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EXPERT REPORT

U.S v. BP Exploration & Production, Inc., et al.

Flow Rates from the Macondo MC252 Well
Submitted on Behalf of the United States

Prepared by:

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Confidential per BP

A. Professional Background

I am a mechanical engineer specializing in multiphase fluid flow. I have worked at Sandia National Laboratories (SNL or Sandia) in Albuquerque, NM for 28 years. Sandia is a Department of Energy (DOE) National Nuclear Security Agency (NNSA) national laboratory devoted to work on nuclear weapons, broader defense and deterrent systems, homeland security, and a variety of energy programs. I am currently a Principal Member of the Sandia Technical Staff. Throughout my career at Sandia my work has focused on multiphase fluid flow, including flows in: geothermal wells, nuclear reactors, CO2 fire suppression systems, and numerous cooling systems. I have a wide variety of experience in many practical and academic problems involving thermodynamics, fluid flow, and heat transfer. I have served as a key member of a variety of investigative teams examining a wide variety of topics that included non-performance of complex systems and accident investigations. The accident investigations included an accidental rocket ignition, a lithium reactor fire, and a nuclear reactor coolant spill (for the DOE and the Nuclear Regulatory Commission).

I have a Ph.D. in Mechanical Engineering from Arizona State University (1985), where my thesis examined multiphase flow of different fluids through complex systems from both modeling and experimental viewpoints. I have a M.S. and B.S. in Nuclear Engineering from the University of Illinois (1977) and the University of Virginia (1976), respectively. My studies were concentrated in multiphase flow through complex systems. From 1981 to 1985, I was a Lecturer in the Arizona State University Mechanical Engineering and Energy Systems department. I have authored over 30 journal publications and hold two U.S. patents on novel techniques of controlling gas/solid flows. I was a registered Professional Engineer in Ohio from 1980 until 2006.

B. Involvement in Deepwater Horizon Response

In May 2010, I was enlisted to assist in the DOE response to the Macondo well blowout in the Gulf of Mexico. Engineers from three DOE NNSA laboratories, Sandia, Los Alamos National Laboratories (LANL), and Lawrence Livermore National Laboratories (LLNL), supported the United States' response to the blowout. The problems I worked on during the response largely involved fluid flow through pipes, which is my professional area of focus. While I did not have a specialized background in petroleum engineering, the same engineering and physical principles apply to petroleum engineering as other engineering disciplines. I applied those principles during the response. I was called upon to perform a variety of calculations related to assessing the flow path in the well, assessing the implications of a number of engineering projects intended to capture, stem, collect, or stop the flow from the well (e.g., cutting the riser, installation of the Capping Stack, the Well Integrity Test), and estimating the flow rate from the well. I spent several weeks at BP's offices in Houston where I interacted regularly with BP engineers working on the response, including flow assurance, reservoir, and petroleum engineers. On a number of occasions, BP's engineers presented the DOE NNSA lab engineers with engineering problems with the purpose of "comparing notes" on findings and solutions. For example, in mid-May 2010, BP requested that the DOE NNSA engineers calculate the bottom hole pressure given a measured pressure at the BOP and an assumed flow rate because BP engineers were initially unsure that their standard oil codes would appropriately model unusual geometries..

During the response, the DOE NNSA engineers, including myself, conducted estimates of the flow rate of oil from the Macondo well. I performed calculations of the flow rate into, through, and out of the Top Hat 4 device installed by BP. I also estimated the flow rate at the time the Capping Stack was installed and eventually used to shut in the well (July 12-15, 2010) and the cumulative flow from the well over the 86 days of the blowout. These calculations are documented in a Sandia Report (A. C. Ratzel III, DOE-NNSA Flow Analysis Studies Associated with the Oil Release following the Deepwater Horizon Accident, September 2011, SAND 2011-1653) (DOE-NNSA Flow Analysis Report).[1] I calculated the predicted increase in flow that could result from cutting off the kinked riser just above the Lower Marine Riser Package (LMRP). At the request of BP engineers I also calculated potential flow rates through the rupture discs in the Macondo well casing below the seafloor.

C. Executive Summary

This report presents calculations regarding the flow of oil from the Macondo well in 2010. A series of calculations designed to determine the flow rate, or a lower bound of the flow rate, for various points in time is presented. This report also updates and/or refines certain calculations prepared during the Macondo well response, including calculations contained in the DOE-NNSA Flow Analysis Report, based on additional data and information.

1. I estimate the flow of oil from the well on July 14 and 15, 2010 (just prior to shut-in) at 53,000 barrels of oil per day (bopd).[2] This is consistent with BP estimates of 51,500 bopd[3] and 59,098 bopd[4] conducted during the same time period. The DOE NNSA lab team initially presented its estimates to BP engineers in Houston in late July 2010. At that time, BP did not present an alternate estimate.

2. Using the 53,000 bopd estimate referenced above, I also integrate the flow over the entire incident period to obtain a total oil release of approximately 5 million barrels. The assumptions used in generating my calculations of the total release are strongly supported by analysis of BOP pressure data recorded during the blowout (S. K. Griffiths, *Environ. Sci. Technol.*, 46 (10), 5616–5622, 2012). Other studies conducted by BP are also

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[1] Exhibit 9361
[2] All references to "barrels of oil" or bopd in this report refer to a stock tank barrel of oil – 42 gallons at 60 F and 14.696 psi
[3] Exhibit 9453 (Appendix A.1).
[4] Exhibit 9491 (Appendix A.2).

consistent with the flow rates used to obtain this total flow including those of BP engineers and BP contractor ADD Energy.[5]

3. A new calculation is presented that examines the pressures and flows measured during the Top Kill event at the end of May 2010. Based on these measurements, I estimate the flow rate for May 28, 2010 to be over 60,000 bopd, which is consistent with the flow rates I estimated for that same time period in the integrated flow estimate referenced above. I also conclude that the flow rate is certainly greater than 43,000 bopd during this time period. This estimate is consistent with the flow rates I used in determining the total flow.

4. A calculation is also presented that examines the flow from the well during the time period around June 15, 2010 when pressure measurements from BP's collection device Top Hat 4 were available. I estimate the flow to be approximately 60,000 bopd. This same calculation is applicable to all time periods from June 3, 2010 when Top Hat 4 was installed until July 11, 2010 when Top Hat 4 was removed in order to install the Capping Stack. This calculation also provides a lower limit on the flow of 43,000 bopd in that time period based on collection rates and assuming zero flow from the Top Hat 4 skirt. Of course there was always flow from beneath the Top Hat 4 skirt during that period, so the 43,000 bopd figure provides a lower bound. Again this is consistent with the flow rates used in determining the total flow.

The calculations described in 3. and 4. above can be combined with estimates based on other methods to establish lower bounds on the flow rate at various times as well as on the total amount of oil released.

D. Calculations

1. Flow Rate Estimate for July 14 and 15 of 2010

After the capping stack was installed on the well, accurate geometry and measured pressures allowed estimates of the flow rate through the capping stack hardware. When this was added to collected flows from connections to the original BOP, the total flow from the reservoir could be estimated. The three DOE NNSA Lab Teams and BP prepared such estimates. The DOE NNSA Lab work was documented in DOE-NNSA Flow Analysis Report. A flow rate of 53,000 bopd was estimated. It is important to note that this is the flow rate with the Capping Stack installed. The Capping Stack provides additional backpressure reducing flow by approximately 4%.

[5] Exhibit 9452, Appendix A.3 (Post event simulation of Top Kill procedure, June 29, 2010), Exhibit 9455 (June 29, 2010 "Top Kill Modeling"); Exhibit 9254 ("Relief well kill for Macondo MC 252 #1, Well Kill Modeling and Evaluations, July 2010).

Fig. 1 : Photo of the Capping Stack prior to Installation

By focusing on flow within the Capping Stack components, specifically the kill and choke lines (see Figure 2), issues and uncertainties for the upstream flow conditions could be avoided. Specifically, during preparations for well shut-in, closure of the Capping Stack middle ram, and other valves on the kill and choke lines provided sets of pressure data from which flow could be computed. During the various flow events, the flow either passed through the Capping Stack or was extracted from pipes on the BOP to surface ships prior to entering (upstream of) the Capping Stack. The extracted flow rates were measured, and the flow through the Capping Stack could be estimated based on measured pressures.

Figure 2 below shows in schematic the Capping Stack geometry with additional detail on the kill- and choke-line piping systems. At different times between July 14 and July 15, the flow was directed through different portions of the Capping Stack piping system. With an estimate of the fluid resistances through the two flow paths and the crude oil properties, the DOE-NNSA lab team was able to use the measured pressure to estimate the flow rate. Alternatively, multiple measurements of flow through the Capping Stack were used to independently determine the fluid resistances and ultimately the flow rate.

For some of these calculations we used a "resistance coefficient method." In this method, resistance coefficients (also referred to as "K factors") are used to characterize the pipes, bends, elbows, contractions, and expansions in the Capping Stack piping system. In late July 2010, BP provided the DOE NNSA lab teams with BP's preferred geometry for the Capping Stack, but we also reviewed drawings of the Capping Stack provided by BP.[6] BP also provided us with BP's proposed K factors for the elbows, contractions, and fittings and with the oil collection rates used in the DOE NNSA lab team calculations.[7]

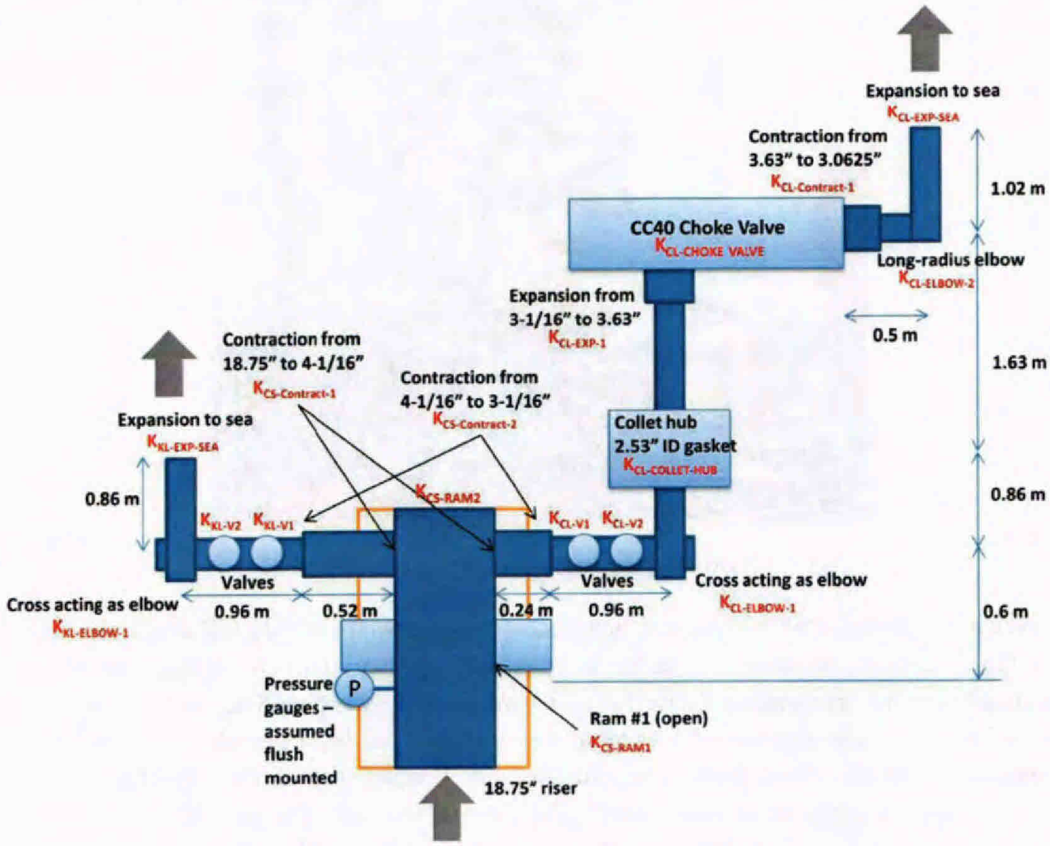

Fig. 2 : Capping-stack geometry, with the geometry K factor locations shown. Note that the top ram (Ram #3) of the CS is not shown.

More details of the Capping Stack analysis can be found in the DOE-NNSA Flow Analysis Report (Appendix A.1).

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[6] Exhibits 9576 (Appendix A.4) (July 27, 2010 Email from Farah Saidi to Arthur Ratzel, et al. re: "Choke side and kill side Drawings" w/ attachments). BP did not provide us with as-built drawings of the Capping Stack.

[7] Exhibit 9469 (July 27, 2010 Email from Trevor Hill to Arthur Ratzel, et al. re: "FW: Rates during integrity test (revised)" w/ attachments).

Post-incident, I had the opportunity to examine the Capping Stack equipment at the NASA Michoud facility on more than one occasion and to review additional measurements of the equipment. The measurements were very consistent with the dimensions used in the analysis. Only minor differences were noted, and these had very little impact on the flow results.

The DOE-NNSA Flow Analysis Report concluded that the potential error uncertainty in the 53,000 bopd flow estimate for the last day was +/- 10%. This was based upon expert consensus and the fact that the flow estimate was calculated through different flow paths, with different collection rates, and these all yielded similar results. An alternate method was also presented where the resistances were not input, but derived from the pressure data, and this also provided a similar estimate. At the time, I personally thought that the uncertainty bound should be +/- 20% for the flow rates during the last days. It is now my opinion that the uncertainty bound is smaller based on review of additional studies that obtained similar flows.

The pipe flow calculations used to estimate the flow generally are material for undergraduate fluid mechanics students, however estimates of *multiphase* flows based on pressure measurements are more complex. In this section I will discuss some of the items that have the potential to impact the accuracy of the DOE-NNSA flow estimate for the last days of flow.

The estimates documented in the DOE-NNSA Flow Analysis Report assumed that the oil could be simulated by a single phase fluid with a homogeneous density. There is significant literature discussing the accuracy of this assumption. A standard reference (J. G. Collier, Convective Boiling and Condensation, McGraw Hill, 1972, p. 93) states that using a homogeneous model (average density) results in satisfactory representation of the experimental data for sudden flow contractions of multiphase flows. On page 94 it is stated that the use of homogeneous flow to approximate the flow through an orifice overestimates the experimental pressure drop (and thus my estimated flow would be too low). Much of the literature regarding the use of a homogeneous fluid to represent a multiphase flow can be traced back to the original work of Chisholm (D. Chisholm, Prediction of pressure gradients in pipeline systems during two-phase flow, Fluid Mechanics and Measurements in Two-Phase Flow Systems, The Institution of Mechanical Engineers, Proceedings 1969-1970, Volume 184 Part 3C, 1970). Chisholm clearly shows that depending upon the exact situation; this assumption sometimes results in an overestimate of the flow, and sometimes results in an underestimate of the flow.

I have repeated the calculations within the DOE-NNSA Flow Analysis Report using the correlations of Chisholm, and found no significant change in the estimate when using multiphase correlations. In fact, the estimated flow *increased* by 4%. Another expert in this case, Bushnell (2013), used a multiphase flow computer simulation of the flow through the capping stack, and also found that the predicted flow rate with a multiphase calculation was 3% above what was predicted with a homogeneous single phase assumption.

Another assumption that was made within the calculations presented in the DOE-NNSA Flow Analysis Report was that the individual flow elements (e.g., lengths of pipe, pipe contractions and expansions, elbows, tees, etc.) could be treated independently. The close proximity of those flow elements potentially could alter their impact on the pressure drop, and therefore reduce the accuracy of flow rate prediction. Computational fluid dynamics (CFD) modeling conducted by Bushnell (2013) explored this by simulating the multidimensional flow through the various elements. In this way they did not have to rely upon tabulated flow resistances (K factors) for the individual elements. Bushnell's results were very similar to the results found in the DOE NNSA Flow Analysis Report, which indicates that the components can indeed be treated independently. This provides additional confidence that our approach was correct.

Finally, the temperature of the flow was not accurately known. The DOE-NNSA Flow Analysis Report used 180 F as the temperature of the flow. This number was provided to us by BP personnel from their calculations of the heat transfer within the well. The U.S. government team tried to obtain temperature measurements from BP, but these were never provided. It has been suggested by BP (BP's Preliminary Response to the Flow Rate and Volume Estimates Contained in Staff Working Paper No. 3, October 2010) that the temperature should be 200 F. The DOE-NNSA Flow Analysis Report concluded that if a temperature of 200 F was used, the flow rate would decrease by 2%. BP has also suggested that the temperature could be as high as 220 F since this was the maximum temperature measured during an investigation by Woods Hole Oceanographic Institute (WHOI) (C. M. Reddy, et al., Composition and fate of gas and oil released to the water column during the Deepwater Horizon oil spill, www.pnas.org/cgi/doi/10.1073/pnas.1101242108).[8] Apparently, obtaining accurate temperature measurements proved a difficult task.An increase to 220 F would yield another 2% reduction in the estimate. But I note that the 220 F measurement presented by WHOI as being the maximum temperature recorded, implying that WHOI had lower measurements.

BP has suggested that phase separation was an important aspect to multiphase flow that was not accounted for in the DOE NNSA Flow Analysis Report.[9] It was suggested that as flow was removed from the choke and kill lines within the original BOP, non-representative phase fractions were removed, leaving an unknown oil mixture to flow through the Capping Stack or Top Hat 4. It was suggested that this could invalidate the densities (and thus the flow rates) calculated within the collection devices installed above the BOP. Examination of the collection records from the various ships reveals that the Gas-Oil-Ratio (GOR) data was quite noisy, but there were no obvious trends with flow rate or between separate extraction points. (see figure 3 below derived from BP collection data (BP-HZN-2179MDL07266155.xlsx and BP-HZN-2179MDL07266256.xlsx).[10] This implies that the mixtures removed for collection were indeed

[8] Depositions of Arthur C. Ratzel and Ronald C. Dykhuizen.
[9] Depositions of Ratzel and Dykhuizen.
[10] According to BP's records, the Helix Producer GOR was 2366 using the average GOR from the Q4000.

representative of the reservoir oil, and thus the densities used in the flow calculations were indeed reasonable.

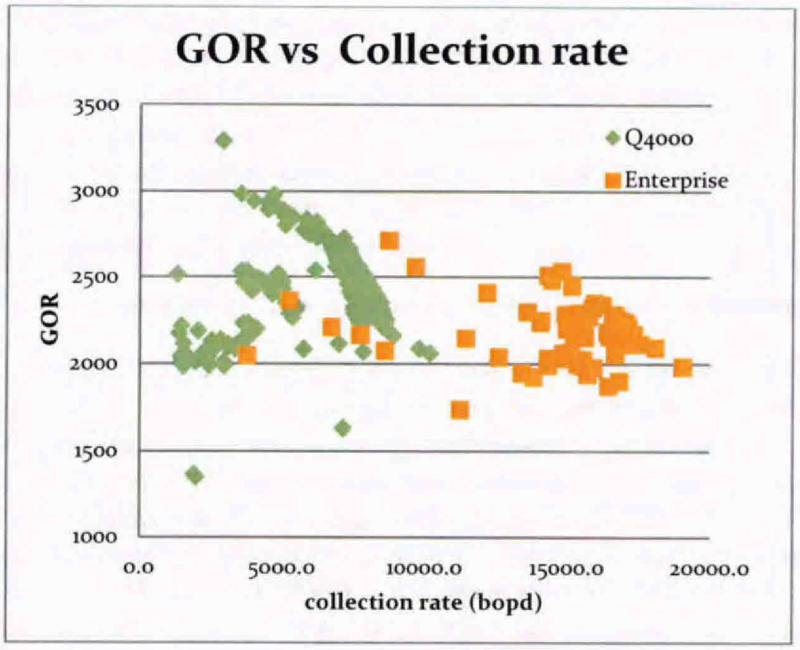

Fig. 3: Measured GOR as a function of the collection rate

BP installed pressure gauges on the Capping Stack prior to deploying it. These gauges were intended to allow BP and the U.S. Government response team to monitor the pressure buildup in the well when the well was shut in due to concerns over well integrity (i.e., whether shutting the well in at the Capping Stack would cause hydrocarbons to flow out of the well casing into the surrounding substrata). BP designated these pressure gauges PT-3K-1 and PT-3K-2. For the pressure measurements used in the DOE-NNSA Flow Analysis study, only PT-3K2 was used because BP identified it as the most accurate at the time of the operation. This gauge was determined to be very accurate by BP engineer Matthew Gouchnour's study.[11] This BP report showed that this gauge had an error of less than 10 psi, which results in a very small change in the flow rate. When one considers that the sea bottom ambient pressure was used to calibrate this gauge, there is essentially no error in the ambient pressure since the ambient pressure is subtracted from the gauge reading. The impact of any error in the pressure gauges on my calculations is negligible.

[11] Exhibits 8680, 8679.

Since the issuance of the DOE-NNSA Flow Analysis Report, a number of studies have become available that support the conclusion for the total flow on the final day. These include a paper by Dr. Stewart K. Griffiths ("Oil Release from Macondo Well MC252 Following the Deepwater Horizon Accident," S. K. Griffiths, *Environ. Sci. Technol.*, 46 (10), 5616–5622, 2012), pp 5616–5622), reports of Kelkar and Raghavan (2013), Bushnell (2013), Pooladi-Darvish (2013), and various BP studies including calculations by BP engineers Farah Saidi (51,500 bopd)[12] and Adam Ballard (59,098 bopd).[13] These all use different techniques to estimate the flow using BP's pressure data. In addition, BP Vice-President Richard Lynch testified that BP calculated a flow rate of 56,000 bopd through the Capping Stack based on these same pressure data.[14] Based on those calculations and the calculations documented in this report, my uncertainty is reduced.

2. Estimate of the integrated oil flow over the duration of the spill

Once the flow rate from the last days is found, one may determine the flow for the various days from April 20 to the capping of the well. I estimate the total release from the Macondo well to be approximately 5 million barrels. The assumptions used in generating my calculations of the total release are strongly supported by analysis of BOP pressure data recorded during the blowout ("Oil Release from Macondo Well MC252 Following the Deepwater Horizon Accident," S. K. Griffiths, *Environ. Sci. Technol.*, 46 (10), 5616–5622, 2012). Other studies conducted by BP are also consistent with the flow rates used to obtain this total flow including those of BP engineers and BP contractor ADD Energy.[15] The Top Kill and Top Hat 4 calculations described below give me additional confidence in my estimate.

I helped prepare the estimate of the integral of the flow within the DOE-NNSA Flow Analysis report. First it was observed that the measurements of pressures at the bottom of the BOP (pressure gauge PT-B) exhibited a steady decline. This indicated that the depletion of the reservoir was steady over the course of the 86 day spill as one would expect. The final shut in pressure allowed an estimate of the total depletion of the reservoir.

The DOE-NNSA Flow Analysis report included two instances of major geometrical changes in the well geometry: 1) the removal of the damaged riser just above the BOP/LMRP, and 2) the installation of the Capping Stack. The DOE NNSA team calculated that the removal of the riser would increase flow by 4% or less. BP independently estimated the effect of the riser removal as 2 to 5%.[16] The Capping Stack decreased flow by approximately 4% (so the flow rate immediately prior to the Capping Stack installation would have been approximate 4% higher than the 53,000 bopd I calculated with the Capping Stack in place). Even with the choke and/or

[12] Exhibit 9453 (Appendix A.1).
[13] Exhibit 9491 (Appendix A.2).
[14] Deposition of Richard Lynch (May 19, 2011), p. 372.
[15] Exhibit 9452, Appendix A.3 (Post event simulation of Top Kill procedure, June 29, 2010), Exhibit 9455 (June 29, 2010 "Top Kill Modeling"); Exhibit 9254 ("Reliev well kill for Macondo MC 252 #1, Well Kill Modeling and Evaluations, July 2010).
[16] Exhibit 11171 (Appendix A.5).

kill lines open, the Capping Stack provided an additional restriction to the flowing oil as evidenced by a pressure above ambient recorded within the Capping Stack. The riser in a similar manner provided additional resistance.

BP has suggested (BP's Preliminary Response to the Flow Rate and Volume Estimates Contained in Staff Working Paper No. 3, October 2010) that the integral estimate did not account for the erosion during the incident contending that this would yield an increasing flow with time. However, the steady decline in the BOP pressure is consistent with depletion of the reservoir and suggests that the erosion was not an important factor. In fact, Dr. Griffiths' work ("Oil Release from Macondo Well MC252 Following the Deepwater Horizon Accident," S. K. Griffiths, *Environ. Sci. Technol.*, 46 (10), 5616–5622, 2012) shows that the BOP data indicate that simple models can be formulated that do not include erosion and can well represent the BOP pressure data. In an attempt to account for some time period where the flow may have been reduced due to initially small flow paths, the integral presented within the DOE-NNSA Flow Analysis report assigned zero flow for the first two days of the incident when the well was flowing at a high rate to atmospheric conditions on the rig floor. I do not believe that erosion had a significant effect on overall flow from the well past the second day of the blowout.

