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Managing Circulation Losses with Synthetic Base Drilling Fluid

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ABSTRACT

Controlling circulation loss during well construction can be more than just selecting the proper type of lost circulation material (LCM). A fully engineered approach may be required. This approach incorporates borehole stability analysis, equivalent circulating density (ECD) modeling, leak-off flow-path geometry, drilling fluid and LCM material selection to help minimize effects on ECD, on-site monitoring using pressure while drilling (PWD) techniques, and timely application of LCM and treatments.

Once a decision has been made on what to use, it is necessary to decide on how much of each material to use. Basing the amount of LCM on a volume basis rather than a weight basis is advocated. This choice results in using much lower weights of fiber materials that have a low specific gravity (SG). Pretreatment with LCM prior to drilling high risk lost circulation zones is advocated, with subsequent treatments added as sweeps, rather than into the bulk drilling fluid system in the suction pit.

In many cases treatments on the rig are simplified and made more efficient by the use of one-sack combinations of lost circulation materials that are engineered for different applications, such as seepage versus severe lost circulation.

INTRODUCTION

Debate on the type of material, amount and when to add it to the active system for lost circulation is ongoing and unending. Decisions on current applications are generally influenced by positive past experiences. Representative laboratory data is expensive and difficult to obtain due to the scale of the experiments. Information obtained from Drilling Engineering Association joint industry experiments (DEA 13) done on 30"x30"x30" shale blocks at the Drilling Research Labs, Terra Tec, in the 1980's, gave insight into the problem.

Results showed prevention of lost circulation in oil base mud (OBM) required the inclusion of adequate levels of properly sized loss circulation material (LCM) in the drilling fluid itself, since the fractures were difficult to stop once propagating past the initiation stage[1,2,3,4] The theory to go with the observations is that an adequate loading of properly sized materials causes "tip screen out" immediately after the fracture is initiated, preventing further growth and propagation.

WELL CONSTRUCTION PLANNING

Borehole Stability Modeling

The use of borehole stability modeling in well planning can provide the "road map" within which the ECD must be controlled.[5,6,7]

In order to develop an adequate borehole stability model, an in-depth understanding of the physics and chemistry of the interaction between the drilling fluid and the formation is extremely important. The engineering problems of borehole instability are closely connected with bulk properties of the formation such as, strength and deformation. Other factors, like pore pressure, temperature, time in open hole, length of open hole interval, tectonics, etc., can directly impact drilling operations. Drilling a hole into a formation in equilibrium induces stress concentration in the vicinity of the borehole. A precondition for a stable well-bore while drilling is the existence of a balance between the near-well-bore stress concentration and the rock strength. In cases where the stresses considerably exceed the strength the resulting imbalance can lead to borehole destabilization.

The first stage of well-bore stability analysis consists of identifying and interpreting the problems observed in the field. Correct identification and classification of the well-bore instability at hand is of utmost importance for any additional analysis. Well-bore instability observed while drilling can be grouped into five basic types:

- washout or hole enlargement,
- tight hole or creep,
- altered, damaged or plastic zone,
- lost circulation; and
- well-bore breathing.

The first three types of instability are associated with the near well-bore region; and they are sometimes collectively referred to as near well-bore collapse. In contrast, lost circulation and well-bore breathing are attributed to mud invading the far field as a result of either hydraulically induced tensile fractures or losses occurring to permeable formations or other types of thief zones such as natural fractures and faults.

A hydraulic fracture is initiated in an intact formation, by too high a mud weight. The high mud pressure causes tensile failure. Following fracture initiation, the fracture may propagate depending on the maximum borehole pressure and the formation will take in drilling fluid resulting in lost circulation.

Mud weight predictions required to mechanically stabilize the borehole are heavily influenced by parameters like in-situ stresses, pore pressure, strength, well trajectory, hole angle, etc. Near-well-bore pore pressure, effective stresses and strength can be altered due to drilling fluid exposure and influence time-dependent borehole instability.

Several analytical solutions have been derived for an arbitrary borehole orientation assuming elastic rock behavior[5, 8]. These are generally considered to make conservative predictions. More sophisticated models based on viscoelastic, elastoplastic and non-linear approaches have been proposed[8,9,10,11]. These new models are thought to be more realistic than a simple elastic analysis, since rocks rarely behave in a purely elastic manner until ultimate failure. In cases where laboratory testing of cores is possible and well-defined rock properties can be obtained, contemporary rigorous non-linear modeling techniques can be applied. However, in most practical circumstances, the poor definition of key input parameters (i.e., in-situ stresses and rock strengths) justifies at best, a simplistic conservative elastic analysis. In these cases the rock strength is determined by utilizing a peak-strength criterion[5,12] (e.g., von Mises, Drucker-Prager, Mohr-Coulomb failure criterion).

Typical results obtained from the above models can provide the upper and lower limit for a safe mud weight as a function of the hole inclination angle (as shown in Figure 2). The upper limit in this case being the mud weight above which extension fracturing or fracture propagation would occur and result in excessive drilling fluid losses. The lower limit is set by formation pore pressure or the minimum mud weight required to prevent borehole collapse, whichever is greater.

