Petroleum Engineering 324 — Well Performance
Daily Summary Sheet
Spring 2009 — Blasingame/Ilk

Date: **06 February 2009**

Materials Covered in Class Today:

**1. Lecture:**
- **"Material Balance"**

**2. Exercise:**
- **Exercise 5 - Well Test "Strip Chart" Summary Plots**

**3. Quiz:**
- **Quiz 6 - Wellbore Pressure Profile — Pressure Drawdown/ Buildup Test Sequence**

Comment(s):

**1. Monday 09 February 2009**
- **Continue: "Material Balance"**
- **Quiz?**

# Material Balance

**Objective**: ***Derive the material balance relation for a slightly compressible liquid (oil) in the presence of other phases (gas and water), as well as the material balance relation for a dry gas.***

***Notes*:**

# <u>Material Balance</u>: Historical Perspective

***"It seems no longer fashionable to apply the concept of material balance to oilfields, the belief being that it has now been superseded by the application of the more modern technique of numerical simulation modeling.***

***Acceptance of this idea has been a TRAGEDY and has robbed engineers of their most powerful tool for investigating reservoirs and understanding their performance rather than imposing their wills upon them, as is often the case when applying numerical simulation directly in history matching."***

*L.P. Dake*
*The Practice of Reservoir Engineering, Elsevier* (2001)

***Notes*:**

# Material Balance: Orientation

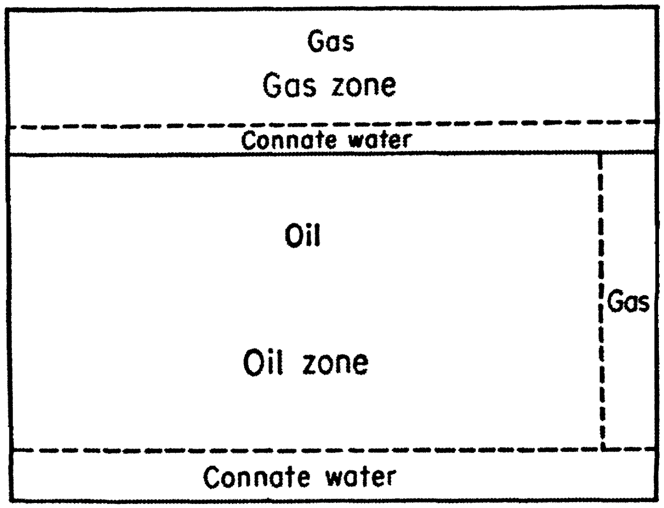
## Issues:

- Oil MBE (must know all data, also $c_f(p)$).
- Gas MBE (abnormal pressure, water drive).

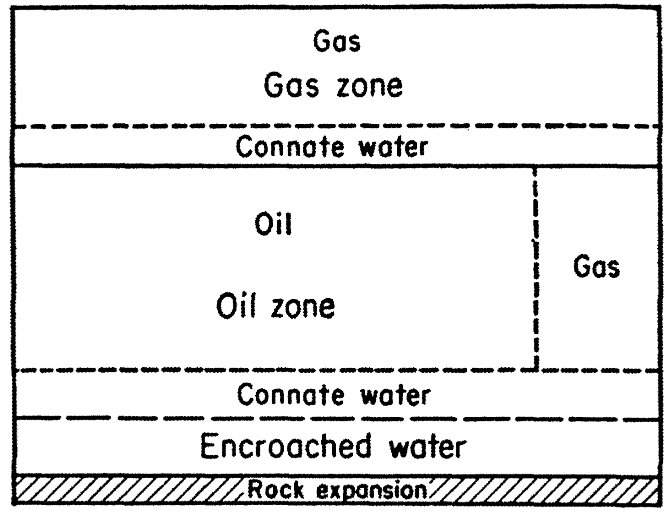
## Topics:

- "Accounting" Concept of Material Balance:
  - Require all inflows/outflows/generations.
  - (Average) reservoir pressure profile is *REQUIRED*.
  - Require rock, fluid, and rock-fluid properties (at some scale).
- Oil Material Balance:
  - Less common than gas material balance (pressure required).
- Gas Material Balance:
  - Volumetric dry gas reservoir ($p/z$ versus $G_p$ (straight-line)).
  - Abnormally-pressured gas reservoirs (various techniques).
  - Waterdrive/water influx cases (always problematic).
- Material Balance yields RESERVOIR VOLUME!

# **Material Balance**: *General Concept*




a. Initial reservoir conditions.

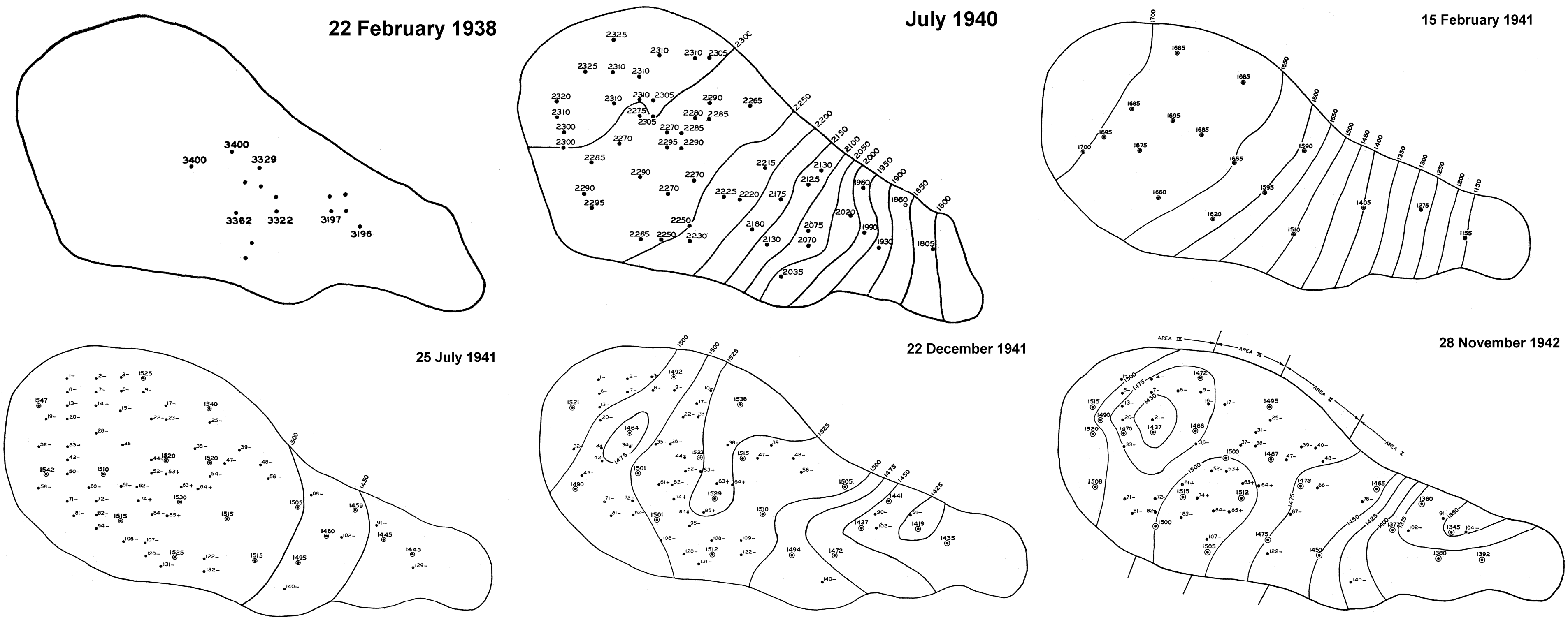



b. Conditions after producing $N_p$ STB of oil, and $G_p$ SCF of gas, and $W_p$ STB of water.

- From: *Petroleum Reservoir Engineering* — Amyx, Bass, and Whiting (1960).

- **Material Balance**: Key Issues
  - Must have accurate production measurements (oil, water, gas).
  - Estimates of average reservoir pressure (from pressure tests).
  - Suites of PVT data (oil, gas, water).
  - Reservoir properties: saturations, formation compressibility, etc.

