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Mud Flow During Kill Ron Dykhuizen & Charlie Morrow

June 1, 2010

11296
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Department of Energy review required before public release
Reviewer Name/Org: Larry Shippers, 6471 Date: 14 July 2009
Guidance (if applicable): N/A

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SNL008-002116

Where did the mud flow?

- **We were provided data for a single kill operation on 5/28/2010**
 - We desire to determine where the 9800 barrels of mud went
 - Based on transient pressures measurements
 - Consistent with visual observations
- **Unknowns complicate the analysis**
 - What was the initial condition of the well
 - What fluid initially resides in each well bore volume (especially important for transient kill analysis)
 - What flow paths are available to the mud
 - What is the condition of the various (Hanger, BOP, cement, etc.) seals
- **Calculations will assume a 50 barrel per minute mud flow which is NOT equal to the maximum flow of almost 80 barrels per minute**
 - Friction results scale approximately with the square of the flow
 - Head results are independent of the flow
 - Assume a Newtonian mud with viscosity of 0.2 poise (results are slightly sensitive to this value)

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Mud Volume Considerations

- **9800 barrels of mud pumped**
 - Volume of central casing is 739 barrels (correction of BP estimate of 943 barrels)
 - 16 inch annular volume is 1039 barrels
- **Mud could have gone up past BOP seals**
- **Mud could have gone down central casing and out past the shoe into a geologic formation**
- **Mud could have gone down the central casing and out up the drill string**
- **Mud could have gone down the 16 inch annulus and out into a geologic formation**
- **Mud could have gone down the 16 inch annulus, out burst discs, and into a geologic formation**

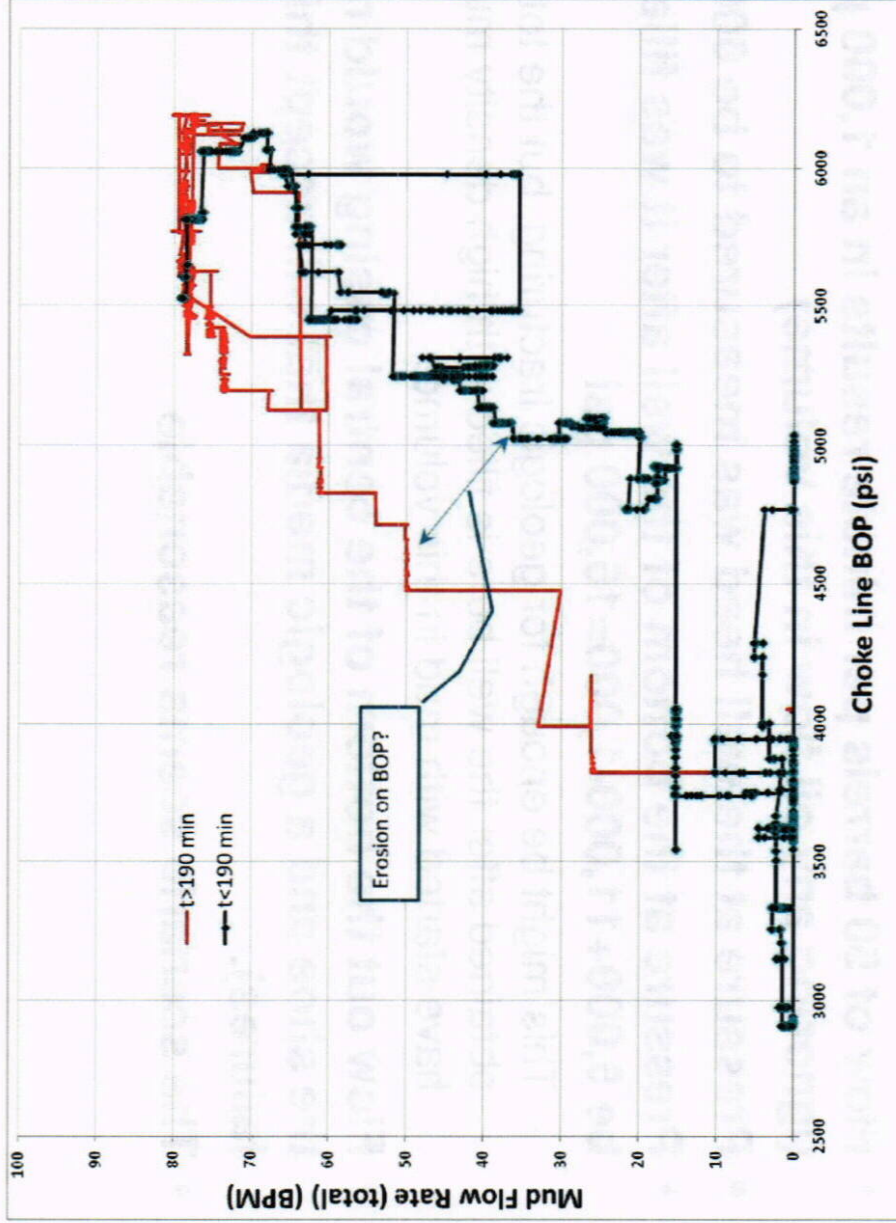
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Up past BOP seals