Fluid Selection

100% Oil Mud vs. Invert Emulsion Oil Mud

No testing was done during DEA 13 on this issue. Assuming that the filtrate from either mud is the base oil only, i.e., no water, there should be no difference in the fracturing characteristics of the fluids. Oil mud is considered to be a "non penetrating" fluid due to the high capillary entry pressure for oil. The amount of oil is not the issue. What may be an issue is the rheology and solids loading of different fluids. The negative aspects of these two properties can be the increase in ECD, thus raising the pressure above the fracture initiation and propagation pressure. The positive aspect of solids loading can be the increase in solids concentration in the fracture causing tip screen-out and stopping further fracture propagation.

Salinity

Lowering the pore pressure around the well-bore by removing water (i.e., low activity/high salinity) in an intact formation increases the effective tangential stress, thus requiring a higher pressure to break down the formation. This phenomenon is a near well-bore phenomenon, so if we have already established a fracture during a LOT, the fracture reopening pressure may be lower than the pressure required to break down the virgin formation, consequently any effect due to higher salinity is nullified.

New Synthetic Fluid System

A new commercial synthetic based fluid that contains no commercial clay or organophylic lignite can lower the colloidal content of the mud and produce a greater tolerance for drill solids. As drilling depth and the percent of solids increase, the ECD, viscosity and yield point of this fluid remain stable. Specialized thinners developed for this system can produce flatter rheology profiles in both cold water and down-hole environments. These thinners work rapidly and do not require multiple circulations to see results.

The unique combination of materials can provide stable viscosity through a wide range of temperatures, high resistance to contaminants and low ECD (Figure 1). Comments from the paper on the initial field use states; “Its consistently good rheology performance in cold temperatures can also make it an effective defense against small Pore Pressure – Frac Gradient margins commonly encountered in deepwater drilling.” [13]

Hydraulics ECD Modeling

Once the mud weight operating windows have been identified in the wellbore stability modeling process, then hydraulic simulations can be initiated to help determine projected ECD levels. An earlier paper detailed the coupling of wellbore stability and hydraulics modeling into a single process in support of an extended reach North Sea well[14,15] The principal factors in wellbore hydraulic predictions include:

- pump rate
- hole and drill pipe geometry
- hole cleaning efficiency
- rate of penetration
- drill pipe rotation speed

To achieve ECD predictions within a window of acceptability, operating ranges of each of these major factors should be determined. Hence, the simulation process can be quite lengthy. However, with fine-tuning, the iterative process can produce ECD predictions that can be used with some confidence.

Drilling fluids laden with LCM materials can pose particular problems for ECD prediction. The size and shape of the particles can often render use of standard rotating viscometers like the Fann 35® VG meter useless in mapping fluid behavior. The major recourse is use of a pipe viscometer, but results measured with it can be suspect if the drilling fluid contains large amounts of LCM. A common technique is to use the pipe viscometer to measure pressure drops with and without LCM. Increases in pressure drop as a function of LCM loading can be measured. Factors can then be applied to standard hydraulics programs to account for the additional pressure drop caused by LCM additions.

If LCM additions are made through the use of pills or sweeps, then their volumes should be anticipated and modeled hydraulically as they pass up the annulus through channels of varying diameters. It is important to remember that even with the best-placed and best-formulated LCM pills, much of the LCM material will not remain downhole but will be circulated up through the annulus and over the shakers at surface.

Once the width of the ECD windows has been determined in the modeling process, then decisions can be made based on the anticipated severity of formation fracturing / drilling fluid losses and well economics whether to pretreat the system with LCM or deal with the problem when/if the problem occurs. Usually, a drilling fluid system pretreated with LCM will contain less LCM than one formulated when losses occur. Accordingly, the ECD increases of a pretreated system are usually less than those of fluids more heavily-laden with LCM.

Pretreatment Materials

It is a reasonable observation, from rock mechanics and hydraulic fracture theory, to surmise that it is easier to prevent fracture propagation than to later plug the fracture and prevent fluid re-entering. These observations have been verified in the field and in the DEA 13 studies. One example for a land job occurred when a consultant did not want to run LCM in the mud while drilling an area that was prone to lost circulation. Lost circulation did occur, and could not be stopped. Several thousand feet of open hole were lost. The well was re-drilled with LCM carried in the mud. It was not "without-incident", but was drilled successfully to TD.

It is for these reasons that we propose carrying LCM in the active synthetic base drilling fluid (SBF) when drilling probable lost circulation zones, such as a "rubble" zone beneath salt. Use of a pretreatment can have the added benefit of mitigating well-bore breathing, seepage losses and/or potential lost circulation while drilling depleted zones.

The DEA studies showed sized calcium carbonate to be an effective lost circulation material. A flake LCM was not effective and fibers were not tested. The graphitic carbon materials were not available at the time this study was undertaken.

