Technology used to Quantify Oil Released in Deepwater Horizon (Macondo) Blowout

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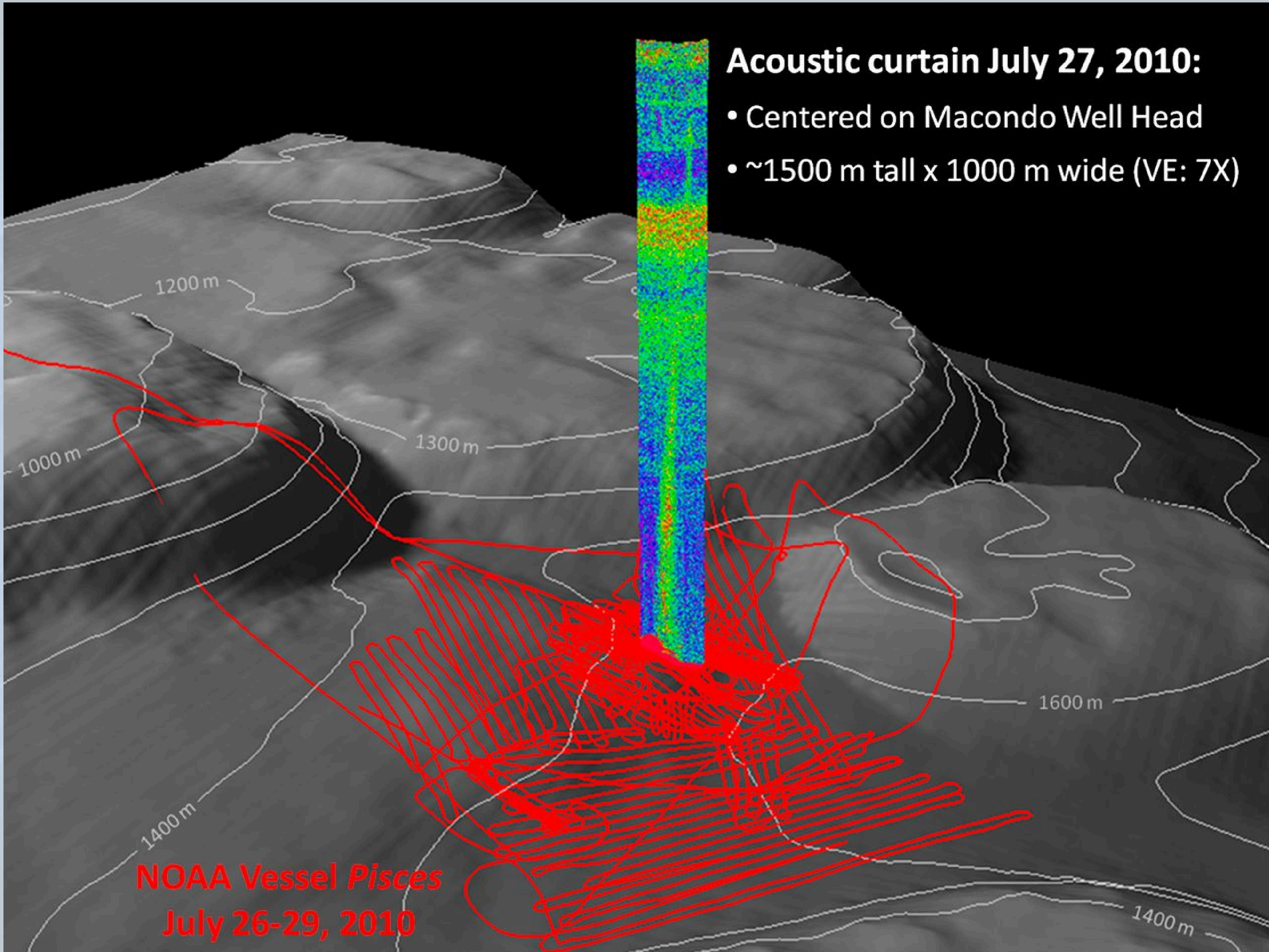
NTVA Trondheim Section

Deepwater Horizon Blowout


Acoustic curtain July 27, 2010:
• Centered on Macondo Well Head
• ~1500 m tall x 1000 m wide (VE: 7X)
1200 m
1000 m
1300 m
1600 m
1400 m
1400 m
NOAA Vessel Pisces
July 26-29, 2010

About me

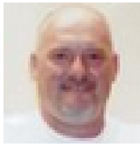
- Born & raised: Oklahoma, USA
- BSc: Stanford U. (1978)
- Arrived Trondheim Aug. 1978
- Taught 1st NTH course, 1980.
- NAVF Research scholarship, 1980-83.
- Dr.techn. NTH, 1984
- Professor, NTH, 1985-90, 1992-present
- Thermodynamics & flow of petroleum reservoir fluids.

About the Lecture

- April 20, 2010: Macondo (Deepwater Horizon) blowout.
  - Eleven workers die.
  - 3-5 million barrels stock-tank oil (STO) released into Gulf of Mexico during a period of 87 days.
- July 15, 2010: Macondo blowout stopped.
- Jan. 2012 I was engaged by BP as a technical expert.
  - Provided comprehensive fluid analysis and PVT models.
  - Analysis used in quantifying amount of STO released.
  - Oct. 14, 2013: Provided testimony (2 hours) to the U.S. District Court in New Orleans, Judge Carl Barbier presiding.

DEEPWATER HORIZON VICTIMS

Jason C. Anderson, 35, Midfield, Texas, father of two.

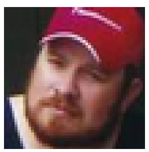


Aaron Dale Burkeen, 37, Philadelphia, Miss., married, father of two (14-year-old daughter Aryn and 6-year-old son Timothy), died four days before his 38th birthday.

Donald Clark, 49, Newellton, La., married to Sheila Clark.

Stephen Ray Curtis, 39, Georgetown, La., married and had two teenagers. Taught his son to hunt and play baseball and was active in his church.

Roy Wyatt Kemp, 27, Jonesville, La., married to Courtney Kemp.



Karl D. Kleppinger Jr., 38, Natchez, Miss., U.S. Army veteran of Operation Desert Storm, enjoyed NASCAR and cooking barbecue. Married with one son, Aaron.

Gordon L. Jones, 28, Baton Rouge. Wife Michelle Jones was nine months pregnant with their second son when he died.

Keith Blair Manuel, 56, Gonzales, La., father of three (Kelli Taquino, Jessica Manchester and Ashley Jo Manuel). Engaged to Melinda Becnel. Had season tickets to Louisiana State University baseball and football games.

Dewey A. Revette, 48, State Line, Miss., married with two daughters. Had been with Transocean for 29 years.

Shane M. Roshto, 22, Liberty, Miss., married to Natalie Roshto, father of 3-year-old Blain Michael.

Adam Weise, 24, Yorktown, Texas. During time off, the former high school football star spent time with his girlfriend, hunted deer and fished from his boat.

Jason

Aaron

Donald

Stephen

Roy

Karl

Gordon

Keith

Dewey

Shane

Adam

March 27, 1980

Aleksander L. Kielland drilling rig collapse (owned by Stavanger Drilling Company)

123 (workers) died

Why Quantify Barrels Oil Released?

- USA Cleanwater Act Section 311.
- Penalty: $1,100 – $4,300 per barrel of oil at stock tank conditions.
  - Released into federal waters.
  - $1,100: “accidents do happen” (no negligence)
  - $4,300: if gross negligence found
- Estimated release 3.2–5.0 million stock-tank oil barrels.
- Range of possible penalty: ~**4-20 billion USD** (25-125 millard NOK).
- Penalty revenue distributed between states and federal governments.

