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# Experimental Investigation of Permeability and Fluid Loss Properties of Water Based Mud Under High Pressure-High Temperature Conditions

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## ABSTRACT

Drilling in deeper formations and in high pressure and high temperature (HPHT) environments is a new frontier for the oil industry. Fifty years ago, no one would have imagined drilling in more than 10,000 feet of water depth like we do today. However, more issues need to be researched, tested, and studied in order to maintain a good drilling efficiency as deeper depths are drilled. One of these issues is the great effect that drilling at HPHT conditions has on the behavior of drilling fluids.

The goal of this research was to study fluid loss properties of water based mud and its effect on permeability under HPHT dynamic conditions utilizing advanced laboratory equipment that allows for wide ranges of pressure and temperature. Filtration tests were performed at both ambient and HPHT conditions. After several laboratory evaluations of fluid loss additives available in the market, Polysal HT was found to be the most effective in reducing the fluid loss of the water based mud for both static and dynamic tests at HPHT conditions. It is economically designed to be saturated in salt and other brine system. An additive that encapsulates particles with protective polymer coating as colloid. Drilling fluid stabilizer especially in drilling hydratable shale and a remarkable effectiveness in wide range make up water (high saline and high hardness). The fluid loss behavior of the mud and the characteristics of the filter cake produced are the basic factors that need to be considered when determining mud treatment.

A detailed workflow of experiments using equipment from OFITE HPHT Fluid Apparatus with differential pressure of 500 psi under 230°F with 2.5” filter paper (30 minutes) as well as OFITE Permeable Plugging Tester with 1,200 psi differential pressure @ 230°F using a ceramic disc were conducted. Also tests were conducted using the Low Temperature- Low Pressure API Filter Press at 100 psi @77°F with 3.5” filter paper for the purpose of comparison.

**Key words:** Permeability; Fluid loss; Water based mud; High pressure high temperature

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## INTRODUCTION

Drilling fluid behavior should be studied and researched in order to get better drilling efficiency and less fluid losses. This topic has been for years the subject of research and many laboratory studies. Most of these studies focused on the methods and parameters involved in the study of drilling fluid characteristics. Mud can act unexpectedly under HPHT conditions and testing its properties at these conditions produces results that differ from those obtained from testing under static conditions. Drilling fluids’ interaction with the spacer fluid is also critical[1]. Kruegerfound out that the API filter loss tests (standard and high pressure) shouldn’t be considered accurate when testing for the losses in mud that has viscosity reducers under dynamic conditions[2]. He also studied the quantities of dynamic fluid loss in water based muds when adding substances to the drilling fluid such as CMC, starch, polyacrylate, and viscosity reducers. He found that–in dynamic system-starch and viscosity reducers were the most useful additives. However, when using API fluid test, the results deduced that CMC, starch and polyacrylate were the most beneficial additives. So he deduced that industry was paying so much on the API filter loss test (standard or at high temperature high pressure) expecting it to be accurate, instead of focusing on the dynamic filtration tests (at HPHT) whose results were more accurate since their conditions were very similar to the reservoir conditions.

