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Manipulation of the Water Phase Salinity of Invert Emulsion Drilling Fluids to Widen the Safe Drilling Window

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Abstract

In today's increasingly complex well designs, often the range in drilling fluid densities required to prevent hole collapse without fracturing the wellbore (e.g., the safe drilling window) is narrow. This case is often seen in deepwater wells and in wells having high angles of deviation, and hence is very pertinent to drilling extended-reach drilling (ERD) wells. With increasing step-outs, the drilling equivalent circulating density (ECD) continues to climb with increasing measured depth (MD) while the true vertical depth (TVD) remains fairly constant. The net result can be that as horizontal departure lengths continue to increase, the drilling ECD violates the safe drilling window.

Recently, studies[1,2,3] were presented to the industry in which the effect of changes in the water phase salinity (WPS) of invert emulsion drilling fluids (IEF) were investigated as a function of rock strength for two very different shales: a deepwater West Africa shale and a more-competent Oklahoma shale. After a 3-hr exposure time, the changes in rock strength with different WPS levels were measured directly and results were qualitatively consistent for the two shales.

In this paper, the effect of changes in the WPS of invert emulsion fluids on the safe drilling window is demonstrated in two different scenarios: a deepwater case and an ERD case. The respective safe drilling windows are simulated with conventional elastic rock modeling using parameters outlined in the two scenarios.

This work demonstrates that there are extra 'tools in the toolbox' that can have positive effects on widening the safe drilling window in complex wells. In such cases the chemistry of the invert emulsion can play a significant role in providing for increasing well step-outs to be drilled.

Introduction

The drilling of challenging wells is often characterized by a narrow safe drilling window, which is bounded on the top by the fracture initiation pressure and on the bottom by the wellbore hole collapse pressure. A schematic of a typical safe drilling window is seen in **Fig. 1**. The safe drilling window is commonly gauged in terms of equivalent mud weight (EMW) and represents the acceptable range of density acceptable for maintaining wellbore stability. When wellbore is circulated, as during drilling operations, the EMW is equivalent in value to the ECD. When the wellbore is static the EMW is equivalent in value to the equivalent static density (ESD). Depending on the downhole pressure and temperature conditions, the ESD is often not the same in value as the density measured under ambient conditions, something especially true when invert emulsion drilling fluids are used.

As is seen in Fig. 1, the safe drilling window becomes more narrow with increasing hole angle, since the deviated wellbore profile requires increased EMW to prevent collapse but at the same time reduces the pressure required to initiate fractures. Hence in ERD wells, the safe drilling window can become very narrow at the higher angles of deviation, as is shown in **Fig. 2**.

In the drilling of ERD wells with long departures, the ECD will continue to increase with increasing measured depth, as the frictional pressures produced while circulating increase with hole length while the TVD does not increase by much, if at all. The effect of ECD in this well type serves to increase the operating EMW to the point where the upper bound of the safe drilling window can be violated and initiation of wellbore fracturing is predicted, as is seen in **Fig. 3**.

Widening the Safe Drilling Window

Given a particular field application that exhibits a narrow safe drilling window profile, the choices available to the drilling engineer are as follows:

- Drill within the bounds of the narrow window, reducing the drilling fluid density and/or fluid rheology as needed in order to obtain reduced ECD. Much of the attention of the drilling fluids industry has been devoted to this area of study, often without success. At times, the reductions in fluid rheological properties have produced unplanned events such as poor hole cleaning and barite sag occurrence.
- Investigate the possibility of increasing the upper bound of the safe drilling window to obtain higher fracture gradient(s). With rock mechanics modeling, it can be seen that current industry-accepted attempts to reduce permeability at the wellbore wall through enhanced

sealing / particle plugging efforts can produce higher formation fracture initiation pressures.[4,5,6,7] The cited references show much effort has been given to expanding our understanding in this area.

- Investigate the possibility of decreasing the lower bound of the safe drilling window to obtain lower densities to prevent hole collapse. Theoretically, interaction of the drilling fluid with the rock at the wellbore wall can lead to changes in rock strength. Recent work done in this area shows the possibilities of harnessing this technology to widen the safe drilling window, and is the subject of the material presented in this paper.

Experimental Results

Previous papers[1,2,3] have discussed the experimental procedures and results of the use of invert emulsion fluid (IEF) chemistry to alter the mechanical properties of shales. With use of a special test device, namely the Inclined Direct Shear Test Device (IDSTD), a rock sample exposed to a circulating fluid under confining pressures can be sheared after a set exposure time. Results can then be compared to gauge changes in the original rock strength with changes in the rock exposed to the drilling fluid.