Subsequent work, based on these data and observations, resulted in the development of lost circulation materials that could be carried in the drilling fluids without significantly affecting the rheology or fluid loss characteristics. Initial materials were ground and sized shot coke. [16,17,18,19] A later material was a specially manufactured graphitic carbon that is still commercially available.[20]

One of the more unique characteristics of this material is a compressive property, allowing it to "mold" itself into the fracture tip, promoting screen-out. If the pressure is released, the material "rebounds", thus continuing to plug the fracture completely.

Graphitic carbon and sized calcium carbonate have proven to be effective main materials when carried as a pretreatment in the drilling fluid – and are generally the primary constituents of initial lost circulation treatments. In general, 5-10 ppb of graphitic carbon plus 10-15 ppb of sized calcium carbonate is used as a pretreatment. A total weight of 20-25 ppb is desirable.

Subsequent Treatments

As drilling progresses, additional make-up materials may need to be added to maintain pretreatment levels. In addition, well-bore breathing and loss of circulation may be observed. The question is – do you use more of the same or added lost circulation materials or change chemical lost circulation treatments. The response will generally depend on the severity of the losses and potential risk.

Real-time lost circulation severity modeling with fracturing simulators in future drilling operations may provide information on the options for an appropriate response and the associated risk. [21] For example, it would include a predicted leak-off flow-path geometry and fracture volume that can allow quick calculation of the LCM volume needed to cure losses as changes occur in drilling conditions, such as increasing wellbore pressures and depths. Real-time geomechanics and interval pressure test analysis can provide key input data for the hydraulic fracturing software model to predict fractures vs. other types of leak-off flow-paths.

By premixing LCM materials prior to use, rather than mixing on the fly, the proper amounts and particle size distributions can be maintained. It may be possible in some cases to ease logistics some what by mixing a "concentrate" that can then be diluted by the active mud on location to the desired LCM level; or use one-sack products currently available that have been engineered for these specific applications. The relative ratio of materials should be normalized based on specific gravity of each, to provide equivalent volumes, rather than adding them on an equal weight basis.

Since higher concentrations of materials can aid in fracture tip screen-out and prevention of further fracture propagation, it can be more effective to add later treatments to the drilling fluid system as sweeps. This type of addition will help insure the wellbore sees a higher concentration of particulate materials, in general, and the larger particles, in particular. These "preventive" sweeps should contain a nominal 50 ppb of the selected materials.

Treat by Weight or Volume

Conventionally the industry has normally calculated the amount of lost circulation material to use on a weight basis – either equal weights of material combinations or some weight ratio based on previous experience. We propose that the treatment should be calculated on a volume basis, normalizing the weights by using the specific gravity (SG) of the materials. Comparing fibers to calcium carbonate is a good example. A nominal SG for many fibers that are used is about 0.5, while calcium carbonate has an SG of 2.7. If we use equal weights of these materials (1:1 weight ratio), the volume ratio of fibers to calcium carbonate is (5.4):1. This ratio is an extreme case for LCM, since these specific gravities are at the nominal extremes from each other, but fibers are very commonly used. Since fibers also tend to cause increased viscosity and potential for plugging while pumping through the bottom hole assembly, using a volume calculation brings their use into a more practical range.

Table 1 shows the factors required to normalize calcium carbonate, walnut and fibers to graphitized carbon. Multiplying the weight of graphitized carbon by these factors can give you the weight for an equal volume of each material. A simple spread sheet can be set up to do this calculation from which the engineer can then pick the amounts of materials to be used in a pill (Table 2). This example is not to imply that a 1:1 volume ratio for different materials is always best; the ratio is normally determined by field experience. A common weight ratio that we suggest for combinations of GC:CC:fiber is 1:2:(0.25) . This is a nominal **volume** ratio of 1:(1.5):1.

WELL CONSTRUCTION APPLICATIONS

ECD Monitoring

The ability to detect potential lost circulation problems early can be of paramount importance, since prevention can be significantly more effective than curing lost circulation. The claim that prevention can be significantly more effective than curing lost circulation is particularly true for any drilling practice that results in a higher equivalent circulating density (ECD). A significant development in recent time is the use of PWD™ pressure-while-drilling tools that can allow the ECD to be monitored in "real time", providing down-hole eyes for the driller. Accurate hydraulics models should account for the ECD effects of cuttings loading in the annulus, drill pipe rotation, and compressibility of synthetic-based fluids with temperature and pressure [especially important in deepwater drilling], all of which can produce higher ECD levels downhole than those expected based on surface densities and possibly lead to wellbore breathing and induce lost circulation[22,23]. With proper interpretation, these tools can provide insight on shallow water flows[24], kicks and well control, fluid loss/gain (breathing), leak-off tests (LOT) and lost circulation, hole cleaning, hole collapse and pack-offs, mud properties and drilling practices.

Leak Off Test

Fundamental to helping prevent lost circulation is the determination of an accurate LOT along with borehole stability modeling that takes into account both mechanical considerations, and how they vary with bore hole azimuth and angle, plus chemical effects. Even though carrying a LOT to the fracture extension stage provides valuable rock mechanics data, the resulting fracture can seriously lower the maximum mud weight that may be used to safely drill the interval without lost circulation.[25] Consequently, stopping the test as early as possible after the pressure plot starts to "roll-over" is preferred.

