Picture from: http://stop2012.blogspot.es/img/iceberg.jpg

Agenda

- Conventional well testing – brief summary
- Introduction to tight gas reservoirs – characteristics, behavior & challenges
- Methods
- Multi-fractured horizontal wells
- Remarkable conclusions
- Q&A

Conventional Well Testing

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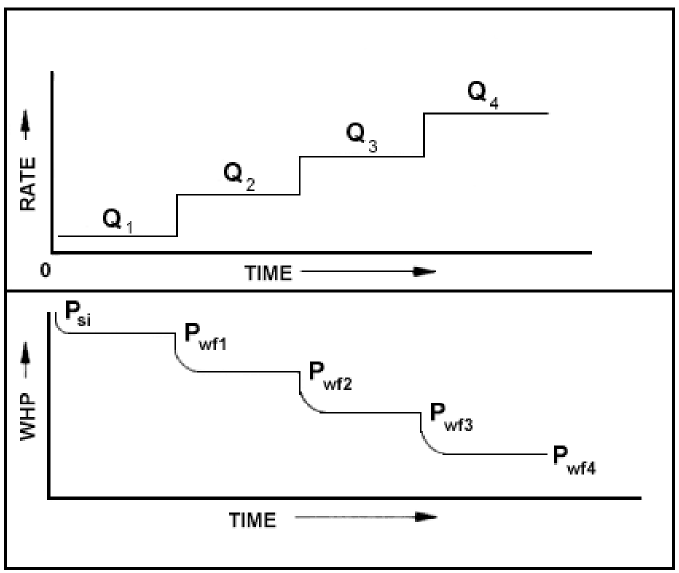
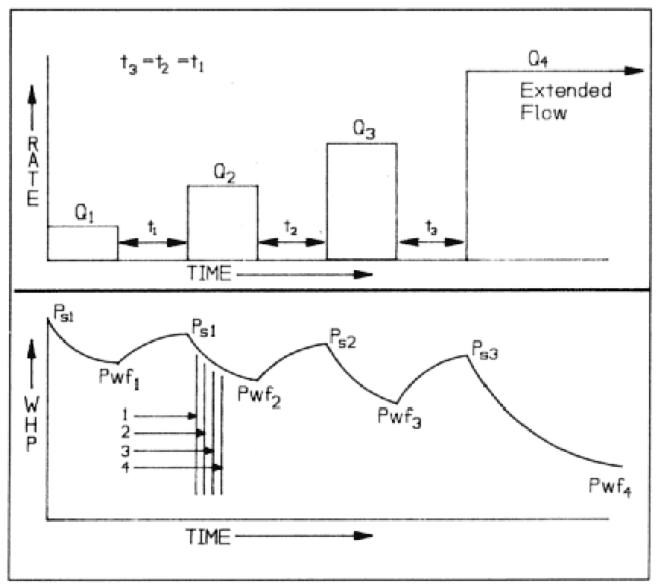
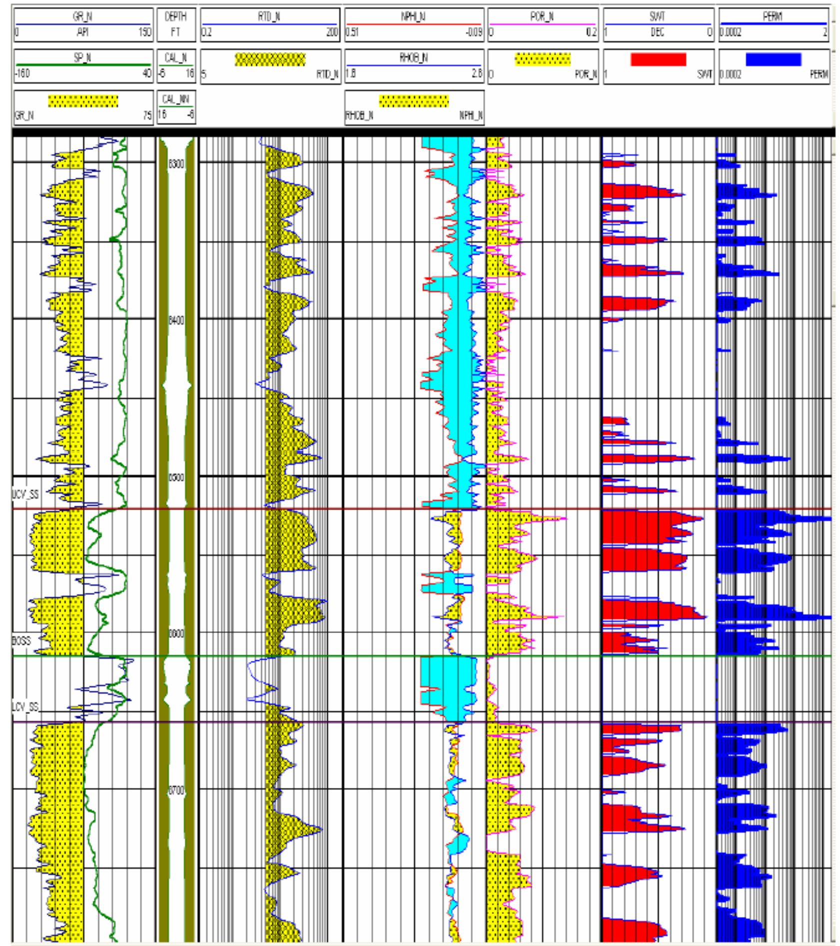
- Most of the conventional well testing techniques rely on boundary dominated flow, identification of pseudo-radial or radial flow, mass balance (P/Z) and decline curve analysis
- Common methods include Build-Ups, Flow-after-Flow, Isochronal Tests, Modified Isochronal Tests and others
- Techniques based on measuring pressures rather than rates. Pressure Transient Analysis (PTA)





Tight Gas Reservoirs

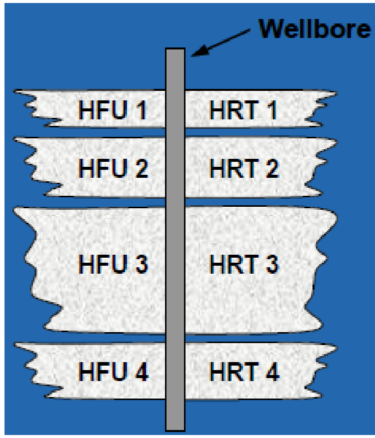
- Very low permeability. By definition less than 0.1 mD
- Low porosity. In general less than 15 %
- Heterogeneous rocks
- Highly anisotropic
- Water saturation hard to quantify
- Difficult to define gross to net pay
- Multilayer reservoirs
- Commingled production
- Complex depositional systems
- Presence of natural fractures either open or healed
- Require hydraulic fractures to be commercially viable



Log from: Using Multi-layer Models to Forecast Gas Flow Rates in Tight Gas Reservoirs. Sergio Armando Jerez Vera. MsC. TAM

Hydraulic Flow Units (HFU)

- **Multilayered Reservoirs**
  - Difficult to allocate flow rate to every zone as it is also difficult to define pay zone
  - Multiple fractures with different characteristics
  - Commingled production
- **Results from well testing**
  - Volume averaged solutions



Input Rock Properties

HFU No.	HRT No.	h (ft)	k_g (md)	ϕ (%)	S_w (%)
1	1	10	0.0729	8.43	10.0
2	2	30	0.0175	7.45	20.0
3	3	120	0.0043	6.57	40.0
4	4	40	0.0009	5.65	50.0
Avg./Total		200	0.0090	6.61	36.4

Picture from: SPE 109625

- **Approach**
  - Reservoir or Hydraulic Flow Unit concept (RFU, HFU)
  - Defined as correlatable and mappeable regions in the reservoir that practically possess consistent petro-physical and fluid properties that control fluid flow and characterize its static and dynamic behavior. Their definition is based usually on comparing porosity and permeability but definition can be further refined utilizing other parameters such as water saturation, pore pressure, etc
  - Well logs are mainly available data for units definition
  - Average properties can be geometric or arithmetic

Time to Reach BDF

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Non-stimulated Reservoir				Stimulated Reservoir			
Formation Permeability [mD]	Drainage Area [acres]	Start Pseudo-steady [days]	Start Pseudo-steady [years]	Formation Permeability [mD]	Fracture Half-Length [ft]	Start Pseudo-Radial [days]	Start Pseudo-Radial [years]
0.001	40	11000	30.1	0.001	100	2528	6.9
0.001	640	176000	482.2	0.001	500	63203	173.2
0.01	40	1100	3.0	0.001	1000	252813	692.6
0.01	640	17600	48.2	0.01	100	253	0.7
0.1	40	110	0.3	0.01	500	6320	17.3
0.1	640	1760	4.8	0.01	1000	25281	69.3
1	40	11	0.0	0.1	100	25	0.1
1	640	176	0.5	0.1	500	632	1.7
10	40	1	0.0	0.1	1000	2528	6.9
10	640	18	0.0	1	100	3	0.0
100	40	0	0.0	1	500	63	0.2
100	640	2	0.0	1	1000	253	0.7

Φ= ?	0.1	fraction
μ= ?	0.02	cp
Ct= ?	2.00E-04	1/psi
tD=?	4	dim

1 acre = 0.4 ha = 0.004 km^2

- **During transient flow, reservoir acts as infinite acting**
- **Strictly speaking the term "pseudo-steady state" only applies to constant rate production**

Impact on Well Testing

- It takes a very long time to reach boundary dominated flow (BDF) in low to very low permeability reservoirs such in tight gas ones ! This implication could mean weeks, months or even years for very low permeability reservoirs
- Approximately linear 1D flow geometry due to combined effects of very low permeability and the practical necessity of hydraulic fracturing
- For instance most of the time well is under transient flow and drainage area is changing as time goes by
- In multilayered formations that could be either hydraulic fractured or not, due to variations in permeability and and fracture half length, different flow regimes may co-exist. Layers with lower permeability may be in transient flow while higher zones may be in BDF
- Need to use other approaches such as Rate Transient Analysis (RTA) instead of PTA

What We Want to Know

Gas in place (GIP), drainage area

K, Por, Sw (Reservoir prop's)

- "…A tight gas reservoir can not produce commercial volumes of gas at economical flow rates unless stimulation and / or hydraulic fracturing treatments are successfully designed and implemented…"

Quote from: Analysis from Long Term Behavior in Tight Gas Reservoirs. Jorge Alberto Arevalo Villagran. PhD. TAM

Gas rate, K, depletion rate, forecasting

- "…Hydraulic fracturing QAQC axiom: pump the job as designed and prove it…"

Quote from: Onshore Hydraulic Fracturing QA / QC Manual. V1.0. BP

Xf, Kf, S, (Frac prop's), Optimized ?

