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Extensive Pre-Well Integrated Modeling Aids in Successful Drilling of Challenging Well: A Case Study

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Abstract

A North Sea operator intended to drill a large-diameter well in an area where wellbore (in)stability was an issue. Previously, problems were experienced while drilling a deep shale formation at high hole angles. A wellbore (in)stability study was performed to help optimize mud weight requirements in the intermediate intervals, and mud weight ranges were identified to aid in minimizing drilling problems. Once the appropriate mud weight ranges were identified, attention then turned to Equivalent Circulating Density [ECD] predictions, especially important in the large diameter interval. The limited mud pump capacity coupled with the planned large diameter wellbore served to compromise hole cleaning efficiency, which in turn complicated control of ECD. Pre-well hydraulic simulations were run to obtain predictions of ECD as functions of several drilling parameters as well as mud weight. Results of the modeling efforts were incorporated in the operator’s drilling program and are described in a separate paper presented at this same conference.

Introduction

Challenging ERD wells require an integrated approach in the pre-well planning process to help maximize success in the drilling operation. Often wellbore trajectories are highly-deviated, and problems such as wellbore (in)stability and hole cleaning typically arise. While these two areas are usually dealt with separately, they are more often co-mingled issues: good hole cleaning is difficult to maintain when wellbore (in)stability problems are present, and a hole often becomes unstable when good hole cleaning is lacking.

With the changing mud weight window between the minimum mud weight and the maximum allowable mud weight at increasing hole angle, the need to control ECD while cleaning the wellbore became increasingly important. ECD issues were further complicated by limited mud pump capacity that compromised hole cleaning efficiency and by the large hole diameter proposed for the interval containing the bend and the bend section.

In this study, drill pipe rotation speed, drill pipe size, rate of penetration, cuttings size, and pump output were evaluated as functions of Hole Cleaning Efficiency [HCE]. The resulting circulating pressure drops and annular mud weight including drilled cuttings were then converted to values of ECD. These predictions were then given to the Operator for use in their pre-well planning.

Well Design

The well discussed in this paper was drilled as an extended-reach platform development well. The planned wellpath is found in Figure 1. Wellbore stability issues were raised in both the interval containing the kick-off point and in the following interval that contained the tangent section. Information pertinent to both intervals is presented in this paper.

Only in the large-diameter interval immediately under the 20-in casing were hole cleaning and hydraulics issues considered particularly demanding. Hence, the hydraulic issues raised in this paper are pertinent only to the large-diameter interval. In this interval, after kicking-off, the angle was quickly built to 40° and held there until near the end of the interval, where deviation increased to 65° from vertical.

Wellbore Stability Modeling

Borehole instability in shales in most cases arises from insufficient hydrostatic support on the borehole wall, resulting from either inadequate mud pressure gradient or a time-dependent increase in near-wellbore pore pressure. An increase in water content in the near-wellbore region will result in lowered shale strengths[1]. The movement of water in and out of a shale is governed by a number of mechanisms[2]. The most influential mechanism[1, 3] involves the hydraulic pressure difference (ΔP) between the wellbore pressure and the shale pore pressure and the chemical potential differences (Δu) between the drilling fluid filtrate and the shale pore fluid. Supposing the shale was drilled in the presence of a fluid of correct density, such that tensile or shear failure (inadequate mud weight) or tensile fracturing (excessive mud weight) do not occur, then there are three mechanisms which exposure to the drilling fluid may cause instability with time:

- elevation of near-wellbore pore pressure due to mud pressure invasion, leading to an effective reduction in mud pressure support
- elevation of swelling pressures (e.g. due to inappropriate cation selection leading to unfavourable cation exchange at clay sites), that reduce effective stresses
- chemical alteration and weakening of shale matrix cementation bonds.

Because oil-based muds (OBM) and water-based muds (WBM) function differently in the presence of reactive shales, each will be discussed individually.

Oil-Based Muds. The effectiveness of OBM in stabilising shales has been well documented. The osmotic transport of water from the shale to the OBM through a semi-permeable membrane provided by the OBM emulsifiers has long been regarded as the fundamental driving mechanism. Laboratory data presented previously [1,2,3] based upon the two fundamental driving forces (ΔP and Δu) and hydraulic and osmotic transport mechanisms are used to explain why an OBM is effective in stabilizing shales:

- the presence of threshold capillary entry pressures between the OBM and low permeability shales.
- These capillary entry pressures are translated to a net compressive radial stress on the borehole wall that promotes hole stability.

Laboratory experiments confirm the theory that the OBM emulsifier surrounding discrete water droplets can provide the characteristics of a semi-permeable membrane, which allows the osmotic transport of water to or from the shale. The OBM water phase activity (molar free energy) is manipulated to help ensure water is transported from the shale. This can lead to an increase in shale strength in the near-wellbore region.

Water-Based Muds. WBM / shale interaction is more complex than a OBM / shale system, since the hydraulic pressure difference lies in communication[4]. The net compressive radial stress at the wellbore wall dissipates with time until there is pressure equalization between the wellbore and the shale (ΔP=0). At this point, there is no effective mud pressure support against the shale, and the shale will fail. The severity of this occurrence depends on a number of factors, not least of which are shale permeability and the magnitude of ΔP.

Since shale mineralogy varies across the whole spectrum of argillaceous materials, it would seem almost impossible to design a WBM which would be capable of eliminating changes in swelling pressures and cementation integrity. For example, potassium ion (K^+) may be useful in inhibiting swelling of montmorillonite clays, has little or no effect on illites, and may increase swelling pressures in kaolinite.

It was recognised by researchers[1,2] that the low permeability, clay-rich matrices of intact shales exposed to WBM may act as a non-ideal membrane, since the mobility of solutes through the pore network varied with solute type and was a function primarily of the solute hydrated radius. Hence, the term “membrane efficiency” has been used to characterize the ability of WBM to control the flow of water from shale. Laboratory measurements of membrane efficiency of many WBM fluids have been made[5]. For example, using Pierre II shale, the membrane efficiency of a 20 wt% KCl brine solution has been measured at 6.0%, a level much lower than the membrane efficiency levels of OBM which theoretically are 100%.

