Flow Estimate by Analysis of Top Hat and Riser

National Labs – Houston Team

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Analysis Presentation Outline

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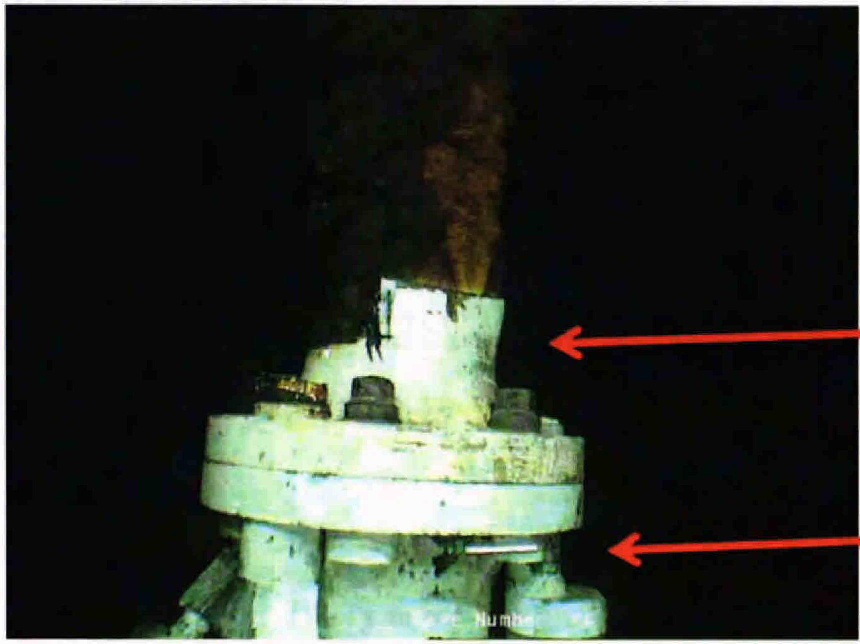
1. Problem Statement

- 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.