Lost Circulation Treatments

Lost Circulation Materials

Combinations of individual materials are normally used to “cure” lost circulation incidences. Almost every waste- or by-product known to man has probably been pumped down a borehole somewhere as a lost circulation material. In general, these materials can be classified as deformable solids, particulates and fibers. Some of the most common deformable materials are graphitic carbon (GC), ground battery casings and ground tires. Some common particulate materials are sized calcium carbonate (CC) and walnut hulls. Fibers can come from a variety of sources, including ground peanut and almond shells.

Of these and other similar materials, we have found the graphitic carbon to be the most effective and consider it to be the main ingredient in most combinations. This individual material has a minimum effect on the rheology of SBM and has been pumped as a pill through mud motors in excess of 100 ppb to successfully control lost circulation incidences.

In addition, it has been successfully used in lower concentration combinations for such diverse applications as controlling seepage losses and preventing lost circulation while drilling depleted sands and curing lost circulation in horizontal boreholes penetrating faults.

An example for the latter application was a recent well experiencing significant losses into an unmapped fault/fracture zone, and “traditional” calcium carbonate pills did not have a marked effect on the loss rate. A combination pill with essentially equal-volumes of graphitic carbon and calcium carbonate was suggested. There was concern about limitations by the MWD tools in the string, so 30 ppb was the maximum pill size allowed. Losses were cured almost immediately, and the operator was able to continue drilling.

On another well, fault-related losses and poor geology prompted the need for an off-bottom cement kick-off plug. The rig spotted a chemically cross linked pill, but losses continued. We recommended a GC/CC pill formulated as above, which stopped all losses when pumped.

In general, pills with concentrations as low as these may not be successful and are not recommended when rig costs are high. More normal concentrations are 40-60 ppb or higher. We have many cases where up to 80 ppb of combination GC/CC materials have been pumped through motor assemblies successfully when fibers are not used in the pill.

Engineered Lost Circulation Material Combinations

There is such a variety of materials and size distributions available that it is many times confusing to the drilling staff as to what is best to use. A ready solution to the confusion is to provide premixed combinations containing specified materials and sizes for different applications. Treatment specifications and inventory are then greatly simplified. Three example combinations are given here; two containing graphitic carbon and one containing only acid soluble material for safer use in the pay-zone, though there is no evidence that graphitic carbon causes formation damage.

*Combination D for **D**epleted Sands and Seepage Losses* is a blend of fine GC and other lost circulation materials in a pellet form. The multi-component pellets can be used in all types of drilling fluids and are designed to disperse readily to help seal depleted zones and micro-fractured formations. It can be used as a pre-treatment, added as a pill in a slug pit, or added directly into the active system as maintenance for lost circulation prevention. The pellet form can reduce the bulk significantly, conserving storage space and creating less waste bags to be disposed.

This combination is designed to have a d50 of 80 microns, allowing about 90% to pass through an 84 mesh shaker screen.

*Combination S for **S**evere Lost Circulation Incidences* is a blend of coarser GC and other coarser lost circulation materials in a pellet form. It can be used in all types of drilling fluids and is designed to disperse readily and help cure severe losses. It is used as a pill, since the d50 is on the order of 950 microns.

*Combination E for **E**asy Removal in a Pay Zone* is a blend of acid soluble lost circulation control materials designed for use in non-damaging fluids, but can be used in any drilling fluid. It is 97% soluble in 15% hydrochloric acid. It is compatible with all drilling and completion fluids and disperses easily in clear brines. The combination has a bimodal size distribution, designed for all types of losses, distributed around 20 and 1500 microns.

Chemical Treatment Systems

These are systems whose components interact in some manner to synergistically create a more viscous, pliable lost circulation treatment. A common example is a chemical cross-linked system where a chemical species in low concentrations interacts with a polymer to build a high molecular weight polymer chain, significantly increasing the viscosity of the fluid. This type of system has been successfully applied in many cases, but sometimes suffers due to the uncertainty of the bottom hole circulating temperature (a significant design parameter) where the circulation loss has occurred. Two systems are described here that do not use a cross-linking mechanism, but still develops a very viscous, pliable treatment.

Combination F that Forms a ***F****lexible Sealant Treatment* is one way to circumvent the lack of knowledge on the bottom hole circulating temperature by pumping a two component system – one component down both the drill pipe and the other down the annulus that mixes below the bit and reacts before entering the lost circulation zone. The uncertainty of where the lost circulation occurred must be off-set by the size of the pill that is pumped. A spacer is used before and after the reactive pill pumped down the drill pipe; while the drilling fluid is the second component that is pumped down the annulus. These systems are designed for both SBM/OBM and water base fluids[26]. Over one thousand successful treatments have been performed with these systems after a number of conventional LCM pills and cements have been applied without success. These types of LCM squeeze systems have cured complete and sustained losses of 600 to 1200 bbls. per hour in massive fractures, in conductive faults miles in length, and in sealing underground blowout exit zone fractures with differential pressures of several thousand psi.