# <u>Material Balance</u>: *Average Reservoir Pressure*

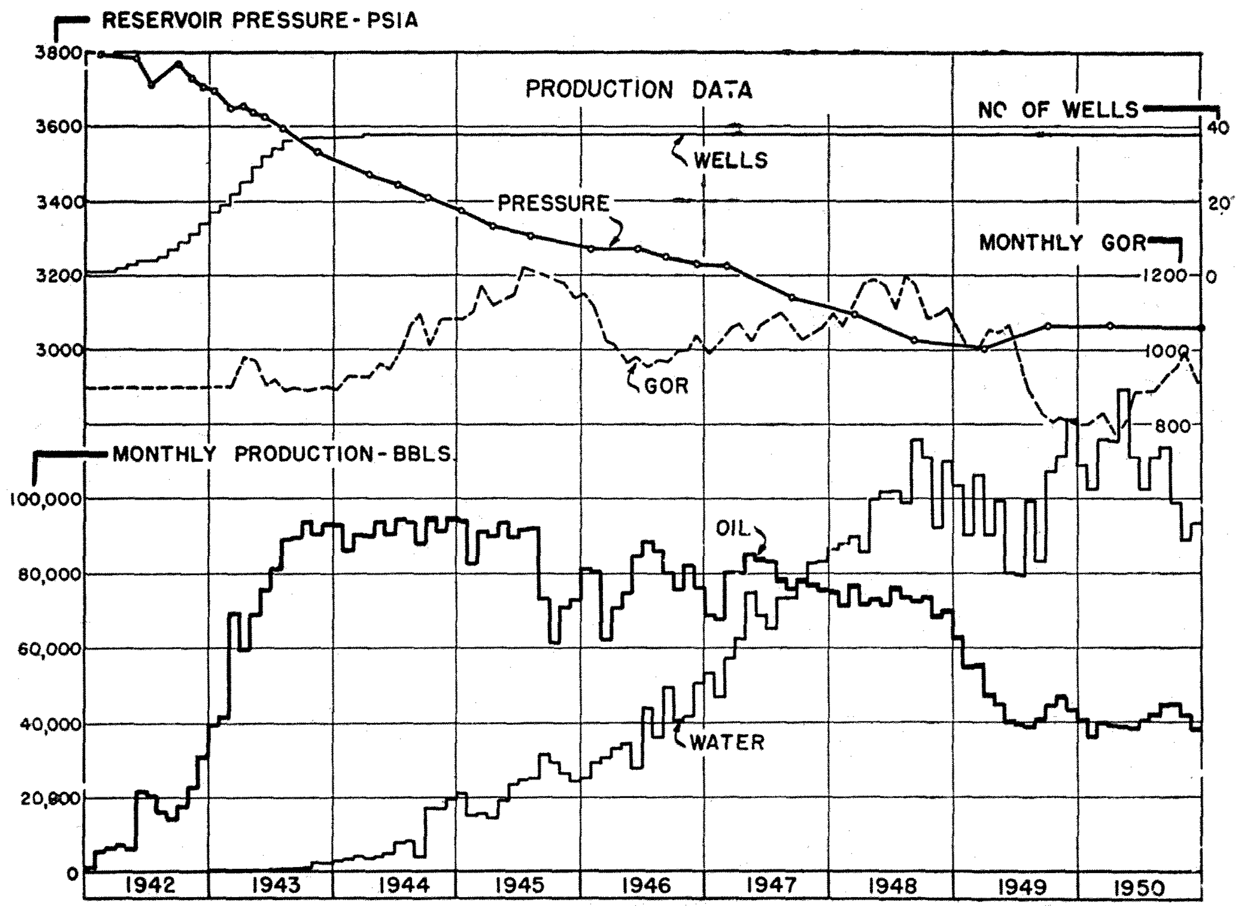



- From: *Engineering Features of the Schuler Field and Unit Operation* — Kaveler (SPE-AIME, 1944).

- **<u>Average Reservoir Pressure</u>: Key Issues**
  - **Must have "average" pressures over volume or area (approximation).**
  - **Pressure tests must be representative ($p_{avg}$ extrapolation valid).**
  - **Can average using cumulative production (surrogate for volume).**

# **Material Balance**: *Example Data Set*

- From: *Application of the Material Balance to a Partial Waterdrive Reservoir* — van Everdingen (SPE, 1953).




- **Black Oil Material Balance Case**: (Example Data Set)
  - Note that all fluid functions are given: $N_p$, $W_p$, and $GOR$ (for $G_p$).
  - Average reservoir pressure is presumed correct.
  - Authors cite "partial waterdrive" — remains a contentious issue.

# Material Balance: *Oil Material Balance Relations*

- **Oil Material Balance Relations:**

**"Black Oil" Material Balance: ($p$>$p_b$)**

$$\overline{p} = p_i - \frac{1}{Nc_t}\frac{B_o}{B_{oi}}N_p$$

**"Solution Gas Drive" (Oil) Material Balance: (all $p$)**

$$N_p\left[B_o + (R_p - R_s)B_g\right] + W_pB_w = \quad \textbf{(Withdrawal (RB))}$$

$$N\left[(B_o - B_{oi}) + (R_{si} - R_s)B_g\right] \quad \textbf{(Oil Expansion (RB))}$$

$$+ mNB_{oi}\left[\frac{B_g}{B_{gi}} - 1\right] \quad \textbf{(Gas Cap Expansion (RB))}$$

$$+ (1+m)NB_{oi}\frac{(c_wS_{wi} + c_f)}{(1 - S_{wi})}(p_i - \overline{p}) \quad \textbf{(Water Exp./Pore Vol. Comp. (RB))}$$

$$+ W_eB_w \quad \textbf{(Water Influx (RB))}$$

# Material Balance: *Recovery Factors* (*Oil*)

## Example: Black Oil Recovery ($p>p_b$)

$$\overline{p} = p_i - \frac{1}{Nc_t}\frac{B_o}{B_{oi}}N_p \quad \text{or} \quad \frac{N_p}{N} = \frac{B_{oi}}{B_o}(p_i - \overline{p})c_t$$

**Black Oil Recovery:** $(\overline{p} \rightarrow 0)$

**$B_{oi}/B_o$=0.95** **$p_i$=5000 psia** **$c_t$=10x10$^{-6}$ psi$^{-1}$**

$$\frac{N_p}{N} = (0.95)((5000 \text{ psia}) - (0 \text{ psia}))(10\text{x}10^{-6}\text{psi}^{-1})$$

$$\frac{N_p}{N} = 0.0475 \text{ or } 4.75 \text{ percent recovery!}$$

# Material Balance: *Gas Material Balance Relations*

- **Gas Material Balance Relations:**

**General Gas Material Balance:**

$$\frac{\bar{p}}{\bar{z}}\left[1-\bar{c}_e(\bar{p})(p_i-\bar{p})\right]=$$

$$\frac{p_i}{z_i}-\frac{p_i}{z_i}\frac{1}{G}\left[G_p-G_{inj}+W_p R_{sw}+5.615\frac{1}{B_g}\left[(W_p-W_{inj})B_w-W_e\right]\right]$$