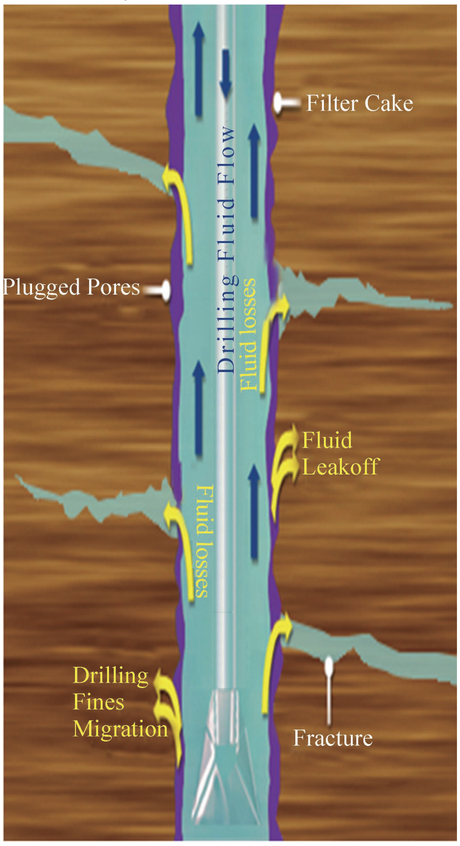


**Figure 1**
**Filter Cake Formation**

Roodhart stated that the commonly used 30 minutes API filtration test was inadequate especially in dynamic conditions[3]. Also, he concluded that the range for fluid data testing (1,000 psi [7-MPa] differential) was lacking and deficient. Shadravan and Amani investigatedthe HPHT challenges in drilling and completions[4]. Lee et al. researched the rheological properties of an extreme HPHT drilling fluids[5]. Amani et al. compared the rheological properties of oil based and water based drilling fluids under HPHT conditions[6]. Shadravan et al. looked at the possibility of fluid loss in underbalanced situations[7]. Bland et al. mentioned that there were many parameters that need to be taken into consideration while designing and monitoring drilling fluids for HPHT conditions[8]. These parameters included pressure and temperature effects on hydraulic calculations (while drilling under HPHT conditions at large depths, mud is subjected to high pressures and temperatures for long period of time) and PVT behavior of the base fluid (where the usual conditions considered by industry in fluid PVT measurements ranged from 15 psi per 750 °F to 20,000 psi/350 °F, but this range was exceeded while drilling under HPHT conditions). In addition, drilling efficiency was affected greatly by HPHT conditions where the use of additives like barite to increase the mud weight for such conditions caused lower drilling efficiency where the percentage of dispersed solids increased. This has many disadvantages (like decreasing hydraulic and cutting efficiency) during drilling high compressive formations under HPHT conditions.

Elkatatny and Nasr-El-Din studied the formation of filter cake under static and dynamic conditions[9]. They deduced that the same filtrate quantity was formed during dynamic and static conditions. However, dynamic conditions' spurt volume exceeded that under static conditions and when the filtration process reached an end, the part of the filtrate near to the drilling fluid had zero porosity and permeability. Further results by the CT scan proved that ceramic disk properties (like permeability and porosity) varied significantly during filtration and this should be taken into account during filter cake calculation. Properties ofwater based drilling fluids under HPHT dynamic testing conditions that can be measured include spurt loss, quality of plugging, total fluid loss, and cake formation thickness. Crespo et al. looked at some fluid loss related problems such as formation fracture, lost circulation, and well-control problems as a result of surge and swab pressures for yield-power-law drilling fluids[10].

## 1. POROSITY AND PERMEABILITY

Porosity can be defined as the percentage of void space that exists within a certain rock to the total rock volume. This void space consists of many pores. The connections between these pores and allows hydrocarbon to flow is known as permeability.

Porosity can be a result of deposition (primary porosity), can develop through the alteration of the rock over time such as when certain grains are dissolved (secondary porosity), or can be a result of fracturing of the rock (fracture porosity). Effective porosity is the portion of the void space that is interconnected allowing the flow of fluids through the rock. Total porosity on the other hand includes all the void space as a fraction of the bulk volume of the rock. Therefore, effective porosity is less than the total porosity since it doesn't include the isolated pores. Figure 2 shows the pores of a core sample obtained through micro-scanning and how pores can be interconnected or isolated.


**Figure 2**
**Micro–Scanned Ceramic Sample (Core) Showing Before Segmentation, Pores and After Segmentation**

Permeability is defined as the capacity for flow through porous media. It is defined by Darcy's law as:

$$q = \frac{k\,A}{\mu} \times \frac{\mathrm{d}p}{\mathrm{d}x}\ .$$

Darcy's law is usually used in order to determine the flow through permeable media. Where $k$ is the formation permeability, $q$ is the formation flow rate, $\mu$ is the fluid viscosity and $\mathrm{d}p/\mathrm{d}x$ represents the pressure change per unit length of the formation.

Chelton discusses in his paper how Darcy's law is applied to drilling fluid filtration[11]. He discusses how at deeper wells, where high temperature high pressure conditions occur, long period of time is required to make trips when it is necessary to change drilling bits. It's during these trips where static filtration occurs as mud is not being circulated. In this case, Darcy's law was used to determine if the data obtained using the modified cap can fit filtration theory.

The static filtration model in rectangular coordinates is based on Darcy's Law, which governs static filtration. In this case, the expression obtained by integrating Darcy's motion equation is represented as follows:

$$\frac{t}{V} = \frac{\mu}{A\frac{\mathrm{d}p}{\mathrm{d}x}} \times \left[\frac{\alpha_c C \rho_1 V}{2A} + R_m\right].$$

Where $\alpha_c$ is the filter cake resistivity that can be related to the filter cake permeability through its porosity and the density of the solid particles.

