Invited Lecture

Petroleum Engineering 324 — Well Performance
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Start-Up: What You are Supposed to Know

Petroleum Engineering 324 — Well Performance
Course Evaluation (Blasingame)

Please provide a self-evaluation of the course competencies by addressing the questions given below.

Competency:

1. I can explain the relationships between porosity and permeability; and how these properties influence the flow of fluids in reservoir rocks.
   - [ ] Not At All
   - [ ] Not Well
   - [ ] Adequate
   - [ ] Well with Effort
   - [ ] Easily
   - [ ] NR

2. I can use correlations and laboratory data to estimate the properties of reservoir fluids which are relevant for reservoir engineering — analysis and modeling.
   - [ ] Not At All
   - [ ] Not Well
   - [ ] Adequate
   - [ ] Well with Effort
   - [ ] Easily
   - [ ] NR

3. I can sketch a plot of pressure versus logarithm of radius and identify the primary flow regimes (i.e., transient radial flow, pseudosteady-state flow, and steady-state flow behavior).
   - [ ] Not At All
   - [ ] Not Well
   - [ ] Adequate
   - [ ] Well with Effort
   - [ ] Easily
   - [ ] NR

4. I can derive and apply the material balance relation for a slightly compressible liquid oil system and the material balance relation for a dry gas system.
   - [ ] Not At All
   - [ ] Not Well
   - [ ] Adequate
   - [ ] Well with Effort
   - [ ] Easily
   - [ ] NR

5. I can derive and apply the steady-state flow equations for horizontal linear and radial flow of liquids and gases, including the pseudopressure and pressure-squared forms.
   - [ ] Not At All
   - [ ] Not Well
   - [ ] Adequate
   - [ ] Well with Effort
   - [ ] Easily
   - [ ] NR

6. I can derive and apply the pseudosteady-state flow equations for the "black oil" and "dry gas" reservoir systems ("black oil" — pressure form; "dry gas" — pseudopressure form).
   - [ ] Not At All
   - [ ] Not Well
   - [ ] Adequate
   - [ ] Well with Effort
   - [ ] Easily
   - [ ] NR

7. I can derive and apply the "skin factor" concept derived from steady-state flow to represent damage or stimulation (including the apparent wellbore radius concept).
   - [ ] Not At All
   - [ ] Not Well
   - [ ] Adequate
   - [ ] Well with Effort
   - [ ] Easily
   - [ ] NR

8. I am familiar with and can derive the diffusivity equations for liquids and gases — and I am aware of the assumptions, limitations, and applications of these relations.
   - [ ] Not At All
   - [ ] Not Well
   - [ ] Adequate
   - [ ] Well with Effort
   - [ ] Easily
   - [ ] NR

9. I am familiar with and can use of dimensionless variables and dimensionless solutions to provide a generic mathematical representation for a particular reservoir model.
   - [ ] Not At All
   - [ ] Not Well
   - [ ] Adequate
   - [ ] Well with Effort
   - [ ] Easily
   - [ ] NR

10. I am familiar with and can use the concepts of temporal (time) and spatial superposition — time superposition is used for variable rate/pressure problems; spatial superposition is used to generate reservoir boundary configurations (faults, closed boundaries, etc.).
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR

11. Well Test Analysis — Conventional Plots
    For well test data, I can construct, interpret, and analyze "conventional plots" as follows:
    a. Pressure versus time to establish the parameters related to wellbore storage (domination) behavior (i.e., the "early time" plot).
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
    b. Pressure versus the logarithm of time (pressure drawdown case) or versus the logarithm of superposition time (e.g., Horner Time for the pressure buildup case) to establish the parameters related to radial flow behavior (i.e., the "semilog" plot).
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
    c. The logarithm of pressure drop and pressure drop derivative versus the logarithm of time (or an appropriate superposition time function) to establish the parameters for wellbore storage, radial flow, and vertical fracture behavior (i.e., the "log-log" plot).
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR

12. Well Test Analysis — Type Curve/Model-Based Analysis
    For well test data, I can use a static type curve solution or a graphical model presentation from a software package to analyze well test data obtained from:
    a. An unfractured well which includes wellbore storage distortion and radial flow behavior (including damage/stimulation (i.e., skin effects)).
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
    b. A vertically fractured well (finite or infinite fracture conductivity cases) which includes wellbore storage distortion, fracture flow regimes, and radial flow behavior.
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
    c. A well test performed in a reservoir with closed boundaries or sealing faults.
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
    d. A well test performed in a "dual porosity" or "naturally fractured" reservoir system.
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR

13. Production Data Analysis
    I can analyze, interpret, model, and forecast well production performance as follows:
    a. Estimate the "absolute open flow" from a gas well "deliverability" test.
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
    b. Develop and use an Inflow Performance Relation (IPR) which uses flowrate, wellbore pressure, and aver-age reservoir pressure data to create an interpretative/predictive relation.
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
    c. Estimate the "reserves" for an oil or gas well using plots of rate versus time (logarithm rate format) and rate versus cumulative production.
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
    d. Use decline type curves (or an equivalent software-based tool) to analyze production data from an unfractured or hydraulically fractured oil or gas well.
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
    e. Provide a forecast of future rate or pressure performance of an oil or gas well using empirical methods (hand/software) and analytical/numerical models (software).
    - [ ] Not At All
    - [ ] Not Well
    - [ ] Adequate
    - [ ] Well with Effort
    - [ ] Easily
    - [ ] NR
Pressure Transient Analysis (PTA)

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Well Deliverability:

- The first efforts to analyze well performance were an attempt to quantify well potential — *not to estimate reservoir properties*.
- The original well deliverability relation was *completely empirical* (derived from observations), and is given as:

\[ q = C\left(p^2 - p_{wf}^2\right)^n \]

- This relationship is rigorous for low pressure gas reservoirs, \(n=1\) for laminar flow.)
Q. Can the "gas deliverability" or "AOF" be derived?
A. Sort of, see steps below — assume \((\mu_g z)\) product is constant.

Darcy's Law:

\[ \nu_r = \frac{q_g B_g}{A_r} = + \frac{k}{\mu_g} \left[ \frac{dp}{dr} \right] \left[ A_r = 2\pi rh \right] \] or \[ q_g = \frac{k}{\mu_g B_g} (2\pi h) \left[ \frac{r}{dr} \frac{dp}{dr} \right] \]

Separating and Integrating:

\[ \frac{q_g}{2\pi kh} \int_{r_w}^{r_e} \frac{1}{r} dr = \int_{p_w}^{p_e} \frac{1}{p} \frac{1}{\mu_g B_g} dp \left[ B_g = \frac{p_{sc} T}{p T_{sc} z_{sc}} \right] \]

Which Reduces to: \([(\mu_g z) = \text{constant}]\)

\[ \frac{q_g}{2\pi kh} \left[ \ln(r_e/r_w) \right] = \frac{T_{sc} z_{sc}}{T p_{sc} (\mu_g z)_c} \int_{p_w}^{p_e} p dp \]

Performing the Pressure Integration:

\[ q_g = 2\pi \frac{kh}{\ln(r_e/r_w)} \frac{T_{sc} z_{sc}}{T p_{sc} (\mu_g z)_c} \frac{1}{2} \left( p_e^2 - p_w^2 \right) \rightarrow q_g = C(p_e^2 - p_w^2) \]

Discussion: \textit{Derivation of Well Deliverability Relation}

- Actually an empirical result (see Rawlins and Schellhardt (1935)).
- Derivation from steady-state flow (above) is useful for illustration.
- Derivation for pseudosteady-state is similar (but has a couple of hand waves in it).
**Deliverability Testing: Well Deliverability (4-point test)**

\[
q = C(\overline{p}^2 - p_{wf}^2)^n
\]

- **Discussion:** *Well Deliverability (4-point test)*
  - Probably oldest "reservoir engineering" technique.
  - Assumption of pseudosteady-state flow is the weakest link in analysis.
  - Does not directly relate time, rate, and pressure performance.