Rate Transient Analysis (RTA)

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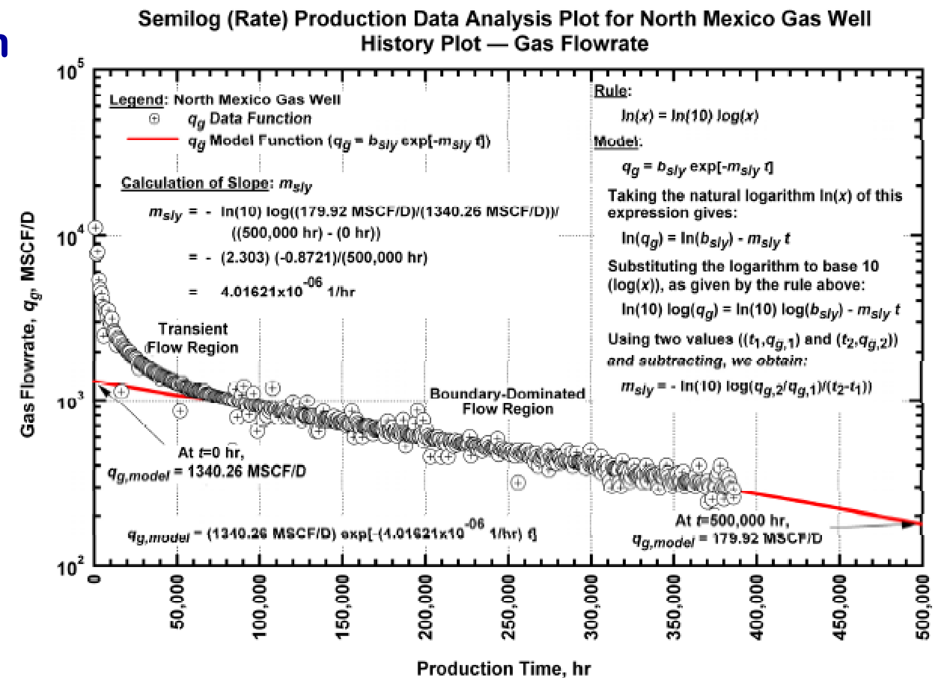
- Another approach to predict field performance (past and future)
  - Also known as Production Data Analysis (PDA)
  - Analysis of rate-time instead of pressure-time (pressure is also required !)
  - Combined analysis of rate and bottom hole flowing pressure
  - Empirical methods
  - Type curves analysis
  - Finite difference methods
  - Analytical solutions
- Curve fitting
  - Standard decline curve analysis
  - Advanced decline curve analysis
  - History matching using analytical models
  - Derived originally for single layer reservoirs
  - Expanded for applications to TG reservoirs



Graph from: Production Analysis Notes. Tom Blasingame. TAM - 2009

Gas in Place (GIP)

- Volumetric methods for conventional reservoirs
  - Subsurface maps (structural, cross-sectional, isopach)
  - Availability of sufficient information (extension and variation of pay thickness)
  - Least accurate at early stage of field development (scarce data)
  - Drainage area and recovery factor hard to estimate in tight reservoirs
- Mass balance methods
  - Allow analyzing past performance and forecasting future behavior
  - Require to shut-in the well for a while to estimate a representative value of the reservoir pressure. In tight gas reservoirs, it could take from weeks to years
  - From economic perspective, nobody wants a production loss for testing purposes if other methods could provide same or even better information
  - In tight gas reservoirs, it is almost impossible to obtain accurate estimates of average reservoir pressure
  - Conventional mass balance (P/Z) does not provide reliable values of recoverable reserves

Arp's Method

- **Utilization**
  - Analyze production data
  - Predict future well performance
  - Estimate ultimate reserves (EUR)
- **Assumptions**
  - Future behavior of the well would be governed and characterized by any trend of its past performance
  - Those trends remain unchanged during well life
  - Completely empirical. No physical basis. Highly unlikely in nature
  - BDF
- **Math behind**
  - Exponential decline
  - Hyperbolic decline
  - Harmonic decline

Case		Rate-Time Relation	Cumulative-Time Relation
Exponential:	(b=0)	$q_g = q_{gi}\exp[-D_i t]$	$G_p = \frac{q_{gi}}{D_i}[1-\exp[-D_i t]]$
Hyperbolic:	(0<b<1)	$q_g = \frac{q_{gi}}{(1+bD_i t)^{(1/b)}}$	$G_p = \frac{q_{gi}}{(1-b)D_i}[1-(1+bD_i t)^{1-(1/b)}]$
Harmonic:	(b=1)	$q_g = \frac{q_{gi}}{(1+D_i t)}$	$G_p = \frac{q_{gi}}{D_i}\ln(1+D_i t)$

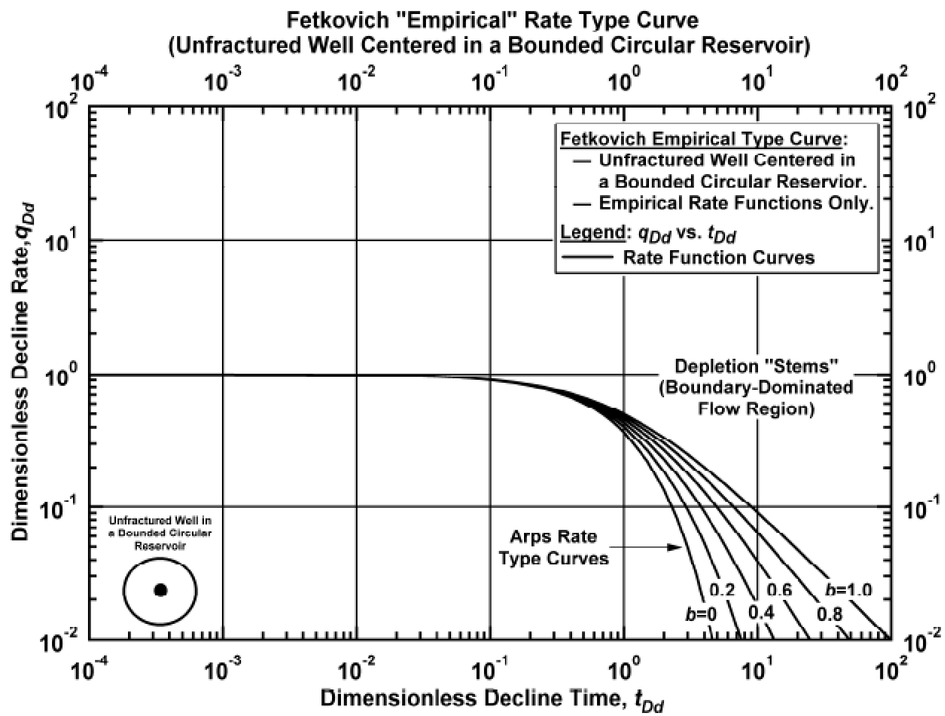
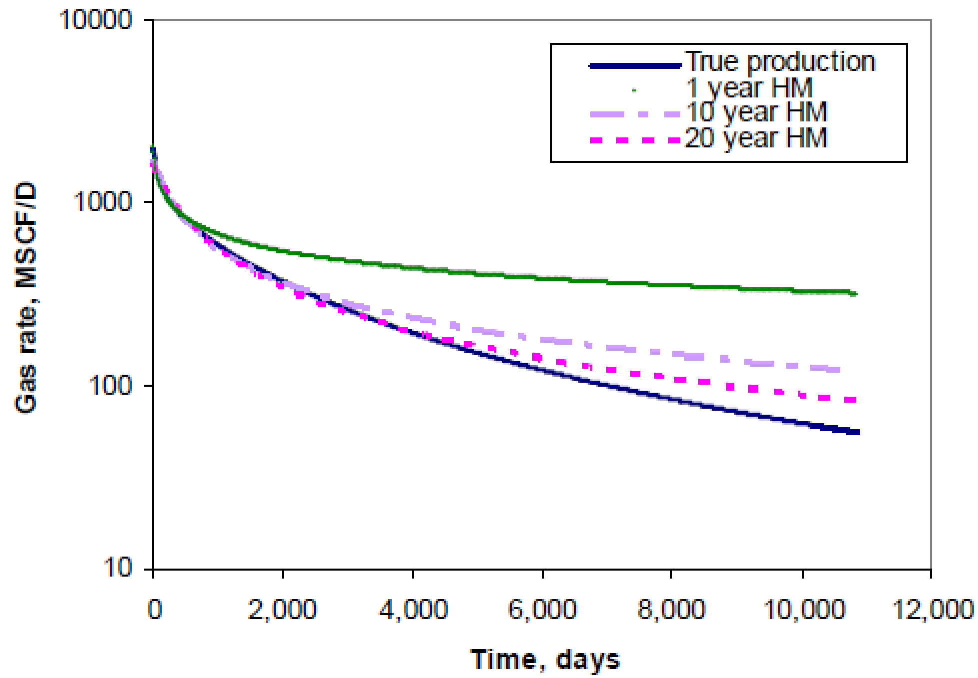


Table & Graph from: Production Analysis Notes. Tom Blasingame. TAM - 2009

Arp's Method

- **Limitations**
  - Typically production data is not stabilized therefore
  - "b" parameter is not constant over time. Decreases with depletion
  - It is not uncommon to see "b" > 1
  - Overestimation of reserves and future performance
- **Enhancements**
  - Use an average "b_e" coefficient as described by Chen on SPE 108176. During entire depletion "b_e" will be less than 1
  - Find a function that describes "b" behavior as stated by T. Blasingame work