The DOE-NNSA Flow Analysis report used an estimate of the final reservoir pressure of 10,050 psi, and a BP critique (BP's Preliminary Response to the Flow Rate and Volume Estimates Contained in Staff Working Paper No. 3, October 2010) states that the final average pressure is more accurately represented as 10,600 psi, but does not provide the basis for that pressure. If we assume BP's proposed final reservoir pressure is correct, this results in a 3% reduction in the integrated flow rate from the well. However, other experts in this case who have considered or calculated the final average reservoir pressure have found it to be greater than 10,050, but less than 10,600 (e.g., Kelkar and Ragahavan (2013) and Pooladi-Darvish (2013). If we accept a fluid temperature of 220 F, this would only reduce the integral by an additional 4%.

3. Top Kill Calculation

The pressure and flow data recorded during the Top Kill event allowed an independent estimate of the oil flow rate during that time period. I estimate that flow rate to be greater than 60,000 bopd. During the Top Kill, BP pumped heavy mud down the Macondo well in an effort to overcome the momentum of the hydrocarbons flowing up the wellbore, drive the hydrocarbons back down into the reservoir, and ultimately use a wellbore of heavy mud to "kill" the well.

In brief, using the known pump rates of heavy mud and the measured pressure readings from the BOP pressure gauge (PT-B) during the Top Kill event in a relatively simple calculation, I estimate a *lower bound* flow rate during the Top Kill on May 28, 2010 of 43,000 bopd. This bound assumes that there was zero flow of oil through the BOP during Top Kill. We know that this is conservative because Top Kill failed implying that the oil flow did not stop. If I estimate the flow of oil out of the well during the Top Kill procedure, I obtain an estimate of the flow for times outside of the Top Kill event over 60,000 bopd (for the time period around May 28, 2010). Since there is no indication that the flow rate changed significantly before and after the Top Kill, it is reasonable to conclude that the flow rate before Top Kill also was over 60,000 bopd.[17] The details of my calculation follow below.

For my analysis I need to define three time periods.

1. Idle time: no mud flow, the test ram open and a BOP pressure measurement was approximately 3500[18] psi.
2. Kill time: 78 barrels per minute (bpm)[19] mud flow, the test ram open, BOP pressure approximately 5500 psi.[20]
3. Normal time: no mud flow, test ram closed BOP pressure approximately 4350 psi.

The ambient pressure is 2200 psi at all times.

The pressure drop through the system from the BOP gauge to the sea can be approximated by the following equation during normal time:

$$(P_{BOP} - P_{amb})_n = K_n \rho_{HC} Q_{HCn}^2 \qquad [1]$$

Note that Q_{HC} has units of volumetric flow rate at the conditions within the BOP. It has not been corrected to get standard barrels. The subscript *n* denotes normal time (no mud injection and the test rams closed).

During the top kill, mud was injected through the choke line of the BOP. Thus, an alternate equation for use during the kill time (mud pumping and test ram open):

$$(P_{BOP} - P_{amb})_k = K_k \rho_{ave} (Q_{mud} + Q_{HCk}^2)^2 \qquad [2]$$

An average density is used to account for the mixing of the streams as the two fluids flow through the BOP:

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[17] Exhibit 5066, BP-HZN-2179MDL00412974 (June 11, 2010 email from Paul Tooms to Kent Wells, et al., Subject: Historical BOP Pressure w/ attachment) (Appendix A.6).

[18] In this section I will use the 966 psi correction on the BOP pressure gauge that was determined by BP during the top kill. All pressures are reported by BP and include that correction. I have not analyzed whether or not that that is the correct offset.

[19] 78 bpm is the equivalent of 112,320 barrels per day.

[20] BP-HZN-2179MDL07557142 "052810 SS BP Kill Job Blue Dolphin TJH.xls"; Exhibit 8687, (BP-HZN-2179MDL06124348-49 ("MC252_DataDump_071810").

$$\rho_{ave} = \frac{\rho_{mud}Q_{mud}+\rho_{HC}Q_{HCk}}{Q_{mud}+Q_{HCk}} \qquad [3]$$

The following equation represents the idle time condition:

$$(P_{BOP} - P_{amb})_i = K_i \rho_{HC} (Q_{HCi})^2 \qquad [4]$$

We expect that $K_i \approx K_k$, since the geometry is not changed, but the densities might be significantly different. Estimate of the average density is not trivial for one has to account for the mixing of two different temperatures of cold mud and hot oil. During the top kill, I think it is reasonable to assume that the mud flow through the BOP is equal to the rate injected by the ship. It cannot be greater, and it is likely not less since we know that the top kill did not work and mud was observed exiting the riser.

Combining equations 4 and 2, the following result is obtained:

$$Q_{HCi} = \sqrt{\frac{(P_{BOP}-P_{amb})_i}{(P_{BOP}-P_{amb})_k}} \sqrt{\frac{\rho_{ave}}{\rho_{HC}}} \sqrt{\frac{K_k}{K_i}} (Q_{mud} + Q_{HCk}) \qquad [5]$$

The mud density is given as 16.4 pounds per gallon (ppg) (1965 kg/m^3). The oil density changes as it passes through the flow system due to the changing pressure and temperature. The following table can be used to estimate the effective oil density (taken as the square root of the product of the oil density at the inlet [just below the BOP] and outlet of the system). The volume factor converts a volumetric flow of oil to standard barrels. The incoming oil is assumed to be at 200 F, and the mud at 40 F. The Sandia equation of state[21] was used to estimate the densities. The following table is used to estimate the fluid densities during the top kill events. The volume factor is used to translate standard barrels to actual fluid volumes:

Table 1: Oil densities during top kill events.

	P_{BOP}	P_{amb}	Temp F	oil ρ inlet	oil ρ outlet	Effective ρ HC	ρ_{mud}	volume
Normal time	4350	2200	200	518	326	388	-	0.32
Idle time	3500	2200	200	461	326	411	-	0.30
Kill time	5500	2200	74	642	464	546	1965	0.43
Conservative	5500	2200	40	-	-	-	1965	-

[21] For details see DOE NNSA Flow Analysis Report.

It will first be assumed that the oil flow during the top kill event is zero (last row in Table 1). This will yield a lower bound in the oil flow prior to the top kill event via equation 5 by setting the hydrocarbon flow rate to zero. This assumption allows us to estimate the mixture density as the mud density via equation 3, which trivially reduces to the mud density. Equation 5 is then evaluated as follows:

$$Q_{HCi} = \sqrt{\frac{3500-2200}{5500-2200}}\sqrt{\frac{1965}{388}}\sqrt{1}(78\ bpm + 0) = 110\ bpm = 158{,}000\ bopd \qquad [6]$$

Using the volume factor, this flow becomes 48,000 bopd during idle time. This is corrected for the increased back pressure due to the closing of the test ram to obtain a flow of 43,000 bopd during normal time. This is a very conservative calculation to demonstrate a lower bound of the oil flow at the end of May from the Macondo well. This calculation is independent of any previous calculations, including those documented in the DOE-NNSA Flow Analysis Report.

Note, my assumptions are provided below:

1. The oil flowing through the BOP during the top kill is small (therefore zero) compared to the mud flow rate. Assuming a zero flow rate of oil during the top kill only provides a lower bound on the flow rate of oil prior to the top kill. We know that the oil flowing through the BOP is not zero during the top kill due to two reasons: 1) the BOP pressure was measured at 5500 psi which is below the shut in pressure, and 2) the top kill did not succeed.

2. The flow constant (K_i=K_k) is unchanged by the top kill event. In examination of the BOP pressure record before and after the Top Kill event one can conclude that the normal time flow was not significantly altered, if at all, during the top kill. This was also observed by senior BP investigators.[22]

[22] Exhibit 5066, BP-HZN-2179MDL00412974 (June 11, 2010 email from Paul Tooms to Kent Wells, et al., Subject: Historical BOP Pressure w/ attachment) (Appendix A.6).

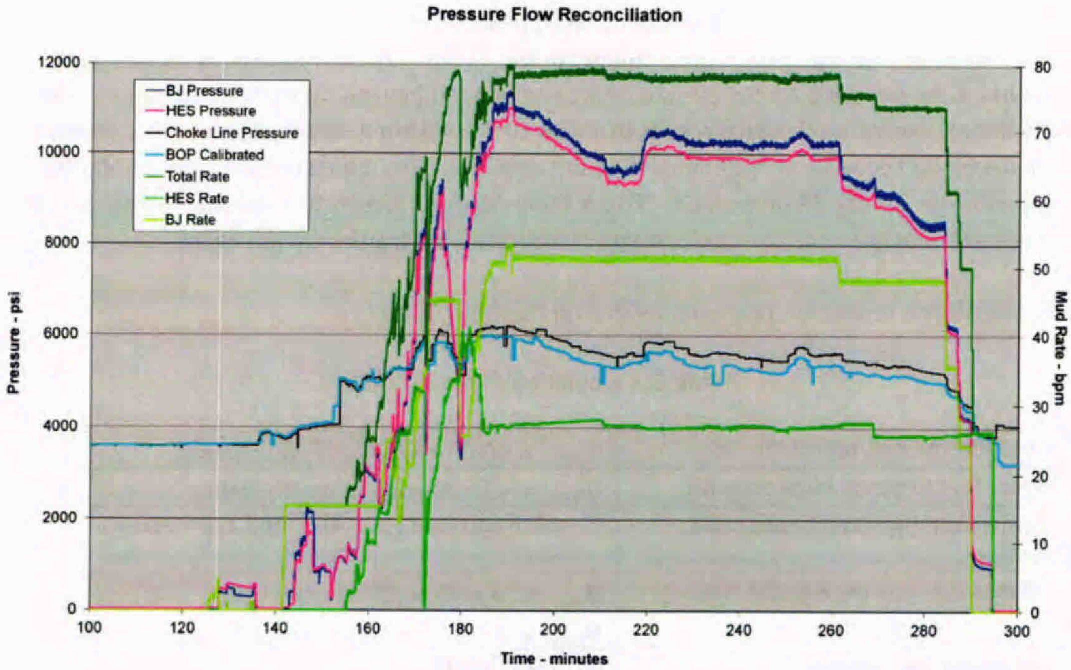


Fig. 4: BP Post-Top Kill Analysis Pump Rate and Pressure Analysis ("052810 SS BP Kill Job Blue Dolphin TJH.xls" BP-HZN-2179MDL07557142).

The calculation presented above is only a lower bound due to the unknown oil flow rate through the BOP during the top kill event. It is possible to estimate the oil flow rate through the BOP during the top kill event from the measured BOP pressure change and estimates of the reservoir depletion. This requires an assumption of no erosion (of the BOP or the well components) between the time of the top kill and final shut in. Based on the data available, this is a reasonable assumption.

Using the method to estimate flow as a function of time contained in the DOE-NNSA Flow Analysis Report, one obtains a flow rate of 60,000 bopd during day 38 of the blowout (the Top Kill time period, but without the mud injection). This is based on a reservoir pressure of 11150 psi for day 38 and an elevation head of 3000 psi. During the mud injection, the BOP pressure increases from 4350 psi to 5500 psi. This increased BOP pressure is estimated to reduce the well flow to 43,500 bopd. This calculation uses the resistance from the reservoir to the BOP gauge, a 3000 psi elevation head, and thus does not assume any BOP resistance value (and thus is applicable to the condition of the BOP with test ram open).[23] This 43,500 bopd of oil flow is greater than the zero flow assumed above (during the mud injection). A mixture temperature of

[23] BP closed and opened the bottom variable bore ram ("test ram") of the BOP during the response. The open or closed state of the test rams correlated with changes in the BOP pressure (PT-B).

68 F is obtained by assuming that the heat capacitance of the oil and the mud are the same. If this flow is inserted into equation 5, the estimate for the oil flow during idle time is 78,000 bopd. This has to be corrected for the closure of the test ram (an increase in the back pressure) to get a flow during normal time, which results in a flow of 70,000 bopd, which is reasonably consistent with the 60,000 bopd used to estimate the fluid densities. This would suggest that the 60,000 bopd estimate for day 38 in the DOE-NNSA Flow Analysis Report is a reasonable estimate of the normal time (no mud flow and test ram closed) flow during the top kill event.

The calculation results are best summarized on the table below:

Table 2: Calculation of top kill flows

From DOE-NNSA report day 38	Q_{HCn} = 60,000 bopd (test ram closed)
Correct for increased back pressure	Q_{HCk} = 43,500 bopd (test ram open)
Calculate mixture temperature and densities	T = 68 F (given T_{mud} = 40 F and T_{oil} = 200 F)
Calculate oil flow during idle time	Q_{HCi} = 78,000 bopd (test ram open)
Correct for normal time	Q_{HCn} = 70,000 bopd (test ram closed)
Compare to top estimate	60,000 ≈ 70,000

The calculations presented above shows that the pressure data recorded during the top kill event was indicative of a flow over 60,000 bopd during time periods around May 28, 2010. It also shows that a lower limit of 43,000 bopd can be easily defended. This is consistent with a BP engineer's observation conclusion that flow rates were between 44,000 and 77,000 bopd at the time based on his own modeling of the Top Kill.[24]

The calculation of the temperature of the flowing fluid through the BOP during the Top Kill can be called in question. Therefore, the entire calculation was repeated using a mud temperature of 70 F, which resulted in a mixture temperature of 97 F. This did not change the lower bound result of 43,000 bopd since the mud density is assumed independent of temperature. The best estimate of the flow increased from 70,000 bopd to 71,000 bopd with the increased temperature. This shows that the mud temperature is not a source of a significant error in the calculation. The mud temperature cannot be outside of the range considered here.

4. Top Hat 4 Flow Rate Estimate

The pressure measurements obtained during the operation with Top Hat 4 allow another opportunity to evaluate the flow rate. However, due to the large uncertainties regarding the flow rate escaping the imperfect seal (named the skirt) between the top hat and the riser, this estimate

[24] Exhibit 9452, Page 8 (Post event simulation of Top Kill procedure, June 29, 2010), Appendix A.3.

is best formulated as a conservative lower limit to the flow rate (43,000 bopd). Accounting for skirt flow, I estimate the flow rate to be approximately 60,000 bopd for the period Top Hat 4 was installed (June 3, 2010 through July 11, 2010).

An analog pressure gauge was installed on Top Hat 4 through a stab (see Fig. 6 below). The pressure reading was so small (2 psi above the sea floor ambient) that pressure corrections for small elevation differences needed to be made. While Top Hat 4 was installed, oil constantly exited through 3 open vents at the top of the Top Hat, and through the skirt beneath (see Fig. 5 below). Flow was also being collected through the riser from the center of the Top Hat, and from lines attached to the original BOP. The flow through the vents was relatively easily calculated for the geometry was well known. The elevated Top Hat pressure, plus the effects of buoyancy, forced the oil out through these vents. The flow rates collected were also easily incorporated into the flow estimate since these were measured. The flow out the skirt was more difficult to calculate since the geometry was not well known. The skirt was severely damaged upon installation. Also complicating the skirt flow was that the positive pressure was countered by buoyancy to such an extent that the net pressure forcing flow out of the seal was poorly defined.

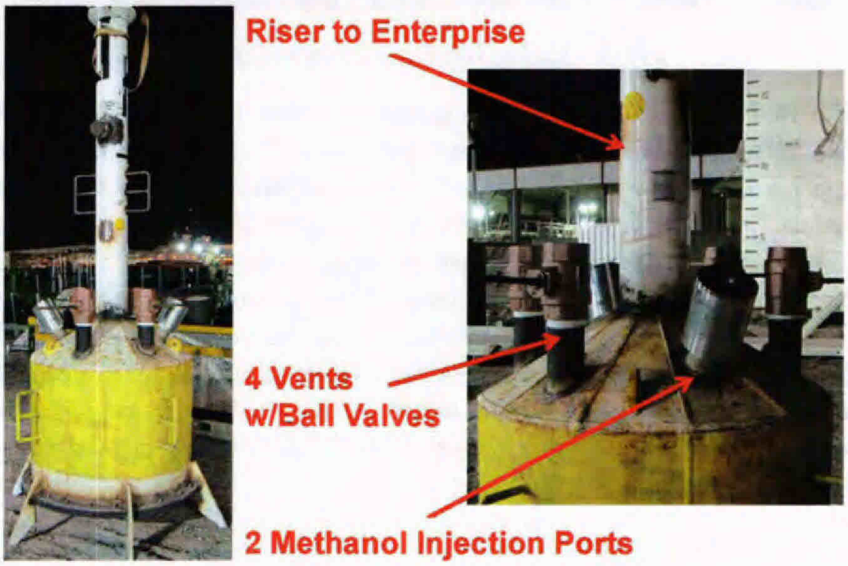


Fig. 5: Top Hat 4 Before Deployment

Fig. 6 : Analog Top Hat 4 Pressure Gauge

In mid-June 2010, I calculated a flow through the Top Hat vents of 23,000 bopd using an assumed 200 F oil temperature ("Flow Estimate by Analysis of Top Hat and Riser," June 15, 2010, Appendix A.7). This was at a time period when the collection rate was 15,000 bopd. I estimated that the flow through the skirt was 45,000 bopd. However, the skirt flow estimate was very approximate due to items mentioned above. In defense of this estimate, it was observed that during time periods when the collection was turned off (due to processing problems), the plume exiting the skirt was not visually changed. This implies that the collection rate was small compared to the skirt flow. If the skirt flow is assumed zero, the calculation presented here provides a minimum flow of 38,000 bopd for June 15, 2010. This is a very conservative lower bound since it was obvious from the video images that the flow rate past the skirt was significant.

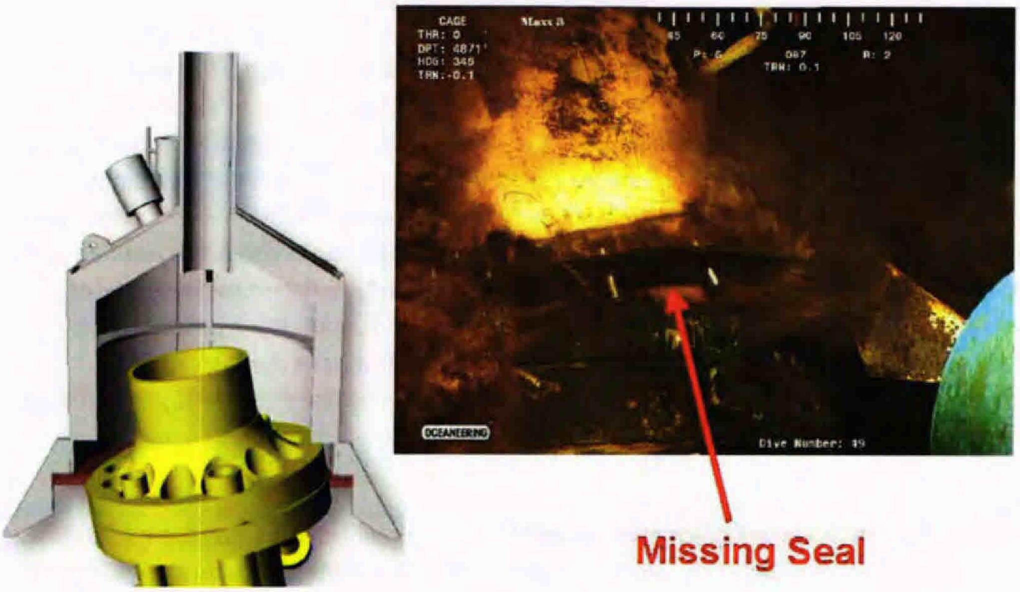


Fig. 7: Image of Top Hat over Riser With Missing Seal

The Top Hat pressure needed to be carefully controlled.[25]. It was stated by BP that the pressure level had to be less than 15 psig to avoid forces that might remove the Top Hat. It also had to have a high enough pressure so that it would not entrain water through the skirt, which would cause hydrates to form and clog the Top Hat 4 rendering it useless. I calculate that this minimum pressure is 1.1 psi (measured at the gauge elevation).

The condition of Top Hat 4 was constantly monitored via video to assure that there always was flow out of the skirt. Thus, one can be assured that the Top Hat 4 pressure never dropped below 1.1 psi even on the days when the pressure gauge was not working or was not installed. At this pressure, I can calculate a flow out of the skirt is zero (that is what determines the pressure level), and the flow out of the vents is 18,000 bopd. If the 18,000 bopd is added to the maximum collection rate at that time period (> 25,000 bopd)[26], one obtains a very conservative lower limit for the flow during Top Hat 4 as > 43,000 bopd. There were no time periods when the flow out the skirt was zero, so this lower limit of the flow should not be considered an estimate of the total flow out of the well during this time period. Since the Top Hat 4 was used from June 3, 2010 through July 11, 2010, this *lower bound* flow rate of 43,000 bopd would apply to that entire period of 39 days.

[25] E.g., BP-HZN-2179MDL04869503.

[26] Exhibit 9490 (BP Daily Oil and Gas Collection Rates).

E. Approach to the Problem

When one is faced with a difficult problem with limited data, one should assemble a multi-disciplinary team to examine the problem from different angles. It is especially important to consider all available data. A multi-disciplinary approach is cited as one of the strengths of Sandia National Laboratories. For example, I recently served on an accident investigation team for a reported "lithium fire." The assembled expert team determined that the accident was not a fire even though flames were observed. Rather, the event was caused by a molten metal water explosion, and the venting of the hot gas products into the ambient environment resulted in the observed hydrogen flame. I also was involved in another study to determine the cause of detrimental oxidation of a coating created by spraying molten metal onto a cold substrate. It was thought to be impossible to measure oxidation rates of the 20-micron particles in flight. However, the assembled panel designed a system to measure the oxidation in flight, and built a predictive model. Outside experts with diverse expertise brought valuable insights to each project.

Similarly, the United States Government assembled such a multi-disciplinary team of scientists and engineers, including personnel from a number of the DOE National Laboratories, to assist in the response to the Macondo blowout and to estimate the flow rate from the well. Calculation of the flow rate from the Macondo well is also a difficult problem that benefits from a multi-method, multi-disciplinary approach. Flow rates from wells are typically determined by separating the liquid and gas flows, and measuring each separately using well calibrated flow meters. Such flow meters were not available on the Macondo well. Thus, we must rely on other methods to make the most of the available data to determine the flow rates as a function of time, and integrate those rates to determine the total amount of oil released from the reservoir. It was also deemed possible to estimate the total flow from the reservoir from depletion parameters. The various methods proposed involved classic petroleum and reservoir engineering principles to different degrees. Many incorporated engineering and mathematical principles from other fields. Many relied upon mathematical optimization techniques to maximize the utility of the data available.

I have found that the results of multi-disciplinary teams allowed more confidence than reliance upon the work of a single analyst. Based on my understanding of the analyses done on behalf of the United States during the response and in this litigation, the United States has assembled a wide variety of experts to examine the problem using a variety of methods each felt best addressed the question. The fact that results obtained were consistent with each other provides additional confidence in the conclusions reached.

F. Conclusions

In summary, I estimate the flow rate through the capping stack to be 53,000 bopd just before the well was shut in. Based on that estimate, consideration of the depletion of the reservoir, and the steady decline in BOP pressure, I estimate total release of oil from the Macondo well to be approximately 5 million barrels. My independent calculations of flow at the time periods of Top Kill (over 60,000 bopd), and Top Hat 4 (~60,000 bopd), BP's flow rate studies, and the work of other experts in this matter, give me additional confidence in my estimate of the cumulative release of oil.

The opinions expressed in this report are my own and are based on the data and facts available to me at the time of writing. Should additional relevant or pertinent information become available, I reserve the right to supplement the discussion and findings in this report.

G. Information Required the Federal Rules of Civil Procedure

1. This report contains my opinions, conclusions, and reasons therefore.

2. A general statement of my qualifications is contained in the Background section on page 1. A more detailed statement of my qualifications and a list of publications is included in Appendix B.

3. I have received no compensation for my expert work in this case aside from my regular salary from Sandia National Laboratories.

4. I have not previously testified as an expert witness.

5. The facts and data I considered in forming my opinions are listed in Appendix C. I also reviewed and considered a substantial amount of data during my work responding to the Macondo blowout, including data provided by BP.

APPENDIX A

APPENDIX A.1

9453

Exhibit No. ______

Worldwide Court Reporters, Inc.

From: Saidi, Farah
Sent: Sat Jul 17 20:48:37 2010
To: Hill, Trevor
Subject: Estimated rate technical note
Importance: Normal
Attachments: Macondo Flow Rate Estimate Based on Well Test Data.doc; P loss in the choke line.xls;
Attachments: Macondo Flow Rate Estimate Based on Well Test Data.doc; P loss in the choke line.xls;

Trevor,

Please find attached the note explaining the methodology in calculating the total rate along with the spread sheet. Please review and let me know if you have any comments.

I will be at home on Sunday. If you need me to come in for any reason please let me know. Otherwise I will see you on Monday.

Regards,
Farah Saidi
GOM SPU Flow Assurance Technical Authority
BP
Office 281-366-5746
Cell 832-978-4121

Macondo Flow Rate Estimate Based on Well Test Data

The objective of this note is to document the data and calculation method used in estimating Macondo flow rate.