Judge Carl Barbier

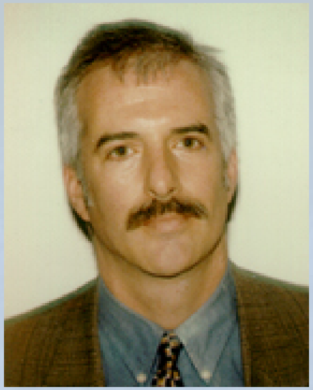
United States District Court for the Eastern District of Louisiana

Appointed by President Bill Clinton, 1998.

How to Quantify Barrels Oil Released?

- Technical experts hired.
  - US Government.
  - BP (& Anadarko)
  - Halliburton
- Data made available.
  - Geology.
  - Rock properties.
  - Fluid properties.
  - Pressures, volumetric rates.
  - Massive number of reports related to blowout.

Prof. Martin Blunt
Stanford U. (previously)
Imperial College (currently)
PhD, Cambridge (Physics)
BP Expert



Prof. Robert Zimmerman
Imperial College
PhD, UC Berley (Rock Mechnics)
BP Expert

Prof. Alain Gringarten
Imperial College
PhD, Stanford U. (Petroleum Eng.)
BP Expert

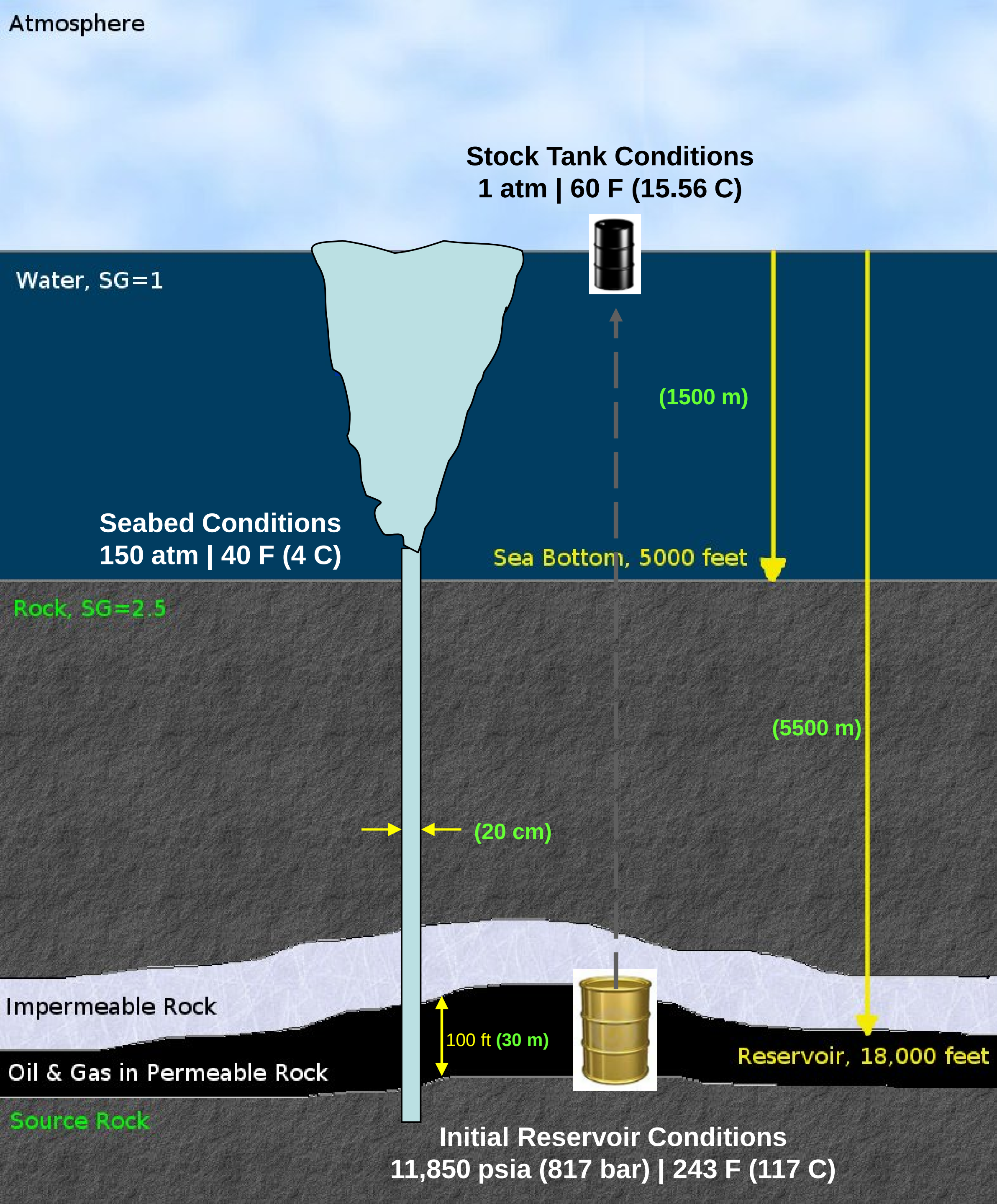
Dr. Robert Mott
MA Mathematics, Cambridge U.
PhD, London U. (Physics)
BP expert **(working with me)**

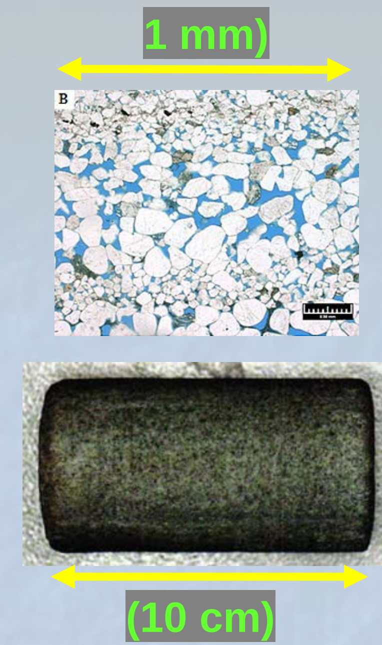
… and many others

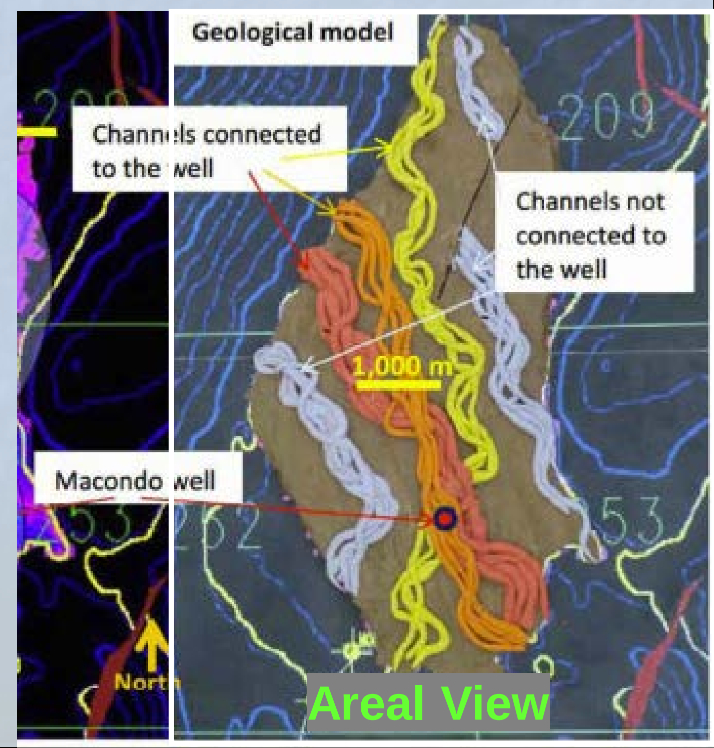
Prof. Leif Larsen
Prof. II, U. Stavanger
PhD, UC Irvine (Mathematics)
US Government expert

How to Quantify Barrels Oil Released?

