AADE-10-DF-HO-42

Maximize Drilling Time by Minimizing Circulation Losses

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Abstract

An improved product has been designed to control lost circulation. The product possesses high strength over a broad range of densities with a variety of fluids. This paper discusses the results of several factors considered to evaluate its field performance. The new high-fluid-loss, high-strength (HFHS) lost circulation treatment is compared to other technologies that are currently offered in the field to mitigate partial and severe lost circulation.

The HFHS lost circulation solution is a dry single-sack product with an increased strength that resists mechanical damage and is compatible with fresh water, sea water and non-aqueous fluids (NAF). The operating density range is between 7 and 16 lb/gal and is stable up to 350°F (177°C). An HFHS pill has been successfully pumped through bit jet sizes as small as 10/32 in. as well as pumped through a jar, mud motor and MWD tool. The new HFHS lost circulation treatment was specifically designed to possess these advantages in order to maximize rig efficiency in most wellbore pressure sensitive zones where significant drilling fluid losses are prevalent.

Introduction

Lost circulation is responsible for some of the most difficult and costly challenges operators encounter during the drilling process. Although there are several practices traditionally used to mitigate lost circulation, to date there are very few methods that are routinely successful when treating severe losses (≥100 bbl/hr). Historically, some of the more commonly used methods have included cross-linked polymer, gunk/cement and particulate squeeze treatments, with work on the latter forming the prime focus of this study.

Using specially developed laboratory techniques, a new product was designed and compared to a number of conventional squeeze treatments commonly used in the field to mitigate severe lost circulation. The high-fluid-loss, high-strength (HFHS) lost circulation treatment is designed to defluidize rapidly on demand, leaving behind a compacted matrix of solids that is strong enough to withstand the physical stresses associated with drilling. The HFHS lost circulation treatment is a one-sack product comprised of specially sized and selected solids. When mixed with either aqueous or non-aqueous fluid (NAF), the pill is subsequently pumped and squeezed downhole. Unlike many of the systems that are currently available, an HFHS lost circulation treatment can be weighted-up with barite while still retaining high strength.

This paper discusses the importance of strength with regard to HFHS lost circulation treatments and describes the evaluation techniques used. Laboratory data are presented comparing a number of particulate squeeze treatments, in addition to some yard trial results of the newly developed HFHS lost circulation solution.

Circulation Losses

To minimize fluid losses when drilling, a filter cake is ideally and evenly deposited over the face of the formation allowing the wellbore to support increased pressures. However, circulation losses can occur in either a single point or over a broad location. A filter cake cannot properly form in severely fractured formations, nor highly permeable, low pressure or depleted zones. In turn, the absence of a sufficient filter cake may lead to partial or whole mud loss into the formation. Such lost circulation events can be classified as partial losses (10-100 bbl/hr) or severe losses (≥100 bbl/hr). In addition to the expense of losing valuable drilling fluid, other costly drilling issues that are attributed to lost circulation are non-productive time, collapse of the wellbore, stuck pipe, blowouts and even well abandonment in extreme cases.

An HFHS pill is designed to lower drilling fluid losses by placing a calculated concentration of specially designed solids at the Lost Circulation Zone (LCZ). The single-sack HFHS treatment is mixed at the rig site in water, seawater, brine or NAF. After being pumped downhole, the pill is effectively spotted and squeezed into the thief zone. During the squeeze operation, the liquid carrier of the HFHS pill is defluidized into the formation. Upon defluidizing, the solids seal the loss zone forming a strong and durable plug. As the filtrate is squeezed into the formation and the consolidated matrix of solids increases in thickness, so does the resistance to differential pressures and mechanical stress. The unique chemical and material composition of the HFHS lost circulation treatment creates a strong matrix that provides excellent sealing capabilities for a wide variety of lost circulation scenarios.

The remainder of this paper will review the newly developed HFHS lost circulation solution and compare it to other technologies that are currently offered in the field for similar applications. The basis for product comparison will be the survival of the product under high differential pressure conditions and a shear strength evaluation encompassing a variety of conditions.

Increasing the Fracture Gradient

Downhole formations exhibit various levels of permeability and porosity. While drilling, one of the many causes of severe mud losses may be due to highly permeable or severely fractured formations that do not allow for the deposition of an acceptable mud filter cake. In this circumstance, it is extremely difficult for the driller to maintain circulation, because the wellbore pressure will exceed the pore pressure and whole mud is lost. One possible solution for this lost circulation event would be to spot an HFHS pill to form a seal along the interface of the formation. After HFHS pill defluidization, the strong, impermeable plug will provide a sturdy foundation for a mud filter cake which can withstand high differential pressures.

