Reservoir Engineering Aspects of Unconventional Reservoirs

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Brief Biography: Blasingame

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

● Counts: (Dec 2015)
  ■ 57 M.S. (thesis) and 32 M.Eng. (report, non-thesis) Graduates
  ■ 13 Ph.D. Graduates
  ■ Over 140 Technical Articles

● Recognition:
  ■ SPE Distinguished Member (2000)
  ■ SPE Distinguished Service Award (2005)
  ■ SPE Distinguished Lecturer (2005-2006)
  ■ SPE Uren Award (2006)
  ■ SPE Lucas Medal (2012)
  ■ SPE DeGolyer Distinguished Service Medal (2013)
  ■ SPE Distinguished Achievement Award for PETE Faculty (2014)
  ■ SPE Honorary Member (2015)
  ■ SPE Technical Director for Reservoir Description and Dynamics (2015-2018)

● Current Research Activities: (Dec 2015)
  ■ Production Performance Analysis for Shale/Tight Reservoir Systems
  ■ Flow Phenomena in Ultra-Low Permeability Reservoir Systems
  ■ Correlation of Permeability with Mercury Injection Capillary Pressure
  ■ Performance Behavior of Naturally Fractured Reservoir Systems
  ■ Development of Time-Rate-Pressure Relations for Unconventional Reservoirs
  ■ Numerical Modeling of Ultra-Low Permeability Reservoir Systems
  ■ Correlation of Production Metrics with Completion Parameters
Facts of life...
- Analogs
- EUR
- IP
- Early Productivity
- Time-Rate Analysis
- Time-Rate-Pressure Analyses

Comments on recovery...
- Early EUR?
- EUR = f(t)?
- Well Spacing?

Shale Well Performance is a function of ...
- Porosity.
- Permeability.
- Reservoir thickness.
- Well placement.
- Natural fractures.*
- (Over-) pressure.*
- Thermal maturity.*
- Well spacing.*
- Well stimulation.*

* Defining factors (Blasingame)
Things that SHOULD help...
- Production Logs
- Optimal Proppant Design/Placement
- Stimulation Stages/Perforation Clusters

Things that DEFINITELY WOULD help...
- Measured $p_{wf}$
- Downhole Fluid Sampling

QUANTIFYING reservoir properties?
- Pressure Transient Analysis
- Production Analysis
- Petrophysical analysis

(... but just a snapshot in time)
(... obvious, but)
(... geology + logs)

(... yes, this is my favorite song)
(... sooner or later)

(what does this give us in ultra-low $k$ rock?)
($p_{tf}$ may not be sufficient, liquid-loading, etc.)
(theory ≠ application)


Pore Space: Very Small Spaces

Pore Space: *Image of Shale Pore Space (Haynesville)*

Core Scale: Core Images (Haynesville — Macro and SEM scales)

Legend:
A. Core slab of unlaminated mudstone facies showing homogeneous matrix with few thin-shelled filibranch bivalves (example at arrow).

B. (Ar-ionmilled SEM image showing different pore types of the Haynesville including organic (o), interparticle (ip), and moldic (M) micropores and nanopores.

C. Core slab of the bioturbated mudstone facies showing carbonate bioclasts and bioturbation.

D. Core slab of the laminated mudstone facies showing laminations of clay, organics, carbonate bioclasts (arrow), peloids (arrow), and mollusk shells.

Flow Models: *Flow in Small Conduits*

(a) Bulk Diffusion (Darcy's Law).

(b) Knudsen Diffusion.

(c) Surface Diffusion (Klinkenberg Flow).

**Guidance:**
- Darcy's law $\rightarrow$ typical flow assumption.
- Knudsen diffusion $\rightarrow k(p)$.
- Surface diffusion $\rightarrow$ slip (Klinkenberg).