Area Geology

Based on the Formation Evaluation and Gas Analysis Log a few general descriptions of the lithology could be discerned. The formations from 2000 ft to 6000 ft TVD can be broadly described as shale or mudstone type with soft bulky fissile shale interspersed in a few layers. The three main geologic markers are Miocene, Oligocene and Eocene.

The focus of the current wellbore stability analysis was on wells drilled through the lower Miocene and below. Rose plots of the fault orientations in each event confirm that there is no preferred fault orientation from horizon to horizon.

Chemical Potential Model

The chemical potential borehole stability model used in the current analysis addresses key issues in modeling borehole (in)stability problems for high angled extended reach applications [1,3]. The model’s computer program utilizes contemporary programming techniques and outputs information in terms of the mud weight as a function of hole angle and optimum salinity (for oil based muds). In modeling, the two dominant factors are considered:

- In the case of OBM, a continuous oil phase exerts a confining pressure on the borehole wall. This is because the mud-column pressure in most cases exceeds the formation pressure and does not exceed the threshold capillary entry pressure. In the case of WBM, the net radial support offered by the continuos phase may be altered over a period of time due to mud pressure penetration.
- The difference in the molar free energies of the water dispersed in the oil-based mud and the shale provides the mechanism for the hydration or dehydration of the shale. In the case of WBM, the

molar free energies of all the constituents within the shale and the WBM provide the driving forces for ionic and water transport into and out of the shales.

At any given time, the stability issue is ultimately controlled by the relationship between the borehole stress-state and the rock strength.

Previous Problems Encountered

Previous wells drilled from the platform have had trajectories that built hole angles to 82 degrees in the deeper 12 1/4" hole interval. The high angle of attack into a problematic shale at 12800-13000 ft TVD has been a source of several hole instability occurrences. These instabilities were mainly in the form of hole pack-offs and collapse primarily due to weak rock strength and laminated structure of the shale. As a consequece of the borehole instability, a field-scale wellbore stability analysis was conducted. The final results of mud weight predictions as a function of hole angle and well direction are presented in Figure 2. The angle and azimuth information at 13,000 ft TVD of two offset wells (A and B) are shown on the minimum mud weight predictions polar chart in Fig. 2. Table 1 contains the data used in the analysis.

Conclusions from the wellbore stability study included:

- The higher hole angles in directions perpendicular to the orientation of the maximum horizontal stess required higher mud weights relative to wells drilled in the directions of the maximum horizontal stess.
- The higher deviation angles required higher mud weights that were thought to be destabilizing the problem shale on a time-dependent basis. As a result, the higher densities served to increase mud pressure penetration into the weak shale laminations.
- The laminations in the shale limited the angle of attack due to weak bedding plane-related rock strength anisotropy. This meant that when the well trajectory was parallel to the bedding planes more hole collapse problems were observed as compared to when the well trajectory was perpedicular to the bedding planes, where relatively fewer hole collapse problems were observed.

The findings of the wellbore (in)stability study supported changing the well trajectory design for the upcoming well so that the problem shale encountered in the 12-1/4 inch hole interval would be drilled at lower angle to help reduce instability problems. This change in the well design required a shallower depth for the kick-off point and the build-and-hold section in the previous large-diameter interval.

Hole Stability Modeling for the Large-Diameter Interval

After the initial data gathering exercise, a borehole stability analysis was performed for the large-diameter interval. Table 1 includes the modeling input parameters used. Results of the borehole stability analysis are presented in Figure 3. The reported mud weights used to drill the interval are also shown in Figure 3.

No significant hole instability problems were observed while drilling the hole interval. To help minimize mud pressure penetration into the shale zones, the mud weights used while drilling were maintained slightly above the minimum level required for shale stability.

Hole Cleaning Modeling Theory.

Once the mud weights required to maintain a stable borehole were identified, the pre-well planning study then focused on hole cleaning in the large-diameter interval below the 20-in casing.

The hole cleaning calculation methodology used in this paper were developed from earlier steady-state hole cleaning modeling work [6, 7]. Key parameters involved in hole cleaning modeling include:

- Mud density
- Fluid rheological parameters
- Cuttings size and shape
- Pump rate
- Hole geometry
- Drill pipe eccentricity
- Hole angle

Since publication of the earlier papers, two more major factors were integrated into the calculations. These factors, described by others [8, 9] include:

- Drill pipe rotation
- Rate of penetration

To quickly summarize the model's numerical methods, the following important items are calculated:

- The fluid rheological parameters are calculated using the Herschel-Bulkley rheological model. The numerical model and its parameters have been described previously [10].
- With estimated values for drill pipe eccentricity, the point velocities in all sections of the annulus are calculated using numerical techniques.
- Particle settling velocities for both static and dynamic cases are calculated using the methodology proposed earlier by Chien [11].
- A fine-mesh grid scheme valid for eccentric wellbore is used to model the annulus cleaning efficiency.
- The volume of cuttings removed by drill pipe rotation for the input drilling conditions is

approximated and adjusted for ROP.

- Dimensionless cuttings bed height predictions are calculated as fractions of the annular diameter projected to be covered by a permeable cuttings bed. This prediction corresponds to the case where flow rate and drill pipe rotation ceases and all cuttings settle on the low side of the hole.
- With the effect of drilled cuttings taken into account, the calculated pressure drops and circulating annular mud densities for each section of a wellbore are integrated together to arrive at a final annular mud weight and ECD.

Hole Cleaning and Hydraulic Modeling

Once the proper mud weight was determined for use in drilling the large-diameter interval below the 20-in casing shoe, hole cleaning and hydraulic simulations were initiated. The goal of the extensive pre-well simulation process was to determine the ranges of various drilling fluid and operational parameters that would provide good hole cleaning while drilling with WBM and keep ECD below the fracture gradient.

Many variables were investigated in the pre-well planning process, which included:

hole diameters:	17.5-in and 16-in
drill pipe sizes:	5.5-in and 6.625-in
hole deviation:	40° and 65°
average cuttings diameters:	0.25-in to 0.75-in
drill pipe rotation speed:	50 – 110 rpm
drilling fluid rheological properties	

A water-based drilling fluid having the rheological properties and density as shown in Table 2 and Figure 4 [Fluid 1] served as the principal test case for hydraulic simulations. As this fluid was a WBM subjected only to moderate temperature and pressure conditions downhole, surface fluid density and rheological properties were not adjusted for downhole conditions. However simulations were later run to help determine the effect of increasing the WBM rheological properties on hole cleaning.