- Fundamental engineering principles.
  - Volumetric material balance.
    - Initial volume containing reservoir hydrocarbons (V_{Ri}).
    - Shrinkage of reservoir volume to oil volume at stock tank conditions (S).
    - Pore volume compressibility (c_p).
    - Fluid compressibility (c_f).
    - Initial reservoir pressure (p_{Ri}).
    - Final producing rate prior to end of blowout (q_f).
  - Hydrostatic pressure conversion.
    - Surface pressures measured after blowout ($p_s(t)$).
    - Density spatial and time variations ($\rho(z,t)$).
    - Thermal convection in wellbore after blowout ($T(z,t)$).
  - Darcy flow in porous media.
    - Final reservoir pressure after blowout (p_{Rf}) by model extrapolation.


Atmosphere
Stock Tank Conditions
1 atm | 60 F (15.56 C)
Water, SG=1
(1500 m)
Seabed Conditions
150 atm | 40 F (4 C)
Sea Bottom, 5000 feet
Rock, SG=2.5
(5500 m)
(20 cm)
Impermeable Rock
100 ft (30 m)
Reservoir, 18,000 feet
Oil & Gas in Permeable Rock
Source Rock
Initial Reservoir Conditions
11,850 psia (817 bar) | 243 F (117 C)


1 mm)
B
(10 cm)


Geological model
Channels connected to the well
Channels not connected to the well
1,000 m
Macondo well
North
Areal View

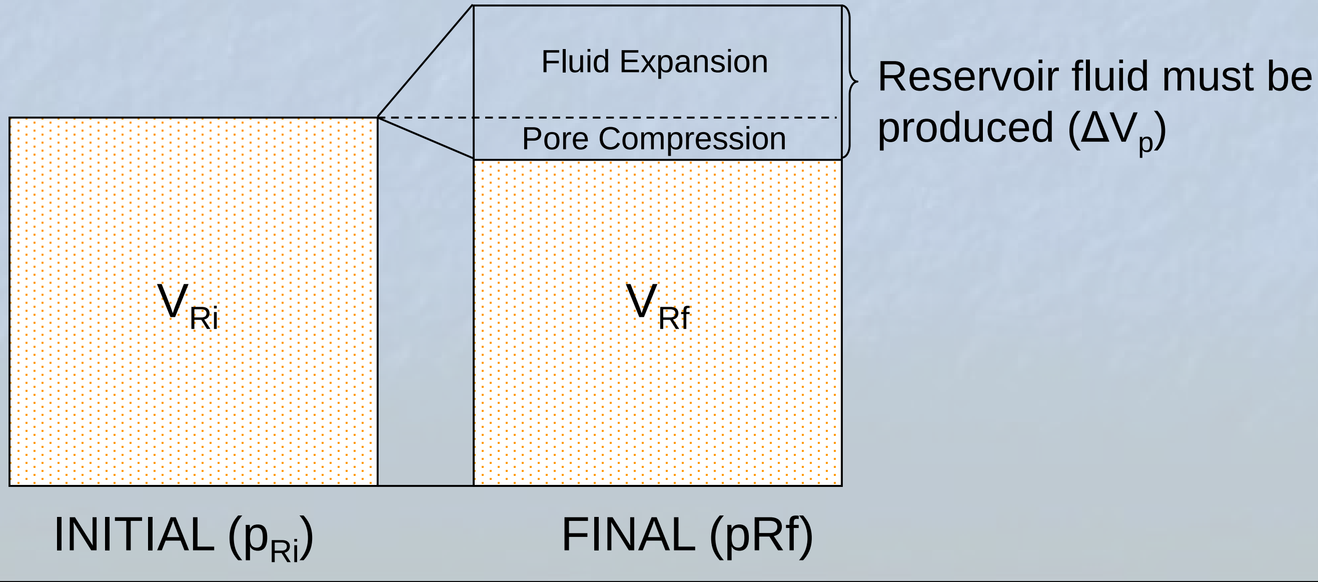
Volumetric Material Balance

$$c_R = -\frac{1}{V_R}\frac{dV_R}{dp_R} = \text{constant}$$

$$c_R = c_{pore} + c_{fluid} = \text{constant}$$

$$\Delta V_p = V_{Ri} \cdot c_R \cdot \Delta p$$

$$\Delta p = p_{Ri} - p_{Rf}$$



Shrinkage Factor

- Reservoir fluid produced must be expressed as a stock-tank oil (STO) volume, to levy the Clean Water Act penalty.

- The term "shrinkage factor" (SF) is used to describe the ratio of STO volume to the reservoir volume from which it comes.
  - For example, taking all of the original reservoir fluid at initial pressure (V_{Ri}) to surface (stock tank) conditions, the resulting STO volume would be N, and "initial" SF_i is:
    - $SF_i = N / V_{Ri}$ or $N = V_{Ri} SF_i$
  - Likewise, taking all of the produced reservoir fluid during the blowout (ΔV_p) to surface (stock tank) conditions, the resulting STO volume would be N_p and "final" SF_f is:
    - $SF_f = N_p / \Delta V_p$ or $N_p = \Delta V_p SF_f$

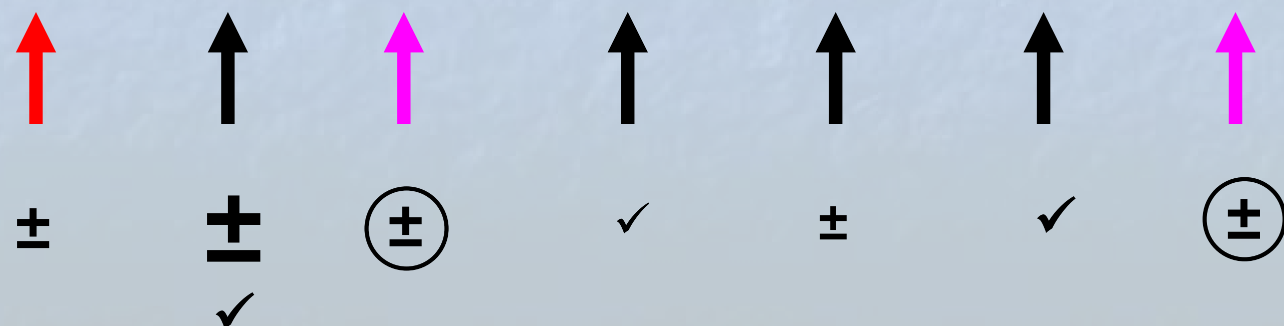
Material Balance Equation

- Rewriting the volumetric material balance in terms of stock tank oil volumes,

$$N_p = N \cdot c \cdot \Delta p = N \cdot c \cdot (p_{Ri} - p_{Rf})$$

$$N_p = V_{Ri} \cdot SF_i \cdot c \cdot (p_{Ri} - p_{Rf})$$

$$N_p = (V_{Ri} \cdot SF_i) \cdot (c_{fluid} + c_{pore}) \cdot (p_{Ri} - p_{Rf})$$

