mechanism. X-ray diffraction measurements on montmorillonite samples soaked in the shale inhibitor solutions show a decrease in layer spacing with increasing shale inhibitor concentrations. This is a reverse of the trend typically observed for polyglycols and supports the hypotheses of a new inhibitive mechanism. The measurements also provide evidence that the degree of protonation of the shale inhibitor is important to the binding mechanism and that the shale inhibitor molecule is indeed present in the interlayer space. Also, the molecular modeling studies with neutral amine shale inhibitors of various molecular weights indicated that, at some molecular weight, the compound binds across the interlayer space in a bridging fashion. Such an effect would help explain the increase in inhibition efficiency of this compound over other tested compounds of varying structures and molecular weights.

Encapsulation/Clay Dispersion Reduction

The polymeric additive in this high-performance water-base mud provides reduction in clay dispersion and some shale inhibition by encapsulation of shale particles. The newly developed polymer has a molecular weight and charge density that impart superior encapsulation by limiting water penetration into the clays. Controlled molecular weight of the polymer allows significant flexibility in a wide range of mud densities and mud formulations. The high charge density of the polymer provides salt tolerance capability in the HPWBM. The encapsulator in the HPWBM has the ability to control the swelling and dispersion of the water-sensitive clays without having significant adverse effect on rheological properties of drilling fluid formulations.

Anti-accretion and Anti-agglomeration Agent

Significant work has been carried out in shale-inhibition and encapsulation chemistry in the drilling fluid industry. However, only limited attention has been paid to anti-accretion and anti-agglomeration of clays. The newly developed HPWBM addresses the problems and risks related to accretion and cuttings agglomeration. The newly developed anti-accretion agent is a specific blend of surfactants and lubricants. It is especially designed to coat drill cuttings and metal surfaces to reduce the sticking tendency of hydrated solids on the surface of the metals. The composition also provides anti-agglomeration of the hydrated particles to resist gumbo balling. Hydratable clays become less prone to adhere to steel surfaces allowing the bit and bottom-hole assembly to drill more efficiently. The chemical composition of the anti-accretion agent will assist in preventing any buildup of drill solids below the bit, allowing the cutter to make continuous contact with new formation for improved rate-of-penetration. The special blend of surfactants and lubricants in the product not only reduces bit and/or bottom hole assembly balling, but also lowers torque and drag by reducing the coefficient of friction.

Test Procedures and Discussion of Results

Several test methods were utilized to evaluate the inhibitive properties of the shale inhibitors and HPWBM. The test methods used were bentonite inhibition, bulk hardness, Slake durability and accretion. Typical chemical compositions of the HPWBM and other fluids tested are found in **Tables 1a-d**.

Bentonite Inhibition

The ability of a shale inhibitor to prevent the yielding of bentonite and maintain a low rheological profile is the simplest useful test for the evaluation of shale inhibitors. An experiment based on such a concept was performed by carrying out a series of inhibition tests in fresh water. This inhibition evaluation procedure was designed to simulate the relatively slow incorporation of yielding clays into a drilling fluid, as occurs while drilling active shales in the field.

The test method determines the maximum amount of API bentonite that can be inhibited by a single (8.0

lb/bbl) treatment of shale inhibitor over a period of several days. One-barrel equivalent of fresh water containing 8.0 lb/bbl of shale inhibitor was treated with 10-lb/bbl bentonite every day. After heat aging at 150°F for 16 hours, the rheological properties were measured before adding another portion of bentonite. These daily additions of bentonite and aging were continued until the sample became too viscous to evaluate.

The performance of the amine shale inhibitor in the HPWBM was compared with potassium chloride and a commercial quaternary amine shale inhibition in fresh water. **Fig. 1** shows the 3 rpm reading on Fann VG meter Model 35 and **Fig. 2** shows the yield point on bentonite swelling. The newly developed shale inhibitor in the HPWBM showed excellent inhibitive properties compared to KCl and a commercial quaternary amine shale inhibitor at 8-lb/bbl treatment.

<u>Bulk Hardness Test</u>

The performance of the HPWBM was further evaluated using a bulk hardness tester (**Fig. 3**). The bulk hardness tester is a device designed to give an assessment of the hardness of shale cuttings exposed to a drilling fluid. The hardness of the shale cuttings relates to inhibitive properties of the fluid being evaluated. In this test, shale cuttings are hot rolled in the test fluids for 16 hours at 150°F. After hot rolling, the shale cuttings are recovered on a screen, washed with brine and then placed into the bulk hardness tester. Using a torque wrench the cuttings are extruded through a plate with holes. Depending upon the hydration of the cuttings, the torque may reach a plateau region or may continue to rise during the extrusion. The harder the cuttings, the higher the torque reading and the more inhibitive the mud system.