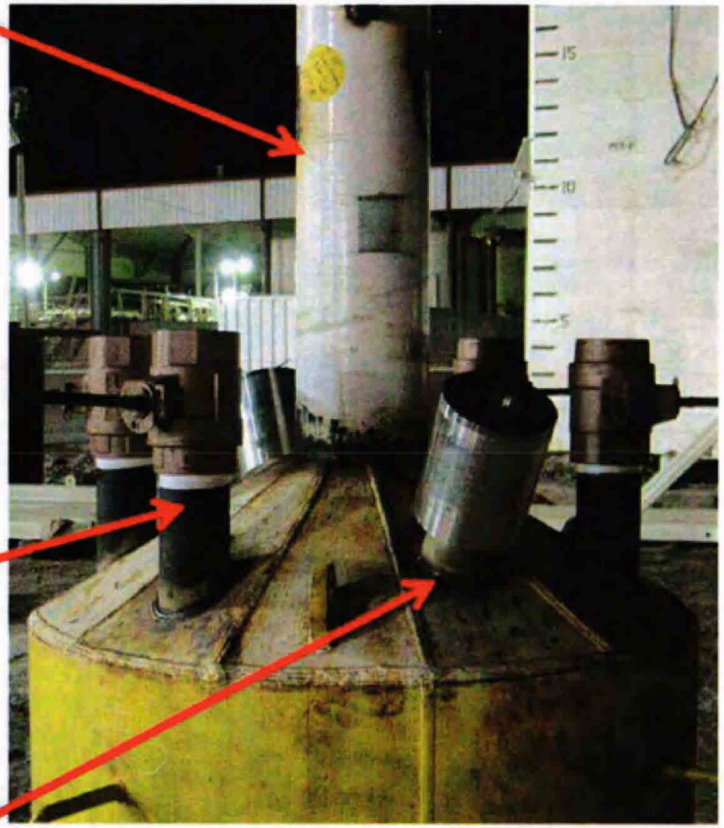


Riser Stub

Top of Flex Joint

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

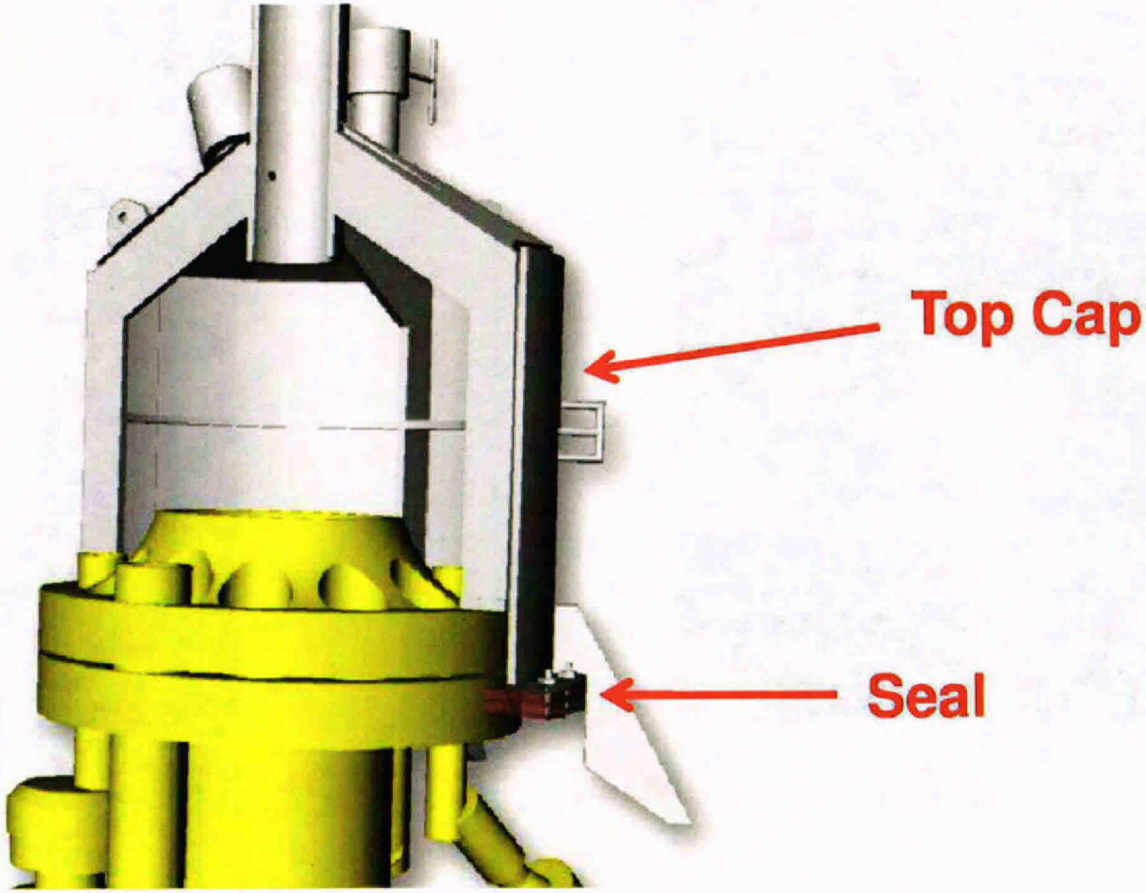
Riser to Discoverer Enterprise Drillship