Graph from: SPE 108176

- *Observed Behavior of Decline Parameter (D):*

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

- *Solving for Flowrate:*

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

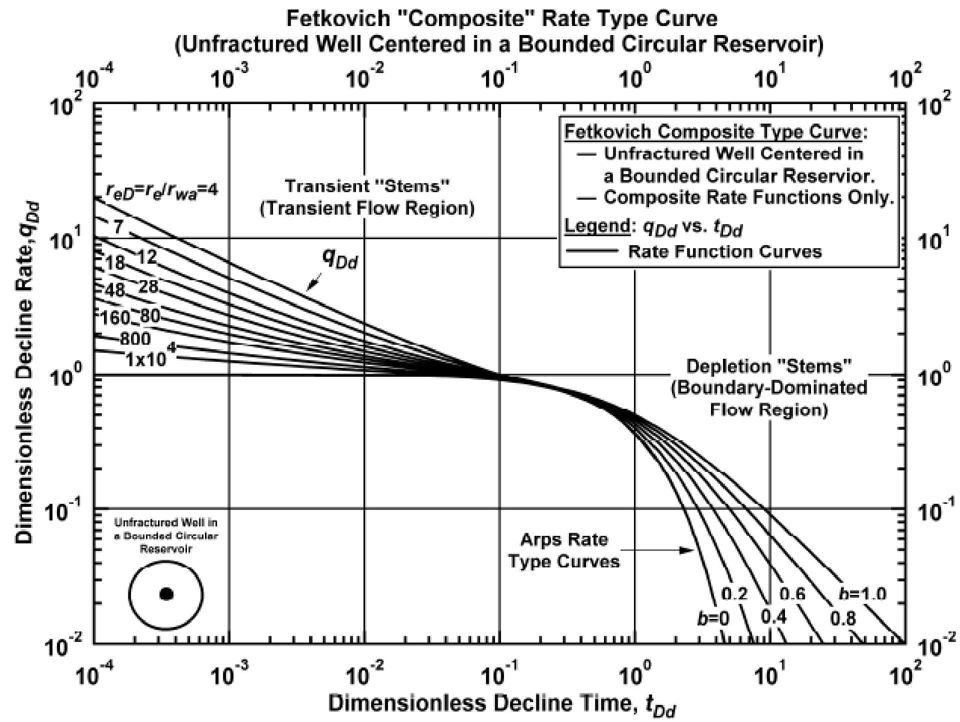
- *Solving for the b-Parameter:*

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

Equations from: Production Analysis Notes. Tom Blasingame. TAM - 2009

Fetkovich's Composite Method

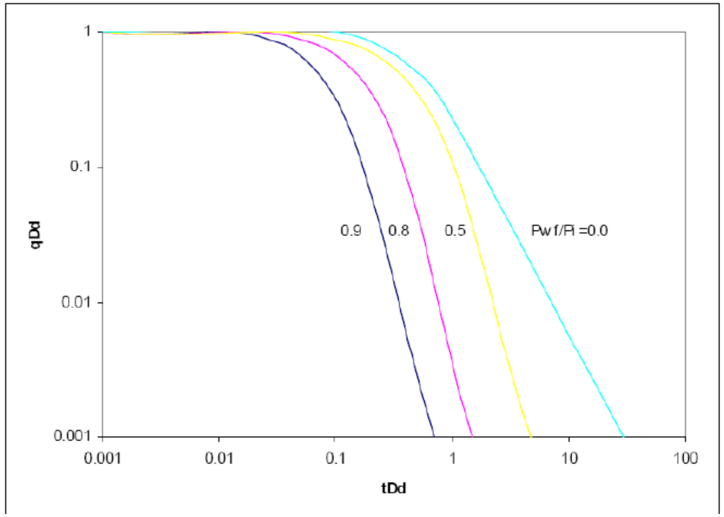
- Utilization
  - Analyze production data
  - Predict future well performance
  - Estimate ultimate reserves (EUR)
  - Allows analyzing well performance not only during BDF but also during transient flow
- Assumptions
  - Constant bottom hole pressure
  - Derived for liquids
  - Radial flow in a circular drainage area
  - Transient and BDF
- Math behind
  - Analytical solution for transient period
  - Arp's solution for BDF



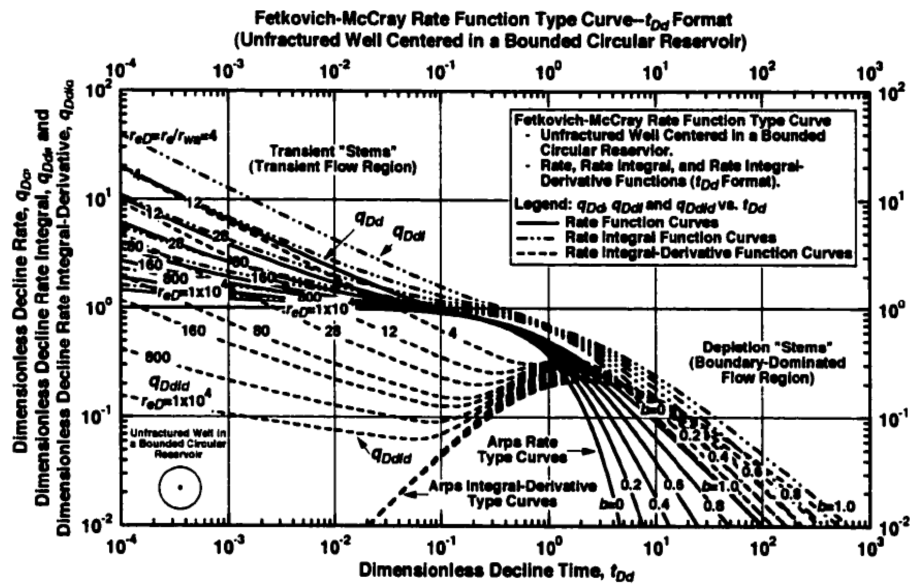
Graph from: Production Analysis Notes. Tom Blasingame. TAM - 2009

Fetkovich's Composite Method

- **Limitations**
  - Only valid for liquids
  - Well produced at constant bottom hole pressure
- **Enhancements**
  - Combination of back pressure gas rate equation and material balance. Replaces Arp's section
  - Introduction of derivative function
- **Additional features**
  - Allow estimating not only EUR but also permeability, hydraulic fracture dimensions, skin factor and drainage area
  - Derivative allows better matching



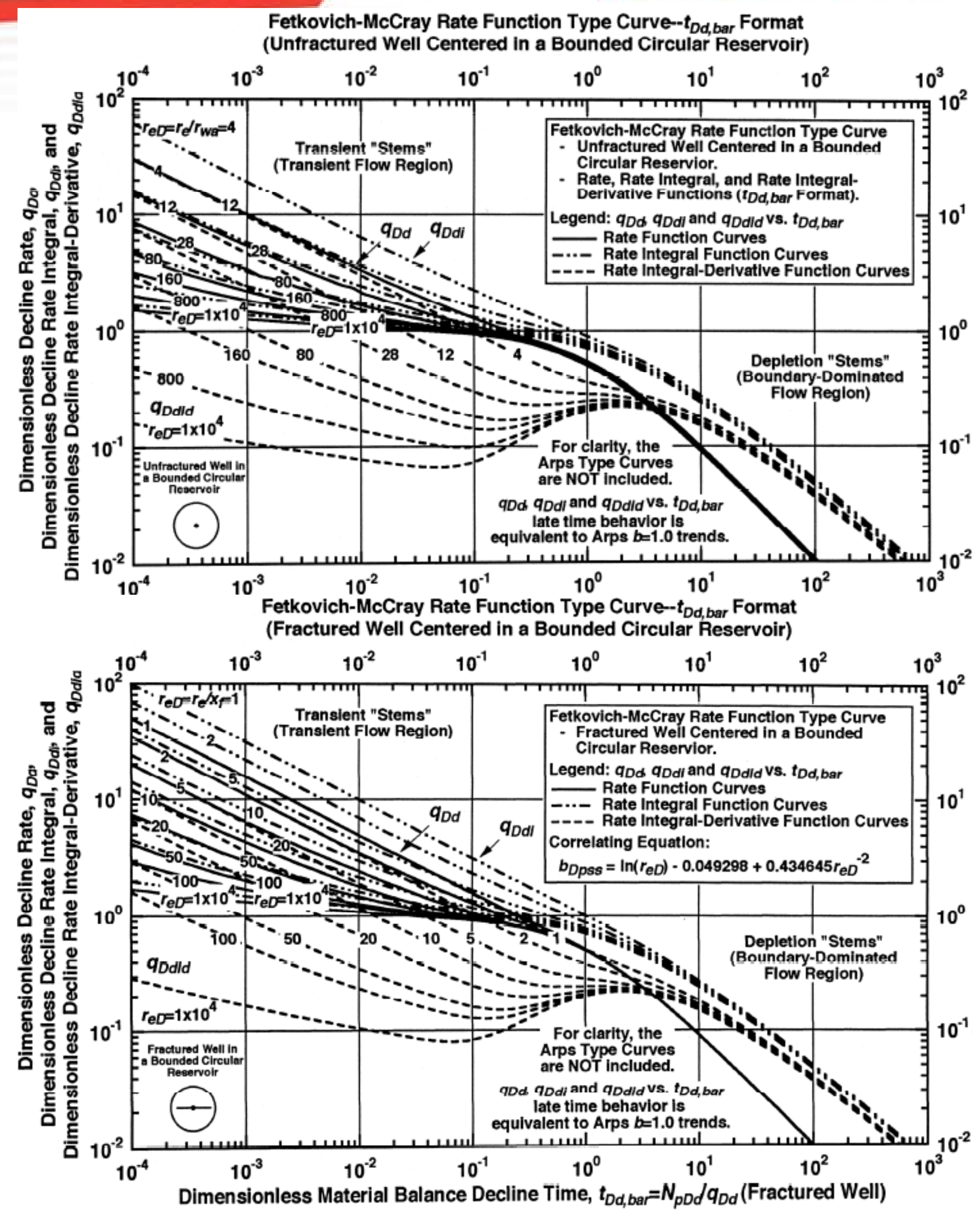
Graph from: Using Multi Layer Models to Forecast Gas flow Rates in Tight Gas Reservoirs – Sergio Armando Jerez Vera – MsC - TAM



Graph from: Analysis of Long Term Behavior in Tight Gas Reservoirs – Jorge Alberto Arevalo Villagran – PhD - TAM

Palacio / Doublet / Blasingame's Type Curves

- **Limitations**
  - Bounded circular reservoir
- **Enhancements**
  - Introduction of derivative function and integral derivative. Better matching and identification
  - Use of MBT. All solutions converge to a common stem. Strong confirmation of BDF
- **Additional features**
  - One curve for unfractured wells and other for stimulated wells



Graphs from: Production Analysis Notes. Tom Blasingame. TAM - 2009

Material Balance Time (MBT)