Hole angle. Two hole angles were used in the simulations: 40° for the upper part and 65° for a short section near the bottom of the 16-in interval.

Hole and drill pipe sizes. All hole cleaning modeling was done using the 2 hole ID and 2 drill pipe OD sizes. The Operator had a two-fold purpose here:

1. They wanted to see how much worse cleaning would be with a 17.5-in bit compared to cleaning with a 16-in bit.
2. With each hole diameter, the Operator wanted to compare predicted cleaning with 5.5-in drill pipe compared with that using 6.625-in drill pipe.

In Figure 5, cleaning simulation results are shown for the 4 hole-size / drill pipe combinations at 40°, and Figure 6 contains similar results at 65°.

The results at 40° show that good cleaning was to be expected for 0.25-in diameter cuttings at the pump rates used in the simulations. As expected, cleaning efficiencies improved with increasing pump rate and smaller hydraulic diameter. In the simulations at 65°, HCE predictions were lower than those at 40°. Moreover, the spread between the simulation results widened significantly.

Cleaning efficiency in the high angle sections [> 40° from vertical] can also be evaluated using cuttings bed height [CBH] simulations. Using the predicted cuttings accumulation values generated in the hole cleaning program and a given value for cuttings bed permeability, a CBH result can be calculated. This value represents the case where the mud pumps are turned off and all debris falls to the low side of the hole. The height of the cuttings bed and the relative position of the drill pipe can be readily depicted and a second set of cleaning estimates can be generated.

Figure 7 contains CBH predictions for the same cases cited above at 65°. The position of the bottom of the drill pipe is shown for the 16-in / 6.625-in case. The results predict that roughly 20-25 % of the annular gap is covered in drilled cuttings when pump rates are 800-1000 gpm. Only when the pump rate is 1200 gpm do the bed height predictions fall at or below the bottom side of the drill pipe. In agreement with earlier HCE results, less annular accumulation is expected with increasing pump output and reduced hydraulic diameter.

Effect of average particle diameter. The effect of particle diameter on hole cleaning was also investigated. Particle size can significantly affect particle slip velocity under static conditions, and the effect is even greater under dynamic conditions. In the simulations performed here, a range of particle sizes from 0.25-in to 0.75-in average diameter was simulated for the two deviation angles.

Figure 8 shows the simulation results for the 4 hydraulic diameter cases at 40° from vertical. In these simulations, pump output was held at 1000 gpm with 80 rpm rotation speed on the drill pipe. A similar set of simulations at 65° is depicted in Figure 9. As expected, the results show that cleaning efficiency decreases with increasing particle size, and the effect is more pronounced at the higher hole angle. These results indicated to the Operator that a less-aggressive bit that would cut smaller cuttings would be preferred given the operational constraints of this interval [large-diameter hole, pump pressure limits, etc].

Fluid rheological properties. As part of the optimization process in the pre-well planning phase, the effect of increasing fluid rheological properties on hole cleaning was investigated. A WBM [depicted as Fluid #2 in Figure 4] having elevated rheological parameters as listed in Table 1 was included in the simulation matrix.

HCE predictions by pump output for the entire annulus are shown in Figure 10 for the two WBM rheological profiles. Here the average cuttings diameter and drill pipe rotation speed were held at 0.25-in and 80 rpm respectively. Results show little apparent change in cleaning for the two cases simulated. However, velocity modeling studies in eccentric wellbore[12] have clearly demonstrated that there can be a wide divergence in fluid velocity above and below the eccentric drill pipe. Increased fluid rheological properties serve to exacerbate the resulting flow diversion, often resulting in little to no flow under the drill pipe. With no fluid movement under the drill pipe, cleaning at elevated hole angles suffers. Hence to properly evaluate cleaning in eccentric wellbore, cleaning under the drill pipe must also be investigated[7].

In these studies, the annular area lying immediately under the rotating drill pipe was also evaluated for cleaning efficiency. Except for cases where the drill pipe is in a concentric position, cleaning in the narrow part of the annulus should never be as efficient as it is in the wide part of the annulus. However, for good hole cleaning performance at elevated hole angles in the field, HCE values should not hover at the 0 or near-zero level. At these very low levels of HCE, cleaning is nearly entirely dependent upon the mechanical effects of drill pipe rotation.

Figure 11 demonstrates that the higher-viscosity Fluid 2 would clean under the drill pipe much less efficiently than the base Fluid 1. Cuttings removal under the drill pipe for Fluid 2 ranges between 25-33% of that for Fluid 1. In the 65° section near the end of the large-diameter interval, use of a high-viscosity fluid to enhance drilling performance is not recommended.

Predicted Equivalent Circulating Densities.

With the results of the hole cleaning simulations in hand, ECDs with cuttings in the annulus were predicted using the following input parameters:

Hole ID	16-in
Drill pipe OD	5.5-in and 6.625-in
Pump output	800 – 1200 gpm
Rate of penetration	50 – 100 ft/hr
Cuttings diameter	0.25-in

Figure 12 shows the ECD predictions by pump rate and hole angle. Circulating with no ROP gave a baseline ECDs of 12.12-12.13 lbm/gal eq. With the ROP levels simulated, ECDs were predicted to rise to 12.35 - 12.45 lbm/gal eq. As expected, the higher the rate of penetration, the higher the predicted ECD. In Figure 13, only the data at 1000 gpm is shown, and the predicted increase in ECD with increasing ROP is more evident. These predicted ranges were well within the Operator's pore pressure–formation fracture gradient window.

Drilling of the ERD well.

In the first half of the year 2000, the 20-in casing was drilled out and the well was TD'd a few weeks later. The planning of the drilling operation, mud system selection, etc. are described in a companion paper presented at this same technical forum[13].