- The drill string was determined to be in place, and likely a reasonably obstruction free flow path.
- Testing on May 25 indicated that each BOP seal provided some seal (pressure drop), but flow did exist in annular space around the drill string.
- It was thought that injection into the lowest BOP elevation would flow down into the well since the test RAM would be open and the upper seals would remain (possibly improved by bridging material and added hydraulic pressure).
- BP concludes that if a large amount of mud flowed passed the BOP seals, they would exhibit a large erosion; However, the final pressure drops were near the initial pressure drops indicating little erosion (a qualitative conclusion).
- A counter argument: the BOP is a failed component
 - The BOP pressure flow characteristics may be highly nonlinear
 - Seals may have eroded away, but maybe the bridging material added more resistance and masked this change.

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Hysteresis or Erosion: 5/28 test



The cross plot of flow vs. pressure indicates either a hysteresis or an erosion of the flow path resulting in less pressure required later in the test.

BP initially explained this may be an indication of formation opening and closing due to geologic fracturing.

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Flow down the central well casing

- **If mud fills the central casing, it would exhibit an 11,000 psi head**
- **Flow of 50 barrels per minute results in an 1,000 psi friction loss (ignoring any oil flow in this volume)**
- **Pressure at the well head was measured to be 6000 psi**
- **Pressure at the bottom of the well after it was filled with mud would be $6,000+11,000-1,000=16,000$ psi**
 - This might be enough for geologic fracturing, but the total pressure is only obtained after the well bore is filled with high density mud. All kill tests may have started with mud in this volume.
- **Flow out the bottom of the central casing would require a failure of the shoe and a geologic media that will accept this mud flow (two failures).**
- **The scenario seems reasonable**

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Simple Fracture Model

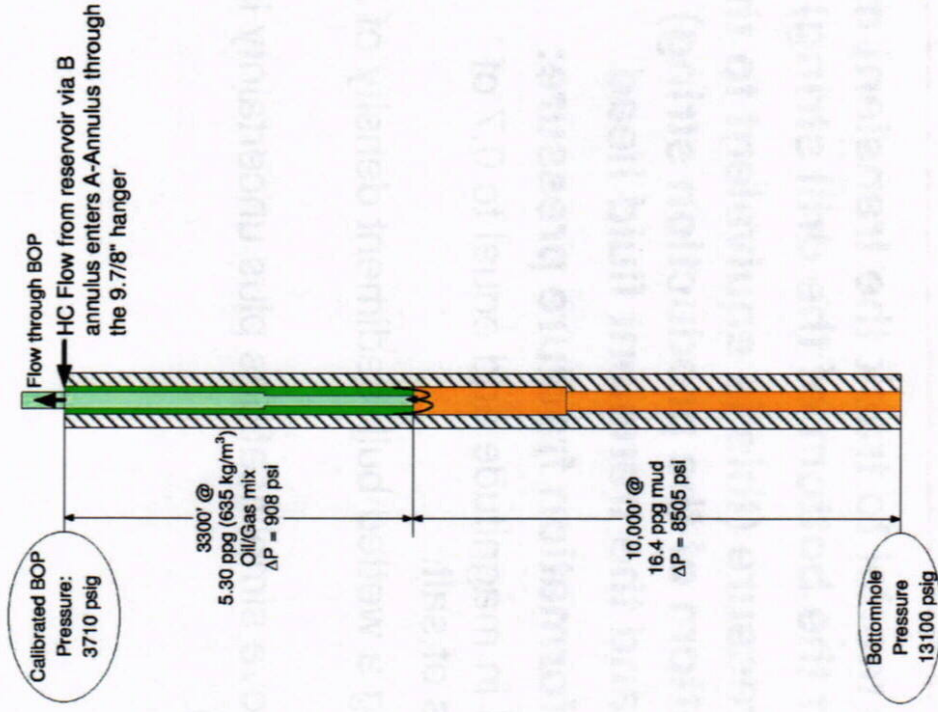
- We developed a simple fracture model to track the transient mud level (from an initial condition at the bottom of the drill string)
- We calculate the bottom hole pressure (this is equivalent to the bottom of the annulus or the bottom of the production string) due to the measured BOP pressure and the transient fluid head
- We plot this with the estimated formation fracture pressure:
 - Horizontal principle stresses equal in magnitude and equal to 0.7 of overburden stress. Ignored effects of salt.
 - Overburden stress calculated using a wetted bulk sediment density of 2200 kg/m³
 - Uncertainty range derived from above simplifications plus uncertainty in rock tensile strength (500 psi assumed)