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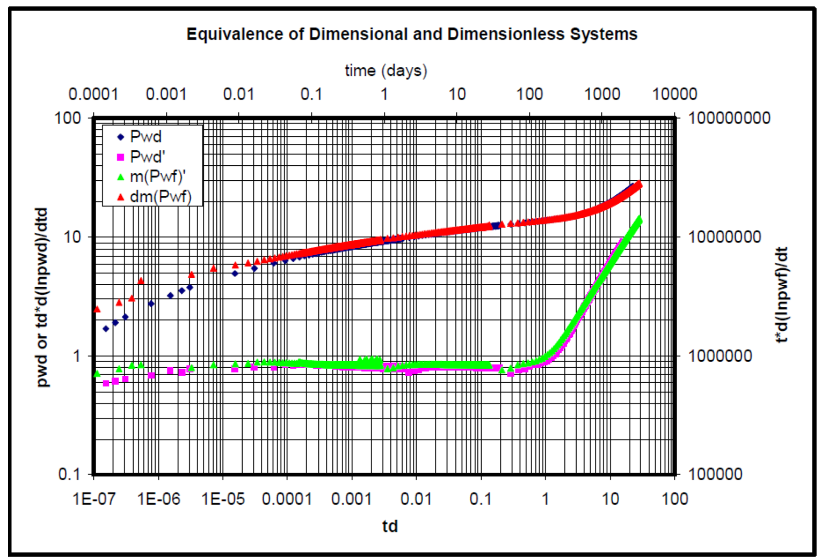
- **Weakness of traditional methods**
  - Unreliable average reservoir pressure
  - Variations in rate
  - Different solutions for constant rate and constant pressure using chronological time. Confusion and misinterpretation
- **Approaches and benefits**
  - Use of superposition for accounting varying flowing gas rates
  - Chronological time is converted into Material Balance Time
  - Same time used by Agarwal and Lee to linearize transient analysis of gas wells
  - Agarwal later confirmed that constant rate and constant pressure solutions were equivalents if MBT is used
  - Vast well known analytical solutions for constant rate can be used for constant pressure cases
  - MBT yields reservoir volume

$$t_{mba,gas} = \frac{\mu_{gi} c_{gi}}{q(t)} \int_0^t \frac{q(t)}{\mu_g(\overline{p}) c_g(\overline{p})} dt$$

$$\tilde{t} = \frac{G_p}{q_g}$$



Graph from: Production Data Analysis of Shale Gas Reservoirs – Adam Michael Lewis – BsC - LSU

Normalized P & T Drop Functions

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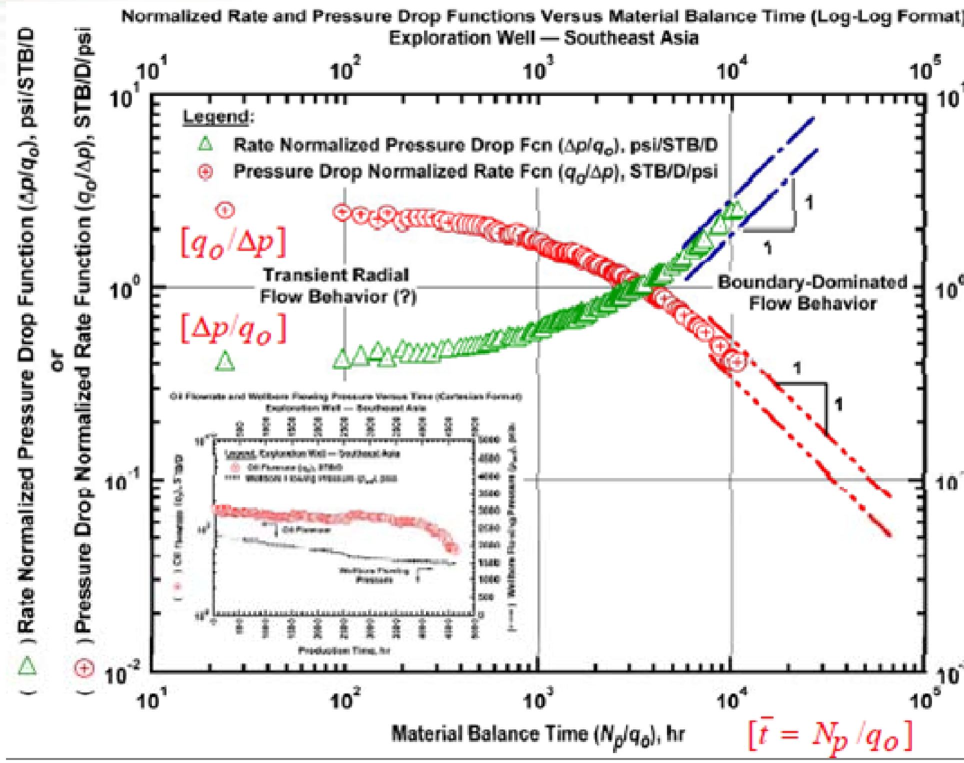
- **Utilization**
  - Analyze production data
  - Predict future well performance
  - Estimate ultimate reserves (EUR)
  - Allows analyzing well performance not only during BDF but also during transient flow
- **Assumptions**
  - Transient and BDF
  - Use of MBT
- **Math behind**
  - Simple linear function between MBT and general BDF relation



$$\bar{t} = \frac{N_p}{q_o}$$

$$\frac{\Delta p}{q_o} = b_{o,pss} + m_{o,pss}\,\bar{t}$$

$$\frac{q_o}{\Delta p} = \frac{1}{b_{o,pss} + m_{o,pss}\,\bar{t}}$$

Graph and equation from: Production Analysis Notes. Tom Blasingame. TAM - 2009

Normalized P & T Drop Aux Functions

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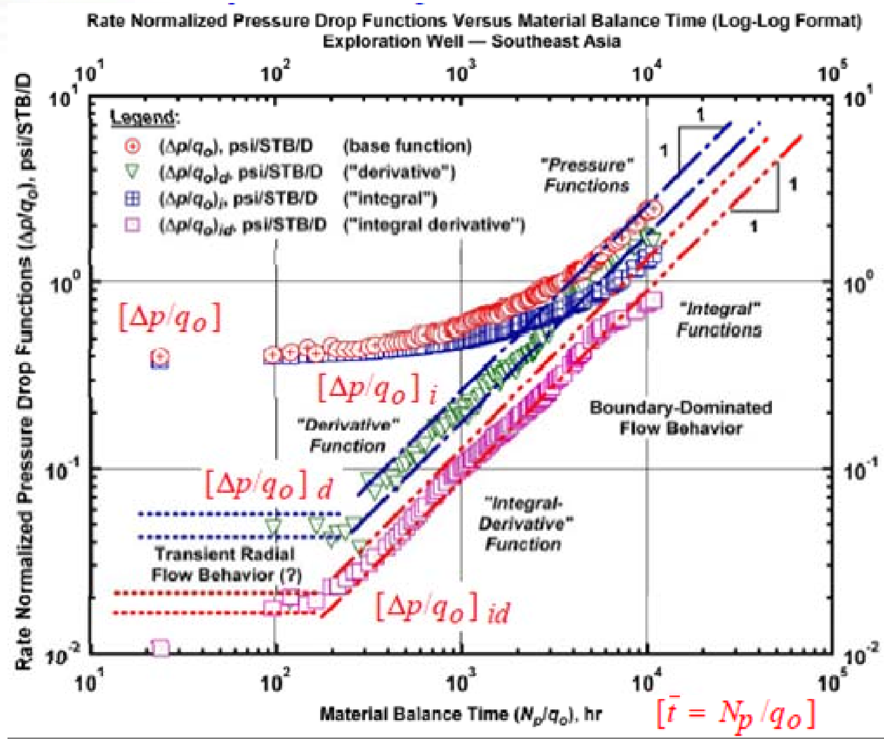
- **Utilization**
  - Analyze production data
  - Predict future well performance
  - Estimate ultimate reserves (EUR)
  - Allows analyzing well performance not only during BDF but also during transient flow
- **Assumptions**
  - Transient and BDF
  - Use of MBT
- **Math behind**
  - Normalized rate and pressure drop are functions of MBT
  - Derivative, integral and integral derivative auxiliary functions provide smooth data functions which should provide a better matching and interpretation



Normalized Pressure Drop:

- "Pressure Derivative"

$$\left[\frac{\Delta p}{q_o}\right]_d = \bar{t}\frac{d}{d\bar{t}}\left[\frac{\Delta p}{q_o}\right]$$

- "Pressure Integral"

$$\left[\frac{\Delta p}{q_o}\right]_i = \frac{1}{\bar{t}}\int_0^{\bar{t}}\left[\frac{\Delta p}{q_o}\right]d\bar{t}$$

- "Pressure Integral-Derivative"

$$\left[\frac{\Delta p}{q_o}\right]_{id} = \bar{t}\frac{d}{d\bar{t}}\left[\left[\frac{\Delta p}{q_o}\right]_i\right]$$

Normalized Flowrate:

- "Rate Derivative"

$$\left[\frac{q_o}{\Delta p}\right]_d = \bar{t}\left|\frac{d}{d\bar{t}}\left[\frac{q_o}{\Delta p}\right]\right|$$

- "Rate Integral"

$$\left[\frac{q_o}{\Delta p}\right]_i = \frac{1}{\bar{t}}\int_0^{\bar{t}}\left[\frac{q_o}{\Delta p}\right]d\bar{t}$$

- "Rate Integral-Derivative"

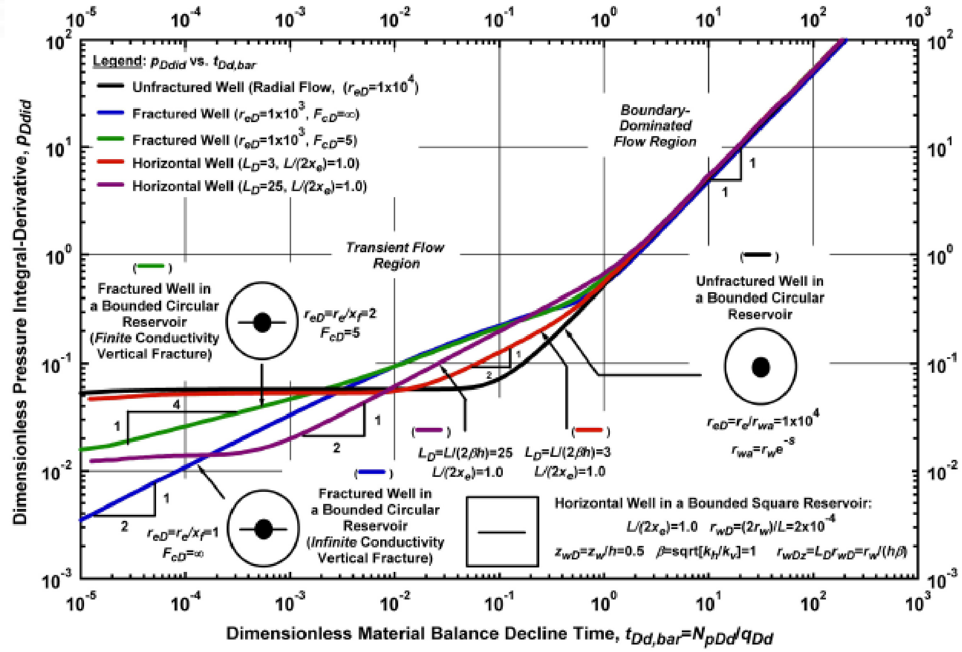
$$\left[\frac{q_o}{\Delta p}\right]_{id} = \bar{t}\left|\frac{d}{d\bar{t}}\left[\left[\frac{q_o}{\Delta p}\right]_i\right]\right|$$