In rock physics, flow mechanics dictate that the flow must be through empty void space or through a miscible phase in multiphase flow. As porosity is defined as the ratio of void space to empty space, and using the definition of permeability above, we can then infer that factors such as pore size and pore-throat geometry control permeability. Focusing more on our scope of research we can hypothesize that the greater the porosity of our sample disks, the more fluid loss we can expect through the sample, especially because the test is single phase.

These two main parameters (porosity and permeability) play a very important role in the critical properties of the used drilling fluid. The main objective of the research is to study how HTHP conditions change such crucial mud properties like fluid loss, filter cake thickness, spurt loss and so forth. These properties are effected during drilling especially in high temperature and pressure drilling conditions which are sought today to get more oil from high depth's formations.

In order to test the mentioned properties of the used water based mud under a range of temperature and pressure conditions (low versus, HTHP), low temperature low pressure and high temperature high pressure (HTHP) filter presses were used. Moreover, both static and dynamic filtration tests were carried out in order to get a better picture of the changes the mud undergo and creates in the near wellbore region while drilling.

Static filtration is when the filtered mud stays still and thus no erosion happens to the mud cake. Dynamic filtration, on the other hand, is when the filtered mud is circulated where this results in erosion of the cake being created at a certain shear rate. Figure 3 represents a literature study that explained the differences between static and dynamic filtration tests[12].

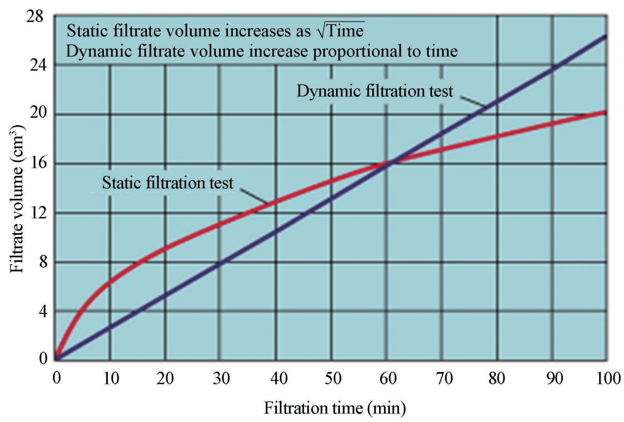


**Figure 3**
**The Variation of the Filtrate Volume as a Function of Filtration Time for Static and Dynamic Filtration Tests**

## 2. SIGNIFICANCE

Drilling fluid (mud) serves many different purposes. To begin with, it is responsible for maintaining wellbore stability. It is also the first of the two barriers that protect us from facing a kick or a blowout while drilling. Add to that the fact that drilling fluids carries important reservoir information from subsurface by circulating the cuttings out of hole for our studies. Further, it cools and lubricates the bit and it has many other benefits like giving us a nice circular hole and other useful advantages.

From these benefits one can deduce the importance of having the drilling fluid maintain its characteristics and properties under all the conditions that it might face in the well. The toughest of these circumstances will be at high depths where the mud will face high pressure and high temperature (HPHT) conditions that will result in a change in its behavior and a decrease in its value and efficiency.

Research and testing drilling fluids usually either focused on static conditions while testing or on a certain range of pressure and temperature that are far exceeded in nowadays drilling projects[8]. So there is a great need for studying drilling fluids behavior under HPHT conditions and especially under dynamic conditions that act as a simulator for what really happens down-hole. This paper will focus on studying the performance and the change in some important properties of water based drilling fluids under HPHT dynamic conditions.

When drilling is underway, the blood of the system, an essential component to this process that is, is drilling fluid. This fluid will remove cuttings, cool and lubricate the bit. Also, this fluid is used for pressure maintenance. If a wellbore kick is not controlled, a blowout could occur, resulting in loss of life, property and time.