After the extensive pre-well planning efforts, the Operator decided to drill the large-diameter with a WBM having density and rheological properties similar to those recommended here. To help reduce potential hole cleaning problems below the 20-in casing, a 16-in diameter hole was drilled instead of a 17.5-in hole. A tandem 5.5-in / 6.625-in drill string was used, with the larger pipe placed in the lower part of the hole where hole angles ranged from 40° to 64° from vertical. Hole cleaning problems were minimal and the large diameter hole was cased with 13.375-in pipe shortly thereafter.

The 12.25-in and 8.5-in intervals that followed were drilled routinely with a low-toxicity paraffin-based mud.

Actual Equivalent Circulating Densities

Pressure-while-drilling [PWD] tools were used while drilling the well to monitor downhole circulating pressures. Three points near the end of the large diameter interval were selected for study of circulating ECD. For each of the selected points, rotary drilling operations were in progress [eg, no sliding] and all necessary data incluidng BHA configuration were available. Actual PWD results were compared with results using the same hydraulic / hole cleaning model used in the pre-well planning. Key drilling parameters used in the comparison are found in Table 3.

The results show very good agreement between the model predictions and actual field data. Average errors in ECD predictions were:

Average error	0.073 lbm/gal eq
Average % error	0.60 %

Figure 14 shows the measured and predicted ECD and actual mud weights for the three cases. As noted earlier, pre-well predictions of ECD under simulated drilling conditions ranged from 12.35-12.45 lbm/gal eq. Some differences in ECD values between the predictions and the actual are expected since various drilling parameters [eg, ROP, drill pipe rpm, fluid rheology, etc.] used while drilling were different from those used in the simulations. The results show that predictions made in the pre-well planning process can closely approximate field results when similar operating parameters are used. With enhanced advances in hydraulic modeling, these predictions are now better than "ballpark" estimates.

Pre-Well Planning Conclusions

Once the many simulation runs were made in wellbore (in)stability and hole cleaning modeling, the following conclusions resulted:

- Using key input parameters, the wellbore (in)stability model was successfully used to predict both the maximum and minimum mud weights as functions of hole angle and azimuth.
- A mud weight of 12 lbm/gal would be required to drill the large-diameter interval and keep the shale section stable. The minimum mud weight predictions were very close to the actual mud weights used while drilling the 16-in interval.
- A pump rate somewhere between 1000 and 1200 gpm would provide good cleaning in the large-diameter interval. Better hole cleaning efficiency can be expected with increased pump output.
- A WBM having a rheological profile similar to that of Fluid 1 was recommended. Use of high viscosity fluids similar to Fluid 2 should be avoided in the high angle sections.
- The particle diameter of drilled cuttings was demonstrated to be an important factor for hole cleaning efficiency in the large diameter interval. Less aggressive PDC bits with reduced cutter diameters were recommended so smaller cuttings would be cut and cleaned from the wellbore.
- A maximum ECD of 12.35-12.45 lbm/gal could be expected while drilling with a 12 lbm/gal Fluid 1 in the simulated operating ranges.
- The ECD measured near the bottom of the 16-in interval agreed quite closely with those generated in the pre-well planning.
- The hole cleaning and hydraulic model used in this study proved to be quite useful in the pre-well planning process as well as in the post-well analysis.

Acknowledgements

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Nomenclature

BHA = bottomhole assembly
ECD = equivalent circulation density
EMW = equivalent mud weight
H-B = Herschel-Bulkley rheological model
H-B 'K' = fluid consistency index [plastic viscosity]
H-B 'n' = fluid flow index
H-B τ_0 *= yield stress*
API PV = plastic viscosity using API protocol
ROP = drilling rate of penetration
rpm = revolutions per minute
TD=total depth
TVD=true vertical depth
API YP = yield point using API protocol

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Table 1: Input parameters for the borehole stability analysis for 12.25- and 16-inch intervals.

Parameter	16-in	12.25-in
Hole Size (inch)	16.00	12.25
Modeled TVD-SS (ft)	6000	13000
Overburden Stress Gradient, S_v (psi/ft)	0.79	0.94
Max. Horizontal Stress Gradient, S_H (psi/ft)	0.68	0.72
Min. Horizontal Stress Gradient, S_h (psi/ft)	0.67	0.70
Pore Pressure, P_o (psi/ft)	0.452	0.47
Mohr-Coulomb Cohesion (psi)	100	1083
Mohr-Coulomb Friction Angle (deg)	25.2	32
Tensile Strength (psi)	0	50
Young's Elastic Modulus (psi)	740,000	100,000
Poisson's Ratio	0.32	0.25
Skempton's Coefficient*	0.93	0.92
Undrained Poisson's Ratio*	0.43	0.36

Assumed

Table 2: Drilling Fluid Properties Used in Pre-Well Simulations

Property	Fluid 1	Fluid 2
600 rpm	80	90
300 rpm	56	67
200 rpm	45	57
100 rpm	33	45
6 rpm	13	24
3 rpm	11	22
API PV [cP]	24	23
API YP [lbf/100 ft^2]	32	44
H-B 'n'	0.59	0.55
H-B K lbf/100 ft^2 s^n]	1.25	1.65
H-B τ_0 [lbf/100 ft^2]	8.0	18.0
Mud weight [lbm/gal]	12.0	12.0

Table 3: Key Parameters Used in ECD Calculations

Parameter	Point 1	Point 2	Point 3
Measured depth [ft]	8081	8654	8844
True vertical depth [ft]	7030	7340	7423
Hole angle [degrees]	46	63	64
Mud weight [lbm/gal]	12.0	12.0	12.2
Avg. particle diameter [in]	0.25	0.25	0.25
Pump output [gpm]	1068	1095	1100
H-B ‘n’	0.58	0.54	0.61
H-B K lbf/100 ft^2 s^n]	1.36	2.00	1.07
H-B τ_0 [lbf/100 ft^2]	7.8	6.2	6.9
ROP [ft/hr]	104	29	64
Drill pipe speed [rpm]	119	118	116