In this paper, the experimental results published earlier for the West Africa shale are used to show predicted changes in the magnitude of the lower bound of the safe drilling window using rock mechanics modeling. The experimental results published earlier for this shale exposed to the fluid for a 3-hour time are reproduced here in **Table 1**. In the experimental tests, three (3) IEFs were used, with the only difference between them being their water phase salinity:

1. 50,000 ppm calcium chloride WPS (0.986 activity)
2. 200,000 ppm calcium chloride WPS (0.83 activity)
3. 350,000 ppm calcium chloride WPS (0.521 activity)

The West Africa shale was reported to have a native WPS of 150,000 ppm calcium chloride equivalent (0.899 activity).

Based on the experimental results using the tests with mineral oil as the baseline, pertinent conclusions reached earlier included the following:

- The low WPS IEF weakened the West Africa shale the most.
- The intermediate WPS IEF weakened the West Africa shale somewhat.
- The high WPS IEF strengthened the West Africa shale.
- The measured changes in rock strength were consistent with industry-accepted IEF membrane efficiency and osmotic pressure theory.
- An IEF with a WPS equal to that of the West Africa shale connate water salinity (e.g., a 'balanced' activity fluid) weakened the shale slightly after the 3-hour exposure time. To stabilize the shale while in contact with the IEF, the shale 'chemo-mechanical balance' would have to be determined and applied in the field. Experimental evidence showed this balance would require an IEF with greater than 150,000 ppm $CaCl_2$ equivalent WPS.

Rock mechanics simulations were then run to determine the changes these fluids would have on the hole collapse pressures after a 3-hr exposure time.

Field Case Examples

In order to draw the safe drilling windows, two basic cases are constructed for the modeling:

- A deepwater vertical wellbore with a 4,000-ft water depth. Hole deviation angles ranged from 0° (vertical) to 20° from vertical.
- A land ERD well at two different depths: 6500 ft and 8000 ft TVD. Simulations were run for hole angles ranging between 0 and 90° from vertical, typical angles used in ERD well profiles.

Table 2 and **Table 3** contain the various parameters used in the modeling of the safe drilling windows for the two well profiles. To keep the number of variables within reason, a constant pore pressure was applied in all cases. The deepwater profile contains an isotropic (e.g., downhole earth stresses are constant or nearly-constant in all directions) and an anisotropic case, where there is directional variation in the downhole stresses. Elastic rock modeling is used in all cases, and the compressive shear failure results were calculated using the PBORE-3D™ software program from the University of Oklahoma PoroMechanics Institute. Hypothetical ECD values for the drilling operation are inserted to better define the magnitude of the drilling problem(s).

Deepwater Case Simulations

Simulations were run for an impermeable shale exposed to the three IEFs and the base case for an isotropic and an anisotropic downhole stress state. From the software, an example of the output for one fluid case across all hole deviation angles is seen in **Fig. 4**. The boundary between the blue area (hole collapse area of instability) and the green area (stability) represents the minimum EMW needed to maintain prevent hole collapse. Because the deepwater case presented here has low deviation angle and four fluids are presented, the results read from output like Fig. 4 are presented in a different format.

Deepwater Isotropic Case. In **Fig. 5**, the effects of the 3-hr exposure time on the impermeable West Africa shale are seen for the isotropic stress state. The shale can be drilled with the lowest EMW with use of the highest WPS IEF, since this fluid actually strengthened the shale in the experimental tests. Compared to drilling with the 50,000 ppm WPS IEF, 0.6-0.7 lbm/gal less mud weight would be required with use of the high WPS IEF to keep the shale stable under the predicted downhole conditions. A differential of 0.3-0.4 lbm/gal EMW is seen if the intermediate WPS IEF is used in the comparison. In a tight safe drilling window, the saving of 0.3-0.4 lbm/gal EMW can be significant. These results also show that an IEF having inadequate WPS can actually cause the EMW to prevent hole collapse to increase, thereby narrowing the safe drilling window.

Deepwater Anisotropic Case. The case was also examined for an anisotropic stress state and the results are shown in **Fig. 6**. Because of the differential of the stresses in the horizontal drilling plane, higher EMW are needed to maintain stability. The same basic pattern seen for the isotropic state is seen here, except the predicted densities are higher, as expected. Given a drilling fluid ESD of 10.2 lbm/gal for a static wellbore (as during trips or when there is no circulation), the shale would be unstable with use of the 50,000 ppm WPS IEF, and be barely stable with use of the 200,000 ppm WPS IEF. Assuming while circulating the system ECD is 10.4 lbm/gal, the shale is again predicted to fail with use of the 50,000 ppm WPS IEF. If we assume a fracture initiation pressure equivalent of 10.6 lbm/gal (due to a weak zone lying somewhere above the shale), the safe drilling window can be widened between 0.4-0.7 lbm/gal with use of the high WPS fluid. This extra margin can be beneficial in the event of an unplanned pressure surge, as can occur during trips (surges) or with hole pack-offs.