Graph and equation from: Production Analysis Notes. Tom Blasingame. TAM - 2009

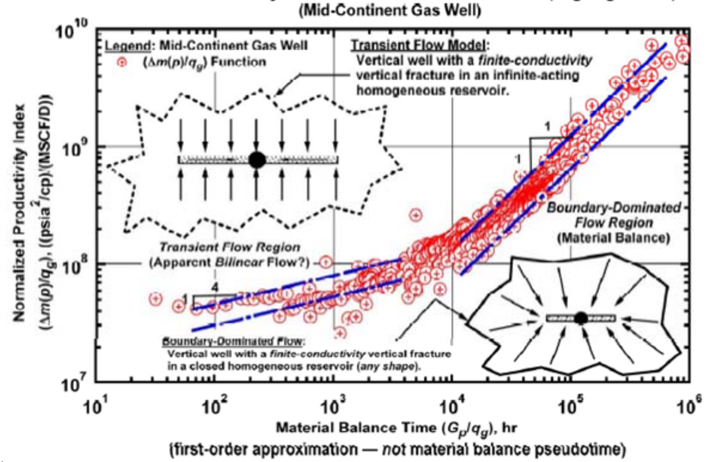
Normalized Productivity Index

- **Utilization**
  - Analyze production data
  - Predict future well performance
  - Estimate ultimate reserves (EUR)
  - Multiple well configurations
  - Allows analyzing well performance not only during BDF but also during transient flow
- **Assumptions**
  - Transient and BDF
  - Use of MBT
  - Material balance behavior is independent of reservoir shape
- **Math behind**
  - Simple functions between MBT and general BDF relation

Type Curve for Dimensionless Pressure Integral-Derivative (p_{Ddid}) — $t_{Dd,bar}$ Format
Various Reservoir Models and Well Configurations (as noted)



Normalized Productivity Index Versus Material Balance Time (Log-Log Format)
(Mid-Continent Gas Well)

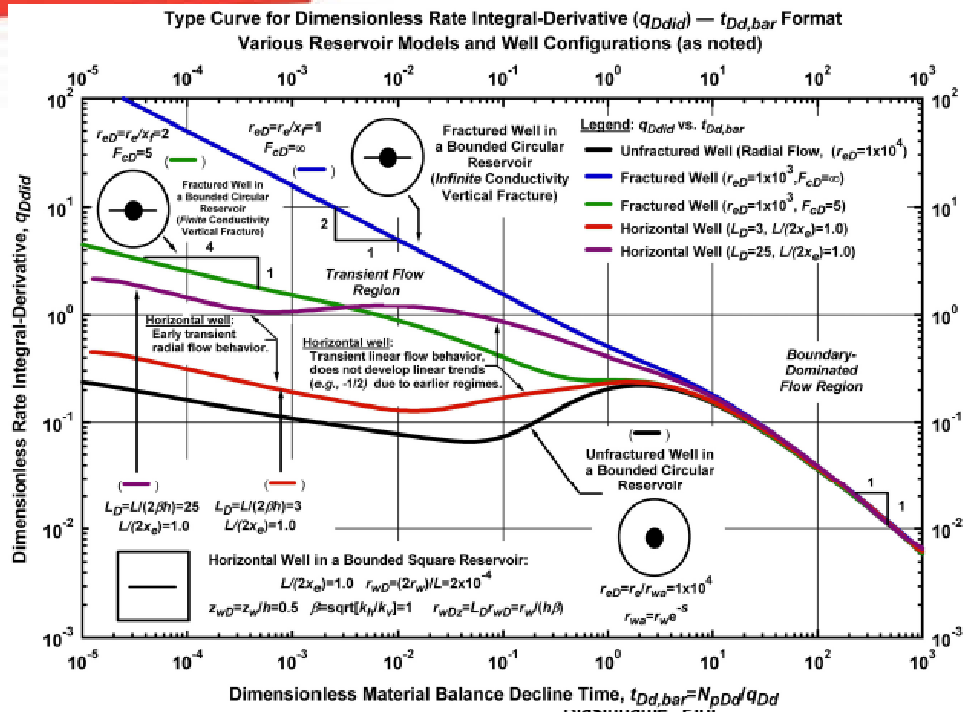


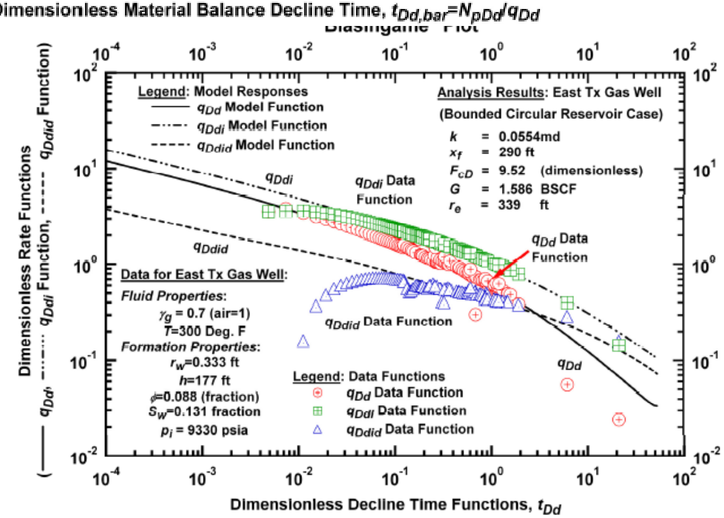
$$\bar{t} = \frac{N_p}{q_o} \qquad \left[\frac{\Delta p}{q_o}\right]_i = \frac{1}{\bar{t}}\int_0^{\bar{t}}\left[\frac{\Delta p}{q_o}\right]d\bar{t} \qquad \left[\frac{\Delta p}{q_o}\right]_{id} = \bar{t}\,\frac{d}{dt}\left[\left[\frac{\Delta p}{q_o}\right]_i\right]$$

Graphs and equations from: Production Analysis Notes. Tom Blasingame. TAM - 2009

Blasingame's Plot

- **Utilization**
  - Analyze production data
  - Predict future well performance
  - Estimate ultimate reserves (EUR)
  - Multiple well configurations
  - Allows analyzing well performance not only during BDF but also during transient flow
- **Assumptions**
  - Transient and BDF
  - Use of dimensionless time functions
- **Math behind**
  - Simple functions between MBT and general BDF relation





Graph and equations from: Production Analysis Notes. Tom Blasingame. TAM - 2009

$$\bar{t} = \frac{N_p}{q_o} \qquad \left[\frac{q_o}{\Delta p}\right]_i = \frac{1}{\bar{t}}\int_0^{\bar{t}}\left[\frac{q_o}{\Delta p}\right]d\bar{t} \qquad \left[\frac{q_o}{\Delta p}\right]_{id} = \bar{t}\left|\frac{d}{d\bar{t}}\left[\left[\frac{q_o}{\Delta p}\right]_i\right]\right|$$

Quadratic Model Method (QMM)

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Equations from: SPE 98042

- Utilization
  - Analyze production data
  - Estimate gas in place (GIP) and ultimate reserves (EUR)
- Assumptions
  - Volumetric dry gas reservoir
  - Pseudo-steady state flow conditions
  - Pwf, bottom= constant
  - Model includes pressure dependent properties
- Math behind
  - Rate and time data matched simultaneously to five different plotting functions
  - Quadratic rate-time / rate cumulative functions
  - Better match than Arps's method

Plotting Function	Function Type	Result
q_g vs. G_p	Quadratic	Root = G
$(q_g)_{i,G_p}$ vs. G_p	Quadratic	Root = 1.5 G
$\dfrac{q_{gi} - q_g}{G_p}$ vs. G_p	Linear	Intercept, G_{pmax} = 2 G
$\dfrac{(q_g)_{i,G_p} - q_{gi}}{G_p}$ vs. G_p	Linear	Intercept, G_{pmax} = 3 G
$\dfrac{(q_g)_{i,G_p} - q_g}{G_p}$ vs. G_p	Linear	Intercept, G_{pmax} = 1.5 G

Method derived from rigorous coupling of gas material balance equation for a volumetric dry gas system and a modified version of the stabilized gas flow equation for a gas well producing at constant bottom hole flowing pressure

Quadratic Model Method (QMM)

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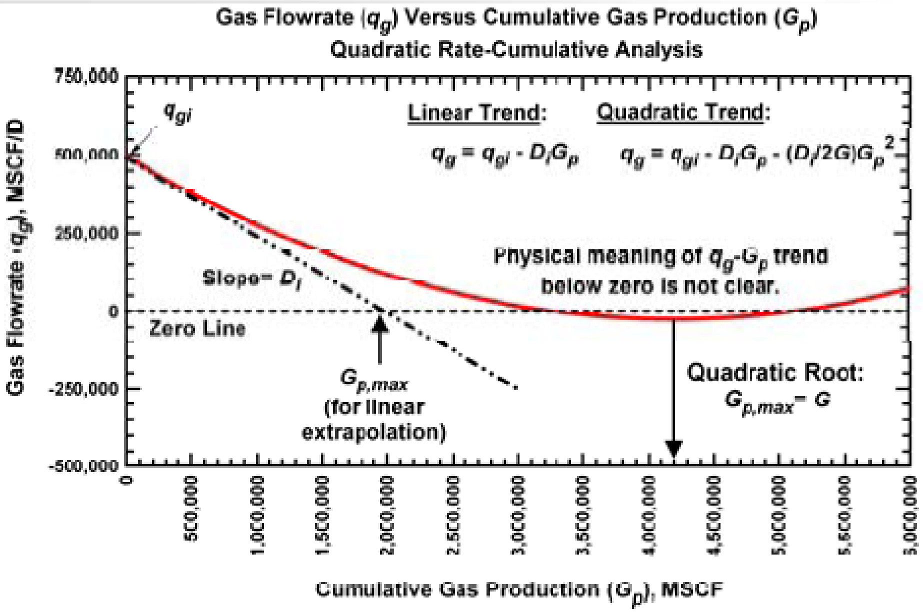
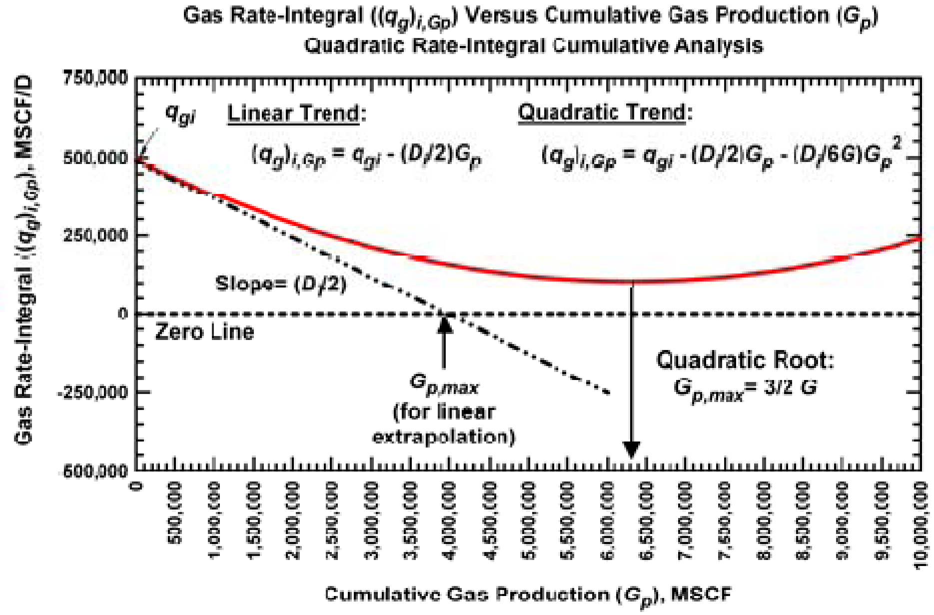
Graphs from: SPE 98042