For the drilling fluid to complete its functions, it must maintain its density, viscosity and other rheological parameters. These parameters are subjected to change under HPHT conditions and are difficult to measure[13]. Some wells are so deep and the conditions so harsh, that conventional Logging While Drilling (LWD) and Measurement While Drilling (MWD) tools do not function. Therefore, if a drilling engineer was to know the fluid properties under these conditions, the best out of his limited options is to rely on hydraulic and thermal models for downhole pressure information[8]. This is where the significance of this research comes into play. It is important to maintain the pressure in a wellbore, which implies knowing and being able to accurately model the drilling fluid properties. These properties are difficult to measure under HPHT conditions, our research will aim to fill this gap in the case of water based muds by investigating the fluid loss from this mud under these conditions

## 3. OBJECTIVES

This is an experimental study of the impact of having HPHT reservoirs on the drilling fluids loss. Three different cases will be studied at different conditions.

An API Filtration and fluid loss equipmentwill be used in order to test the mud capacity to withhold its filtrates under the HTHP as well as from static to dynamic condition.

Experiment #1 consist of low pressure, low temperature conditions. The second one is at HTHP using a static model. Finally, the last experiment will also be at HTHP conditions but using a dynamic model. Fluid loss models (beyond the conventionals such as viscosity, gel strength, yield point and so forth) will then be compiled.

The Polysal HT, a modified starch that serve as the fluid loss control additivealong with Bentonite and Polypac UL will generally do the job.

## 4. METHODOLOGY

The investigation of fluid loss properties from water based muds under three tests specifically linked the conditions of drilling fluid under High Pressure-High Temperature operations.

The effect of the chemicals used are fundamental to sustain the desired properties, however, the external settings can severely affect the preferred assets.

The first will be a conventional viscometer and filter press apparatus. The second an HPHT filter press, and the third a higher technology HPHT testing machine that is rarely available and expensive to purchase and maintain.

Certain parameters were set to acquire the optimum stability of the mud before subjecting it to an enormous amount of peripheral state.

### 4.1 Experimental Materials and Formulation

This research proposal will investigate the effect of High Temperature – High Pressure conditions on the required properties on total fluid loss, cake formation thickness, spurt loss, and quality of the plugging.

The drilling fluids to be tested will be water-based systems that will be prepared in the lab based on industrial standards. Different additives and polymers will be used in the design fluid systems.

Several devices that are available in our lab will be utilized in this project:

(a) Low Temperature and Low Pressure Filter Press (API Fluid Loss), Static.

The API filter press unit (Figure 4) helps to evaluate the cake building properties of the drilling fluids under a pressure 100 psi at room temperature in 30 minutes filtration. A simultaneous bleeding from this unit can be regarded as a standard and will serve as the basis for comparisons.

This set-up only requires an elevated pressure at ambient temperature that are considered as low on both condition at static stage of operation.

(b) High Temperature and High Pressure Filter Press, Static.

This equipment (Figure 5) is similar to the normal API filter press except that it tests the fluid loss under elevated temperatures and pressure to simulate downhole condition.

**Figure 4**
**API Filter Press**

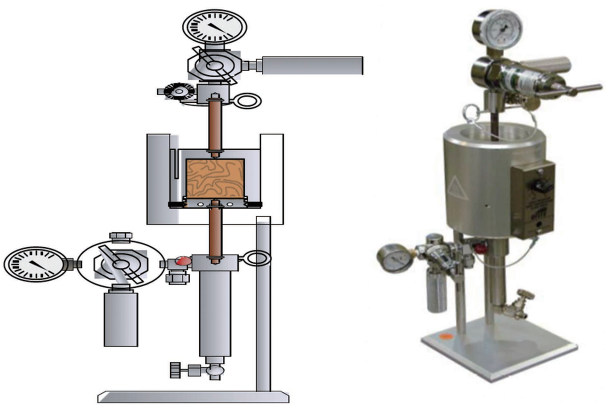

**Figure 5**
**HPHT Filter Press**

(c) Permeability Plugging Tester, Dynamic.

As a modified standard of HTHP filter design, this equipment (Figure 6) is often used in environmental laboratories.

This equipment is very useful in fluid loss filtration operation by plugging without the interference of particles settling on the ceramic disc instead of filter paper during the heat up process.

A dynamic filtration mechanism which is supported with piston and hydraulic oil. The expansion of mud sample as it is subjected to the high pressure and high temperature conditions passes through the filtering medium called ceramic disc which has a definite size (microns) and number of mesh.

These are the drilling fluid chemicals which are widely used in operation that acquire the properties of good quality mud (water based mud).