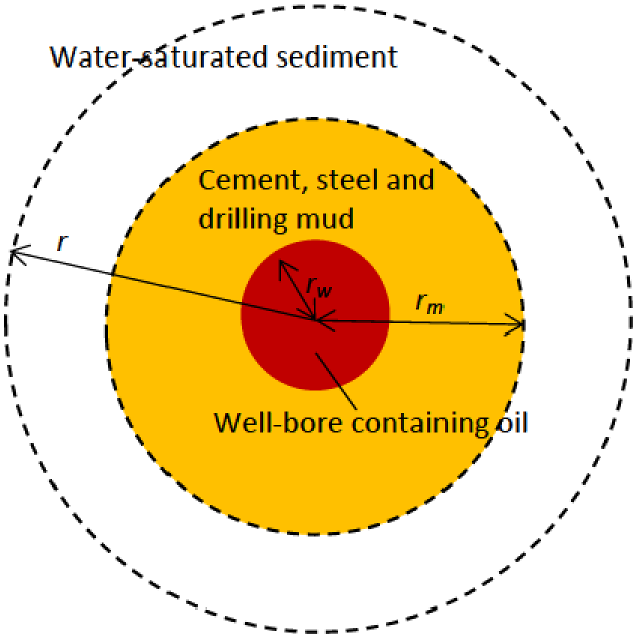


Reservoir Pressure After Blowout

- Hydrostatic Pressure Conversion.

$$p_w(t) = p_{cs}(t) + g\int_s^w \rho(T(z,t), p(z,t))dz$$

- Thermal convection in wellbore after blowout ceased (T(z,t)).



At all times, $T(r \to \infty) = T_o$

For $t \le t_p$, $T(r=r_w)=T_r$

For $t>t_p$, constant total energy

$T_o = 40^oF$; $T_r = 243^oF$.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \alpha_T \frac{\partial T}{\partial t}$$

$$\frac{1}{\alpha_T} = \frac{\kappa_s}{\Gamma_T} = \frac{\kappa_s}{\phi \rho_w C_w + (1-\phi)\rho_s C_s}$$

Thermal Convection

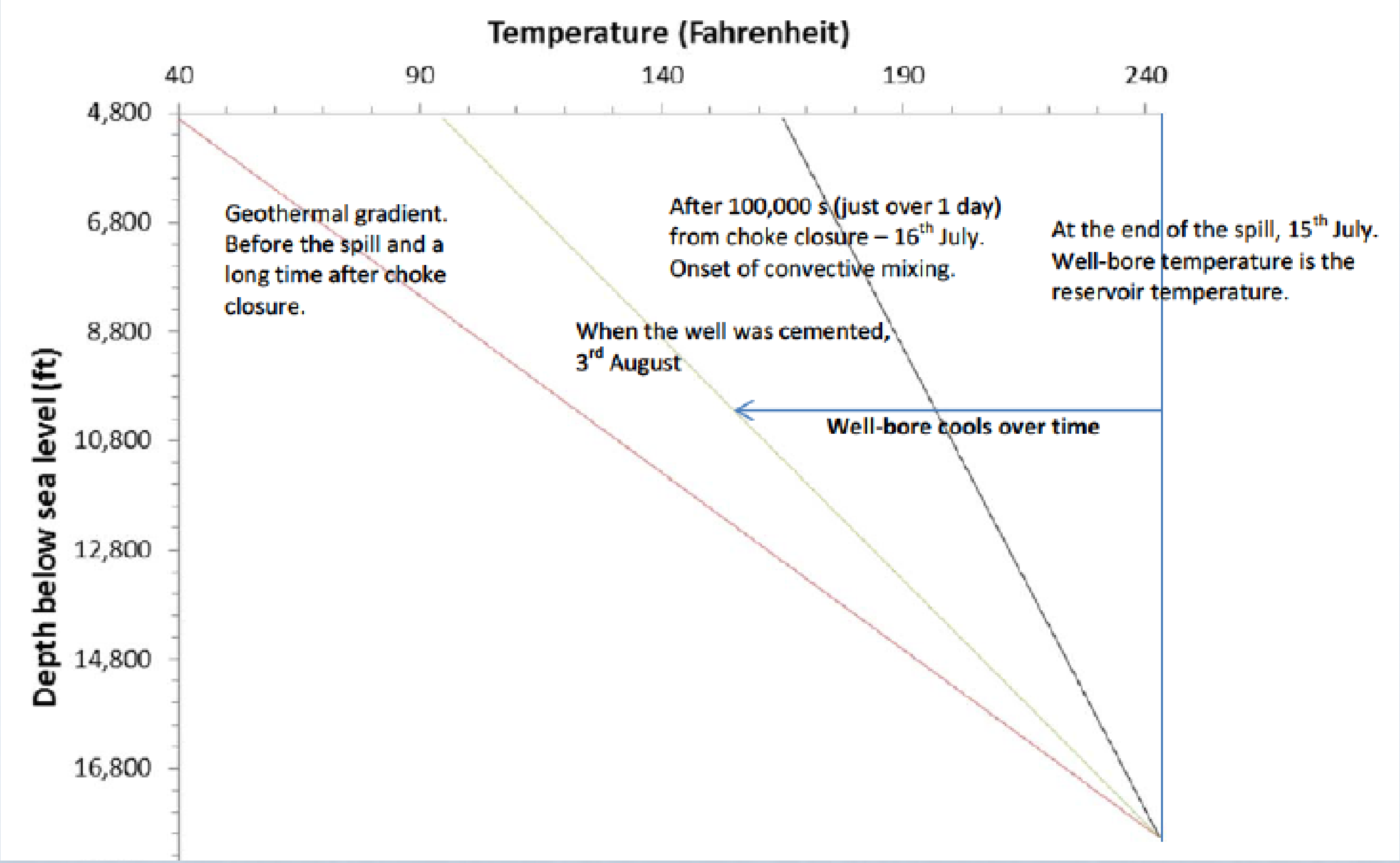


Figure B.5. Predicted temperatures at the well-bore as a function of depth, at different times. To a good approximation, at any given time the temperature varies linearly with depth from some (decreasing) value at the sea bed to 243°F at the reservoir. After around 1 day (100,000 s) we see the onset of convective mixing. This may locally distort the temperature profiles, giving regions of constant temperature with depth. However, conservation of energy prevents the average temperatures varying significantly from what is shown here.

Reservoir Pressure After Blowout

- Hydrostatic Pressure Conversion.

$$p_w(t) = p_{cs}(t) + \int_s^w \rho(T(z,t), p(z,t))dz$$

- Empirical equation derived, based on rigorous solution:

$$p_w = p_{cs} + 3210 + \frac{7}{120}(p_{cs} - 6600) + \frac{5}{4}\left[8 + 55.7\log_{10}\left(\frac{\Delta t}{100{,}000}\right)\right]$$

