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Flexible Drilling Fluid Formulation and Application

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Abstract
Generic drilling fluids with well known attributes are used for drilling in many areas. Many times there is a need to enhance these fluids to perform in order to achieve a critical drilling objective. A number of additives are available for specific purposes. An additive which improves shale stability, reduces high temperature-high pressure filtrate, and provides lubricity is a good example. Another example is a component which increases rate-of-penetration and reduces torque and drag. Other products included in this suite of performance enhancing additives are a filtration control additive, a reactive cuttings/wellbore stabilizer and a high temperature stabilizer.

Case histories illustrate enhanced performance achieved by generic mud systems supplemented with these products. Also, providing required mud properties in a high density mud over a range of salinities that includes fresh water, sea water, and 20% sodium chloride brine is easily accomplished with this suite of additives. Field examples demonstrate the ability of these performance enhancing additives to achieve drilling objectives in a variety of challenging environments.

Introduction
Drilling fluid development usually focuses on developing a complete application or system to meet identified customer needs. In many cases, this strategy works well and results in a new application for the oil and gas well drilling industry that economically meet well requirements.[1] At other times, an existing system comprised of generic products that provide adequate performance is used. Generic drilling fluids, for example: polymer, non-dispersed, dispersed, gyp, lime, and salt – can meet performance requirements in many well applications. They provide simple solutions that are well understood and economical. In many cases, however, a more flexible approach between a high performance fluid and the generic system is best. Taking an existing, well-known fluid and improving it with state-of-the-art additives has many benefits.

Principles of Flexible Fluid Formulation
The concept of flexibility in the formulation of drilling fluids calls for consideration of how the performance of a generic fluid might be enhanced in a specific drilling situation. The following are examples of such situations:

- Better borehole stability when drilling shale
- Faster rate-of-penetration and improved lubricity
- Lower filtration rate with minimal increase in viscosity
- More competent shale cuttings to reduce dilution requirements
- Increased viscosity stability in high-temperature wells

Implementation of the flexible drilling fluid concept requires the development of specialty drilling fluid additives to obtain the desired performance improvements. In some instances a single additive might serve the purpose, while other circumstances might call for a combination of additives. The following is a discussion of specific specialty additives selected to enhance performance in a specific drilling situation.

Better Borehole Stability in Shale
Borehole stability is often a problem when drilling shale formations that contain fractures – either natural or induced. Experience has shown that borehole stability in these formations can be improved by use of drilling fluids that contain additives such as oxidized asphalt, sulfonated asphalt, and Gilsonite®. These materials apparently serve to help seal the fractures in the shale.

A major cause of borehole instability in shale is the transfer of water from a water-based drilling fluid to the shale. This is affected by the water activity of the drilling fluid relative to that of the formation water, along with the nature of the membrane that develops at the drilling fluid/shale interface.[2, 3]

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It has been found that complex polyols such as methyl glucoside and polyglycerol can be added to a drilling fluid to both lower the water activity and contribute to a membrane that lessens hydration and weakening of formation shale.

In addition to shale stabilization, both the asphaltic additives and the complex polyols also help to reduce high temperature-high pressure filtration and improve lubricity. A blend of methyl glucoside and sulfonated asphalt results in a specialty product that can be added to most generic drilling fluids to provide better borehole stability in shale as well as better overall drilling performance. An example of the typical improvement realized in field mud properties by addition of 2 – 3 vol% of this liquid shale treatment is shown in Table 1.

Faster Rate-of-Penetration and Improved Lubricity

Essential to fast rate of penetration is a clean bit, be it drag, mill tooth, or diamond. Bit balling and plugging can be problems when drilling shale formations using a water-based drilling fluid. These problems can be addressed by treating the drilling fluid with oil along with an emulsifier and oil-wetting agent[4], although this might not be feasible because of environmental concerns. A specially formulated, environmentally acceptable ester-based additive offers a better method of maintaining a clean bit and low torque and drag. The product is designed to reduce interfacial tension and emulsify in most water-based drilling fluids. It provides very low coefficient of friction, both metal-to-metal and metal-to-formation, by forming a hydrophobic film on metal surfaces. Table 2 lists the results obtained from testing the complex ester additive in the laboratory. The addition of 3 vol% of the complex ester resulted in lubricity coefficient reduction of 18% in a weighted mud.