The bulk hardness tests were carried out on the HPWBM and the performance was compared against state-of-the-art inhibitive mud systems. **Fig. 4** shows the comparison of HPWBM, calcium chloride brine mud and PHPA/NaCl mud on Arne clay and **Fig. 5** on Oxford clay. Both of the tests show that shale cuttings hot rolled in HPWBM were much harder than calcium chloride or PHPA/NaCl based muds. **Fig. 6** also differentiates the performance characteristics of HPWBM in bulk hardness test. Both the calcium chloride as well as PHPA/NaCl muds made ribbons during extrusion of hot rolled shale cuttings while HPWBM did not extrude completely and made a pallet. A similar comparison was carried out on PHPA/KCl/NaCl system using field cuttings and the results of this test are given in **Fig. 7**, which show the superior performance of HPWBM against the conventional inhibitive system containing potassium chloride.

<u>Slake Durability Test</u>

The HPWBM was further evaluated using the Slake durability test. This is similar to the hot rolling dispersion test but it provides a harsher, more abrasive environment. **Fig. 8** shows the Slake durability tester. The evaluation consists of placing a known quantity of specially sized shale cuttings in a round cage immersed in test fluid container. Then the cage with cuttings is rotated for a set period of time. During rolling, the hydrated cuttings will break up and disperse, and will pass through the cage screen. The cuttings remaining in the cage after the test period are washed, dried and weighed. The percent recovery of shale cuttings is calculated.

Three different field cuttings were evaluated in this test and the performance of the HPWBM was compared against PHPA/KCl/NaCl fluid. The results of these tests are shown in **Fig. 9**. Recoveries from 60 - 98% were obtained in HPWBM as compared to 25 to 85% in the PHPA/KCl/NaCl system.

<u>Accretion Test</u>

Accretion is one of the most important tests for evaluating the inhibitive and performance characteristics of HPWBM. The test consists of placing a steel bar in a hot rolling cell in which the test fluid and cuttings are placed. The cuttings are evenly distributed around the centralized accretion bar. The cell is closed and rolled at room temperature for a specific period of time. After rolling, the bars are removed and a photo of the bars is taken. The percent weight of the cuttings adhering to the bar is calculated after removing, washing the cuttings, and drying the sample.

The pictures in **Figs. 10a-e** illustrate the performance of the HPWBM in the accretion test as compared to several state-of-the-art high inhibitive mud systems. **Fig 11** shows the percent accretion on four different shale cuttings. The HPWBM has practically no accretion for all of the various types of clay cuttings tested as compared to other high performance water-base muds, which had as much as 80% accretion.

Conclusions

A new highly inhibitive water-base fluid system has been developed for drilling applications in highly reactive and dispersive shale formations. The laboratory results show that the system significantly reduces clay dispersion, hydration and accretion of cuttings. The inhibitive components of HPWBM have been specifically designed to impart maximum chemical stabilization to both swelling and dispersive clay formations. Molecular modeling of the shale inhibitor suggests that the shale inhibitor works by binding the amine molecule to the clay via a metal-cation exchange mechanism. The newly developed HPWBM is a viable alternative to other state of the art inhibitive water-base mud systems.

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Table 1a Typical Composition of HPWBM	
Seawater (mL)	293.0
NaCl (g)	80.4
PAC (g)	4.0
Polymer viscosifier (g)	0.25
Encapsulator (g)	4.0
Shale Inhibitor (g)	10.5
Anti-accretion agent (g)	17.5

Table 1b Typical Composition of Calcium Brine Mud	
Freshwater (mL)	210.0
11.6 lb/gal Calcium Chloride Brine (mL)	135.0
Viscosifier (g)	1.0
Fluid loss agent (g)	2.0
MgO (g)	0.5
Encapsulator (g)	2.0
Anti-accretion agent (g)	10.0

Table 1c Typical Composition of Silicate Mud	
Freshwater (mL)	290.0
NaCl (g)	54.5
Silicate (g)	43.0
Soda ash (g)	0.5
KCl (g)	17.5
PAC (g)	2.0
Fluid loss agent (g)	3.0
XCD polymer (g)	1.5
Anti-accretion agent (g)	10.0