q_g vs G_p Model



$(q_g)_{i,Gp}$ vs G_p Model



- **Interpretation**
  - Curve trend above line of zero rate reflects typical decline
  - Slope through q_{gi} is dimensionless decline rate constant "D_i"
  - Intercept of curve with zero rate line is the maximum gas than can be produced at initial conditions
  - Minimum point denotes actual value of gas in place (GIP)

- **Interpretation**
  - Similar quadratic behavior to q_g vs G_p model. Curve is never negative. Integral function
  - Slope through q_{gi} is dimensionless decline rate constant "$D_i/2$"
  - Intercept of curve with zero rate line is the maximum gas than can be produced at initial conditions
  - Minimum point has G_{pmax}= 1.5 GIP

Quadratic Model Method (QMM)

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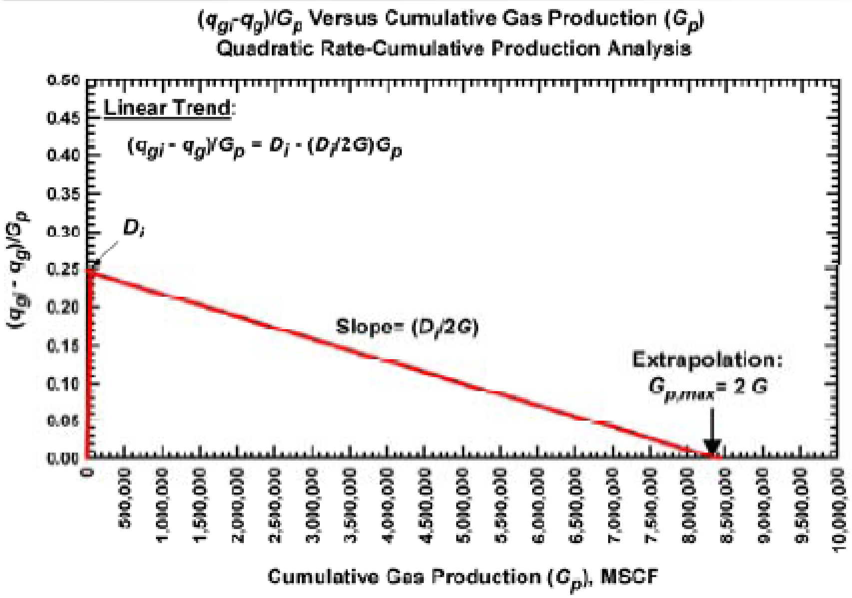
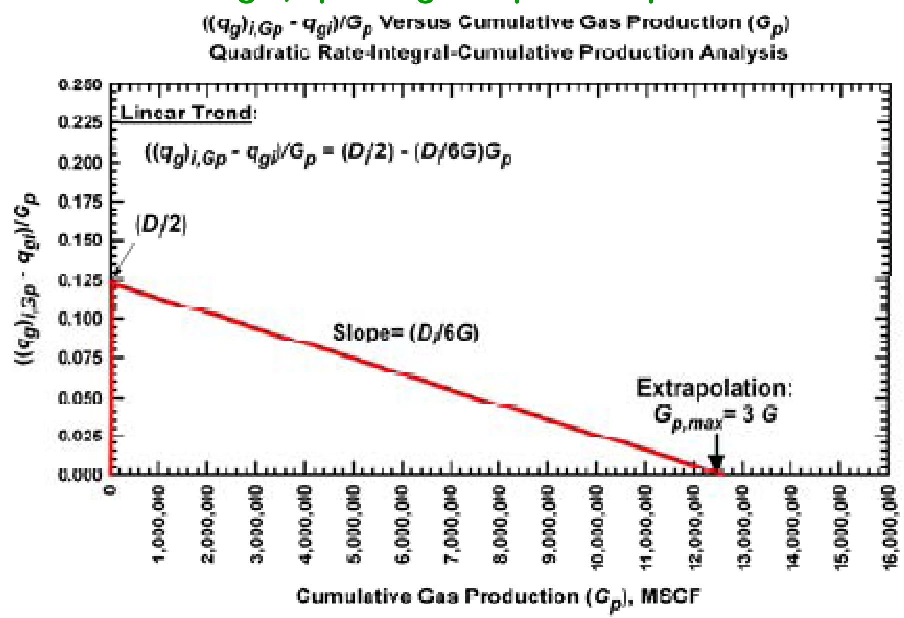
Graphs from: SPE 98042

$(q_{gi} – q_g)/G_p$ vs G_p Model



- **Interpretation**
  - Function not significantly affected by long term transient flow
  - Initial gas flow rate (q_{gi}) is the most difficult parameter to match
  - Straight line. Intercepts Y axis at D_i
  - Slope of straight line is dimensionless decline rate constant "$D_i/2G$"
  - Intercept X axis at G_{pmax}= 2G

$((q_g)_{i,Gp} – q_{gi})/G_p$ vs G_p Model



- **Interpretation**
  - Smoother function than previous one. Occasionally affected by extended transient flow behavior
  - Straight line. Integral function. Intercepts Y axis at $D_i/2$
  - Slope of straight line is dimensionless decline rate constant "$D_i/6G$"
  - Intercept X axis at G_{pmax}= 3G

Quadratic Model Method (QMM)

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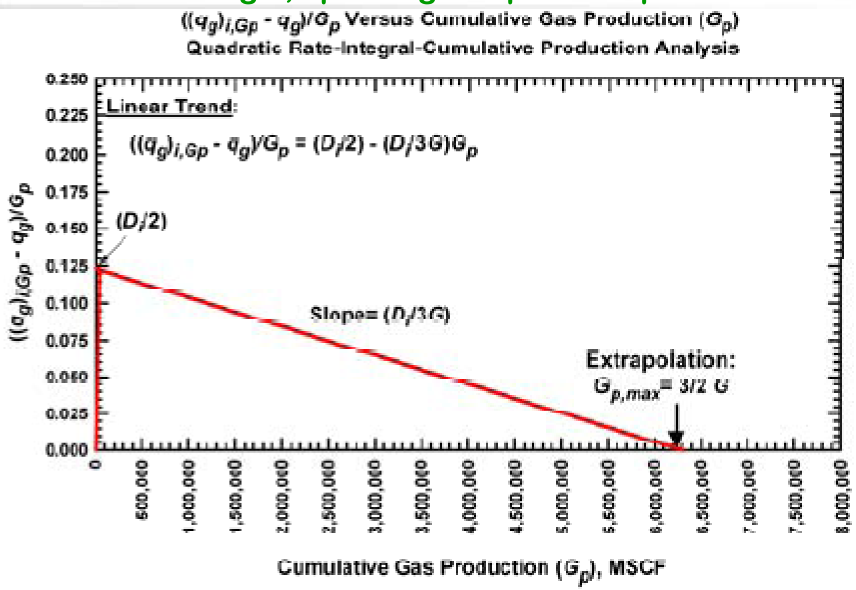
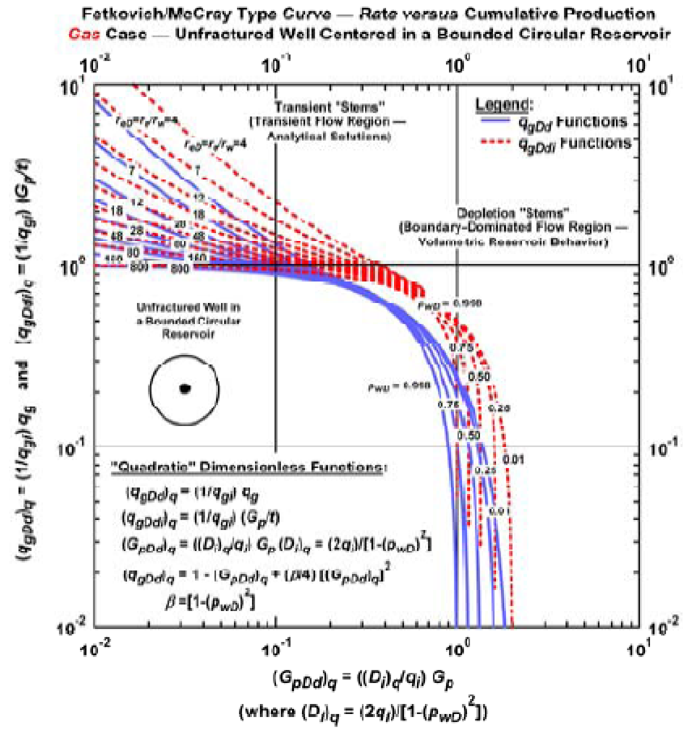
Graphs from: SPE 98042