ERD Drilling Case

Next the safe drilling window of an impermeable shale in an ERD well was examined. Here the results will be plotted as a function of hole angle from 0° to 90°from vertical. For a single case as shown in **Fig. 7**, the software can produce hole collapse pressure predictions for all possible hole angle / azimuth combinations, something very useful when simulating anisotropic downhole stress states.

Simulations were run for two different depths in this case: the shale at 6500-ft TVD and at 8000-ft TVD as seen in **Fig. 8** and **Fig. 9** respectively. The downhole stress state is assumed to be isotropic in this case. The EMW needed to prevent hole collapse at all hole angles is lower for the shallower case than for the deeper case. In all cases, the highest WPS IEF can stabilize the West Africa shale with the lower EMW. Given a maximum ECD allowable of 16 lbm/gal could be used in the 8,000-ft TVD case, then the ERD well could only be drilled up to a maximum deviation angle of 40° with the lowest WPS IEF and only up to 50° with the intermediate WPS IEF. A maximum deviation angle of 70° is predicted with the highest WPS IEF.

Assuming no ECD or fracture gradient restraints on this well profile, a horizontal wellbore could be drilled with 0.5 – 0.9 lbm/gal less EMW if the highest WPS IEF is used.

Conclusions

A number of conclusions can be drawn from the material presented in this study:

- The changes in rock strength as a result of interaction with drilling fluids can be used to predict changes in the safe drilling window.
- Drilling with IEFs having adequate water phase salinities can help reduce the drilling fluid densities required to prevent hole collapse. Conversely, IEF having inadequate water phase salinities can increase the densities required to prevent hole collapse, thereby narrowing the safe drilling window.
- The widening of the safe drilling window can be considered in terms of the density required to maintain wellbore stability at a specific hole angle or it can be viewed as the increase in hole angle that can be safely drilled at a set mud weight or ECD value.
- The study of the change in rock strength as a function of interaction with drilling fluid is only beginning and needs more attention and discussion for drilling critical wells with narrow safe drilling windows.

Acknowledgments

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Nomenclature

D-P = *Drucker-Praeger rock failure model*
ECD = *Equivalent circulating density*
ESD = *Equivalent static density*
EMW = *Equivalent mud weight*
IEF = *Invert emulsion drilling fluid*
TVD = *True vertical depth*

σ_V = *Overburden stress (psi/ft)*
$\sigma_{H\,max}$ = *Maximum horizontal stress (psi/ft)*
$\sigma_{h\,min}$ = *Minimum. horizontal stress (psi/ft)*

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Table 1: West Africa Shale Strength Parameters

Fluid Type	Cohesive Strength (psi)	Internal Friction Angle (°)
Mineral Oil	1480	4.5
IEF (50K ppm $CaCl_2$)	1160	6.4
IEF (200K ppm $CaCl_2$)	1360	5.2
IEF (350K ppm $CaCl_2$)	1420	6.2

Table 2: Parameters Used in Deepwater Modeling

Parameter	Isotropic Case	Anisotropic Case
TVD (ft)	9500	9500
Water depth (ft)	4000	4000
σ_V (psi/ft)	0.791	0.791
$\sigma_{H\,max}$ (psi/ft)	0.73	0.75
$\sigma_{h\,min}$ (psi/ft)	0.73	0.65
Pore pressure (psi/ft)	0.51	0.51
Rock permeability type	impermeable	impermeable
Rock failure model	D-P	D-P
Poisson's ratio	0.3	0.3

Table 3: Parameters Used in Land ERD Modeling

Parameter	Isotropic Case 1	Isotropic Case 2
TVD (ft)	6500	8000
Water depth (ft)	0	0
σ_V (psi/ft)	1.04	1.04
$\sigma_{H\,max}$ (psi/ft)	0.82	0.82
$\sigma_{h\,min}$ (psi/ft)	0.82	0.82
Pore pressure (psi/ft)	0.477	0.477
Rock permeability	100% impermeable	100% impermeable
Rock failure model	D-P	D-P
Poisson's ratio	0.3	0.3