In some cases a more important application of these systems is to improve wellbore pressure containment (WPC) for improved shoe LOT results and also for further drilling in long open holes without setting pipe.[21] Figure 3 shows the before and after treatment LOT results for a deep HPHT well drilled with SBM that was saved from abandonment by the treatment.

Combination H that ***H****ydrates to Form a Pliable Treatment* is a simpler system than one that chemically cross-links. It has a component that absorbs large amounts of water when it hydrates, increasing both volume and viscosity. By incorporating this material along with engineered combinations of GC and other materials, a hybrid chemical/particulate treatment is created.[27]

The treatment is pumped prior to complete hydration, thus having a lower viscosity but still capable of carrying the particulate material. Upon entering the lost circulation zone the hydration reaction continues, forming a very viscous plug. If high temperatures should eventually dehydrate the treatment, the engineered sized solids remain to plug the lost circulation zone.

An operator had two successes on two applications where they were suffering massive losses after drilling out of salt 4 ppg overbalanced (in a pore pressure regression regime). MWD indicated the losses occurred at a sand/shale interface. In one case they had pumped a 100 ppb GC pill without success (a treatment with a high rate of success) before pumping the Combination H.

CONCLUSIONS

Developing and following a thorough plan can be essential to mitigate lost circulation using synthetic oil base fluids.

Prevention of lost circulation in oil base systems of any type is easier than curing the problem once it occurs.

Graphitic carbon has demonstrated in the field to be one of the more effective lost circulation mitigation materials.

"One-sack" engineered combinations of sized lost circulation materials can simplify lost circulation treatment.

Sizing lost circulation treatments by volume of material can be a more realistic approach than using weight, particularly when incorporating materials such as fibers with a relatively low specific gravity.

NOMENCLATURE

BHA = bottomhole assembly
ECD = equivalent circulation density
EMW = equivalent mud weight
Ppb = pounds per barrel
ROP = drilling rate of penetration
rpm = revolutions per minute
TD= total depth
TVD=true vertical depth
WPC=wellbore pressure containment
FG=frac gradient
LOT=leak-off test
FIT=formation integrity test
MWD=measurement while drilling
HPHT=high pressure high temperature
SBM=synthetic based mud
OBM=oil based mud
DEA=Drilling Engineering Association

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REFERENCES

See end notes.

1. Morita, N. Black, A. D., and Fuh, G. F., "Theory of Lost Circulation Pressure"; SPE 20409; 65th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, New Orleans, LA., September 23-26, 1990.