**"Dry Gas" Material Balance: (*no reservoir liquids*)**

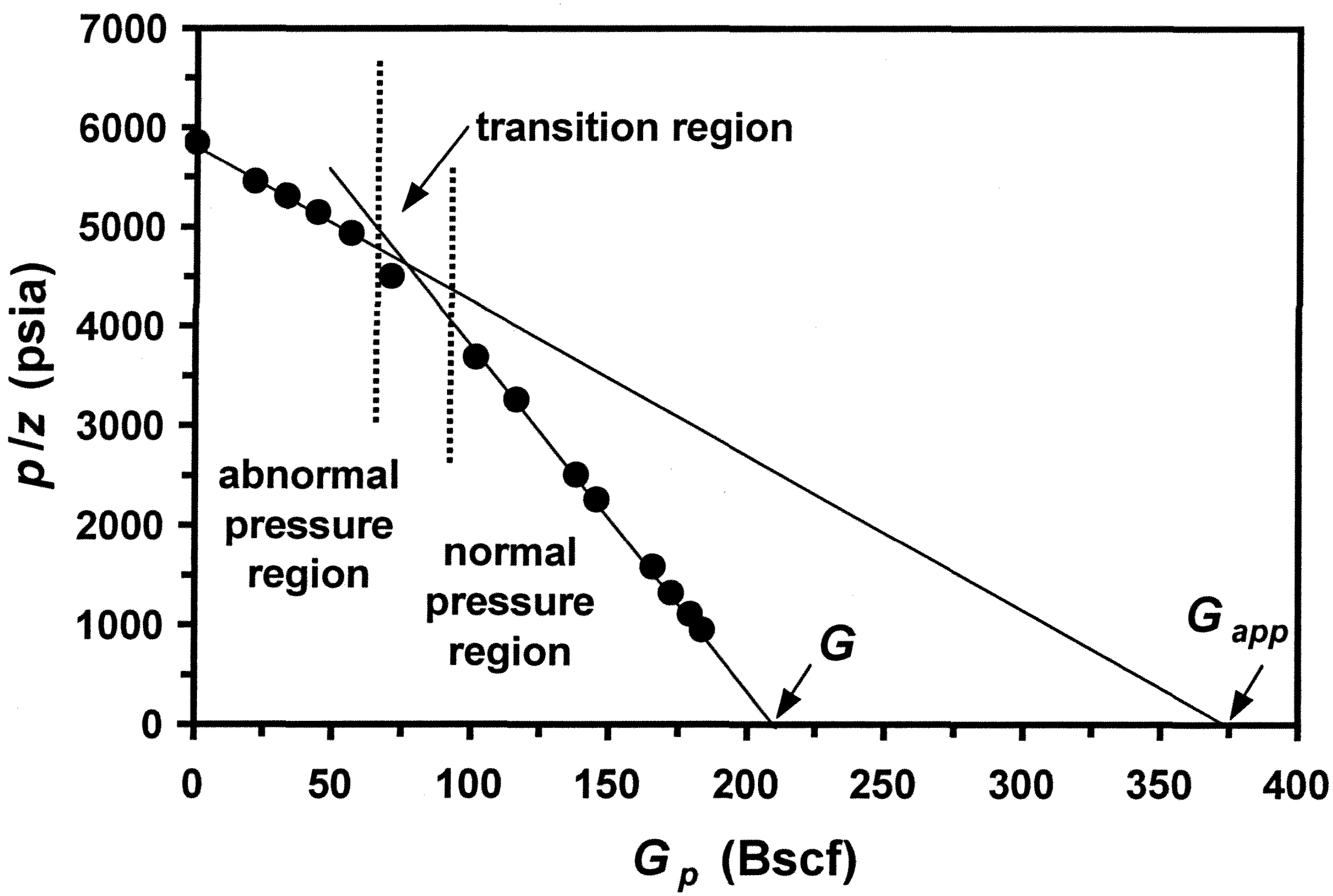
$$\frac{\bar{p}}{\bar{z}}=\frac{p_i}{z_i}\left[1-\frac{1}{G}G_p\right]$$

**"Abnormal Pressure" Material Balance: ($c_f=f(p)$)**

$$\frac{\bar{p}}{\bar{z}}=\frac{p_i}{z_i}\frac{1}{\left[1-\bar{c}_e(\bar{p})(p_i-\bar{p})\right]}\left[1-\frac{G_p}{G}\right]$$

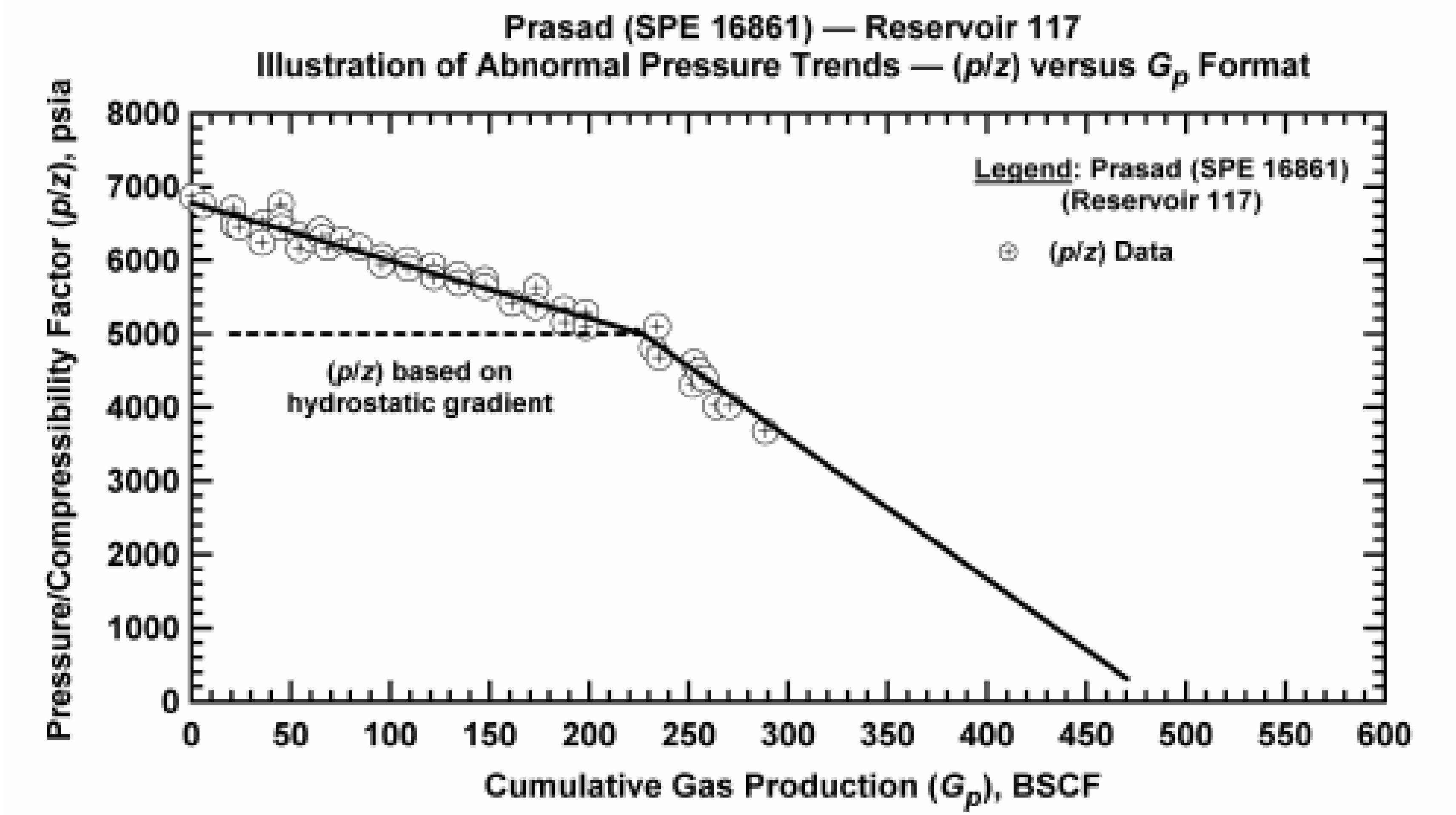
$$\bar{c}_e(\bar{p})=\frac{1}{(1-S_{wi})}\left[S_{wi}\bar{c}_w+\bar{c}_f+\left[\left[\frac{V_{pNNP}}{V_{pR}}\right]+\left[\frac{V_{pAQ}}{V_{pR}}\right]\right](\bar{c}_w+\bar{c}_f)\right]$$