$((q_g)_{i,Gp} - q_g)/G_p$ vs G_p Model



Quadratic Model Type Curve

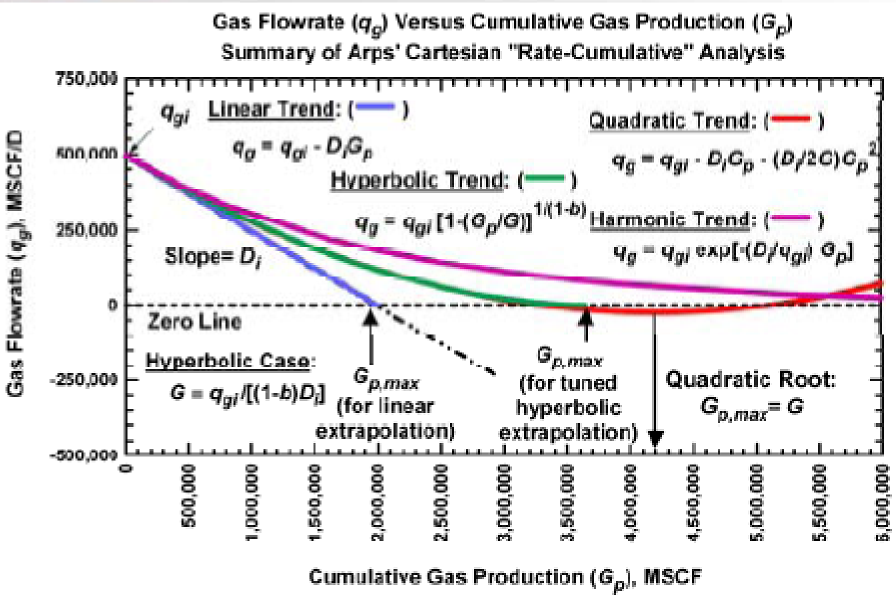


- **Interpretation**
  - q_{gi} has been eliminated. An extended transient flow period could affect the integral function. Some distortion may arise under certain conditions, so certain caution must be exercised . Most sensitive of the proposed functions
  - Straight line. Intercepts Y axis at $D_i/2$
  - Slope of straight line is dimensionless decline rate constant "$D_i/3G$"
  - Intercept X axis at G_{pmax}= 3G/2

- **Interpretation**
  - Dimensionless rate and time-averaged rate vs dimensionless cumulative production based on the quadratic model

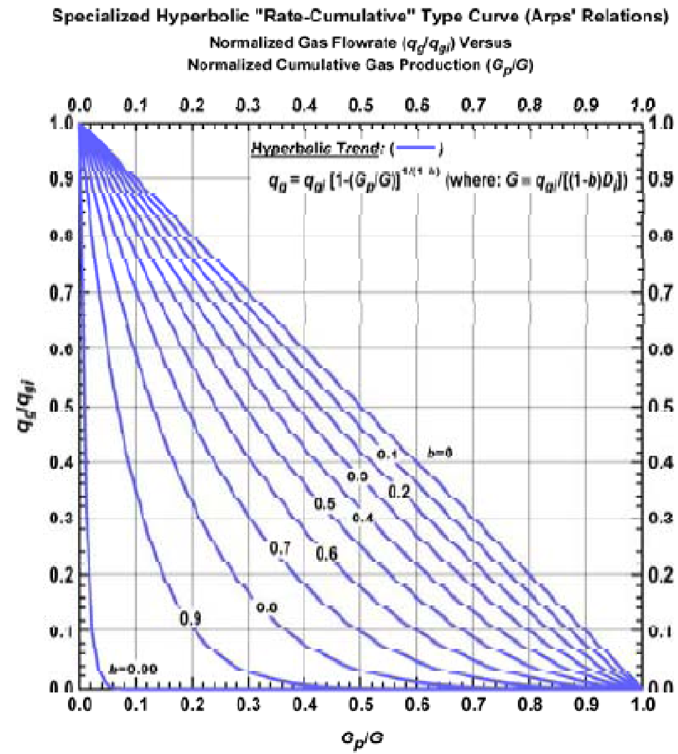
Quadratic Model Method (QMM)

Graphs from: SPE 98042



- **Comparison of methodologies**
  - Tuned hyperbolic extrapolation matches quadratic model
  - Harmonic model over-predicts results

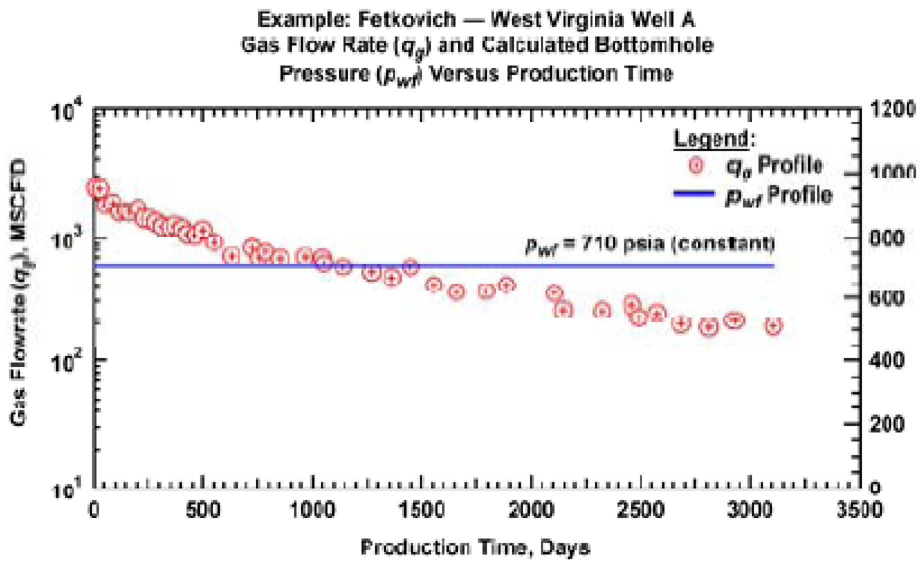
Confirmation Plot

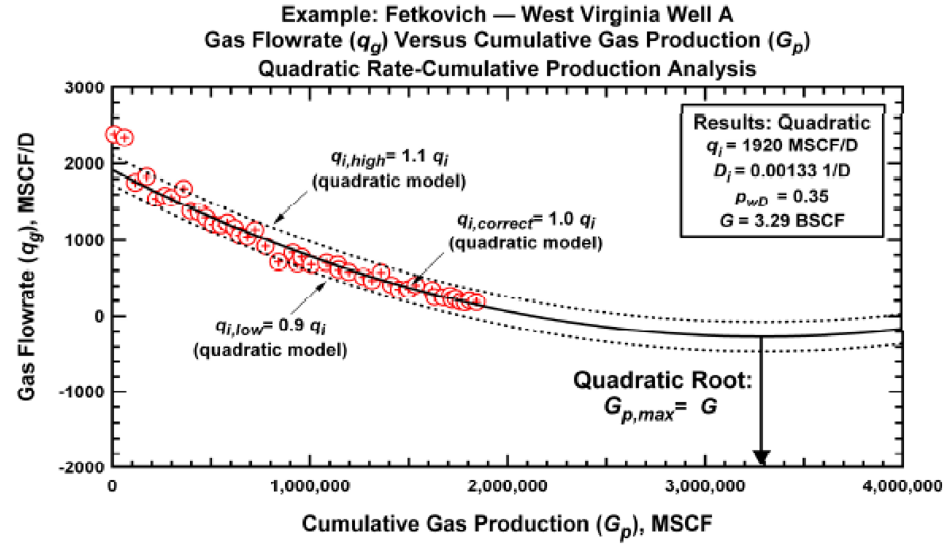


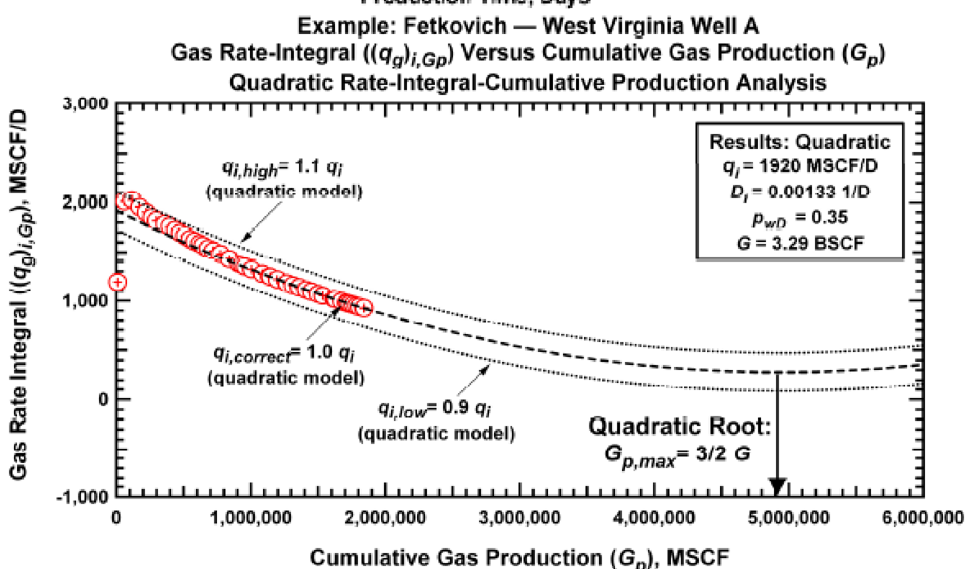
- **Interpretation**
  - Redefined plot using an approach similar to Arps's curves to qualify hyperbolic decline for analysis purposes