A well integrity test was conducted on July 15, 2010. The recorded pressure at the Capping Stack and flowrate of surface facilities (Q 4000 & Helix Producer) are used to calculate the total rate.

The system geometry used in this calculation is comprised of:

- 6 ft of 18.75 inch vertical pipe from capping stack gauge to the 3 inch choke line inlet
- 18.75" by 3.0625 inch cross
- 6 ft of 3.0625 inch horizontal pipe upstream of the choke
- 4 inch choke
- 2.5 ft of 3.0625 inch vertical pipe downstream of choke

The total pressure drop in the system is comprised of:

- Friction loss
- Hydrostatic loss
- Contraction loss (change in pipe size - 18.75 inch to 3 inch)
- Change in flow direction
    - Flow changing direction from the ram to 3 inch choke line pipe. For pressure drop calculations this is assumed as "Tee used as elbow"
    - 90 degree bend from choke line to choke assembly
    - Sharp entrance from 3 inch pipe on the discharge of choke to ocean

Friction, hydrostatic and contraction pressure losses are calculated by multiphase flow simulation, PIPESIM. This software is an industry accepted steady state simulator. The piping from the Capping Stack pressure gauge position to the choke outlet piping was modeled in PIPESIM (excluding the bend & the Tee).

The pressure drop due to change in flow direction is calculated manually since PIPESIM is one dimensional and does not calculate the pressure drop in bends and elbows. This pressure drop is calculated by"

$$\text{Delta P} = 1/2\,(K\,\rho\,V^2)$$

Where

K = resistance coefficient factor (dimensionless)

K = 1 for "Tee used as elbow"

K = 0.43 for 90 degree elbow

K = 0.5 for sharp entrance

ρ = mixture density of the fluid (lb/ft^1)

V = mixture density (ft/sec)

Mixture density and mixture velocity is also obtained by PIPESIM for at a given rate.

The final rate is calculated by trial and error using a combination of delta P and flowrate. There are 3 stages during which pressure data were used in estimating the rate:

- Stage 1, when flow was via Q4000, Helix Producer and fully open Choke - Recorded pressure was 2,625 psia
- Stage 2, after Q was shut in and flow was via Helix Producer and fully open Choke - Recorded pressure was 2,794 psia

1. Stage 3, after Helix Producer was shut in and entire flow was thru fully open choke - Recorded pressure was 3,061 psia

The procedure for estimating the rate is:

- Assume a total rate (52,000 stb/d)
- For stage 1 subtract Q4000 and Helix Producer rate (7,130 & 12,000 stb/d respectively) from the total rate to calculate the rate thru the choke (52,000 - 7,130 - 12,000 = 32,870 stb/d)
    - Record the pressure at the Capping Stack gauge (2,625 psi) to calculate the system pressure loss (375 psi using 2250 psia as back pressure)
    - From the total system pressure loss table (see table 1 over leaf) find the calculated delta P for the assumed rate (32,870 stb/d)) thru the choke and compare it to the accrual data (calculated 336 psi versus actual 387 psi). This is ~ 13% error is pressure and 6% in rate.
- For stage 2 add Q4000 rate (7,130 stb/d) to current flow thru the choke (32,870 sb/d +7130 stb/d = 40,000 stb/d). This is the total rate thru the choke. The calculated pressure drop for this rate is 493 psi versus actual 544 psi. This corresponds to 9% error in pressure and 5% error in rate.
- For stage 3 when all the surface vessels are shut in, the entire assumed 52,000 stb/d rate is thru the choke. For this rate the calculated pressure drop is 828 psi versus 811 psi actual data. This corresponds to 2% error is pressure and 0.1% error in rate.
- Therefore the estimated rate thru the choke is 51,500 stb/d.

Rate	Liquid Rho	gas Rho	Holdup	Mixture Rho	Mixture vel	Tee Used as sharp elbow		Sharp Edge Entrance		90° Elbow (std, r/d=1)		Friction - hydr
						K	Delta P	K	Delta P	K	Delta P	
(stb/d)	lb/ft^3	lb/ft^3		lb/ft^3	ft/sec		(psi)		(psi)		(psi)	delta P PSI (fr
30000	44.739	7.969	0.34	20.47014	160.8054	1	114.2	0.5	57.1	0.43	49.1	
31000	44.737	7.962	0.34	20.4656	165.139	1	121.9	0.5	61.0	0.43	52.4	
32000	44.736	7.357	0.34	20.46152	171.5916	1	129.9	0.5	65.0	0.43	55.9	
33000	44.734	7.593	0.34	20.22094	176.9827	1	136.6	0.5	68.3	0.43	58.7	
34000	44.675	7.966	0.34	20.31842	181.3726	1	145.7	0.5	72.9	0.43	62.7	
35000	44.675	7.966	0.34	20.31842	187.7616	1	154.5	0.5	77.2	0.43	66.4	
36000	44.67	7.6	0.34	20.2718	193.149	1	163.5	0.5	81.7	0.43	70.3	
37000	44.7	7.97	0.34	20.4582	198.5349	1	172.3	0.5	86.2	0.43	74.1	
38000	44.7	7.97	0.34	20.4582	203.9195	1	183.5	0.5	91.7	0.43	78.9	
39000	44.79	7.96	0.34	20.4822	209.3036	1	193.3	0.5	96.6	0.43	83.1	
40000	44.79	7.96	0.34	20.4822	214.6841	1	203.4	0.5	101.7	0.43	87.4	
41000	44.673	7.6530	0.34	20.314928	220.054	1	213.9	0.5	107.0	0.43	92.0	
42000	44.7	7.94	0.34	20.4384	225.4423	1	222.7	0.5	111.3	0.43	95.7	
43000	44.7	7.94	0.34	20.4384	230.8198	1	234.8	0.5	117.4	0.43	101.0	
44000	44.7	7.94	0.34	20.4384	236.1936	1	245.9	0.5	123.0	0.43	106.7	
45000	44.7	7.94	0.34	20.4384	241.5667	1	257.2	0.5	128.6	0.43	110.6	
46000	44.7	7.94	0.34	20.4384	246.9379	1	268.8	0.5	134.4	0.43	115.6	
47000	44.7	7.94	0.34	20.4384	252.3073	1	280.6	0.5	140.3	0.43	120.7	
48000	44.7	7.94	0.34	20.4384	257.6747	1	292.7	0.5	146.3	0.43	125.8	
49000	44.7	7.94	0.34	20.4384	263.0401	1	305.0	0.5	152.5	0.43	131.1	
50000	44.7	7.94	0.34	20.4384	268.4036	1	317.5	0.5	158.8	0.43	136.5	
51000	44.7	7.94	0.34	20.4384	273.7649	1	330.4	0.5	165.2	0.43	142.1	
52000	44.7	7.94	0.34	20.4384	279.1242	1	343.7	0.5	171.8	0.43	147.8	
53000	44.7	7.94	0.34	20.4384	284.5988	1	357.0	0.5	178.5	0.43	153.5	
54000	44.7	7.94	0.34	20.4384	289.8537	1	370.6	0.5	185.3	0.43	159.4	
55000	44.7	7.94	0.34	20.4384	295.2096	1	384.4	0.5	192.2	0.43	165.3	

45° Elbow (std, r/d=1)	0.22
45° Elbow (std, r/d=1)	0.16
90° Elbow (std, r/d=1)	0.43
90° Elbow (long radius, r/d=1.5)	0.27
Tee used as elbow	1
Tee, run	0.54
Gate Valve	0.11
Ball Valve (reduced port)	0.16
Globe	4.34
Butterfly	0.27
Lift Check Valve	10.8
Swing Check Valve	1.63
Sharp Entrance	0.5
Pipe Exit	1

Table 1 - Total pressure loss from Caping Stack Gauge to Choke Discharge

1. Flow is thru Q4000, HP1 & Choke

Assume total rate		(stb/d)	52000
Recorded Q 4000		(stb/d)	7130
Recorded HP1		(stb/d)	12000
Assumed Choke		(stb/d)	32870
Recorded P @ K2 Gauge _Green (psia)			2625
Recorded Delta P (psi)			375
Calculated delta P @ assumed Choke rate			336
Calculated rate at recorded delta P (stb/d)			35000

2. Q 4000 shut in

Recorded Q 4000		(stb/d)	0
Recorded HP1		(stb/d)	12000
Assumed Choke		(stb/d)	40000
Recorded P @ K2 Gauge _Green (psia)			2794
Recorded Delta P (psi)			544
Calculated delta P @ assumed Choke rate			493
Calculated rate at recorded delta P (stb/d)			42000

3. Q 4000 & HP1 shut in

Recorded Q 4000		(stb/d)	0
Recorded HP1		(stb/d)	0
Assumed Choke		(stb/d)	52000
Recorded P @ K2 Gauge _Green (psia)			3061
Recorded Delta P (psi)			811
Calculated delta P @ assumed Choke rate			828
Calculated rate at recorded delta P (stb/d)			51500

Document Produced Natively

Rate	Liquid Rho	gas Rho	Holdup	Mixture Rho	Mixture vel	Tee Used as sharp elbow		Sharp Edge Enterance		90° Elbow (std, r/d=1)		Friction - hydrostatic & Contraction	Total Delta P
						K	Delta P	K	Delta P	K	Delta P		
(stb/d)	lb/ft^3	lb/ft^3		lb/ft^3	ft/sec		(psi)		(psi)		(psi)	delta PPSI (from Pipesim)	
30000	44.739	7.968	0.34	20.47014	160.8054	1	114.2	0.5	57.1	0.43	49.1	58.477	278.8
31000	44.737	7.962	0.34	20.4655	166.199	1	121.9	0.5	61.0	0.43	52.4	62.2	297.5
32000	44.735	7.957	0.34	20.46152	171.5915	1	129.9	0.5	65.0	0.43	55.9	66.0338	316.8
33000	44.734	7.593	0.34	20.22094	176.9827	1	136.6	0.5	68.3	0.43	58.7	69.9779	333.6
34000	44.879	7.686	0.34	20.31842	182.3728	1	145.7	0.5	72.9	0.43	62.7	74.0316	355.3
35000	44.879	7.686	0.34	20.31842	187.7616	1	154.5	0.5	77.2	0.43	66.4	78.1936	376.3
36000	44.87	7.6	0.34	20.2718	193.149	1	163.5	0.5	81.7	0.43	70.3	82.4636	398.0
37000	44.7	7.97	0.34	20.4582	198.5349	1	172.3	0.5	86.2	0.43	74.1	86.8414	419.4
38000	44.7	7.97	0.34	20.4582	203.9195	1	183.5	0.5	91.7	0.43	78.9	91.3257	445.4
39000	44.79	7.96	0.34	20.4822	209.3026	1	193.3	0.5	96.6	0.43	83.1	95.9163	469.0
40000	44.79	7.96	0.34	20.4822	214.6841	1	203.4	0.5	101.7	0.43	87.4	100.6123	493.1
41000	44.873	7.6638	0.34	20.314928	220.064	1	213.9	0.5	107.0	0.43	92.0	105.413	518.3
42000	44.7	7.94	0.34	20.4384	225.4423	1	222.7	0.5	111.3	0.43	95.7	110.3178	540.1
43000	44.7	7.94	0.34	20.4384	230.8188	1	234.8	0.5	117.4	0.43	101.0	115.3254	568.6
44000	44.7	7.94	0.34	20.4384	236.1936	1	245.9	0.5	123.0	0.43	105.7	120.4341	595.0
45000	44.7	7.94	0.34	20.4384	241.5667	1	257.2	0.5	128.6	0.43	110.6	125.6448	622.1
46000	44.7	7.94	0.34	20.4384	246.9379	1	268.8	0.5	134.4	0.43	115.6	130.9568	649.7
47000	44.7	7.94	0.34	20.4384	252.3073	1	280.6	0.5	140.3	0.43	120.7	136.3695	677.9
48000	44.7	7.94	0.34	20.4384	257.6747	1	292.7	0.5	146.3	0.43	125.8	141.882	706.7
49000	44.7	7.94	0.34	20.4384	263.0401	1	305.0	0.5	152.5	0.43	131.1	147.4937	736.1
50000	44.7	7.94	0.34	20.4384	268.4035	1	317.6	0.5	158.8	0.43	136.5	153.2038	766.1
51000	44.7	7.94	0.34	20.4384	273.7649	1	330.4	0.5	165.2	0.43	142.1	159.0116	796.6
52000	44.7	7.94	0.34	20.4384	279.2322	1	343.7	0.5	171.8	0.43	147.8	164.9691	828.3
53000	44.7	7.94	0.34	20.4384	284.5988	1	357.0	0.5	178.5	0.43	153.5	170.9758	860.0
54000	44.7	7.94	0.34	20.4384	289.9637	1	370.6	0.5	185.3	0.43	159.4	177.0784	892.4
56000	44.7	7.94	0.34	20.4384	295.3266	1	384.4	0.5	192.2	0.43	165.3	183.2763	925.3

45° Elbow (std, r/d=1)	0.22
45° Elbow (std, r/d=1)	0.16
90° Elbow (std, r/d=1)	0.43
90° Elbow (long radius, r/d=1.5)	0.27
Tee used as elbow	1
Tee, run	0.54
Gate Valve	0.11
Ball Valve (reduced port)	0.16
Globe	4.34
Butterfly	0.27
Lift Check Valve	10.8
Swing Check Valve	1.63
Sharp Entrance	0.5
Pipe Exit	1

1. Flow is thru Q4000, HP1 & Choke

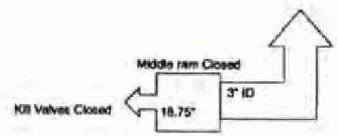
Assume total rate	(stb/d)	52000
Recorded Q 4000	(stb/d)	7130
Recorded HP1	(stb/d)	12000
Assumed Choke	(stb/d)	32870
Recorded P @ K2 Gauge _Green (psia)		2825
Recorded Delta P (psi)		375
Calculated delta P @ assumed Choke rate		336
Calculated rate at recorded delta P (stb/d)		35000

2. Q 4000 shut in

Recorded Q 4000	(stb/d)	0
Recorded HP1	(stb/d)	12000
Assumed Choke	(stb/d)	40000
Recorded P @ K2 Gauge _Green (psia)		2794
Recorded Delta P (psi)		544
Calculated delta P @ assumed Choke rate		493
Calculated rate at recorded delta P (stb/d)		42000

3. Q 4000 & HP1 shut in

Recorded Q 4000	(stb/d)	0
Recorded HP1	(stb/d)	0
Assumed Choke	(stb/d)	52000
Recorded P @ K2 Gauge _Green (psia)		3061
Recorded Delta P (psi)		811
Calculated delta P @ assumed Choke rate		828
Calculated rate at recorded delta P (stb/d)		51500



HP = 12 mbd

APPENDIX A.2

9491

Exhibit No. ______

Worldwide Court Reporters, Inc.

Document Produced Natively

COMPLEX

		7/15/2010 1:45 AM	
P :	2624	2381	psia
dP :	424	181	psi
Total Containment :	0	23,000	stb/d
HP1 :	0	15,000	stb/d
Q4000 :	0	8000	stb/d
dQ :	0	2394	stb/d
Actual V Containment :	0	88473	bbl/d
Actual V dQ :	0	9209	bbl/d
Liquid Holdup :	0.38	0.36	-
V Factor :	1.4045	1.3848	bbl/stb
Venting Rate :	**62,039**	**41,433**	stb/d
	2200	**psia (ambient)**	
	9.88	**stb/d/psi** 9.88	0.00

SIMPLE

		7/15/2010 1:45 AM	
P :	2624	2381	psia
dP :	424	181	psi
Total Containment :	0	23,000	stb/d
HP1 :	0	15,000	stb/d
Q4000 :	0	8000	stb/d
dQ :	0	2280.558	stb/d
V Factor :	1.4045	1.3848	bbl/stb
Venting Rate :	**59,098**	**38,378**	stb/d
	2200	**psia (ambient)**	
	9.42	**stb/d/psi** 9.42	0.00

APPENDIX A.3

From: Lockett, Tim
Sent: Tue Jun 29 11:32:28 2010
To: Hill, Trevor
Cc: MC252_Email_Retention
Subject: Top kill simulation cases
Importance: Normal
Attachments: Post event simulation of the Top Kill procedure.doc

Trevor

I have now looked at TopKill #1 and 2 using the same resistances and well PI as are needed to get a first pass 'reasonable' match to TopKill#3.

The results are not bad. TopKill#1 shows some interesting features, and the suggestion that the flow resistance increased during the top kill procedure. TopKill#2 only seemed to use a low mud rate and had an odd pressure build over the procedure.

Attached is my previous write-up extended with these latest results. Could we maybe get some time later to talk through the value in taking these further with this premise. I would also value some discussion on:

- the timing of when the test rams were opened before TopKill#1 and when they were closed at the end of TopKill#3
- the 966 psi fixed offset over and above the column labelled "Lower BOP" in the xls databooks.
- and confirmation of the junk shot application in TopKill#3 as there is a time when the pressure rises when the mud rate is constant and this is not represented by OLGA.

<<...>>

From the discussion with Henry it seems that up until yesterday his model was not yet working, at least with his fluid files. I believe his premise is different (since his model includes the annuli in detail) so there should not be duplication between our work. It would therefore be beneficial to see if his model can show similar or better levels of agreement with the data.

Best regards

Tim

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Email: tim.lockett@uk.bp.com

Calibration of the well model with a dual flow path

Data

Top Kill transient data referenced in this section are from the following sources:

- Top Kill #3: "052810 SS BP Kill Job Blue Dolphin TJH.xls"
- Top Kill #2: "052710 SS BP Kill Job Blue Dolphin.xls"
- Top Kill #1: "052610 BJ Data.xls"

Premise

The premise on which this section of work is based is that there is flow up the drill string and also up the casing and through the BOP rams.

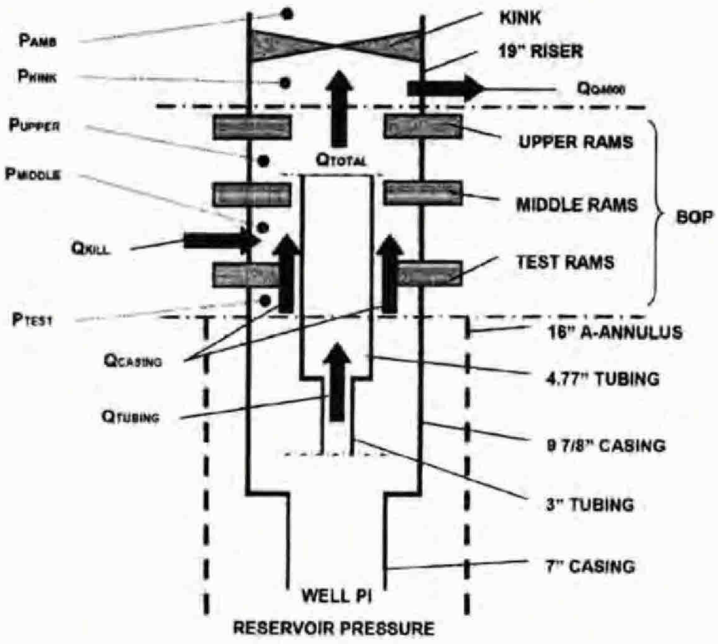

Figure 1: Subsurface and BOP premise for top kill simulation

Model

The model is summarised as having flow up the liner and casing as far as the base of the drill-pipe, and then two parallel flow paths:

- Up the drillpipe to the topmost section of the BOP stack, then through the last rams and out to the riser, kink and sea ambient pressure

- Up the remaining height of the casing, through the test rams, middle rams (which represent more than one set), ,then out to the riser, kink and sea ambient pressure

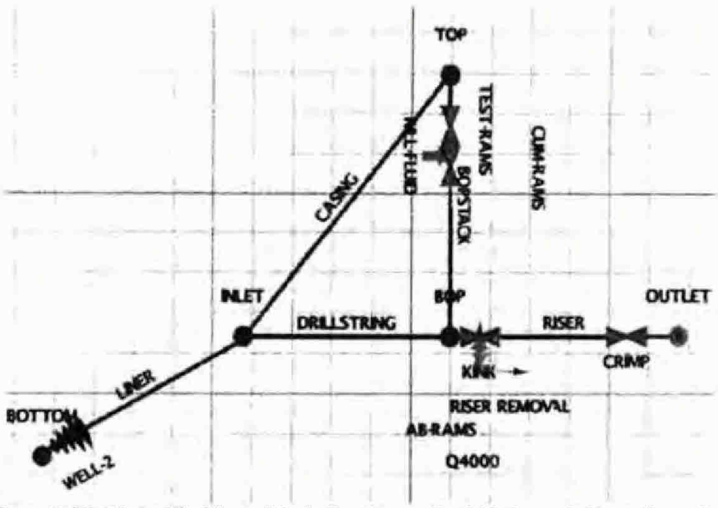

Figure 2: OLGA model of the well including flow up the drill pipe and also up the casing

Drilling Fluid

Drilling fluid was represented as having a density of 16.4 ppg (1972 kg/m^3) and being a Bingham fluid with yield stress of 15 lb/100ft^2 (7 Pa) and a plastic viscosity of 30 cPoise. Due to lack of data, no variation with temperature or pressure was included. With this non-Newtonian description, the effective viscosity of the mud as a function of shear rate is shown below

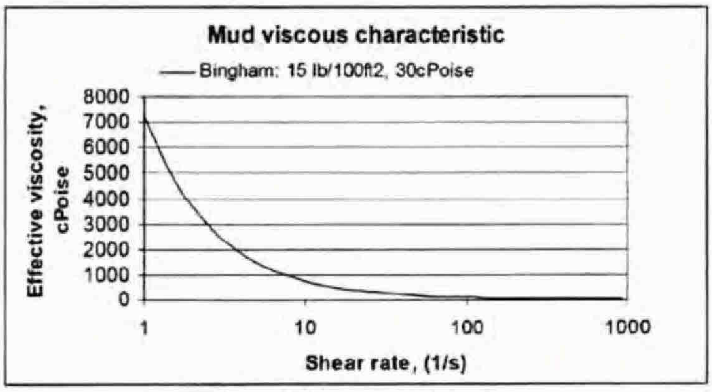

Figure 3: Mud viscous behaviour

Calibration against current operating state

The model was initially calibrated by allowing the pressures at the following locations to be matched:

- Pressure below the test rams: 4400 psia
- Pressure below the middle rams: 3760 psia
- Pressure below the upper rams: 2550 psia

In order to match these pressures, the open area of the test rams, middle rams and upper rams was adjusted to represent a leak path through the rams. In the case of the test rams and middle rams, this leak path is external to the drill-pipe.

The parameter of the case is the well PI. Values of 4, 5 and 6 sbbl/d/psi were tested and found to be insufficient to achieve the pressure of 4400 psia at the test rams.

A well PI of 10 sbbl/d/psi was tested and was found to be sufficient to achieve this pressure, and generated an excess flow through the BOP rams of 18000 bbl/d in addition to a flow of 25800 sbbl/d through the drill pipe (Total 43900 sbbl/d). The open area of the rams for this case were as follows:

A/B rams	5.8	sq in
C M U rams	1.1	sq in
Test rams	1.3	sq in

Higher well PI values would generate larger flows while meeting this pressure, well PIs between 7 and 10 would generate lower flows and may still be able to meet this pressure.

Difference from the state prior to the top kill procedure

Two differences exist in the state of the well at the time of the top kill procedure:

- The test rams were opened to allow the top kill attempt to proceed. This change was included in the model
- At the time that the top kill was attempted, the old riser, including the kink, was in place. This aspect has not been included in the model for all cases. If this resistance is included then the top kill case will generate higher pressures in the BOP stack and it is more likely that the case would result in killing the well.

Top Kill Simulation

The top kill simulation was tested for the highest rate of mud, 78 bbl/min (this was incorrectly modelled as 366 kg/s which corresponds to a mud rate of 70 bbl/min) with the expectation of generating a pressure in the region of 6000 psia at the BOP stack.

Case 1: PI = 10 sbbl/d//psi

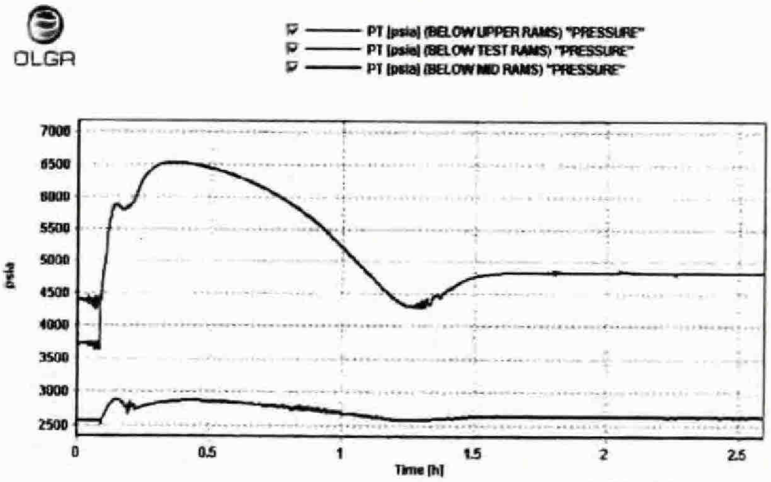

Figure 4: Pressure trace during the top kill simulation, PI = 10 sbbl/d/psi

The initial pressures in the BOP stack prior to starting the top kill can be seen on the far left hand side - the top kill starts after 300 s of simulation. The peak pressure during the top kill is understood to be approximately 6000 psia. This case therefore exceeds the measured pressure, suggesting that the resistance of the rams has been over-estimated and in fact the rams allow a greater flowrate to pass. Had the kink resistance also been included the pressure would have been still higher (approx another 200 psi).