Reservoir Pressure After Blowout

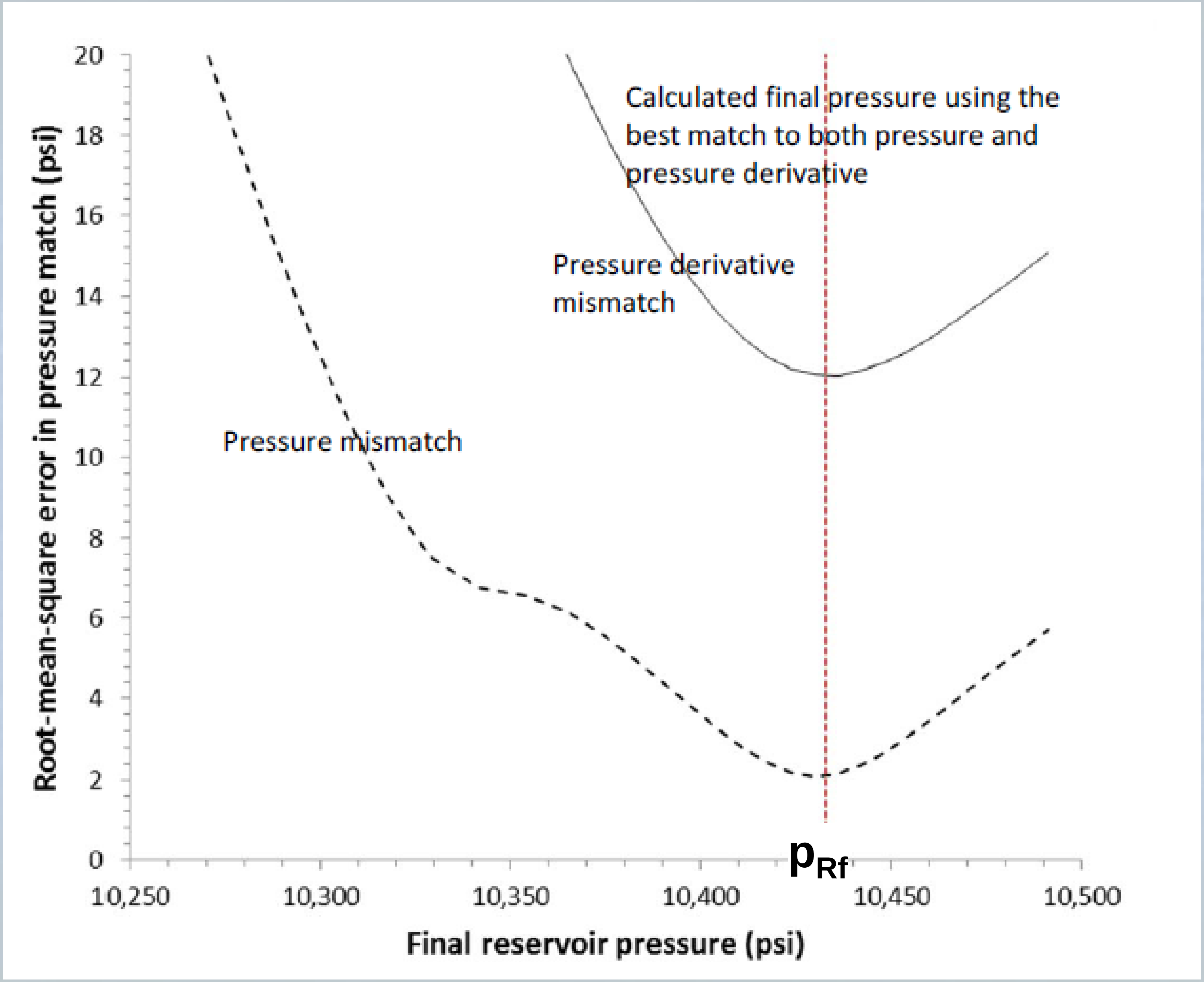
- Interpret $p_w(t)$ with analytical flow model with several unknown parameters, including final reservoir pressure after infinite shut-in time (following blowout).
  - Use a least-squares model regression with pressures and pressure derivatives as data.

$$O = \sum_{i=1}^{n} w_i \left(p_i - p_t(t_i)\right)^2 + \sum_{i=2}^{n-1} w_i \left(\frac{p_{i+1} - p_{i-1}}{\ln(t_{i+1}) - \ln(t_{i+1})} - \frac{dp_t}{dln(t)}\bigg|_{t_i} \right)^2$$

D.1. Parameter matches, sensitivities and model comparisons

D.1.1 Definitions and best-match values. Table D.1 summarizes the properties that we can derive from the pressure analysis. They are all introduced in Appendix C. Table D.2 provides my values of these properties using the methods presented in Appendices C and E and Section 4.3.

Parameter	Defining equation	Meaning	Found from
η	$\eta = \frac{\mu Q_0}{4\pi K h}$ (C.11)	Draw-down in radial flow. Uses height *h* at the well (93 ft), and final flow rate.	Value of pressure derivative
τ_W	$\tau_W = \frac{\alpha W^2}{16}$ (C.15)	Time for pressure to see channel width	End of radial flow regime
τ_1	$\tau_1 = \alpha L_1^2$ (C.59)	Time for pressure to reach channel end	Match to channel flow pressure build-up
τ_2	$\tau_2 = \alpha L_2^2$ (C.59)	Time for pressure to reach the other channel end	Match to channel flow pressure build-up
β	$\beta = \frac{2\mu Q_o}{KhW\sqrt{\pi\alpha}} = \frac{\mu Q_o}{2\sqrt{\pi\tau_W}Kh}$ (C.38)	Draw-down in linear flow	Slope of channel flow pressure regime
Δp	$\Delta p = \frac{\sqrt{\pi}}{2}\frac{\beta}{(\sqrt{\tau_1}+\sqrt{\tau_2})}t_p$ (C.66)	Pressure decline	Final stabilized pressure