One limitation of the complex esters is that the ester degrades under conditions of high temperature and high alkalinity. Although this happens under different conditions depending on the mud density and formulation, an alternative suitable for wells with bottom-hole temperatures to above 400ºF (200ºC) is required. For this reason, a synthetic based, high temperature version of the product that does not contain the ester has been developed. The additive performs to enhance rate-of-penetration and improve lubricity with the added benefit of enhanced temperature stability.

When either of the additives is added to water-based drilling fluid, the resulting emulsified droplets serve to reduce filtration and contribute to development of membrane to limit shale hydration. The film strength of the emulsion can be enhanced by inclusion of another specialty additive, an oxidized sub-bituminous coal.

Lower Filtration with Minimal Increase in Viscosity

Colloidal materials such as clay, starch, and cellulosic derivatives are customarily used to lower the filtration of water-based drilling fluids. A disadvantage to this is that the colloids serve to increase plastic viscosity, tending to reduce rate of penetration. A specialty additive offers an alternative approach. Based on oxidized sub-bituminous coal, the additive serves to deflocculate the clays in the drilling fluid, lowering both the effective viscosity and the filtration rate. If the drilling fluid contains a non-aqueous phase such as the complex ester, the additive will concentrate into the emulsion film. This causes smaller emulsion droplets that have high film strength. The result is further reduction in filtration with minimal viscosity increase.

One of the most interesting aspects of this material is its enhanced performance in high chloride environments. This results in cost effective filtration control in high salt mud like those used in deep water for methane hydrate control. For example, as shown in Table 3, when compared to conventional mud grade lignite in a high salt mud, the high-temperature high-pressure filtrate for the same concentration of material is almost half of the lignite treated fluid.

High Temperature Enhancement

Controlling gelation in water based mud systems is of primary importance when drilling with weighted water-based fluids. A non-chrome based zirconium compound has been found to be very effective for the control of fluid properties at high temperatures.[5]

Figure 1 gives a mud consistometer viscosity graph for base clay slurry and the base clay slurry treated with the zirconium additive. The thermal flocculation point for the clay slurry is 225ºF (107ºC). When treated with 1 lb/bbl of the zirconium compound, the thermal flocculation point increases to 360ºF (182ºC). The improvement in temperature stability is not as dramatic for most fully formulated drilling fluids, but substantial improvements in properties with minimal addition is routinely observed in the field. An example of increased thermal stability for a 17.6 lb/gal (2,110 kg/m³) field mud is shown in Figure 2.

Reactive Wellbore/Cuttings Stabilizer

The application of silicate fluids usually calls for high concentrations of silicates. An application using a small concentration of potassium silicate in water drilling has recently been developed.[6] This application has the potential to improve wellbore quality in many areas where water drilling or a simple flocculated mud is used. This improved quality can, in turn, result in deeper drilling with water prior to “mudding up”. Also, by reducing hole wash out, it can improve cementing success.

Maintaining a concentration of reactive silicate in a drilling fluid can provide benefits including improved cuttings firmness.[7] The use of potassium carbonate in combination with complex polyols and potassium silicate results in increased cuttings firmness.

Case Histories

A number of case histories that illustrate the application of a flexible drilling fluid formulation are given. In each case, the mud was formulated using specialty additives.

Case History – Roger Mills County, Oklahoma, USA

On a sidetrack from an existing well, the main objective was to improve log quality by avoiding tool sticking from thick filter cakes on sands. The methyl glucoside/sulfonated asphalt additive was recommended at a concentration of 2 vol% in the 14.5 lb/gal (1,738 kg/m³) fresh water mud.

The well was sidetracked with 6-1/2 in (165.1 mm) hole at 15,500 ft (4,724 m) out of 7 in (177.8 mm) casing. The log quality improved with no tool sticking. Additionally, much higher rates of penetration were realized with 8-10 ft/hr (2.4-3.0 m/hr) drilling rate instead of 6-8 ft/hr (1.8-2.4 m/hr) that is typical. Due to the improved drilling rate, the section was drilled to 16,450 ft (5,014 m) in 8 days. The typical drilling time for this interval in offset wells was 12 days.