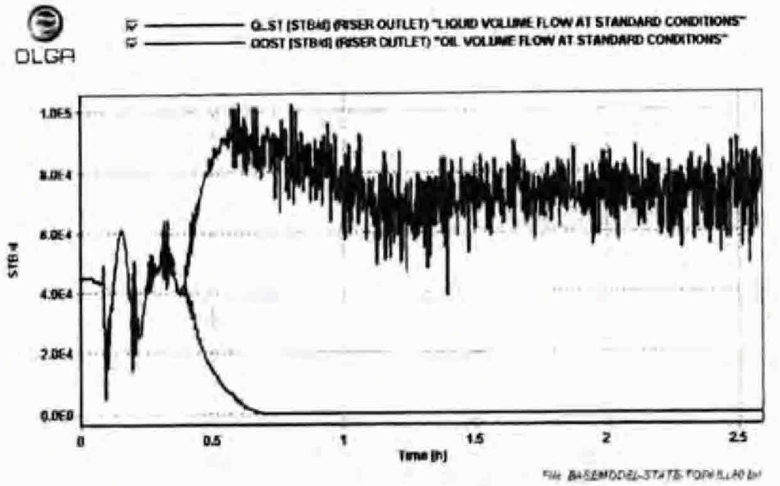

Figure 5: Flowrate trace exiting through the riser during the top kill (total liquid and oil, the difference being mud), PI = 10 sbbl/d/psi

In this case the top kill is successful, the oil rate falls to zero allowing a mud column to be built. This behaviour deviates from actual events.

The additional conclusion for this case is that if the kink resistance had been included then the well would have also been killed (killed more easily) and hence there is no requirement to re-run this case including the kink resistance.

Case 2: PI = 20 sbbl/d/psi

The calibration of the rams given the pressures for current operation was completed for a well PI of 20 sbbl/d/psi. With this calibration, the flowrates were found to be:

- 25200 sbbl/d up the drill pipe
- 51800 sbbl/d up the casing and up through the rams
- Total: 77100 sbbl/d

The open area of the rams for this case were as follows:

A/B rams	10.9	sq in
C M U rams	3.25	sq in
Test rams	3.6	sq in

For this case, the kink resistance was then calibrated, before the top kill case was undertaken. In order to do this calibration, it was assumed that the resistances derived from the current operating state (test, middle and upper rams) would have applied with the same effective open areas. This uses the assumption that the top kill operation did not itself materially effect the integrity of the rams (eg through erosion).

This assumption is weak and if incorrect would imply that more flow is coming from the well after the top kill than would have been the case before the top kill.

The kink and riser was therefore added and the open area was calibrated to give:

- Pressure of 2700 psia upstream of the kink.
- The leaks on the kink itself were not modelled. This has no impact on the results since the pressure measured upstream of the kink does not influence the split of flow between the leaks at the kink compared with the flow along the old riser.

The open area of the kink for this case was 8.16 sq in. Because the leaks at the kink were not separately modelled, this area would include both the 'kink' area (for flow along the riser, assuming there is no other restriction) and the area of the 3 or 4 leaks at the kink combined.

As a consequence of including the kink restriction, the pressures in the BOP stack were increased to the following values:

- Below the test rams: 4562 psia
- Below the middle set of rams (C/M/U rams): 3890 psia
- Below the upper set of rams (A/B rams): 2928 psia

This increased backpressure reduced the flowrate from the well to the following values:

- 24000 sbbl/d up the drill pipe
- 50400 sbbl/d up the casing and up through the rams
- Total: 74400 sbbl/d

Comparing the flowrates with and without the kink restriction, the flowrate increase due to removing the kink is around 3.5%.

With the model calibrated in this way, the top kill was simulated at the highest flowrate (80 gpm) with the test rams opened.

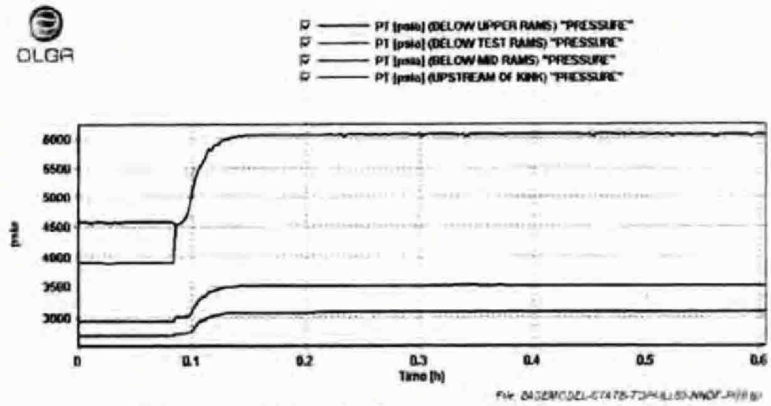

Figure 6: Pressure trace during the top kill simulation, PI = 20 sbbl/d/psi

The initial pressures in the BOP stack prior to starting the top kill can be seen on the far left hand side - the top kill starts after 300 s of simulation. The pressure rises to 6000 psia and does not change with time indicating that a mud column is not being built in the well.

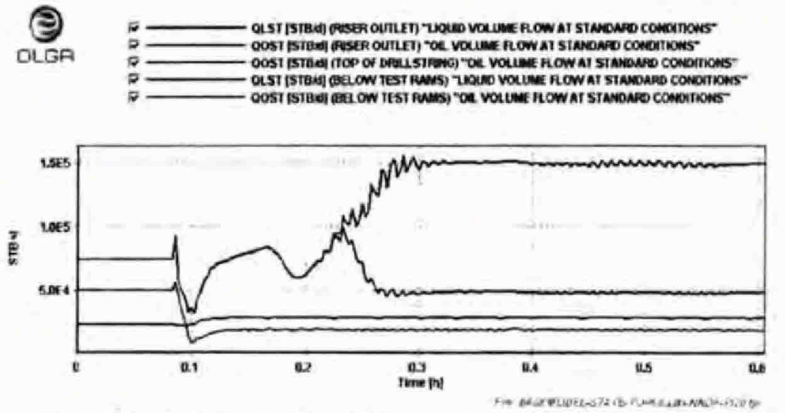

Figure 7: Flowrate trace exiting through the riser during the top kill (total liquid and oil, the difference being mud), PI = 20 sbbl/d/psi

Conclusions at this time (from PI = 10 and 20 cases)

The following conclusions are therefore indicated based on the following two key assumptions:

- the model with two paths for flow is a valid representation of what is happening in the well

- and that the resistances derived from the current operation can be retrospectively applied to the conditions before the top kill event (which might not be true if the top kill mud caused additional erosion of the rams).

On this basis it is concluded that it is highly likely that the actual operation lies between these the two cases modelled here, and so it can be inferred that the PI of the well is probably in the range 10 - 20 sbbl/d/psi. The implication is that the flowrate from the well is now probably in the range 44000 - 77000 sbbl/d, of that approximately 25000 bbl/d would be expected to come through the drill pipe and the remainder through the casings/rams in the BOP stack.

Options for further study:

- Intermediate well PI values
- Model top kill rates lower than 80 bbl/min (for additional checks vs pressure)

PI = 12.5 and 15

Cases were repeated with PI values of 12.5 and 15. In both cases the well was not killed (albeit with the slightly lower mud rate of 70 bpm in place of the intended 79 bpm used). Of the 4 cases run, the results from the PI=15 case looked to be a close match to the actual pressure data. Further work will therefore be run using the PI=15 well description.

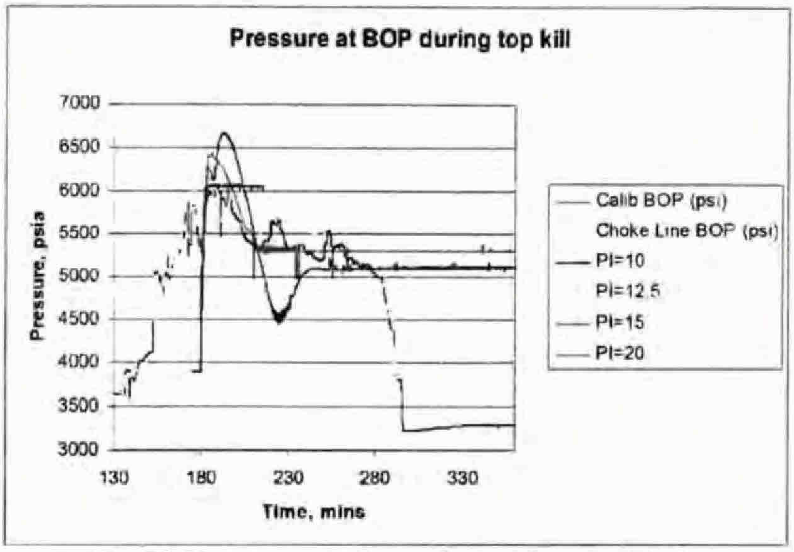

Figure 8: Pressure response during top kill, across the range of well PIs

PI = 15

For this case, the procedure above was repeated but with the following changes:

- Mud rate to mimic the actual delivery (ignoring the delay inherent in the volume delivery at sea surface compared with sea bed)
- Kink opening adjusted to set a pressure of 2700 psia at the same time that the middle set of rams is adjusted to set a pressure of 3670 psia.
- Upper rams set to be 100% open because the pressure basis on which to set these rams has now been lost by including the kink at this time.

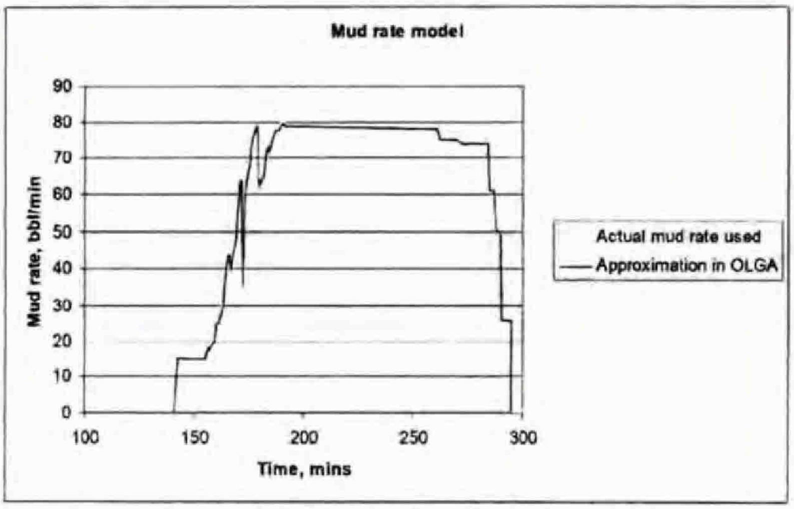

Figure 9: Mud rate modelling (input to the OLGA model)

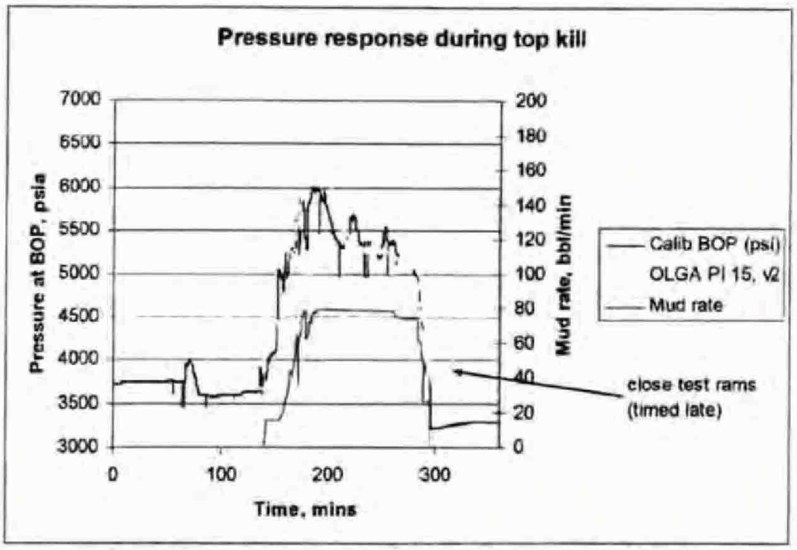

Figure 10: Pressure at the BOP (OLGA result) with PI = 15 sbbl/d/psi

This case shows a good deal of promise in matching the actual results, with the following areas of possible deficiency:

- The holes in the kink were not modelled. This may well impact the peak pressure of 6400 psia vs the actual peak of 6000 psia. This can be included in the model.
- The test rams were not closed when the mud supply was turned off. This impacts the pressure at time = 310 mins onwards. This aspect was considered by restarting the simulation. The simulation is then symmetric in that the pressure at the end is essentially the same as the pressure at the start, which differs from the actual result where a 315 psi decline is seen across the top kill operation (start to finish).
- The decision to model the upper rams as being fully open in this case should be revisited. Current operation (with the kink removed) suggests a differential pressure of 300 psi exists across these rams. Other options for modelling this condition are:
    - Retain the open area from a case which models the current condition (without the kink) and apply it to this case.
    - Retain a 300 psi differential even with the kink in place, such that the pressure below the upper rams is 3000 psia.

Kink resistance removed:

The pressure below the upper rams was set to be 2560 psia before starting the top kill. In doing this, the upper rams were set to represent the flow resistance of the rams and kink combined.

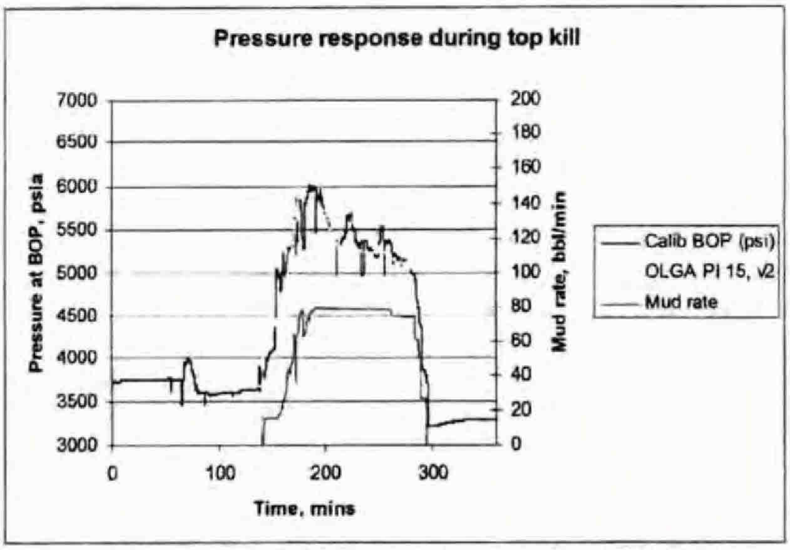

Figure 11: Pressure at the BOP (OLGA result) with PI = 15 sbbl/d/psi and with the kink resistance removed (encompassed within the setting of the resistance for the upper rams)

The early pressure rise in this case (time = 146 - 157 mins) exceeded the actual result. It was deduced that this is associated with the test rams being opened in the model to allow the top kill to proceed. In practice, the test rams were already open at this time. The model was therefore re-based such that the pressure below the middle rams (3670 psia) and upper rams (2550 psia) was set with the test rams open, with the following result:

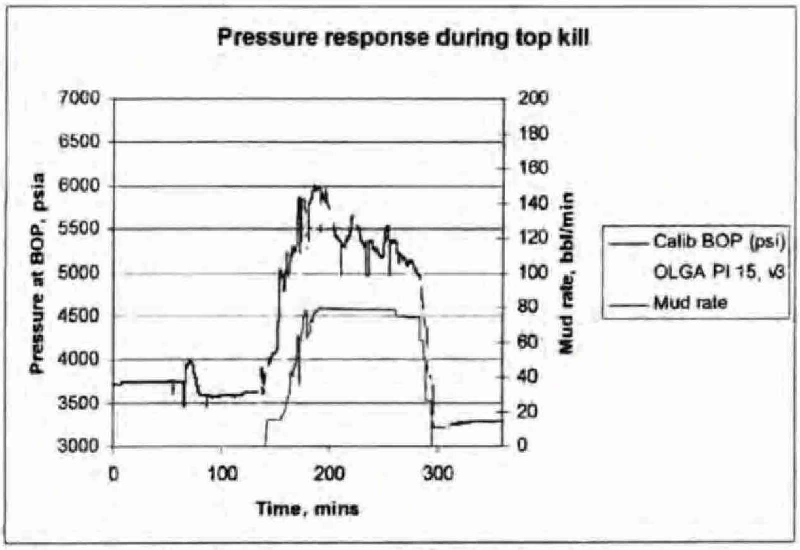

Figure 12: Top kill#3 with Test Rams Open while setting the initial pressure of 3670 psia

This case shows a better match to the early pressure increase than the previous case, and possibly also the peak pressure, at the expense of a worse match for the pressure through the later stages. The relatively flat pressure response late in the top kill event corresponds to little/no mud column. In order to gain a better match this case was re-run with a lower well productivity index of 12 sbbl/d/psi.

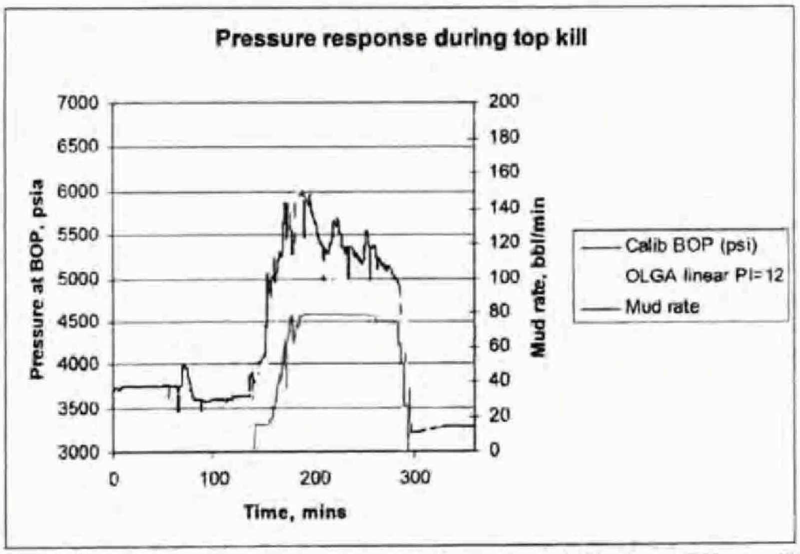

Figure 13: Simulation of Top Kill #3, resistances calibrated to give 3670 psia and 2550 psia with the test rams open, well PI = 12 sbbl/d/psi

In this case the initial pressure rise (to ~4100 psia) is well captured.

The junk shot was applied during the early stages of Top Kill #3 and this may in part explain the significant rise in pressure at a time of 152 minutes whereas the OLGA result has a pressure increase as the mud rate is ramped up starting at a time of 158 minutes.

The peak pressure is well captured (6000 psia), and the subsequent decline in peak pressure corresponds in the OLGA model to building a mud column in the casing.

The two 'humps' in the pressure decline are not reproduced by this OLGA model but in the context of building a mud column in the casing such a pressure response might correspond to shedding part of the column before it is complete down the casing, and then rebuilding it. In this context it is important to recognise that the OLGA model includes a *linear* well productivity to describe the inflow.

The case ends at a lower pressure than it started because the test rams are closed (in the model) when the mud flow is turned off. The timing of the closure of the test rams in practice is not known (at this time).

The mud column formed in this case is shown below:

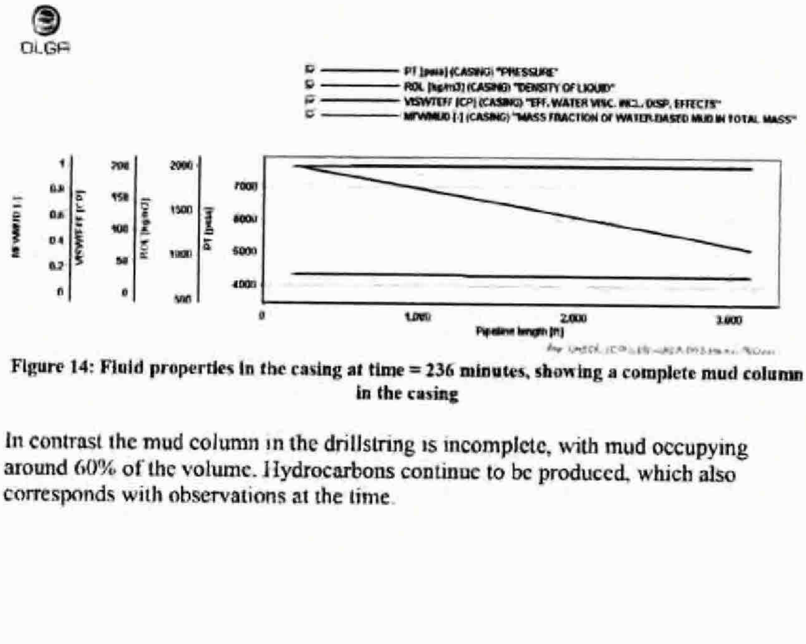

Figure 14: Fluid properties in the casing at time = 236 minutes, showing a complete mud column in the casing

In contrast the mud column in the drillstring is incomplete, with mud occupying around 60% of the volume. Hydrocarbons continue to be produced, which also corresponds with observations at the time.

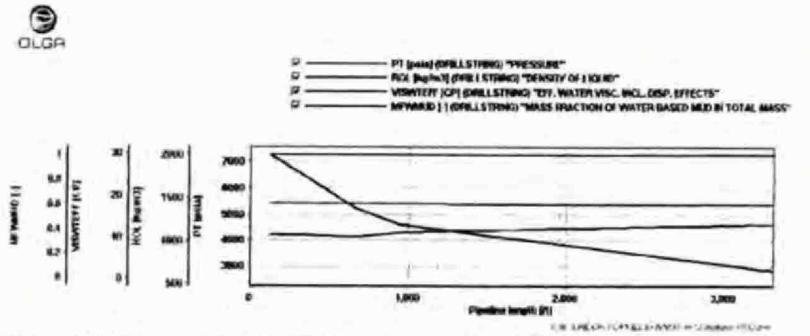

Figure 15: Fluid properties in the drill string at time = 236 minutes, showing a partial (60%) mud column in the drill string

For completeness, the case was re-run with a well PI of 10 sbbl/d/psi, with the following result:

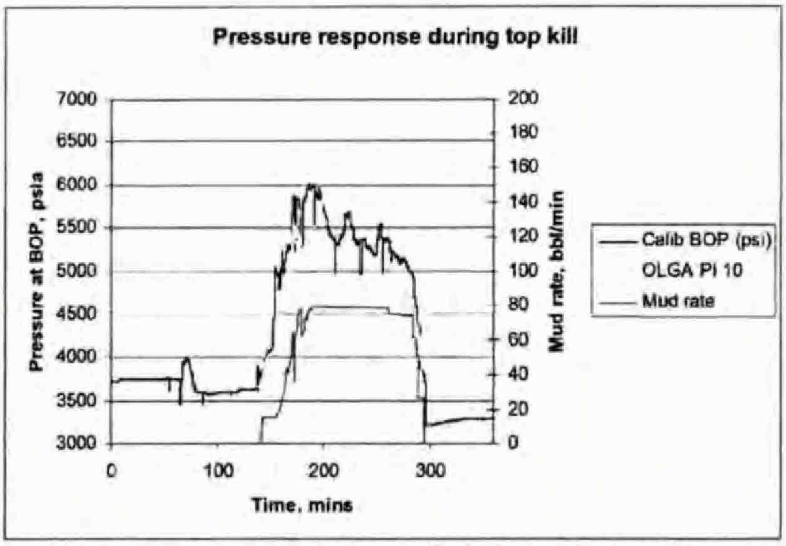

Figure 16: Simulation of Top Kill #3, resistances calibrated to give 3670 psia and 2550 psia with the test rams open, well PI = 10 sbbl/d/psi

As previously identified, this case succeeds in killing the well. The failure of the OLGA result to capture the timing of the second pressure peak at time = 190 minutes reflects the mud column that is built in the casing during the first peak (time ~ 180 minutes).