# <u>Material Balance</u>: *Gas — Abnormal Pressure*



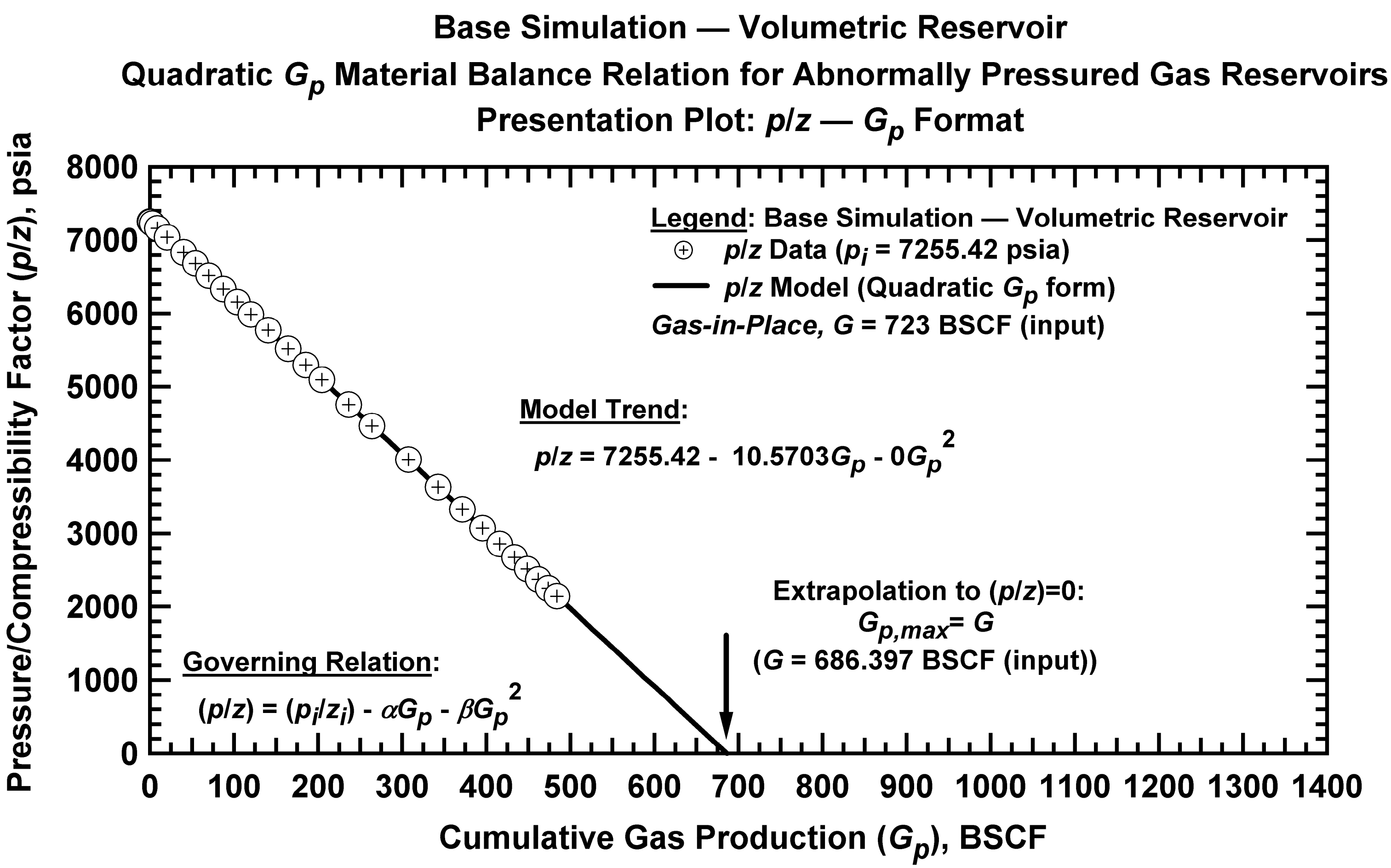

- **<u>Gas Material Balance</u>: Abnormally Pressured Reservoir Schematic**
  - **Normal pressure production sequence (volumetric depletion, *G*).**
  - **Abnormal pressure production sequence ($G_{app}$).**

# <u>Material Balance</u>: *Gas* — *Abn. Pressure* (*US GOM*)



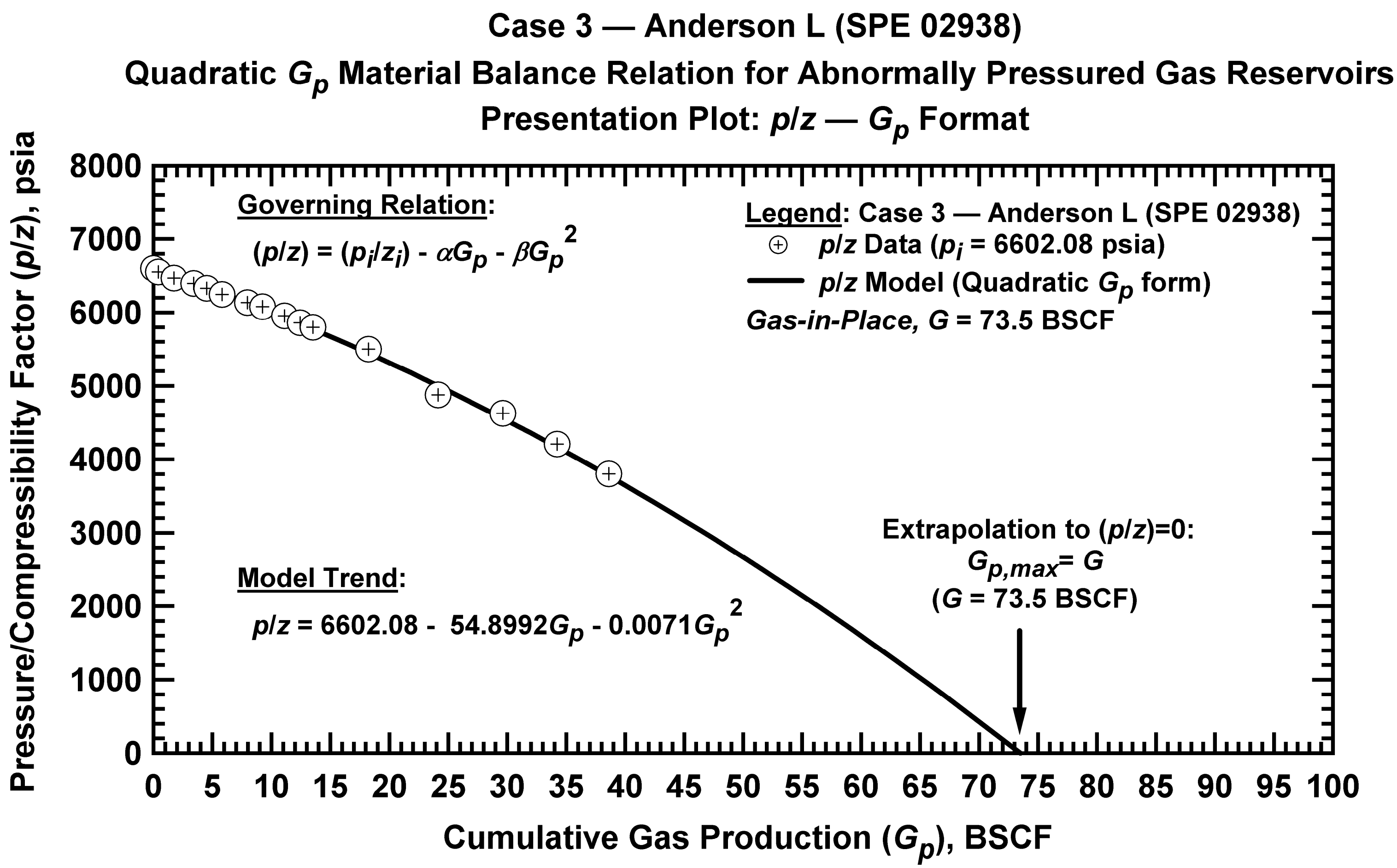

- **<u>Gas Material Balance</u>: Abnormally Pressured Reservoir Schematic**
  - **Normal pressure production sequence (volumetric depletion, *G*).**
  - **Abnormal pressure production sequence ($G_{app}$).**
  - **Note the position of the "pivot point" is at hydrostatic pressure.**

# Material Balance: *Gas* — *Normal Pressure*




- **"Dry Gas" Material Balance**: Normal Pressured Example
  - Volumetric reservoir — no external energy (gas expansion only).
  - *p/z* versus $G_p$ yields unique straight-line trend.
  - Linear extrapolation yield gas-in-place (*G*).

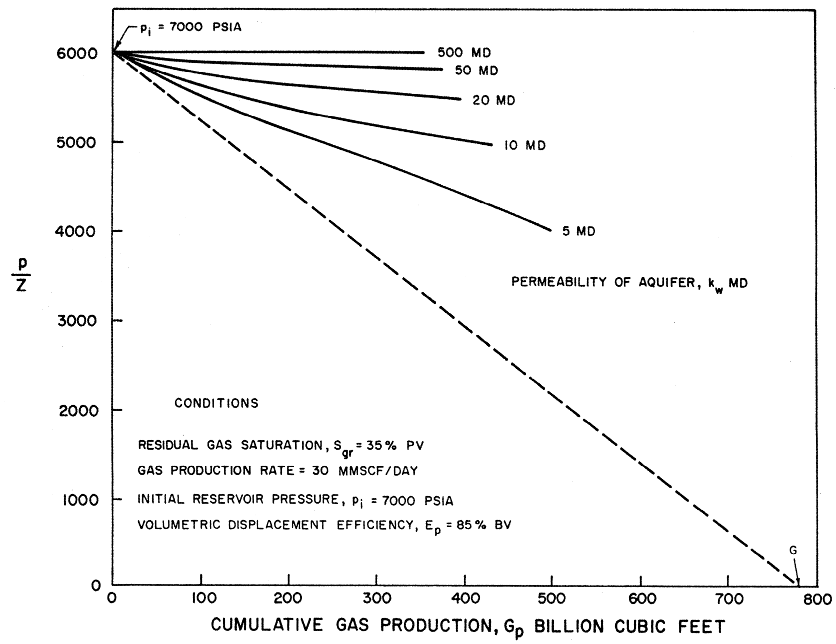
# Material Balance: Gas — *Abnormal Pressure*



