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Performance-Based Reservoir Characterization – State-of-the-Technology

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Lecture materials located at:
link → http://www.pe.tamu.edu/blasingame/data/
folder → z_SPE_DL
Q. What is "Performance-Based Reservoir Characterization?"
A. In the context of this lecture, "Performance-Based Reservoir Characterization" is the diagnosis, analysis, and interpretation of production data taken from an individual well — and the integration of the results of this analysis with other forms of data (e.g., petrophysical data, results of well test analysis, geological data, etc.).
Prelude: Guidelines for Production Analysis

- **Guidelines: Performance-Based Reservoir Characterizations**
  - **REVIEW** production data for consistency (allocations, accuracy, etc.).
  - **REVIEW** well history, particularly recompletions/stimulations.
  - **GATHER/CORRELATE** petrophysical data (core, logs, etc.).
  - **PERFORM** simplified analysis of production data (Arps, EUR, etc.).

- **REVIEW** measured rate/pressures (quality check).
- **PERFORM** model-based analysis of production (and well test) data.

- **INTEGRATE** results at different scales (without reservoir simulation).
Primer: Reservoir Engineering

"Ok, now what?"

Darcy's Law:

\[ q = (-) \frac{1}{141.2} \frac{kh}{\mu B} \left[ r \frac{\partial p}{\partial r} \right] \]

Oil Material Balance Eq.: \((p > p_b)\)

\[ \bar{p} = p_i - \frac{1}{N_{C_t}} \frac{B_o}{B_{oi}} N_p \]

Oil Diffusivity Eq.: \((p > p_b)\)

\[ \frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} = \frac{1}{0.0002637} \frac{\phi \mu c_t}{k} \frac{\partial p}{\partial t} \]

Oil Pseudosteady-State Flow Eq.: \((p > p_b)\)

\[ \bar{p} = p_{wf} + 141.2 \frac{\mu o B_o}{kh} \left[ \frac{1}{2} \ln \left( \frac{4}{e^y} \frac{1}{C_A} \frac{A}{r_w^2} \right) + s \right] q_o \]

Q. What do I need to know for reservoir engineering ... ?
A. All you need is ... Darcy's law and material balance.

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Performance-Based Reservoir Characterization — State-of-the-Technology
Q. How is PA like Child Psychology?
A. You always learn something (about you) that you don't like.
Orientation: *Production Analysis (PA) Data*

Logarithmic Flowrate and Cartesian Pressure Versus Production Time
(Mid-Continental (US) Gas Well)

Q. **What is Production Analysis (PA)?**

A. Combined analysis of rate and flowing bottomhole pressure data.
Q. Does material balance time function correctly? (use an example)
A. Typical low productivity gas well example (mid-Continent US).
Q. History of Production Analysis (PA)?

A. Various "historical" stages — see below:

- **PA up to 1970?** (estimate reserves, maximum rate, and future rates)
- **PA 1970-1990?** (estimate reservoir properties — simple models \(p_{wf}=\text{con}\))
- **PA 1990-2000?** (estimate reservoir properties — general \(q\) and \(p_{wf}\) profiles)
- **PA 2000-?** (interactive diagnosis, analysis-by-modelling, and forecasting)
**Q. "Rate-Time" Plot: log($q_o$) versus $t$?**

**A. Base "performance" plot for PA.**

(1 min)


**Hyperbolic Trend:**

$$q_o = q_{oi}(1+bD_it)^{1/b}$$

**Exponential Trend:**

$$q_o = q_{oi} \exp(-D_it)$$

**History: Production Analysis (PA) — $q(t)$**
Q. What is an Estimated Ultimate Recovery (or EUR) plot?
A. Plot $q(t)$ vs. $N_p$, extrapolate to zero rate using a straight line $((EUR)_{exp})$. 

Q. What is an Estimated Ultimate Recovery (or EUR) plot?
A. Plot $q(t)$ vs. $N_p$, extrapolate to zero rate using a straight line $((EUR)_{exp})$. 

