Consideration for EUR in Unconventional Reservoirs

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Brief Biography — Tom Blasingame

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Short Bio: Blasingame

● Role:
  — Professor, Texas A&M U.
  — Holder of the Robert L. Whiting Professorship
  — B.S., M.S., and Ph.D. degrees from Texas A&M U. (PETE)

● Counts: (September 2012):
  — 10 Ph.D. Graduates
  — Over 100 Technical Articles

● Honors:
  — Distinguished Member of the Society of Petroleum Engineers (2000)
  — SPE Distinguished Service Award (2005)
  — SPE Distinguished Lecturer (2005-2006)
  — SPE Uren Award (2006)
  — SPE Lucas Medal (2012)

● Current Research Activities:
  — Nano-Scale Flow Phenomena
  — Evaluation of Well Performance Data for Shale/Liquids-Rich Systems
  — Numerical Modeling of Ultra-Low Permeability Reservoir Systems
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Schematic Time-Rate Analysis

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Discussion: *Schematic Production Performance Plot*

- The schematic represents the most common approach to EUR.
- Used *CAREFULLY*, this should be valid (other methods needed).
Time-Rate: Flow Regimes — *Multi-Fracture Horizontal Well*

### Discussion:
- **1:2 Slope** \( \rightarrow b=2 \) (*HIGH* fracture conductivity).
- **1:4 Slope** \( \rightarrow b=4 \) (*LOW* fracture conductivity).
- This is a schematic, *it overly simplifies the system.*
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Conventional Time-Rate Analysis

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Time-Rate: Modified Hyperbolic Rate Relation

Modified Hyperbolic Rate Relation:

\[
q(t) = \begin{cases} 
q_{i,\text{hyp}} & (t < t^*) \\
(1 + bD_i t)^{1/b} & (t > t^*) 
\end{cases}
\]

Decline Function: \(D(t)\)

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

Hyperbolic Function: \(b(t)\)

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

\(\beta\) Function: \(\beta(t)\)

\[\beta(t) = t \frac{1}{q} \left| \frac{dq}{dt} \right| = t D(t)\]

Discussion:

- \(qDb\) functions are DIAGNOSTIC.
- \(D(t)\), \(b(t)\), and \(\beta(t)\) are evaluated continuously (at all points).
- This shale gas case exhibits \(b=2\) behavior \(\rightarrow q = a\sqrt{t}\) (Linear Flow).
- Appears to be "hyperbolic," but this is just the Linear Flow portion.
**Time-Rate: Power-Law Exponential Rate Relation**

**PLE Rate Relation:**

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

**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: \( b(t) \)**

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

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

**\( b \) Function: \( b(t) \)**

\[ \beta(t) \equiv t \left[ \frac{1}{q} \frac{dq}{dt} \right] = t \, D(t) \]

**Discussion:**

- \( qDb \) functions are DIAGNOSTIC.
- Power-law exponential relation is derived from: \( D_\infty + n\hat{D}_i t^{-(1-n)} \)
- No direct analog to hyperbolic case.
- This is a "tight gas" reservoir case.
**Time-Rate: Continuous EUR**

- **Hyperbolic Relation** [focus on \(b(t) = \text{constant}\)]
- **Power-Law Exponential Relation** [focus on \(D(t) = \text{constant}\)]
- **Use \(q_g\) vs. \(G_p\)** [straight line]
  
  Extrapolate late-trend

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**Discussion:**

- EUR is computed at each "time step" (cumulative or incremental).
- EUR estimated for each model.
- EUR comparison plots probably min/max trends.

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### Continuous EUR (CEUR) process plots.

- 50 days
  - EUR = 6.04 BSCF
  - \(G_{p,max} = 0.37\) BSCF

- 250 days
  - EUR = 4.92 BSCF
  - \(G_{p,max} = 1.03\) BSCF

- 2000 days
  - EUR = 3.10 BSCF
  - \(G_{p,max} = 2.58\) BSCF

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### CEUR hyperbolic, PLE, and \(q-G_p\) summary plots.

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### CEUR governing equations.

- **[hyperbolic]**
  \[
  q_g(t) = \frac{q_g}{(1 + b D_i t)^{(1/b)}}
  \]

- **[PLE]**
  \[
  q_g(t) = \hat{q}_g \exp[-D_\infty t - \hat{D}_i t^n]
  \]

- **[q\(_g\) vs. \(G_p\)]**
  \[
  q_g(t) = q_{g_i} - D_i G_p \quad [G = q_{g_i}/D_i]
  \]

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### CEUR master summary plot (all results).