<table>
<thead>
<tr>
<th>Flow regime</th>
<th>Knudsen Number</th>
<th>Flow Model</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum (Viscous) flow</td>
<td>$Kn &lt; 0.01$</td>
<td>Darcy's equation for laminar flow and Forchheimer's equation for turbulent flow.</td>
<td>Assumes immobile fluid at the pore wall.</td>
</tr>
<tr>
<td>Slip flow</td>
<td>$0.01 &lt; Kn &lt; 0.1$</td>
<td>Darcy's equation with Klinkenberg or Knudsen's correction.</td>
<td>Knudsen's correction is more accurate, but Klinkenberg's correction is easier.</td>
</tr>
<tr>
<td>Transition flow</td>
<td>$0.1 &lt; Kn &lt; 10$</td>
<td>Darcy's law with Knudsen's correction can be applied.</td>
<td>Knudsen's diffusion equation is the more reliable approach.</td>
</tr>
<tr>
<td>Knudsen's (Free Molecular) Flow</td>
<td>$Kn &gt; 10$</td>
<td>Knudsen's diffusion equation.</td>
<td>For very small pore-throat radii (shales).</td>
</tr>
</tbody>
</table>

Reserves: Conventional Versus Unconventional

**Conventional Reservoirs**
- Localized structural trap
- External hydrocarbons sourcing
- Hydrodynamic influence
- Porosity important
- Permeability > 0.1 md
- Permeability ≠ f(p)
- Traditional phase behavior (PVT)
- Minimal extraction effort
- Significant production history
- Mid-late development life-cycle
- Few wells for commerciality
- Base reserves on volumetrics
- Assess entire prospect before drilling
- Boundary-dominated flow (months)

**Unconventional Reservoirs (Shales)**
- "Continuous-type" deposit
- Self-sourced hydrocarbons
- Minimal hydrodynamic influence
- Porosity may not be important
- Permeability << 0.1 md
- Permeability = f(p)
- Complex (HP/HT) PVT
- Significant extraction effort
- Limited production history
- Early development life-cycle
- Many wells for commerciality
- Base reserves on analogs
- Prospect driven by drilling
- No boundary-dominated flow

Contributions From:
Brad BERG, Anadarko

[Map of global shale gas resources](http://www.eia.gov/analysis/studies/worldshalegas/)
Work Path: Analysis of Well Performance

Model: Time-Rate
Basis: Proxy model
- Predictions
- EUR
- Correlations
Time: Minutes/well

Model: Time-Rate-Pressure
Basis: Analytical/Numerical
- Predictions
- EUR/SRV
- Estimate Properties
Time: ~1 hour/well

Model: Time-Rate-Pressure
Basis: Full Numerical
- Predictions
- EUR/SRV
- Flow Mechanisms
Time: Days to weeks/well
Time-Rate Behavior: Typical Flow Regimes in Unconventional Reservoir Systems

**Linear Flow:**
(fracture flow does not interfere)

**Required Model Parameters:**
- Permeability ($k$)
- Fracture half-length ($x_f$)
- Fracture conductivity ($F_c$)
- Drainage area ($A$)
- Skin factor ($s$)
- Well length ($L_w$)
- Number of fractures ($n_f$)

**"SRV" Flow:**
("depletion")
(fracture flow does interfere)

**"Post-SRV" Flow:**
("Compound Linear Flow")
Time-Rate Behavior: (Formation) Linear Flow — Theory

Solution for a Single Fracture: (transient linear flow)

\[ pD = \sqrt{\pi t Dxf} \]

\[ q = \frac{1}{8.128494} (p_i - p_{wf}) \frac{1}{B} \sqrt{\frac{\phi c_t}{\mu}} \sqrt{k} A_xf \frac{1}{\sqrt{t}} \left[ A_xf = 2xfh \right] \]

\[ q = C A_xf \frac{1}{\sqrt{t}} \begin{bmatrix} C = \frac{1}{8.128494} (p_i - p_{wf}) \frac{1}{B} \sqrt{\frac{\phi c_t}{\mu}} \sqrt{k} \end{bmatrix} \]

Additive Fractures: (transient linear flow)

Note:
These solutions are only valid for transient linear flow [i.e., the case of non-interfering pressure distributions (due to the fractures)].

\[ q_{tot} = C \left[ A_{xf,1} + A_{xf, 2} + A_{xf, 3} + A_{xf, 4} + \ldots + A_{xf, n} \right] \frac{1}{\sqrt{t}} \]

\[ q_{tot} = C \left( A_{xf} \right)_{tot} \frac{1}{\sqrt{t}} \]
**Time-Rate Behavior: (Formation) Linear Flow — Practice (Synthetic Example)**