In order to test this application, a Permeability Plugging Apparatus (PPA) was used to simulate and measure mud loss and HFHS pill defluidization across a 190-µm aloxite disc at room temperature. The water- and oil-based drilling fluid formulations that were used for this testing can be found in Table 1 and Table 2. Neither the water-based drilling fluid (WBM) nor oil-based drilling fluid (OBM) formed a filter cake on the 190-µm aloxite disk at the low differential pressure of ~50 lb/in.2. This simulated whole mud lost to a highly permeable formation, whereas the HFHS pill defluidized under the same low differential pressure conditions until a rigid plug of solids was formed on the disks (Fig. 1a & Fig. 1b).

After the HFHS pill formed a seal on the disk, the PPA was disassembled and base mud was poured behind the plug (Fig. 3a). Using an ISCO 1000 Model D Syringe Pump, the newly formed seal was tested for failure under increasing, step-wise increments of differential pressure over time. The HFHS treatment was able to withstand differential pressures up to at least 1,500 psi, which was the upper pressure limit of the instrument (Fig. 2a & Fig. 2b). The HFHS matrix decreased the permeability and porosity of the formation interface where the mud was initially lost. The decrease in pore space volume and fluid conductivity provided a compatible support for the mud to form an impermeable filter cake (Fig. 3b).

The implications of a strong seal along the interface of a highly permeable formation can be considered with the following example. The pore pressure (PP) at 10,000 ft (3,050 m) may be 4,680 psi (equivalent to a 9.0 lb/gal drilling fluid) and the fracture gradient (FG) may be 4,940 psi (equivalent to a 9.5 lb/gal drilling fluid). This presents a narrow pressure window for drilling operations. If the drilling fluid density is below 9.0 lb/gal, fluid from the formation could enter the wellbore and possibly cause a collapsed wellbore or even blowout. On the other hand, having a drilling fluid with a density above 9.5 lb/gal could fracture the formation, inducing lost circulation. This situation is applied to the standard equation to calculate bottomhole pressure (BHP) at true vertical depth (TVD):

$$\text{BHP} = \text{MW} \times 0.052 \times \text{TVD} \qquad \text{Eq. 1}$$
$$\text{PP} = 9.0 \times 0.052 \times 10{,}000 = 4{,}680 \text{ psi} \qquad \text{Eq. 2}$$
$$\text{FG} = 9.5 \times 0.052 \times 10{,}000 = 4{,}940 \text{ psi} \qquad \text{Eq. 3}$$

Under these drilling circumstances, there exists a small operating window of only 260 psi (4,940 psi – 4,680 psi) in which the density of the fluid must be maintained to prevent a collapsed hole or formation fracture. A proposed solution would be to spot the HFHS pill with the intent to increase the fracture gradient of the formation.

The HFHS lost circulation treatment was tested to withstand a differential pressure of at least 1,500 psi. Therefore, in this example, the use of an HFHS treatment could potentially increase the fracture gradient in the local region of the wellbore to 6,440 psi (4,940 psi + 1,500 psi) under the right conditions. Furthermore, Eq. 1 can be used to calculate the allowable mud weight from this increased fracture gradient:

$$6440 = \text{MW} \times 0.052 \times 10{,}000 \qquad \text{Eq. 4}$$
$$\text{MW} \cong 12.4 \text{ lb/gal} \qquad \text{Eq. 5}$$

The HFHS pill increases the allowable mud weight of the drilling fluid from 9.5 lb/gal to about 12.4 lb/gal. This provides a wider pressure drilling window and allows reasonable room for Equivalent Circulation Density (ECD) without fracturing the formation or permitting fluid influxes or hole collapse. In this scenario, the use of the HFHS lost circulation treatment would enable the operator to continue drilling at a heavier mud weight. Potentially, this may increase the depth at which the next casing string is to be placed, and could also possibly lead to the access of deeper targets. [Obviously, this example is for illustration purposes, only. In a real-life situation, greater planning would be required, in particular with regard to formation characteristics and squeeze pressures.]