**Table 1**
**Drilling Fluids Products for WBM**

| Chemical name | Usage |
|---|---|
| Caustic soda | pH control |
| Soda ash | Hardness control, Ca++ |
| Sodium chloride | Initial weighing agent |
| Flowzan | Viscosifier |
| Polysal HT | Viscosifier and fluid loss control |
| Polypac UL | Fluid loss control |
| Bentonite | Viscosifier and fluid loss control |
| Calcium carbonate | Weighing agent, low |
| Barite | Weighing agent |

**Table 2**
**Fluid Loss Experimental Matrix**

| Products | Matrix of fluid loss test | | |
|---|---|---|---|
| | Mud | | |
| | 1 | 2 | 3 |
| Drill water | 264 | 262.2 | 260.4 |
| Soda ash | 0.25 | 0.25 | 0.25 |
| Caustic soda | 0.3 | 0.3 | 0.3 |
| NaCl | 108 | 108 | 108 |
| Flowazn | 1.25 | 1.25 | 1.25 |
| Polysal HT | 2.5 | 5 | 7.5 |
| $CaCO_3$, Med | 25 | 25 | 25 |
| Barite | 122.5 | 122.5 | 122.5 |
| **Test requirements** | **Polysal concentration, ppb** | | |
| | **2.5** | **5** | **7.5** |
| | **3.5" Filter paper (Ofite)** | | |
| API, 30 mins | | | |
| **HTHP, 30 mins 230 °F/500 psi** | **2.5" Filter paper (Ofite)** | | |
| Spurt, 30" | | | |
| Total (2×30') | | | |

| **PPT/HTHP, 30 mins 230 °F/1,200 psi** | **Ceramic disc filtering Medium, (Ofite)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 20 um | 50 um | 120 um | 20 um | 50 um | 120 um | 20 um | 50 um | 120 um |
| Spurt, 30" | | | | | | | | | |
| 1' | | | | | | | | | |
| 5' | | | | | | | | | |
| 7.5' | | | | | | | | | |
| 15' | | | | | | | | | |
| 30' | | | | | | | | | |
| Total (2×30') | | | | | | | | | |

 

**Figure 6**
**Permeability Plugging Tester**

### 4.2 Polysal HT

A modified starch which is especially used in controlling the fluid loss of drilling based material. The most commonly used types of muds are the water-based mud and the oil-based mud. Oil-based mud can uphold its' rheological properties at HTHP conditions and that's why it's preferred over water-based mud. However, due to some cost and environmental regulations, water-based mud is favored in thiscase[14]. Therefore, the additive used in this research was the Poly-sal HT. It's a high-quality filtration additive for all water-based muds. It was mainly used to help control filtration and rheology stability in the drilling fluid. This is highly effective in high salinity and high hardness brines such as KCl and NaCl. Also, it minimizes filtration damage to production zones. It has the capacity to carry cuttings adequate for good hole cleaning. It's known to be economical and effective in saturated-salt in brine systems which is evaluated in this research.

From an economical aspect, we can see that using this additive is not only economical but also highly affective. These can also be proven by the results obtained.

## 5. RESULTS AND DISCUSSION

**Table 3**
**Low Pressure-Low Temperature Fluid Loss Test Result, 100 psi/30 minutes**

| | Polysal HT concentration, ppb | | |
|---|---|---|---|
| API, 100 psi | 2.5 | 5 | 7.5 |
| Time, min | Filtrate volume, cc | | |
| 30 | 6.8 | 4.8 | 3.5 |

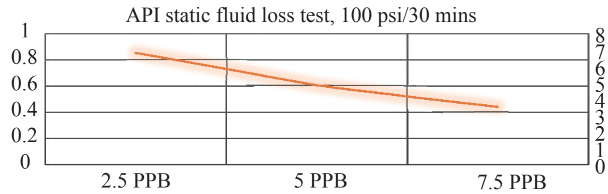


**Figure 7**
**Low Pressure-Low Temperature Static Fluid Loss Test Graphical Result, 100 psi / 30 minutes**

**Table 4**
**High Pressure-High Temperature Static Fluid Loss Test Result, Differential Pressure: 500 psi, 230°F/30 minutes**

| HTHP, 500 psi, 250 °F | Polysal HT Concentration, ppb | | |
|---|---|---|---|
| | 2.5 | 5 | 7.5 |
| Time, min | Filtrate Volume, cc | | |
| 0.5 | 3.4 | 4.3 | 5.6 |
| 1 | 4 | 5.1 | 6.2 |
| 5 | 5.1 | 6.1 | 6.9 |
| 7.5 | 5.8 | 6.5 | 7.6 |
| 15 | 7.2 | 9.2 | 11.2 |
| 30 | 15.1 | 18.2 | 23.8 |
| Total | 30.2 | 36.4 | 47.6 |