T.A. Blasingame  Performance-Based Reservoir Characterization — State-of-the-Technology
Review of Arps' Equations: (Hint: listen, don't look)

**Case** | **Rate Relation** | **Cumulative Relation**
--- | --- | ---
**Exponential: (b=0)** | \( q = q_i \exp(-D_i t) \) | \( N_p = \frac{q_i}{D_i} [1 - \exp(-D_i t)] \)
**Hyperbolic: (0<b<1)** | \( q = \frac{q_i}{(1 + bD_i t)^{(1/b)}} \) | \( N_p = \frac{q_i}{(1 - b)D_i} \left[ 1 - (1 + bD_i t)^{1 - (1/b)} \right] \)
**Harmonic: (b=1)** | \( q = \frac{q_i}{(1 + D_i t)} \) | \( N_p = \frac{q_i}{D_i} \ln(1 + D_i t) \)

**Arps' observations:**
- \( b=0 \) — Reservoir is highly undersaturated (\( p>p_b \)).
- \( b=0 \) — Gravity drainage and no free surface.
- \( b=0.5 \) — Gravity drainage with free surface.
- \( b=0.667 \) — Soln. gas-drive reservoir (\( \bar{p} \) vs. \( N_p \) → linear).
- \( b=0.333 \) — Soln. gas-drive reservoir (\( \bar{p}^2 \) vs. \( N_p \) → linear).

**Based on What Theory???

**Loss Ratio:**
\[
 a \equiv \frac{1}{D} \equiv -\frac{q}{dq/dt}
\]

**Loss Ratio Derivative:**
\[
 b \equiv \frac{d}{dt} [a] = \frac{d}{dt} \left[ \frac{1}{D} \right] = -\frac{d}{dt} \left[ \frac{q}{dq/dt} \right]
\]

**Empirical!**

Q. Theory for Arps' equations?

A. Arps derived exponential and hyperbolic equations from loss ratio.
Q. What is the "Fetkovich" Decline Type Curve, and how is it used?
A. A composite of analytical ($p_{wf}=$con) and empirical (Arps) solutions — used as a "type curve" (data overlay) to estimate reservoir properties.

Exponential model:

\[ q = q_i \exp(-D_i t) \]

Hyperbolic model:

\[ q = \frac{q_i}{(1 + bD_i t)^{(1/b)}} \]

- **b-values**
  - $b=0$: $p_{wf}$ = constant
  - $b=1$: $q_o$ = constant ($q_o/\Delta p$ formulation).
  - $b>1$: transient flow or external drive energy.
Q. What is the "Carter" Decline Type Curve, and how is it used?
A. A numerically-generated gas rate solution ($p_{wf}=$con) — used as a "type curve" (data overlay) to estimate reservoir properties.
Modern PA: Orientation

"Modern production analysis (PA) is a mature and functional process — but we have to recognize that these methods may make us overconfident in our abilities to diagnose, interpret, and analyze a particular field data case."

Blasingame

Q. What are the major advances in PA?

A. Various "advances" — see below:
   - Variable $q$/variable $p_{wf}$ analysis methods.
   - Auxiliary plotting functions to improve analysis.
Modern PA: Material Balance Time (Application)

\[ \bar{t} = \frac{N_p}{q_o} \]
\[ \frac{\Delta p}{q_o} = b_{o,pss} + m_{o,pss} \bar{t} \]
\[ \frac{q_o}{\Delta p} = \frac{1}{b_{o,pss} + m_{o,pss} \bar{t}} \]

Q. Application of material balance time?
A. Requires pressure and rate histories (accurate rates essential).

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Modern **PA**: Auxiliary Plotting Fcns (Appl. 1)

\[
\bar{i} = \frac{N_p}{q_o} \\
\left[ \frac{\Delta p}{q_o} \right]_d = \bar{i} \frac{d}{dt} \left[ \frac{\Delta p}{q_o} \right] \\
\left[ \frac{\Delta p}{q_o} \right]_i = \frac{1}{\bar{i}} \int_0^t \left[ \frac{\Delta p}{q_o} \right] dt \\
\left[ \frac{\Delta p}{q_o} \right]_{id} = \bar{i} \frac{d}{dt} \left[ \frac{\Delta p}{q_o} \right]
\]

Rate Normalized Pressure Drop Functions Versus Material Balance Time (Log-Log Format)

Exploration Well — Southeast Asia

**Legend:**
- \((\Delta p/q_o)\), psi/STB/D (base function)
- \((\Delta p/q_o)_d\), psi/STB/D ("derivative")
- \((\Delta p/q_o)_i\), psi/STB/D ("integral")
- \((\Delta p/q_o)_{id}\), psi/STB/D ("integral derivative")

**Q. Application 1 — What is the "Normalized Productivity Index" plot?**
**A. Pressure drop auxiliary functions versus material balance time.**
Q. Application 2 — What is the "Blasingame" plot?