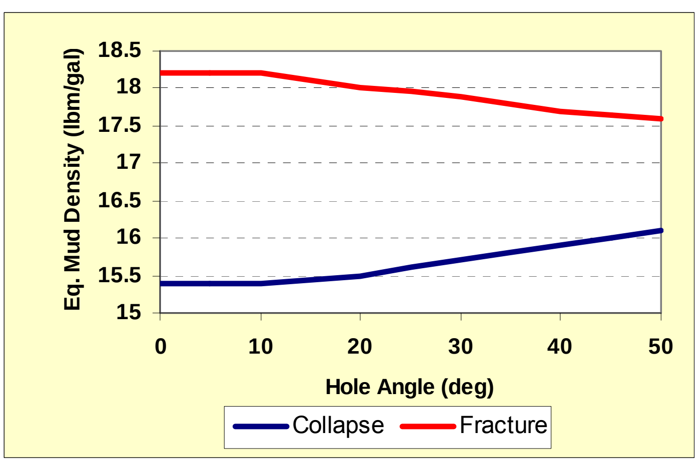

Fig. 1 – A typical safe drilling window up to 50° deviation.

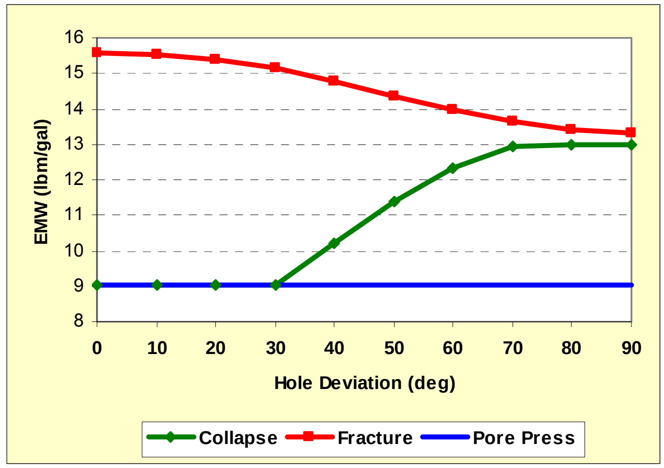

Fig. 2 – Example of a narrow safe drilling window, North Sea ERD well.

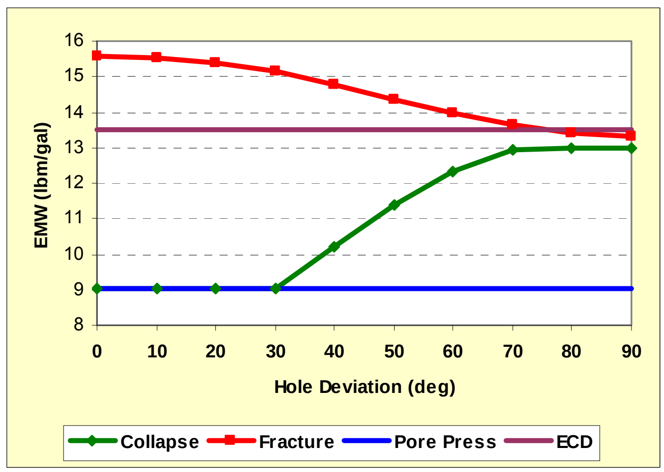

Fig. 3 – An example of ECD violating the safe drilling window (ECD = 13.5 lbm/gal).

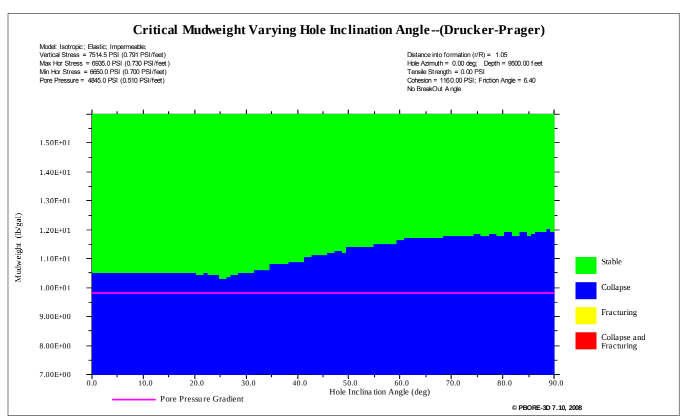

Fig. 4 – Example of output from software model.