Table 1d Typical Composition of PHPA/NaCl Mud	
Freshwater (mL)	323.0
NaCl (g)	73.2
NaOH (g)	1.0
Bentonite (g)	5.0
PAC (g)	2.5
PHPA (g)	1.0
Polymer viscosifier (g)	1.0

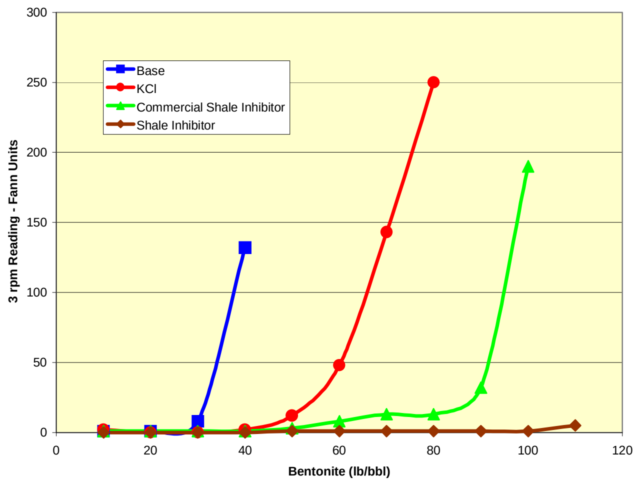

Fig. 1 – Bentonite inhibition test comparing the 3 rpm Fann readings of three shale inhibitors and the base fluid.

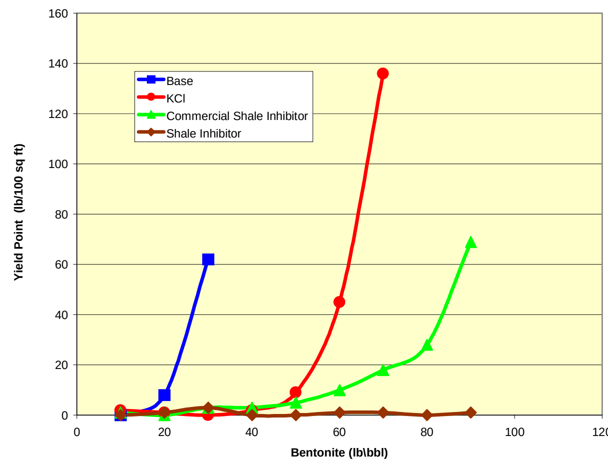

Fig. 2 –Bentonite inhibition test comparing the yield point of three shale inhibitors and the base fluid.

Fig 3 – Bulk hardness tester.

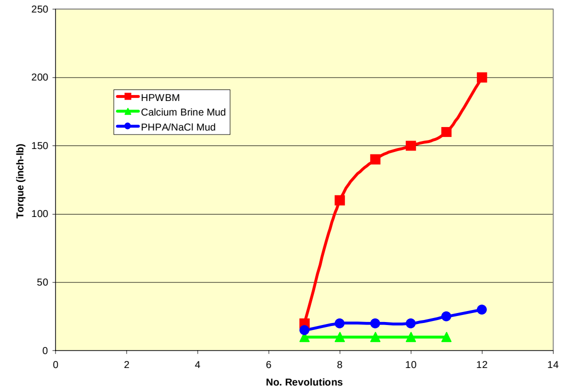

Fig 4 – Bulk hardness test comparing the torque readings on Arne Clay cuttings from three inhibitive systems.

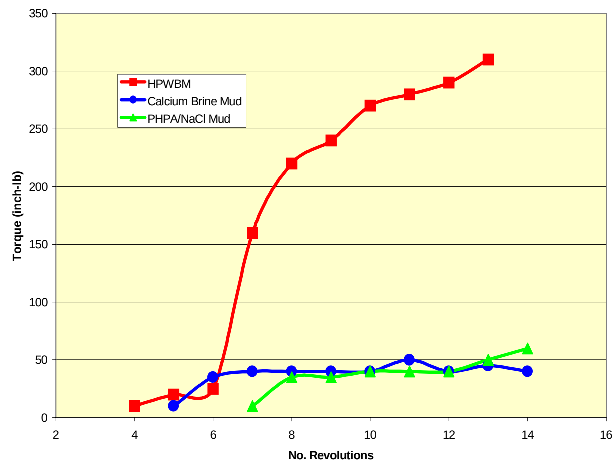

Fig. 5 – Bulk Hardness test comparing the torque readings on Oxford Clay cuttings from three inhibitive systems.