Case History – Eugene Island, Gulf of Mexico

Deep continental shelf drilling is an active area where many operators are looking for long-lived gas reserves for the U.S. energy market. Deep shelf drilling has the following problems: high mud weights, lost circulation, high bottom-hole temperature, and slow drilling rates.

A well programmed for a depth of 18,500 ft (5,640 m) has been drilled with a formulated flexible drilling fluid. Upon drilling out the 11-5/8 in (295 mm) liner at 11,000 ft (3,353 m), the system (a generic lignosulfonate fluid) was converted to a flexible fluid by adding 2 vol% of the rate-of-penetration additive and 3 vol% of the methyl glucoside/sulfonated asphalt. These concentrations of materials were maintained to total depth. The days vs. depth and mud density vs. depth curves are given in Figures 2 and 3.

Two instances of non-productive time occurred that resulted in an additional 7 rig days on the well. The first was the result of the failure of an under-reaming tool to enlarge the hole sufficiently in the 20 in (508 mm) hole section. This cost 2 days of rig time. The second instance of non-productive time was due to the failure of a liner top packer and required 5 days of rig time.

Excellent hole conditions and rapid drilling progress allowed the elimination of one casing string. The well reached its geological objective on time and under budget despite the two instances of non-productive time.

Case History – Brooks County, Texas

Depleted sands with equivalent densities of less than 2 lb/gal (240 kg/m³) and a requirement for a 12 lb/gal (1,440 kg/ m³) mud density created a situation where the generic lignosulfonate mud used previously had resulted in the inability to get logs in intermediate hole.

A flexible formulation utilizing 3 vol% of the methyl glucoside / sulfonated asphalt with 1 vol% of polyglycerol was recommended. Additionally, mud sweeps containing sized carbonates, fibers and Gilsonite were recommended every 100 ft (30 m).

The 9-7/8 in (251 mm) intermediate hole was drilled from 2,525 ft (770 m) to 8,580 ft (2,615 m). After wiping out tight spots at 5,300 ft (1,615 m), the interval was logged and formation pressures measured with a formation test tool. Casing was run to bottom. Lost returns occurred while cementing. This well was the first time that formation testing using a wire-line test tool had been successful in this field.

Case History – Adriatic Sea, Italy

Drilling shallow, reactive formations in large hole sizes in environmentally sensitive areas requires innovative fluid designs. A conventional polymer or salt polymer mud will require high dilution rates. Bit balling, tight hole, and mud rings had plagued offset wells drilled with water mud.

This well, drilled in the Adriatic foredeep area would normally require oil mud for trouble free drilling. The use of oil mud was not considered due the larger hole sizes of up to 16 in (406 mm) and the large volumes of mud and cuttings that would require disposal. The product proposed was a combination of silicate and complex polyols used in conjunction with potassium carbonate.[7]

A simple polymer mud enhanced with the silicate / complex polyol inhibitor and potassium carbonate was used to drill the well. The concentration of the inhibitor was 10.5-12.25 lb/bbl (30-35 kg/m³) and the concentration of potassium carbonate was 2.25-14 lb/bbl (6-40 kg/ m³).

Drilling operations were performed in 55 days vs. 65 days programmed for the 10,400 ft (3,200 m) well. The rotating time was 426 hrs resulting in an average rate-of-penetration of 26 ft/hr (8 m/hr). No drilling problems were reported. Photo 1 shows the cuttings from the system in the 16 in hole section (406 mm). With the cost of an oil mud at US$190 per barrel (US$1,192/m³), the polymer based flexible fluid cost of US$40 per barrel (US$246/m³) provided considerable savings.

Summary of Case Histories

The case histories show that flexible drilling formulations using specialty additives can result in lower drilling costs and improved performance.

In all cases, a more general mud type was improved upon with the specialty additives. This resulted in meeting the operator's requirements with a small cost increment over the more typical approach.

