Reservoir Engineering Aspects of Unconventional Reservoirs

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Overview

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Overview:

- Brief Biography
- Orientation
- EUR 101:
  - Schematic production plot.
- Perspectives on Production Analysis:
  - Historical aspects.
  - Modern methods.
- Closing Perspectives:
  - Where we are.
  - Big questions.
  - Personal perspectives.
- Reality Check:
  - Nelson — pore/molecule size chart.
  - Loucks — et al shale pore space.
- Questions/Discussions
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Brief Biography — Tom Blasingame

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Short Bio: Blasingame

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June 2011

Short Biography: (suitable for introductions)
Dr. Tom Blasingame is a Professor and he is the holder of the Robert L. Whiting Professorship in the Department of Petroleum Engineering at Texas A&M University in College Station Texas. He holds B.S., M.S., and Ph.D. degrees from Texas A&M University — all in Petroleum Engineering. In teaching and research activities Dr. Blasingame focuses on petrophysics, reservoir engineering, analysis/interpretation of well performance, and technical mathematics.

Dr. Blasingame's research efforts deal with topics in applied reservoir engineering, reservoir modeling, and production engineering. Dr. Blasingame has made numerous contributions to the petroleum literature in well test analysis, analysis of production data, reservoir management, and general reservoir engineering (e.g., hydrocarbon phase behavior, natural gas engineering, inflow performance relations, material balance methods, and field studies). To date (June 2011), Dr. Blasingame has graduated 46 M.S. (thesis), 28 M.Eng. (report, non-thesis), and 10 Ph.D. students, and he has performed several major field studies involving geology, petrophysics, and engineering tasks.

Dr. Blasingame is a member of the Society of Petroleum Engineers (SPE), the Society for Exploration Geophysicists (SEG) and the American Association of Petroleum Geologists (AAPG). Dr. Blasingame is a Distinguished Member of the Society of Petroleum Engineers (2000) and he is a recipient of the SPE Distinguished Service Award (2005), the SPE Uren Award (for technology contributions before age 45) (2006), and he has served as an SPE Distinguished Lecturer (2005-2006). Dr. Blasingame has prepared over 100 technical articles; and he has chaired numerous technical committees and technical meetings. Dr Blasingame also served as Assistant Department Head (Graduate Programs) for the Department of Petroleum Engineering at Texas A&M from 1997 to 2003, and Dr. Blasingame has been recognized with several teaching and service awards from Texas A&M University.
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Orientation

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Orientation: Reservoir Engineering Aspects of UR

Where we want to be: (or so we think)
- **Fit for purpose stimulation** (... oil/gas/condensate/geology)
- **More effective reservoir monitoring** (... this is important!)
- **Early EUR** (... prediction/correlation)
- **Well Spacing** (... geology + PVT + modeling)

How do we get there...
- **Better understanding of flowback/dewatering** (... optimization)
- **Pressure-dependent properties**... (... $k$, $F_cD$, desorption?)
- **Understanding of the pore-scale** (... what flows when/how)
- **Petrophysics** (... conventional petrophysics not adequate)
- **PVT** (... oil/gas/condensate/water — HP/HT)

Facts of life...
- **Analogs** (... need to understand uncertainty (very high))
- **EUR** (... minimum of 6-9 months for high confidence)
- **IP** (... may be uncorrelated with EUR)
- **Early Productivity** (... poor wells don't get better)
- **Time-Rate Analysis** (... not representative? (chaotic operations))
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EUR 101

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Discussion: Schematic Production Performance Plot

- The schematic represents the most common approach to EUR.
- Used CAREFULLY, this may be valid, but more methods needed.

- Estimated Ultimate Recovery (EUR) [The area under the hybrid (hyperbolic-exponential rate curves)]

- "Switch Point" from Hyperbolic to Exponential

- Economic Limit (\(q_{\text{limit}}\)) in rate

- Economic Limit (\(t_{\text{limit}}\)) in time
Reservoir Engineering Aspects of Unconventional Reservoirs

Perspectives on Production Analysis

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**Arps Relations: Base Relations**

**Loss Ratio:**
\[ \frac{1}{D} \equiv - \frac{q_g}{dq_g/dt} \rightarrow q_g = q_i \exp[-D_i t] \]

**Loss Ratio Derivative:**
\[ b \equiv - \frac{d}{dt} \left[ \frac{q_g}{dq_g/dt} \right] \rightarrow q_g = \frac{q_i}{(1 + b D_i t)^{(1/b)}} \]