Density

The drilling window defines the range of hydraulic pressures required to maintain wellbore integrity while avoiding fracturing or collapse of the hole (Growcock et al. 2009). Maintaining this balance of downhole pressures can be achieved by adjusting the density of the drilling fluid. Likewise, the density of an HFHS treatment could be tailored to match the density of the drilling fluid being used at the location of the LCZ. An HFHS pill can be mixed and pumped within a density ranging from unweighted to 16 lb/gal. This wide selection of applicable densities for the one-sack HFHS product allows for its use in numerous problematic zones, including depleted/low pressure zones, as well as extended reach wells.

Fluid Compatibility

The HFHS pill can be mixed in any base fluid – water, brine, synthetic or diesel oil. The selection of the base media for a drilling fluid often depends upon the reactivity of the formation(s) being drilled and other specialized functions such as wellbore cleaning, providing shale stability and coefficient of friction, etc. In fact, different types of fluids are frequently used at different drilling depths. Therefore, the HFHS pill was designed to be compatible with as many different types of base fluids as possible. The compatibility with both aqueous and non-aqueous liquids provides for the HFHS treatment to be used in virtually any severe lost circulation event.

Product Testing

Conventional laboratory methods for evaluating lost circulation materials often entail measuring fluid loss as a means of qualifying sealing ability. The levels of complexity for these procedures vary. The test methods range from using simple, low-pressure, API fluid loss tests that use filter paper, to more sophisticated tests involving slots, ceramic discs or natural cores. In some cases, specialized instruments that simulate fractures in both shale and porous substrates have been utilized to value the worth of a particular lost circulation material (Sanders et al. 2008).

Many of these standard techniques are well established and accepted throughout the drilling industry. However, they are not necessarily suitable for evaluating all lost circulation materials, nor their wide range of properties. Squeeze pills, such as HFHS lost circulation treatment, which rely on a defluidizing or dehydration element to function, are included in this category.

In order to compare and evaluate the performance of defluidizing systems, a new measurement was needed: one that could supplement results from conventional tests, assess defluidizing ability and quantify each system by measuring its strength.

The Importance of Shear Strength

Prior to drilling, stable compression stresses exist within the undrilled formation. These stresses, as illustrated in Fig. 4, can be resolved into a vertical or overburden axial stress (σ_z), and two horizontal stresses – maximum, σ_H and minimum, σ_h (Al-Awad 1996). In order to stabilize these forces during drilling operations, drilling fluids function to replace the initial support supplied by the rock (Bruce 1999). Therefore, in the event of a severe LCZ, when the drilling fluid can be partially or totally lost to the formation, the spotted pill must be able to withstand the rock stresses in the vicinity of the wellbore. These forces are redistributed by the hydraulic pressure of the mud (σ_r), the axial stress of the formation (σ_Z), as well as the shear stresses ($\tau_{\theta Z}$) within the sealed zone (Al-Awad 1996). Additionally, mechanical shearing is present at the interface between the seal of the loss zone and the wellbore.

Therefore, it is hypothesized that shear strength, not compressive strength, should be the mechanical property used to compare the strength of severe lost circulation solutions.

Shear strength is defined as “the internal resistance of a material to shear stress” (Allaby 1999). Shear stress is “the stress which acts parallel to a plane on which a force has been applied” (Allaby 1999). Therefore, after a squeeze pill is defluidized, its shear strength indicates its ability to internally resist stresses from multiple directions, including hydraulic pressures from the wellbore, as well as the simultaneous axial stresses from the formation. Furthermore, shear strength indicates the interstitial cohesive forces that exist within the lost circulation material. The ability to form a rigid, cohesive structure within a fracture, LCZ or unconsolidated formation is particularly important.

A modified “Push-Out Test Method,” based upon a design by BP – Sunbury, was used to measure the shear strength of various severe lost circulation solutions currently found in the industry. In this test, a defluidized filter cake of pre-determined thickness is first formed onto a 20-μm aloxite disc at 400 psi and pressure maintained for a set period of time at room temperature. Subsequently, the push-out device is utilized, whereby hydraulic piston pressure is applied onto the filter cake to the point where maximum shear strength at failure of the cake is attained. In this assessment, the products were evaluated for their performance when mixed in various base fluids (aqueous- and NAF) and different mud densities (varying from unweighted to 16 lb/gal).

In both aqueous- and NAF-based pills, the shear strength of the unweighted HFHS lost circulation treatment was far higher than all of the other products tested for comparison (Fig. 5a & Fig 5b). However, the shear strength values for all of the squeeze pills decreased significantly when using increasing amounts of the solid weighting agent (API-grade barite). However, the HFHS treatment retained the highest degree of strength of all products assessed at all mud densities tested as both aqueous- and NAF-based pills (Fig. 6a and Fig. 6b).