Conclusions

Additives have been developed for improving:

- Shale stability and fluid properties
- Rate-of-penetration and lubricity
- Filtration control
- Thermal stability
- Cuttings firmness and stability

These additives have been used in hundreds of wells in areas such as the Rocky Mountains, Mid-Continent, Gulf Coast, Gulf of Mexico, and the Adriatic Sea.

Utilizing a flexible formulation philosophy allows the well requirements to be targeted with specific additives. This eliminates much of the extra cost associated with high performance mud systems that may provide more than needed.

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Table 1 – Formulation with Methyl Glucoside / Sulfonated Asphalt

Sample identification	Base	Base + Liquid Shale Treatment
Fresh water, bbl	0.85	0.82
Wyoming bentonite, lb	12	12
Low molecular weight PHPA, lb	1	1
Synthetic polymeric deflocculant, lb	1	1
Low viscosity polyanionic cellulose, lb	1	1
Potassium chloride, lb	2	2
Potassium hydroxide, lb	0.5	0.5
Barite, lb	221	221
Methyl glucoside / sulfonated asphalt, vol%	-	3
Hot rolled at 150°F, hrs	16	16
Density, lb/gal	12.5	12.5
600 rpm / 300 rpm	62 / 36	74 / 41
200 rpm / 100 rpm	26 / 16	30 / 19
6 rpm / 3 rpm	3 / 2	3 / 2
Plastic viscosity at 120°F, cPs	26	35
Yield point, lb/100 ft^2	10	6
Gel strengths – 10 sec/10 min, lb/100 ft^2	4 / 17	5 / 30
pH	10.2	10.6
API fluid loss, ml/30 min	4.5	4.0
HTHP at 300°F, ml/30 min	19.2	14.4
Lubricity coefficient	0.291	0.237
Hot roll dispersion test (Pierre II shale)		
Initial shale weight, gm	20.0	20.0
Recovered shale weight, gm	17.5	17.8
% Recovery, 80 mesh screen	87.5	89.0

Table 2 – Formulation with Complex Ester Lubricant

Formulation/Properties	Base Flex Fluid	Complex Ester
Hot rolled at 150°F, hrs	16	16
Fresh water, bbl	0.83	0.83
Wyoming bentonite, lb	25	25
Xanthan gum, lb	0.2	0.2
Lignosulfonate, lb	2	2
Lignite, lb	4	4
Caustic soda, lb	1	1
Barite, lb	202	202
Methyl glucoside / sulfonated asphalt, vol%	2	2
Complex ester, vol%	-	3
Density, ppg	12.4	12.3
600 rpm / 300 rpm	47 / 27	51 / 30
200 rpm / 100 rpm	18 / 11	21 / 12
6 rpm / 3 rpm	4 / 3	5 / 4
Plastic viscosity @ 120 °F, cP	20	21
Yield point, lb/100 ft^2	7	9
Gel Strengths, lb/100 ft^2	4 / 8	5 / 11
API filtrate, ml/30 min	5.8	5.5
pH	11.0	10.4
Lubricity Coefficient	**0.224**	**0.184**

Table 3 – Humalite vs. Lignite Comparison

Composition -	Humalite	Lignite
Water	0.86 bbl	0.86 bbl
NaCl	53.2 lb	53.2 lb
XC polymer	0.5 lb	0.5 lb
NewPac	0.75 lb	0.75 lb
NewEdge	12.0 lb	-
NewLig	-	12.0 lb
Caustic	2.5 lb	2.5 lb
Polyglycerol	3%	3%
Barite	99 lb	99 lb
RevDust	30 lb	30 lb
Properties -		
Plastic viscosity, cPs	17	19
Yield point, lb/100ft²	17	21
Gels – 10 sec/10min, lb/100ft²	3 / 6	4 / 8
pH	9.9	9.9
API filtrate, mL/30 min	4.4	6.4
HTHP filtrate @ 250°F, mL/30 min	18.4	34.6

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Figure 1
Temperature Stability
(Fann Consistometer)