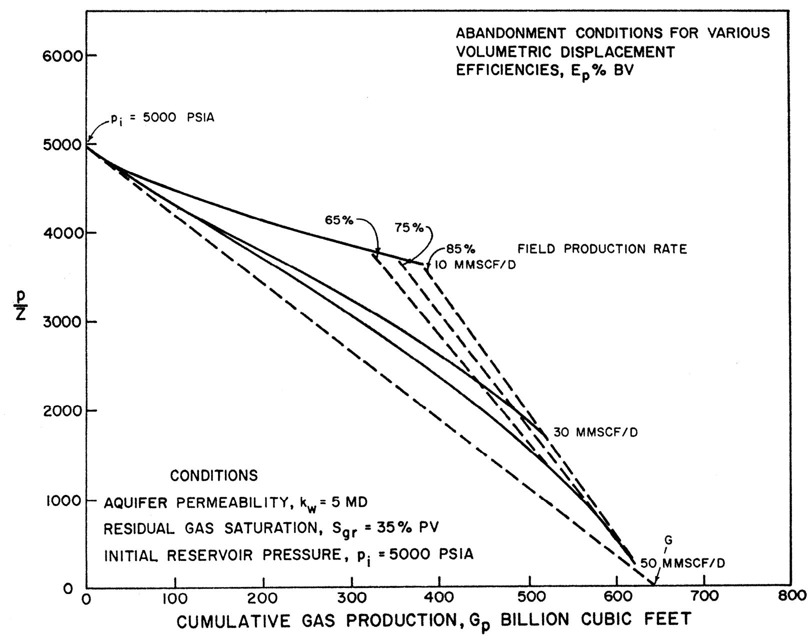

- **"Dry Gas" Material Balance: Abnormally Pressured Reservoir**
  - Volumetric reservoir — no water influx or leakage.
  - $p/z$ versus $G_p$ yields unique quadratic trend (approximate MBE).
  - Quadratic extrapolation yield gas-in-place ($G$).

# Material Balance: Gas — Water Influx

● From: *Unsteady-State Performance of Water Drive Gas Reservoirs*, Agarwal (Texas A&M Ph.D., 1967).




a. Gas Material Balance Plot: *p/z* vs. $G_p$ — simulated performance. Note effect of aquifer permeability on field performance.




b. Gas Material Balance Plot: *p/z* vs. $G_p$ — simulated performance. Note effect of displacement efficiency ($E_p$).

- **Gas Material Balance: Water Drive Gas Reservoir**
  - Pressure (hence *p/z*) is maintained during production via water influx.
  - Agarwal used an unsteady-state aquifer for this case.
  - Numerous other aquifer models (analyst must choose).

# Material Balance: *Questions to Consider*

**Q1. What is the "weakest link" in material balance?**

**A1. Need for very accurate production records — particularly average reservoir pressure (which is rarely available).**

**Q2. What is the strength of material balance?**

**A2. It is an accounting method, essentially *independent of the reservoir model*. It provides an estimate of initial reservoir volume being sampled by the wells under production.**

**Q3. Future of material balance?**

**A3. Difficult to say, essentially being (or has been) replaced by numerical reservoir simulation.**

# *Material Balance*

# *Applications in Pressure Transient Testing*

# <u>Material Balance</u>: *Wellbore Storage Equations*

- Wellbore Storage Material Balance Equation:
  - The fundamental material balance equation for wellbore storage is given as:
    - $q_{sf} = q_{sur} + \frac{24C_s}{B}\left[\frac{dp_w}{dt} - \frac{dp_{tbg}}{dt}\right]$ ($q_{sf}$ = sandface rate, $q_{sur}$ = surface rate)
  - Assuming $q_{sf}$ =0 and $p_{tbg}$=constant, then integrating, we obtain the material balance relation for the <u>*Wellbore Storage Domination*</u> flow regime. In this case <u>all</u> fluid is either produced from (drawdown) or into (buildup) the wellbore.
    - $p_{wf} = p_i - m_{wbs}\, t$ ($p_{wf}$ vs. $t$, Drawdown tests)
    - $p_{ws} = p_{wf}(\Delta t{=}0) + m_{wbs}\, \Delta t$ ($p_{ws}$ vs. $\Delta t$, Buildup tests)

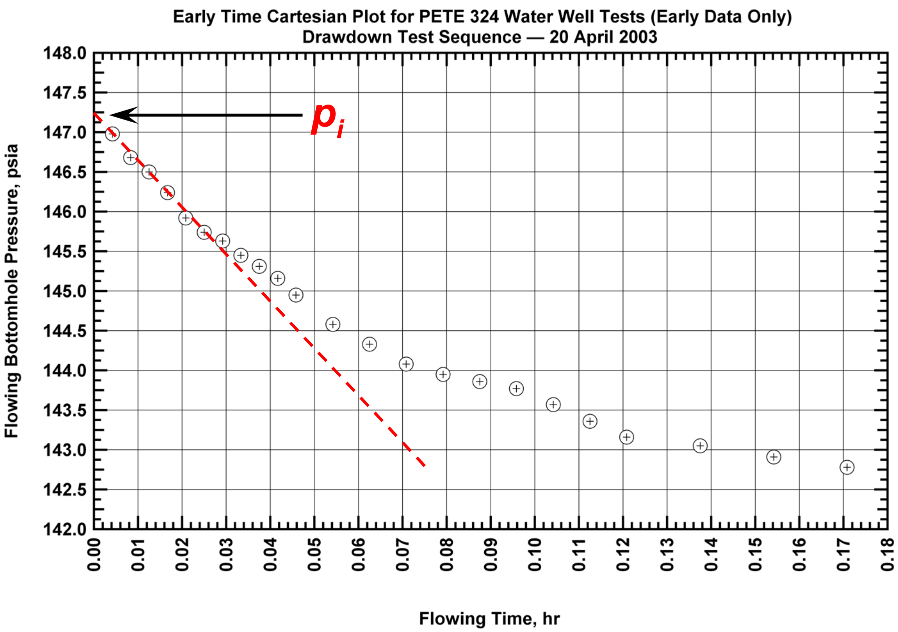
    where

    - $m_{wbs} = \frac{q_{sur}B}{24\, C_s}$

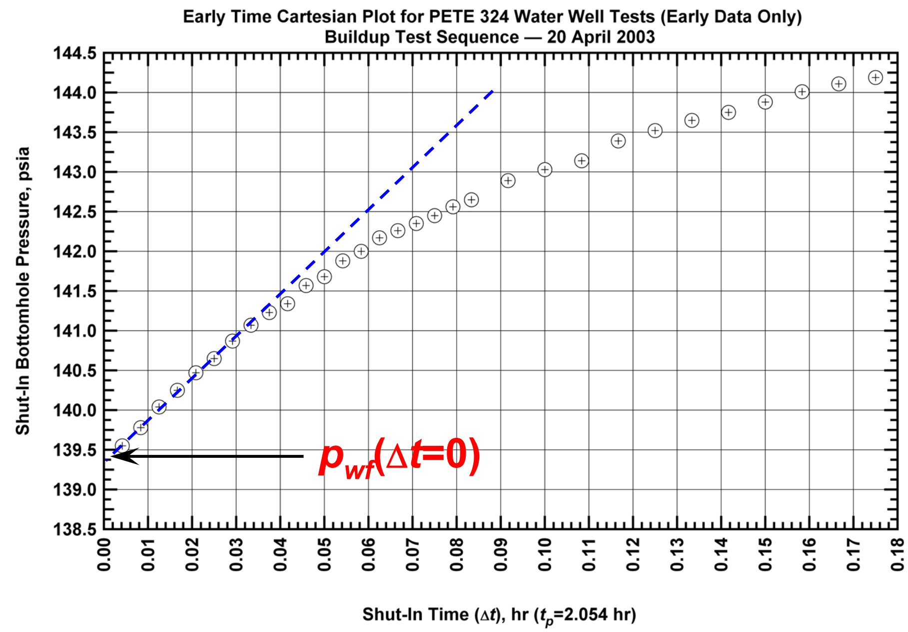
    and the wellbore storage coefficient terms ($C_s$ variables) are given by:

    - $C_s = V_{wb}c_{wb}$ for a wellbore filled with a compressible fluid
    - $C_s = \frac{144\, A_{wb}}{5.615\, \rho}\frac{g}{g_c}$ for a wellbore with a rising or failing liquid level