Fig. 6 Oxford clay cuttings exposed to inhibitive fluid and then extruded using the Bulk Hardness procedure.

Fig 7a – Field cuttings exposed to inhibitive fluid and then extruded using the Bulk Hardness procedure.

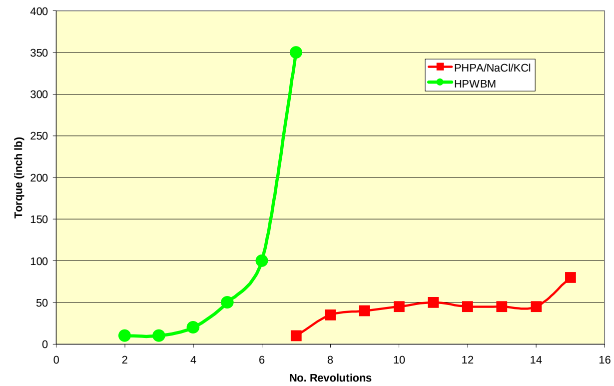

Fig. 7b – Comparison of the Bulk Hardness data of inhibitive fluids using the field cuttings shown in Fig. 7a.

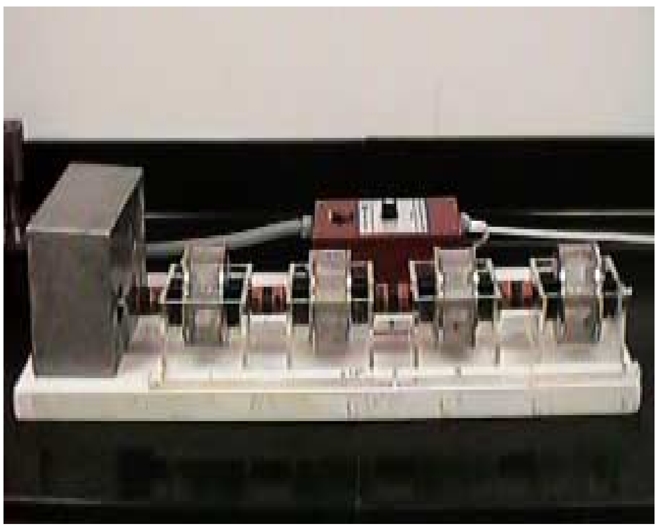

Fig 8 – The Slake durability tester.

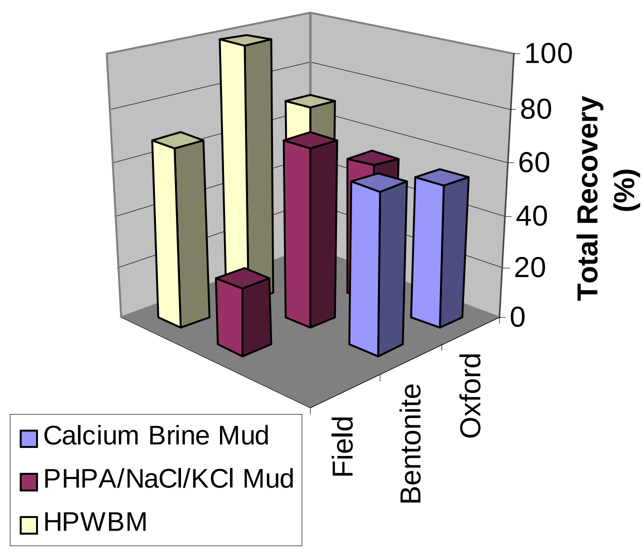

Fig. 9 – Comparison of three types of clay cuttings exposed to various inhibitive muds as measured by percentage of cuttings recovery using the Slake durability test.