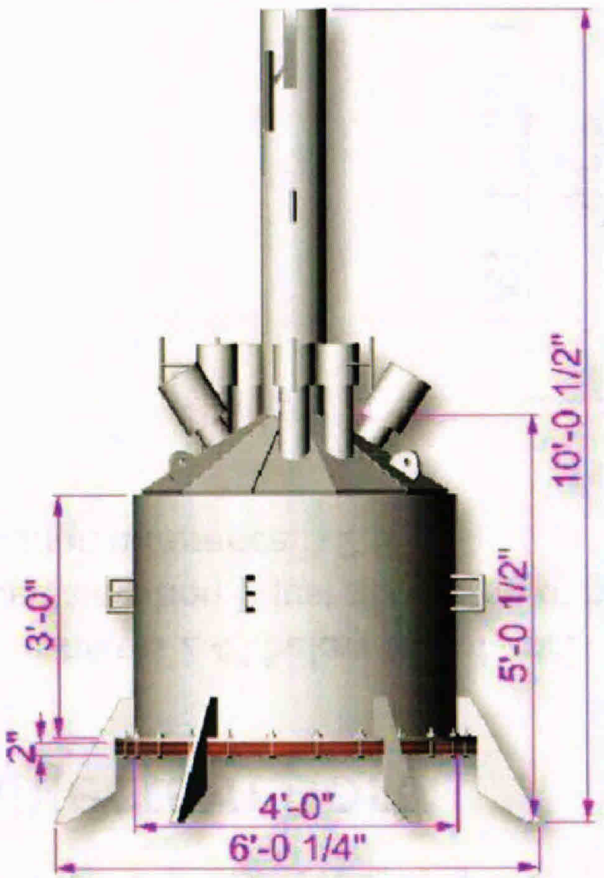
4 Vents w/Ball Valves

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

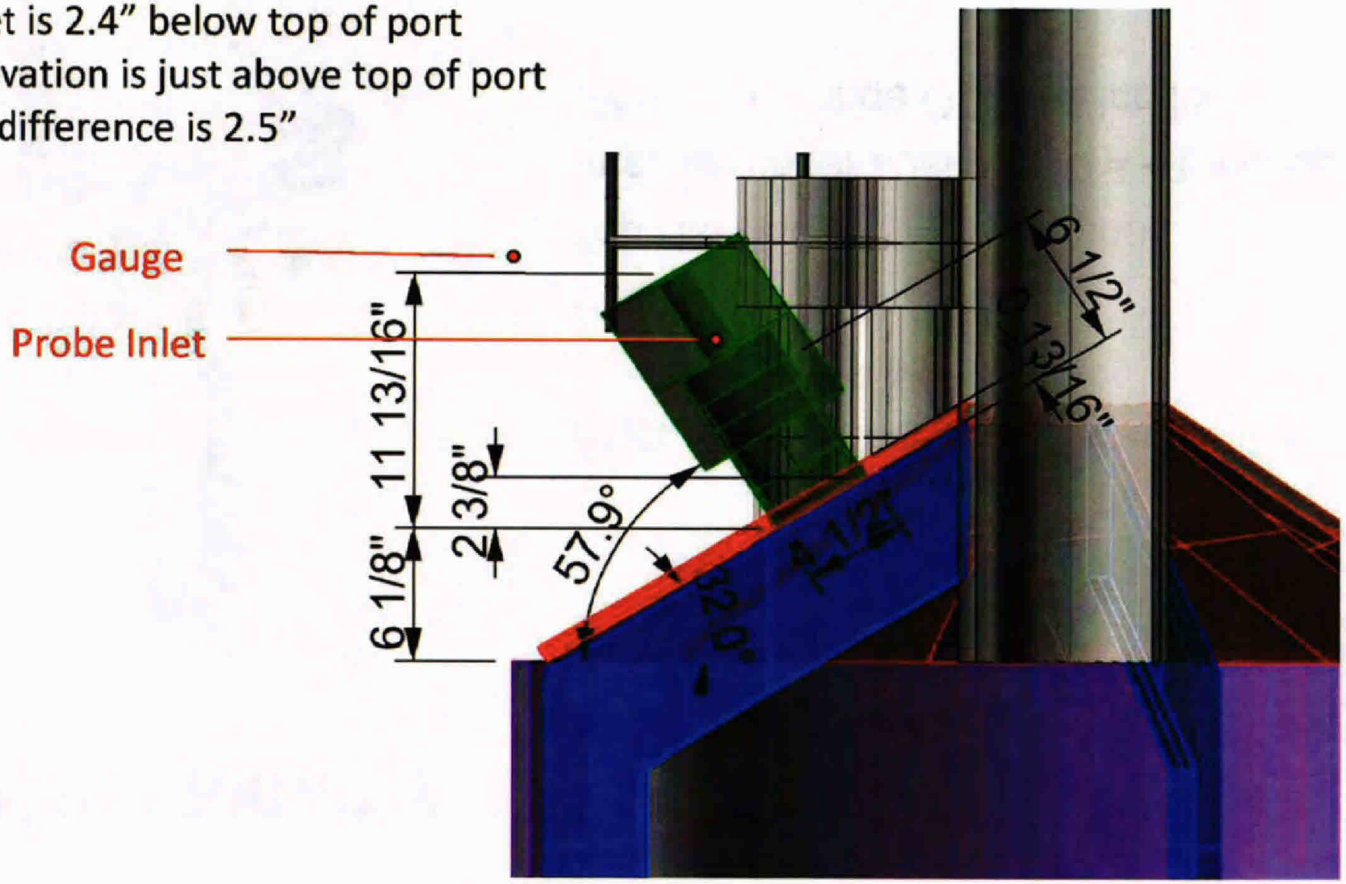
Top Hat Body ID = 46.5 inches

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

Material Description

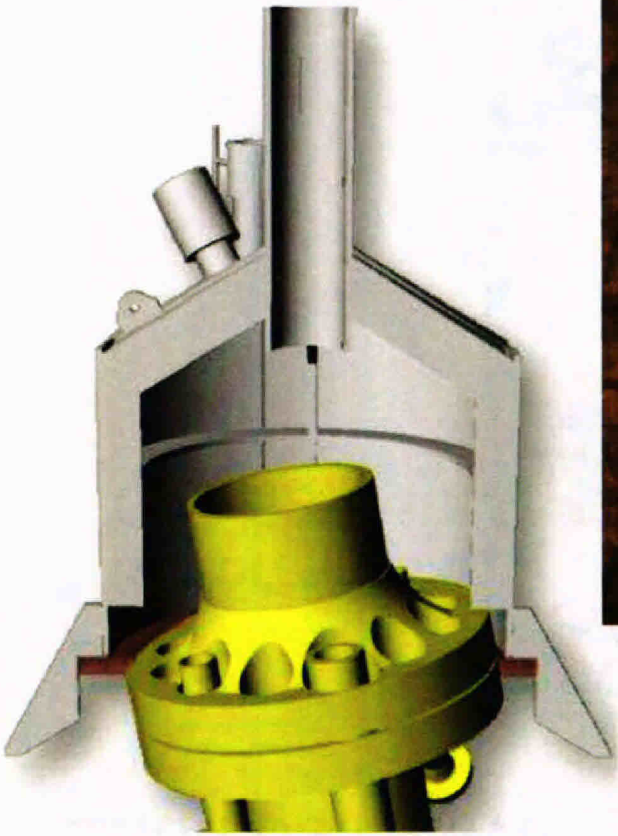
ITEM	PART NAME	MATERIAL (STANDARD)	MATERIAL (NACE)
1	Handle*	Ductile Iron	Ductile Iron
2	Handle Bolt	Standard Hex Bolt	Standard Hex Bolt
3	Weather Guard	Polyethylene	Polyethylene