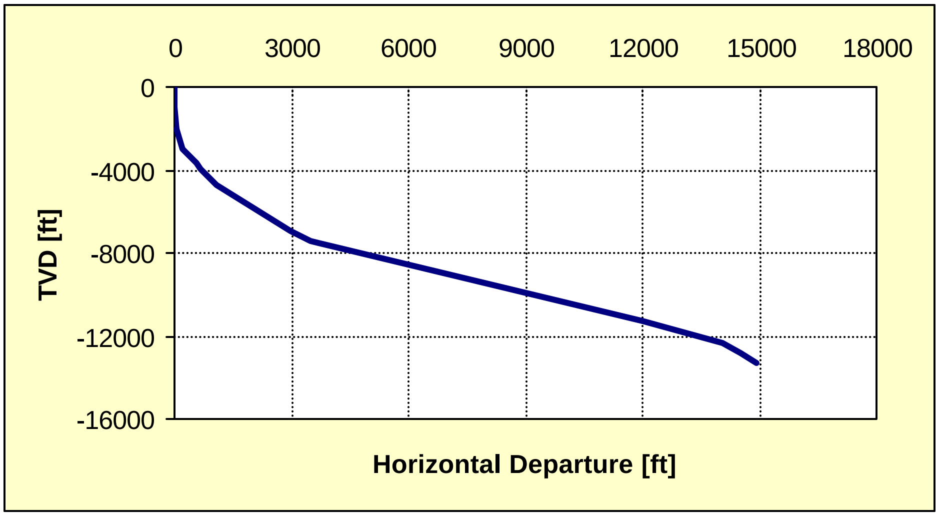
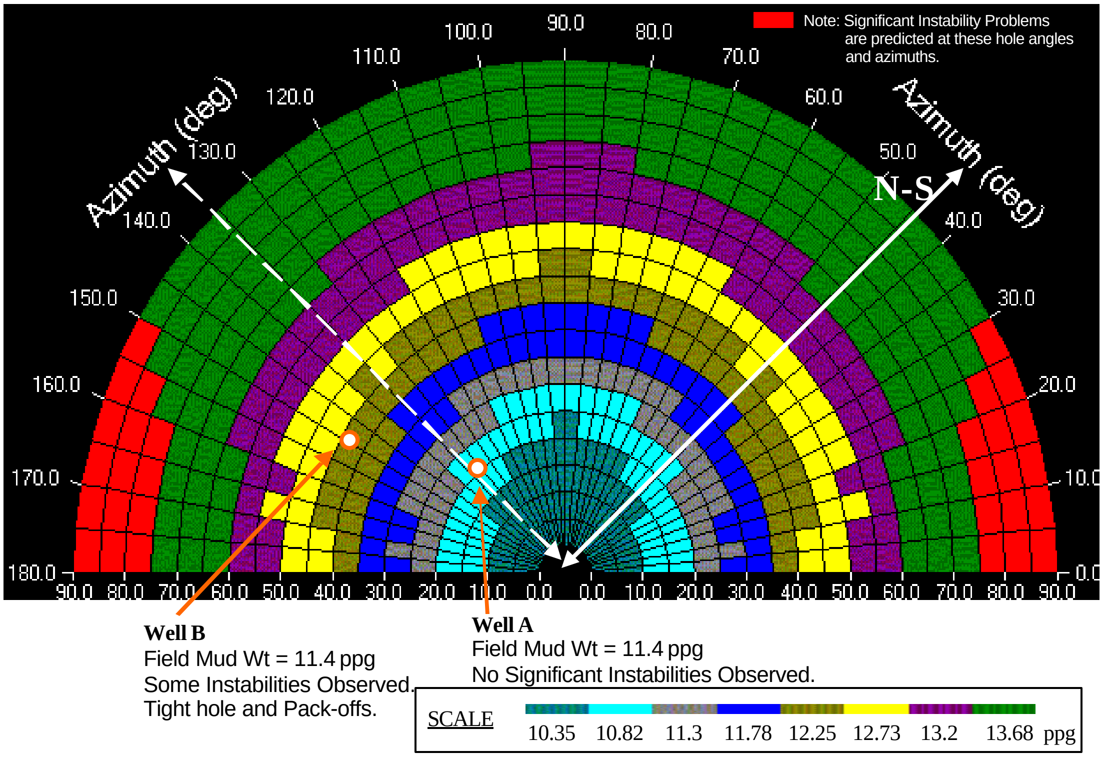


Figure 1: Wellpath of ERD development well.



Polar Chart for Predicted Mud Weight to Prevent Shear Failure (Collapse)

Modeling TVD = 13000 ft, 6%Horizontal Stress Anisotropy, Poro-elastic Analysis

🟥 Note: Significant Instability Problems are predicted at these hole angles and azimuths.

Well B
Field Mud Wt = 11.4 ppg
Some Instabilities Observed.
Tight hole and Pack-offs.

Well A
Field Mud Wt = 11.4 ppg
No Significant Instabilities Observed.

Figure 2: Minimum mud weight predictions as a function of hole angle and azimuth for the 12-1/4-inch interval.