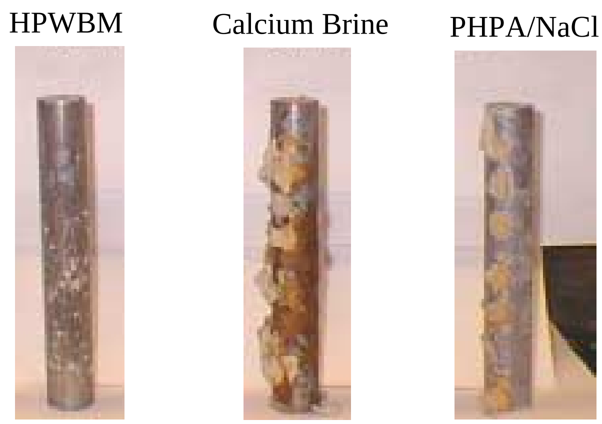

Fig 10a – Arne clay

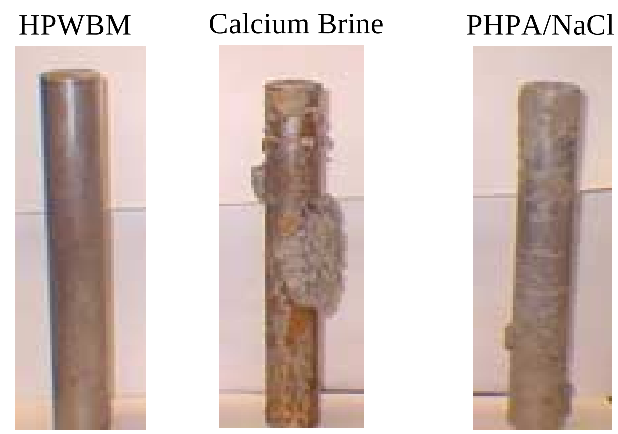

Fig 10b - Foss Eikeland clay

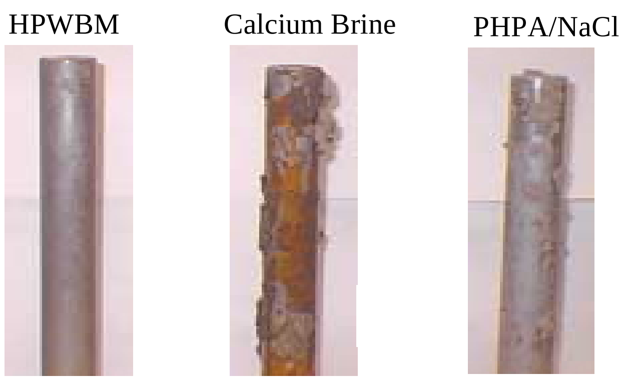

Fig. 10c - Oxford clay

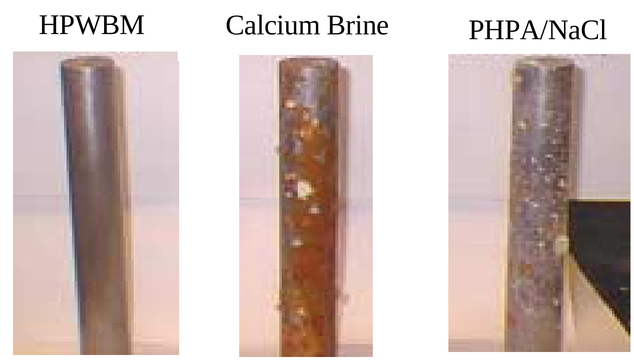

Fig. 10d - Bentonite clay

Fig. 10a-d – Accretion tests using three different inhibitive muds (HPWBM, Calcium brine, PHPA/NaCl mud) and four different clays (10a – Arne, 10b- Foss Eikeland, 10c – Oxford, 10d – bentonite clay).

Fig 10e – Accretion tests using two inhibitive muds and field cuttings from the Gulf of Mexico.

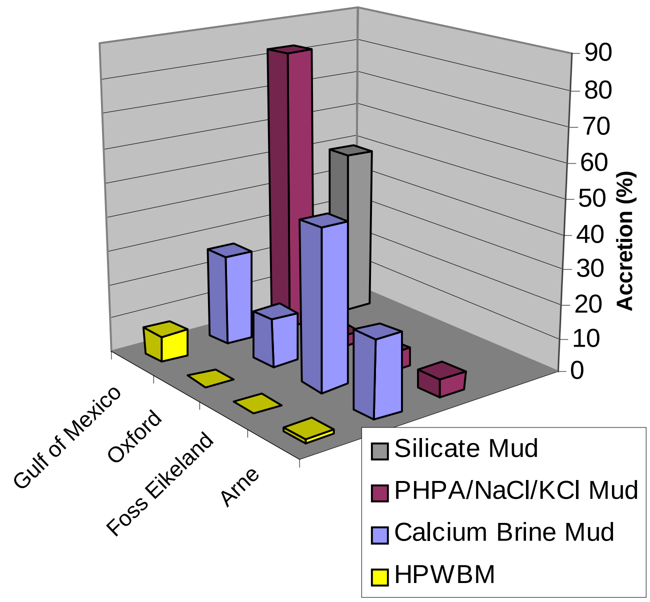

Fig. 11 – Comparison of four types of clay cuttings exposed to various inhibitive muds as measured by the percentage accretion.