4	Lock Plate Retainer	Carbon Spring Steel	Carbon Spring Steel
5	Lock Plate	Carbon Steel	Carbon Steel
6	Dust Cover	Polyethylene	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.

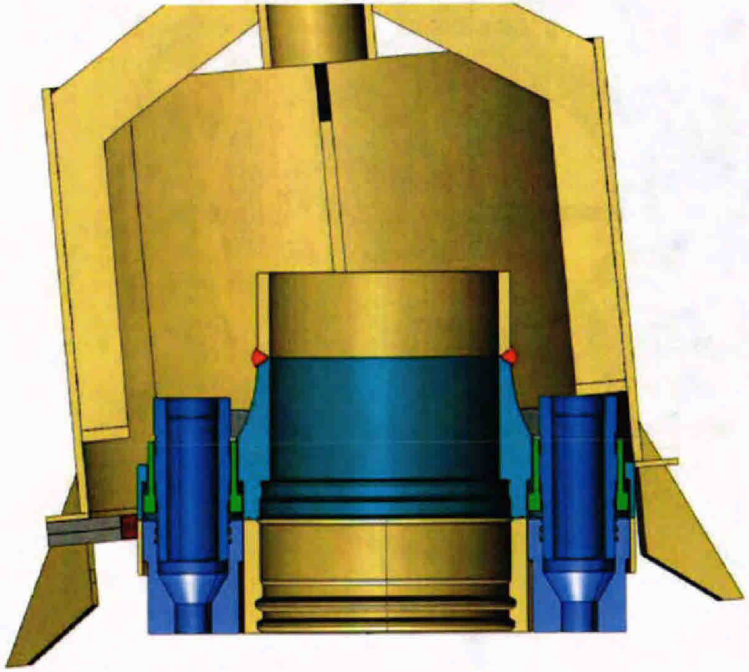
Dimensional Data

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	8	5.75	.87	.747	1.373	20	8.75	33	P-4127-DI	-
4x3x4	4R-S32-SE	4R-S32N-SE	3	750	8.75	4.37	8	5.75	.87	.747	1.373	20	8.75	35	P-4127-DI	525
4x3x4	4R-S42-SE	4R-S42N-SE	3	1000	8.75	4.37	8	5.75	.87	.747	1.373	20	8.75	35	P-4127-DI	525