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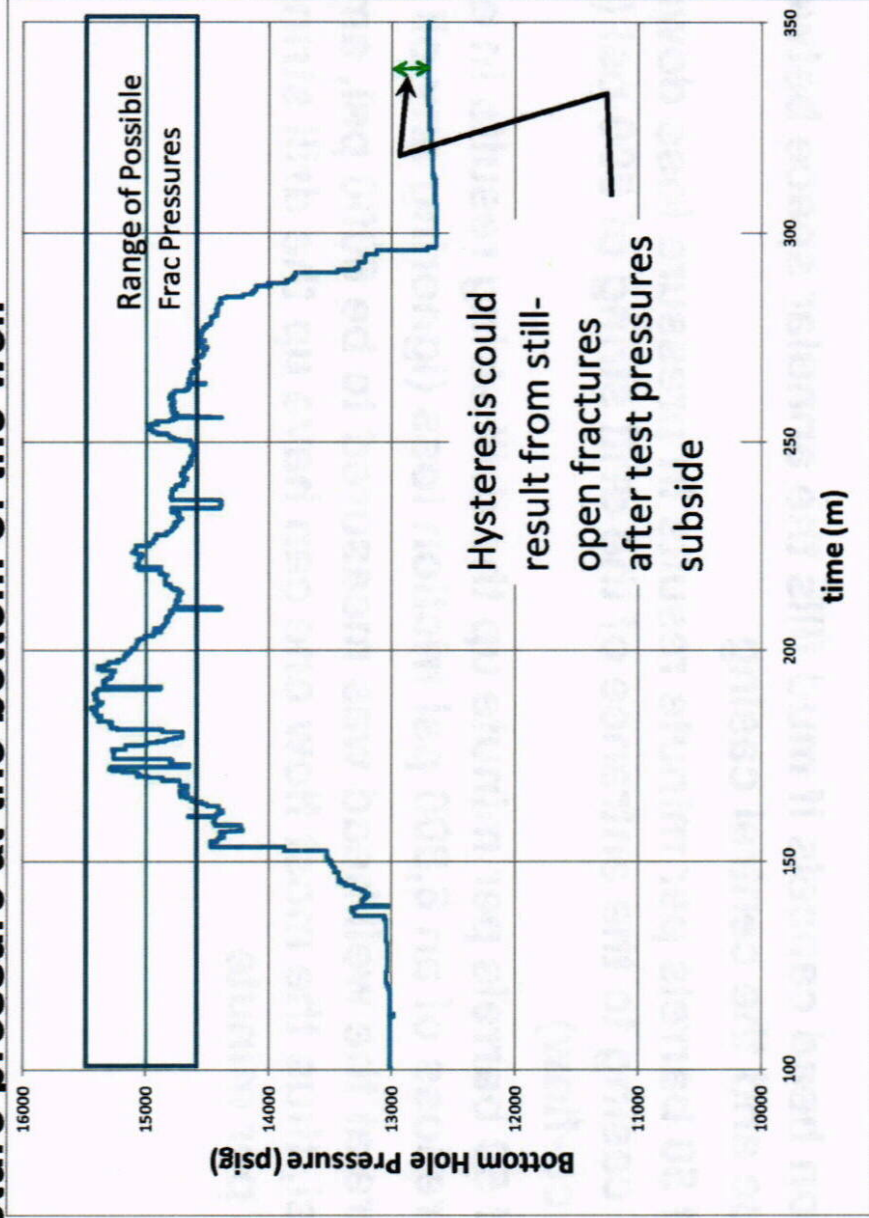
Simple Fracture Model – Initial Condition

- The initial condition includes a short head of organics and a longer head of mud.



