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Estimates of Conditions in the Gulf
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Department of Energy review required before public release
Reviewer Name/Org: Larry Shipers, 6471 Date: 14 July 2009
Guidance (if applicable): N/A

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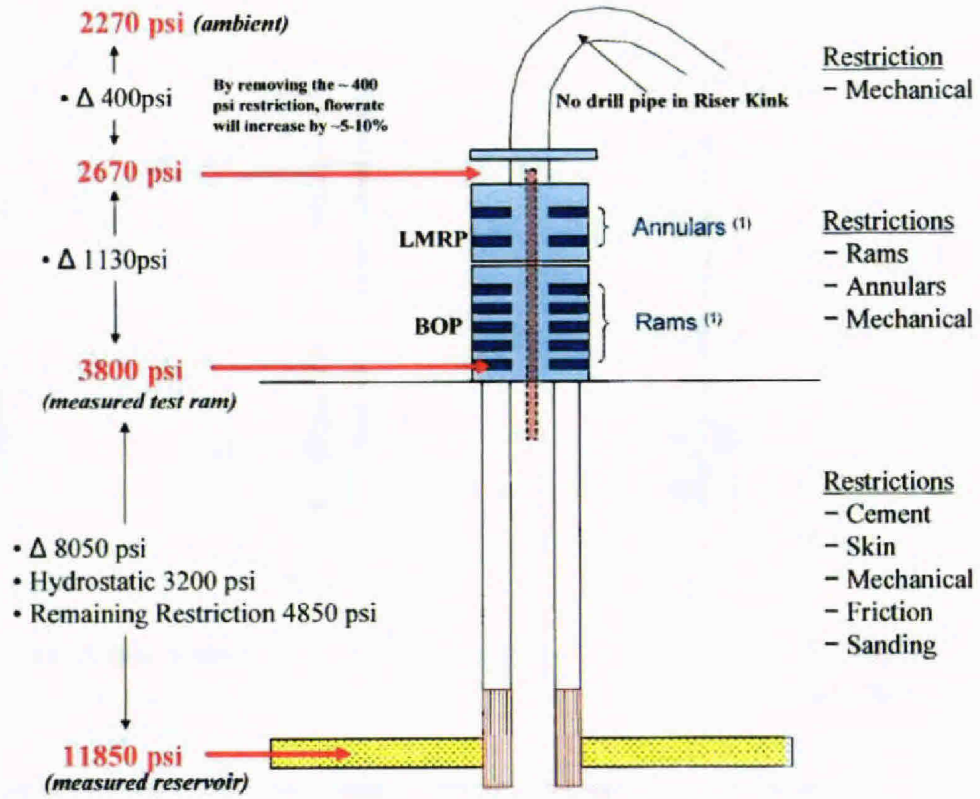
Purpose

- Provide insight into the physics of the problem
  - What might the flow look like
  - What restrictions (or damage) are required to match the pressure measurements
- Provide a sanity check on BP calculations
  - Is their model of the fluid reasonable
  - Is their model of the flow paths reasonable
  - Is their estimate of the flow rate reasonable