A. Rate auxiliary functions versus material balance time.
**Modern PA: Palacio Type Curve (Con. \( p_{wf} \) case)**

\[
q_{o,i} = \frac{1}{t} \int_0^t q_o \, dt \\
q_{o,id} = t \left[ \frac{d}{dt} q_{o,i} \right]
\]

"Palacio" Rate Function Type Curve (SPE 25909) — \( t_{Dd} \) Format
(Unfractured Well Centered in a Bounded Circular Reservoir)

Q. Enhancement of the functions on the original Fetkovich type curve?
A. "Palacio" type curve uses auxiliary rate functions (better resolution).

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*Performance-Based Reservoir Characterization — State-of-the-Technology*
Modern PA: *Doublet Type Curve (Con. Rate Eq.)*

\[
\bar{t} = \frac{N_p}{q_o} \left[ \frac{q_o}{\Delta p} \right]_{i} = \frac{1}{\bar{t}} \int_{0}^{\bar{t}} \left[ \frac{q_o}{\Delta p} \right] d\bar{t} = \bar{t} \left[ \frac{d}{d\bar{t}} \left[ \frac{q_o}{\Delta p} \right] \right]_{i}
\]

"Doublet" Rate Function Type Curve (SPE 28688) — \(t_{Dd,\text{bar}}\) Format
(Unfractured Well Centered in a Bounded Circular Reservoir)

Q. Type curve solution for variable-rate/variable pressure case?
A. "Doublet" type curve uses material balance time function.
Q. What is the "Normalized Productivity Index" plot (and how is it used)?

A. This is pressure transient analysis (PTA) analog analysis plot.
Q. What is the "Blasingame" plot (and how is it used)?
A. This is the decline curve analysis plot (i.e., modern Fetkovich plot).

Modern PA: "Blasingame" Plot

\[ \bar{t} = \frac{N_p}{q_o} \left[ \frac{q_o}{\Delta p} \right]_i = \frac{1}{t} \int_0^t \left[ \frac{q_o}{\Delta p} \right] dt \]

Type Curve for Dimensionless Rate Integral-Derivative (\(q_{Dd, id}\)) — \(t_{Dd, bar}\) Format

Various Reservoir Models and Well Configurations (as noted)

Legend: \(q_{Dd, id}\) vs. \(t_{Dd, bar}\)
- Unfractured Well (Radial Flow, \(r_e D = 1 \times 10^4\))
- Fractured Well (\(r_e D = 1 \times 10^3, F_{CD} = 5\))
- Fractured Well (\(r_e D = 1 \times 10^3, F_{CD} = \infty\))
- Fractured Well (\(r_e D = 1 \times 10^3, F_{CD} = 5\))
- Horizontal Well (\(L_D = 3, L/(2x_a) = 1.0\))
- Horizontal Well (\(L_D = 25, L/(2x_a) = 1.0\))

Q. What is the "Blasingame" plot (and how is it used)?
A. This is the decline curve analysis plot (i.e., modern Fetkovich plot).
Modern PA: Analysis-by-Modelling

- **Variable-rate case:**
  \[ p = p_i - 141.2 \frac{B \mu}{kh} \sum_{j=1}^{n} (q_j - q_{j-1}) p_{SD,cr} (t_D - t_D, j-1) \]

- **Variable pressure drop case:**
  \[ q = \frac{1}{141.2} \frac{kh}{B \mu} \sum_{j=1}^{n} (p_i - p_{wf,j}) q_{D,cp} (t_D - t_D, j-1) \]

**Approach:**

1. **ASSEMBLE:** Time-pressure-rate (TPR) data.
2. **PERFORM:** Quality control (particularly on pressure data).
3. **ESTABLISH:** Initial reservoir model using normalized PI/Blasingame plots.
4. **GENERATE:** Rate data + model → \( p_{wf}(t) \); pressure data + model → \( q(t) \)
5. **GENERATE:** Forecast of production and/or pressure performance.

**Q. What is "Analysis-by-Modelling"?**

**A. Interactive (dynamic) analysis using a specified reservoir model.**
Modern PA: Analysis-by-Modelling (Oil Case)

"Base Data" Plot:

Oil Flowrate and Wellbore Flowing Pressure Versus Time (Cartesian Format)
Exploration Well — Southeast Asia

Q. What is the analysis procedure for an oil case?
A. Assemble TPR data, check data, initialize model, refine, forecast.

"Data Check" Plot:
Modern PA: Analysis-by-Modelling (Oil Case)

"Normalized PI" Plot:

"Blasingame" Plot:

Q. Behavior of "normalized PI" and "Blasingame" plots for this case?
A. Both plots perform EXTREMELY well → driven by data quality.
Modern **PA: Analysis-by-Modelling (Oil Case)**