Pumpability

Two sets of yard trials were performed to minimize concerns often associated with pumping a lost circulation material through various jet nozzles and a bottomhole assembly (BHA). The first yard trial was a jet nozzle test, which was performed in a closed-loop system where 3 x 24/32-in., 3 x 16/32-in., and 3 x 10/32-in. nozzles were each placed in their own respective jet boxes. The HFHS pill was pumped at estimated rates of 100, 200, and 400 gal/min through each jet size. The yard trial was successful, as no plugging occurred in the nozzles, charger pump or triplex pumps (Fig. 7a).

The purpose of the second yard trial was to mix and pump an HFHS pill through a BHA. The BHA was composed of a jar, mud motor, MWD tool and a 6¾-in. bit with 3 x 14/32-in. nozzles. The HFHS pill, which had a concentration of 40 lb/bbl, was successfully mixed through a hopper and passed through the BHA at 120 and 240 gal/min without plugging (Fig. 7b).

Discussion

A unique product has been designed to mitigate severe lost circulation. This product has been compared to a number of squeeze treatments that are currently used throughout the drilling industry for similar applications. Using a new test to measure shear strength, in addition to several conventional methods, HFHS lost circulation solution was shown to perform extremely well in comparison to all other products tested. An HFHS treatment exhibits superior resistance to shear over a wide density range, and also when mixed in different base fluids. This product was successfully yard trialed, during which time it was rigorously evaluated for its potential use in the field.

With general concerns over rig storage space, dry single-sack products, such as HFHS lost circulation solution, reduce transportation and storage costs and simplify mixing. Other potential benefits of the new lost circulation solution include: an increased strength that resists mechanical damage; improved wellbore cohesive strength; compatibility with fresh water, sea water, and non-aqueous fluids; compatibility with the surrounding drilling fluid and formation; a wide operating density range of at least 7 to 16 lb/gal; thermally stable up to 350°F (~177°C); and can be premixed in advance with no activator or retarder needed. The new HFHS technology was specifically designed to possess these advantages in order to maximize rig efficiency in most wellbore pressure sensitive zones where significant mud losses are prevalent.

Acknowledgments

The authors would like to thank the management of M-I SWACO for their permission and support in publishing this paper. Special thanks are also extended to Dr. Mark Aston of BP – Sunbury, and to Dr. Jim Friedheim and Steve Young of M-I SWACO for their valuable input.

Nomenclature

σ_h = *Horizontal Stress – minimum*
σ_H = *Horizontal Stress – maximum*
σ_r = *Hydraulic Pressure of Mud*
σ_Z = *Vertical, Axial Stress – From Formation*
$\tau_{\vartheta Z}$ = *Shear Stress within LCZ*
BHA = *Bottomhole Assembly*
BHP = *Bottomhole Pressure*
FG = *Fracture Gradient*
HFHS = *High Fluid Loss High Strength*
LCZ = *Lost Circulation Zone*
MW = *Mud Weight*
NAF = *Non Aqueous Fluid*
OBM = *Oil-Based Drilling Fluid*
PP = *Pore Pressure*
PPA = *Permeability Plugging Apparatus*
TVD = *True Vertical Depth*
WBM = *Water-Based Drilling Fluid*

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Table 1 – 10.4-lb/gal generic WBM Formulation

Component	***Concentration (lb/bbl)***
Water	294
Sodium Chloride	75
Viscosifier	1.00
Filtration Control Additive	4.00
Magnesium Oxide	1.00
Barite	62.67

Table 2 – 12-lb/gal generic OBM Formulation

Component	***Concentration (lb/bbl))***
Synthetic Oil	167
Viscosifier	3
Lime	3
Emulsifier	7
Wetting Agent	2
25% Calcium Chloride	71
Filtration Control Additive	0.5
API Standard Clay	25
Barite	225

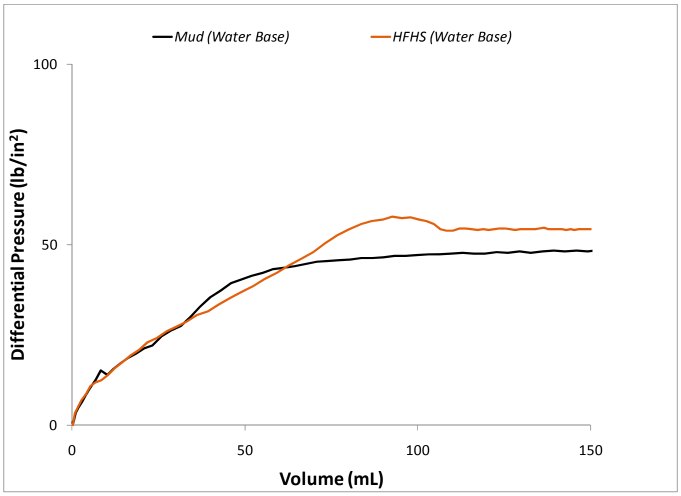

Fig. 1a – Comparison of WBM loss to defluidization of aqeuous-based HFHS pill.

