Module for:
Analysis of Reservoir Performance
Pressure Transient Testing

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(25 November 2003)
Module for:

Analysis of Reservoir Performance

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Orientation

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(25 November 2003)
Pressure Transient Testing

- Orientation — This module focuses on familiarization with deliverability tests and the analysis and interpretation of pressure transient test data. The following issues must be clear: test design, data acquisition/data quality control, and test execution are critical activities.

- Deliverability Testing:
  - "4-point" tests are appropriate (analyze as well tests).
  - Isochronal/modified isochronal testing is difficult.

- Pressure Transient Test Analysis/Interpretation:
  - Conventional analysis — specialized plots.
  - Model identification — type curves, simulation, etc.
  - Test design — simplicity is the key.

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Deliverability Testing — *Basics*

a. "Standard" 4-point test deliverability test — note that the rates increase (to protect the reservoir).

b. "Isochronal" test sequence — note that each "buildup" is required to achieve $p_i$.

c. Modified "Isochronal" test sequence — note that each "buildup" is *not* required to achieve $p_i$.

\[
q = C (\bar{p}^2 - p_{wf}^2)^n
\]

\[
\Delta p^2 = \bar{p}^2 - p_{wf}^2 = aq + bq^2
\]

\[
q = C [ p_p (\bar{p}) - p_p (p_{wf}) ]^n
\]

\[
\Delta p_p = p_p (\bar{p}) - p_p (p_{wf}) = aq + bq^2
\]

d. Governing equations for "deliverability" test analysis/interpretation.

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Well Test Analysis — *Multirate Testing*

**Summary of Well Test Analysis (Conventional Approach)**

Well CII-018 (A-098) [Test Date: 7 August 1992]

- **Flowrate, \( q \)**: 57000 MSCF/day
- **\( p_{wf} \) at \( \Delta t = 0 \)**: 2445 psia
- **Reservoir Condition**: Homogeneous
- **Well Condition**: Wellbore Storage & Skin
- **Boundary Condition**: Infinite
- **Wellbore Storage Coeff., \( c_{sf} \)**: 0.28 STB/psi
- **\( c_{sf}/c_{sf} \)**: 0.46
- **\( \alpha_D \)**: 469
- **Total Skin Factor, \( s' \)**: 5.71
- **Mechanical Skin Factor, \( s \)**: 2.86
- **Non Darcy Coefficient, \( D \)**: 5x10^{-5} (MSCF/day)^{-1}
- **Permeability-Thickness, \( kh \)**: 6170 md-ft
- **Permeability, \( k \)**: 9.49 md
- **Mobility, \( k/\mu \)**: 233 md/cp

**Well Test Summary Plot — Well CII-018 (A-098)** [Test Date: 7 August 1992]

*a. Multirate (4-point) rate sequence (note pressure match (solid trend through the data)).*

**Log-log Analysis Plot — Well CII-018 (A-098)** [Test Date: 7 August 1992]

*b. Log-log "summary plot" — note good agreement in comparison of data and model.*

c. Results summary — note that non-Darcy flow, changing wellbore storage, and an infinite-acting reservoir system were considered in this analysis.
Well Test Analysis — "Well Interference"

Well interference plot for Well C-II-18 (A-098)

a. "Well Interference" plot — note the linear trend through the data functions (confirms interference).

b. Log-log "summary plot" — note the corrected and uncorrected data (well interference).

c. Horner semilog plot — note the two semilog trends confirm the radial composite model.

Discussion:

- "Well interference" is much more common than previously thought — and we must recognize the characteristic behavior on each plot:
  - Specialized plot (a).
  - Log-log plot (b).
  - Semilog plot (c).

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Well Test Analysis — *Radial Flow Analysis* (1/6)

**Log-log “preliminary analysis”** plot — wellbore storage and radial flow ($C_s, k$).

**Semilog “middle-time”** plot — used to analyze radial flow behavior ($k, s$).

**Cartesian “Arps”** plot — used to estimate average reservoir pressure.

**Cartesian “early-time”** plot — used to analyze wellbore storage ($p_0, C_s$).

**Horner “middle-time”** plot — used to analyze radial flow behavior ($k, s, p^*$).

**Log-log “summary”** plot — summary of all analysis ($C_s, k, s, A$, etc.).

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*Pressure Transient Testing* Slide — 8
Example: "Preliminary Analysis" (log-log).

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Example: "Horner Semilog Analysis" (semilog).
Example: "Muskat-Arps Plot" (Cartesian).
● Example: "Analysis Summary Plot" (log-log).

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Example Analysis: (Lee text (1st edition), Example 2.2)

**Given Data:** (Lee text (1st edition), Example 2.2)

These data are taken from Example 2.2 in the Lee text, *Well Testing*. These data are for a pressure "buildup" test run on an oil (liquid) well.