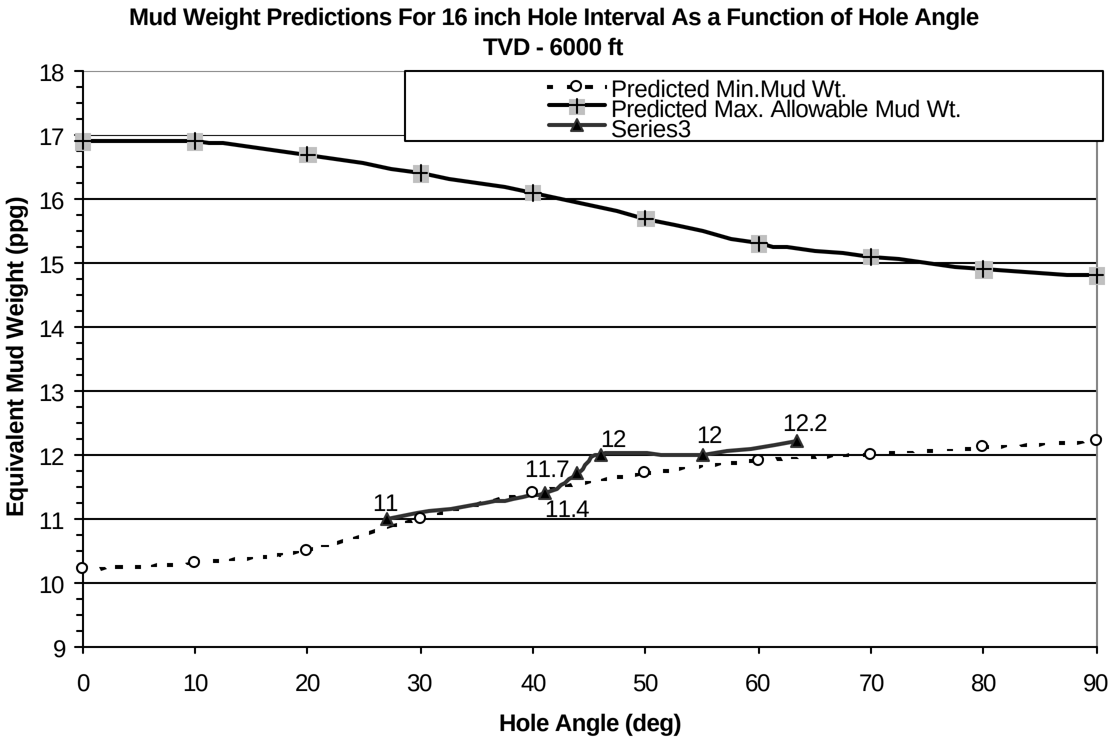


Figure 3: Mud weight predictions as a function of hole angle for the 16 inch hole interval**.**

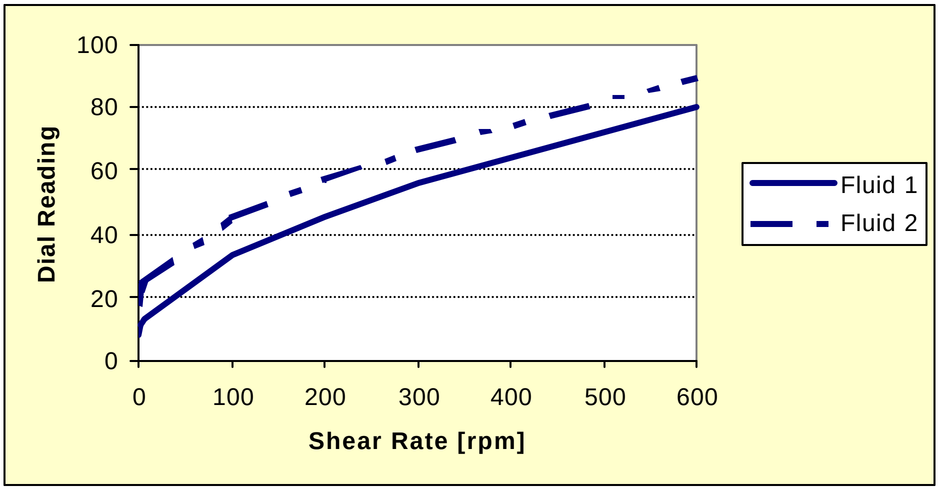


Figure 4: Rheological profiles of WBM Fluid #1 and #2.

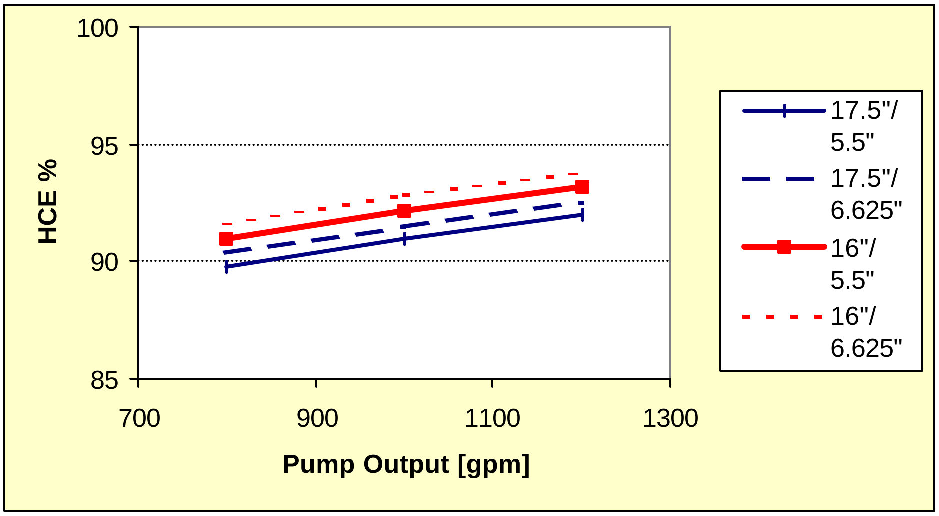


Figure 5: Hole Cleaning Efficiency Predictions for 4 cases at 40°, 0.25-in cuttings.

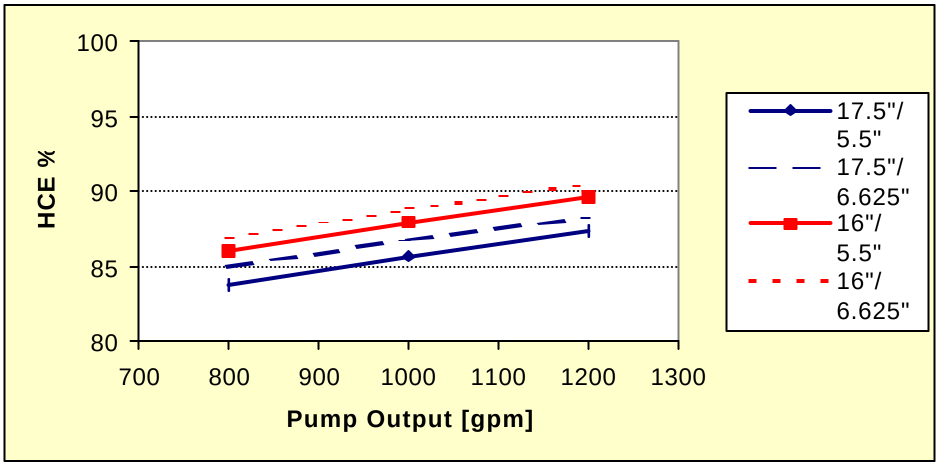


Figure 6: Hole Cleaning Efficiency Predictions for 4 cases at 65°, 0.25-in cuttings.