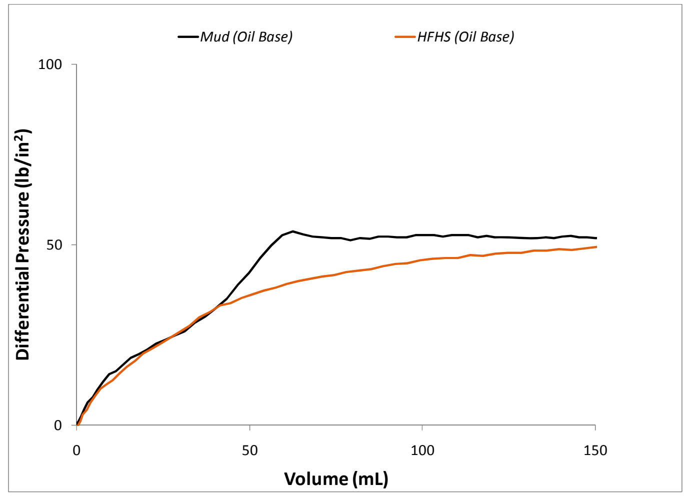

Fig. 1b – Comparison of OBM loss to defluidization of NAF-based HFHS pill.

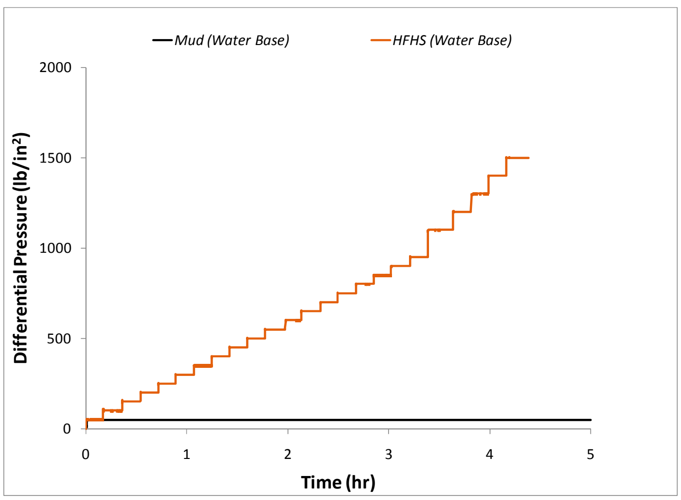

Fig. 2a – Aqueous-based HFHS pill is able to withstand at least 1,500 lb/in^2 differential pressure, whereas the WBM alone could not withstand 50 psi differential pressure.

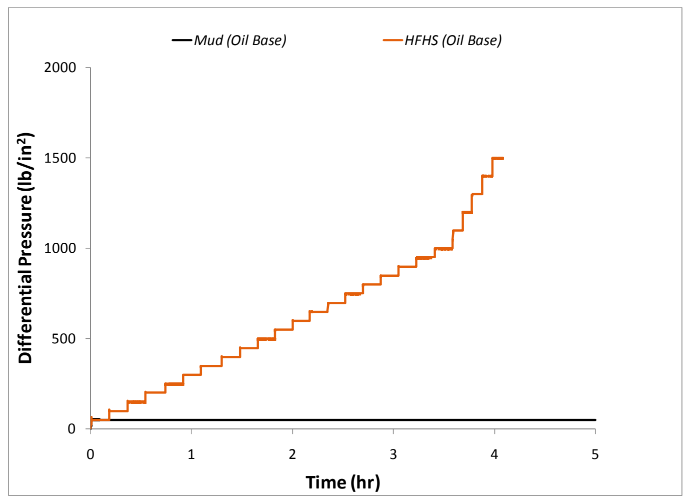

Fig. 2b – NAF-based HFHS pill is able to withstand at least 1,500 lb/in^2 differential pressure, whereas the OBM alone could not withstand 50 psi differential pressure.