# Material Balance: *Wellbore Storage Behavior*




a. **Wellbore Storage Plot: Pressure *DRAWDOWN* case — note the early linear portion of the data.**




b. **Wellbore Storage Plot: Pressure *BUILDUP* case — note the early linear portion of the data.**

**_DRAWDOWN_ Material Balance Relation:**

$$p_{wf} = p_i - m_{wbs} t$$

***Buildup* Material Balance Relation:**

$$p_{ws} = p_{wf}(\Delta t = 0) + m_{wbs} \Delta t$$

# Material Balance: *Pseudosteady-State Equations*

- Equation for Boundary-Dominated (or Pseudosteady-State) Flow
  - The material balance equation for this case is given as:
    - $\bar{p} = p_i - 5.615 \dfrac{N_p B_o}{\phi h A c_t}$ (for $q$ constant, $N_p = qt$)
  - The so-called "pseudosteady-state flow equation" is: (without derivation)
    - $\bar{p} = p_{wf} + q b_{pss}$

    where

    - $b_{pss} = 141.2 \dfrac{\mu B_o}{kh}\left[\ln\left[\dfrac{r_e}{r_w}\right] - \dfrac{3}{4} + s\right]$ (for a circular reservoir)

    and

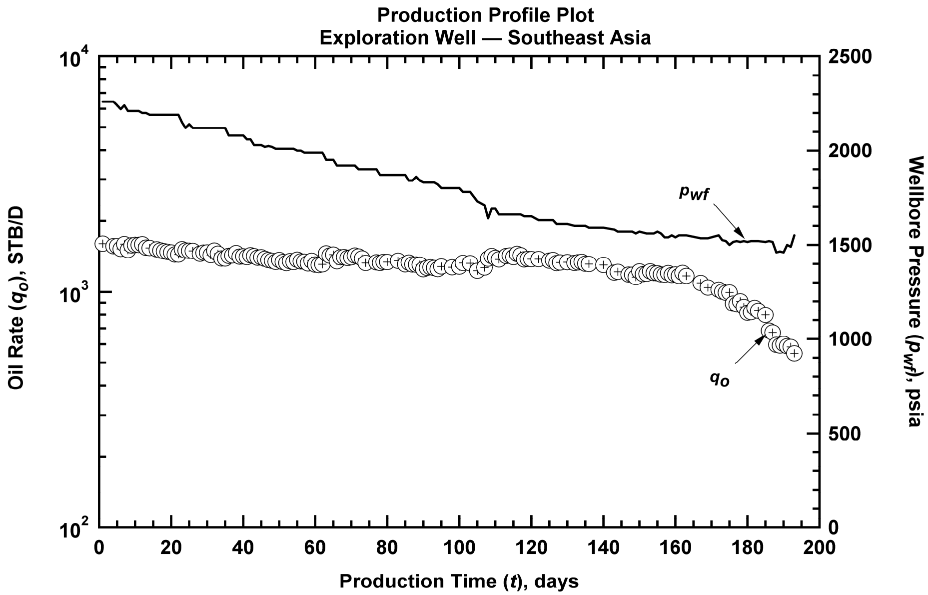
    - $b_{pss} = 141.2 \dfrac{\mu B_o}{kh}\left[\dfrac{1}{2}\ln\left[\dfrac{4}{e^{\gamma} C_A}\dfrac{A}{r_w^2}\right] + s\right]$ (general reservoir ($\gamma$=0.577216...))
  - Combining the material balance and pseudosteady-state flow equations gives
    - $\dfrac{p_i - p_{wf}}{q} = b_{pss} + \dfrac{1}{N c_t}\dfrac{B_o}{B_{oi}}\dfrac{N_p}{q}$
  - For a constant flowrate, $q$, the above relation becomes
    - $p_{wf} = p_i - q b_{pss} - 0.23395 \dfrac{q B_o}{\phi h A c_t} t$

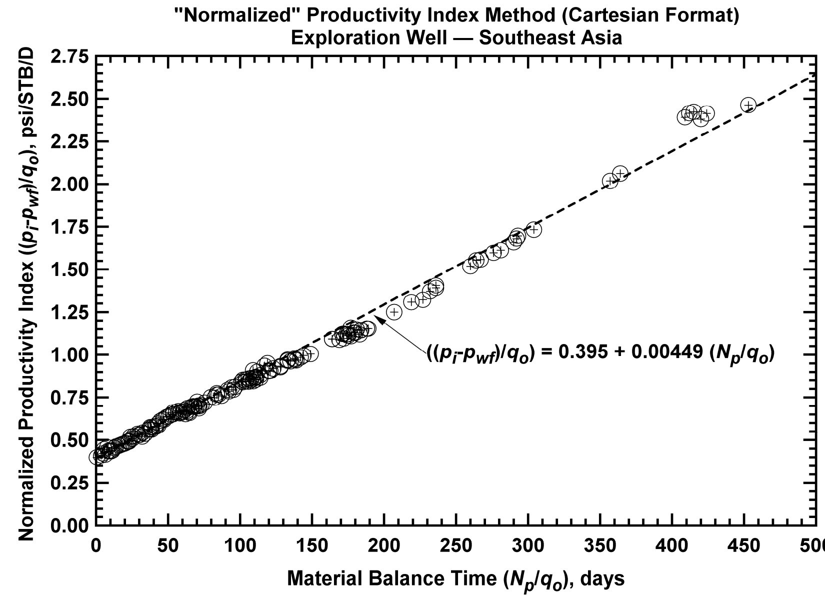
    or writing more compactly, we have

    - $p_{wf} = p_{int} - m_{pss} t$, where $m_{pss} = 0.23395 \dfrac{q B_o}{\phi h A c_t}$ and $p_{int} = p_i - q b_{pss}$.

# Material Balance: *Pseudosteady-State Flow* (*Oil*)

$$\frac{\Delta p}{q_o} = b_{o,pss} + m_{o,pss}\,\frac{N_p}{q_o}$$



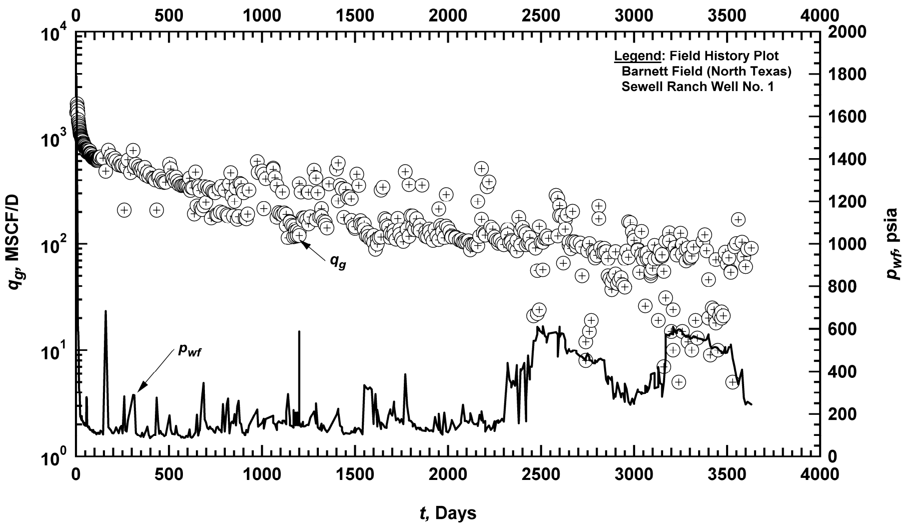



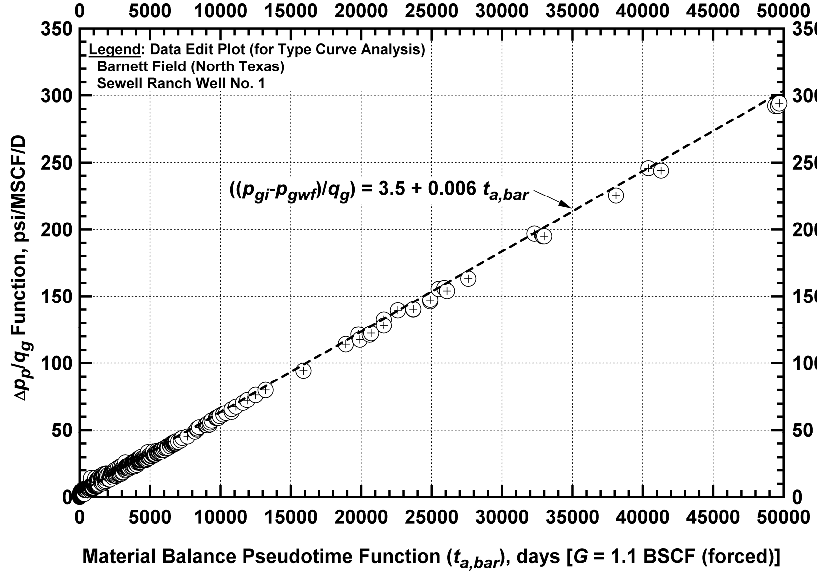

- **Pseudosteady-State Flow**: ***Oil***
  - PSS/Boundary-dominated flow is a very strong feature.
  - Simple concept of rate normalization is extremely effective.
  - Difficult to distinguish degradation of production.