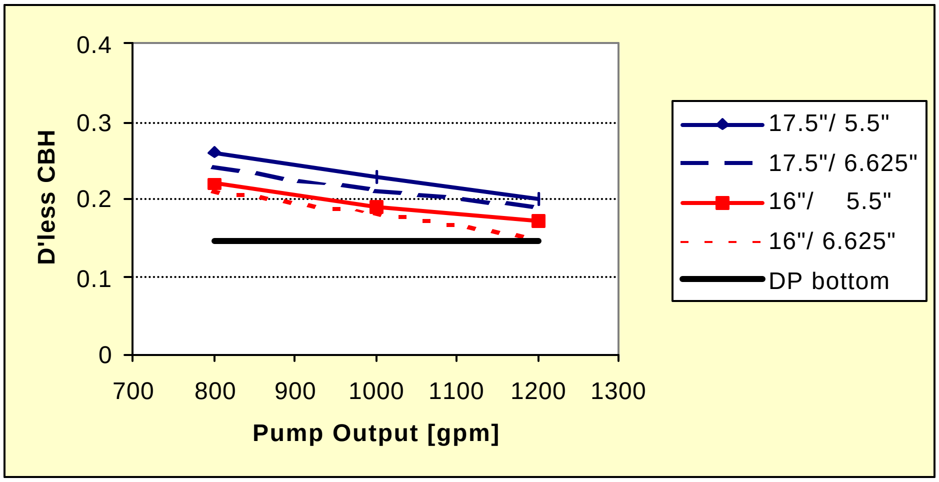


Figure 7: Cuttings Bed Height predictions for 4 cases at 65°, 0.25-in cuttings.

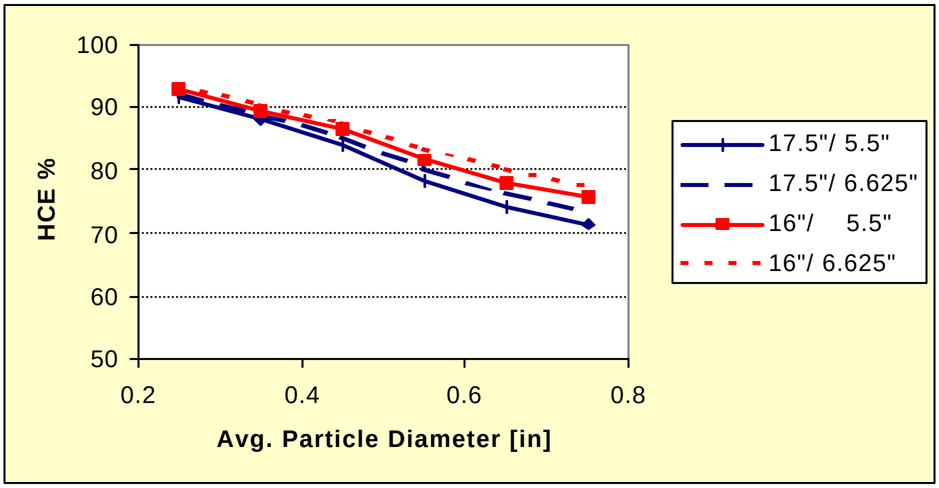


Figure 8: Effect of average particle size on cleaning at 40°, 1000 gpm.

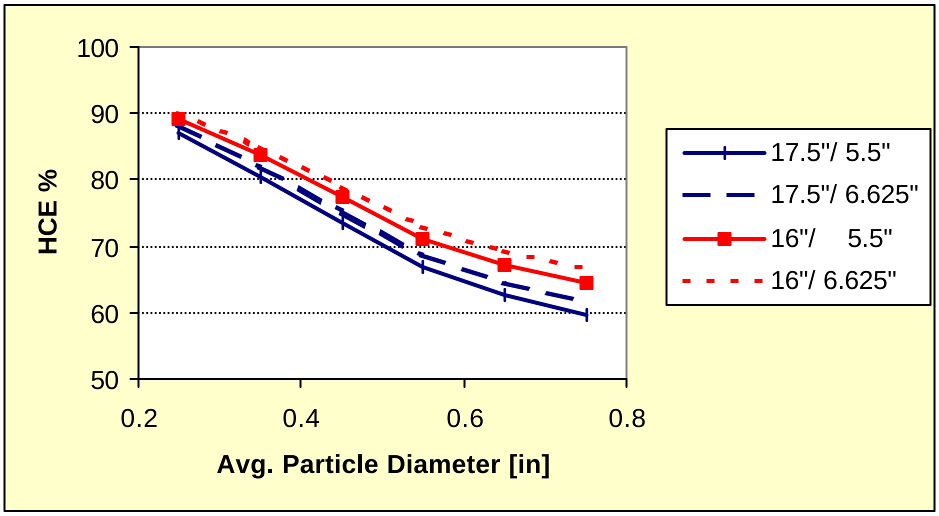


Figure 9: Effect of average particle size on hole cleaning at 65°, 1000 gpm.

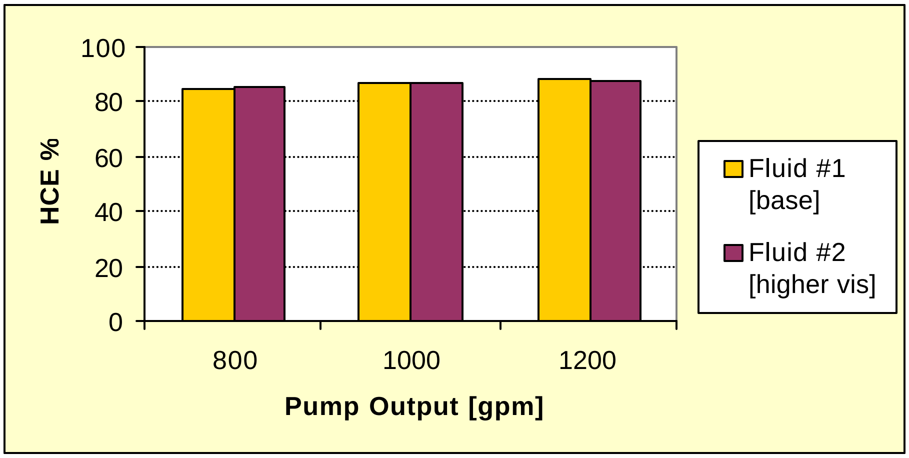


Figure 10: Effect of increased rheological properties on cleaning in the full annulus, 65°, 0.25-in cuttings.