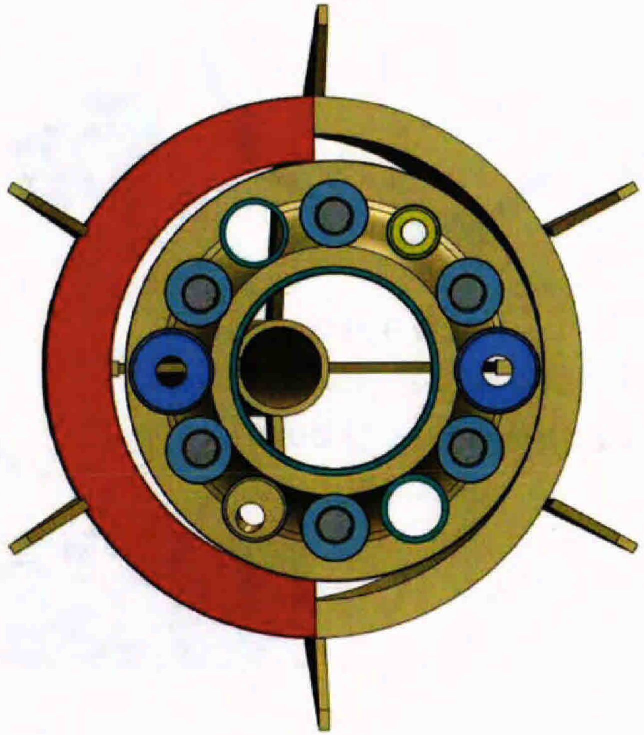
- The Top Hat is tilted 5 degrees relative to flange and is shifted laterally. The seal has been damaged.