- **Formation Linear Flow**
  - Log-log diagnostic plot: \( \log[q(t)] \) versus \( \log[t] \) (slope = -1:2)
  - "\( qDb \)" (time-rate) plot: \( \log[q(t)] \log[D(t)] \log[b(t)] \) versus \( \log[t] \)
  - "Traditional" plot: \( q(t) \) versus \( 1/\text{SQRT}[t] \) (straight-line portion)
  - **Extrapolation using a linear flow model will over-predict EUR…**

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![Schematic Performance for a Gas Well](image1)

- **Region of over-extrapolation…**

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![Schematic Performance for a Gas Well](image2)

- **Formation Linear Flow** (Straight-Line Trend).
Time-Rate Behavior: Flow Regimes for a Multi-Fracture Horizontal Well

For Shales: | days | weeks | months | years | decades | ...

Discussion:
- 1:2 Slope → b=2 (HIGH conductivity) — formation LINEAR flow regime.
- 1:4 Slope → b=4 (LOW conductivity) — BILINEAR flow regime.
- Schematic is over-simplified to illustrate basic behavior.
Flow Regimes: (Barnett Shale Example)

- Schematic illustrates flow regimes exhibited by time-rate-pressure data.
- Duration/existence of flow regimes is **DIFFERENT** for each play.

Pseudo-elliptical flow regime (flow from matrix to collection of fractures) might exist after fracture interference.

\( \text{EUR}_{LF} \) (VERY OPTIMISTIC)

\( \text{EUR}_{Dep} \) (CONSERVATIVE ???)
Discussion:
- $qDb$ functions are DIAGNOSTIC.
- $D(t)$ and $b(t)$ evaluated from data.
- $b=2$ behavior = Linear Flow.
- Case appears to be "hyperbolic."

Rate Relation:

$$q(t) = \begin{cases} 
q_{i,\text{hyp}} \frac{D_{\text{lim}}}{D_i}^{1/b} & (t < t^*) \\
q_{\text{lim}} \exp[-D_{\text{lim}}(t-t_{\text{lim}})] & (t > t_{\text{lim}})
\end{cases}$$

$$t_{\text{lim}} = \frac{1}{bd_i} \left[ \frac{q_{i,\text{hyp}}}{q_{\text{lim}}} \right]^{b-1}$$

$D(t)$ Function:

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

$b(t)$ Function:

$$b(t) \equiv \frac{d}{dt} \left[ \frac{1}{D(t)} \right] \equiv \text{constant}$$
Time-Rate Relations: *Power Law Exponential Rate Model*

**Power-Law Exponential: (PLE)**

— Observed Behavior of $D(t)$:

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

— Integrating to solve for $q(t)$:

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

— Differentiating to solve for $b(t)$:

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

**Stretched Exponential: (SEM)**

— Observed Behavior of $q(t)$:

$$q(t) = \hat{q}_i \exp[-(t / \tau)^n]$$

— Differentiating to solve for $D(t)$:

$$D(t) \equiv -\frac{1}{q(t)} \frac{dq(t)}{dt} \approx n\tau^{-n} t^{n-1}$$

— Differentiating to solve for $b(t)$:

$$b(t) = \frac{1-n}{n} \tau^n t^{-n}$$

**Literature:**

- Kohlrausch (1854).
- Kisslinger (1993)
- Decays in random, disordered, chaotic, heterogeneous systems (e.g., relaxation, aftershock decay rates, etc.).

Valkó (2009)

$$q(t) = \hat{q}_i \exp[-(t / \tau)^n]$$

Jones (1942) and Arps (1945)

$$q(t) = q_o \exp \left[ -\frac{D_o t^{m-1}}{100(m-1)} \right]$$

**Discussion:**

- Models are the same when $D_\infty = 0$.
- The Power-Law Exponential model was derived from observations (Blasingame/Ilk).
- The Stretched-Exponential model was taken from a statistics text (Valko).
Time-Rate Behavior: *Power-Law Exponential Rate Relation*

**PLE Rate Relation:**

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

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

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

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


Clean-up/flowback effects are not significant for this case.
Time-Rate Relations: *Power Law Exponential Rate Relation*

**Power Law Exponential (PLE) Model**

**Rate Relation:**
\[ q(t) = \hat{q}_i \exp\left[ -D_\infty t - \hat{D}_i t^n \right] \]

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

**b(t) Function:**
\[ b(t) \equiv \frac{d}{dt} \left[ \frac{1}{D(t)} \right] \]
\[ \approx \frac{n\hat{D}_i (1-n)}{[n\hat{D}_i + D_\infty t^{(1-n)}]^2} t^{-n} \]