**Q. Performance of final model match? (i.e., rate and pressure functions)**

**A. Extraordinary agreement of model and data → data quality ...**
Modern **PA: Analysis-by-Modelling (Gas Case)**

**"Base Data" Plot:**

Production Data Analysis Plot for East Texas Gas Well
"Summary" History Plot — Rate and Pressure Functions

- **Legend:**
  - Red circles: $q_g$ Production Data
  - Blue triangles: $P_W$ Production Data (measured surface/converted bottomhole)
  - Green line: $P_{WS}$ Well Test Data (measured bottomhole)

**"Data Check" Plot:**

- **Legend:**
  - Blue circles: $P_{WS}$ Measured (well test data)

**Step 1: Data Review**

**Q. Analysis-by-modelling for gas cases?**

**A. Same general procedure...**
**Modern PA: Analysis-by-Modelling (Gas Case)**

"Normalized Productivity Index" Plot: (Gas)

**Q. Behavior of "normalized PI" and "Blasingame" plots for this case?**

**A. Both plots perform VERY well → data quality.**
Modern PA: Analysis-by-Modelling (Gas Case)

Q. How well can a gas case be modeled?
A. Depends on the data — can be excellent...

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Step 3: History Match

Modern PA: Analysis-by-Modelling (Gas Case)

Production Data Analysis Plot for East Texas Gas Well
"Summary" History Plot — Rate and Pressure Functions

Legend: East Texas Gas Well
- $q_g$ Data Function
- $\rho_{wf}$ Data Function
- $q_g$ Model Response
- $\rho_{wf}$ Model Response

Analysis Results: East Tx Gas Well
(Bounded Circular Reservoir Case)
- $k = 0.0554$ md
- $x_f = 290$ ft
- $F_{CD} = 9.52$ (dimensionless)
- $G = 1.586$ BSCF
- $r_e = 339$ ft

Q. How well can a gas case be modeled?
A. Depends on the data — can be excellent...

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Performance-Based Reservoir Characterization — State-of-the-Technology

Step 3: History Match
Q. **Analysis of individual pressure transient tests?**

A. **Should be easy — very careful data acquisition is required.**
Summary: Production Analysis (PA)

"The future looks familiar ... We should be able to perform continuous reservoir monitoring using production analysis (PA). The theory and tools are well-established — the trick is vigilant data acquisition and quality control"

Blasingame

Q. Status check for PA?
A. Theory, tools, future of PA summarized below:
   - PA Theory? (variable \( q \)/variable \( p_{wf} \) analysis methods proven)
   - PA Tools? (software products are robust and easy to use)
   - PA Future? (better acquisition, numerical models, continuous analysis)
Q. What are the problems of pressure data related to PA?

A. Put simply – pressure data (quality/quantity) remain weakest link.

- **Reality**: All pressure data are suspect. (review ALL pressure data)
- **Fantasy**: Pressure at bottomhole conditions. \( p_{tf} \rightarrow p_{wf} \) conversion issue
- **Future**: \( p_{wf} \) (bottomhole measurements) common. (rate becomes issue)
Summary: Production Analysis (PA) — Rates

Rate and Cumulative Production Comparison:

Q. What are the problems of flowrate data related to PA?
A. Flowrate data — beware of allocations/frequency of measurements.

- **Reality**: Rates are generally better than pressures. (allocations!)
- **Fantasy**: Rates measured at high frequency. (rate-pressure mismatch)
- **Future**: Downhole flowrate measurement. (continuous analysis)

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"Technology ... is a queer thing. It brings you great gifts in one hand, and it stabs you in the back with the other."  
C.P. Snow (1905-1980)

**Discussion: Current Assessment — Production Analysis (PA)**

- **Analysis?** (Very good tools for PA and PTA (incremental improvements))
- **Modelling?** (Analytical modelling is sufficient, numerical modelling evolving)
- **Data Issues?** (Improvement in data handling (good/bad data, large volumes))
- **Data Acquisition?** (Lack of innovation in testing/monitoring methodologies)
- **Integration?** (Breakthrough to integrate PA/PTA results with other data)
**Current Assessment: PA Reality Check**

Reservoir Engineering Model
- Works 95+ percent of the time...
- Why? *Pressure and volume averaging of reservoir properties.*
- When does it not work? *High contrast in reservoir properties.*

Actual Reservoir Model
- Complex geology.
- Complex fluid behavior.
- Poor lateral (and vertical) continuity.