Conclusions for Top Kill #3

This analysis concludes that

- The starting condition for the top kill has been set such that
  - The test rams are open
  - The pressure in the BOP stack is 3670 psia
  - The pressure in the upper portion of the BOP stack (below the upper rams) is 2550 psia, and this includes the flow resistance of the kink
- A reasonable representation has been developed for top kill #3 using a well PI is ~12 sbbl/d/psi, whereby:
  - The peak pressures are reasonably well represented,
  - The well is not killed at the mud rates which were used,
  - The pressure response declines as a result of building a mud column in the casing (behind the drill string)
  - Hydrocarbons continue to flow up through the drill string throughout the procedure (as observed)
- Certain features of the pressure response (humps) are not represented by the model. These features could be explained by a lack of stability in the mud column (shedding and subsequent rebuilding).
- The model suggests that with a well PI of 10 the well would have been expected to be killed. Equally, with a well PI of 15 the pressure response

would have been expected to be constant at constant mud rate, indicating that no mud column was built in the casing.

Overall the model is considered to be robust enough to apply it to the other top kill datasets.

Other Top Kill data sets

Three top kill attempts were made over the time 26, 27, 28 May 2010. The intent is to define a model using Top Kill #3 (above) and then test it unchanged on TopKill#1 and #2. The well PI should remain constant. The resistances in the BOP rams will be treated as being constant but may well in practice have eroded. To gain a good match with this model it is therefore anticipated that the resistances applied in TopKill#3 would be less (larger leak path) than would be needed to get a good match in TopKill#1.

Top kill #2

The data used in this comparison is "BOP, psi", which is formed from the data recorded in column "Lower BOP" with an additional 966 psi added. This offset is carried forward from the TopKill#3 spreadsheet.

The mud rate is taken from a column headed "Mech rate, bpm".

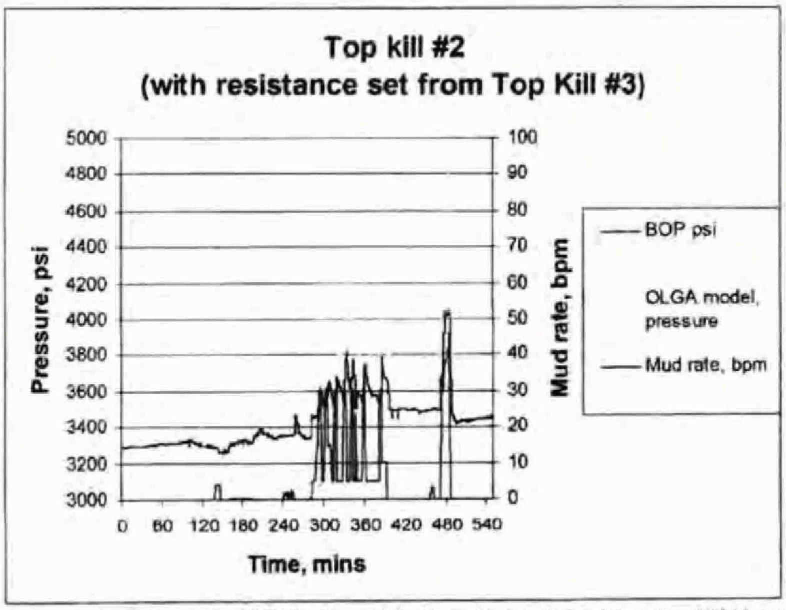

Figure 17: Simulation of Top Kill #2 using model with resistances defined from Top Kill #3 and a well PI = 12 sbbl/d/psi

Figure 17 shows the following:

- the initial pressure in the OLGA model (3670 psia) is significantly higher than the pressure which was recorded.
- The peaks in pressure in the OLGA model are significantly graeter in amplitude in the OLGA model than was recorded.
- The mud rate in this top kill attempt was quite low and the OLGA model does not indicate the formation of a mud column.

Across the top kill procedure, OLGA returns to the same pressure that it started with. The data shows a gain in pressure of ~300 psi. This behaviour might be consistent with gradual flushing out of a mud column formed during top kill #1.

Top kill #1

The data used in this comparison is "BOP, psi", which is formed from the data recorded in column "Lower BOP" with an additional 966 psi added. This offset is carried forward from the TopKill#3 spreadsheet. For comparison, data headed "Kill line BOP" is also plotted.

The mud rate is taken from a column headed "Combined rate".

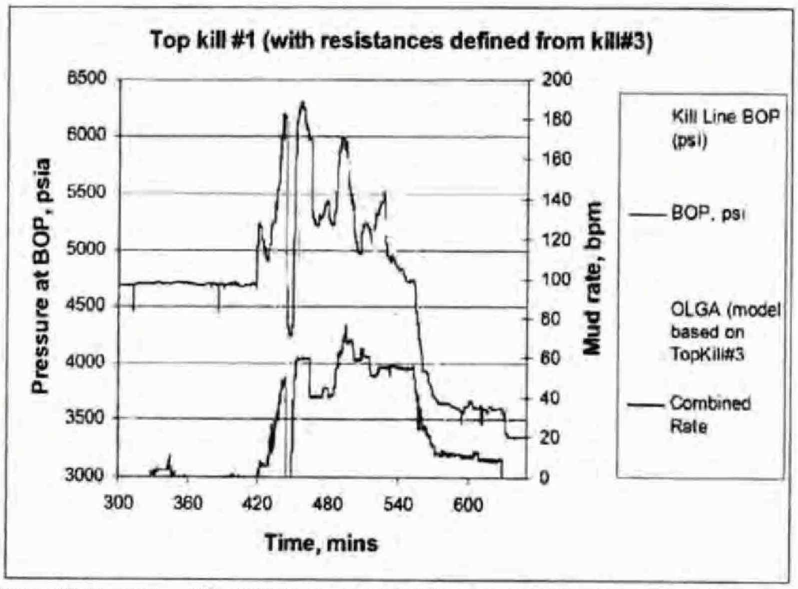

Figure 18: Simulation of Top Kill #1 using model with resistances defined from Top Kill #3 and a well PI = 12 sbbl/d/psi

Figure 18 shows the following features:

- The OLGA model pressure starts at a pressure (3670 psia) which is significantly lower than the "BOP" pressure but is more consistent with the pressure in the kill line during the short period of mud injection which preceded the main top kill attempt (time = 300 - 350). The pressure recorded as "Lower BOP" is 966 psi lower than the "BOP" pressure.

- From a time of 420 minutes onwards, the "BOP" pressure and the kill line pressure are in good agreement with each other. The reliability of "BOP" pressure before a time of 420 minutes is therefore uncertain. A possible explanation is that this higher reading would be consistent with the test rams being closed at this time, and if modelled as such, the OLGA model would reproduce this.
- During the initial stages of the top kill, the first two peaks in pressure are significantly under-predicted by the OLGA model. This suggests that the flow resistance was greater during this time.
- The third peak is better represented by the OLGA model.
- Across the three peaks, the OLGA model is largely mimicking the mud rate, in that the first and second peaks in pressure have lower mud rates than the third peak. It is therefore surprising that the third pressure peak is lower than the first and second, and suggests that a resistance that was present during the first two peaks was removed prior to the third peak.

The OLGA model for this case does not form a mud column in the casing although a small amount of mud (7% volume) does collect towards the top of the casing when flowing at the peak rate (third peak, 77 bpm).

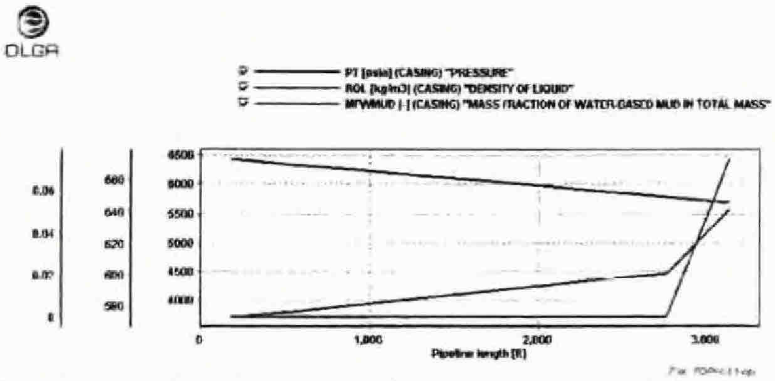

Figure 19: Fluid properties in the drill string at time = 493 minutes, showing a small (7%) mud collection towards the top of the casing

Having failed to form a mud column, the pressure in the OLGA model remains relatively stable with time while flowing at a constant mud rate of 60 bpm (time = 530 - 553 mins). In contrast the actual result over this time period shows a declining pressure at constant mud rate which would be consistent with a mud column being formed.

Further work with this case:

- Ascertain the additional resistance that would be required to bring the first and second peaks to the pressure levels that were recorded.

- Ascertain the additional resistance that would be required to bring the third peak closer to 6000 psi AND would lead to some formation of mud column in the casing during the time period 530 - 553 mins.

APPENDIX A.4

From: Saidi, Farah
Sent: Tue Jul 27 20:14:36 2010
To: 'Ratzel, Arthur C'; sgirrens@lanl.gov
Cc: Hill, Trevor
Subject: Choke side and kill side Drawings
Importance: Normal
Attachments: 3 Ram Stack with chok & Kill schematic.doc; FW: Dimensions of Side Outlets

As per your request

Regards,
Farah Saidi
GOM SPU Flow Assurance Technical Authority
BP
Office 281-366-5746
Cell 832-978-4121

9576
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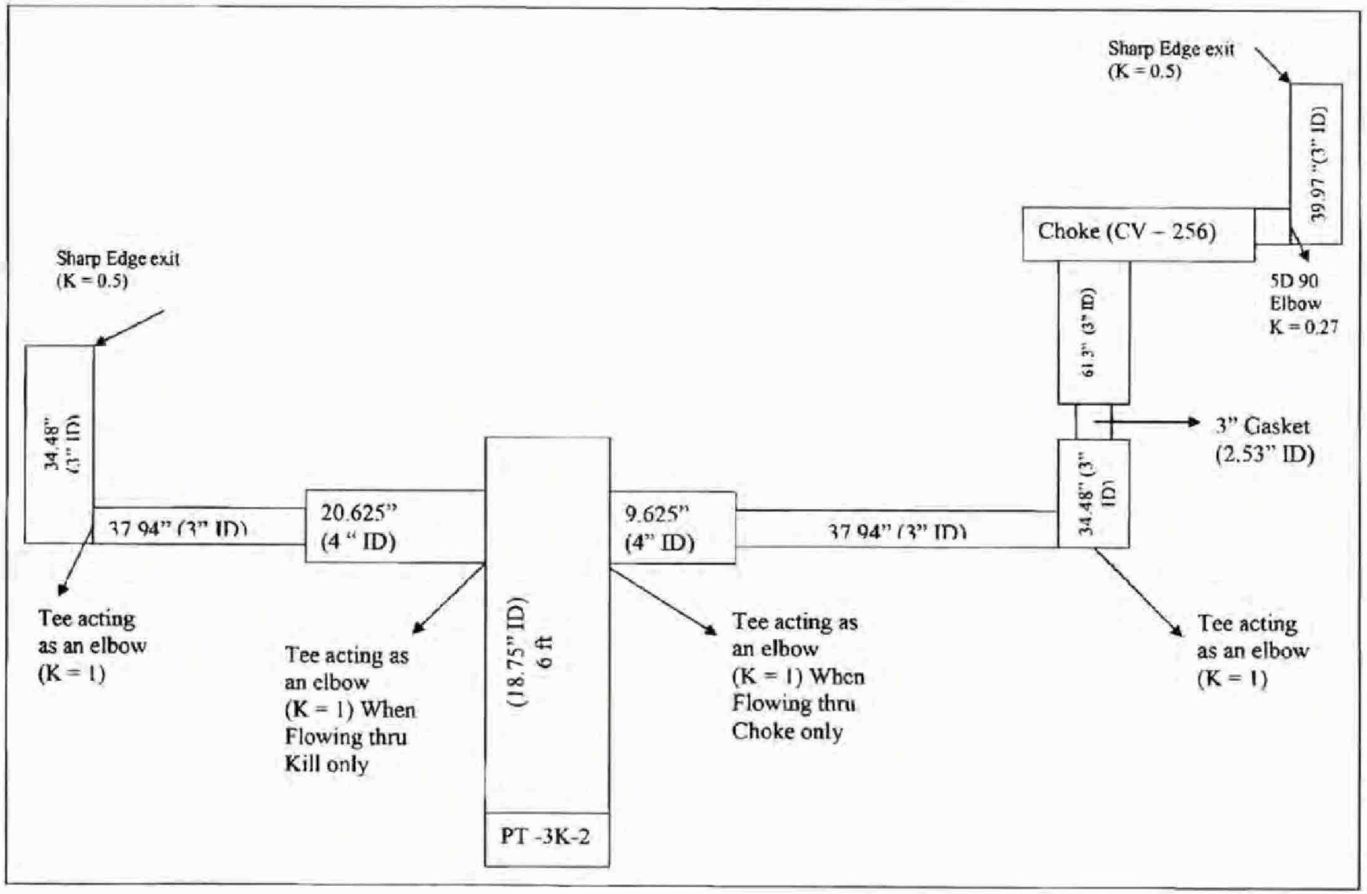


Sharp Edge exit
(K = 0.5)
39.97 "(3" ID)
Choke (CV – 256)
5D 90
Elbow
K = 0.27
61.3" (3" ID)
3" Gasket
(2.53" ID)
34.48" (3" ID)
Sharp Edge exit
(K = 0.5)
34.48" (3" ID)
37.94" (3" ID)
20.625"
(4 " ID)
9.625"
(4" ID)
37.94" (3" ID)
(18.75" ID)
6 ft
Tee acting
as an elbow
(K = 1)
Tee acting as
an elbow
(K = 1) When
Flowing thru
Kill only
Tee acting as
an elbow
(K = 1) When
Flowing thru
Choke only
Tee acting
as an elbow
(K = 1)
PT -3K-2

From: Strachan, Alex (JPK)
Sent: Mon Jul 26 19:25:05 2010
To: Cargol, Mike (UNKNOWN BUSINESS PARTNER); Saidi, Farah
Subject: FW: Dimensions of Side Outlets
Importance: Normal
Attachments: FLOW PATH.pdf; CC40HP Assembly SK-171594-13.pdf

Farah

Drawing showing flow path through Capping stack and Choke arrangement drawing.

Regards

Alex U. Strachan

(Temporary Direct : +1 (281) 366 2653
(Cell : +1 (281) 907 3554 It is sometimes necessary to dial 1 even from a Houston Number
: email : Alex.strachan3@bp.com
* location BP America, Houston, IMT WestLake 4

From: Turlak, Rob (Houston) [mailto:Rob.Turlak@deepwater.com]
Sent: Thursday, July 01, 2010 6:04 PM
To: Steen, Jack W. (QuaDril); Boughton, Geoff (Houston)
Cc: Rogers, Bruce A (Houston); Strachan, Alex (JPK); Arabie, Wilson (Frontline Group)
Subject: RE: Dimensions of Side Outlets

Here you go. In one view valves are rotated out of position for clarity because we could not get internal configuration of valves from WOM.

Rob

Priveleged and Confidential Attorney-Client Communication Document(s) prepared in anticipation of Litigation

From: Steen, Jack W (QuaDril) [mailto:Jack.Steen@bp.com]
Sent: Thursday, July 01, 2010 10:24 AM
To: Boughton, Geoff (Houston); Turlak, Rob (Houston)
Cc: Rogers, Bruce A (Houston); Strachan, Alex (JPK); Arabie, Wilson (Frontline Group)
Subject: Dimensions of Side Outlets

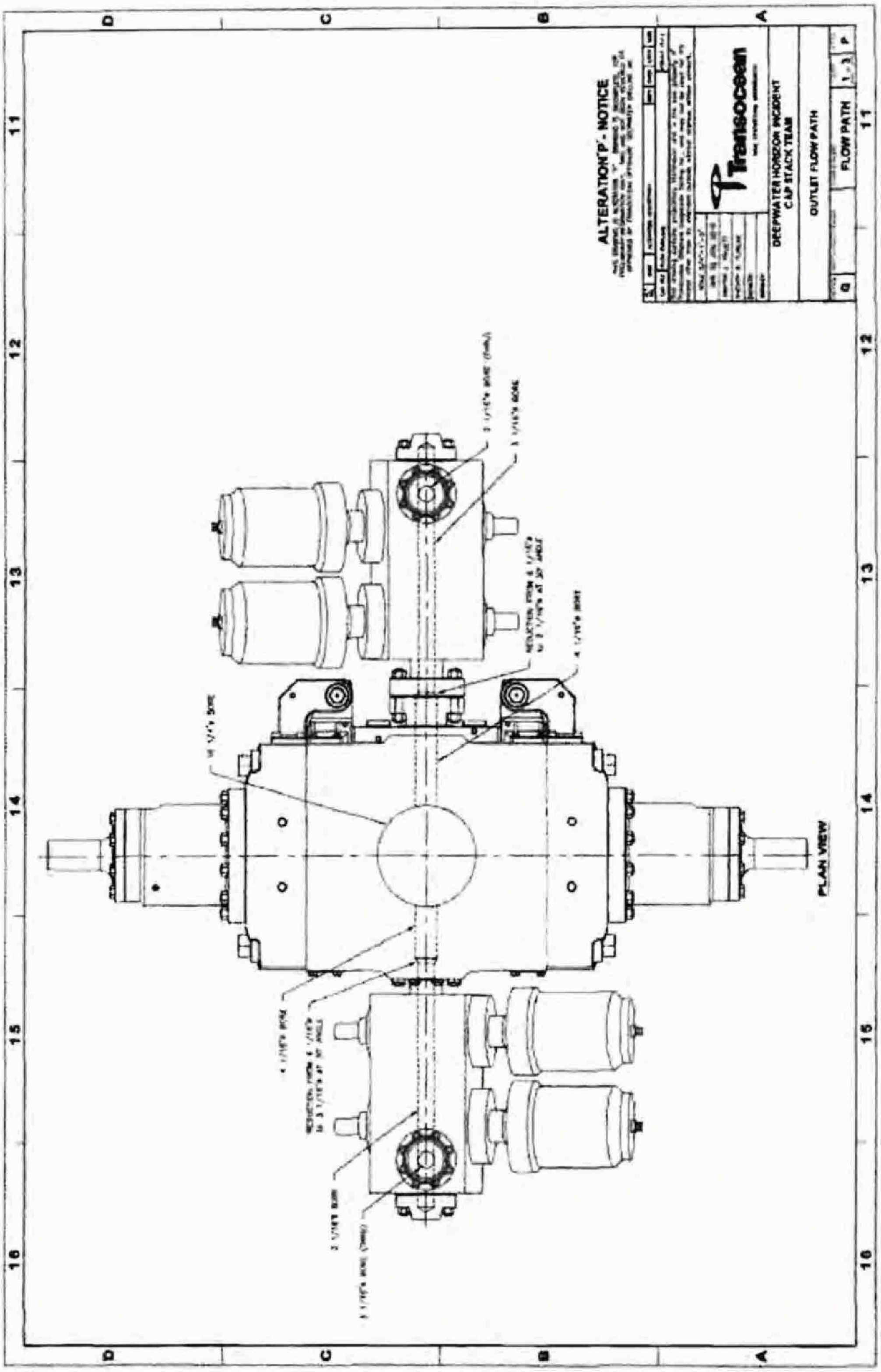
Geoff / Rob,

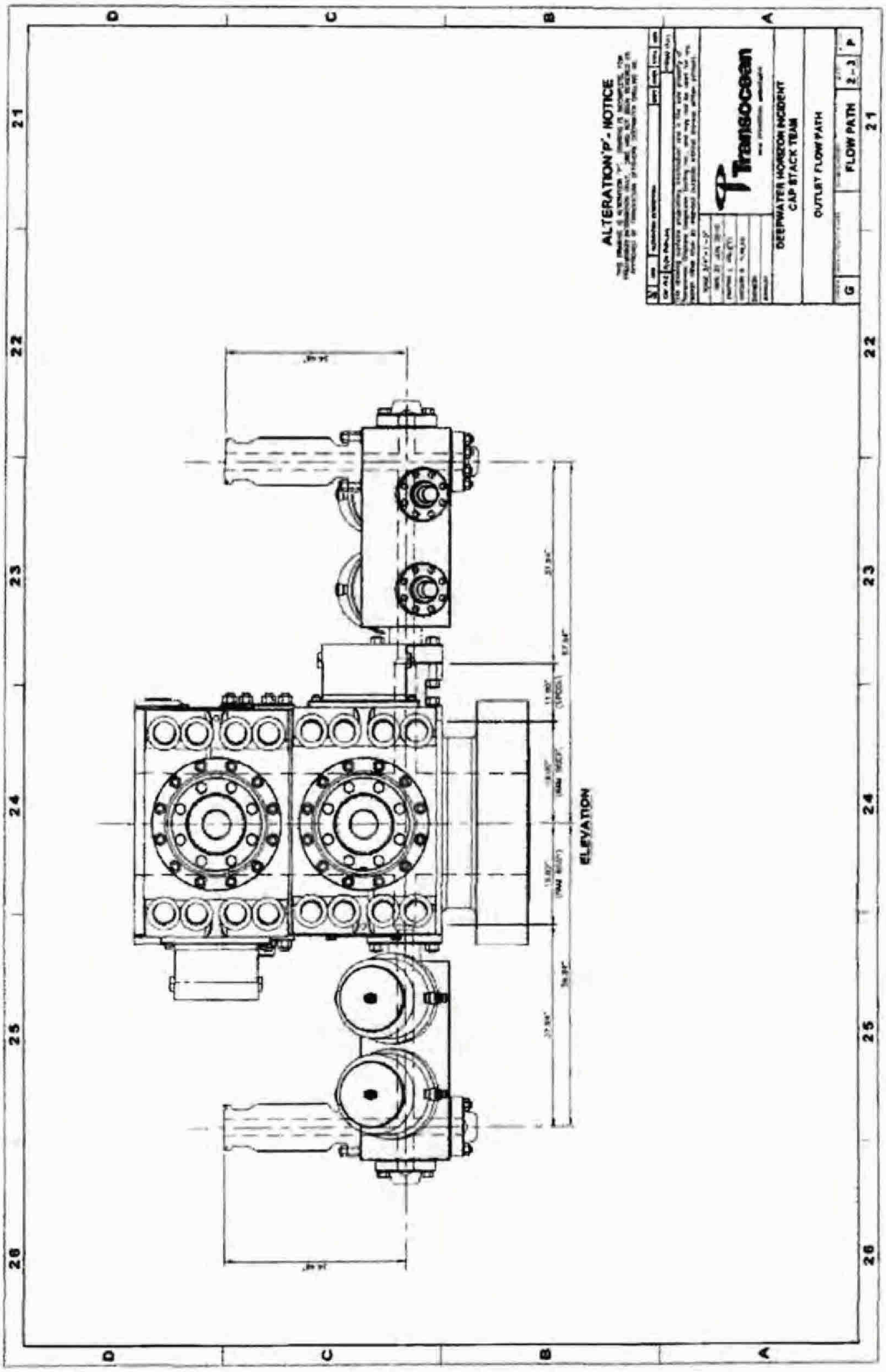
We are beginning to do some flow modeling. Do you have a close up, dimensioned drawing showing the configuration of the side outlet valves on the Capping Stack? We would like to see the spool length on the "new" kill side, as well as the length of the valve blocks themselves and the length of the hub outlets above them.