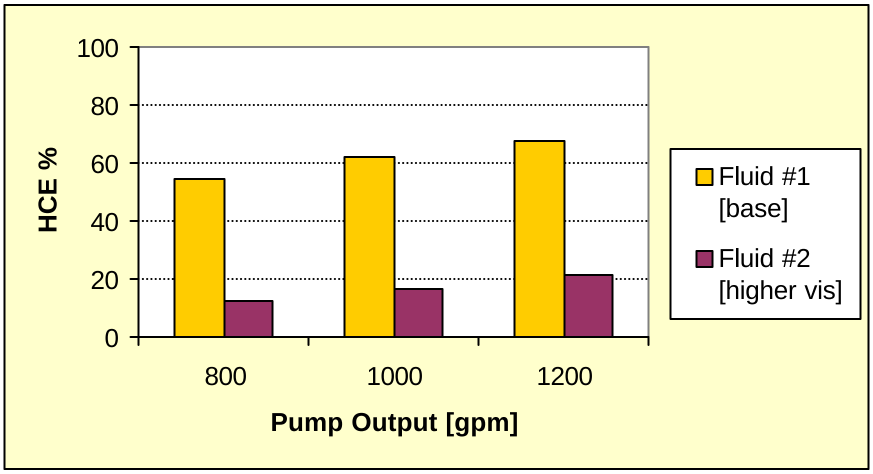


Figure 11: Effect of increased rheological properties on cleaning under the drill pipe, 65°, 0.25-in cuttings.

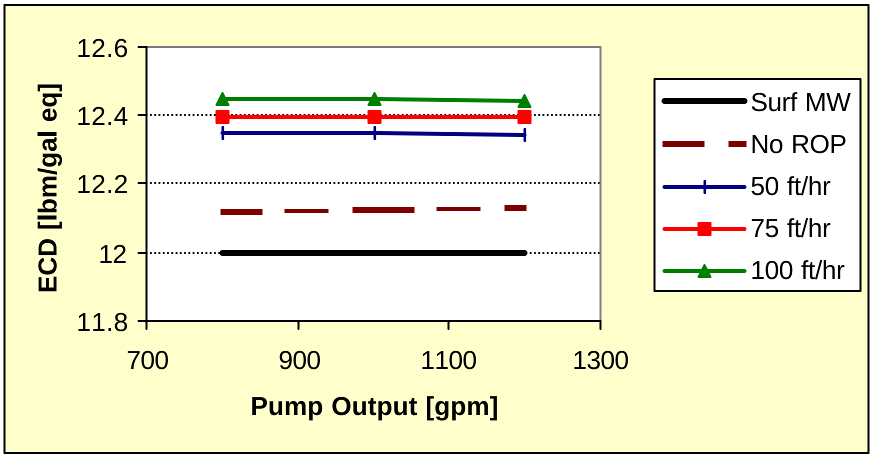


Figure 12: ECD Predictions by pump rate and ROP for Fluid #1, 16 x 6.625-in.

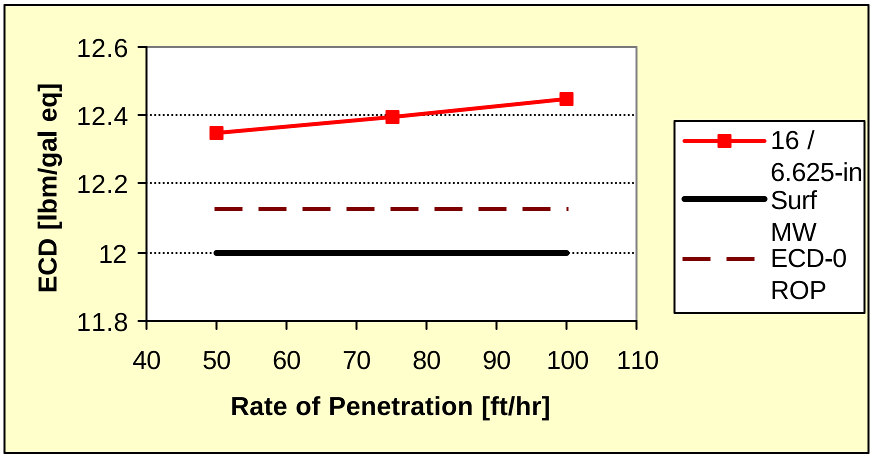


Figure 13: ECD Predictions by ROP for Fluid #1, 1000 gpm, 16 x 6.625-in.

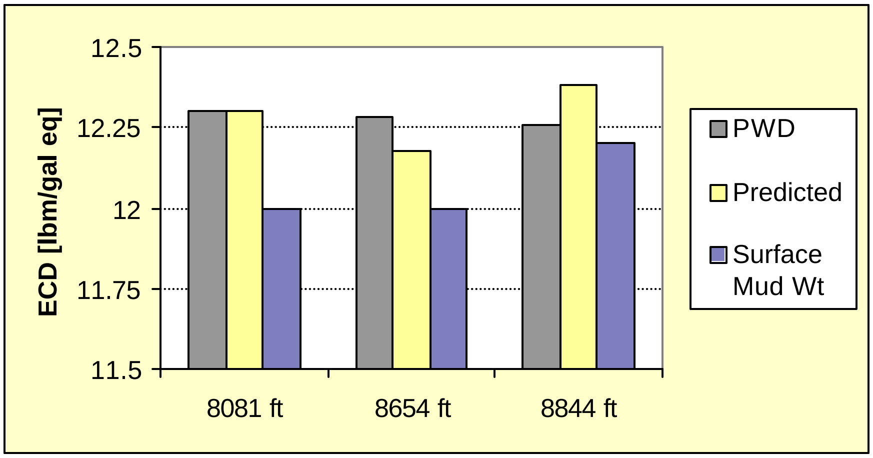


Figure 14: Measured and Predicted ECDs and surface mud weights while drilling at 3 points near end of 16-in interval**.**