Original Pressure Measurements



(1) All Rams and Annulars Closed

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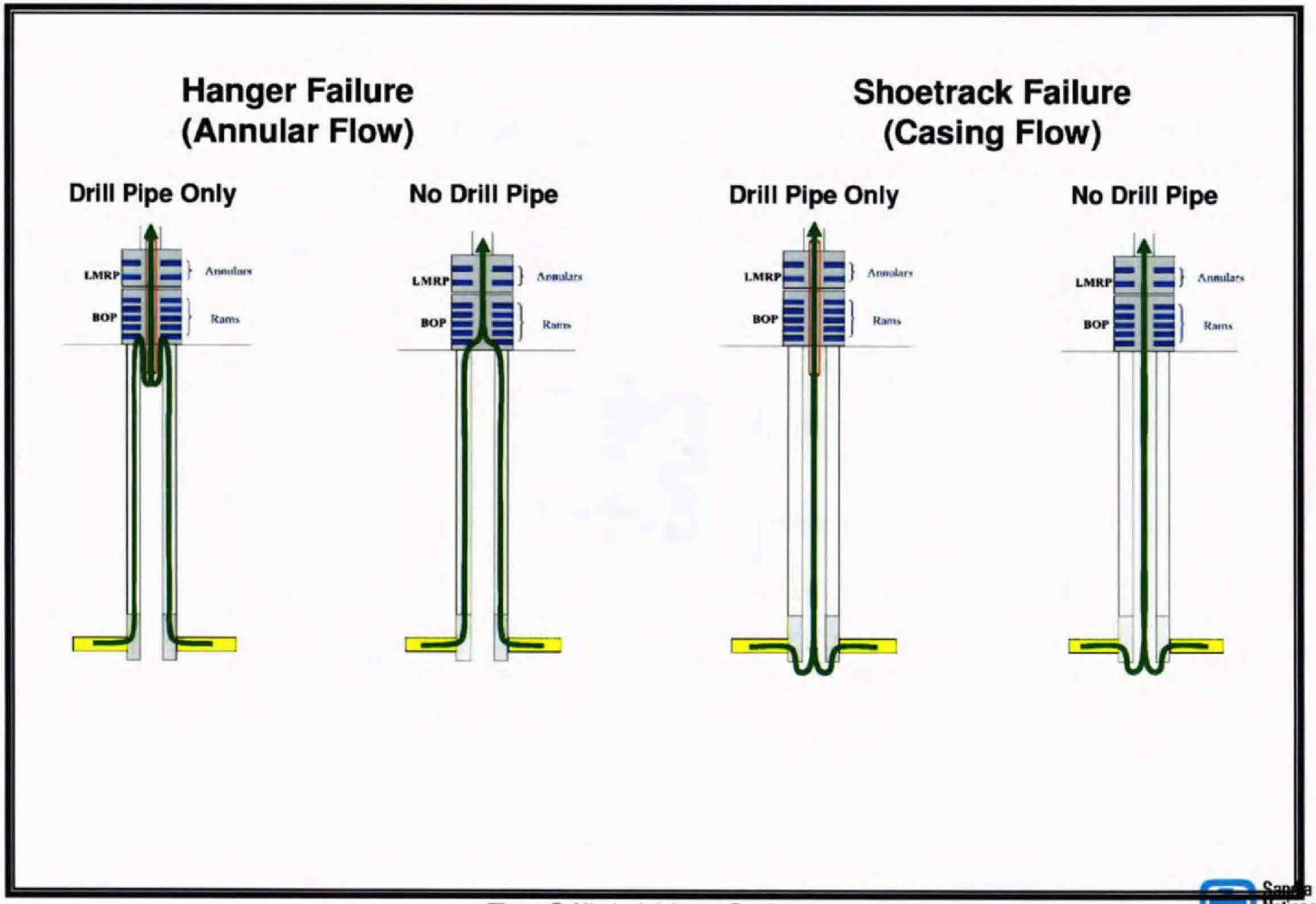
Four Scenarios



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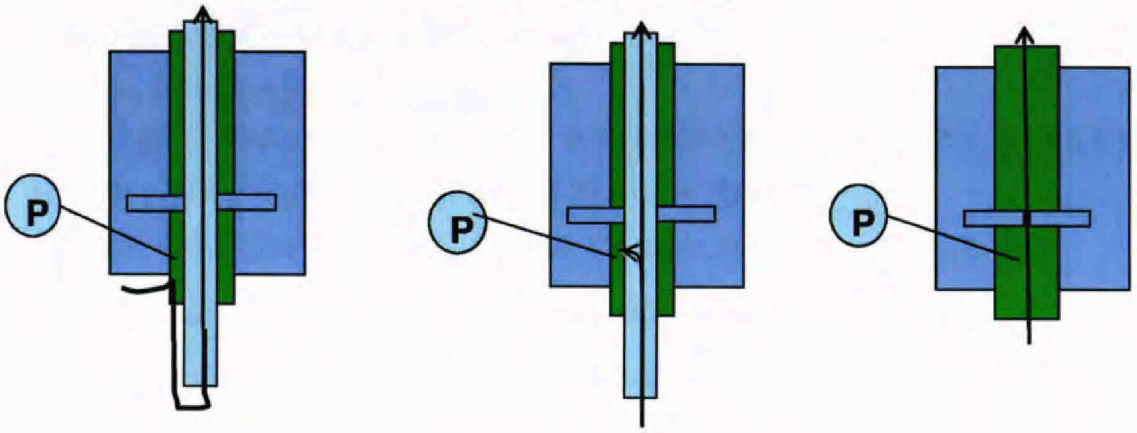
Geometry Questions (1)

- **How can the flow get out of the reservoir?**
  - The radial cement isolation of the reservoir may have failed
    - Radial failure allows flow into the annular space
    - Requires a second failure of the annular separator to allow flow into the central portion of the well or into the BOP
  - The cement shoe may have failed
    - requires a path for oil to flow below the reservoir bottom or a deeper reservoir than estimated (likely also requires a failure of the radial cement emplacement to allow a downward path for the oil).
  - Both events also requires a failure of the BOP

Geometry Questions (2)

- **How can the measured 3800 (3100) psi Test Ram press. be real?**
  - Pressure well above ambient, so flow must exit from this region to the 2270 psi ambient
    - **CASE 1:** Flow from some portion of the wellbore is cycled into BOP the annular region around the an intact drill string, which downstream enters the drill string at a lower elevaton, and exits through the BOP
    - **CASE 2:** A stagnant fluid path from leaks in a damaged drill string into the annular region around the drill string
    - **CASE 3:** The drill string is completely missing, and the fluid is forced through constrictions in the BOP prior to exiting



