Module for:
Analysis of Reservoir Performance

Pressure Transient Testing

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Pressure Transient Testing

● Orientation — This module focuses on familiarization with deliverability tests and the analysis and interpretation 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.
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 \( p_i \).

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

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

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

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

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

\[
q_{sc} = C \left( \bar{p}_R - p_{wf} \right)^n = C(\Delta p)^n
\]

where

- \( q_{sc} \) = flow rate at standard conditions, MMscfd
- \( \bar{p}_R \) = average reservoir pressure obtained by shut-in of the well to complete stabilization, psia
- \( p_{wf} \) = flowing sandface pressure, psia
- \( \Delta p \) = \( \bar{p}_R - p_{wf} \)
- \( C \) = a coefficient which describes the position of the stabilized deliverability line
- \( n \) = an exponent which describes the inverse of the slope of the stabilized deliverability line.

a. Basic "pressure-squared" relation that is presumed to describe gas flow — analogous form can be derived from steady-state flow theory (Darcy's law).

\[
\Delta \bar{p} = \bar{p}_R - \bar{p}_{wf} = a' q_{sc} + b' q_{sc}^2
\]

where

- \( a' q_{sc} \) = pressure-squared drop due to laminar flow and wellbore effects
- \( b' q_{sc}^2 \) = pressure-squared drop due to intermittent-turbulent flow effects.

\[
\Delta \bar{p} = \bar{p}_R - \bar{p}_{wf} = a q_{sc} + b q_{sc}^2
\]

where

- \( \bar{p}_R \) = pseudo-pressure corresponding to \( \bar{p}_R \)
- \( \bar{p}_{wf} \) = pseudo-pressure corresponding to \( p_{wf} \)
- \( a q_{sc} \) = pseudo-pressure drop due to laminar flow and well conditions
- \( b q_{sc}^2 \) = pseudo-pressure drop due to inertial-turbulent flow effects.

c. Traditional "deliverability" plot — probably derived from empirical plotting of data.

d. Modified "deliverability" plot — note that \( b q_{sc}^2 \) must be known (... need alternative approach).
Deliverability Testing — 4-Point Tests

- Basic deliverability test analysis — note the difference in the simplified and "LIT" cases.

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

**Discussion:**
- The value "value" of deliverability tests is in the process — the data can be be more effectively analyzed as "well test data" than as deliverability data. However, deliverability analysis can serve as a quality control (data checking).
Isochronal Test Analysis — Note the multiple trends.

\[ \frac{\Delta p}{q} = \frac{p_p(P_0) - p_p(P_w)}{q} = a_t + bq \]

\[ a_t = \frac{1.422 \times 10^6 T}{k_s h} \left( \frac{r_d}{r_w} \right)^{3/4} + s \]

\[ b = \frac{1.422 \times 10^6 D_T}{k_s h} \]

\[ r_d = \sqrt{\frac{k_s f}{377 \phi \mu_c c_i}} \]
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

$c_{sf}/c_{wf}$ : 0.46

$\alpha_D$ : 469

Total Skin Factor, $s'$ : 5.71

Mechanical Skin Factor, $s$ : 2.86

Non Darcy Coefficient, $D$ : $5 \times 10^{-5}$ (MSCF/day)$^{-1}$

Permeability-Thickness, $kh$ : 6170 md-ft

Permeability, $k$ : 9.49 md

Mobility, $k/\mu$ : 233 md/cp

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

(04 December 2002)
**Well Test Analysis — "Well Interference"**

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**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.

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**Discussion:**

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

a. Log-log "preliminary analysis" plot — wellbore storage and radial flow ($C_s$, $k$).

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 ($k$, $s$, $p^*$).

e. Cartesian "Arps" plot — used to estimate average reservoir pressure.

f. Log-log "summary" plot — summary of all analysis ($C_s$, $k$, $s$, $A$, etc.).
Well Test Analysis — Basic Plots (1)

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

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Well Test Analysis — Basic Plots (2)

Example: "Horner Semilog Analysis" (semilog).
Well Test Analysis — Basic Plots (3)

Log-log Summary Plot -- Lee Text Example 2.2
(Including Simulated Performance)

Data for Lee Example 2.2:
Reservoir Properties:
- \( c = 17.0 \times 10^{-6} \) psia\(^{-1} \)
- \( r_w = 0.198 \) ft
- \( h = 69 \) ft
- \( q = 0.039 \) (fraction)