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- **a.** Typical flow regimes encountered during production (liquid system).
- **b.** Typical "flow-after-flow" or 4-point test, (assumes pseudosteady-state flow for each rate).
- **c.** "Deliverability" or "Backpressure" plot used to estimate maximum well productivity.
Discussion: Flow Regimes (Unfractured Wells)

- **INFINITE-ACTING RADIAL FLOW (IARF)** is the most "popular" regime.
- **PSEUDOSTEADY-STATE (PSS) flow** → CLOSED BOUNDARIES.
- **STEADY-STATE (SS) flow** → CONSTANT PRESSURE (not realistic).

Schematic drawing of geometry and boundary conditions for radial flow, constant-rate cases.

PTA Solutions: Unfractured Well (Skin Factor Concept)

Discussion: Skin Factor Concept (Unfractured Wells)

- Finite skin concept → zone of "altered" permeability near the well.
- Infinitesimal skin concept → mathematical convenience.
- Negative skin has mathematical (and physical) limitations.
PTA Solutions: Fractured Well

Discussion: Flow Regimes

- **FORMATION LINEAR flow** does not exist (a few seconds at most).
- **FORMATION linear flow** → High fracture conductivity.
- **BILINEAR flow** → Low fracture conductivity.

**Discussion: Fracture Flux Distributions**

- Discretized fracture must be solved numerically.
- High-conductivity fracture → flux distribution IS NOT significant at well.
- Finite-conductivity fracture → flux distribution IS significant at well.
PTA Solutions: Fractured Well (Fracture Damage)

Discussion: Fracture Damage Comparison

- Argument: Finite conductivity can be modeled as damage... (false!)
- "Fluid loss" damage is referred to as "fracture face" skin. (not correct)
- "Choked fracture" damage is just a constant skin factor. (not correct)
**Discussion: Skin Factor Correlation**

- Developed to relate *Pseudoradial* flow skin factor and fracture cases.
- Useful in 1980's to generate a skin factor that managers could understand for cases of fractured wells (still used for that purpose ...).

Valko Correlation: \( u = \ln(C_{ID}) \)

\[
\frac{r_w e^{-s}}{x_f} \approx \exp \left[ -\frac{1.648546 - 3.002711 \times 10^{-1} u + 1.506532 \times 10^{-1} u^2}{1 + 2.136604 \times 10^{-1} u + 9.513761 \times 10^{-2} u^2 + 8.276996 \times 10^{-3} u^3} \right]
\]

Alternative Correlation:

\[
\frac{r_w e^{-s}}{x_f} \approx \frac{1}{2} \left[ 1 - 4.622848 \times 10^{-2} \exp(-4.354799 \times 10^{-3} C_{ID}) ight]
- 3.536031 \times 10^{-1} \exp(-1.314478 \times 10^{-1} C_{ID})
- 5.87493 \times 10^{-1} \exp(-8.119795 \times 10^{-1} C_{ID})
\]

Fracture patterns are due to stress orientation.
Large-scale fractures can yield tremendous productivity.
Stress state changes during production (depletion) — re-fracture?
Discussion: Warren and Root Model

- "Borrowed" (i.e., stolen) from Barenblatt and Zheltov.
- By far the most popular "heterogeneous" reservoir model.
- Some physical limitations, but its simplicity provides unique flexibility.
Discussion: Fracture Models

- Kazemi initially produced "slab" model using numerical simulator.
- De Swaan developed the solution for transient interporosity flow.
- Najurieta developed Laplace domain form of De Swaan result.
PTA Type Curves: \( WBS + IARF \) ("Bourdet-Gringarten")

- "Starting point" for virtually all pressure transient test analysis.
- \( p_D' \): \( WBS \) domination = "unit slope;" Infinite-acting radial flow (IARF) = 1/2.
Type Curve: Sealing Faults ("Stewart") (unfractured well)

- Solutions for sealing faults have a distinct (and unique) behavior.
- The radial composite model can be virtually indistinguishable (check geology!).

Type Curve: Fractured Well (WBS) ("Economides") ($C_{Fd} = 1$) [CfD = F_cD]

- Very strong bi-linear flow signature.