**Discussion:**
- *qDb* functions are DIAGNOSTIC.
- PLE derived from: \( D_\infty + n\hat{D}_i t^{-(1-n)} \)
- No direct analog to hyperbolic case.
- This is a "tight gas" reservoir case.
Rate-Time Analysis: *Calibration — Linear Flow (Gas Shales)*

Data taken from publicly available sources — Horizontal Shale (Dry) Gas Wells ONLY

**Discussion:**
- **START** of "Linear Flow" (~3-6 months).
- **END** of "Linear Flow" (~9-36 months).
- "Linear Flow" is represented by $b = 2$.
- EUR requires at least 20+ months (except Haynesville ~1 year; and Barnett ~3 years).

Rate-Time Analysis: **Calibration — Linear Flow (Gas Shales)**

Data taken from publicly available sources — Horizontal Shale (Dry) Gas Wells ONLY

Discussion:
- **START** of "Linear Flow" (~3-6 months).
- **END** of "Linear Flow" (~9-36 months).
- "Linear Flow" is represented by linear trends on these plots.
- Square root time plot used to show linear portion of trend ($G_p(t)$ vs. $\text{SQRT}(t)$ is most clear).

Continuous EUR: *Barnett Shale Example*

**Discussion:**
- $G_p$ trend is well-established.
- $q_g$-$G_p$ extrapolation $\rightarrow$ EUR.
- PLE model is slightly conservative.
- MH model is the industry standard.
(Sort of) "Big Data" Analysis: Barnett Shale Example (Data prior to Mar 2013)

Correlation of $G_{p,1Yr}$ vs. Initial Gas Production (Barnett Shale horizontal gas wells).

Histogram of $EUR_{30Yr}$ (Barnett Shale horizontal gas wells).

Correlation of $G_{p,1Yr}$ using Initial Gas Production and various completion parameters (Barnett Shale horizontal gas wells).

Histogram of $EUR_{30Yr}$ (Barnett Shale horizontal gas wells).
Practical Aspects: *Eagle Ford Examples*

Discussion:

- **PLOT**: Oil Productivity Index versus Oil Material Balance Time
- **OBJECTIVE**: Identify flow regimes/behavior exhibited by production data.
Practical Aspects: *Eagle Ford Examples*

Diagnostics:
- **PLOT:** Oil Productivity Index versus Cumulative Oil Production.
- **OBJECTIVE:** (Empirically) Yields project recovery based on flow behavior.
Summary:

- 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)
Challenge Points: "What Keeps Me Up at Night…"

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

● What we THINK know…
  ■ The fracture geometry is ...
  ■ The phase behavior is ...
  ■ The $p_{tf}$ to $p_{wf}$ conversion(s) is/are ...
  ■ Optimal well spacing/orientation/placement ...
  (... planar? complex? who cares?)
  (... extremely complex ... $f$(Volume)???)
  (... early-time heavy water load?)
  (... do this early!)

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

• Closure: Unconventional Reservoirs
  ■ EUR requires 18-36 months of production.
  ■ Significant reservoir heterogeneity.
  ■ Production requires stimulation.
  ■ Reservoir monitoring is essential.
  ■ Overpressure is important.
  ■ Pressure transient testing may help.
  ■ Tight-gas analogs are not perfect.
  ■ Performance management is essential.
  ■ Long-term production testing is critical.
Reservoir Engineering Aspects of Unconventional Reservoirs

End of Presentation

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Suggested Questions:

● **Basic Flow:**
  — Can we model well performance with Darcy flow concepts?
  — We understand phenomena at a given scale, but what about multi-scales?
  — Do we need to worry about PVT confinement issues?

● **Production Performance:**
  — Can we correlate production metrics with less than 18-24 months of history?
  — Are time-rate models a "reliable technology?"
  — What is the value of time-rate-pressure analysis (i.e., RTA)?

● **Predictions:**
  — Who believes we will still be using Arps' relations in: 2020? 2030? 2040? ...
  — Do we need a universal $q(t)$ model?
  — Where does reservoir pressure fit in rate projections?

● **Random Thoughts:**
  — EOR in shales?
  — Re-Fracturing?
  — Next-generation stimulation?