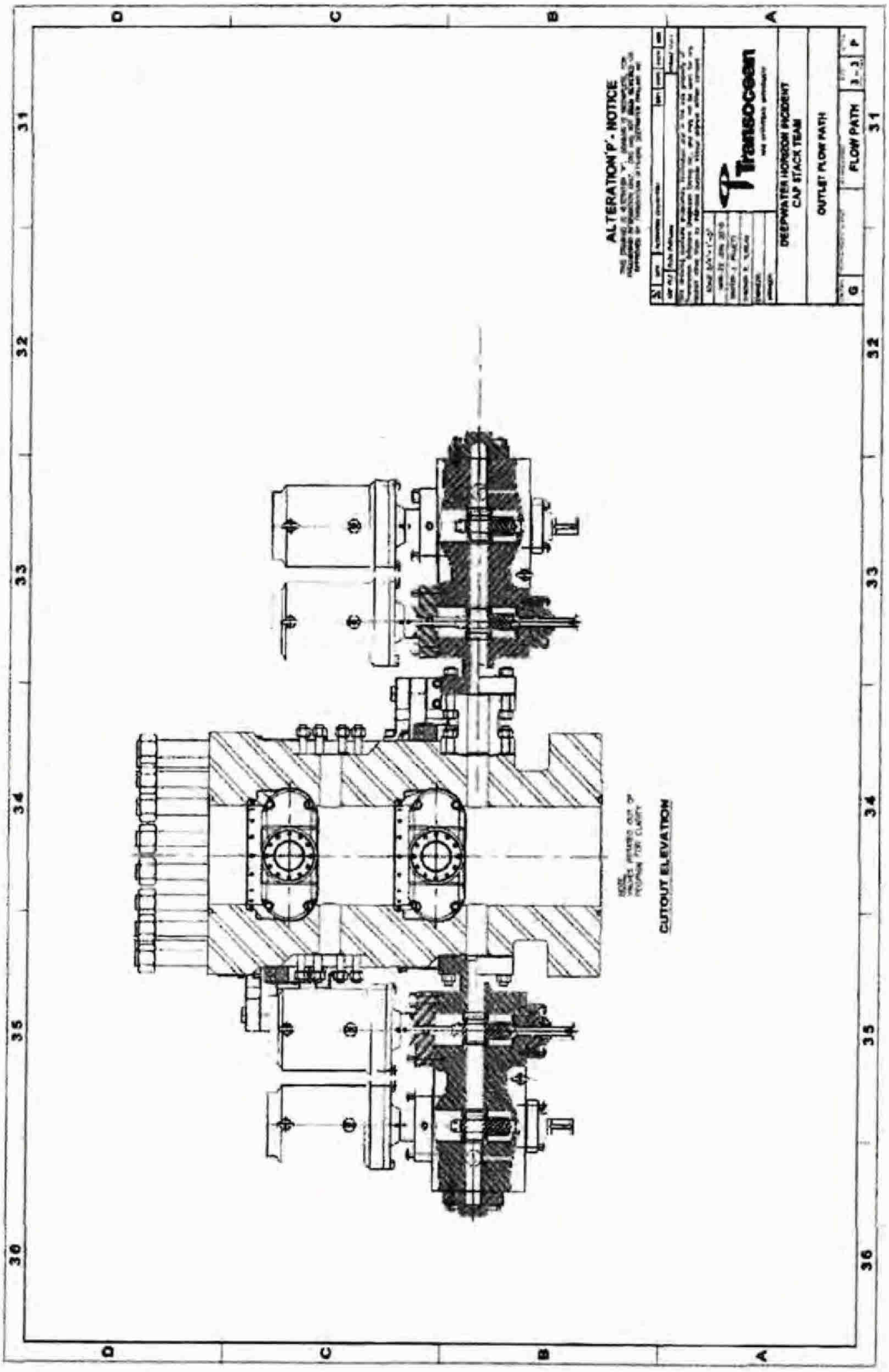
Who is the manufacturer of the valve blocks (is it Hydril like the rams)?

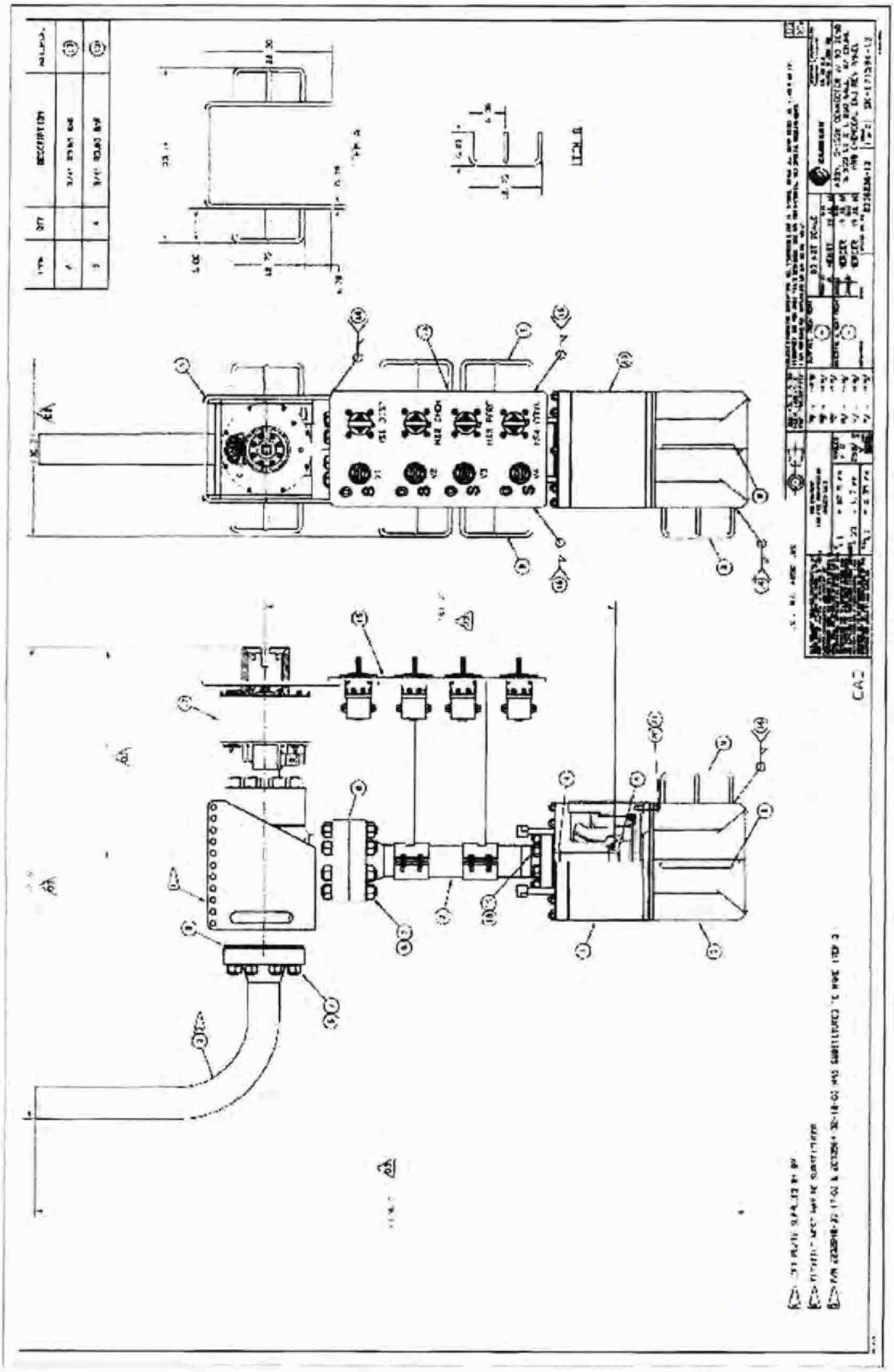
Regards,

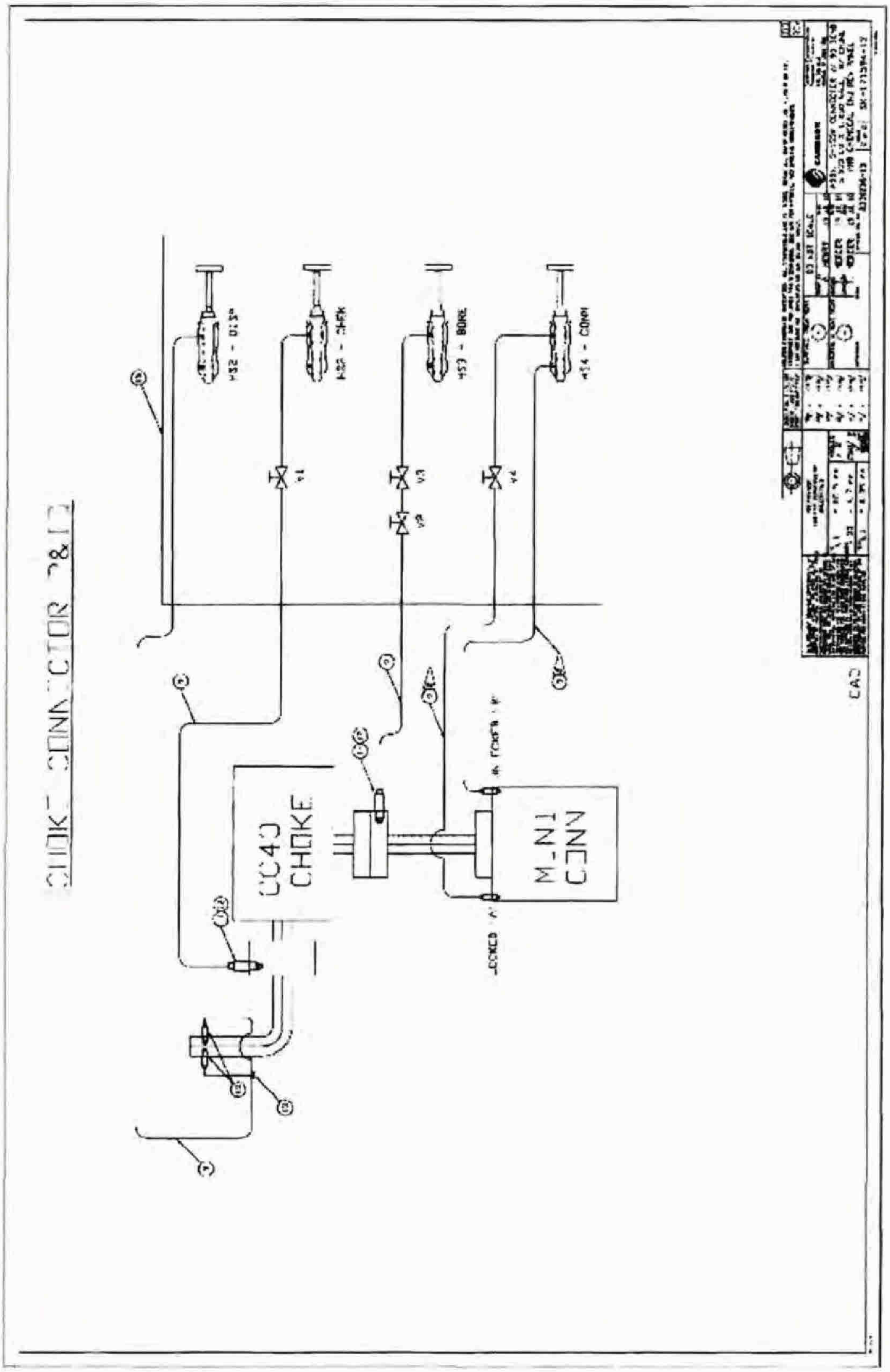
****
Jack Steen
BP DW Wells Delivery
200 Westlake Park Blvd. Ofc. 1058B - WL#4
Houston, TX 77079-2210
281-366-1108 Office
281-844-8904 Cell
jack.steen@bp.com
****


ALTERATION 'P' - NOTICE
Transocean
DEEPWATER HORIZON INCIDENT
CAP STACK TEAM
OUTLET FLOW PATH
FLOW PATH
PLAN VIEW


ALTERATION 'P' - NOTICE
Transocean
DEEPWATER HORIZON INCIDENT
CAP STACK TEAM
OUTLET FLOW PATH
FLOW PATH
ELEVATION


ALTERATION 'P' - NOTICE
Transocean
DEEPWATER HORIZON INCIDENT
CAP STACK TEAM
OUTLET FLOW PATH
FLOW PATH
CUTOUT ELEVATION




CC40
CHOKE
M_N1
CONN

APPENDIX A.5

From: Hill, Trevor
Sent: Sun Jul 04 22:16:36 2010
To: Block, Nathan
Cc: Birrell, Gordon Y; MC252_Email_Retention
Subject: Flowrate change on cutting riser
Importance: Normal
Attachments:
Attachments:

Nathan

Regarding your question about flowrate change on cutting the riser...

Early in the analysis of the MC252 situation a series of predictions was made of the % increase in flowrate for a given reduction in back pressure on the system. There is a report (too large to email) entitled *MC252 Holistic System Analysis*, in which those predictions are described. It resides in the Engineering Team sharepoint site and I can arrange for you to get a copy if required. The key graph from that report is attached. This analysis has been used within BP and in discussions with Secretary Chu when considering possible consequences of proposed actions.

That report was written before specific consideration of the riser cut, but the same analysis was used to illustrate the potential change in flowrate on making the cut.

The pressure was measured at the choke line gas vent port in the BOP/LMRP after top kill attempts on May 26 and 27 giving a value of ~250 psi above seawater ambient. This location is upstream of the riser kink, and therefore gives the maximum back pressure that was generated by the kink and riser.

For a reduction in back pressure of 250 psi, caused by removing the kink and riser, the predicted flowrate increase was 2-5% (given that drill pipe is in place) whatever the starting well head flowing pressure (WHFP) and flowpath option.

This value was used in internal BP discussions, and with DoE representatives. The DoE reported their estimate of 5% increase, but I do not have to hand a record of their assumptions.

The actual total loss in back pressure because of riser kink removal is very uncertain due to the time taken to make the two cuts, with intermediate steps affecting back pressure, and an underlying variation in the wellhead flowing pressure. Indications are that it was less than 250 psi.

I hope that this provides sufficient information to answer your question. Happy to provide more if required.

Regards
Trevor

Trevor Hill
E&P Engineering Technical Authority - Flow Assurance
+44 (0)7879 486974

BP Exploration Operating Co Ltd
Registered office: Chertsey Road, Sunbury on Thames, Middlesex, TW16 7BP, United Kingdom
Registered in England and Wales, number 305943

Flow Assurance BP Intranet Site   Flow Assurance in BP Connect

APPENDIX A.6

From: Tooms, Paul J
Sent: Fri Jun 11 00:04:01 2010
To: Wells, Kent; Birrell, Gordon Y; Clarkson, David; O'Bryan, Patrick L; Dupree, James H; Lynch, Richard; Inglis, Andy G (UPSTREAM)
Cc: Roberts, Jamie Y; Caldwell, Jason; Thierens, Harry H; Maguire, Niall J; Verchere, Christina C; Looney, Bernard; Mazzella, Mark; Grounds, Cheryl A.; Bond, Stan L; Hill, Trevor; Wood, Douglas G; Sprague, Jonathan D
Subject: Historical BOP Pressure
Importance: Normal
Attachments: BOP Pressure History rev3.xls

Attached is a chart showing BOP pressure over time, from when the acoustic transmitter has been operating. The pressures from the transmitter below the BOP test rams have been calibrated against the gauges we installed for the Top Kill and have a correction factor of 966 psi already applied. A number of points can be taken from the graphs, including:

1. Pressures below and across the BOP (with the test rams closed) are broadly the same now as they were prior to the Top Kill. This suggests that overall flow rates have not changed much, unless there is some unexplained mechanism in the well.
2. The pressure drop across the BOP has been relatively consistent, and it can be inferred that drillpipe is present and that flow through it has remained relatively unchanged .
3. The test rams would appear to be holding back pressure when they are closed, which suggests that there is at least some flow past the pipe rams.

This graph will be included in a more complete report on pressures and flow indications which will be issued shortly. However, I thought it useful to share this now as it can dispel certain myths that have taken root amongst the teams. Note that it might be tempting to try and interpret trends for individual parts of the graph – this is not advisable since there is quite a lot of noise in the readings and they are taken infrequently.
<<...>>

Paul

Paul Tooms
VP Engineering
Mobile phone number: +44 (0) 778 597 3421

Address: BP Exploration Operating Company Ltd Building H Chertsey Road Sunbury-on-Thames Middlesex TW16 7LN
Company Details: BP Exploration Operating Company Ltd
Registered Office: Chertsey Road Sunbury-on-Thames Middlesex TW16 7BP
Registered in England and Wales Number 305943

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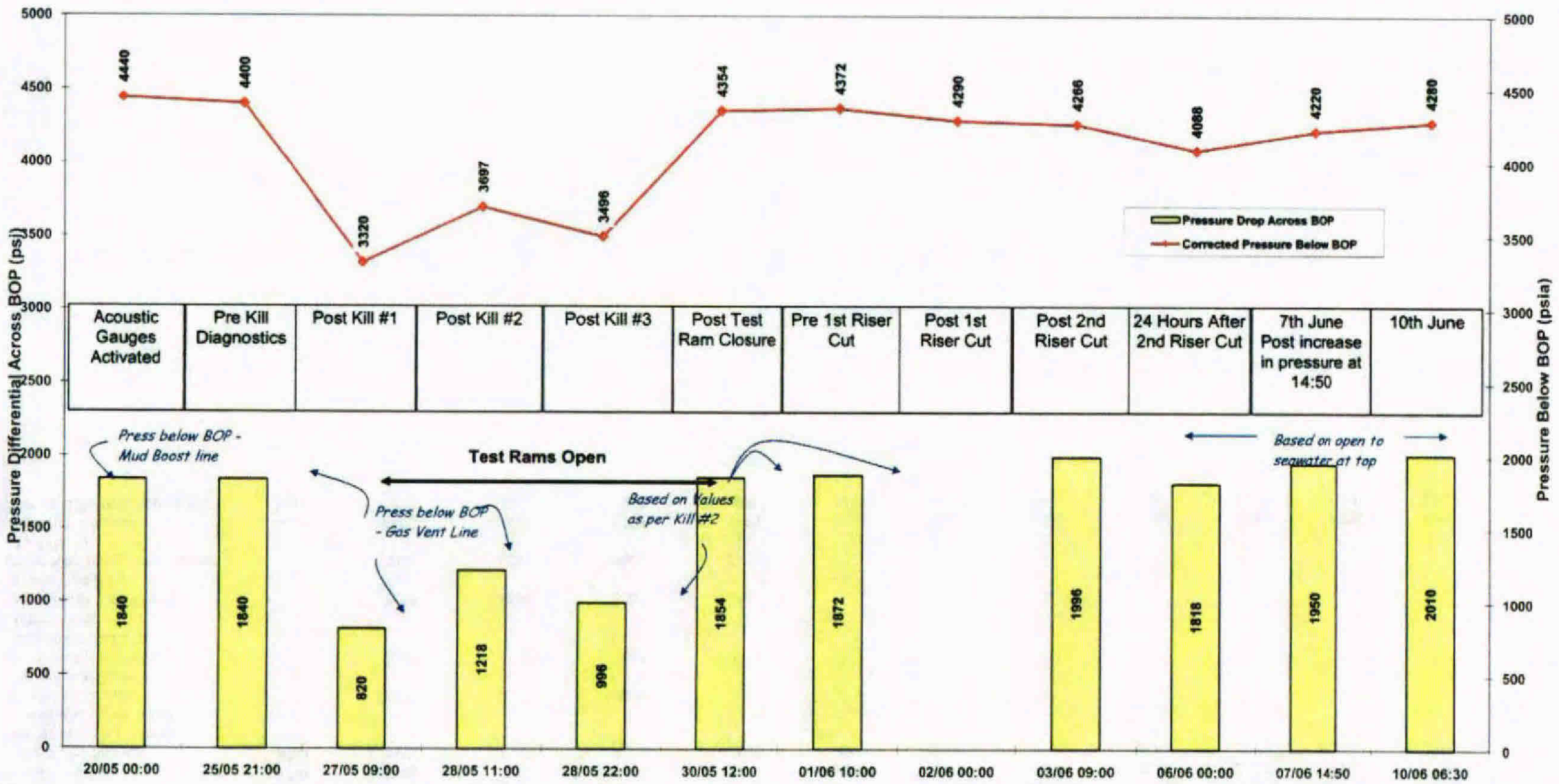
Timing	Acoustic Transponder Activated	Pre Kill Diagnostics	Post Kill #1	Post Kill #2	Post Kill #3	Post Test Ram Closure	Pre 1st Riser Cut	Post 1st Riser Cut	Post 2nd Riser Cut	24 Hours After 2nd Riser Cut	7-Jun	10-Jun
Test Ram Status	Closed	Closed	Open	Open	Open	Closed	Closed	Closed	Closed	Closed	Closed	Closed
Date /Time	20/05 00:00	25/05 21:00	27/05 09:00	28/05 11:00	28/05 22:00	30/05 12:00	01/06 10:00	02/06 00:00	03/06 09:00	06/06 00:00	07/06 14:50	10/06 06:30
Egress Location	End Riser	End Riser	End Riser	End Riser	End Riser	End Riser	End Riser	After Kink	Top BOP	Top BOP	Top Hat	Top Hat
Egress Pressure	2270	2270	2270	2270	2270	2270	2270	2270	2270	2270	2270	2270
Top of BOP Pressure	2600	2560	2500	2479	2500	2500	2500		2270	2270	2270	2270
Mud Boost Line Pressure												
Lower and Upper Annular												
Vent Line Pressure		2560	2500	2479								
Blind/Shear Rams												
Upper Kill Line Pressure		2620	2620	2587	2743							
Casing Shear Rams												
Upper VBRs												
Upper Choke Line Pressure		3240	3130	3381	3153							
Lower Pipe Rams												
Lower Kill/Choke Line Pressure		3670	3280	3665	3395							
Test Rams												
Below BOP Pressure	4440	4400	3320	3697	3496	4354	4372	4290	4266	4088	4220	4280
Pressure Difference Across BOP	1840	1840	820	1218	996	1854	1872		1996	1818	1950	2010

Historical Records Of BOP Pressures



APPENDIX A.7

Flow Estimate by Analysis of Top Hat and Riser

National Labs – Houston Team
June 15, 2010

Analysis Presentation Outline

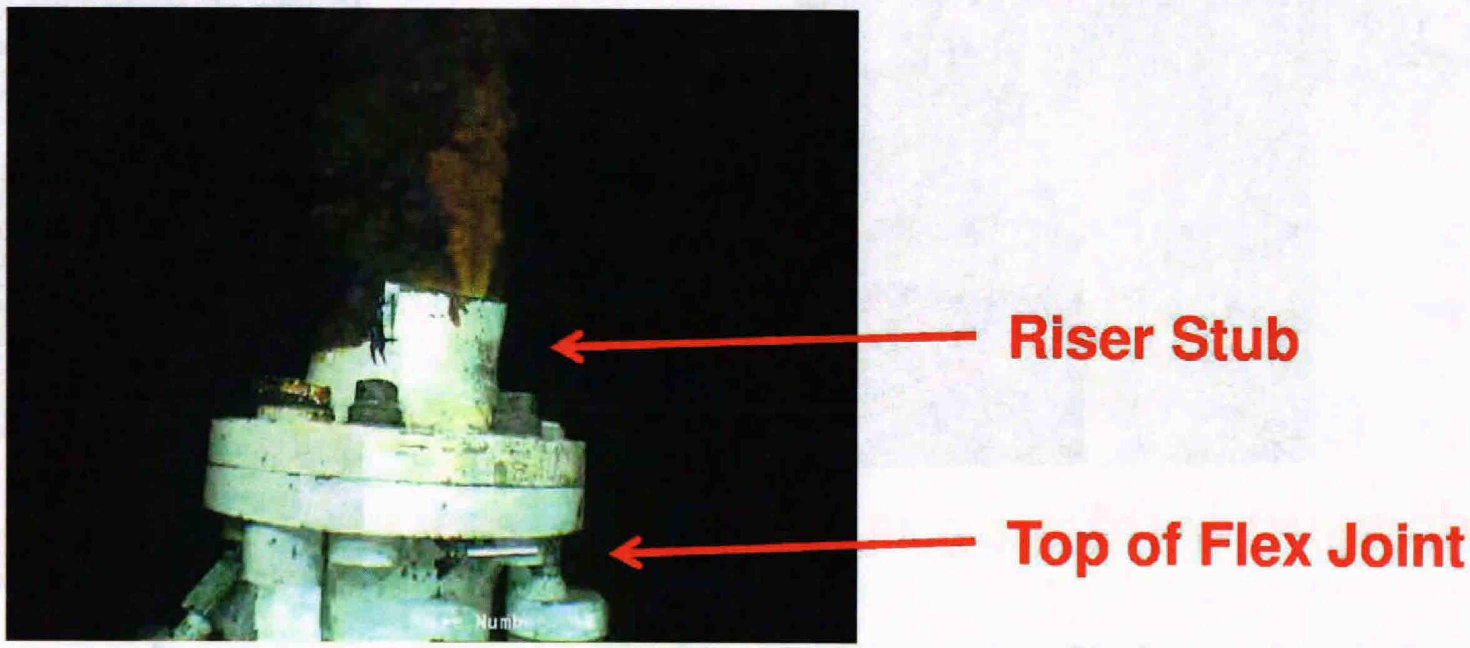
1. Problem Statement
2. System Description
3. System Schematic for Analyses
4. Assumptions Common to All Analyses
5. Results for the Baseline Case
6. Sensitivity Analysis and Uncertainty Discussion
7. Appendices
   1. LANL Defining Equations and Solution Method
   2. SNL Defining Equations and Solution Method
   3. LLNL Defining Equations and Solution Method

1. Problem Statement

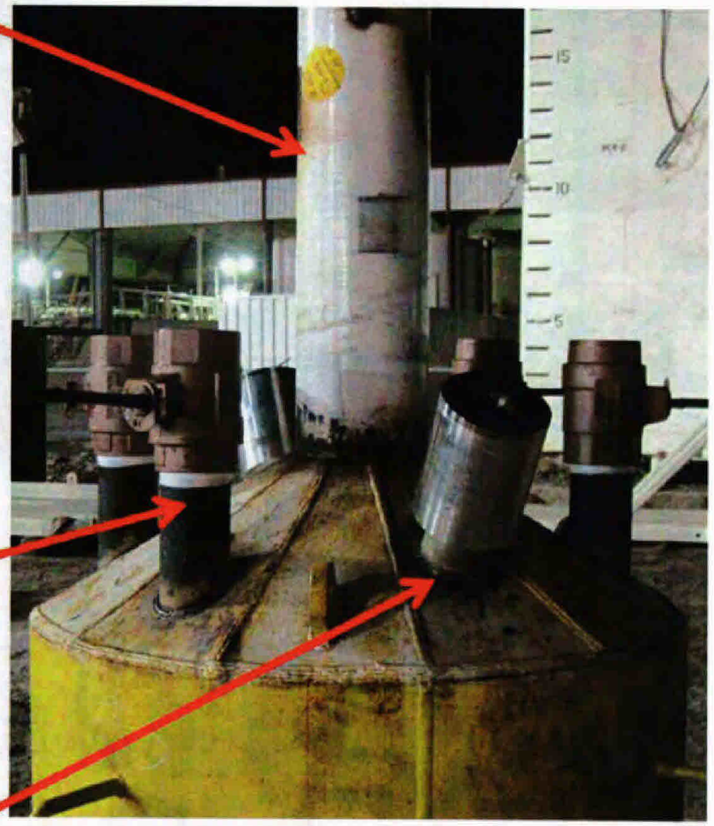
- Estimating total oil flow rate from Macondo Well using fluid dynamics models based on measured pressures
- Three National Laboratory teams have performed independent analyses using a common set of parameters
  - Sensitivity analyses varying internal Top Hat pressure, Internal Top Hat temperature, vent loss factor, skirt loss factor, and skirt vent area
  - Discussion of uncertainties

2. System Description

- Hydrocarbons are emitting from the riser stub at the top of the Flex joint.