Very LOW fracture conductivity (similar to damage).

PTA Type Curves: Fractured Well (WBS) ("Economides") ($C_{fD}=10$)

**Type Curve for a Well with Finite Conductivity Vertical Fracture in an Infinite-Acting Homogeneous Reservoir with Wellbore Storage Effects $C_{fD} = (w k_f)/(k x_f) = 10$**

- **Wellbore Storage Domination Region**
- **Radial Flow Region**
- **Wellbore Storage Distortion Region**

**Legend:** $C_{fD} = (w k_f)/(k x_f) = 10$

- $p_D$: Solution
- $p_{Dd}$: Solution
- $p_{D/d}$: Solution

**Type Curve:** Fractured Well (WBS) ("Economides") ($C_{fD}=10$)  [$C_{fD}=F_{cD}$]

- **$C_{fD}=10$: MEDIUM fracture conductivity.**
- **Pressure drop and pressure derivative signatures vary (linear and bi-linear flow).**
PTA Type Curves: Fractured Well (WBS) ("Economides") \((C_{fD}=10^3)\)

- **Type Curve:** Fractured Well (WBS) ("Economides") \((C_{fD}=10^3)\) \([C_{fD}=F_{cD}]\)
  - **\(C_{fD}=10^3\): VERY HIGH fracture conductivity (infinite fracture conductivity).
  - Very strong (formation) linear flow signature.

"Onur, Satman, and Reynolds" Type Curve: \( p_{wd}' \) vs. \( t_{D\lambda}(1-\omega) \)—Various \( \lambda \) and \( \omega \) Values

Type Curve: Naturally Fractured Reservoir (No Wellbore Storage)
- Pseudosteady-state "interporosity" flow case.
- This is the "cubes" or "Warren and Root" model.

PTA Type Curves: Naturally Fractured Reservoir (No WBS)

"Onur, Satman, and Reynolds" Type Curve: $p^t_{WD}$ vs. $t_D \lambda/(1-\omega)$—Various $\lambda$ and $\omega$ Values

 transient "interporosity" flow case.

 transient "slabs" or "Kazemi" model.

Type Curve for an Unfractured Well in an Infinite-Acting Naturally-Fractured Reservoir with NO Wellbore Storage or Skin Effects — Plotting Format From: paper SPE 23830, Onur, M., and Satman, A.: "New Type Curves to Determine Naturally Fractured Reservoir Parameters"
**Type Curve: Naturally Fractured Reservoir (WITH Wellbore Storage)**

- Pseudosteady-state "interporosity" flow case shown for emphasis.
- This is the "Angel" type curve format.
PTA Field Cases: Infinite-Acting Radial Flow (IARF)

Discussion: Unfractured oil well (SPE 12777)

- This result is an excellent match of all functions.
- \( \beta \)-derivative function is an excellent diagnostic for the wellbore storage and transition flow regimes.
Type Curve Analysis — SPE 13054 Well MACH X3 (Drawdown Case) (Well in a Dual Porosity System ($\rho_{ss}$)— $\omega = 1 \times 10^{-2}$, $\alpha = 1 \times 10^{-1}$)

Legend:
- $p_D$ Solution
- $p_{Dd}$ Solution
- $p_{D\beta d}$ Solution

Reservoir and Fluid Properties:
- $r_w = 0.2917$ ft, $h = 65$ ft,
- $c_t = 24.5 \times 10^{-6}$ psi$^{-1}$, $\phi = 0.048$ (fraction)
- $\mu_0 = 0.362$ cp, $B_o = 1.8235$ RB/STB

Production Parameters:
- $q_{ref} = 3224$ STB/D, $p_{wf}(\Delta t=0) = 9670$ psia

Match Results and Parameter Estimates:
- $[p_D/\Delta p]_{match} = 0.000078$ psi$^{-1}$, $C_{D\beta}^{2s} = 1$ (dim-less)
- $[(t_D/C_D)/t]_{match} = 0.17$ hours$^{-1}$, $k = 0.361$ md
- $C_s = 0.1124$ bbl/psi, $s = -4.82$ (dim-less)
- $\omega = 0.01$ (dim-less), $\alpha = C_D \times \lambda = 0.01$ (dim-less)
- $\lambda = 6.45 \times 10^{-6}$ (dim-less)