2. Onyia, E. C., "An Analysis of Experimental Data on Lost Circulation Problems While Drilling with Oil-Base Mud" (SPE 22581); 68th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Dallas, TX., October 6-9, 1991.
3. Morita, N., Black, A. D., and Fuh, G. F.; "Borehole Breakdown Pressure with Drilling Fluids – I. Empirical Results"; Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 33, No. 1, pp. 39-51, 1996; Elsevier Science Ltd.
4. Morita, N., Black, A. D., and Fuh, G. F.; "Borehole Breakdown Pressure with Drilling Fluids – II. Semi-analytical Solution to Predict Borehole Breakdown Pressure"; J. Rock Mech. Min. Sci. & Geomech. Abstr. Vol. 33, No. 1, pp. 53-69, 1996; Elsevier Science Ltd.
5. Tare, U. A. and Mody, F. K. ,"Novel Approach to Borehole Stability Modeling for ERD and Deepwater Drilling", SPE 52188; SPE Mid-Continent Operations Symposium, Oklahoma City, OK, Mar 28-31, 1999.
6. Tare, U. A. and Mody, F. K. , "The Next Generation of Borehole Stability Analysis – A Chemical Potential Borehole Stability Model for Extended Reach and Deepwater Drilling Applications"; XI Congreso Lation Americano De Perforacion.
7. Asdnoy, B. S., "Classification of Drilling-Induced Fractures and Their Relationship to In-Situ Stress Directions"; Rogaland University, J. Sebastian Bell, Geologic Survey of Canada; The Log Analyst, pp27-42, Nov-Dec, 1998.
8. Nawrocki, P.A., et al.: "Assessment of Some Semi-analytical Models for Non-linear Modelling of Borehole Stresses", paper No. 034, Int. J. Rock Mech. Min. Sci. Vol. 35, No. 4/5, p.522, 1998
9. Bandis, S.C. and Barton, N.: "Failure Modes of Deep Boreholes", Proc., 27th U.S. Symp. On Rock mechanics, Tuscaloosa, AL, p599-605, 1986
10. Veeken, C.A.M. et al.: "Use of Plasticity Models for Predicting Borehole Stability", Proc., Intl. Symp. On Rock at Great Depth, Pau, 2, 835, 1989
11. Wong, S.W., et al.: "The Rock-Mechanical Aspects of Drilling a North Sea Horizontal Well", paper SPE 23040, SPE Offshore Europe Conf., Aberdeen, Sept. 3-6, 1991
12. Bradley, W.B.: "Failure of Inclined Boreholes," J. Energy Res. Tech. (Dec. 1979) 232: Trans., ASME, 101.
13. MacFadyen, M., Vice, P., Womack, C., and Wright, T., "New Synthetic Fluid System Provides Stable Cold-Temperature Rheologies", World Oil, pp 48-55, June 2002.
14. Hemphill, T. and Tare, U., "Extensive Pre-Well Integrated Modeling Aids in Successful Drilling of Challenging Well: A Case Study", paper AADE-01-NC-HO-18 presented at the 2001 AADE National Drilling Conference in Houston (March 27-29).
15. Stawaicz, R., Taylor, S., Hemphill, T., Tare, U., Morton, K., and Valentine, T., "Successfully Replacing Oil-Based Drilling Fluids with Water-Based Drilling Fluids: Case Study Demonstrates Value of Extensive Planning and Execution in Extended-Reach Well", paper SPE 74545 presented at the IADC/SPE Drilling Conference in Dallas (February 26-28, 2002).
16. Fuh, G. F., Morita, N., Boyd, P. A. and McGoffin, S. J., "A New Approach to Preventing Lost Circulation While Drilling"; SPE 24599, 67th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Washington, D.C.; October 4-7, 1992
17. Fuh, Giin-Fa; Morita, Nobuo; Whitfill, Donald. L.; Strah, David A.; (Conoco Inc.), "Method for Inhibiting the Initiation and Propagation of Formation Fractures While Drilling and Casing a Well." US 5,207,282; May 4, 1993.
18. Fuh, Giin-Fa; Morita, Nobuo; Whitfill, Donald. L.; Strah, David A.; (Conoco Inc.), "Method for Inhibiting the Initiation and Propagation of Formation Fractures While Drilling." US 5,180,020; Jan 19, 1993.
19. Whitfill, Donald L.; Kubena, Jr., Edwin; Cantu, Terry S.; Sooter, Matthew C. (Conoco Inc.), "Method for Controlling Lost Circulation in Well Drilling." US 4,957,174; Sep. 18, 1990.
20.. Allemon, J., Owen, B., Cornay, F., and Weintritt, D. J.; "Multi-functional solid lubricant reduces friction/prevents mud loss"; World Oil, pp 87-90, Sept, 1998
21. Wong, H., Sweatman, R., and Deeg, W.: "The Difference Between Fracture Gradient and Wellbore Pressure Containment and the Effect on Drilling Beyond Pressure Limits" paper AADE-03-NTCE-26 presented at the 2003 AADE National Technical Conference in the Formation/Wellbore Stabilization session, Houston, Texas, April 1-3.
22. Power, D., Green, M., Song, J., and Aiello, B., "Well Characterization Procedures for Early Kick Detection and Wellbore Breathing", ETCE 2000/DRILL-10103 ETCE/OMAE Conference, New Orleans, February 14-17, 2000.
23. Tare U., Whitfill, D., and Mody, F., "Drilling Fluid Losses and Gains: Case Histories and Practical Solutions", paper SPE 71368 presented at the 2001 SPE Annual Technical Conference and Exhibition in New Orleans (Sept 30 – Oct 3).
24. Ward, C. and Beique, M.; "PWD Applications for Drilling SWF Zones"; 1999 International Conference on Shallow Water Flow; League City, TX, October 6-8, 1999.
25. Morita, N., Fuh, G., and Boyd, P. A.; "Safety of Casing Shoe Test and Casing Shoe Integrity after Testing", SPE 22557; 66th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Dallas, TX, Oct 6-9, 1991.
26. Webb, S., Anderson, T., Sweatman, R. and Vargo, R., "New Treatments Substantially Increases LOT/FIT pressures to Solve Deep HTHP Drilling Challenges", 2001 SPE Annual Technical Conference and Exhibition, New Orleans, 30 Sep – 3 Oct, 2001.
27. Shaarpour, M., Hart E&P, Feb. 2003

TABLES

Table 1
Normalizing Weight of LCM versus Graphitic Carbon by Using Specific Gravity

Material	**SG**	**Factor**	**Example* (ppb)**
Graphitic Carbon	2.1	1.00	20
Calcium Carbonate	2.7	1.29	25
Walnut	1.2	0.57	0
Fiber	0.5	0.24	5

*50 ppb pill

Table 2
LCM Calculator

LCM Pill

				GC	**material**	**Selection**	**100 bbl**
MATERIAL	**SG**	**FACTOR**	**D50**	**lbs**	**lbs**	**ppb**	**sacks**
graphitic carbon	**2.1**	**1.00**	**300.00**	**20**	**20.0**	**20**	**40**
graphitic carbon	**2.1**	**1.00**	**80.00**		**20.0**		
calcium carbonate	**2.7**	**1.29**	**5.00**		**25.7**	0	**0**
calcium carbonate	**2.7**	**1.29**	**50.00**		**25.7**	**10**	**20**
calcium carbonate	**2.7**	**1.29**	**150.00**		**25.7**	**15**	**30**