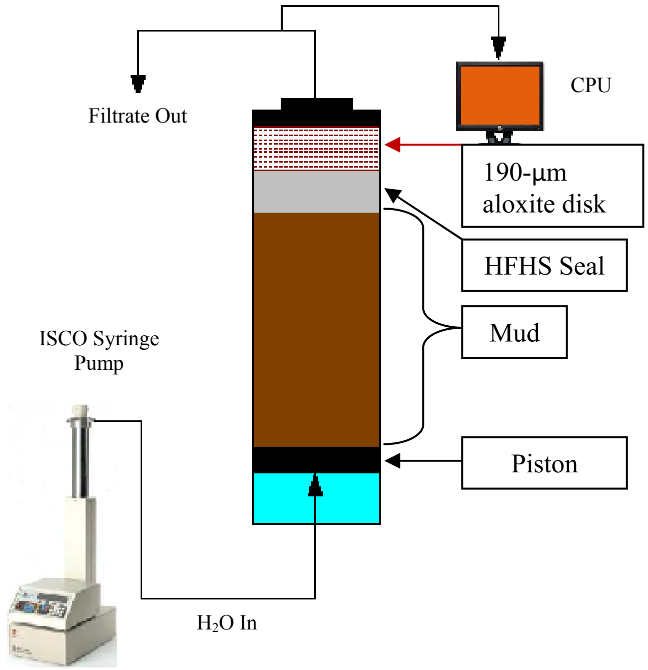

Fig. 3a – Diagram of PPA setup used to assess the maximum pressure differential that the HFHS lost circulation treatment could withstand before failure.

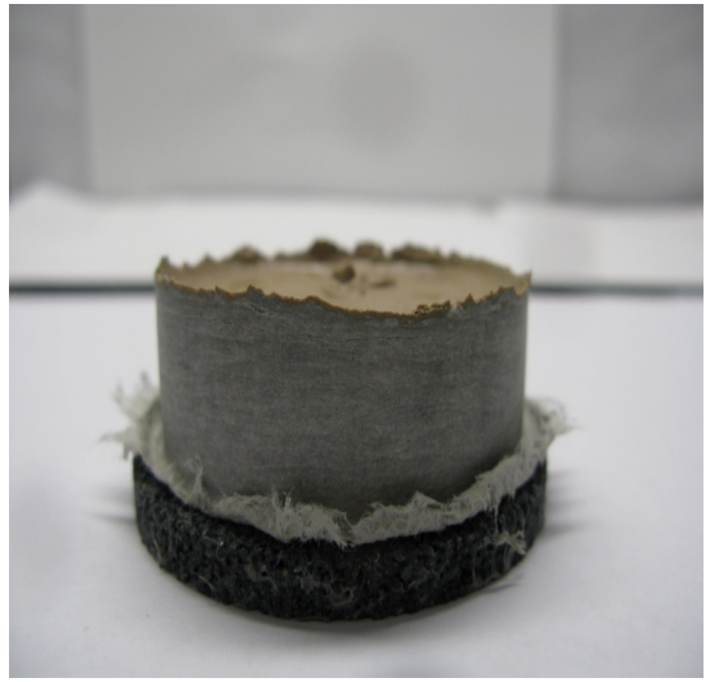

Fig. 3b – After defluidization of the HFHS pill, a seal formed on the highly permeable aloxite disk preventing the mud from being lost through the formation.