**Reservoir properties:**

- \( \phi = 0.039 \)
- \( r_w = 0.198 \text{ ft} \)
- \( c = 17 \times 10^{-6} \text{ psia}^{-1} \)
- \( h = 69 \text{ ft} \)

**Oil properties:**

- \( B_o = 1.136 \text{ RB/STB} \)
- \( \mu_o = 0.8 \text{ cp} \)

**Production parameters:**

- \( p_w(\text{at} \Delta t = 0) = 3534 \text{ psia} \)
- \( q_o = 250 \text{ STB/D} \)
- \( t_p = 13,630 \text{ hr} \)

**Test Data and Data Functions:**

<table>
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<th>( \Delta t, \text{ hr} )</th>
<th>( p_w(t), \text{ psia} )</th>
<th>( p_w(\Delta t), \text{ psia} )</th>
<th>( \Delta p, \text{ psi} )</th>
<th>( \Delta p', \text{ psi} )</th>
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**Graphical Analysis:**

(Lee text (1st edition), Example 2.2)

- **Early Time Cartesian Analysis:** \( p_w \) is plotted versus \( \Delta t \)

\[
C_s = \frac{q_w B_o}{24 m_{wbs}}
\]

- **"Horner" relations:** \( p_w \) is plotted versus \( \log \left( \frac{t_p + \Delta t}{\Delta t} \right) \)

\[
k = 162.6 \frac{q_w B_o}{m_{h}} \]

\[
s = 1.1513 \left( \frac{p_w(t_p) - p_w(\Delta t = 0)}{m} \right) - \log \left( \frac{t_p}{t_p + 1} \right) - \log \left( \frac{k}{\phi_c \mu_o} \right) + 3.2275
\]

- **"MDH" relations:** \( p_w \) is plotted versus \( \log(\Delta t) \)

\[
k = 162.6 \frac{q_w B_o}{m_{h}} \]

\[
s = 1.1513 \left( \frac{p_w(t_p) - p_w(\Delta t = 0)}{m} \right) - \log \left( \frac{k}{\phi_c \mu_o} \right)^2 + 3.2275
\]

- "Modified Muskat" plotting functions: \( p_w \) is plotted versus \( \frac{d}{dM} [p_w] \) to determine \( \tilde{p} \)

  - **"Modified Muskat" Pressure Equation:**
    \[
    \tilde{p} = p_w = a \exp (b \Delta t)
    \]

  - **"Modified Muskat" Pressure Derivative Equation:**
    \[
    \frac{d}{dM} [p_w] = - a b \exp (b \Delta t)
    \]

  - **"Modified Muskat" Plotting Relation:**
    \[
    p_w = \tilde{p} - \frac{1}{b} \frac{d}{dM} [p_w] \]

  \( \tilde{p} \) = intercept of the straight-line trend at \( \frac{d}{dM} [p_w] = 0 \)

**Working relations — Lee text (1st edition), Example 2.2**.

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Module for:
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Type Curve Library:
Radial Flow — Wellbore Storage and Skin Effects

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Well Test Analysis — *WBS Type Curves* (1/4)

- **a.** Type Curve: Radial flow with wellbore storage and skin effects ($p_{D_i}, p_{Ddd}$).
- **b.** Type Curve: Radial flow with wellbore storage and skin effects ($p_{D_i}, p_{Ddi}, p_{Dri}$).
- **c.** Type Curve: Radial flow with wellbore storage and skin effects ($p_{D_i}, p_{Ddia}$).
- **d.** Type Curve: Radial flow with wellbore storage and skin effects ($p_{Di}, p_{Ddi}$).
- **e.** Type Curve: Radial flow with wellbore storage and skin effects ($p_{Di}, p_{Ddi}, p_{Dir}$).
- **f.** Type Curve: Radial flow with wellbore storage and skin effects ($p_{Di}, p_{Dir}$).

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Type Curve: "Gringarten-Bourdet" \((p_D, p_{Dd})\).
Type Curve for an Unfractured Well in an Infinite-Acting Homogeneous Reservoir with Wellbore Storage and Skin Effects

Legend: Radial Flow Type Curves
- $p_D$ Type Curve
- $p_D''$ Type Curve

Wellbore Storage Domination Region $p_D = \text{Unit Slope Line}$

Radial Flow Region $p_D'' = 1/2$

Wellbore Storage Distortion Region

- Type Curve: "Second Derivative" ($p_D$, $p_D''$).

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Type Curve: "Integral Functions" ($p_{Di}$, $p_{Did}$).