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

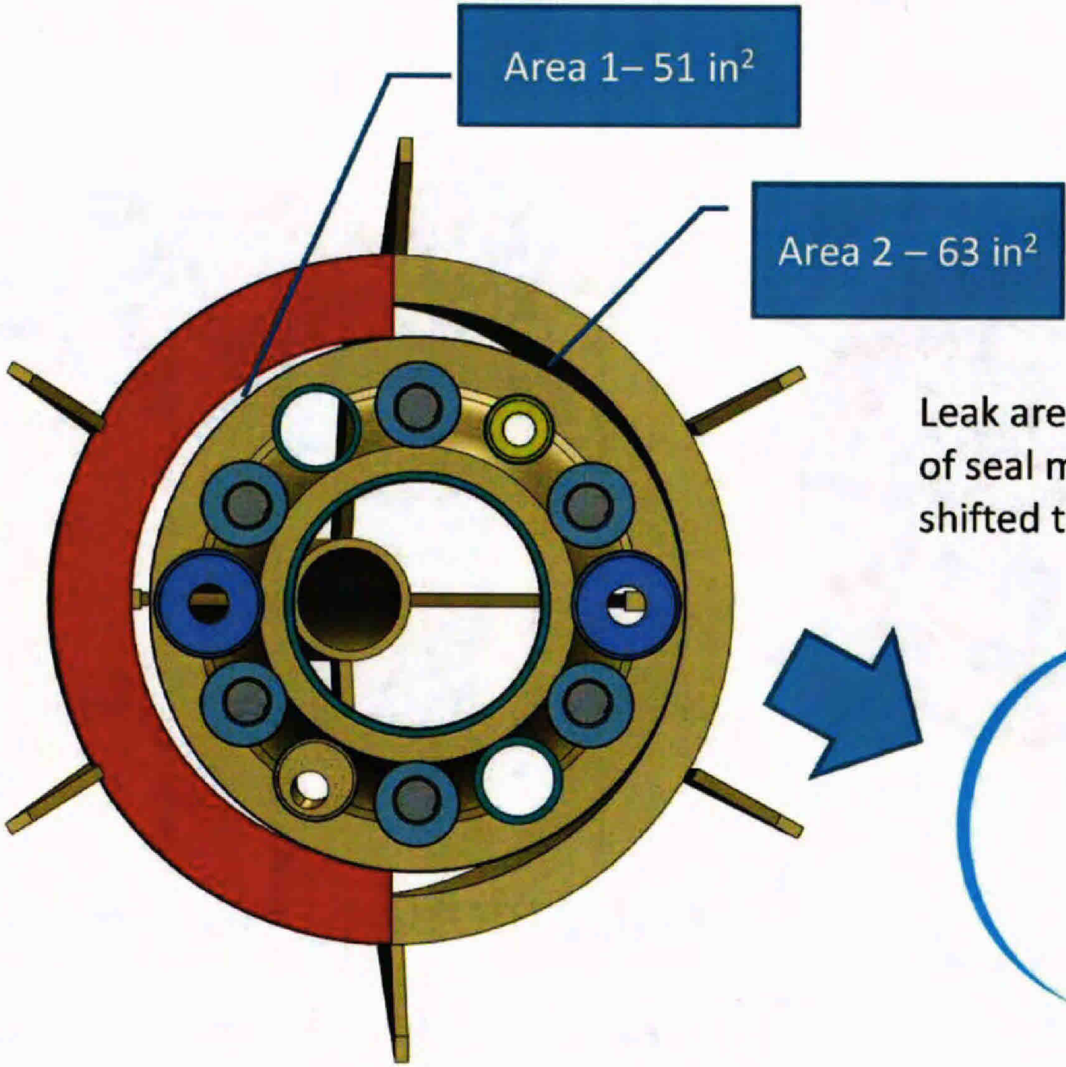


Section View With Half-Seal

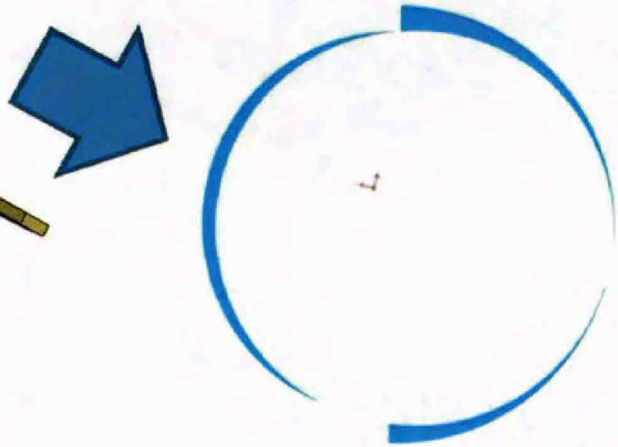


Bottom View With Half-Seal

- Open area of skirt determined using solid model



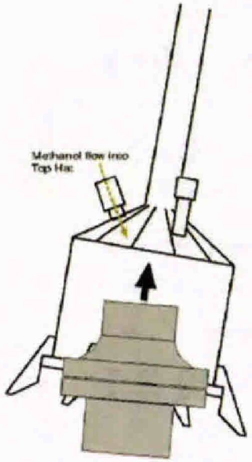
Leak area (114 in²) with half of seal missing and Tophat shifted to the side



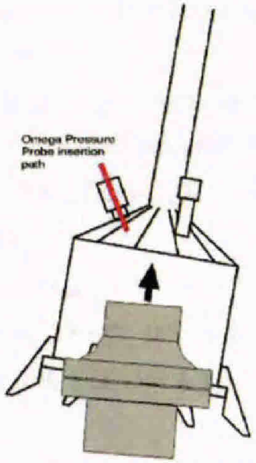
3. System Schematic for Analyses

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

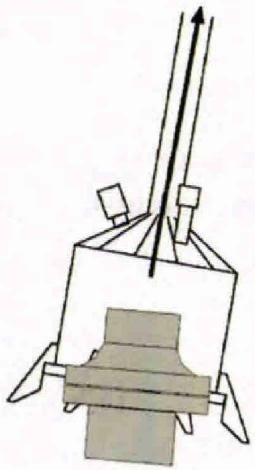
- There are three exiting flow paths:
  - Through the riser (to the Enterprise)
  - Through 3 open vents
  - Around the skirt



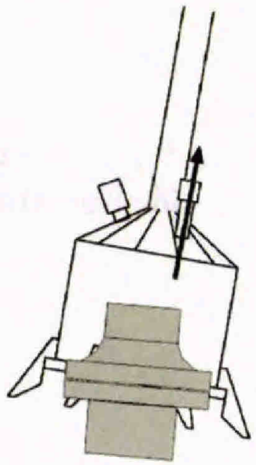
Main flow into Top Hat



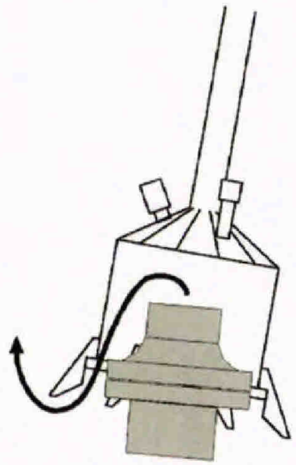
Pressure Probe Configuration



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.)

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

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 $\Sigma\Delta P_{loss} = (1/2)\rho_{ave}u_{ave}^2 K_{loss}$, 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.].

Flow out Vents: 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.