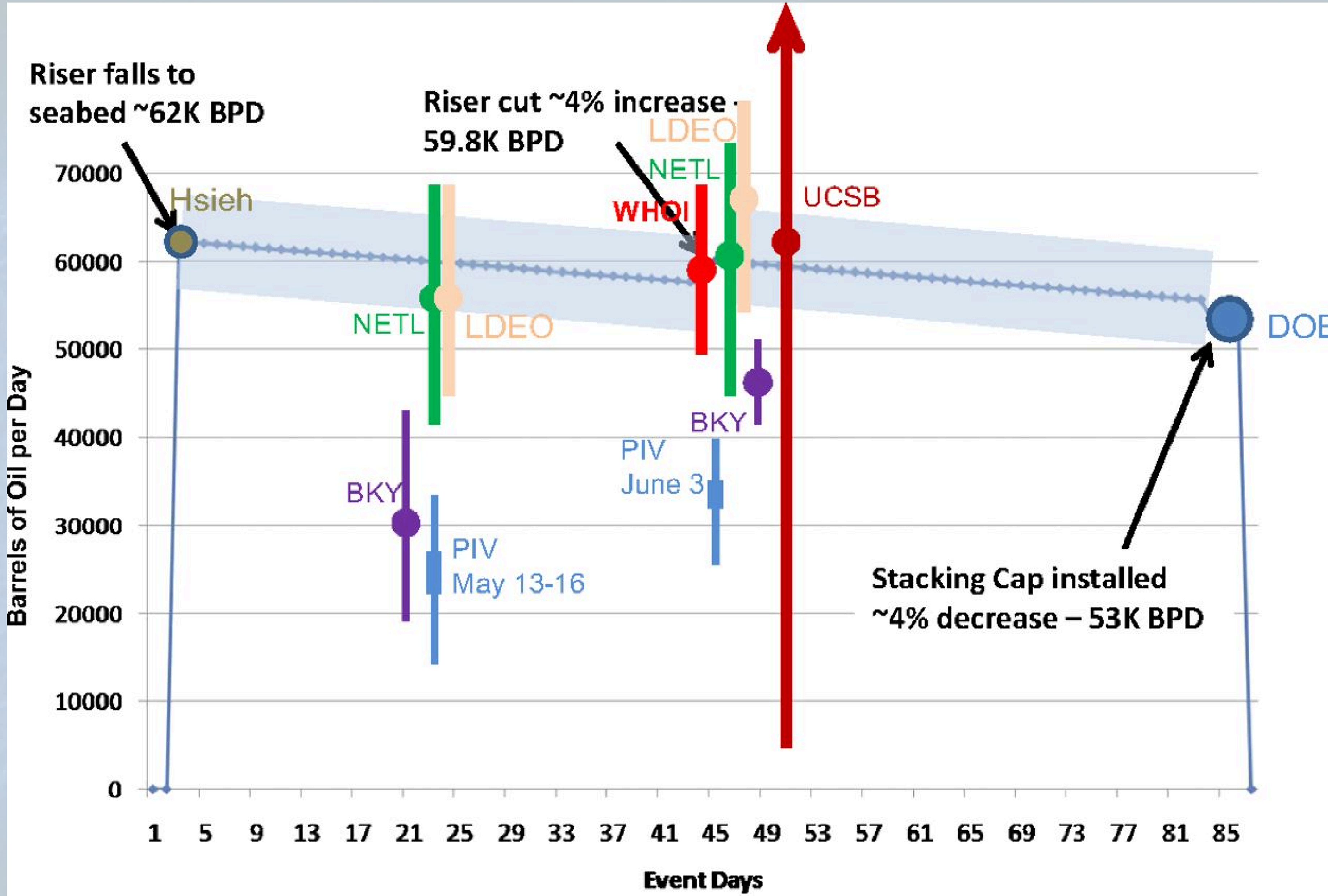


Calculated final pressure using the best match to both pressure and pressure derivative
Pressure derivative mismatch
Pressure mismatch
p_{Rf}
Root-mean-square error in pressure match (psi)
0
2
4
6
8
10
12
14
16
18
20
10,250
10,300
10,350
10,400
10,450
10,500
Final reservoir pressure (psi)

Flow Rate Variation in Time

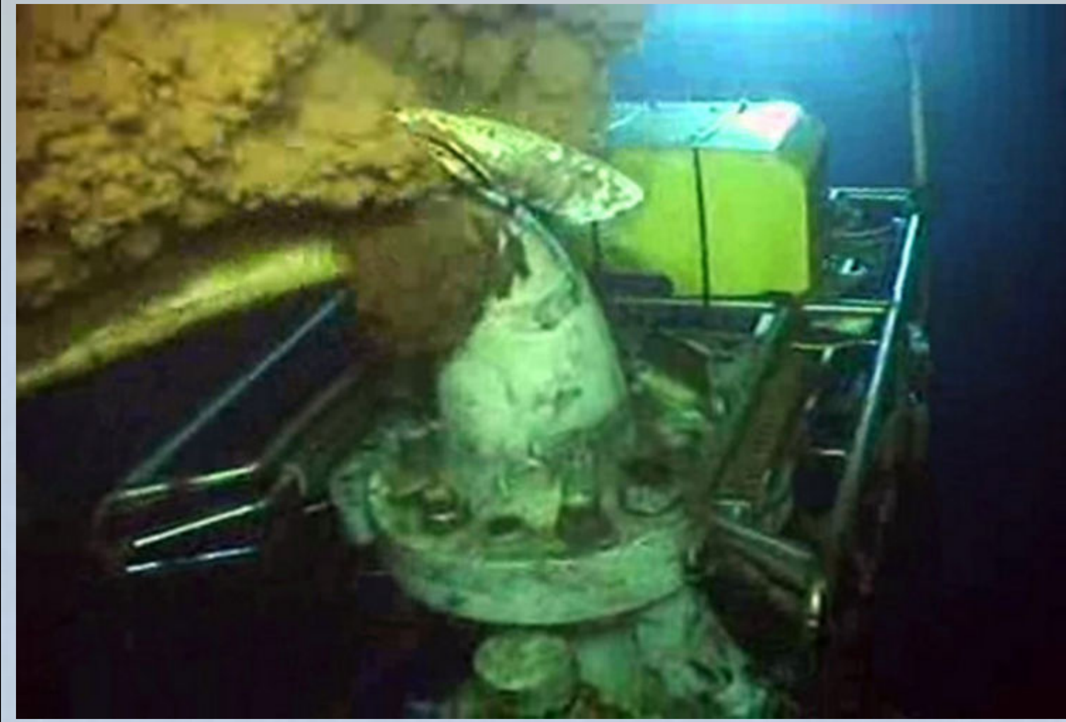
- US government claims that the final rate was the culmination of a continuously, monotonically decreasing rate from the onset of the blowout.
  - This would assume unchanged flow resistance in the pipes to the discharge point at the seabed.
  - BP argues that erosion continuously changed pipe flow conditions, with rate increasing gradually as erosion “cleaned” the flow path, then eventually reached a condition with stable pipeflow resistance and a rate that declined naturally because of declining reservoir pressure.

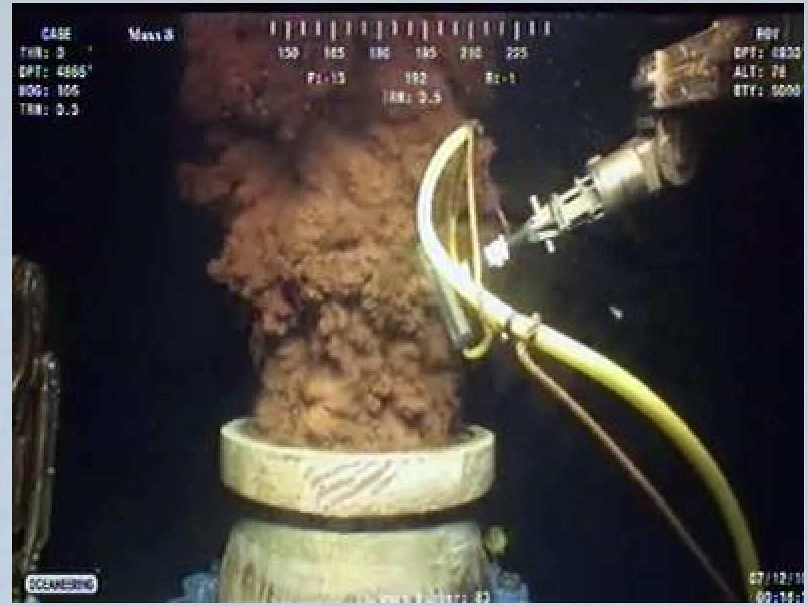
  - The material balance method is independent of the rate-time history, only dependent on the cumulative production at the end of the blowout.
  - Only the flow model used to estimate final reservoir pressure depends on the flow rate – and only at the end of the blowout (measured).