# Material Balance: *Pseudosteady-State Flow* (Gas)

$$p_p = \frac{\mu_{gi} z_i}{p_i} \int_{p_{base}}^{p} \frac{p}{\mu_g z} dp \quad \bar{t}_a = \frac{\mu_{gi} c_{ti}}{q_g(t)} \int_0^t \frac{q_g(t)}{\mu_g(\bar{p}) c_t(\bar{p})} dt$$

$$\frac{\Delta p_p}{q_g} = b_{g,pss} + m_{g,pss} \bar{t}_a$$




- **Pseudosteady-State Flow: *Gas***
  - Must use "pseudo-functions" to account for gas properties.
  - Note very erratic rate and pressure profiles (liquid loading).
  - Simple rate normalization also works well for gas case.

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Name: ______________________________

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Petroleum Engineering 324 — Well Performance
Exercise Problem 05 — Well Test "Strip Chart" Summary Plots
Assigned: 06 February 2009 — Due: 09 February 2009 [to be submitted in class]

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Petroleum Engineering 324 — Well Performance

Exercise Problem 05 — Well Test "Strip Chart" Summary Plots

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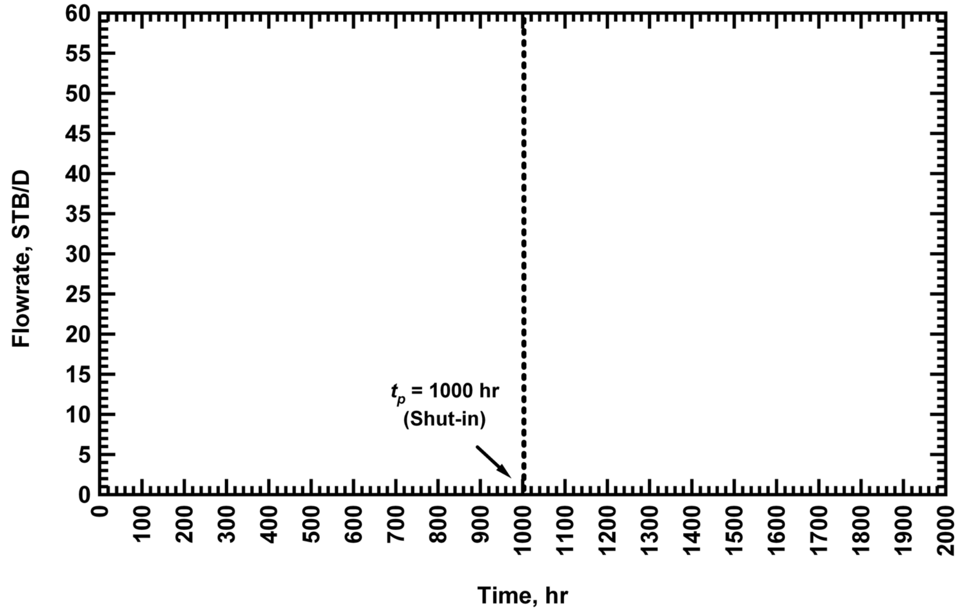
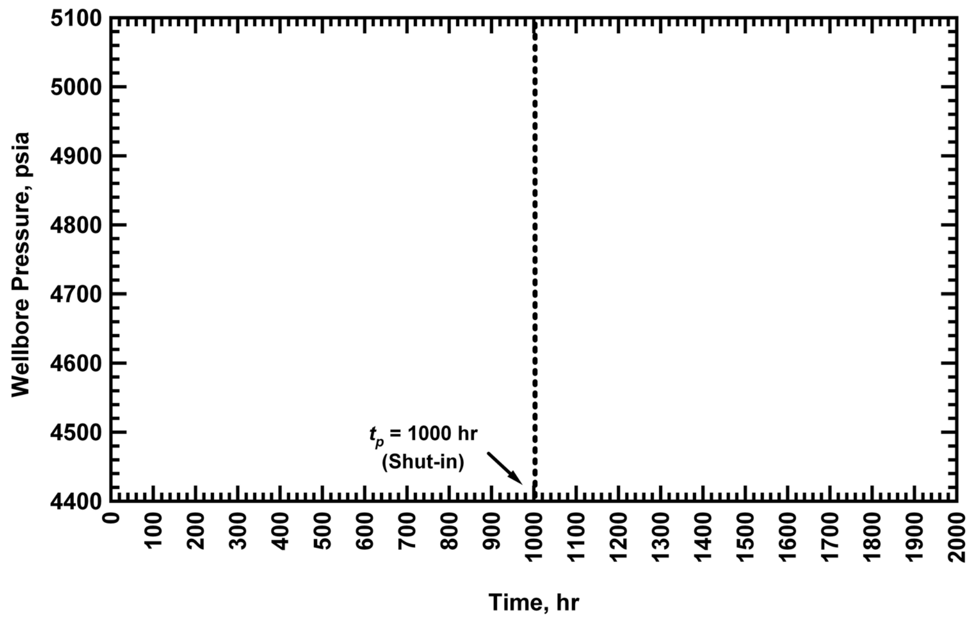
**Rate Profile — Pressure Drawdown/Buildup Test Sequence**




**Wellbore Pressure Profile — Pressure Drawdown/Buildup Test Sequence**

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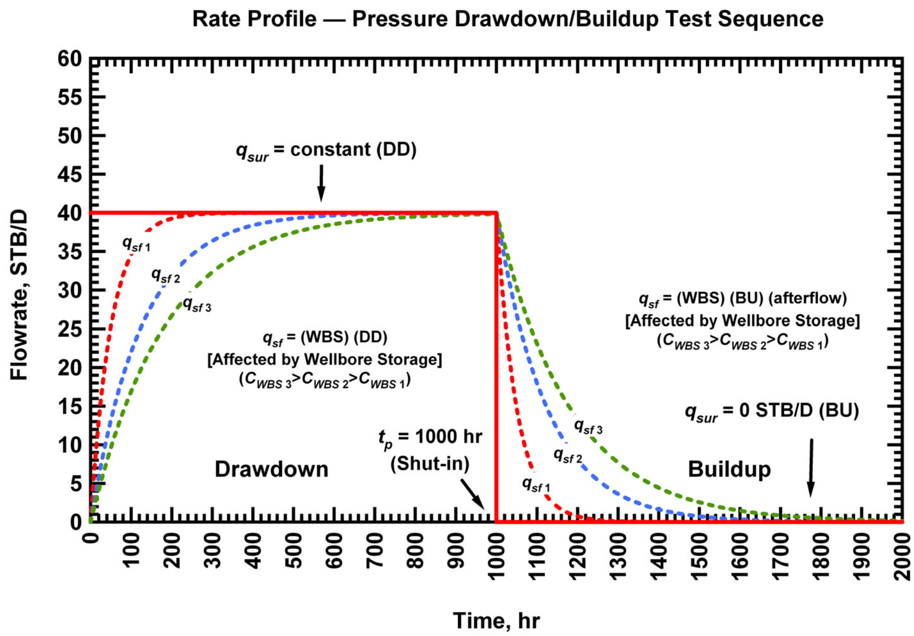