Simple Fracture Model

- This result shows that the pressure level might be controlled by the fracture pressure at the bottom of the well



Down the central well /up the drill pipe

- Elevation head cancels if mud fills the annular space between the drill pipe and the central casing
- Flow of 50 barrels per minute results in pressure loss down the central casing to the entrance of the drill string of 500 psi (ignoring any oil co-flow)
- Flow of 50 barrels per minute up the drill string results in a pressure loss of an 6,800 psi friction loss (ignoring any oil co-flow)
- Pressure at the well head was measured to be 6000 psi, ambient is 2250 psi, thus the most flow one can have up the drill string is 35 barrels per minute

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Flow down the 16 inch annular

- **If mud fills the 16 inch annulus, it would exhibit an 11,000 psi head**
- **Flow of 50 barrels per minute results in an 3,000 psi friction loss**
 - assumes no loss past the failed hanger
 - the friction is concentrated below a depth of 15,000 ft where the flow area is the smallest
- **Pressure at the well head was measured to be 6000 psi**
- **Pressure at the bottom of the well after it was filled with mud would be 6,000+11,000-3,000=14,000 psi**
 - This might be enough for geologic fracturing, but the total pressure is only obtained after the well bore is filled with mud. Leakage into the formation is required before complete filling.
- **Flow out the bottom of the 16 inch annulus would require a failure of the cement and flow into the oil formation, or flow into the geologic formation above the top of cement**
- **A possible conclusion**

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Down the 16 inch annular/ out burst discs

- **The burst discs may have failed due to heating up of the mud left in this space by flow of hot oil in the central well bore (if the hanger did not fail first)**
- **If mud fills the 16 inch annulus to the first burst disc, it would exhibit an 800 psi head**
- **Annular flow of 50 barrels per minute results in an 15 psi friction loss (assuming no loss past the failed hanger)**
- **Pressure at the well head was measured to be 6000 psi**
- **Pressure at the highest burst discs is 6000+800-15 psi**
- **The back pressure is estimated at 3000 psi**
- **Flow out the two burst discs would result a flow of 11.8 barrels per minute**
- **The condition at the lowest burst discs is not significantly different: 12.4 barrels per minute through the two discs**
- **Thus, for all 6 burst discs, the total flow is less than 40 barrels per minute (0.433 inch diameter flow area)**

Counter Current Flow Scaling Analysis

- Is counter current flow of mud down and oil up possible?
- This seems reasonable in the 16 inch annulus where the flow area is approximately 50 inches by 1 inch. Oil could occupy a portion of the perimeter. The following momentum balances on the two individual phases can be written:

$$0 = -\alpha \frac{dP}{dz} - WallFriction_{mud} + \alpha \rho_{mud} g + Drag$$

$$0 = -(1 - \alpha) \frac{dP}{dz} - WallFriction_{oil} + (1 - \alpha) \rho_{oil} g - Drag$$

- To maximize mud flow Drag is zero (no friction between mud down and oil up)
- To maximize mud flow α (the mud volume fraction) approaches unity
- To maximize mud flow gas velocity approaches zero (only slightly negative)

Counter Current Continued

Counter current flow of mud down and oil is possible!

- **This results in the following requirement**

$$WallFriction_{mud} < (\rho_{mud} - \rho_{oil})g$$

- **As long as the mud flow is slow enough to generate a flowing friction less than above, counter current flow is possible**
- **Examples presented in this talk allow counter current flow**
 - 16 inch annular flow 50 barrels per minute
 - Above 15,000 ft depth counter current flow is possible:
 - Wall friction is 0.03 psi/ft < 0.6 psi/ft head difference
 - However, below the 15000 ft depth the requirement is not satisfied:
 - Wall friction is 1.1 psi/ft > 0.6 psi/ft head difference

Other visual observations

- **It was stated that oil reappeared at the kink quickly after the mud flow was stopped**
 - This is consistent with flow of oil up the annulus and mud down the center
- **It was stated that the well condition returned to a steady operation quickly after mud flow was stopped**
 - This is consistent with flow of oil up the annulus and mud down the center
 - Implies that the inventory of the well is unchanged from the beginning of each kill (mud below the drill pipe in center, and no mud in annulus)
 - Hard to make mud flow down the annulus consistent with this unless we have counter current flow
- **Mud flow down the annulus and oil up the center seems unlikely also because:**
 - Mud would prefer to at least initially flow down the center (which would be all gas above the drill string end)

Conclusions

- It is only possible to flow 35 barrels per minute of oil up the drill string under the conditions of 5/28 (this cannot be the major path for the total mud flow)
- It is only possible to flow 40 barrels per minute out of the burst discs (this cannot be the major path for the total mud flow)
 - Change in area due to erosion could increase flow
- There is no clear indication that mud flows up past the BOP seals, but this is still possible.
- Without a major failure of the well casing, the flow must be out the bottom of either the annulus or the center casing. This requires a failure of a seal, however, we already know that at least one seal failure has occurred due to the current flowing oil (unless the source of the oil is a different formation).
- Counter current flow within the 16 inch annulus seems possible
- A likely scenario is flow of oil up 16 inch the annulus and mud down the center bore. This requires both cement seals at the bottom of the well to be broken (double failure).