Oil Properties:
- \( B_o = 1.136 \) RB/STB
- \( \mu_o = 0.8 \) cp

Production Parameters:
- \( q_o = 250 \) STB/D
- \( t_p = 13,630 \) hrs
- \( P_w(\Delta t = 0) = 3534 \) psia

Average Pressure Estimates:
- \( p_{avg} \) Muskat (1 term) = 4408.5 psia
- \( p_{avg} \) Muskat (2 term) = 4408.9 psia
- \( p_{avg} \) RHM(reg) = 4422.8 psia
- \( p_{avg} \) MBH (Lee text) = 4411.0 psia

Results for Lee Text Example 2.2:
- \( k = 7.65 \) md (forced)
- \( s = 5.79 \)
- \( C_o = 5626 \) (Cde\(^{0.6} = 6 \times 10^6 \))
- \( A = 139.7 \) acres (Well Centered in a Square)

Example: "Analysis Summary Plot" (log-log).
Well Test Analysis — Work Relations

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:
\[ \phi = 0.039 \]
\[ r_w = 0.198 \text{ ft} \]
\[ c_t = 17 \times 10^{-6} \text{ psi}^{-1} \]
\[ h \text{ } = 69 \text{ ft} \]

Oil properties:
\[ B_o = 1.136 \text{ RB/STB} \]
\[ \mu_o = 0.8 \text{ cp} \]

Production parameters:
\[ p_{wfb} (\Delta t = 0) = 3534 \text{ psia} \]
\[ q_o = 250 \text{ STB/D} \]
\[ t_p = 13,630 \text{ hr} \]

Test Data and Data Functions:

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Graphical Analysis
(Example 2.2, Lee Text (1st edition))

- Early Time Cartesian Analysis: \( p_{ws} \) is plotted versus \( \Delta t \)
  \[ C_s = \frac{q_{sur} B_o}{24 m_{wbs}} \]
- "Horner" relations: \( p_{ws} \) is plotted versus \( \log \left( \frac{t_p + \Delta t}{t_p} \right) \)
  \[ s = 1.1513 \left( \frac{p_{ws,1hr} - p_{wfb}}{m} \right) - \log \left( \frac{k}{q_{tar} \mu_o} \right) + 3.2275 \]
- "MDH" relations: \( p_{ws} \) is plotted versus \( \log (\Delta t) \)
  \[ k = 162.6 \frac{q_{B_i}}{m h} \]
  \[ s = 1.1513 \left( \frac{p_{ws,1hr} \Delta t}{m} \right) - \log \left( \frac{k}{q_{tar} \mu_o^2} \right) + 3.2275 \]
- "Modified Muskat" plotting functions: \( p_{ws} \) is plotted versus \( \frac{d}{d \Delta t} \left[ p_{ws} \right] \) to determine \( \tilde{p} \)
  - "Modified Muskat" Pressure Equation:
    \[ \tilde{p} = \frac{p_{ws} - \tilde{p}}{\frac{d}{d \Delta t} \left[ p_{ws} \right]} \]
  - "Modified Muskat" Pressure Derivative Equation:
    \[ \frac{d}{d \Delta t} \left[ p_{ws} \right] = - a \tilde{p} \frac{e^{\left[-b \Delta t\right]}}{\Delta t} \]
  - "Modified Muskat" Plotting Relation:
    \[ p_{ws} = \tilde{p} - \frac{d}{d \Delta t} \left[ p_{ws} \right] \]

● Given data — Lee text (1st edition), Example 2.2.
● Working relations — Lee text (1st edition), Example 2.2.

(04 December 2002)
a. Type Curve: Radial flow with wellbore storage and skin effects ($p_{Dr}$, $p_{Dd}$).

b. Type Curve: Radial flow with wellbore storage and skin effects ($p_{Dr}$, $p_{Dd}$, $p_{Dr1}$).

c. Type Curve: Radial flow with wellbore storage and skin effects ($p_{Dr}$, $p_{Dd}$).

d. Type Curve: Radial flow with wellbore storage and skin effects ($p_{Dr}$, $p_{Dd}$).

e. Type Curve: Radial flow with wellbore storage and skin effects ($p_{Dh}$, $p_{Ddh}$, $p_{Dir}$).

f. Type Curve: Radial flow with wellbore storage and skin effects ($p_{Dh}$, $p_{Dir}$).
Type Curve: "Gringarten-Bourdet" ($p_D$, $p_{Dd}$).
Well Test Analysis — *WBS Type Curves (2)*

- **Type Curve:** "Second Derivative) \((p_D, p_{Ddd})\).
Well Test Analysis — WBS Type Curves (3)

- Type Curve: "Integral Functions" ($\rho_{Di}$, $\rho_{Did}$).