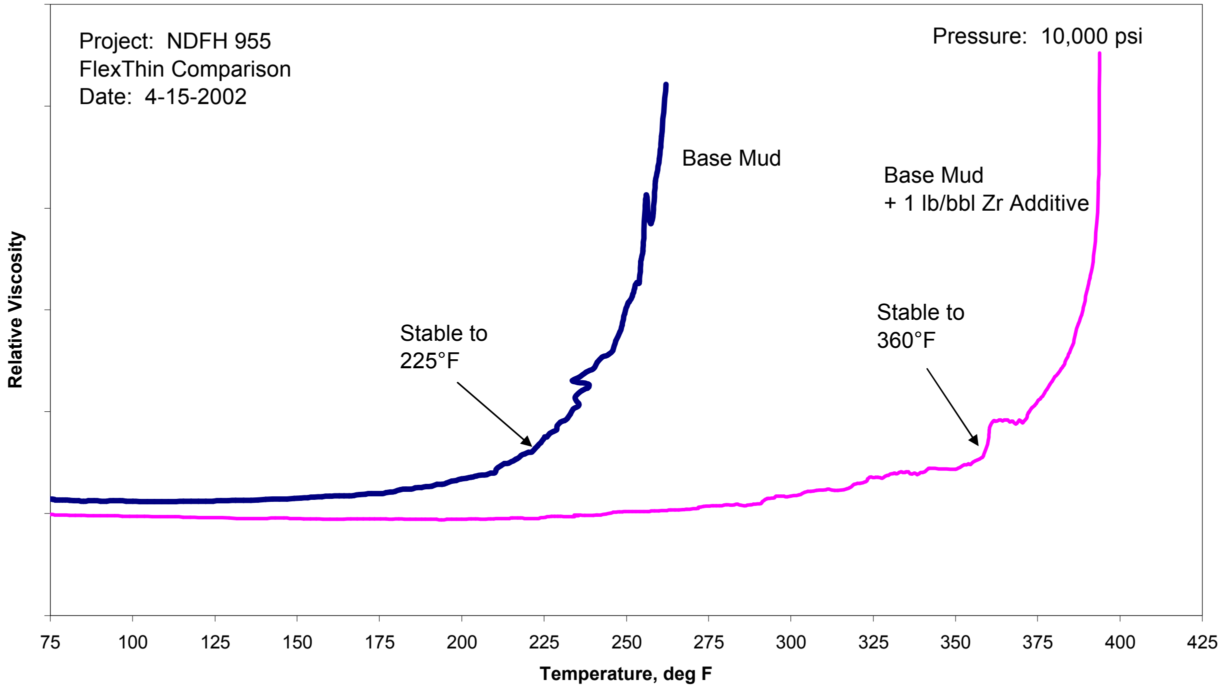

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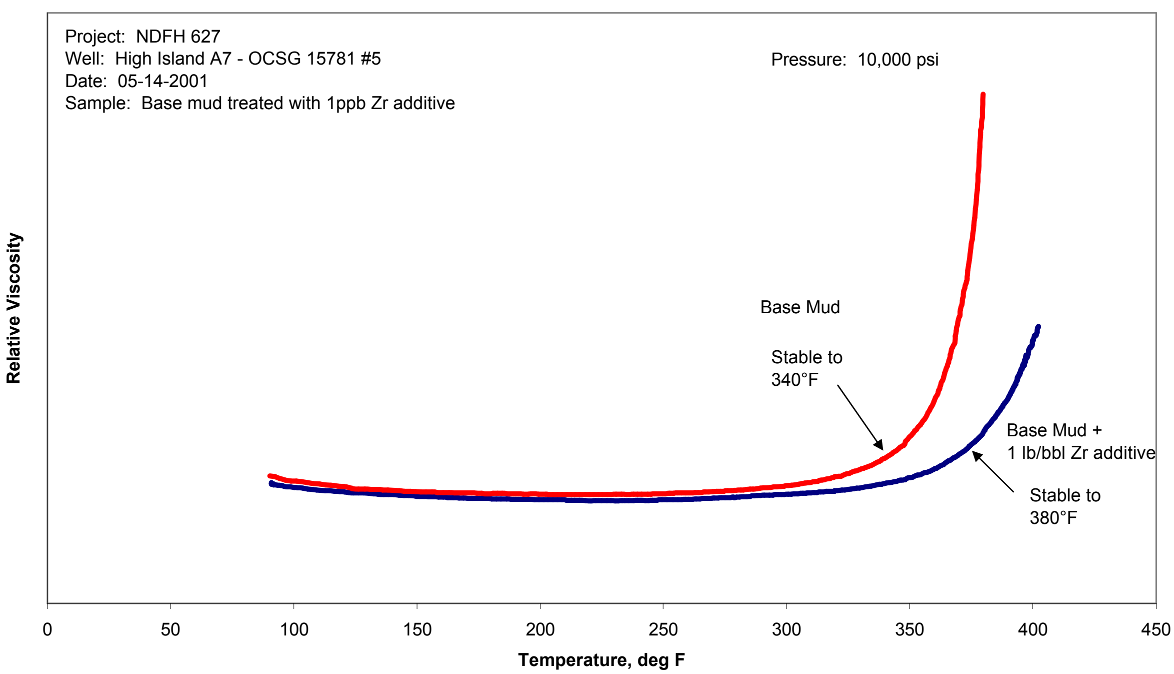
Figure 2
Temperature Stability
(Fann Consistometer)