**Case** | **Rate-Time Relation** | **Cumulative-Time Relation**
--- | --- | ---
*Exponential: (b=0)* | \( q_g = q_i \exp[-D_i t] \) | \( G_p = \frac{q_i}{D_i} [1 - \exp[-D_i t]] \)

*Hyperbolic: (0<b<1)* | \( q_g = \frac{q_i}{(1 + b D_i t)^{(1/b)}} \) | \( G_p = \frac{q_i}{D_i (1 - b) D_i} \left[ 1 - (1 + b D_i t)^{1-(1/b)} \right] \)

*Harmonic: (b=1)* | \( q_g = \frac{q_i}{(1 + D_i t)} \) | \( G_p = \frac{q_i}{D_i} \ln(1 + D_i t) \)

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**Question(s):**
- How were the Arps' rate relations derived?

*The BASIS for the Arps’ relations — i.e., the behavior of the D- and b- parameters, is derived from OBSERVATIONS. These are empirical results.*

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*Analysis of Decline Curves*
J.J. Arps
**Arps' Relations: EUR Plots**

**Question(s):**
- Graphical extrapolations of EUR? Family of "EUR plots" derived from the Arps' exponential and hyperbolic relations. Hyperbolic "EUR plot" requires a modular computing environment (e.g., a spreadsheet), as multiple variables are established simultaneously.

**Case**

**Exponential:** \( b = 0 \)
\[
q_g = q_{gi} - D_i G_p \quad G \equiv \frac{q_{gi}}{D_i}
\]

**Hyperbolic:** \( 0 < b < 1 \)
\[
q_g = q_{gi} \left[ 1 - \frac{G_p}{G} \right] \left( \frac{1}{1-b} \right) \quad G \equiv \frac{q_{gi}}{(1-b)D_i}
\]

**Harmonic:** \( b = 1 \)
\[
q_g = q_{gi} \exp \left[ -\frac{D_i G_p}{q_{gi}} \right]
\]

**Plotting Function**

- \( q_g \) versus \( G_p \)
- \( \log(q_g) \) versus \( \log \left[ 1 - \frac{G_p}{G} \right] \)
- \( \log(q_g) \) versus \( G_p \)

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SPE 98042 (2005)
A Production-Based Method for Direct Estimation of Gas-in-Place and Reserves

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**Arps' Relations**

**EUR Plots**

- **Exponential:** \( b = 0 \)
  \[
  q_g = q_{gi} - D_i G_p \quad G \equiv \frac{q_{gi}}{D_i}
  \]

- **Hyperbolic:** \( 0 < b < 1 \)
  \[
  q_g = q_{gi} \left[ 1 - \frac{G_p}{G} \right] \left( \frac{1}{1-b} \right) \quad G \equiv \frac{q_{gi}}{(1-b)D_i}
  \]

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**Question(s):**
- Graphical extrapolations of EUR? Family of "EUR plots" derived from the Arps' exponential and hyperbolic relations. Hyperbolic "EUR plot" requires a modular computing environment (e.g., a spreadsheet), as multiple variables are established simultaneously.
**Arps' Hyperbolic: Blasingame-Rushing EUR Plot**

**Question(s):**
- Is there a distinctly unique mechanism for establishing the validity of the hyperbolic relation? Yes, the "hyperbolic" decline "type curve" plot yields straight-line trends.

### Hyperbolic Decline: (0<b<1)

\[
q_g = q_{gi} \left[ 1 - \frac{G_p}{G} \right]^{(1-b)} \left[ G = \frac{q_{gi}}{(1-b)D_i} \right]
\]

- a. "Hyperbolic Plot:" (log-log format) — Provides a straight-line for ALL cases.

### Exponential Decline: (b=0)

\[
q_g = q_{gi} - D_i G_p \left[ G = \frac{q_{gi}}{D_i} \right]
\]

- b. "Hyperbolic Plot:" (Cartesian format) — Provides a straight-line ONLY for b=0 case.

**SPE 98042 (2005)**

*A Production-Based Method for Direct Estimation of Gas-in-Place and Reserves*

Decline Type Curve Analysis: *Fetkovich-Carter Type Curve*

**Question(s):**
- Can we perform time-rate analysis using a reservoir model?
  
  Yes, the Fetkovich decline curve (1970's) provides a direct reservoir solution (for $p_{wf}$ = constant).