Discussion: Unfractured oil well in dual porosity system (SPE 13054)
- Derivative functions indicate dual porosity signature — good match.
- "Less-than-perfect" late time data match may be due to rate history effects.
Discussion: Unfractured oil well in dual porosity system: (SPE 18160)

- Strong performance of the $\beta$-derivative function — particularly in the region defined by transition from wellbore storage to transient interporosity flow.
PTA Field Cases: *Hydraulically Fractured Wells*

Discussion: Fractured gas well: buildup test (SPE 9975 — Well 5)
- Wellbore storage effects ($p_{D\beta d}=1$).
- Linear flow regime could be diagnosed clearly ($p_{D\beta d}=1/2$) — very good match.
**Discussion:** Fractured gas well: buildup test (SPE 9975 — Well 10)

- $p_{D^Bd} = 1$ indicates wellbore storage effect.
- The well is either poorly fracture-stimulated, or a "skin effect" has obscured any evidence of a fracture treatment.
Discussion: Fractured gas well: buildup test *(SPE 9975 — Well 12)*

- Wellbore storage domination regime \(p_{D\beta d} = 1\).
- The \(p_{Dd}\) and \(p_{D\beta d}\) signatures in mid-to-late times confirm the well is highly stimulated.
Production Analysis (PA)

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Guidelines for Performance-Based Reservoir Characterizations:

- Review all production data for consistency.
- Review well history, particularly recompletions/stimulations.
- Gather/correlate available petrophysical data (core, logs, etc.).
- Perform simplified analysis of production (Arps, EUR, etc.).

- Attempt to correlate measured rate/pressures (quality check).
- Perform model-based analysis of production (and well test) data.

- Integrate results at different scales to establish correlation(s).
PA Example 1: Allocated Rate Data (Peru)

Data Plots: Batanes Well 3541 (Peru)

- Strong signature of rate data allocation (cumulative production is relatively smooth, but rate profile is necessary for analysis).
- "Reciprocal Rate" plot ($1/q_o$ vs. $N_p/q_o$ (Cartesian format)) does appear hopeless in terms of analysis/interpretation.

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**a. "Cartesian" Plot:** $q_o$ and $N_p$ vs. $t$ — Batanes Well 3541 (Peru). Characteristic signature of allocation in rate.

**b. "Reciprocal Rate" Plot:** $1/q_o$ vs. $N_p/q_o$ — Batanes Well 3541 (Peru). Again we note the allocation signature.
Log-Log Reciprocal Rate Plot: Batanes Well 3541 (Peru)

- While considerable "scatter" exists, a dominant trend emerges.
- This plot is the basis for most modern production data analysis.
Data Plots: Southeast Texas Gas Well

This case is distinctive in that the operator systematically changes the completion on virtually every well — the well is first flowed up casing, then tubing is installed and the well is flowed up the annulus — then later, flow is diverted through the tubing only.
Log-Log "Reciprocal Rate" Plot: Southeast TX Gas Well

- Superposition rate function (without pressure data) mitigates most of the influence of the completion changes (... for this case).

We note that by simply plotting the RATE function, $1/q_g$ versus $G_p/q_g$, we do significantly reduce the influence of the completion changes. However, we must also note that such issues are problem dependent, and care must be taken when completion changes occur.
Pressure Comparison Plots: East Texas Gas Well

- Comparison of calculated and measured $p_{ws}$ data — $p_{ws,cal}$ data are taken from the surface pressure history; $p_{ws,meas}$ data are taken from a bottomhole pressure survey obtained as part of a pressure transient test performed on this well.