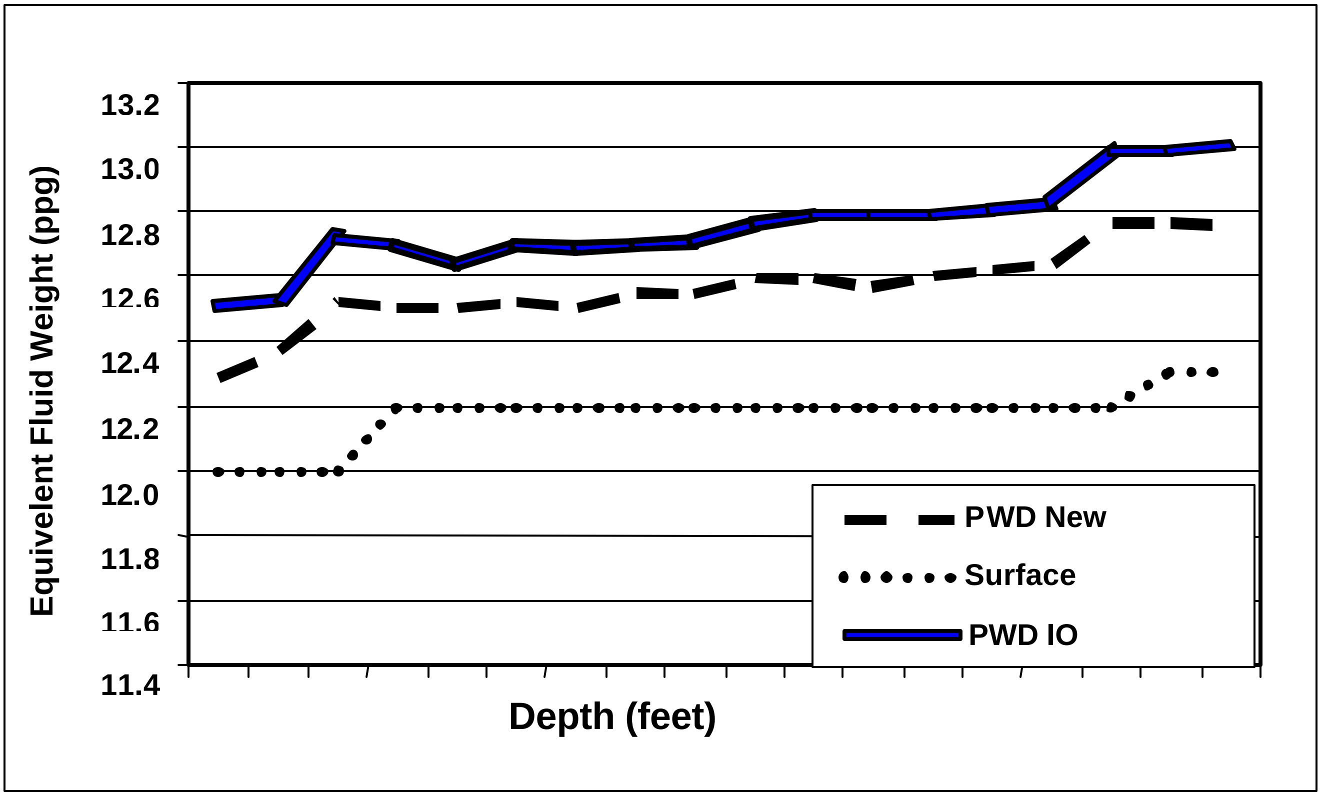

Figure 1 The New System: ECD Comparison

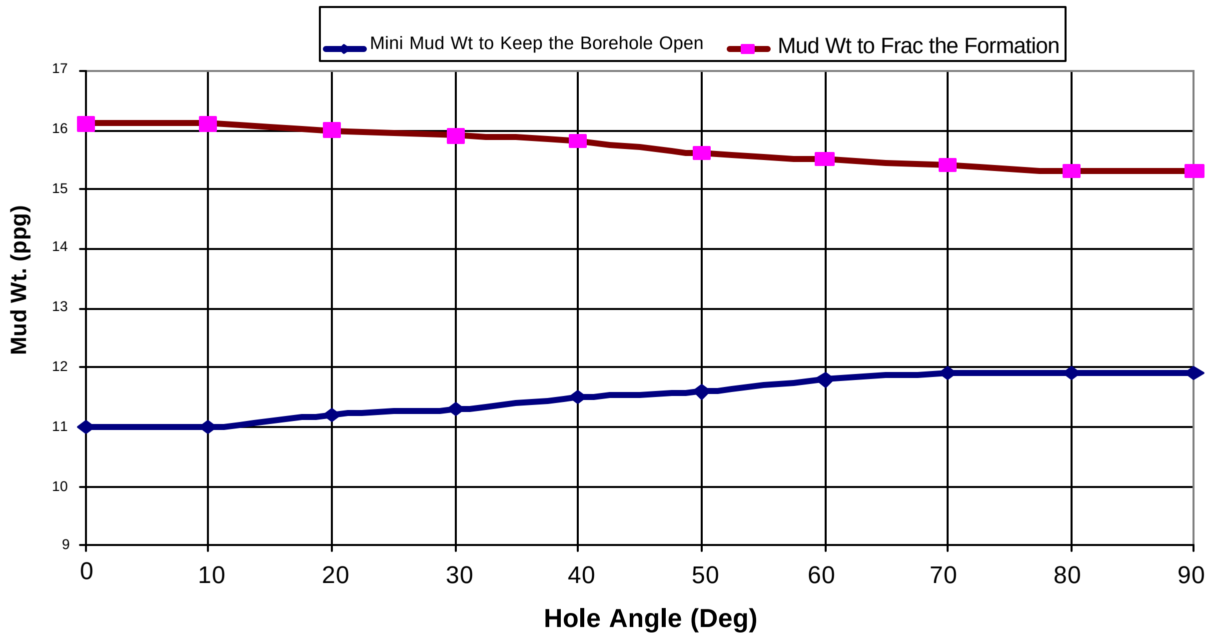

Figure 2. Example output from a linear-elastic borehole stability model showing