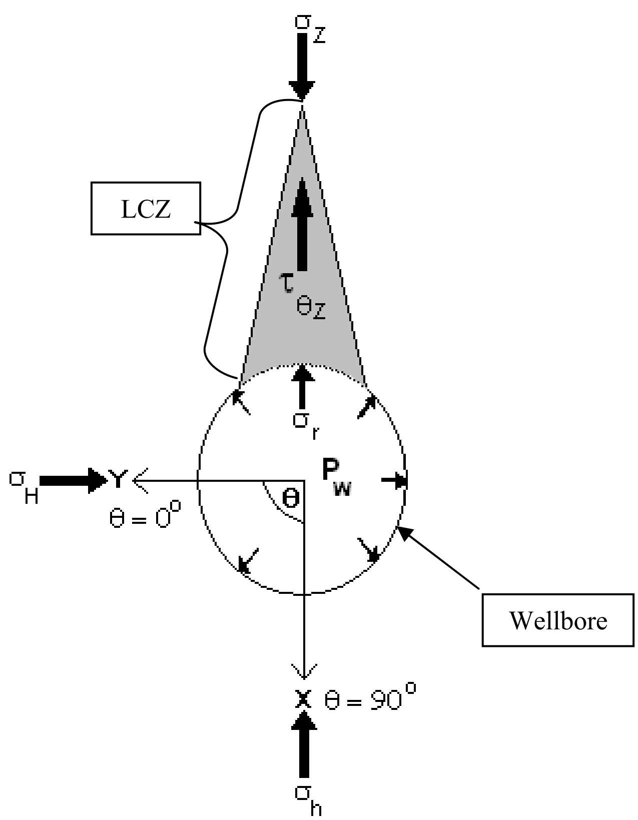

Fig. 4 – The HFHS lost circulation treatment must be able to withstand a variety of stresses, including internal and external shear stresses ($\tau_{\theta Z}$), hydraulic pressure from the drilling fluid (σ_r), and axial stress from the formation (σ_z) (Al-Awad 1996).

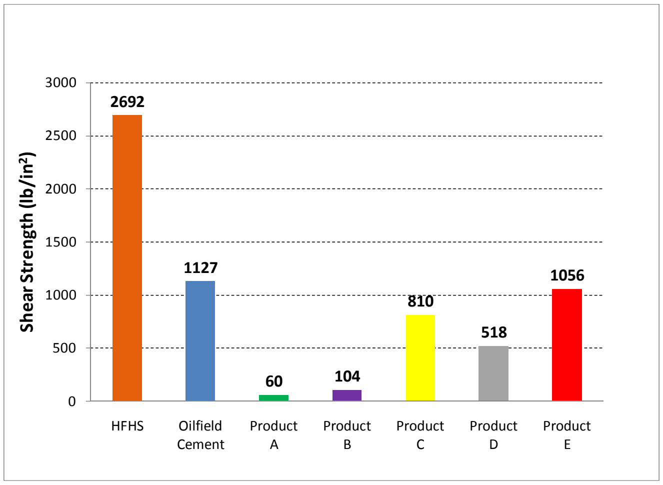

Fig. 5a – Unweighted, aqeuous-based HFHS pill has higher shear strength than all other products tested.

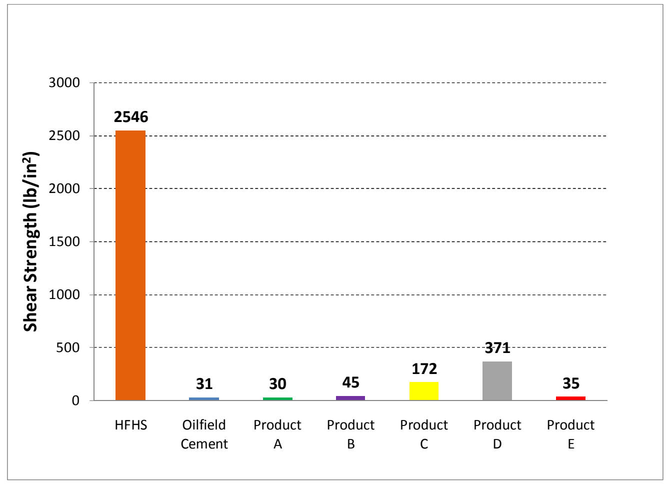

Fig. 5b –Unweighted, NAF-based HFHS pill has higher shear strength than all other products tested. This data shows that the HFHS product is compatible with NAF and maintains almost the same strength as an unweighted water-based HFHS pill, whereas other products are not compatible with NAF.

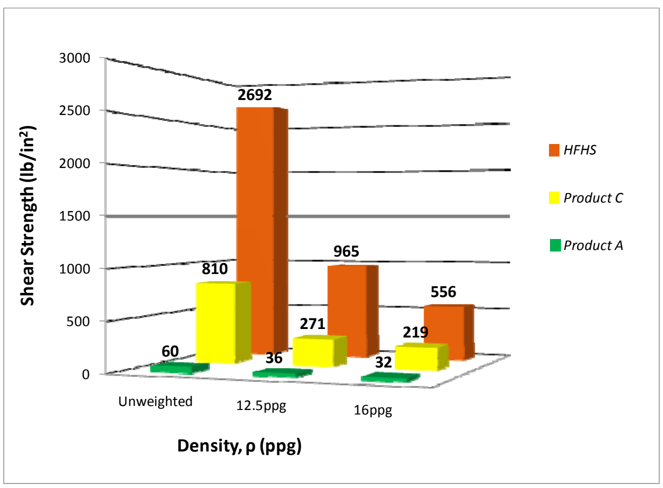

Fig. 6a – Weighted, aqueous-based HFHS pill has higher shear strength than other products tested over a range of mud weights.