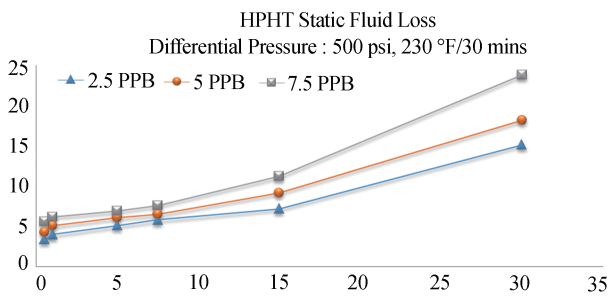


**Figure 8**
**High Pressure-High Temperature Static Fluid Loss Test Graphical Result, Differential Pressure: 500 psi, 230 °F/30 mins**

**Table 5**
**High Pressure-High Temperature Dynamic(PPT)Fluid Loss Test Result and Images, Differential Pressure: 1,200 psi, 230 °F/30 minutes**

| Dynamic | Polysal HT concentration, ppb | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2.5 | | | 5 | | | 7.5 | | |
| Filter mesh, microns | 20 | 50 | 120 | 20 | 50 | 120 | 20 | 50 | 120 |
| Time, min | Filtrate volume, ml | | | Filtrate volume, ml | | | Filtrate volume, ml | | |
| 0.5 | 3 | 4.6 | 10 | 2.4 | 3.6 | 6.3 | 1.6 | 2.8 | 5.8 |
| 1 | 3.6 | 6 | 12.4 | 3.2 | 5.2 | 10.8 | 2.4 | 4 | 7.2 |
| 5 | 6.6 | 10.4 | 16.4 | 5.4 | 8.2 | 15.9 | 4 | 7.8 | 10.2 |
| 7.5 | 7.8 | 14.6 | 28.1 | 6.6 | 12.4 | 20 | 4.6 | 9.2 | 12.5 |
| 15 | 11.9 | 20.4 | 38.2 | 10.2 | 17.1 | 30.4 | 8.2 | 14.2 | 26.2 |
| 30 | 20.7 | 34.1 | 52.6 | 18.1 | 26.4 | 46.8 | 16.8 | 20.2 | 34.8 |
| Total | 41.4 | 68.2 | 103.2 | 36.2 | 52.8 | 93.6 | 33.6 | 40.4 | 67.6 |
| Ceramic pictures ( After test ) |  |  |  |  |  |  |  |  |  |

In the performed experiments in this research, three main tests were carried out to study the permeability and porosity changes that take place when water based mud is circulated at HTHP conditions: API low temperature low pressure filtration test, HTHP filtration test, and PPT filtration test. The operating conditions and the details of the experiments will be explained in the appendix. Note that Polysal HT (additive used for fluid loss control was used at different concentrations in the mentioned tests.

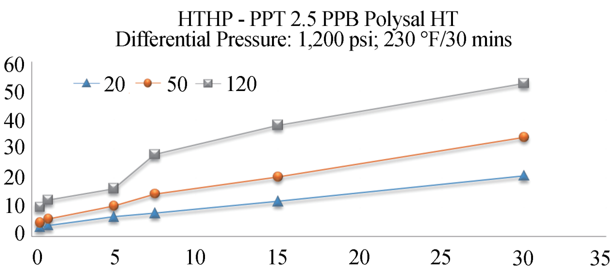


**Figure 9**
**HPHT- Dynamic (PPT) Fluid Loss Test for 2.5 ppb Polysal HT Graphical Result, Differential Pressure: 1,200 psi, 230 °F/30 minutes**

Figures 9,10 and 11 represent the dynamic filtration test results that was performed at a pressure of 1,200 psi and a temperature of 230 °F. Different ceramic discs mesh were used as part of the PPT filtration test where the sizes varied between 20 microns to 120 microns. The tests varied also in the concentration of the used fluid loss additive.