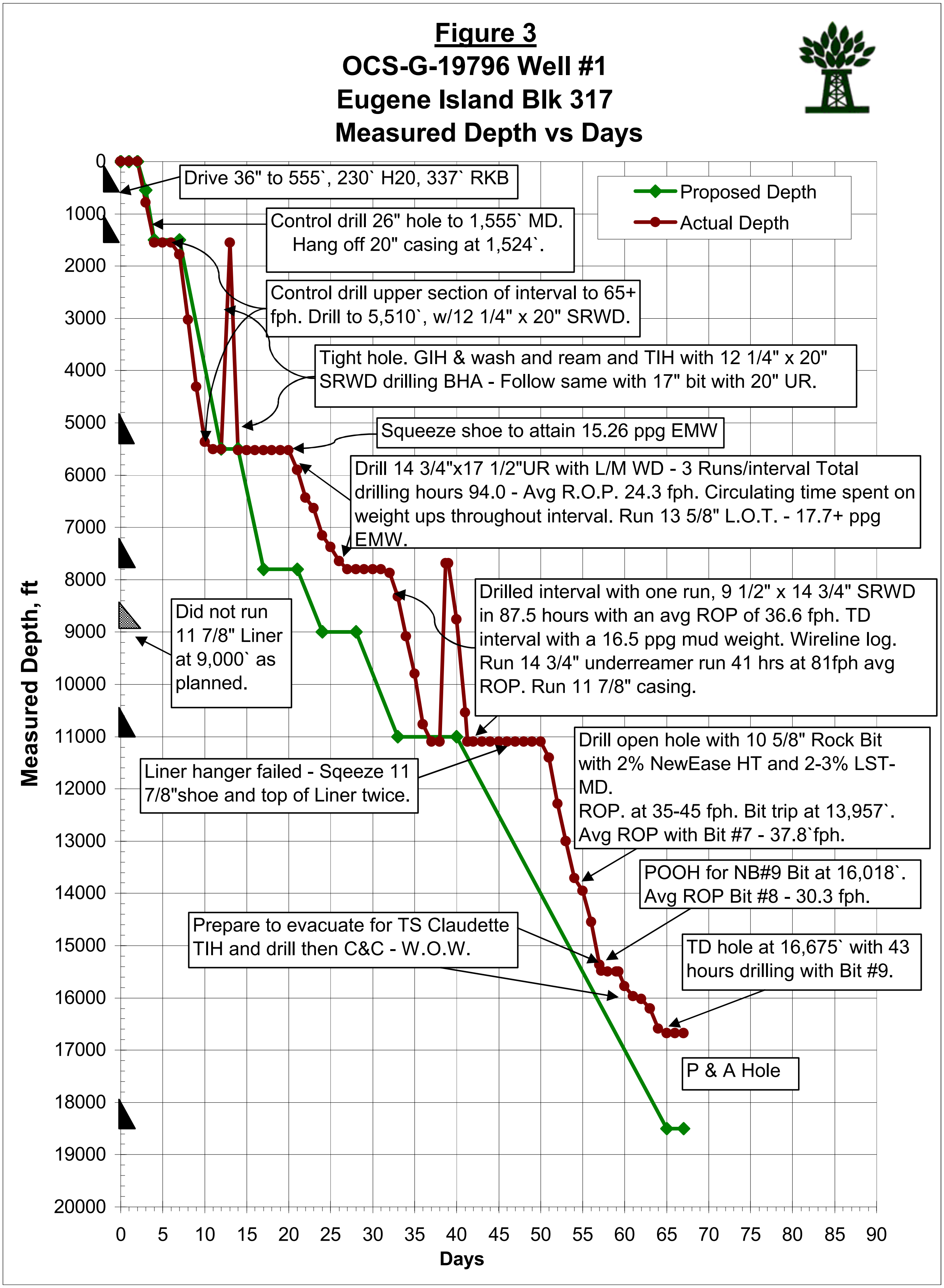


Figure 3
OCS-G-19796 Well #1
Eugene Island Blk 317
Measured Depth vs Days
Proposed Depth
Actual Depth
Drive 36" to 555`, 230` H20, 337` RKB
Control drill 26" hole to 1,555` MD. Hang off 20" casing at 1,524`.
Control drill upper section of interval to 65+ fph. Drill to 5,510`, w/12 1/4" x 20" SRWD.
Tight hole. GIH & wash and ream and TIH with 12 1/4" x 20" SRWD drilling BHA - Follow same with 17" bit with 20" UR.
Squeeze shoe to attain 15.26 ppg EMW
Drill 14 3/4"x17 1/2"UR with L/M WD - 3 Runs/interval Total drilling hours 94.0 - Avg R.O.P. 24.3 fph. Circulating time spent on weight ups throughout interval. Run 13 5/8" L.O.T. - 17.7+ ppg EMW.
Did not run 11 7/8" Liner at 9,000` as planned.
Drilled interval with one run, 9 1/2" x 14 3/4" SRWD in 87.5 hours with an avg ROP of 36.6 fph. TD interval with a 16.5 ppg mud weight. Wireline log. Run 14 3/4" underreamer run 41 hrs at 81fph avg ROP. Run 11 7/8" casing.