• A "Top Hat" has been placed over the riser stub

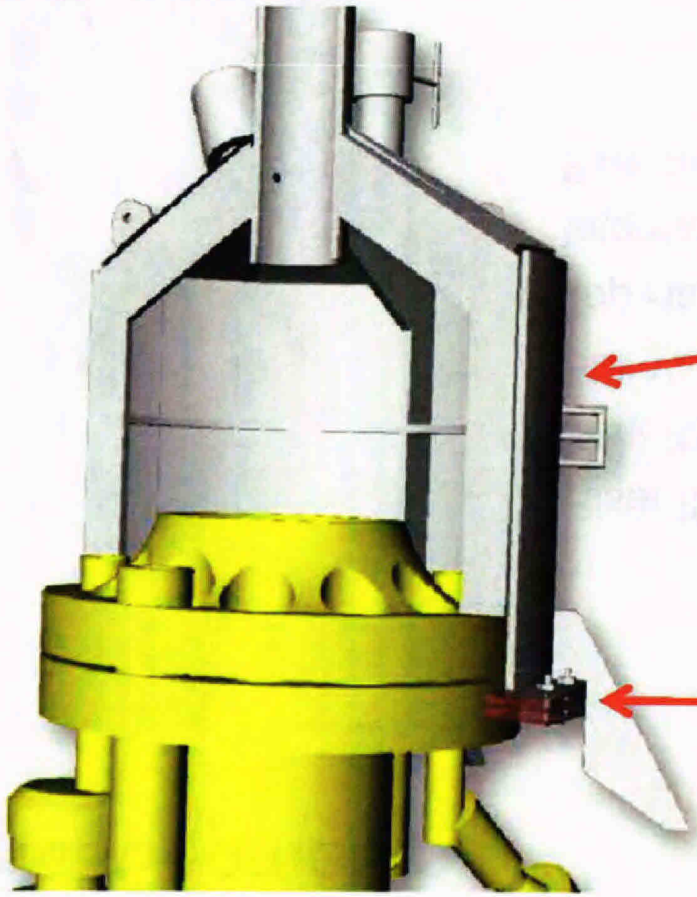


Riser to Discoverer Enterprise Drillship

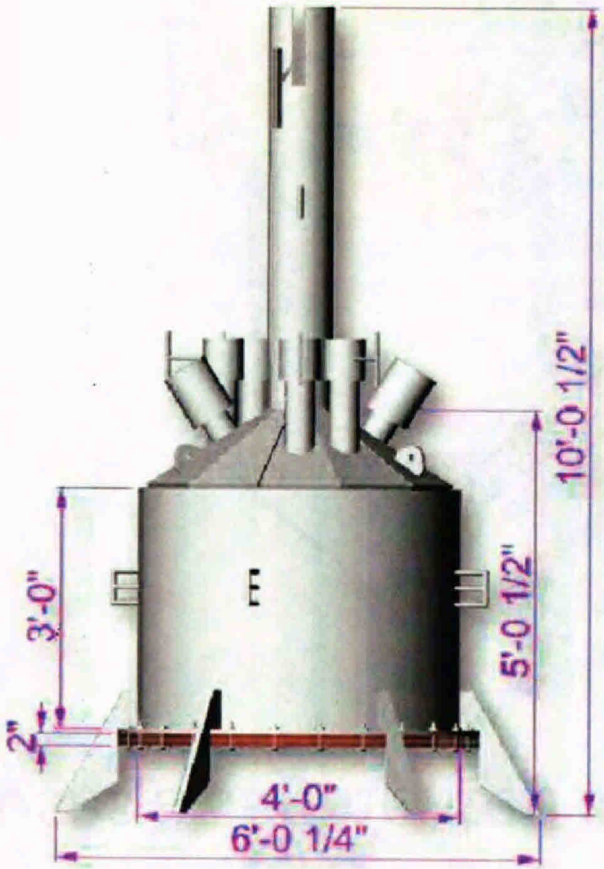
4 Vents w/Ball Valves

2 Methanol Injection Ports

- The Top Hat rests on the flex joint flange and uses a segmented radial seal system



- Top Hat Geometry



Riser ID = 5.5 inches

Vent ID = 4 inches

Ball Valve Port = 3 inches

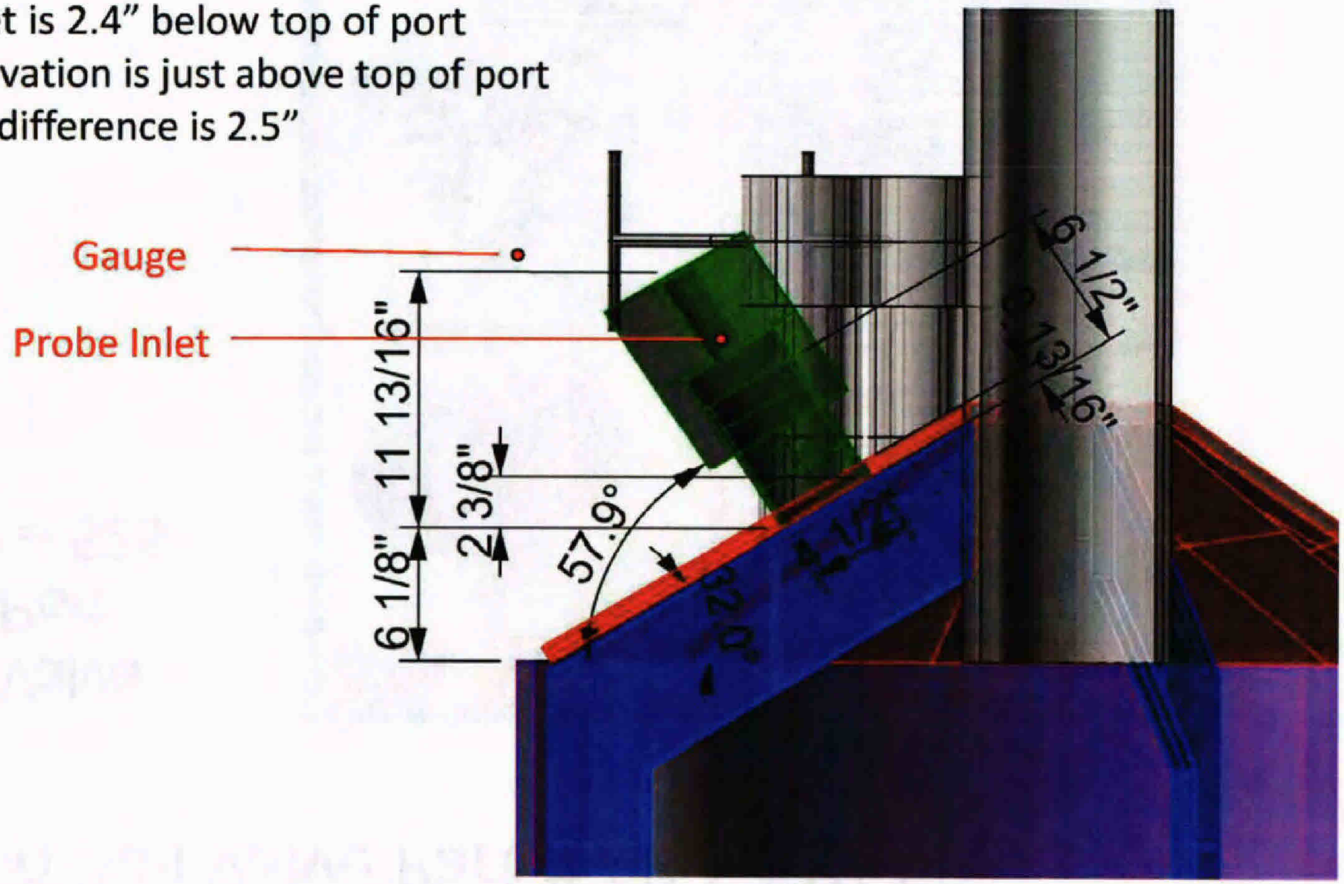
Top Hat Body ID = 46.5 inches

Internal rubber seal ring ID = 41 inches

Flex Joint Flange OD = 42 inches

- The Pressure Probe is placed in a methanol injection port

Probe inlet is 2.4" below top of port
Gauge elevation is just above top of port
Elevation difference is 2.5"



- Balon Ball Valve Part # 4R-S32N-SE

  - 4” Valve
  - 3” Port
  - Cv = 525

BALON Threaded End Connection

Series S Ductile Iron

- Lever Operated Ball Valve
- To 2000 PSI WP
- 1" Through 4"
- Threaded Body Construction

- High Grade Ductile Iron with Better Corrosion Resistance and Greater Yield Strength
- Multi-Seal Seats
- NACE Valves Include 316 Stainless Steel Ball and Stem
- Rugged Locking Device Standard

- Fire Safe Design
- Maintenance Free Sealing

Material Description

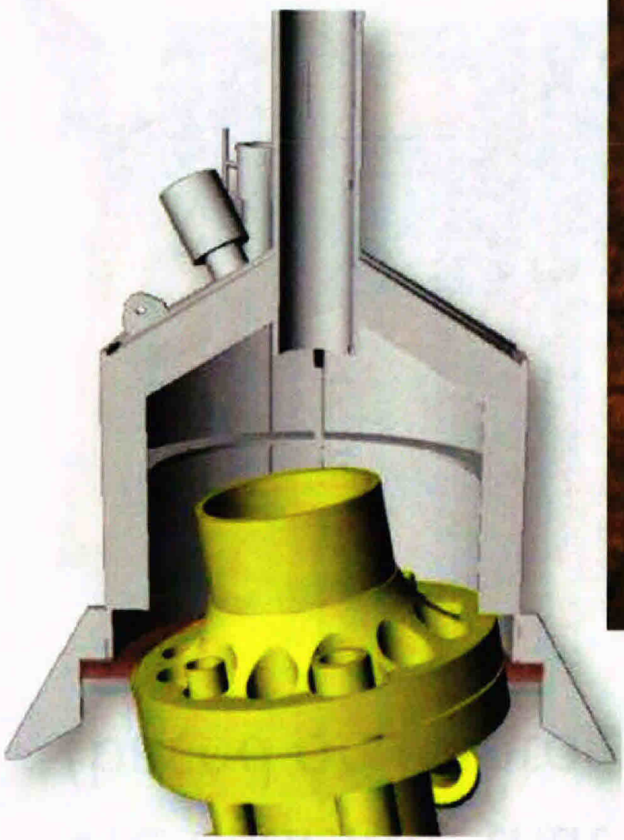
ITEM	PART NAME	MATERIAL (STANDARD)	MATERIAL (NACE)
1	Handle*	Ductile Iron	Ductile Iron
2	Handle Bolt	Standard Hex Bolt	Standard Hex Bolt
3	Weather Guard	Polyethylene	Polyethylene
4	Lock Plate Retainer	Carbon Spring Steel	Carbon Spring Steel
5	Lock Plate	Carbon Steel	Carbon Steel
6	Dust Cover	Polyethylene	Polyethylene
7	Stop Plate Retainer	Carbon Spring Steel	Carbon Spring Steel
8	Stop Plate	Carbon Steel	Carbon Steel
9	Stem O-Ring	Buna-N	Fluorocarbon
10	Stem Seal	TFE	TFE
11	Stem	Carbon Steel	316 Stainless Steel
12	Ball	Carbon Steel Nickel Chrome Plated	316 Stainless Steel
13	Ball Seat	Nylon (TFE Optional)	Nylon (TFE Optional)
14	Body O-Ring	Buna-N	Fluorocarbon
15	End Adapter	ASTM A395 Class 60-40-18 Fully Annealed	ASTM A395 Class 60-40-18 Fully Annealed
16	Body	ASTM A395 Class 60-40-18 Fully Annealed	ASTM A395 Class 60-40-18 Fully Annealed

*Balon valves are designed to be operated with a standard open-end wrench. Handle is optional.

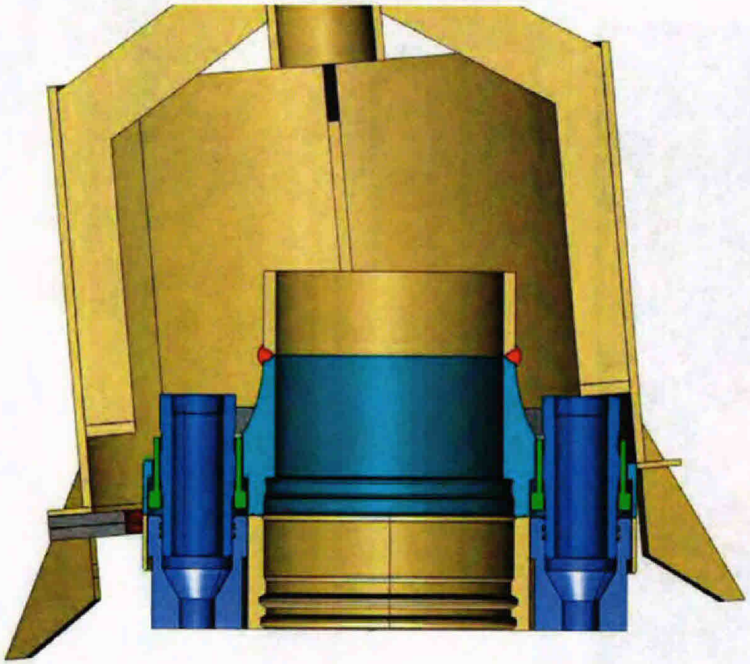
Dimensional Data

SIZE	CATALOG NUMBER STANDARD TRIM CARBON STEEL BALL & STEM	CATALOG NUMBER NACE TRIM 316 SS BALL & STEM	PORT	WP	A	B	D	E	F	G	H	M	N	LBS.	HANDLE	Cv
3x3x3	3F-S42-SE	3F-S42N-SE	3	1000	8.75	4.37	6	5.75	.87	.747	1.373	20	8.75	33	P-4127-01	-
4x3x4	4R-S32-SE	4R-S32N-SE	3	750	8.75	4.37	6	5.75	.87	.747	1.373	20	8.75	35	P-4127-01	525
4x3x4	4R-S42-SE	4R-S42N-SE	3	1000	8.75	4.37	6	5.75	.87	.747	1.373	20	8.75	35	P-4127-01	525

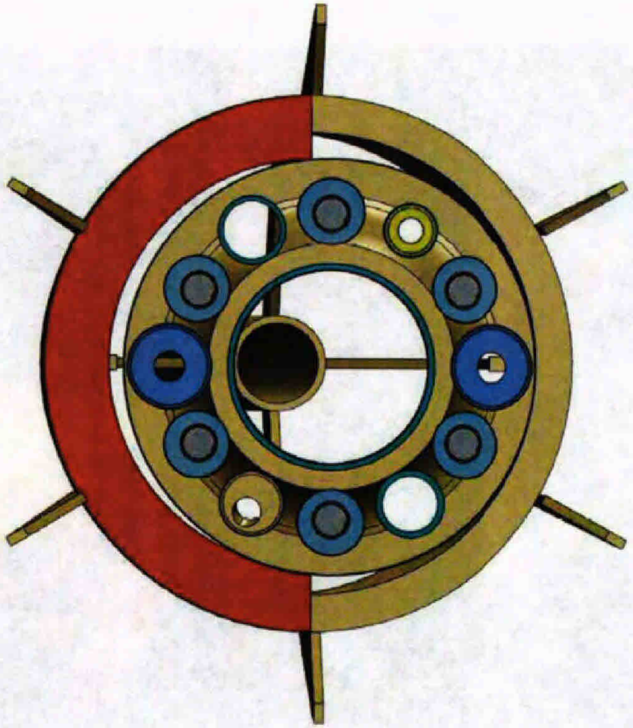
- The Top Hat is tilted 5 degrees relative to flange and is shifted laterally. The seal has been damaged.



- We estimate that 50% of the seal is missing (based on Photographs)

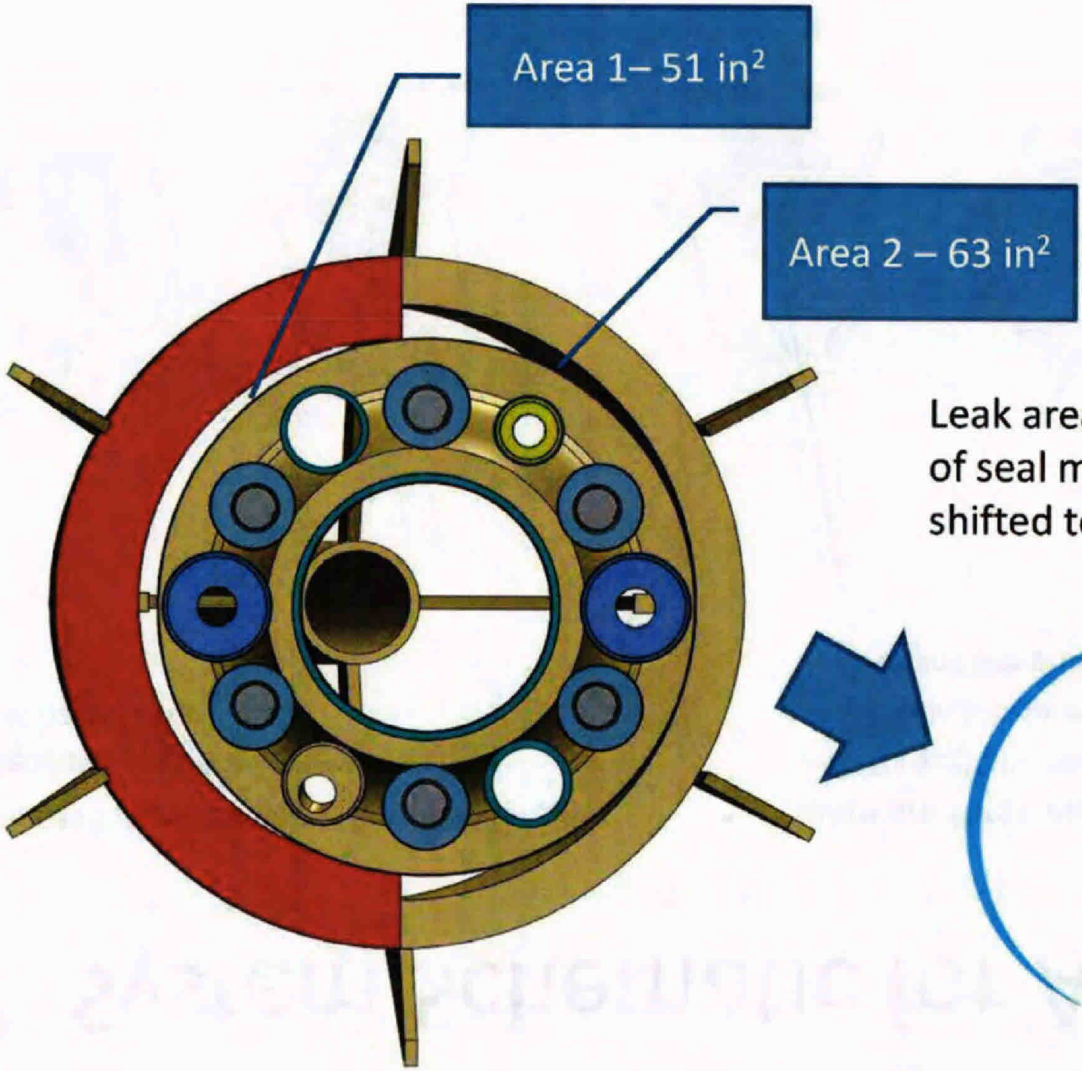


Section View With Half-Seal

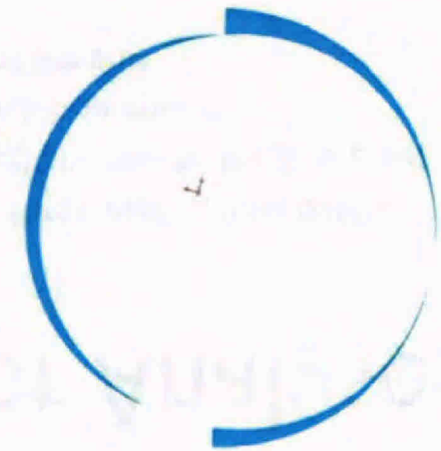


Bottom View With Half-Seal

- Open area of skirt determined using solid model



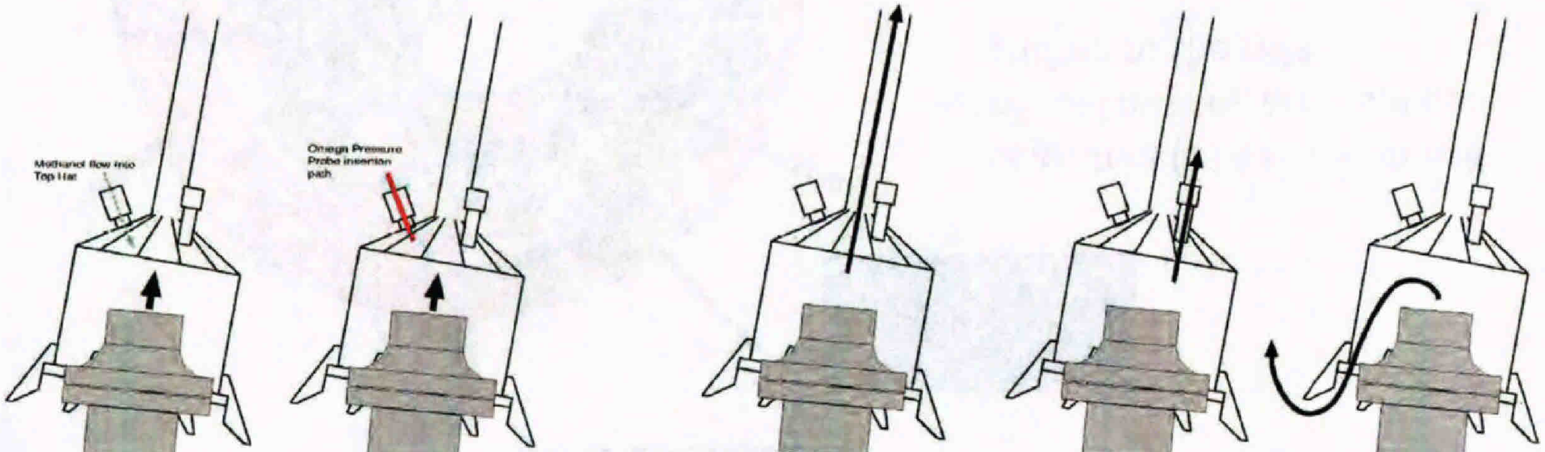
Leak area (114 in^2) with half of seal missing and Tophat shifted to the side



3. System Schematic for Analyses

- Oil/gas inflow through flex-joint (gray)
- Pressure probe inserted into one methanol line

- There are three exiting flow paths:
  - Through the riser (to the Enterprise)
  - Through 3 open vents
  - Around the skirt



Main flow into Top Hat | Pressure Probe Configuration | Flow Path #1: Riser | Flow Path #2: Vents (3) | Flow Path #3: Skirt

4. Assumptions Common to All Analyses

- 1-D fluid flow (pipe or network analysis)
  - Conservation of mass and momentum
  - Steady state
- Head Losses
  - Friction losses in flow channels (Re & roughness, following Moody)
  - Discrete geometry-based head losses (K factors & discharge coeff.)
    - Inlets, exits, slots, valves, etc.
- Heat transfer:
  - Adiabatic in short passages (vent, skirt)
  - Heat transfer or imposed temperature profile in long passages (riser to surface)
- Hydrostatic head (gravity effects)
- Vent, skirt and riser flows are decoupled for analysis
  - Common upstream boundary condition at Top Hat
  - Different downstream boundary conditions
- Ocean water state at Top Hat: 2250 psia, 40 F, density = 1030 kg/m^3
- Well produces 2900 scf gas per bbl oil (2833 in black oil PVT tables)

- Top Hat hydrocarbon fluid state at common reference temperature and pressure

	Temperature (°F)	Pressure (psia)	Density (kg/m^3)	Dynamic Viscosity (Pa*s)	Gas Void Fraction (%)
LANL	200	2250	321	6.43E-5	67.2
LLNL	200	2250	309	6.87E-5	71.7
SNL	200	2250	319	4.60E-4	74

Each Lab developed unique variations on the hydrocarbon equation of state (EOS)
Table values show variance among EOS states in the Top Hat

Density is average (oil + gas)
Viscosity is average (oil + gas)
Void fraction = volume gas/total volume (gas + oil)

5. Results for the Baseline Case

Top Hat Pressure Probe Reading = 2 psi
Top Hat Internal Temperature = 200F

	Total oil flow BBL/d[1]	Skirt	3 Vents	Riser drill pipe (Measured)	Riser drill pipe (Calculated)[2]
LANL	72,700	39,400	18,300	15,000	12,100
LLNL	77,300	42,300	20,000	15,000	14,500
SNL	83,000	45,000	23,000	15,000	15,200

[1]Stock Tank Barrels per day
[2]Calculated riser drill pipe flow provided as a check

6. Sensitivity Analysis and Uncertainty Discussion

- Sensitivity Analysis

Parameter Space for Tri-Lab Top-Hat CFD Calculations; All results are stock tank bbl/d through flow path

		SNL			LANL			LLNL		
Parameter	**Value**	**Riser**	**3 Vents**	**Skirt**	**Riser**	**3 Vents**	**Skirt**	**Riser**	**3 Vents**	**Skirt**
Internal Top Hat Pressure (psia)	1.5 psi	15200	20830	29630	12130	15650	24100	14477	17176	25901
	2 psi (baseline)	15200	23000	45000	12135	18325	39425	14482	20039	42305
	2.5 psi	15200	25500	55760	12140	20655	50300	14491	22629	53937
Internal Top Hat Temperature (degF)	180 F	15280	23780	46420	12130	18740	40390	14464	20448	43259
	200 F (baseline)	15200	23000	45000	12135	18325	39425	14482	20039	42305
	220 F	15180	22770	42880	12129	17925	38500	14491	19630	41441
Vent loss factor, kvent	1.8		25999	45000		20560			22629	
	2.3 (baseline)		23000	45000		18325			20039	
	2.8		20846	45000		16685			18131	
Skirt loss factor, kskirt	1			63640			54875			59045
	2 (baseline)			45000			39425			42305
	3			36742			32380			34712
Skirt Area Factor	74 sq.in.			29211			25250			27264
	114 sq.in. (baseline)			45000			39425			42305
	154 sq.in.			60789			53560			57391

- Uncertainty Discussion:

- While we have examined the sensitivity of our calculations to variations of key parameters, we have not attempted to quantify uncertainty.
- Key Sources of Uncertainty:
  - We do not have high confidence in the pressure reading. Measurement of small pressure differences under these conditions is new territory. Further measurements are planned.
  - We can only infer the condition of the skirt from a few photographs. The skirt loss and area factors were not rigorously determined.

