Perspectives on the Interpretation of Flowback Data from Wells in Shale Reservoir Systems

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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: (April 2015)**
- 55 M.S. (thesis) and 31 M.Eng. (report, non-thesis) Graduates
- 12 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)

**Current Research Activities: (April 2015)**
- Flow Phenomena in Ultra-Low Permeability Reservoir Systems
- Production Performance Analysis for Shale Systems
- Performance Behavior of Naturally Fractured Reservoir Systems
- Numerical Modeling of Ultra-Low Permeability Reservoir Systems
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Orientation — Time-Rate Analysis

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Rationale: Analysis of Well Performance

● "Well Performance Analysis" in Unconventional Reservoir Systems:
  ■ To understand the characteristics which control performance.
  ■ To evaluate completion/stimulation effectiveness.
  ■ To forecast production and estimate reserves (EUR).

● Issues:
  ■ Uncertainty/non-uniqueness (data quality?)
  ■ Understanding of flow regimes (flow mechanisms?)
  ■ Understanding of phase behavior (near-critical fluids?)
  ■ \( p_{tf} \rightarrow p_{wf} \) conversion (water rates?)
  ■ Understanding of stimulated volume (drainage area?)
  ■ Integration of geomechanics (pressure dependencies?)

● Key Points for Analysis and Forecasting:
  ■ Duration of data required for accurate estimates of EUR.
  ■ Optimal well spacing/orientation.
  ■ Reserves estimation method(s) must be "reasonably certain."
Work Path: **Analysis of Well Performance**

- **Completions**
- **Production**
- **Reservoir Fluids**
- **Geomodel**

- **Time-Rate**
  - Model: Time-Rate
  - Basis: Proxy model
  - Predictions
  - EUR
  - Correlations

- **Time-Rate-Pressure**
  - Model: Time-Rate-Pressure
  - Basis: Analytical/Numerical
  - Predictions
  - EUR/SRV
  - Estimate Properties

- **Reservoir Model**
  - Model: Time-Rate-Pressure
  - Basis: Full Numerical
  - Predictions
  - EUR/SRV
  - Flow Mechanisms
Guidance: *Typical Flow Regimes in Unconventional Reservoir Systems*

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

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

**"Post-SRV" Flow:**
("Compound Linear Flow")

**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 \( (n_f) \)
**Time-Rate Behavior: (Formation) Linear Flow — Theory**

**Solution for a Single Fracture: (transient linear flow)**

\[ P_D = \sqrt{\pi t D_x f} \]

\[ q = \frac{1}{8.128494} (p_i - p_{wf}) \frac{1}{B} \sqrt{\frac{\phi c_t}{\mu}} \sqrt{k} A_x f \frac{1}{\sqrt{t}} \]

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

**Additive Fractures: (transient linear flow)**

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

\[ q_{tot} = C (A_x f)^{tot} \frac{1}{\sqrt{t}} \]

**Note:** These solutions are only valid for transient linear flow [i.e., the case of non-interfering pressure distributions (due to the fractures)].
Time-Rate Behavior: (Formation) Linear Flow (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/SQRT[\( t \)] (straight-line portion)
  - Extrapolation using a linear flow model will over-predict EUR…

NO clean-up/flowback effects…

Slide — 8/30
Time-Rate Behavior: Flow Regimes for a Multi-Fracture Horizontal Well

For Shales: days weeks months years decades ...

Early-Time Regimes are HYPERBOLIC?

\[ q(t) \equiv q_i / \left[ (1 + bD_i t)^{1/b} \right] \]
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: \( b(t) \)**

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

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

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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).

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. \( \text{SQRT}(t) \) best view.

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Production Diagnostics

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Production Diagnostics: Flow Regimes

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.

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

\[ \text{EUR}_{Dep} \text{ (CONSERVATIVE ????)} \]

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

\[ q_{g}/p_{i}, \text{MSCF/psi} \]

\[ \text{Pressure Drop Normalized Gas Flowrate,} \]

\[ \text{Time, days} \]
Production Diagnostics: Haynesville Examples

Discussion:
- Diagnosis of the performance of 9 wells producing in the same area.
- Performance comparison of multiple wells to identify characteristics.
- Differences in the productivity = f(completion and operational issues).
Production Diagnostics: *Eagle Ford Examples*

**Discussion:**
- **PLOT:** Oil Productivity Index versus Oil Material Balance Time
- **OBJECTIVE:** Identify flow regimes/behavior exhibited by production data.

Linear flow apparent for first year (approximately).

Some clean-up/flowback effects are evident for these cases.

POSSIBLE depletion effects (could be liquid-loading).
Production Diagnostics: Eagle Ford Examples

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

Diagnostics:

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

This is more of a “consistency/correlation” plot — trends arise (indirectly) from the power-law exponential time-rate relation.
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Flowback: Purpose and Process

Objectives of flowback data analysis:
- Provide a comprehensive workflow for early-time flowback data.
- Provide a unique visualization of flowback data.
- Provide a correlative and integrated analysis of these data.
- Provide an interpretation of specific data features.
- Provide guidelines for flowback testing and optimal recovery.