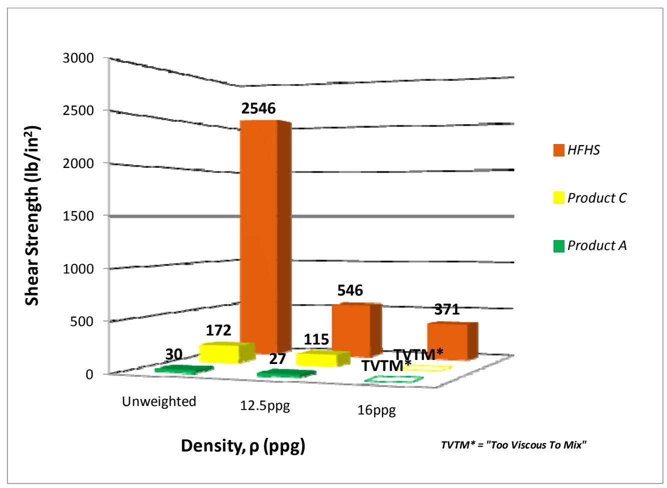

Fig. 6b – Weighted, NAF-based HFHS pill has higher shear strength than other products tested over a range of mud weights.

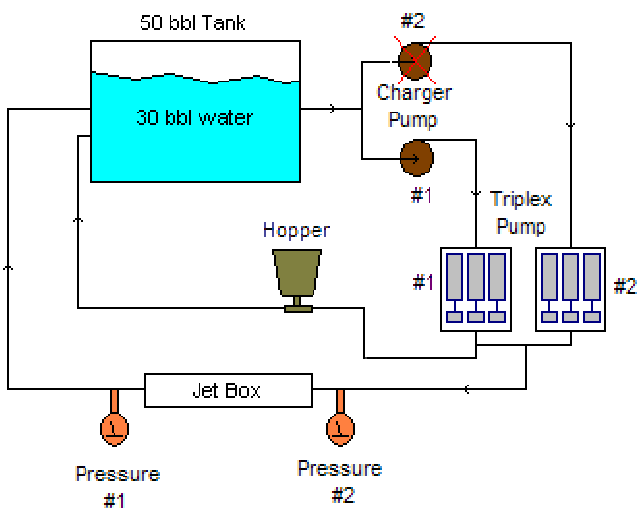

Fig. 7a – Process diagram of flow-loop used at the first yard trial of the HFHS lost circulation treatment. Thirty bbl of 40-lb/bbl HFHS pill was successfully pumped and circulated through a charger pump, triplex pump, and 3 jet boxes – each dressed with its own nozzle size – 3 x 24/32 in., 3 x 16/32 in., and 3 x 10/32 in. – without plugging.

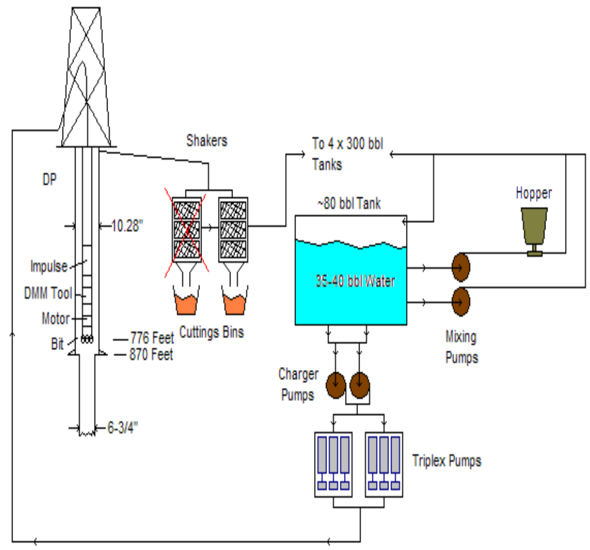

Fig. 7b – Process diagram of second yard trial of the HFHS lost circulation treatment. Thirty-five bbl of 40-lb/bbl HFHS pill was successfully mixed through a hopper and pumped through a charger pump, triplex pump, jar, mud motor, MWD tool and a 6¾-in. bit with 3 x 14/32-in. nozzles.