Equation of State

- We tried to independently develop an equation of state given the measured fluid constituents and their mole fractions
  - This allowed validation of the BP EOS
  - This allowed properties into a fluid code
- The model calculates all thermodynamic properties of the fluid given a pressure and temperature (thus requires iteration)
- The model is coded in Visual Basic (thus requires the finite difference model to be in Excel, which is very slow due to the itterations)
- The model uses Peng-Robinson, and yields properties similar to that provided by BP

Flow Modeling

- We used a simple homogeneous (equal velocity) two phase flow model to determine pressure levels
  - Reasonable for the small domains where the vapor bubble size is large compared to the hydraulic diameter
  - Reasonable for high pressure flows where the vapor and liquid densities are similar
- Flow restrictions need to be added to allow matching the pressure measurements
  - Skin term required at the well inlet since the seal has failed
  - Flow restrictions are reasonable considered the damage caused by the BOP and bending over of the riser pipe.
  - Our calculations in general ignore flow restrictions
  - We calculated between known pressures
    - Reservoir to top of well bore
    - Through BOP
    - Failure to match measured pressures implies that the geometry is wrong

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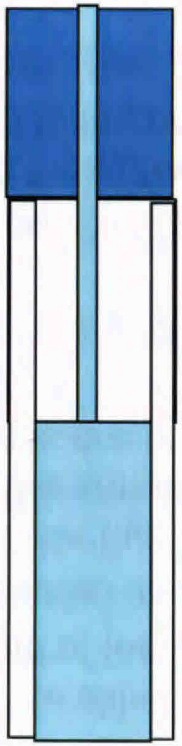
Flow Conditions with Drill string intact



BOP

Gas exists above the end of the drill string since at steady state both gas and liquid needs to enter the drill string

Two phase exists below the end of the drill string at steady state; gas may be bubbling up thru the liquid

If the reservoir leak is through the outer annulus, this outer annulus will be filled with two phase. The annulus around the Drill string is likely mostly gas as the liquid rains down.

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Flow Calculations from the reservoir: 5000 bopd

- We believe that there is a reasonable combination of free parameters (notably the skin factor) that will allow matching the 3800 psi (3100 psi) at the bottom of the BOP
  - We included reservoir draw down and skin factor in a ΔP single parameter
- We calculate that the pressure change through the well bore (central or through the annulus) is mostly due to elevation head (intact geometry flow resistances are negligible). Runs up annulus and center to top to match top pressure
- Scenario 1, 2 and 4 requires matching 3800 psi (3100 psi) at the top of the annulus.
  - 6560 psi (5740 psi) P_{bottom} in scenario 1 and 2
- Scenario 3 requires matching 3800 psi (3100 psi) at the BOP bottom with a gas head to the bottom of the drill string.
  - 6150 psi (xxxx psi) P_{bottom} in scenario 3

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Flow Calculations via the drill string through the BOP (scenario 1; 5000 bopd)

- We assume a 3800 psi boundary condition at the bottom of the BOP
- In scenario 1 and 3 there exists a gas head from the bottom of the BOP to the bottom of the drill string. This yields a pressure of 4070 (3320) psi at the inlet to the drill string.
- The 5000 bopd flow yields a pressure at the top of the BOP of 3370 (2700) psi
- The measurement at the top of the BOP is 2670 (2770) psi.
- For the first set of pressure measurements, the calculation shows that the predicted pressure level is much higher than the measured value. Thus, if the drill string exists, as modeled, we can conclude:
  - The flow might be higher
  - The flow might be restricted
- For the second set of pressure measurements, the calculation shows that the predicted pressure level is slightly lower than the measured value. Thus, if the drill string exists, as modeled, we can conclude:
  - The flow might be a little less if the flow path is not restricted as assumed
  - If the flow path is restricted, the flow is a lot less

Shut In Pressure

- The well bore can be filled with either liquid or gas. A gas fill results in a higher shut in pressure at the top of the well bore (mud line).
- A simple calculation can be made to determine the minimum well bore pressure
  - $P = P_{reservoir} - \rho g H$
- Using a maximum estimate for the liquid density we get a well head pressure of 8500 psi
  - This is above the bubble point and justifies the assumption of an all liquid well
- Using an estimate of a gas density at the geologic average temperature we get a maximum well head pressure of 9500 psi
  - The existence of a gas layer above the oil in the reservoir justifies the assumption of a gas fill
  - It is currently assumed that the well contains a significant amount of liquid, so replacement of this liquid by the gas phase may take a significant amount of time after shutdown.

Conclusions

- We have generated an Equation of state for the reservoir liquid that is validated the BP experimental data
- We have performed independent simulations of the flows through various intact portions of the well bore. These validate that the BP solutions.
  - The pressure changes are mostly due to elevation heads in the annulus or central well bore
- We assume that if the drill string remains in place and is the primary flow path out of the well bore, then the annular space around the drill string below the BOP is mostly gas phase. This results in a different down hole pressure for scenario 3.
- We calculate a range for the maximum well bore pressure after shut in.
- We did not calculate the physical size of the proposed damage required to allow flow from the reservoir or to restrict flow through the drill string in the various scenarios.