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Emerging Ideas/Tools for Time-Rate Analysis

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Governing Relations: Time-Rate Definitions

- **Time-Rate Analysis: Base Definitions** (Arps, 1945)
  - **Loss Ratio:**
    \[
    \frac{1}{D} = -\frac{q_g}{dq_g/dt}
    \]
  - **Loss Ratio Derivative:**
    \[
    b = \frac{d}{dt} \left[ \frac{1}{D} \right] = -\frac{d}{dt} \left[ \frac{q_g}{dq_g/dt} \right]
    \]
- **Approach:**
  - \(D(t)\) and \(b(t)\) provide diagnostic matching functions (\(qDb\) plots).
  - Diagnostic relations can be used to derive empirical models.
Time-Rate Analysis: *Power Law Exponential*

- **History:**
  - SPE 116731 (Ilk et al., 2008).
  - Derived from data \( D(t) \) and \( b(t) \).
  - Analogous to Stretched-Exponential, but derived independently.
  - Has a terminal term for boundary-dominated flow \( D_\infty \).

- **Governing Relations:**
  - **Rate-Time Relation:**
    \[
    q_g(t) = \hat{q}_g t \exp[-D_\infty t - \hat{D}_i t^n] 
    \]
  - **PLE \( D(t) \) Relation:**
    \[
    D(t) = n\hat{D}_i t^{n-1} + D_\infty 
    \]
  - **PLE \( b(t) \) Relation:**
    \[
    b(t) = -\frac{\hat{D}_i (n-1) nt^n}{[D_\infty t + \hat{D}_i nt^n]^2} 
    \]"
Time-Rate Analysis: Duong Model

● History:
  ■ SPE 137748 (Duong, 2011).
  ■ Based on extended linear/bilinear flow regime.
  ■ Extracted from straight line behavior of $q/G_p$ vs. $t$ (Log-Log) plot.

● Governing Relations:
  ■ Duong Rate-Time relation:
    \[
    q_g(t) = q_g i_t^{−m} \exp \left[ \frac{a}{1−m} (t^{1−m} − 1) \right]
    \]
  ■ Duong $D(t)$ Relation:
    \[
    D(t) = mt^{−1} − at^{−m}
    \]
  ■ Duong $b(t)$ Relation:
    \[
    b(t) = \frac{mt^m (t^m − at)}{(at − mt^m)^2}
    \]
**Time-Rate Analysis: Logistic Growth Model (LGM)**

- **History**
  - SPE 144790 (Clark et al., 2011).
  - Adopted from population growth models.
  - Modified form of hyperbolic logistic growth models.

- **Governing Relations:**
  - **LGM Cumulative-Time relation:**
    \[ Q_g(t) = \frac{Kt^n}{a + t^n} \]
  - **LGM D(t) Relation:**
    \[ D(t) = \frac{a - an + (1 + n)t^n}{t(a + t^n)} \]
  - **LGM b(t) Relation:**
    \[ b(t) = \frac{-a^2(n-1) - 2a(n^2 - 1)t^n + (n+1)t^{2n}}{[a - an + (n+1)t^n]^2} \]
Time-Rate Analysis: *PLE, Duong, and LGM Models*

**50 nd Simulation Case**
- **General:**
  - 50 nd case.
  - "qDb" plot
  - All models shown.

- **PLE Model:**
  - Very good match.
  - Indistinguishable.

- **Duong Model:**
  - Very good match.
  - Indistinguishable.

- **LGM Model:**
  - Very good match.
  - Indistinguishable.
Time-Rate Analysis: *PLE, Duong, and LGM Models*

800 nd Simulation Case

- **General:**
  - 800 nd case.
  - "qDb" plot
  - All models shown.

- **PLE Model:**
  - Very good match.
  - Matches BDF regime.

- **Duong Model:**
  - Very good match.
  - Does NOT match BDF.

- **LGM Model:**
  - Very good match.
  - Fair match of BDF.

**BDF = Boundary-Dominated Flow (SRV Regime)**
Time-Rate Analysis: Modified Duong Model

- Modified Duong $q_g(t)$ Relation:
  \[ q_g(t) = q_1 t^{-m} \exp \left[ \frac{a}{1-m} \left[ t^{1-m} - 1 \right] - D_{DNG} t \right] \]

- Modified Duong $D(t)$ Relation:
  \[ D(t) = D_{DNG} + \frac{m}{t} - at^{-m} \]

- Comments:
  - Model very similar to PLE.
  - Matches PSS flow data.
  - Is Duong model "necessary?"
  - Other improvements?
Time-Rate Analysis: Comparison of Modified Duong Models

Discussion:

- **Duong (base) Model:**
  - Transient flow only!
  - Liberal EUR possible.

- **Modified Duong Model 1:**
  - Almost same as PLE.
  - Conservative EUR.

- **Modified Duong Model 2:**
  - Similar to PLE (ripple).
  - Conservative EUR.

Note early-time asymptotic functions.