**a. "Cartesian" Plot: $p_{ws}$ vs. $t$ (calculated and measured $p_{ws}$) — East Texas gas well. Note agreement (production/well test $p_{ws}$).**

**b. Full Scale "Cartesian" Plot: $p_w$ vs. $t$ (calculated and measured $p_w$) — East Texas gas well. Entire production history.**
"Blasingame" Plot: Production Analysis — East TX Gas Well

- Used surface pressure measurements converted to $p_{wf}$.
- Minor issues with early-time analysis, good match of performance.
"Log-Log" Plot: Well Test Analysis — East TX Gas Well

- Used high frequency bottomhole pressure measurements ($p_{ws}$).
- Consistent match of bottomhole and "production" pressure data.
From: Estimation of Underground Oil Reserves by Oil-Well Production Curves — Cutler (1924). Cutler (originally) presented the Cartesian plot (on the left) to illustrate "remaining" production (based on an economic limit). Figure on right (semilog plot) presented to provide a "modern" view of the data. Note the exponential and hyperbolic relations are presented against Cutler's empirical extrapolation (Cutler's "Averaged and Extrapolated" trend is most likely based on a "French" curve (no detail given)).
a. The "engineer's solution" (i.e., the log-log plot) — no theory to support this concept, this plot did not stand the test of time.

b. The "gee it works" plot — I wonder if there is some theory? Yes, but — theory is limited to constant $p_{wf}$ and black oil/solution gas drive systems. Only an approximation for the gas case.

From: Estimation of Underground Oil Reserves by Oil-Well Production Curves — Cutler (1924). *Comparison of various empirical plots in use in the early 1900's to 1940's. The goal of most "production data analysis" was the estimation of reserves for tax purposes.*
Arps Relations: Summary of Time-Rate and Time-Cumulative Equations

**Time-Flowrate**

**Exponential: \( b=0 \)**

\[ q = q_i \exp(-D_it) \]

**Hyperbolic: \( 0<b<1 \)**

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

**Harmonic: \( b=1 \)**

\[ q = \frac{q_i}{(1 + D_it)} \]

**Time-Cumulative Production**

**Exponential: \( b=0 \)**

\[ N_p = \frac{q_i}{D_i} [1 - \exp(-D_it)] \]

**Hyperbolic: \( 0<b<1 \)**

\[ N_p = \frac{q_i}{(1 - b)D_i} [1 - (1 + bD_it)^{1-1/b}] \]

**Harmonic: \( b=1 \)**

\[ N_p = \frac{q_i}{D_i} \ln(1 + D_it) \]
Arps Relations: Flowrate-Cumulative Production Equations

**Exponential: (b=0)**

\[ q = q_i - D_i N_p \]

**Hyperbolic: (0<b<1)**

\[ q = q_i \left(1 - \frac{N_p}{N}\right) \frac{1}{(1-b)} \left[ N \equiv \frac{q_i}{(1-b)D_i} \right] \]

or \((N - N_p) = \frac{q_i^b}{(1-b)D_i} q^{1-b}\)

**Harmonic: (b=1)**

\[ q = q_i \exp\left[-\frac{D_i}{q_i} N_p\right] \]

Plot of: \(q\) versus \(N_p\)

Plot of:

- \(\log(q/q_i)\) versus \(\log[1-(N_p/N)]\)
- \(\log(N-N_p)\) versus \(\log(q)\)

Plot of: \(\log(q)\) versus \(N_p\)
From: Manual for the Oil and Gas Industry — Arnold (1919). Production data correlation is over 80 years old! This plot helped to correlate reserves with production. Theory assumes pseudosteady-state flow conditions and production at a constant bottomhole pressure.
Oil Material Balance Relation:

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

Oil Pseudosteady-State Flow Relation:

\[ \bar{p} = p_{wf} + b_{o, pss} q_o \ b_{o, pss} = 141.2 \frac{\mu_o B_o}{kh} \left[ \frac{1}{2} \ln \left[ \frac{4}{e^\gamma} \frac{1}{C_A} \frac{A}{r_w^2} \right] + s \right] \]

Steps:
1. Differentiate both relations with respect to time.
2. Assume \( p_{wf} = \text{constant} \) (eliminates \( d(p_{wf})/dt \) term).
3. Equate results, yields 1st order ordinary differential equation.
4. Integrate.
5. Exponentiate result.