**Transient Stems:** (left)
- Numerical or analytical model ($p_{wf}$ = constant).
- $q(t)$ is concave up.

**Depletion Stems:** (right)
- $q(t)$ is concave down.
- $b=0$: $p_{wf}$ = con.
- $b=1$: $q_o$ = con. ($q_o/\Delta p$).
- $b>1$: transient flow or external drive energy.
- $\lambda$: numerical gas flow solutions ($\lambda = f(p_{wf}/p_i)$).

**Reservoir Properties:**
- $k$ — y-axis match.
- $G$ — x&y-axis matches.
- $s$ — $r_{eD}$ match.

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**Variables for the Carter Decline Type Curve**

$$t_{Dd} = \frac{q(t)}{kh(p_i - p_{wf})}$$

$$q_{Dd} = \frac{q(t)}{p_{wf}}$$

$$r_{wa} = r_w e^{-\frac{1}{2}}$$

**Arps Rate Type Curves**

$$r_{Dd} = 141.2 \mu_{gi}^2 \frac{r_{eD}}{r_w} \ln \frac{r_e}{r_w} - \frac{1}{2}$$

**Unfractured Well in a Bounded Circular Reservoir**

**Unfractured Well in a Bounded Circular Reservoir**

**Unfractured Well in a Bounded Circular Reservoir**

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*SPEJ (October 1985) 719-728.*

Type Curves for Finite Radial and Linear Gas Flow Systems: Constant Terminal Pressure Case

R.D. Carter, Amoco Production

JPT (June 1980) 1065-1077.

Decline Curve Analysis Using Type Curves

M.J. Fetkovich, Phillips Petroleum
Pseudosteady-State Analysis: Flowing Material Balance Plot

**Question(s):**
- What is the "Flowing Material Balance" plot? In simple terms, $p_{wf}(t)$ data are "converted" to $p_{avg}(t)$ data using the pseudosteady-state flow equation, then plotted as a straight-line extrapolation function and "solved" for gas-in-place.

**"Flowing Material Balance" Plot:**

Example Case 4 — LWF1 Gas Well (SPE 114947)
Normalized Rate-Cumulative Function Plot

- The "Flowing Material Balance" (Normalized Rate-Cumulative Function Plot) formulation is derived using the solution for the diffusivity equation during boundary-dominated flow regime. This formulation provides a direct estimate of the contacted gas-in-place using time, flowing wellbore pressure, and flowrate data.

**Theory:**
- Palacio and Blasingame [1993]
- Mattar and McNeil [1997]
- Agarwal et al [1999]

**Advantages:**
- Straightforward and intuitive.
- Shut-in pressures NOT required.
- Direct estimation of contacted gas-in-place.

**Limitations:**
- Boundary-dominated flow regime must exist.
**Time-Rate-Pressure Analysis: Material Balance Time**

**Question(s):**
- Can the well-reservoir model be inferred from such data? Yes.
- Is diagnosis sufficient? No, we must also be able to model/history match data with a model (complete process).

\[ q_g = \frac{q_{gi}}{(1 + bD_i t)(1/b)} \]

**a.** Raw (daily) rate and pressure data — bottomhole pressures are calculated, note the effect of liquid loading.

**b.** "Transformed" data shows fractured well response at early times, very strong evidence of closed system at late times.

**SPE 25909 (1993)**
Decline Curve Analysis Using Type Curves — Analysis of Gas Well Production Data
J.C. Palacio and T. Blasingame, Texas A&M U.
Question(s):
- Can we use time-rate analysis as a diagnostic? Yes, use $D(t)$ and $b(t)$ functions.
- Differentiation of $q(t)$ data? Intuition is against it — but it is possible with some careful editing and robust differentiation.

SPE 116731 (2008)
Exponential vs. Hyperbolic Decline in Tight Gas Sands — Understanding the Origin and Implications for Reserve Estimates Using Arps’ Decline Curves

PLE Rate Relation:

\[ q(t) \equiv \hat{q}_i \exp[-D_\infty t - \hat{D}_i t^n] \]

Decline Function: $D(t)$

\[ D(t) \equiv -\frac{1}{q} \frac{dq}{dt} \]

\[ \approx D_\infty + n\hat{D}_i t^{-(1-n)} \]

Hyperbolic Function: $b(t)$

\[ b(t) \equiv \frac{d}{dt} \left[ \frac{1}{D(t)} \right] \]

\[ \approx \frac{n\hat{D}_i (1-n)}{[n\hat{D}_i + D_\infty t^{(1-n)}]^2} t^{-n} \]

● Points:
- $b(t)$ and $D(t)$ are evaluated continuously.
- $D(t)$ trend indicates "power-law" behavior.
Modern Decline Analysis: Stretched Exponential Relation

**Question(s):**
- When was the "stretched exponential" model first cited in the Petroleum literature? *Jones (1942) and Arps (1945).*
- Is there a physical representation of the SE model? *Yes, a sum of exponentials.*

**Non-Petroleum Literature:**
- Kohlrausch (1854).
- Decays in random, disordered, chaotic, heterogeneous systems.

**SPE 119369 (2009)**
Assigning Value to Stimulation in the Barnett Shale: A Simultaneous Analysis of 7000 Plus Production Histories and Well Completion Records
P. Valkó, Texas A&M U.