7. Appendices

1. LANL Defining Equations and Solution Method
2. LLNL Defining Equations and Solution Method
3. SNL Defining Equations and Solution Method

7.1 LANL Defining Equations and Solution Method

Assumptions for LANL Top Hat Flow Spreadsheet Model

- Fluid properties interpolated from PVT black oil tables provided by BP June 11, 2010
- Flow regime modeled: one-dimensional separated 2-phase flow
- Pipe diameters and lengths provided by BP for riser flow
- Linear temperature profile imposed from Top Hat to RBK of DE: 200F → 85F
- Assumed a pressure of 1050 psia at RBK of Discovery Enterprise for 15,000 stb/day
- Vents are 4 in ID with a Balon ball valve (Model # 4R-S32N-SE) attached on the end (vent plus ball valve modeled with loss factor of 2.3)
- Skirt modeled as orifice with loss factor of 2
- Sea Floor ambient pressure = 2250 psia, T=40F, density=1030 kg/m^3
- Top Hat internal hydrostatic pressure gradient relative to ambient = 1.2 psi
  $= (9.81\ m/s^2)*(1030\ kg/m^3 - 321\ kg/m^3)*(1.17\ m)$

Equations for LANL Top Hat Flow Spreadsheet Model

One-dimensional, separated two-phase flow was modeled using the following momentum equation which includes friction, gravity, and accelerations due to phase change (Eq. 10.57a from Liquid-Vapor Phase-Change Phenomena by Van Carey, Hemisphere Publishing Corp.)

$$-\left(\frac{dP}{dz}\right) = \left(\frac{1}{\Lambda}\right)\left(\phi_l^2\left[\frac{2f_l G^2(1-x)^2}{\rho_l d_h}\right] + [(1-\alpha)\rho_l + \alpha\rho_v]g + G^2\frac{dx}{dz}\left\{\left[\frac{2xv_v}{\alpha} - \frac{2(1-x)v_l}{(1-\alpha)}\right] + \frac{d\alpha}{dx}\left[\frac{(1-x)^2 v_l}{(1-\alpha)^2} - \frac{x^2 v_v}{\alpha^2}\right]\right\}\right)$$

Where

P = pressure (Pa)
z = height (m)
G = mass flux ($kg/s/m^2$)
x = quality, the ratio of vapor mass flow to total mass flow
α = void fraction, the ratio of vapor flow cross-sectional area to total cross-sectional area
d_h = hydraulic diameter (m)
ρ_l = liquid density (kg/m^3)
ρ_v = vapor density (kg/m^3)
ρ_{ave} = average density (kg/m^3) $=[x/\rho_v + (1-x)/\rho_l]^{-1}$
u_{ave} = average velocity (m/s) $=[G/\rho_{ave}]$
v_l = liquid density (m^3/kg)
v_v = vapor density (m^3/kg)
g = acceleration due to gravity (9.81 m/s^2)

Equations for LANL Top Hat Flow Spreadsheet Model (cont.)

And where

$$\Lambda = 1 + G^2\left\{\frac{x^2}{\alpha}\left(\frac{dv_v}{dP}\right) + \frac{d\alpha}{dP}\left[\frac{(1-x)^2 v_l}{(1-\alpha)^2} - \frac{x^2 v_v}{\alpha^2}\right]\right\}$$

$$\phi_l = \left(1 + \frac{C}{X} + \frac{1}{X^2}\right)^{1/2}$$

Liquid	Gas	Subscript designation	C
Turbulent	Turbulent	*tt*	20
Viscous	Turbulent	*vt*	12
Turbulent	Viscous	*tv*	10
Viscous	Viscous	*vv*	5

$$X = \left[\frac{(dP/dz)_l}{(dP/dz)_v}\right]^{1/2}$$

$$\left(\frac{dP}{dz}\right)_l = -\frac{2f_l G^2(1-x)^2}{\rho_l D}$$

$$\left(\frac{dP}{dz}\right)_v = -\frac{2f_v G^2 x^2}{\rho_v D}$$

$$f_l = B\,\mathrm{Re}_l^{-n}, \qquad \mathrm{Re}_l = \frac{G(1-x)D}{\mu_l}$$

$$f_v = B\,\mathrm{Re}_v^{-n}, \qquad \mathrm{Re}_v = \frac{GxD}{\mu_v}$$

In the above friction-factor relations, for round tubes the constants can be taken to be $B = 16$ and $n = 1$, respectively, for laminar flow (Re_l or $\mathrm{Re}_v < 2000$), or $B = 0.079$ and $n = 0.25$ for turbulent flow (Re_l or $\mathrm{Re}_v \geq 2000$).

Once ΔP is computed from the momentum equation, it is added to $\Sigma\Delta P_{loss} = (1/2)\rho_{ave}u_{ave}^2 Kl_{oss}$, where

ρ_{ave} = average density (kg/m^3) $=[x/\rho_v + (1-x)/\rho_l]^{-1}$

u_{ave} = average velocity (m/s) $=[G/\rho_{ave}]$

K_{loss} = head loss factor

Solution for LANL Top Hat Flow Spreadsheet Model

- The temperatures were imposed
  - for flow up the riser, a linear temperature profile was imposed from the top hat to the surface
  - for vent and skirt flow, a constant temperature (top hat temperature) was imposed

- For flow up the riser, the momentum equation was solved using a spreadsheet finite-difference algorithm with 100-meter (or less) length discretizations

- Pressure drops through area changes, sudden expansions and contractions, and valves were modeled with head loss factors applied to dynamic pressure

7.2 LLNL Defining Equations and Solution Method

Assumptions for LLNL Top Hat Flow Model

- Oil properties interpolated from PVT black oil tables provided by BP
- Gas properties for methane derived from NIST files
- Well production: 2900 scf methane per sbbl oil (oil 76% by mass)
- Cp, Enthalpy derived from incompressible oil data
- Flow regime modeled: one-dimensional fully mixed flow
- Pipe diameters and lengths provided by BP for riser flow
- Heat transfer from riser pipe to ocean ambient, assumed heat transfer correlation
- Assumed a pressure of 1040 psia at RBK of Discovery Enterprise for 15,000 stb/day
- Vents are 4 in ID with a Balon ball valve (Model # 4R-S32N-SE) attached on the end
- Top Hat internal hydrostatic pressure gradient relative to ambient = 1.2 psi
  $= (9.81\ m/s^2)*(1030\ kg/m^3-321\ kg/m^3)*(1.17\ m)$

Equations for LLNL Top Hat Flow Model (1)

One-dimensional conservation equations for mass, momentum and energy

$$\frac{\partial A\rho}{\partial t} + \frac{\partial \rho A v}{\partial z} = 0$$

$$\frac{\partial A\rho v}{\partial t} + \frac{\partial \rho A v^2}{\partial z} + \frac{\partial A p}{\partial z} = S_m$$

$$\frac{\partial A\rho h}{\partial t} + \frac{\partial A\rho v h}{\partial z} = S_e$$

Where

p = pressure
z = position
ρ = density
v = velocity
t = time
S_m = momentum body and viscous terms
S_e = energy source terms
h = enthalpy

Equations for LLNL Top Hat Flow Model (2)

Discretized in the Sinda/Fluint code and using piping K factor loss formulation

Mass: $\sum_k e_k \cdot FR_k = 0$

Energy: $\sum_k e_k \cdot h_k \cdot FR_k + QDOT_i = 0$

$$\frac{dFR_k}{dt} = \frac{AF_k}{TLEN_k}\left(PL_{up} - PL_{down} + HC_k + FC_k \cdot FR_k \cdot |FR|_k^{FPOW_k} + AC_k \cdot FR_k^2 - \frac{FK_k \cdot FR_k \cdot |FR|_k}{2 \cdot \rho_{up} \cdot AF_k^2}\right)$$

Where

e = sign factor (+/-)
FR = flow rate
h = enthalpy
QDOT = energy source and sink terms
AF= area for flow
TLEN=length
PL = pressure
HC = head coefficient (pressure, body force)
FC=tube irrecoverable loss coefficient
FPOW= flow rate exponent if irrecoverable loss term (valued at 1)
AC=tube recoverable loss
FK=head loss coefficient
ρ=density

7.3 SNL Defining Equations and Solution Method

The flow up the riser is calculated based on the measured top hat pressure, the measured collection pressure at the processing ship, and the geometry of the riser pipe. A computer model is developed to calculate the various pressure losses and elevation heads within the riser geometry. The model assumes that the flowing well is in a steady condition both prior to and after the riser removal. The model also assumes that the two-phase fluid can be represented by a single velocity (v) and an single density (ρ), both changing with axial position. The following momentum equation is used to determine the pressure distribution:

$$\frac{d(\rho v^2)}{dx} = -\rho g - \frac{dP}{dx} - f\frac{\rho v^2}{2D}$$

The left hand side represents the change in acceleration of the fluid as the density changes. The right hand side represents the elevation head, the pressure gradient and the wall friction. The friction coefficient, f, is obtained consistent with the assumption of a homogeneous flow in a pipe of diameter, D, using a mass average viscosity of the liquid oil and gas phases.

An energy balance is also written. This assumes an adiabatic flow, and accounts for the changes in the potential energy due to the changing elevation head. The changes in the kinetic energy are ignored for these can be shown to be small.

$$\frac{d\big(\rho(h + gx)\big)}{dx} = 0$$

The adiabatic assumption is not completely justified. The model can also be run by specifying a temperature distribution as a function of elevation.

7.3 SNL Defining Equations and Solution Method, con't

The model requires an equation of state that allows the calculation of the fluid density as a function of the local pressure and the local enthalpy. The model also requires a complete assay of the oil. The equation of state model accounts for the evolution of gas from the mixture as the pressure decreases below the bubble point. This equation of state model provides liquid and vapor thermodynamic and volumetric properties for mixtures of compounds. The model includes both the Peng-Robinson and the Lee-Kesler Plocker equations of state:

- Peng, D.-Y., Robinson, D.B., *Ind. Eng. Chem. Fundam*. 15 (1976) 1, pp. 59-64;
- Lee Byung Ik, Kesler Michael G., *AICHE Journal*, Vol. 21, No.3, May 1975;
- Plöcker Ulf, Knapp Helmut, Prausnitz John, *Ind. Eng. Chem. Process Des. Dev.*, Vol. 17, No. 3, 1978.].

<u>Flow out Vents</u>: During the Top Hat pressure measurement, one vent was closed, and the other three were flowing. The flow out an orifice can be estimated from a simple scaling relation:

$$\Delta P = \frac{K\rho V^2}{2}$$

The above equation relates the dynamic head to the pressure drop through a loss factor (*K*). The vents can be approximated by a short pipe with a ball valve. The manufacturer of the ball valve provided a *Cv* factor (525), which can be converted to a loss factor (given a flow area). Using a flow area of a 4 inch pipe, the loss factor is determined to be 0.83. This is added to an entrance loss of 0.5 and an exit loss of 1.0 (Flow of Fluids through valves, fittings, and pipe, Crane Technical Paper No. 410, Crane Co., NY, NY, 1982). This results in our nominal case for the loss factor of 2.3. The gauge pressure reading requires 3 correction terms.

The first is due to the fact that the gauge elevation is not the same as the pressure port elevation. However, great care was taken to have the lines filled with seawater. Thus, this correction is zero.

7.3 SNL Defining Equations and Solution Method, con't

The second correction term is due to the fact that the pressure port is inside of the methanol port, approximately 8.5 inches above the top of the Top Hat. Thus, the pressure at the top of the Top Hat is 0.1 psi greater.

The third correction term is due to the fact that the vent has a finite height. The flow is not only driven by the Top Hat pressure, but by the density difference over the 16 inch vent height. This results in an increase in the driving pressure of 0.4 psi. Using the nominal loss factor, and the fluid conditions under the hat (only the density is important), we calculate a flow out the hat of 23,000 standard barrels of oil per day for three vents.

Flow out Skirt: The positively pressure Top Hat also drives flow out the lower joint. This is called the skirt. The design included a rubber seal in this region. The skirt flow can be estimated from the same scaling relation as used for the vents. However, the loss factor will be different. The gauge pressure reading requires 3 correction terms.

The first is due to the fact that the gauge elevation is not the same as the pressure port elevation. Again, this correction is zero.

The second correction term is due to the fact that the pressure port is inside of the methanol port, approximately 8.5 inches above the top of the Top Hat. Thus, the pressure at the top of the Top Hat is 0.1 psi greater.

The last correction term is due to the fact that the skirt flow is approximately 4 feet below the top of the Top Hat. The correction of this uses the density difference between the fluid inside of the Top Hat and the seawater. This results in decrease in the driving pressure of 1.2 psi. Using the nominal loss factor (K=2), and the fluid conditions under the hat (only the density is important), we calculate a flow out the hat of 45,000 standard barrels of oil per day for three skirt.

APPENDIX B

Credentials and Publications

Ronald C. Dykhuizen, Ph.D.

Fluid and Thermal Sciences Dept.
Sandia National Laboratories
Albuquerque, NM 87185 (505)844-9105

B.S. Nuclear Engineering, University of Virginia, 1976 Thesis Topic: Numerical Calculation of Gamma Streaming Through Containment Ducts

M.S. Nuclear Engineering, University of Illinois, 1977

Ph.D. Mechanical Engineering, Arizona State University, 1985 Thesis Topic: Two Phase Flow Dynamic Instability Analysis

Academic Experience:

1981-85 Lecturer, Arizona State University, Mechanical Engineering and Energy Systems Department, Tempe

1980-81 Lecturer (Sabbatical replacement), University of Nevada, Mechanical Engineering Department, Reno

1980 Adjunct Lecturer, Ohio State University, Mechanical Engineering Department, Columbus

Industrial Experience:

1985- Principle Member of the Technical Staff, Sandia National Laboratories, Albuquerque, NM. Heat transfer and fluid flow; modeling and experiments.

1977-80 Research Scientist, Battelle Columbus Laboratories, Columbus, OH. Nuclear reactor safety modeling.

1975 Summer student at the United States Nuclear Regulatory Commission, Bethesda, MD. Fuel cycle analysis.

Consulting:

Private Industry: Developed thermodynamic cycles using geothermal energy for power production and cooling.

Public Institutions: Reviewed professional engineering license applications; Reviewed safety reports for shipping containers, waste emplacements and nuclear facilities.

Bio:

Ron Dykhuizen has a wide variety of experience in many practical and academic problems involving thermodynamics, multiphase fluid flow and heat transfer. He has performed well in both modeling and experimental programs. He has been assigned to a number of investigative teams examining a wide variety of topics that included the non-performance of complex systems and accident investigations. Recently, he was integral to the Department of Energy's effort to determine the flow rate of the Gulf of Mexico oil spill.

Honors:

Elected to Tau Beta Pi and Phi Kappa Phi Honor Fraternities

University Fellowship (University of Illinois)

Patents:

U.S. Patent No. 6,110,844, Reduction of Particle Deposition on Substrates using Temperature Gradient Control, August, 29, 2000, with D. Rader and A. S. Geller.

U.S. Patent No. 6,348,687, Aerodynamic beam generator for large particles, February 19, 2002, with J. E. Brockmann, J. R.Torczynski, R. A. Neiser and M. F. Smith

Registered Professional Engineer, Ohio, 1980 to 2006

Member: American Nuclear Society, 1976-1980

Publications and Presentations:

W. A. Carbiener, with R. C. Dykhuizen and others, "2/15 Scale Bypass Experiments," U.S. Nuclear Regulatory Commission, Fifth Water Reactor Safety Research Information Meeting, Gaithersburg, MD (Nov. 7, 1977)

B. S. Asmus, with R. C. Dykhuizen and others, "Potential Environmental Implications of Proposed Alternatives for Nuclear Fuel Services, West Valley, New York," U.S. Department of Energy, Environmental Control Symposium, Washington D.C. (Nov. 28-30, 1978)

H. I. Avci, K. D. Kok, R. G. Jung and R. C. Dykhuizen, "Production of High Temperature Process Heat in Pebble Beds in ICFR Blankets," American Nuclear Society Transactions, Atlanta, GA (June 1979)

K. D. Kok, with R. C. Dykhuizen and others, "Laser Fusion Systems for Process Heat," 2nd International Alternatives Energy Conference, Miami, FL (Dec. 1979)

R. C. Dykhuizen, R. P. Roy and S. P. Kalra, "Numerical Method for the Solution of Simultaneous Nonlinear Equations and Applications to Two-Fluid Model Equations of Boiling Flow," Numerical Heat Transfer, Vol. 7, pp. 225-234 (1984)

R. P. Roy, R. C. Dykhuizen and S. P. Kalra, "A Linearized Time-Domain Two-Fluid Model Analysis of Density-Wave Oscillations in Boiling Flow Systems," Basic Aspects of Two Phase Flow and Heat Transfer, ASME HTD-Vol. 34, 22nd National Heat Transfer Conference, Niagara Falls, NY (Aug. 1984).

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J. G. Watkins, R. C. Dykhuizen, W. L. Hsu, D. N. Hill, and S. L. Allen, "Infrared Thermography of First Wall Components on TMX-U," presented at the 32nd National Symposium of the American Vacuum Society, Houston, TX (Nov. 19-22, 1985)

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J. B. Whitley, with R. C. Dykhuizen and others, "Engineering Considerations for the Tore Supra Pump Limiter," Presented at the 14th Symposium on Fusion Technology, Avignon, France (Sept. 1986)

R. C. Dykhuizen, R. P. Roy and S. P.Kalra, "Two-Fluid Model Simulation of Density-Wave Oscillations in a Boiling Flow System," Nuclear Science and Engineering, Vol. 94, pp. 167-179 (1986)

R. C. Dykhuizen, "Stability of Finite Difference Representations of Partial Differential Equations; A Two Step Process," Journal of Computational Physics, Vol. 70, No. 1, pp. 262-268 (1987)

R. C. Dykhuizen and C. W. Smith, "Fluid Dynamics of a Pressure Measuring System for Underground Explosive Tests," presented at the 4th Containment Symposium, Colorado Springs, CO (Sept. 21-24, 1987)

R. C. Dykhuizen, "Transport of Solutes Through Unsaturated Fractured Media," Water Research, Vol. 21, No. 12, pp. 1531-1539 (1987)

M. F. Smith and R. C. Dykhuizen, "The Effect of Chamber Pressure on Particle Velocities in Low Pressure Plasma Spray Deposition," presented at 1987 National Thermal Spray Conference, Orlando, FLA Sept. 14-17, 1987; Also in Surface and Coating Technology, Vol. 34, No. 1, pp. 25-31 (1988)

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A. S. Geller and R. C. Dykhuizen, "A Study of the Axisymmetric Motion of the Vapor-Coolant Interface in Steam Explosions," presented at the 41st Annual Meeting of the Division of Fluid Dynamics, APS, Buffalo, NY (Nov. 20-22, 1988)

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APPENDIX C

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BP-HZN-2179MDL06907946
SNL019-006763 - 007637
SNL020-003989 - 004429
PNL010-004088 - 004109
SNL022-017352 - 017369
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BP-HZN-2179MDL06095114
SNL002-007562 - 007596
SNL019-005488 - 005523
BP-HZN-2179-MDL05698790; XAK003-201584
BP-HZN-2179MDL07266171
BP-HZN-2179MDL07266172 - BP-HZN-2179MDL07266191
BP-HZN-2179MDL07587512 - BP-HZN-2179MDL07587516
BP-HZN-2179MDL07588543
BP-HZN-2179MDL061243449
BP-HZN-2179MDL07587630 - BP-HZN-2179MDL07587635
BP-HZN-2179MDL07587636
BP-HZN-2179MDL07587650
BP-HZN-2179MDL07587795
BP-HZN-2179MDL07587957
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BP-HZN-2179MDL07589995
BP-HZN-2179MDL07585798
BP-HZN-2179MDL07585802 - BP-HZN-2179MDL07585803;
BP-HZN-2179MDL07585864 - BP-HZN-2179MDL07585866;
BP-HZN-2179MDL07585867;
BP-HZN-2179MDL07586152;
BP-HZN-2179MDL07588599;
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XRD010-017289
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XRD010-017297
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BP-HZN-2179MDL07587630 - BP-HZN-2179MDL07587635;
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SDX009-0001863; SNL516-001862
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BP-HZN-2179MDL00412975;
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BP-HZN-2179MDL00297539;
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BP-HZN-BLY00297541;
BP-HZN-BLY00297542 - BP-HZN-BLY00297559;
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BP-HZN-2179MDL00412974-BP-HZN-2179MDL00412975
BP-HZN-2179MDL071441654
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Deposition of Arthur C. Ratzel, III (w/exhibits)
Deposition of Richard Lynch (w/exhibits)
Deposition of Adam Ballard (w/exhibits)
Deposition of David Barnett (w/exhibits)
Deposition of Simon Bishop (w/exhibits)
Deposition of Richard Camilli BP (w/exhibits)
Deposition of Stephen Carmichael (w/exhibits)
Deposition of Dr. Steven Chu (w/exhibits)
Deposition of Albert DeCoste Schlumberger (w/exhibits)
Deposition of Trevor Hill (w/exhibits)
Deposition of Tom Hunter (w/exhibits)
Deposition of Tom Knox (w/exhibits)
Deposition of Mike Levitan (w/exhibits)
Deposition of Tony Liao (w/exhibits)

Deposition of Timothy Lockett (w/exhibits)
Deposition of (Clifton) Mike Mason (w/exhibits)
Deposition of David McWhorter (w/exhibits)
Deposition of Robert Merrill (w/exhibits)
Deposition of Ole Rygg (w/exhibits)
Deposition of Farah Saidi (w/exhibits)
Deposition of Ruben Schulkes (w/exhibits)
Deposition of Trevor Smith (w/exhibits)
Deposition of Yun Wang (w/exhibits)
Depostion of Ronald C. Dykhuizen (w/exhibits)
Deposition of Matthew Gochnour (w/exhibits)