(04 December 2002) 

PETE 689 (02C) — Pressure Transient Testing 

Well Test Analysis — Bounded Reservoir

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 ($p_{Did}$).

(04 December 2002)  PETE 689 (02C) — Pressure Transient Testing  Slide — 18
Type Curves for Sealing Faults
(Infinite-Acting Homogeneous Reservoir)

- **Type Curve:** "Sealing Faults" ($p_{Dd}$).
Well Test Analysis — Bounded Reservoir (2)

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

- **Model Legend:** Vertical Well in a Rectangular Homogeneous Reservoir
Well Test Analysis — Composite Systems

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

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

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

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

e. Composite Reservoir (all $\eta$ cases).
Type Curve for Well in a Radial Composite Reservoir (All $\eta_r$ Cases)
(Infinite-Acting Homogeneous Reservoir)

Solution from:

Variables:
- $R_{1D} = r_i / r_w = 500$
- $\eta_r = \alpha f$
- $\phi = (\phi C_1) / (\phi C_2)$
- $\lambda = (k_r / \mu_1) / (k_r / \mu_2)$

Legend:
- $\eta_r = 1$
- $\eta_r = 1 \times 10^{-1}$
- $\eta_r = 1 \times 10^{-2}$
- $\eta_r = 1 \times 10^{-3}$

● Type Curve: all $\eta_r$ cases (Tang-Brigham).

(04 December 2002)  P E T E 6 8 9 ( 0 2 C ) — P r e s s u r e T r a n s i e n t T e s t i n g  S l i d e — 2 2
Well Test Analysis — Fractured Wells

a. Type Curve: $C_{ID} =$ various, no $C_{DI}$ cases.

b. Type Curve: $C_{ID} =$1, $C_{DI} =$ various.

c. Type Curve: $C_{ID} =$2, $C_{DI} =$ various.

d. Type Curve: $C_{ID} =$5, $C_{DI} =$ various.

e. Type Curve: $C_{ID} =$10, $C_{DI} =$ various.

f. Type Curve: $C_{ID} =$1$x10^3$, $C_{DI} =$ various.

(04 December 2002)
Well Test Analysis — *Fractured Wells* (1)

- **Type Curve**: Various $C_{FD}$ (Cinco-Samaniego).

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(04 December 2002)
"Pseudoradial flow" skin factor correlation for a fractured well (Cinco-Samaniego).

Data From:
Well Test Analysis — Fractured Wells (3)

- Type Curve: $C_{fD}=2$, various $C_{Df}$ cases.
Well Test Analysis — Fractured Wells (4)

Type Curve: $C_{fD}=1 \times 10^3$, various $C_{Df}$ cases.
**Well Test Analysis — Dual Porosity Reservoirs**

**Pseudosteady-State Interporosity Flow**

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

**Transient Interporosity Flow**

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

- **Type Curve:** \( \lambda_{C_{D}} = 1 \times 10^{-4}, \) **pss** interporosity flow.

- **Type Curve:** \( \lambda_{C_{D}} = 1 \times 10^{-1}, \) **pss** interporosity flow.

- **Type Curve:** \( \lambda_{C_{D}} = 1 \times 10^{-4}, \) **transient** interporosity flow.

- **Type Curve:** \( \lambda_{C_{D}} = 1 \times 10^{-1}, \) **transient** interporosity flow.

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(04 December 2002)  
**PETE 689 (02C) — Pressure Transient Testing**  
Slide — 28
Type Curve: Pseudosteady-State Interporosity Flow (Onur, et al format).
Well Test Analysis — Dual Porosity Reservoirs (2)

Type Curve: Transient 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: $\lambda C_D = 1 \times 10^{-4}$, pss interporosity flow.
Type Curve: $\lambda C_D = 1 \times 10^{-4}$, transient interporosity flow.
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).
(Formation Evaluation and the Analysis of Reservoir Performance)

Module for:
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End of Presentation

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