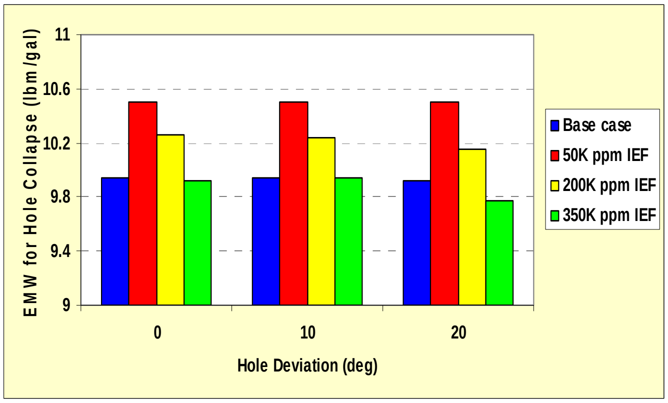

Fig 5 – EMW to prevent hole collapse for isotropic deepwater case.

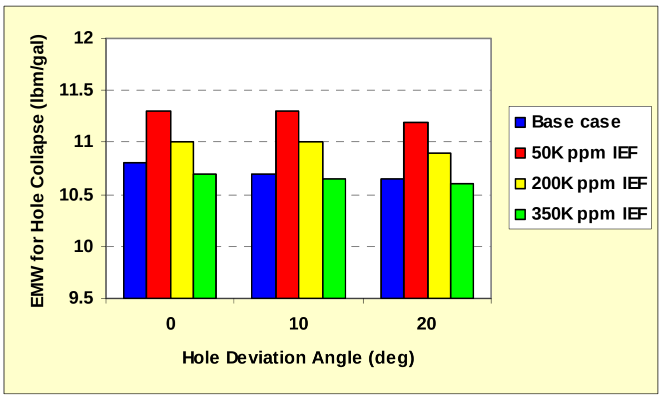

Fig. 6 – EMW to prevent hole collapse for anisotropic deepwater case.

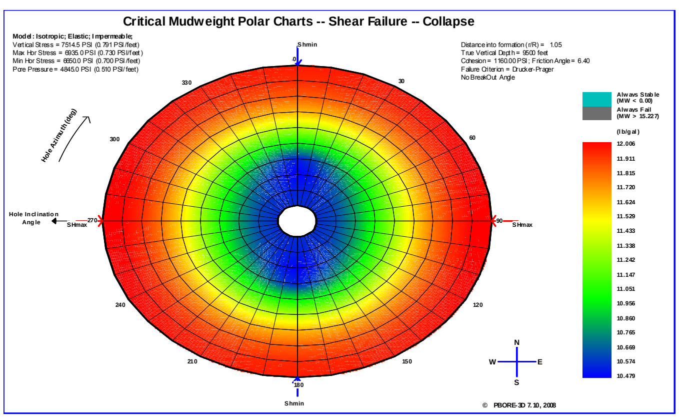

Fig. 7 – Example of output from software model for all possible hole angle and azimuth combinations.

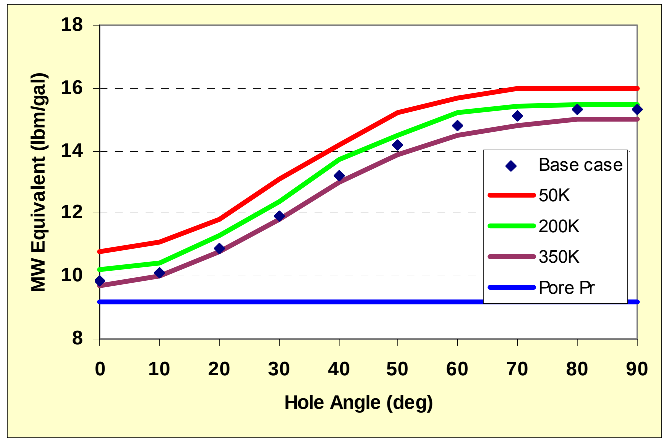

Fig. 8 – Isotropic modeling results for land ERD case, 6500 ft TVD.

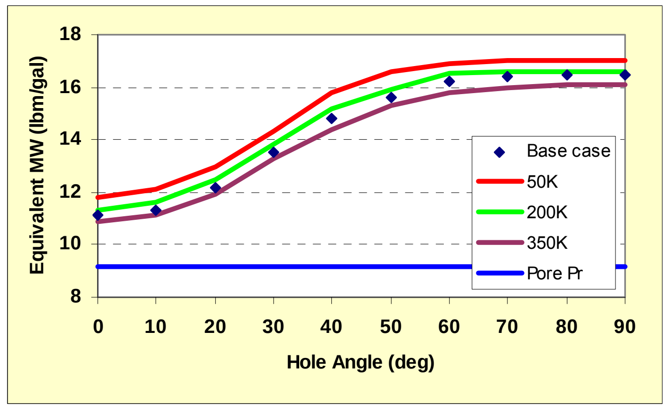

Fig. 9 – Isotropic modeling results for land ERD case, 8000 ft TVD.