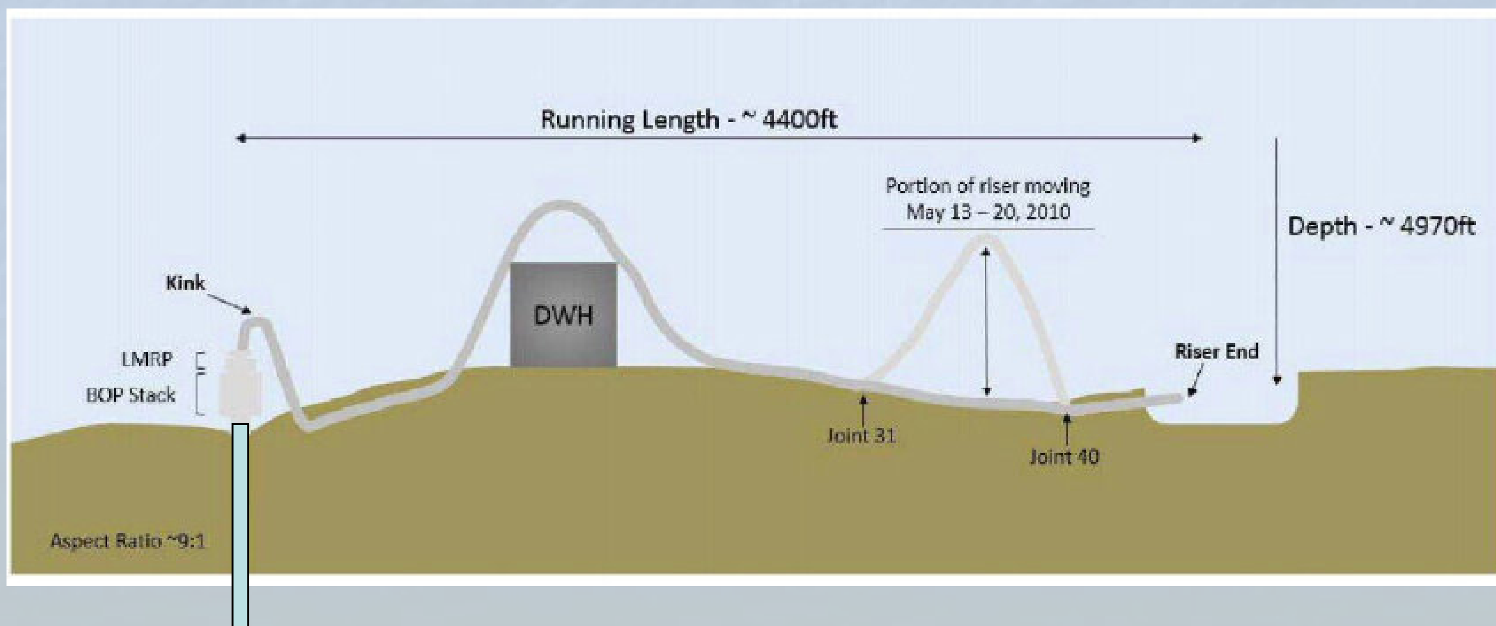


Cumulative Release: ~4.9 million barrels

Cumulative Oil Collected: ~0.8 million barrels (results from BP)





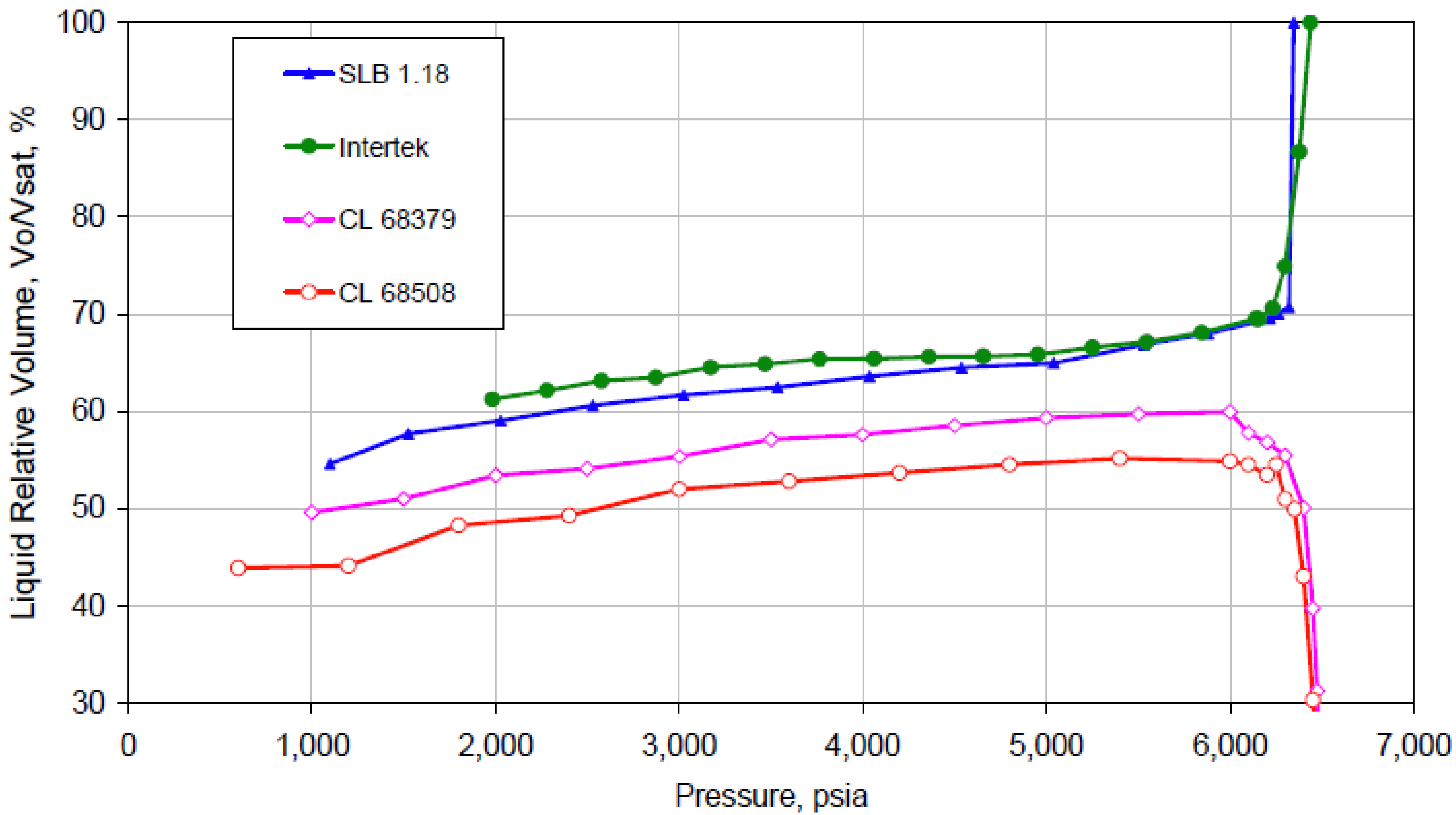


Running Length - ~ 4400ft
Portion of riser moving
May 13 – 20, 2010
Depth - ~ 4970ft
Kink
DWH
LMRP
BOP Stack
Riser End
Joint 31
Joint 40
Aspect Ratio ~9:1

Macondo Fluid Issues

- A complex, near-critical reservoir fluid with unusual critical behavior over a wide range of temperatures.
- Four accurate reservoir fluid samples collected.
  - Two samples exhibit dewpoints over the entire range of temperature from 100-243^{o}F.
  - Two samples exhibit bubblepoints over the entire range of temperature from 100-243^{o}F.
- Near-critical behavior only important in two-phase region, i.e. flowing in pipe during blowout.