**Modern Decline Analysis**

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**Jones (1942) and Arps (1945)**

\[ q(t) = q_o \exp \left[ -D_o \frac{t^{m-1}}{100(m-1)} \right] \]
**Modern Decline Analysis: Continuous EUR**

**Question(s):**
- How to estimate EUR "continuously"?
- Use "segments" of the time-rate history to evaluate EUR regularly in time.

**SPE 132352 (2009)**
*Continuous Estimation of Ultimate Recovery*
S. Currie, D. Ilk, and T. Blasingame, Texas A&M U.

Continuous EUR (CEUR)

- **a. Continuous EUR (CEUR) process plots.**
  - [Graphs showing different EUR plots over time]
  - EUR = 6.04 BSCF
  - EUR = 3.00 BSCF
  - EUR = 2.55 BSCF

- **b. CEUR hyperbolic, PLE, and q-G_p summary plots.**
  - [Graphs showing hyperbolic and PLE relations]

- **c. CEUR governing equations.**
  - \[ q_g(t) = \dot{q}_i / [(1 + bD_i t)^{(1/b)}] \] [hyperbolic]
  - \[ q_g(t) = \dot{q}_i \exp[-D_x t - \hat{D}_i t^n] \] [PLE]
  - \[ q_g(t) = q_g - D_i G_p \quad [G = q_g / D_i] \] \([q_g(t) \text{ vs. } G_p(t)]\)

- **d. CEUR master summary plot (all results).**
  - [Graph showing summary plots and data points]
Modern Production Analysis: *Integration of Results*

**SPE 140556 (2011)**
Integration of Production Analysis and Rate-time Analysis via Parametric Correlations — Theoretical Considerations and Practical Applications
D. Ilk, DeGolyer and MacNaughton, J.A. Rushing, Apache, and T.A. Blasingame, Texas A&M U.

**Horizontal well with multiple vertical fractures:**

**Power-Law Exponential Relations:**

\[
D(t) \equiv -\frac{1}{q} \int dq \approx D_\infty + n\hat{D}_i t^{-(1-n)}
\]

\[
q(t) = \hat{q}_i \exp[-D_\infty t - \hat{D}_i t^n]
\]
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Closing Perspectives

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Where We Are: Reservoir Engineering Aspects of UR

● What we REALLY know…
  ■ Tight gas is relatively easy (... vertical wells, HP/HT, PVT)
  ■ Gas shales are technically viable as a resource (... economics?)
  ■ Horizontal multi-fractured wells (... (now) taken for granted)

● What we THINK know…
  ■ The fracture geometry is (... planar? complex? who cares?)
  ■ The phase behavior (... can be extremely complex)
  ■ The $p_{tf}$ to $p_{wf}$ conversion(s) (... early-time heavy water load?)

● What we may NEVER know…
  ■ Distribution of natural fractures (... impossible?)
  ■ Transport of gas/liquids in shales (... via organic matter?)

● What we SHOULD KNOW in the near future…
  ■ Duration of data required for EUR (... more is always better)
  ■ Better understanding of phase behavior (... not "conventional")
  ■ Optimal well spacing/orientation/placement (... do this early!)
Big Questions: Reservoir Engineering Aspects of UR

● Estimated Ultimate Recovery (EUR)?
  ■ Early EUR? (... can this be meaningful?)
  ■ EUR = f(t)? (... how do we incorporate this?)
  ■ Well Spacing? (... is this really the holy grail?)