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Type Curve Library:
Radial Flow — Boundaries/Composite Reservoir

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a. Type Curve for sealing faults \( (p_{Dd}) \).

b. Type Curve for conductive (leaky) faults \( (p_{Dd}) \).

c. Type Curve for pressure buildup test in a closed rectangular reservoir \( (p_{Dd}) \).

d. Type Curve for pressure buildup test in a closed rectangular reservoir \( (p_{Did}) \).
Well Test Analysis — *Bounded Reservoir* (2/3)

Type Curves for Sealing Faults
(Infinite-Acting Homogeneous Reservoir)

- **Type Curve:** "Sealing Faults\(^{(p_{Dd})}\)."

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Well Test Analysis — **Bounded Reservoir**

- **Type Curve:** "Closed Reservoir" (Buildup Only) ($p_{Dd}$).

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Well Test Analysis — Composite Systems (1/2)

a. Composite Reservoir ($\eta_r = 1 \times 10^{-3}$).

b. Composite Reservoir ($\eta_r = 1 \times 10^{-2}$).

c. Composite Reservoir ($\eta_r = 1 \times 10^{-1}$).

d. Composite Reservoir ($\eta_r = 1 \times 10^{0}$).

e. Composite Reservoir (all $\eta_r$ cases).

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Type Curve: all $\eta_r$ cases (Tang-Brigham).
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Type Curve Library:
Vertically-Factured Wells

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Well Test Analysis — Fractured Wells

1. Type Curve: \( C_{Df} = \text{various} \), no \( C_D \) cases.

2. Type Curve: \( C_{Df} = 1 \), \( C_D \) = various.

3. Type Curve: \( C_{Df} = 2 \), \( C_D \) = various.

4. Type Curve: \( C_{Df} = 5 \), \( C_D \) = various.

5. Type Curve: \( C_{Df} = 10 \), \( C_D \) = various.

6. Type Curve: \( C_{Df} = 1 \times 10^3 \), \( C_D \) = various.

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Type Curve: Various $C_{fD}$ (Cinco-Samaniego).
"Pseudoradial flow" skin factor correlation for a fractured well (Cinco-Samaniego).
Well Test Analysis — Fractured Wells

Type Curve: $C_{fD}=2$, various $C_{Df}$ cases.
Well Test Analysis — Fractured Wells

- Type Curve: $C_{fD}=1\times10^3$, various $C_{Df}$ cases.

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Pressure Transient Testing  
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(Formation Evaluation and the Analysis of Reservoir Performance)

Module for:
Analysis of Reservoir Performance
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Type Curve Library:
Dual Porosity (Naturally Fractured) Reservoirs

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Well Test Analysis — *Dual Porosity Reservoirs* (1/5)

a. Type Curve: \(\omega, \lambda = \text{various, } pss\) interporosity flow.

b. Type Curve: \(\lambda C_D = 1\times10^{-1}, pss\) interporosity flow.

c. Type Curve: \(\lambda C_D = 1\times10^{-4}, pss\) interporosity flow.

d. Type Curve: \(\omega, \lambda = \text{various, transient}\) interporosity flow.

e. Type Curve: \(\lambda C_D = 1\times10^{-1}\), *transient* interporosity flow.

f. Type Curve: \(\lambda C_D = 1\times10^{-4}\), *transient* interporosity flow.

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Well Test Analysis — *Dual Porosity Reservoirs*  (2/5)

**Type Curve: Pseudosteady-State Interporosity Flow (Onur, et al format).**

*Type Curve for an Unfractured Well in an Infinite-Acting Naturally-Fractured Reservoir with NO Wellbore Storage or Skin Effects.* --Plotting Format From: paper SPE 23830, Onur, M., and Satman, A.: "New Type Curves to Determine Naturally Fractured Reservoir Parameters"
Type Curve: Transient Interporosity Flow (Onur, et al format).

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Type Curve: $\lambda C_D = 1 \times 10^{-4}$, pss interporosity flow.
Type Curve: $\lambda C_D = 1 \times 10^{-4}$, transient interporosity flow.
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Example Case: Pre- and Post-Fracture Buildup Tests

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**Example — Pre-Fracture Buildup Analysis (1/4)**

- **a.** Log-log "pre-analysis" plot ($\Delta t_{ae}$ format) — orientation and identification of flow regimes.

- **b.** Cartesian "early-time" plot — used to analyze wellbore storage ($p_0, C_s$).

- **c.** Semilog "middle-time" plot — used to analyze radial flow behavior ($k, s$).

- **d.** Horner "middle-time" plot — used to analyze radial flow behavior ($k, s$, etc.).

- **e.** Log-log "summary" plot ($\Delta t_a$ format) — summary of all analysis ($C_s, k, s$, etc.).