Process:
- Collection and quality control of well performance/completion data.
- Construct/calibrate a base well/reservoir model.
- Construct specialized plots to identify features (i.e., unloading).
- Correlate flowback data by empirical and non-parametric models.
- Implement an assessment loop to guide future practices.
Flowback: Assortment of Plots

Base Plots:
- $q_g$ vs. $t$
- $q_w$ vs. $t$
- $p_{cf}$ vs. $t$
- Choke setting vs. time

Single-Well Plots:
- GWR vs. $G_p$
- GNPI vs. $G_p$
- WNPI vs. $W_p$
- $p_{cf}$ vs. $q_g$
- $p_{cf}$ vs. $q_w$
- $q_g$ vs. $q_w$
- $G_p$ vs. $W_p$

Multi-Well Plots:
- $p_{cf}$ vs. $t$
- $q_w$ vs. $t$
- $q_g$ vs. $t$
- $G_p$ vs. $t$
- GNPI vs. $t$
- $W_p$ vs. $t$
- GPI vs. $t$
- WNPI vs. $t$
- WPI vs. $t$
- GNPI vs. $G_p$
- GPI vs. $G_p$
- WNPI vs. $W_p$
- WPI vs. $W_p$

Rationale for Plots:
- Base Plots: "Historical" data plots.
- Single Well Plots: Comparison of data functions on a per-well basis.
- Multi-Well Plots: Comparison of data functions across several wells.
Flowback: Summary of Wells — SPE 135607

a. Summary Plot — Well A: Water rate "flattens" at later times, choke control is systematic.

b. Summary Plot — Well B: Constant gas rate is achieved, choke control and water profiles are good.

c. Summary Plot — Well C: Some erratic water production data - not well correlated with gas rate, uncorrelated with choke.

d. Summary Plot — Well D: Constant gas rate apparent, choke and water rate appear to be correlated.

e. Summary Plot — Well E: Fairly consistent water and gas rates — but not well correlated with choke changes. Water production (in particular) seems less correlated.
Flowback: **Choke Setting versus Production Time — SPE 135607**

- **a. Crossplot — All wells: Choke size versus production time.**
- **b. Crossplot — Well A: Choke size versus production time.**
- **c. Crossplot — Well B: Choke size versus production time.**
- **d. Crossplot — Well C: Choke size versus production time.**
- **e. Crossplot — Well C: Choke size versus production time.**
- **f. Crossplot — Well E: Choke size versus production time.**
Flowback: Gas-Water-Ratio Versus Cumulative Gas — SPE 135607

Slide — 23/30
Flowback: *Reciprocal Gas PI versus Cumulative Gas — SPE 135607*

![Graphs showing flowback analysis]

- **a.** Crossplot — All wells: Rate normalized surface pressure drop squared versus cumulative gas production.
- **b.** Crossplot — Well A: Rate normalized surface pressure drop squared versus cumulative gas production.
- **c.** Crossplot — Well B: Rate normalized surface pressure drop squared versus cumulative gas production.
- **d.** Crossplot — Well C: Rate normalized surface pressure drop squared versus cumulative gas production.
- **e.** Crossplot — Well C: Rate normalized surface pressure drop squared versus cumulative gas production.
- **f.** Crossplot — Well E: Rate normalized surface pressure drop squared versus cumulative gas production.
Flowback: Casing Pressure versus Gas Flowrate — SPE 135607

a. Crossplot — All wells: Casing pressure versus gas flowrate.
c. Crossplot — Well B: Casing pressure versus gas flowrate.
d. Crossplot — Well C: Casing pressure versus gas flowrate.
e. Crossplot — Well C: Casing pressure versus gas flowrate.
Flowback: Correlations for Well B Flowback Data — SPE 135607

a. Correlation Plot — Well B: GRACE correlation, based on non-parametric correlation of multiple variables (each variable is scaled and correlated).

b. Correlation Plot — Well B: “Exponential Polynomial” — typically the most “flexible” relation. Performance is statistically the best.

c. Correlation Plot — Well B: “Power Law Model 1” — most simple model attempted, average correlation.

d. Correlation Plot — Well B: “Power Law Model 2” — very good correlation, relatively simple model.
Flowback: $p_{cf}$ vs. Cumulative Gas Production — SPE 135607

$p_{cf} = a \exp[-b G_p]$ (?)
Flowback: Work in SPE 135607

Summary:
- Correlation of flowback behavior using a $q_g$ predictive relation.
- Sequence of single-well and multi-well "dashboard" plots.
- Demonstrated analysis processes on a 5-well field example.

Conclusions: (Demonstration of …)
- A parametric correlation of $q_g$ with $q_w$, $p_{tf}$, and choke history.
- A "dashboard" diagnostic plotting approach.
- Diagnostic value of accurate time-pressure-rate (TPR) data.

Recommendations:
- "Optimal drawdown" practices for individual well/field cases.
- Analytical/semi-empirical models for the "water unloading" phase.
- Acquisition/integration of $p_{wf}$ and $T_{wf}$ (bottomhole measurements).
Flowback: *Lagniappe*

*Surface Pressure Difference and Gas Rate (Cartesian)*

[Graph showing data points and trends related to surface pressure difference and gas rate.]

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End of Presentation

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