Liner hanger failed - Sqeeze 11 7/8"shoe and top of Liner twice.
Drill open hole with 10 5/8" Rock Bit with 2% NewEase HT and 2-3% LST-MD.
ROP. at 35-45 fph. Bit trip at 13,957`.
Avg ROP with Bit #7 - 37.8`fph.
POOH for NB#9 Bit at 16,018`.
Avg ROP Bit #8 - 30.3 fph.
Prepare to evacuate for TS Claudette
TIH and drill then C&C - W.O.W.
TD hole at 16,675` with 43 hours drilling with Bit #9.
P & A Hole
Measured Depth, ft
Days
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
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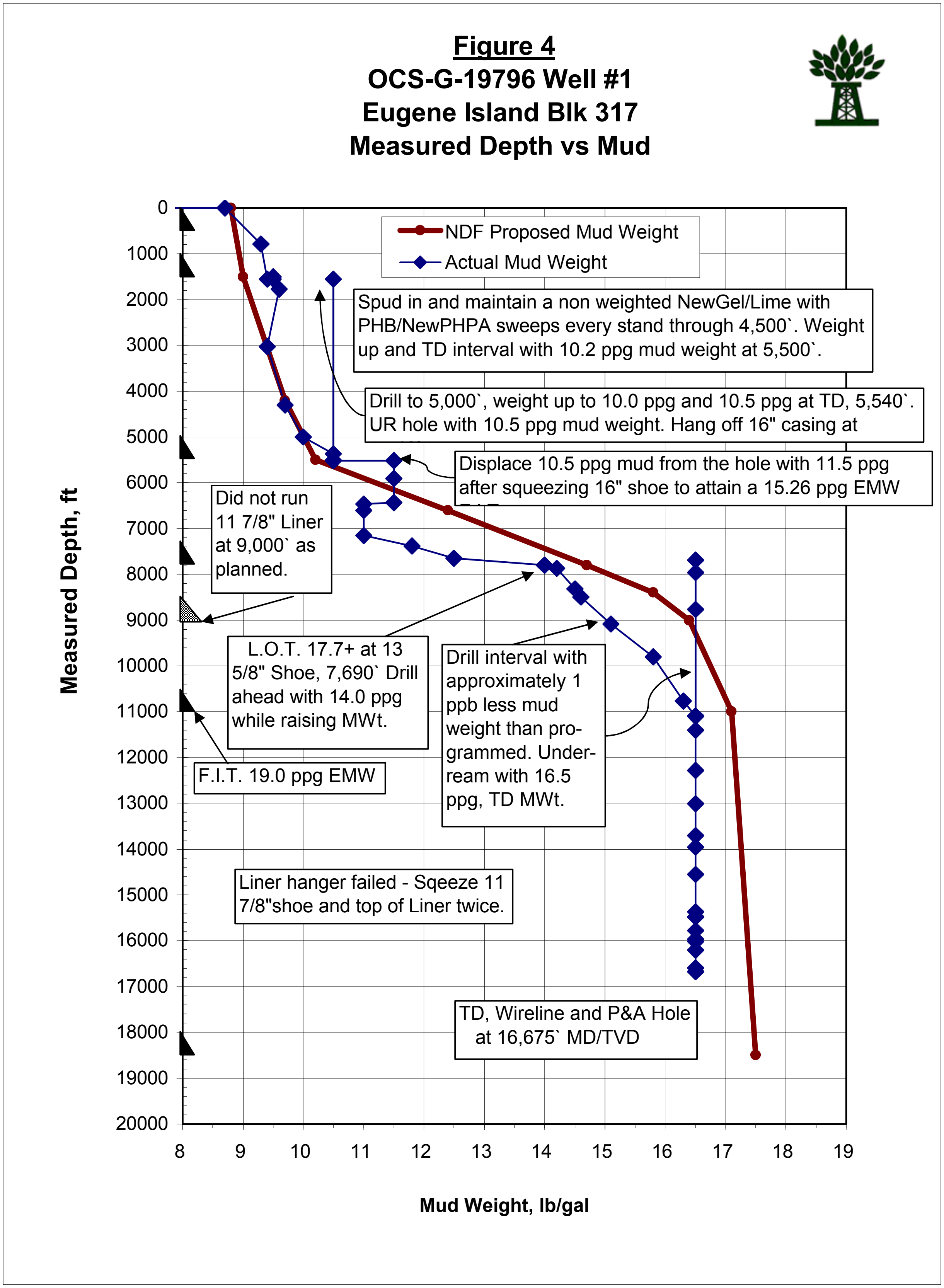
Figure 4
OCS-G-19796 Well #1
Eugene Island Blk 317
Measured Depth vs Mud
NDF Proposed Mud Weight
Actual Mud Weight
Spud in and maintain a non weighted NewGel/Lime with PHB/NewPHPA sweeps every stand through 4,500`. Weight up and TD interval with 10.2 ppg mud weight at 5,500`.
Drill to 5,000`, weight up to 10.0 ppg and 10.5 ppg at TD, 5,540`. UR hole with 10.5 ppg mud weight. Hang off 16" casing at
Displace 10.5 ppg mud from the hole with 11.5 ppg after squeezing 16" shoe to attain a 15.26 ppg EMW
Did not run 11 7/8" Liner at 9,000` as planned.
L.O.T. 17.7+ at 13 5/8" Shoe, 7,690` Drill ahead with 14.0 ppg while raising MWt.
Drill interval with approximately 1 ppb less mud weight than pro-grammed. Under-ream with 16.5 ppg, TD MWt.
F.I.T. 19.0 ppg EMW
Liner hanger failed - Sqeeze 11 7/8"shoe and top of Liner twice.
TD, Wireline and P&A Hole at 16,675` MD/TVD
Measured Depth, ft
Mud Weight, lb/gal
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
8
9
10
11
12
13
14
15
16
17
18
19

Photo 1 – Offshore Adriatic Sea

Cuttings at the shakers, 16-in. section.