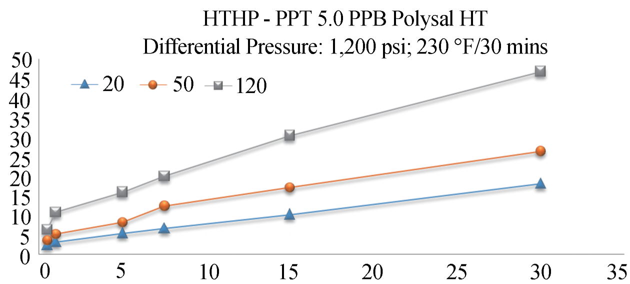


**Figure 10**
**HPHT- Dynamic (PPT) Fluid Loss Test for 5.0 ppb Polysal HT Graphical Result, Differential Pressure: 1,200 psi, 230 °F/30 minutes**

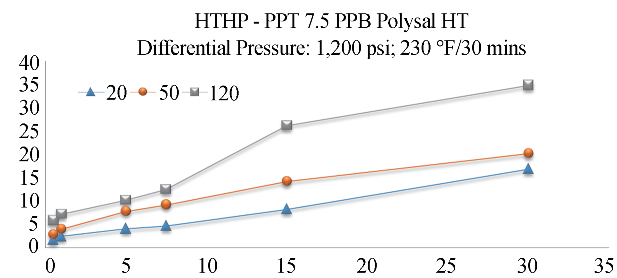


**Figure 11**
**HPHT- Dynamic (PP) Fluid Loss Test for 7.5 ppb Polysal HT Graphical Result, Differential Pressure: 1,200 psi, 230 °F/30 minutes**

 

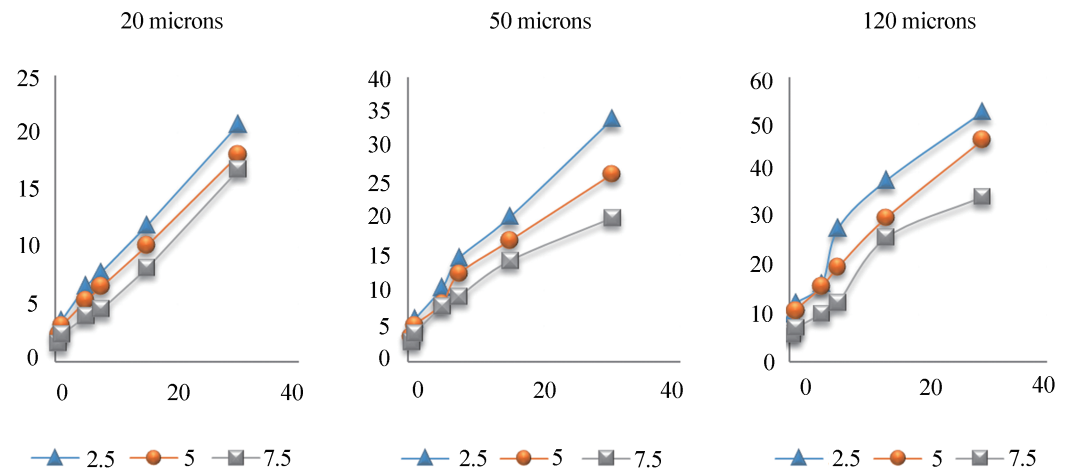


**Figure 12**
**Dynamic Filtration Output Using Ceramic as a Filtering Medium at Different Micron Sizes**

As the results show, permeability is proportional to the flow rate per unit cross sectional area. This can be translated into pore throats in subsurface rock. Therefore, the greater the pore size through which the fluid is going to flow at a constant flow rate, the higher the capacity of the fluid to flow and therefore its permeability.

It can be deduced from these graphs that as the concentration of the Polysal HT increased, less and less filtrate was lost into the formations.

Same results were obtained from the low temperature low pressure API test where smaller filtrate volume was obtained as the concentration of the used Polysal HT increased.

Thus, water based mud under HTHP conditions undergoes many changes in its main parameters like spurt loss, fluid loss, and filter cake thickness. Fluid loss control additives are therefore required in order to handle these changes and maintain the required properties of the used drilling fluid where Polysal HT was the required additive in this case. Dynamic as well as static API filtration tests should be performed before choosing the best additive.

A numerous trials has been set up to test the fluid loss effectivity of the mud used in drilling but a very limited resources targeted the HTHP course due to its collaborative safety and productivity concerns , they call it "Drilling in the Dark" (a time to time check of properties ).