Q. What is the "reality check" with regard to PA?

A. *IT IS JUST TIME-PRESSURE-RATE DATA — don't expect a miracle...*
   - Reservoir scale issues? (petrophysical data, PTA, PA, seismic data, etc.)
   - Results from PTA/PA? (*"reservoir-scale" flow character*)
   - Key to success? (high precision/frequency reservoir performance data)
Current Assessment: Future Work in PTA/PA

Q. What are the prospects for PTA/PA?

A. Data quality/frequency → reservoir characterization:
- Additional reservoir/well models. (elliptical flow, moving boundary, ...)
- Reservoir scaling for PTA/PA. (scaling of petrophysical data?)
- Handling poor quality rate/pressure data. (major issue at present)
- Continuously measured $p_{wf}$ data. (this is coming ... high frequency rates?)
- Multiple well analysis (integration). (analytical (material balance)/models)
- Coupling of analysis/interpretation (3D/3P models). (over-determined case)
Performance-Based Reservoir Characterization –
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End of Presentation

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Selected References: Production Data Analysis

References — Production Data Analysis:

10. Arps J.P.:

T.A. Blasingame Performance-Based Reservoir Characterization — State-of-the-Technology (Appendix)
Selected Vendors: PA Software

**Vendor A: Fekete**
- **Product:** RTA
- **Contact:** Ed Ferguson (ed@fekete.com)
- **web:** www.fekete.com

**Vendor B: Kappa Engineering**
- **Product:** Topaze
- **Contact:** Kevin Siggery (siggery@kappaeng.com)
- **web:** www.kappaeng.com

**Vendor C: Weatherford/eProduction Solutions**
- **Product:** PanSystem
- **Contact:** Carol Marini (Carol.Marini@e-petroleumservices.com)
- **web:** www.ep-solutions.com
Rules for Life: Blasingame

Simple Rules for Life:

- Righty-tighty — lefty-loosey solves most problems in life.
- You can learn a lot from a Chihuahua (no fear, all love).
- Don't mow the grass until the city tells you to.
- Leadership is not defined by vision, strength, integrity, or courage — JUST PASSION.
- If you have to herd cats, then be a rat.
- If you have to hold yourself out as an example, then make sure to be a bad one (Mark Twain).

Important Rules for Life:

- Always work harder than those you work for.
- Never own anything that eats while you sleep.
- Never own anything that needs repainting.

"An empty stomach is not a good political advisor — moral — know your convictions, but take care of yourself as well"

Mahatma Gandhi (+ Blasingame)
Mathematics: Blasingame
(for reservoir engineering)

1. Cheat (approximate, truncate, etc.). (except for material balance)
2. Take the Derivative.
3. Take the Integral.
4. Take the Laplace Transform.
5. Go back to Rule 1 (Cheat).

Favorite Numbers:
0, 1, \infty.
(What else do we need?)

Diffusivity Equations for a Black Oil:
- Slightly Compressible Liquid:
\[ \frac{\partial p}{\partial t} + \nabla \cdot \left( \frac{\phi \kappa T}{k} \nabla p \right) = 0 \]
- Slightly Compressible Liquid:
\[ \nabla^2 p = \frac{\phi \kappa T}{k} \frac{\partial^2 p}{\partial t^2} \] (Small \( p \) and \( c \) form)

"Black Oil" Material Balance: \( p > p_b \)
\[ p = p_i - \frac{1}{N_i} N_p \]

"Solution Gas Drive" (Oil) Material Balance: all \( p \)
\[ \frac{\partial}{\partial t} \left[ E_i(z) \right] = \int_{z_{mi}}^{z_{ni}} E_i(z') dt \] (normal \( z \))

Laplace Transforms

- Original Function \( f(t) \)
- Image Function \( F(s) \)
- \[ \int_0^\infty e^{-st}f(t)dt \]

- Inversion Formula
- Linearity Property
- \( A\mathcal{L}(f(t)) + B\mathcal{L}(g(t)) \)
- \( \mathcal{L}(f(t) + g(t)) \)
- \[ \frac{\mathcal{L}(f(t))}{\mathcal{L}(g(t))} \]
- Differentiation
- \[ \mathcal{L}(f'(t)) \]
- \[ \mathcal{L}(f^{(n)}(t)) \]
- \[ (-1)^n f^{(n)}(t) \]
- Integration
- \[ \int_0^\infty F(s)ds \]
- \[ \frac{1}{s} \mathcal{L}(f(t)) \]
- \[ \int_0^\infty f(t)dt \]
- \[ \frac{1}{s} \mathcal{L}(f(t)) \]
- Convolution (Faltung) Theorem
- \[ \int_0^\infty \mathcal{L}(f(t))
\]