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

\[ D_i = \frac{1}{b_{o, pss}} \frac{1}{Nc_t B_{oi}} \]

\( \gamma \)

\( \mu \)

\( C_A \)

\( r_w \)
Fetkovich "Empirical" Decline Type Curve: Empirical

Fetkovich "Empirical" Rate Type Curve
(Unfractured Well Centered in a Bounded Circular Reservoir)

Fetkovich Empirical Type Curve:
- Unfractured Well Centered in a Bounded Circular Reservoir.
- Empirical Rate Functions Only.

Legend: $q_{Dd}$ vs. $t_{Dd}$
- Rate Function Curves

- Log-log "type curve" for the Arps "decline curves" (Fetkovich, 1973).
- Initially designed as a graphical solution of the Arps' relations.
Fetkovich "Analytical" Decline Type Curve: (constant $p_{wf}$)

- Log-log "type curve" for transient flow behavior (Fetkovich, 1973).
- First "tie" between pressure transient and production data analysis.
Fetkovich "Composite" Decline Type Curve:

- Assumes constant bottomhole pressure production.
- Radial flow in a finite radial reservoir system (single well).

Fetkovich "Composite" Rate Type Curve (Unfractured Well Centered in a Bounded Circular Reservoir)
Fetkovich Decline Type Curve: \( b>1 \)

Fetkovich "Composite" Rate Type Curve (Includes \( b>1 \) cases)
(Unfractured Well Centered in a Bounded Circular Reservoir)

- \( b=1 \) is the constant rate case — no theory to support \( b>1 \) cases for PSS flow.
- Rule: Transient flow — \( q \) concave UP, PSS flow — \( q \) concave DOWN.
Type Curves for Gas Wells:

- Gas cases cannot be fully represented using Arps' (hyperbolic) relations. However, the Arps' relations are often an acceptable approximation.
- Constant $p_{wf}$ gas cases are dependent on the $p_{wf}/p_i$ ratio (path-dependent non-linearity) — and cannot be extended to variable-rate, variable pressure drop.

(Zoom View) Reconstruction of Fetkovich (SPE 04629 — 1973) and Carter (SPE 12917 — 1985) type curves for the gas case (various $p_{wf}/p_i$).
Fetkovich Decline Type Curve: Original Fetkovich Decline Type Curve

- **Fetkovich "Composite" Decline Type Curve:**
  - Assumptions:
    - Assumptions constant bottomhole pressure production.
    - Assumptions radial flow in a finite radial reservoir system (single well).

- Composite of analytical and empirical type curves.
Fetkovich Example Analysis: Decline Type Curve

Type-curve matching example for calculating $K_h$ using decline curve data, Well 13, Field A.

Fetkovich Example Match: SPE 04629 — (Fetkovich)

- Lack of early time data is an omen of things to come.
- Late time data follow an exponential trend (constant $p_{wf}$).
Pseudosteady-State Flow Relations: Oil Example

a. $q_o$ and $p_{wf}$ vs. $t$:
   Exploration Oil Well — Southeast Asia.

b. $\Delta p/q_o$ vs. $N_p/q_o$ (Cartesian):
   Exploration Oil Well — Southeast Asia.

c. $\Delta p/q_o$ vs. $N_p/q_o$ (Log-log):
   Exploration Oil Well — Southeast Asia.

Oil Case:
- Very simple model for pseudosteady-state oil flow behavior.
- Very strong correlation of model with field data.
- $q_o$ and $p_{wf}$ data are well-behaved, good correlation is not surprising.

d. $q_o/\Delta p$ vs. $N_p/q_o$ (Cartesian):
   Exploration Oil Well — Southeast Asia.

e. $q_o/\Delta p$ vs. $N_p/q_o$ (Log-log):
   Exploration Oil Well — Southeast Asia.
Pseudosteady-State Flow Relations: Gas Example

Gas Case:
- Extraordinary correlation of the $\Delta p_q/q_g$ and $q_g/\Delta p_p$ data functions.
- $q_g$ and $p_{wf}$ data have considerable variation due to wellbore effects (liquid (water) loading). Despite these variations, the pseudosteady-state data functions correlate very well.