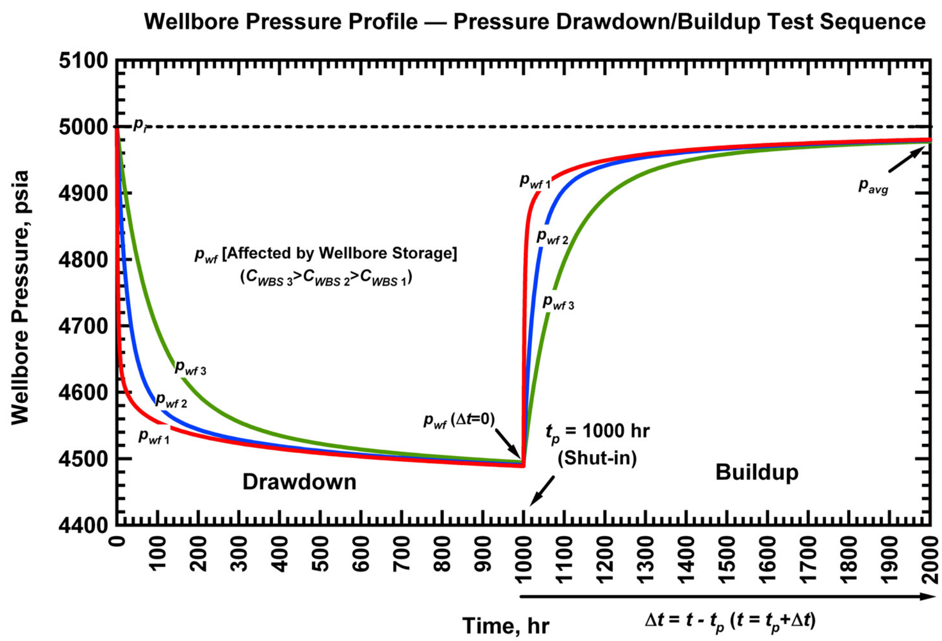

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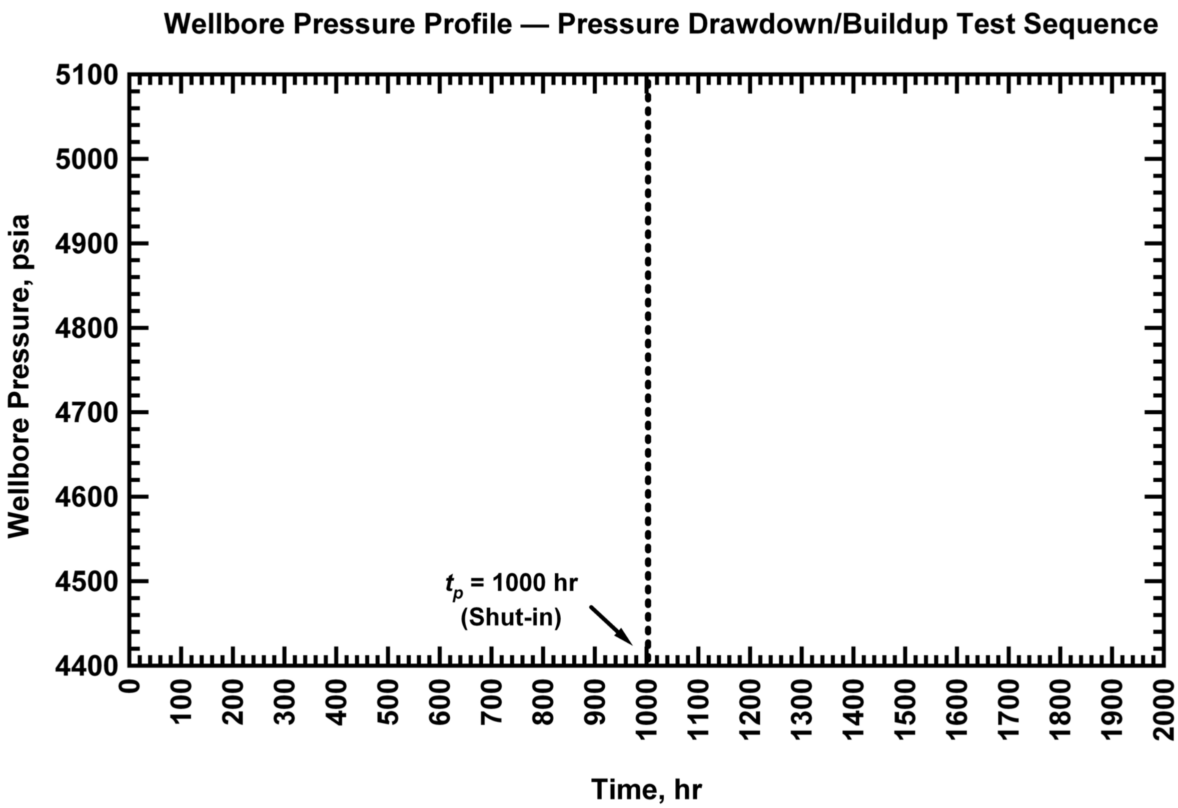
Name: ____________________

Petroleum Engineering 324 — Well Performance
Quiz 06 — Wellbore Pressure Profile — Pressure Drawdown/Buildup Test Sequence
[06 February 2009]

1. You are to sketch a typical pressure profile at the wellbore during a pressure drawdown/buildup sequence on the plot given below, and to label all of the pertinent features. You *MUST* also sketch in the $\Delta t$ time scale for the pressure buildup test.

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"*On my honor, as an Aggie, I have neither given nor received unauthorized aid on this academic work.*"
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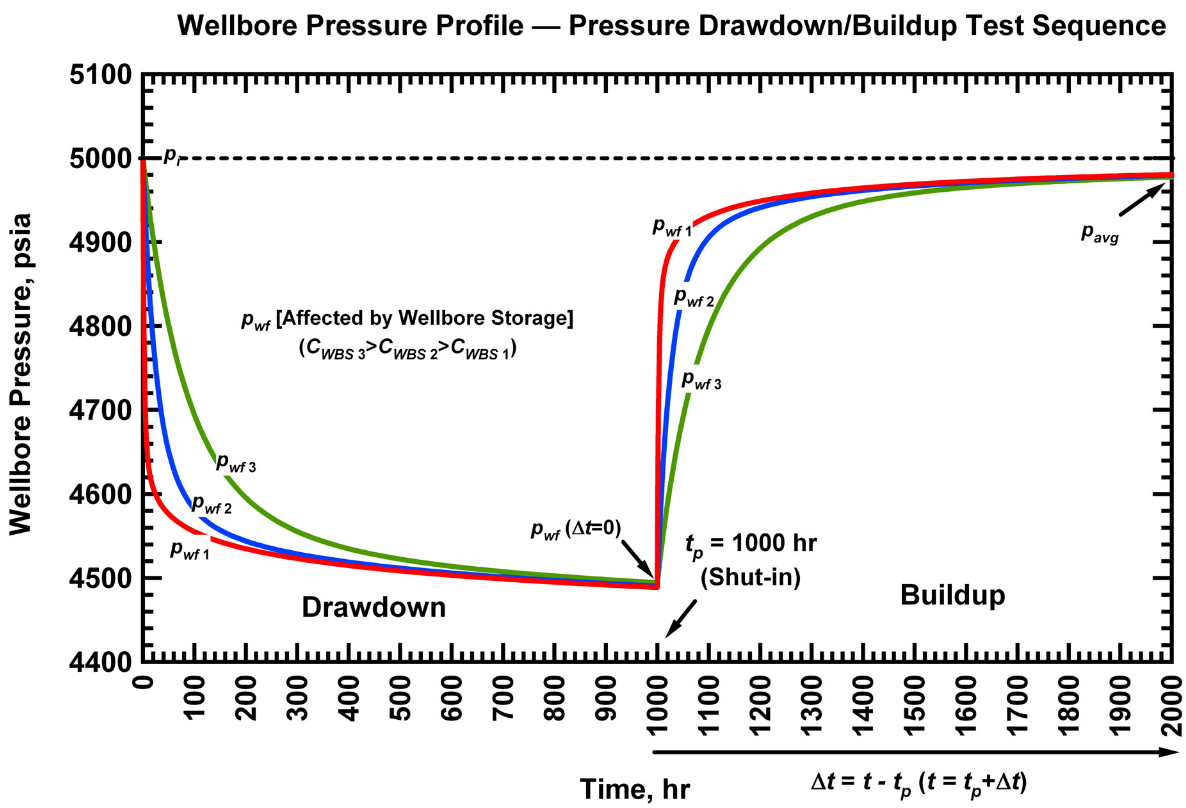
🡐 Person on my left is: ____________________ Person on my right is: ____________________ 🡒

Name: ____________________

Petroleum Engineering 324 — Well Performance
Quiz 06 — Wellbore Pressure Profile — Pressure Drawdown/Buildup Test Sequence
[06 February 2009]

1. You are to sketch a typical pressure profile at the wellbore during a pressure drawdown/buildup sequence on the plot given below, and to label all of the pertinent features. You *MUST* also sketch in the $\Delta t$ time scale for the pressure buildup test.

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