## CONCLUSION AND RECOMMENDATION

(a) Polysal HT is effective in reducing the fluid loss of water based mud for both static and dynamic tests under High-Pressure High Temperature conditions.
(b) The concentration of the fluid loss additives is not linearly related to the amount of fluid discharge as a function of time.
(c) Propertiesof the porous media greatly affect the filtering mechanism and therefore the liquid discharge as a function of pressure and temperature.
(d) The fluid loss behavior of the mud and the characteristics of the filter cake produced are the basic factors that need to be consideredwhen determining the treatment procedures for the alkalinity of the mud, its oil and water content, and the emulsion type and content of the mud. Certain elements such as amount of drill solids which interact in the formation also need to be considered since they are likewise affected by temperature and pressure.

## NOMENCLATURE

$q$: Fluid flow rate/total discharge, cc/min
$k$: Permeability, md
$A$: Filtration area, $cm^2$
$\mu$: Fluid viscosity, cP
$dp/dx$: Pressure drop along the length of the core, psi
$\Delta p$: Pressure drop along the r direction, psi
$V$: Filtrate volume
$\alpha_c$: Filter cake resistivity
$C$: Suspension concentration
$\rho$: Fluid density
$R_m$: Filter medium resistance

## REFERENCES

[1] Shadravan, A., Narvaez, G., Alegria, A., Carman, P., Perez, C., & Erger, R. (2015, March). *Engineering the mud-spacer-cement rheological hierarchy improves wellbore integrity*. Paper Presented at the SPE E&P Health, Safety, Security and Environmental Conference-Americas, Denver, Colorado.

[2] Krueger, R. F. (1963). Evaluation of drilling-fluid filter-loss additives under dynamic conditions. *Journal of Petroleum Technology*, *15*(1), 90-98.

[3] Roodhart, L. P. (1985). Fracturing fluids: Fluid-loss measurements under dynamic conditions. *Society of Petroleum Engineers Journal*, *25*(5), 629-636.

[4] Shadravan, A., & Amani, M. (2012). HPHT 101 - what petroleum engineers and geoscientists should know about high pressure high temperature wells environment. *Energy Science and Technology*, *4*(2), 36-60.

[5] Lee, J., Shadravan, A., & Young, S. (2012). *Rheological properties of invert emulsion drilling fluid under extreme HPHT conditions*. Paper presented at the IADC/SPE Drilling Conference and Exhibition, San Diego, California.

[6] Amani, M., Al-Jubouri, M., & Shadravan, A. (2012). Comparative study of using oil-based mud versus water-based mud in HPHT fields. *Advances in Petroleum Exploration and Development*, *4*(2), 18-27.

[7] Shadravan, A., Nabaei, M., & Amani, M. (2009, October). *Dealing with the challenges of UBD implementation in southern Iranian oilfields*. Paper presented at the Middle East Drilling Technology Conference & Exhibition, Manama, Bahrain.

[8] Bland, R. G., Mullen, G. A., Gonzalez, Y. N., Harvey, F. E., & Pless, M. L. (2006, November). *HPHT drilling fluid challenges*. Paper presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Bangkok, Thailand.

[9] Elkatatny, S., & Nasr-El-Din, H. A. (2012, March). *Properties of filter cake of water-based drilling fluid under dynamic conditions using computer tomography*. Paper presented at the IADC/SPE Drilling Conference and Exhibition, San Diego, California.

[10] Crespo, F., Ahmed, R., Enfis, M., Saasen, A., & Amani, M. (2012, December). Surge and swab pressure predictions for yield-power-law drilling fluids. *SPE Drilling & Completion Journal*, *27*(4), 574-585.

[11] Chelton, H. M. (1967, January). *Darcy's law applied to drilling fluid filtration*. Paper presented at the SPE Drilling and Rock Mechanics Conference, Austin, Texas.

[12] Schlumberger. (2014). *Static filtration*. USA: Schlumberger Oilfield Glossary.

[13] Ibeh, C., Schubert, J., & Teodoriu, C. (2008). *Investigation on the effect of ultra high pressure and temperature on the rheological properties of oil-based drilling fluids*. Presented at AADE Conference and Exhibition, Houston, Texas.

[14] Elward-Berry, J., & Darby, J. B. (1997, September). Rheologically Stable, Nontoxic, High-Temperature Water-Base Drilling Fluid. *SPE Drilling & Completion Journal*, *12*(3), 158-162.

 