- **f.** Log-log "summary" plot ($\Delta t_{ae}$ format) — summary of all analysis ($C_s, k, s$, etc.).

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Example — **Pre-Fracture Buildup Analysis** (2/4)

**Example: "Preliminary Analysis"** (log-log).

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Example — Pre-Fracture Buildup Analysis (3/4)

● Example: "Horner Semilog Analysis" (semilog).

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Example — Pre-Fracture Buildup Analysis (4/4)

● Example: "Analysis Summary Plot" (log-log).

Log-Log Plot (Full Test History)
(Dunn Pre-Fracture Treatment Pressure Buildup Example)

Legend: Mid-Ccontinent Gas Well
(Pre-Fracture Buildup)
- $\Delta p_p = p_{pws} - p_{pwf}$ ($\Delta t=0$), psi
- $\Delta p_p = \Delta t_{ae} \left| \frac{d(p_{pws})}{d\Delta t_{ae}} \right|$, psi

Analysis Results
- $k = 1.57$ md
- $s = 92$
- $C_{D1} = 131.96$ (0.014 RB/psi)
- $C_{D2} = 216.8$ (0.023 RB/psi)
- $I_{Dchf} = 1761$ (0.145 hr)

Effective Pseudotime, $\Delta t_{ae} = \Delta t_a / (1 + \Delta t_a / t_p)$, hours ($t_p = 64$ hr)
Example — *Post-Fracture Buildup Analysis* (1/5)

a. Log-log "pre-analysis" plot ($\Delta t_{ae}$ format) — orientation and identification of flow regimes.

b. Cartesian "early-time" plot — used to analyze wellbore storage ($p_0$, $C_s$).

c. Semilog "middle-time" plot — used to analyze radial flow behavior ($k$, $s$).

d. Horner "middle-time" plot — used to analyze radial flow behavior ($k$, $s$, etc.).

e. "Type curve" plot ($\Delta t_{ae}$ format) — summary of all analysis ($C_{Dh}$, $k$, $x_r$, $C_{ID}$).

f. Log-log "summary" plot ($\Delta t_{ae}$ format) — summary of all analysis ($C_{Dh}$, $k$, $x_r$, $C_{ID}$).

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Example — *Post-Fracture Buildup Analysis* (2/5)

- Example: "Preliminary Analysis" (log-log).

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Example — **Post-Fracture Buildup Analysis** (3/5)

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**Horner Plot (Radial Flow—Includes Rate History)**

(Dunn Post-Fracture Treatment Pressure Buildup Example)

**Legend:** Mid-Continent Gas Well

**Middle Time Linear Trend**

- **Data for Dunn Example:**
  - Fluid Properties:
    - $B_o=0.6052$ RB/MSCF
    - $k_o=0.0345$ cp
    - $c_m=9.55 \times 10^{-5}$ psia$^{-1}$
  - Formation Properties:
    - $r_o=0.33$ ft
    - $h=56$ ft
    - $\phi=0.095$ (fraction)
  - Production Parameters:
    - $p_{wp}(t_f)=2535.2$ psia
    - $t_f=2130$ hr
    - $q=10,500$ MSCF/D
  - Analysis Results:
    - $k = 1.57$ md
    - $x_f = 151.61$ ft
    - $C_{ID} = 5.0$
    - $C_{DF} = 1 \times 10^{-3}$

---

- $p_p^* = 3307.6$ psia
- $p_{ws} = 3307.6 - 233.9 \log [(t_p + \Delta t_a) / \Delta t_a]$ ($p_{ws,1hr} = 2529$ psia)

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● Example: "Horner Semilog Analysis" (semilog).

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Example — Post-Fracture Buildup Analysis (4/5)

Type Curve Analysis—Wellbore Storage and Skin Effects Model (Fractured Well)
(Dunn Post-Fracture Treatment Pressure Buildup Example)

- Example: "Type Curve Plot" (log-log).

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Example — *Post-Fracture Buildup Analysis* (5/5)

- Example: "Analysis Summary Plot" (log-log).

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Module for:
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Comment

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Well Test Analysis — **Scaling**

- Pressure transient analysis "sees" the reservoir as a volume-averaged set of properties.
- New solutions/models will also have this view of the reservoir — but, quantifying heterogeneity may (or may not) be possible by the analysis of pressure transient test data.
- Scaling will remain a major issue — regardless of the mechanism used to analyze reservoir performance.

*From: Simulator Parameter Assignment and the Problem of Scaling in Reservoir Engineering — Halderson (1986).*

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End of Presentation

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References: *Pressure Transient Testing*

Text/References:


General:

1. Course Notes for PETE 324, Well Performance Analysis, Texas A&M U., College Station, TX (http://pumpjack.tamu.edu/~t-blasingame/P324_reference/).

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