Near-Critical Fluid Behavior at All Temperatures (100-243ºF)



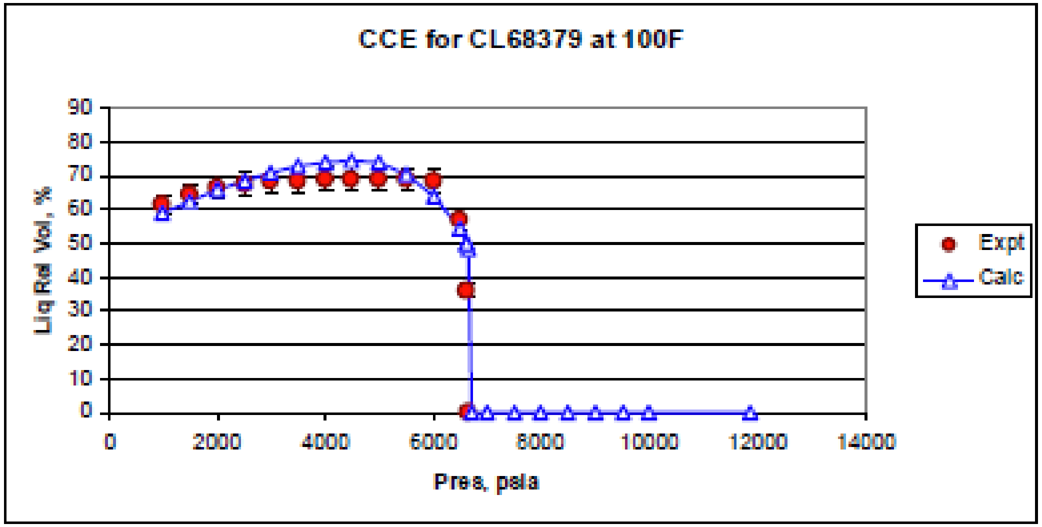


Figure 4. Experimental data and EOS results for CL 68379, relative liquid volume in CCE at 100 F.

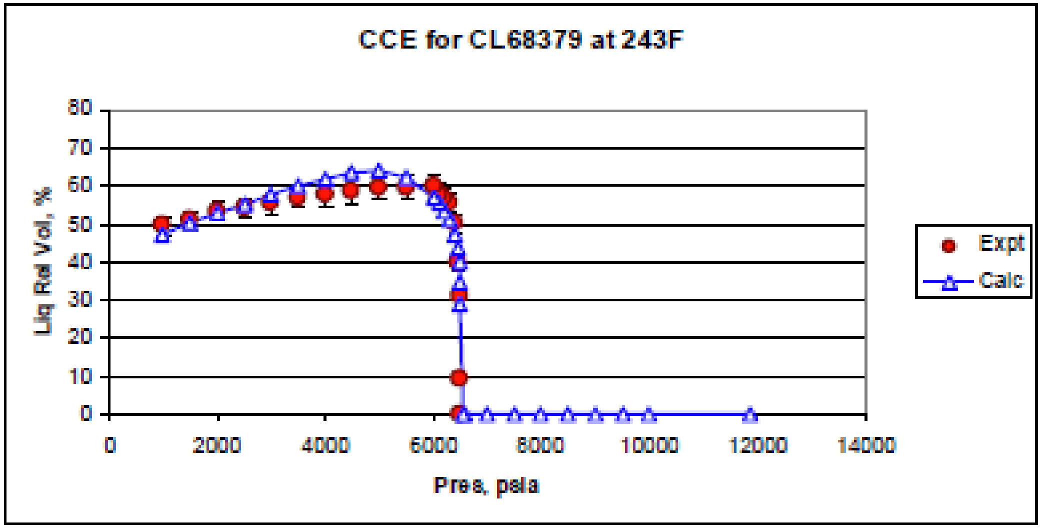


Figure 5. Experimental data and EOS results for CL 68379, relative liquid volume in CCE at 243 F.

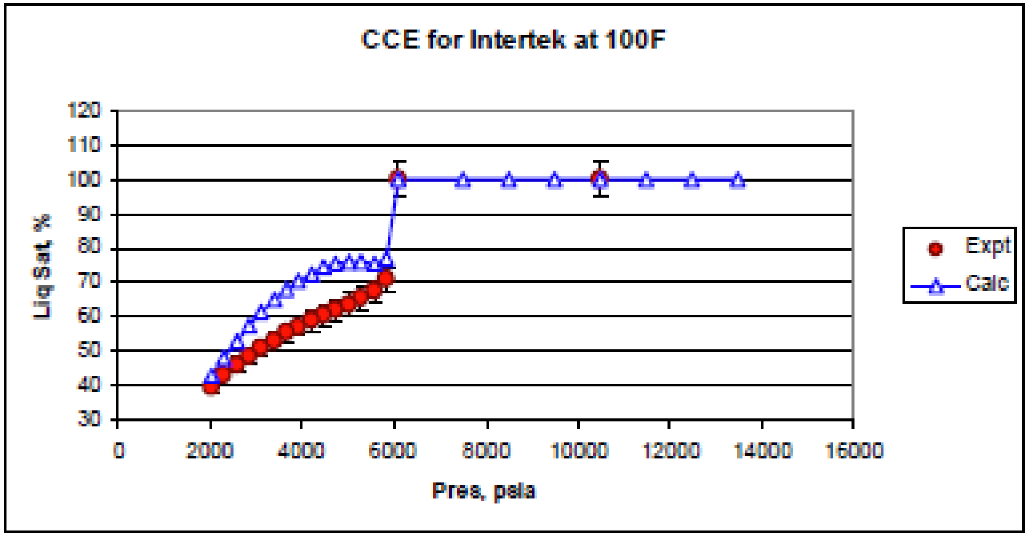


Figure 10. Experimental data and EOS results for Intertek, relative liquid volume in CCE at 100 F.

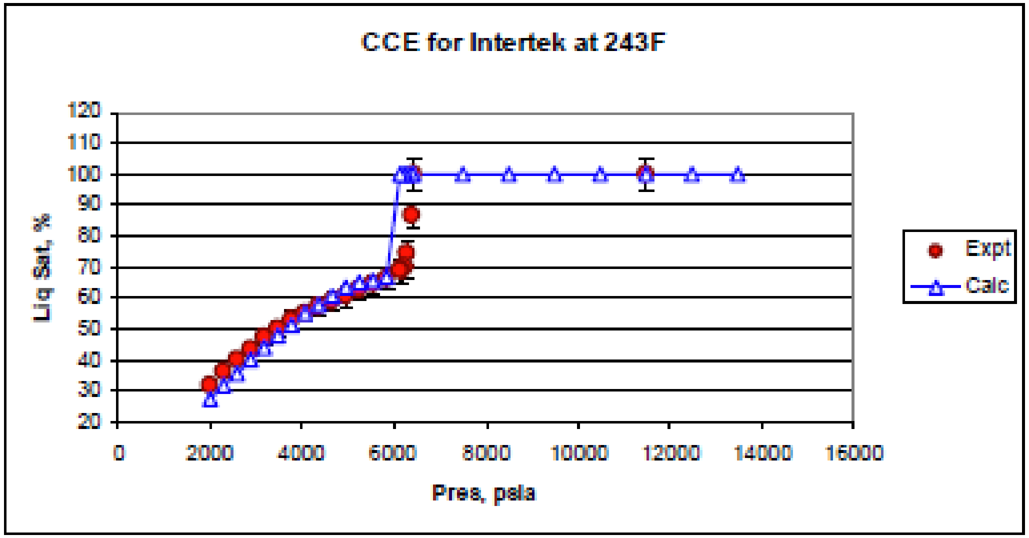


Figure 11. Experimental data and EOS results for Intertek, relative liquid volume in CCE at 243 F.

Conversion to Stock Tank Barrels

- Estimated quantities of reservoir fluid released also require PVT to convert to **stock tank oil barrels**.

- Shrinkage Factor:

$$\frac{\text{Final stock tank oil volume}}{\text{Reservoir fluid volume}}$$

- Can be very dependent on process going from reservoir to stock-tank conditions.

SF expressed as a % (=STB per 100 initial reservoir barrels).

Sources of Shrinkage Factors

- Measured by three independent laboratories on four samples
  - **1-Stage Separator Process** (43 STB/bbl)
  - **4-Stage Separator Process** (47 STB/bbl)

- Calculated by EOS model
  - **Oceanic Process** (~43 STB/bbl)
    - 130 stages.
    - Water solubility & Mixing Assumptions