● QUANTIFYING reservoir properties?
  ■ Pressure Transient Analysis (... ultra-low $k$ ... issues?)
  ■ Production Analysis (... $p_{tf}$ may not be sufficient)
  ■ Petrophysical analysis (... theory ≠ application)

● Liquids-Rich Systems?
  ■ Fluid-Flow Mechanisms (... what is really flowing where?)
  ■ PVT (... near-critical fluids are not trivial)
  ■ Improved Recovery (... we all know this is coming)
  ■ Fit-for-Purpose Stimulation (... higher $F_{cD}$, more complexity)
  ■ Artificial Lift (... fact of life)
  ■ Recovery (... low to extremely low primary recovery?)
Personal Perspectives: *Reservoir Engineering Aspects of UR*

**Never-Ending Arguments…**
- SRV (... what is it, really?)
- Desorption (... significance? timing? relevance?)
- Stimulation Fluids (... where does it go? does it matter?)
- Microseismic (... crystal ball, roulette wheel, or roadmap?)
- Pressure-Dependent Whatever (... so what?)
- Natural Fractures (... if/when/why/what?)
- Dual Porosity/Dual Permeability (... what about the physics?)
- Well Placement/Effect of Layering (... when does it matter?)

**Things that *SHOULD* help…**
- Production Logs (... but just a snapshot in time)
- Optimal Proppant Design/Placement (... obvious, but)
- Stimulation Stages/Perforation Clusters (... geology + logs)

**Things that *DEFINITELY WOULD* help…**
- Measured $p_{wf}$ (... yes, this is my favorite song)
- Downhole Fluid Sampling (... sooner or later)
- Horizontal Core (... why not?)
Last Words: *Reservoir Engineering Aspects of UR*

- **EUR:**
  - Time-Rate Analyses (... may not be sufficient)
  - Time-Rate-Pressure Analyses (... requires reservoir model)
  - Constraints (... e.g., 15 years seems reasonable)

- **Reservoir Modeling:** *(i.e., simulators)*
  - Present (... conventional models with modifications)
  - Near-Future (... fundamental flow kinetics, complex geometries)
  - Distant-Future (... pore-scale phenomena, nano-scale PVT, ?)

- **Reservoir Engineering Tools:**
  - Material Balance Methods (... not applicable at reservoir-scale)
  - Pressure Transient Tests (... surprisingly good in cases [need $k$])
  - Production Analysis (... very good in cases [need good $p_{tf}$ data])
  - Reservoir Fluids (... very complex, near-critical liquids)
  - EOR (... not sure where to start — CO$_2$, lean gas, ???)
  - Ad-hoc Tools (... e.g., Linear flow analysis — lack resolution)
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Reality Check

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Reality Check: **Nelson Pore/Molecule Size Chart**

**Question(s):**

- How small are pores in shale gas? *Note that the size of the pores is on the order of 5-10 times the size of the fluid molecule.*

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Nelson Pore/Molecule Size Chart

*Figure 2.* Sizes of molecules and pore throats in siliciclastic rocks on a logarithmic scale covering seven orders of magnitude. Measurement methods are shown at the top of the graph, and scales used for solid particles are shown at the lower right. The symbols show pore-throat sizes for four sandstones, four tight sandstones, and five shales. Ranges of clay mineral spacings, diatomoids, and three oils, and molecular diameters of water, mercury, and three gases are also shown. The sources of data and measurement methods for each sample set are discussed in the text.

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**AAPG Bulletin, v. 93, no. 3 (March 2009)**

*Pore-throat Sizes In Sandstones, Tight Sandstones, and Shales*

P.H. Nelson, USGS
Reality Check: Shale Pore Space (Barnett Example)

Question(s):
- Where is/are the gas/liquid stored? There is porosity, often in the organic materials.
- Why is the phase behavior of many shales "near critical"? Nanopores?

J. Sedimentary Research, v. 79/12 (2009)  
*Morphology, Genesis, and Distribution of Nanometer-scale Pores in Siliceous Mudstones of the Mississippian Barnett Shale*  
Loucks, R.G., R.M. Reed, S.C. Ruppel, and D.M. Jarvie

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**Fig. 6** — Secondary electron images showing variations in nanopore morphology in organic matter.  
A) Very small (18–40 nm diameter), nearly spherical nanopores.  
B) Larger nanopores (50 nm diameter) showing complex internal structure resembling pillars.  
C) Tubule-like pore throats connecting elliptical pores (white arrows).  
D) Additional tubule-like pore throats connecting ellipsoidal pores (white arrows).  

**Fig. 5** — Nanopores associated with organic matter in the Barnett Shale.  
A) Elliptical to complexly rounded nanopores in an organic grain.  
B) Angular nanopores in a grain of organic matter.  
C) Nanopores occurring in aligned crystallized structures.  
D) Nanopores associated with disseminated organic matter.  
Crystal-rich grains are dark gray; nanopores are black.  

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Tom Blasingame — Texas A&M University (06 June 2011)
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End of Presentation

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