the minimum and maximum mud weight predictions.

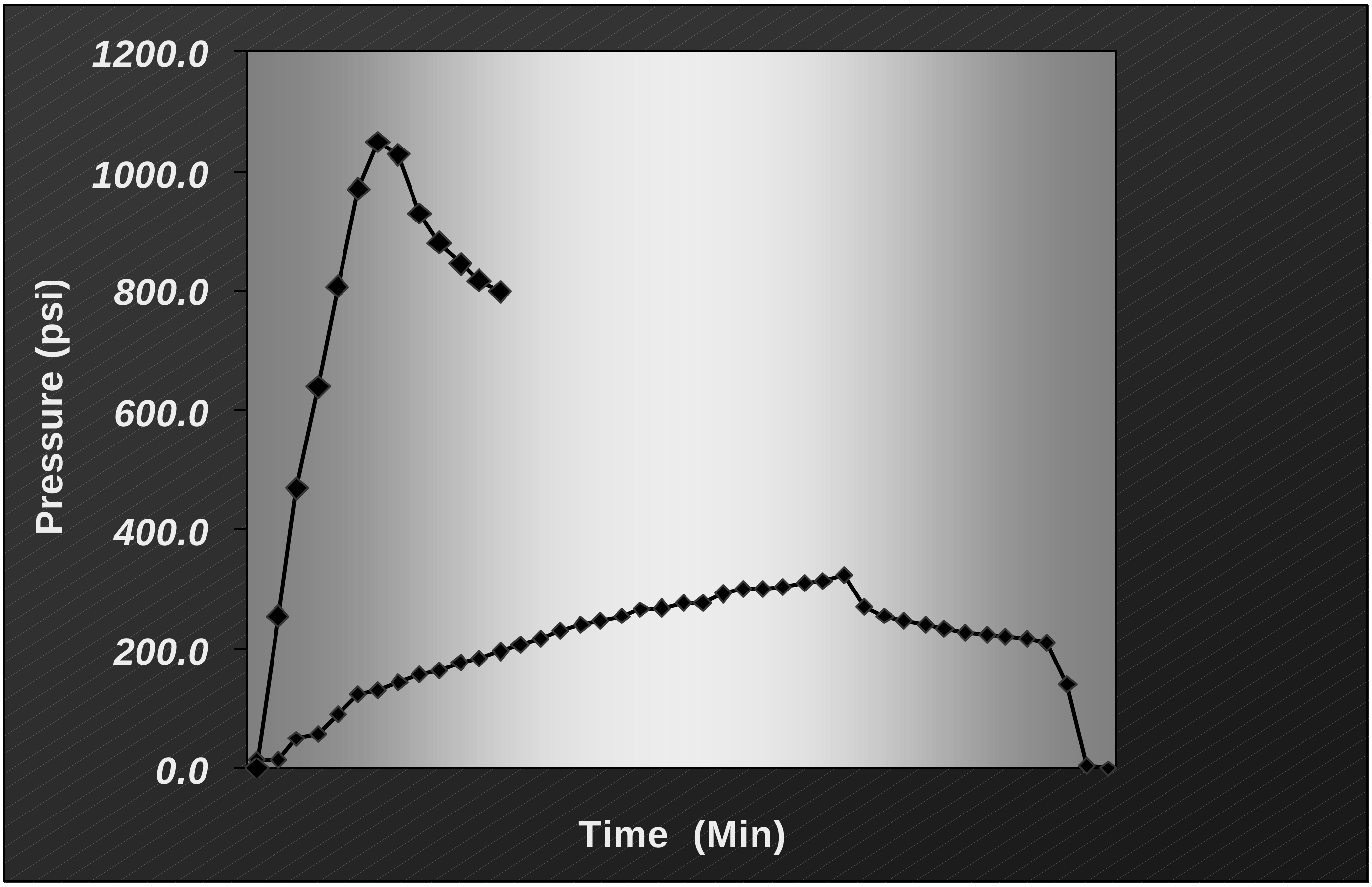

Figure 3. The before (lower curve) and after(upper curve) treatment LOT results for a deep HPHT well drilled with SBM