a. $q_g$ and $p_{wf}$ vs. $t$: Barnett Field Well SR1.
b. $\Delta p_p/q_g$ vs. $t_{a,mb}$ (Cartesian): Barnett Field Well SR1.
c. $\Delta p_p/q_g$ vs. $t_{a,mb}$ (Log-log): Barnett Field Well SR1.
d. $q_g/\Delta p_p$ vs. $t_{a,mb}$ (Cartesian): Barnett Field Well SR1.
e. $q_g/\Delta p_p$ vs. $t_{a,mb}$ (Log-log): Barnett Field Well SR1.
Fetkovich Radial Flow Type Curves

Radial Flow Decline TC:

- "Fetkovich-McCray Original"
- "Fetkovich Derivative"
- "Fetkovich-McCray Material Balance Time" — Uses material balance to rigorously incorporate variations in rate and pressure over time. This technique substantially improves the analysis of variable-rate data.


Radial Flow Case: Palacio/Blasingame Type Curve

Fetkovich-McCray Rate Function Type Curve—$t_{Dd}$ Format
(Unfractured Well Centered in a Bounded Circular Reservoir)

Palacio/Blasingame Type Curve: (constant $p_{wf}$ case)

- Auxiliary functions (rate integral and integral derivative) enhance features.
- Need to use material balance time to account for variable rate.
Radial Flow Case: Doublet/Blasingame Type Curve

Fetkovitch-McCray Rate Function Type Curve—$t_{Dd,bar}$ Format
(Unfractured Well Centered in a Bounded Circular Reservoir)

Doublet/Blasingame Type Curve: (constant $q_o$ equivalent)

- Note "convergence" of late stems to unique trends (material balance time).
- Type curve is valid for variable-rate/variable pressure drop cases.
Vertically Fractured Wells: Pratikno/Blasingame Type Curves


c. Pratikno (2002): "Fetkovich-McCray" format — FINITE conductivity vertical fracture ($F_{cd} = 0.5$).

Decline Type Curves: Fractured Wells

- **Infinite fracture conductivity:**
  - Less complex solution, but somewhat ideal for use in practice.

- **Finite fracture conductivity:**
  - $F_{cd} = 10$: Moderate to high fracture conductivity case.
  - $F_{cd} = 0.5$: Low fracture conductivity case.
Horizontal Wells: Shih/Blasingame Type Curves

Horizontal Well Cases:
- "Infinite-conductivity" horizontal well case(s).
- Dimensionless reservoir model requires several parameters.


Multiwell Analysis: Marhaendrajana/Blasingame Approach

- Multiwell case can be "recast" into single well case using cumulative production for entire field.
- Homogeneous reservoir example shows that all cases (9 wells) align — same behavior observed for heterogeneous reservoir cases.


Log-log plot of rate/pressure drop functions as a function of total material balance time (homogeneous reservoir example).

Agarwal, et al Methodology: (slightly different than Blasingame, et al)

- Basically the same as Blasingame, et al work.
- More like pressure transient test analysis/interpretation.


Rate-time production decline-type curves for radial systems using $t_D$ based on area ($t_D/t_{wa} = 100, 1,000, 10,000$).

Rate-time production decline-type curves for infinite conductivity fracture using $t_D$ based on area ($x_e/x_f = 1, 2, 5, 25$).

Rate-time production decline-type curves for finite conductivity fracture using $t_D$ based on area ($x_e/x_f = 1, 2, 5, 25$ and $F_{cd} = 0.05, 0.5, 500$).
Crafton, et al Methodology: (Rate Normalization)

- From: SPE 37409 — Crafton, et al. (1997) (Fig. 2).
- From: SPE 37409 — Crafton, et al. (1997) (Fig. 5).
- From: SPE 37409 — Crafton, et al. (1997) (Fig. 10).

Crafton, et al Methodology:
- Rate normalized pressure drop versus production time ($\Delta p/q$ vs. $t$).
- Also analogous to pressure transient test analysis/interpretation.
- Very serious limitations — production time is not sufficient for general case of rate variation.