QMM – Example Real Well

Graphs from: SPE 98042



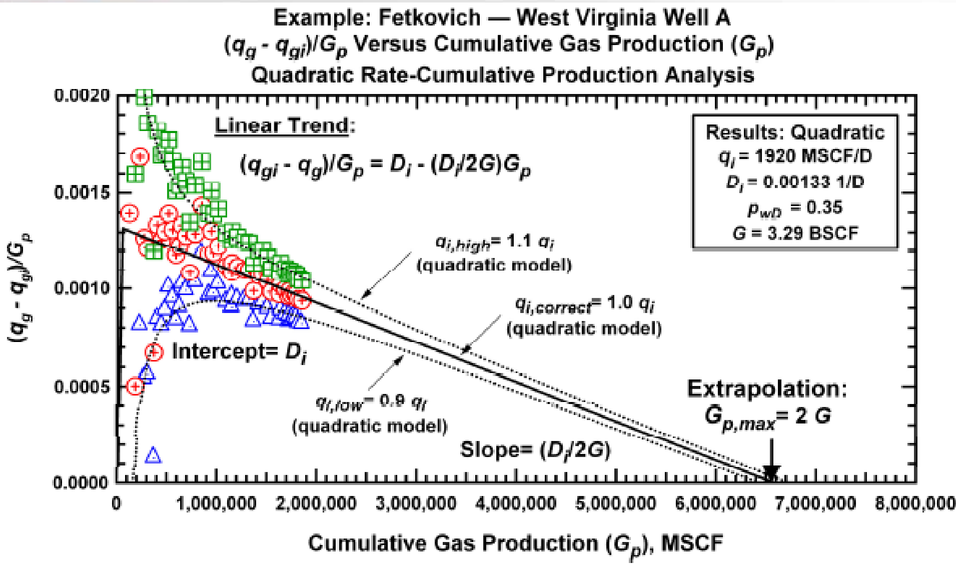


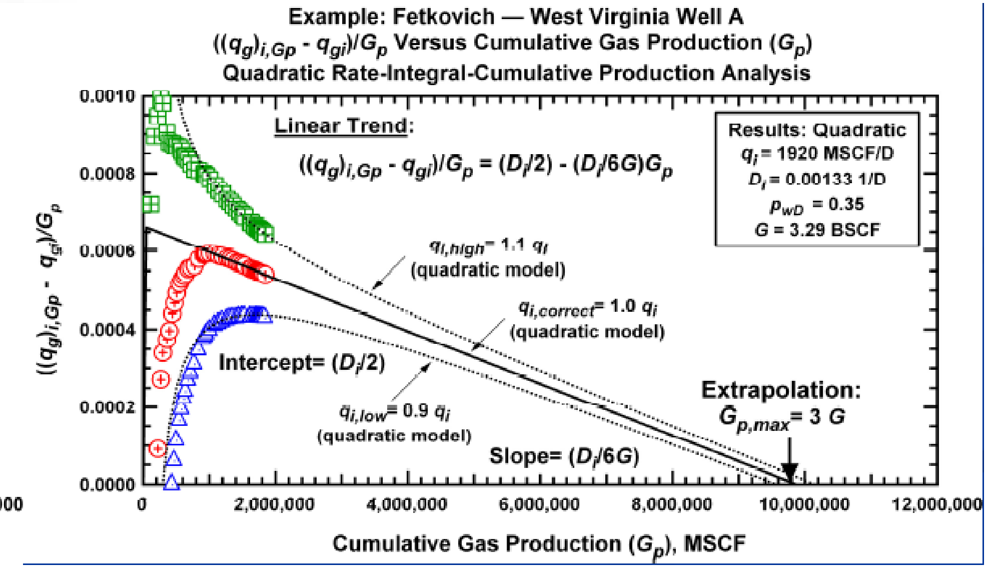


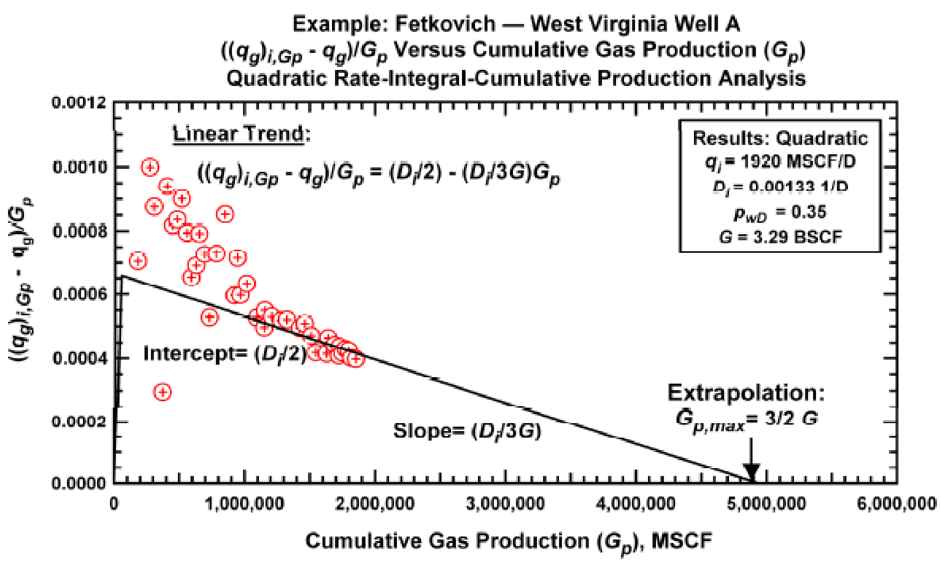
- **Interpretation**
  - First two functions have an excellent match with well data
  - Direct estimation of initial gas rate, dimensionless decline rate parameter and gas in place

QMM – Example Real Well

Graphs from: SPE 98042







Interpretation

- Special functions also have an excellent match with well data. Last function as previously mentioned is most noisy
- Direct estimation of initial gas rate, dimensionless decline rate parameter and gas in place
- Advantage: five different functions must converge to similar estimations. Provides additional strength to analysis methodology

QMM – Example Real Well

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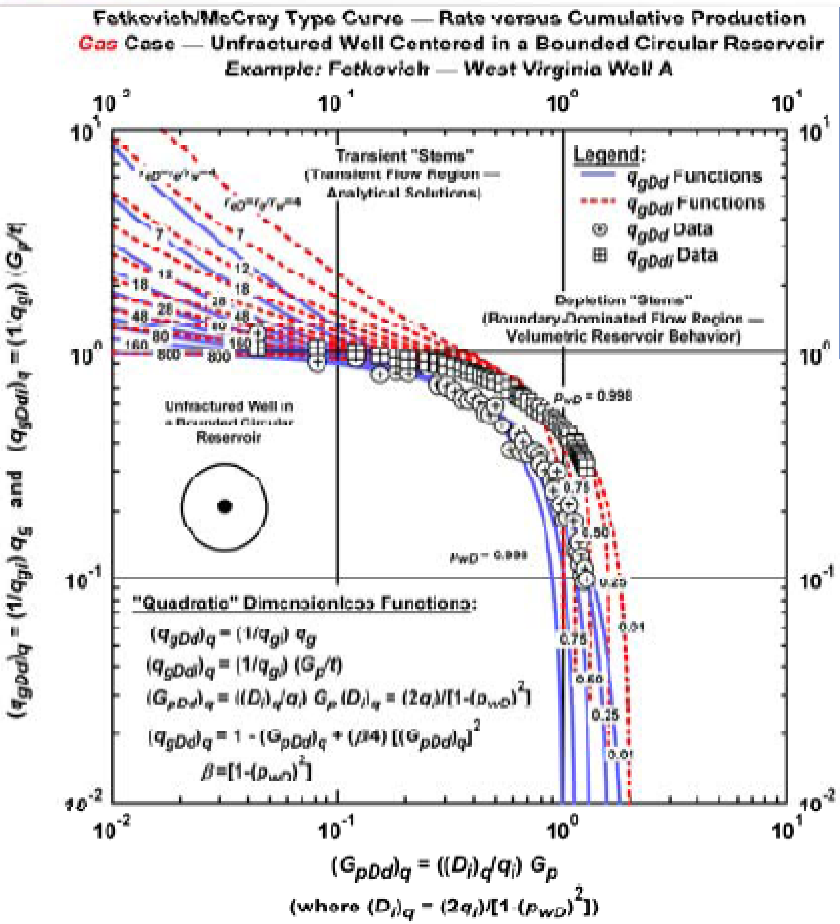
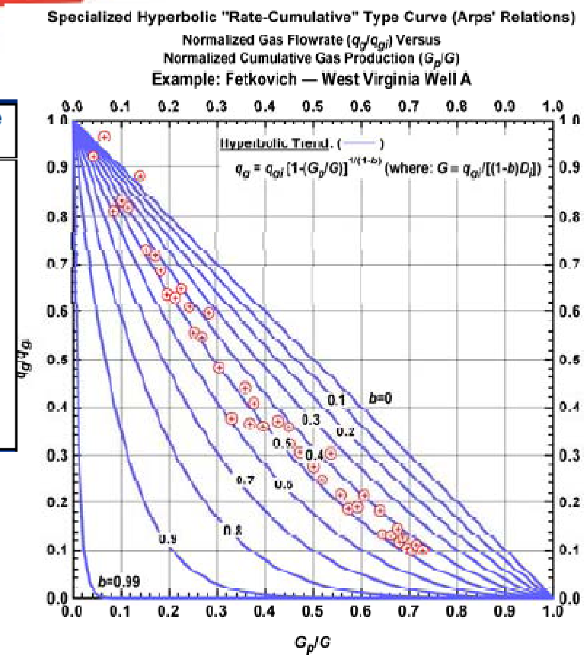
Graphs from: SPE 98042



Method	Gas-in-Place (Bcf)
Quadratic Analysis Method	3.29
Fetkovich, *et al*. (*SPE Form. Eval*., Dec. 1987)	3.36
Fraim, *et al*. (*SPE Form. Eval*., Dec. 1987)	3.04



- **Interpretation**
  - Modified Arps's curves also help into matching process
  - Confirmation plot provides direct estimation of decline rate parameter
  - For comparison purposes GIP estimation from other strong methodologies are presented to support the robustness of this methodology

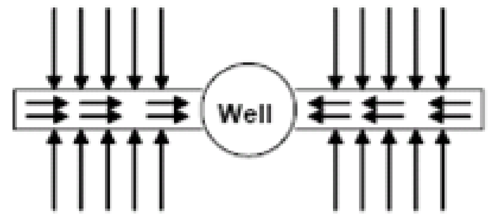
Flow Patterns in a Fractured Well

Pan American ENERGY

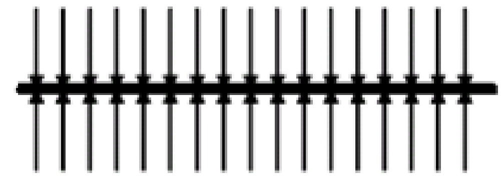
Drawing from: Well Test Analysis in Naturally Fractured Reservoir Using Elliptical Flow – Alpheus Olorunwa Igbokoyi – PhD - OSU

- Fracture linear
  - Very short period. Fluid entering into the wellbore comes from fracture expansion

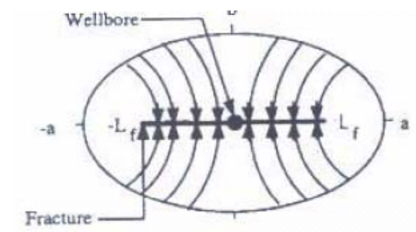
- Bilinear
  - Only evolves in finite conductivity fractures as fluid from surrounding formation flows linearly into the fracture before tip effects begin to influence well behavior



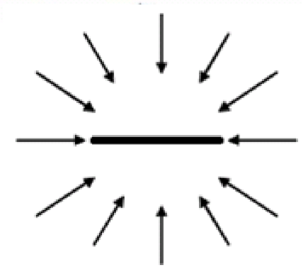
- Formation linear
  - Only occurs in highly conductive fractures. Slope ½ in log-log plots



- Elliptical
  - Transitional period that takes place at the end of the bilinear flow pattern and / or formation linear flow pattern and the onset of the pseudo radial flow pattern



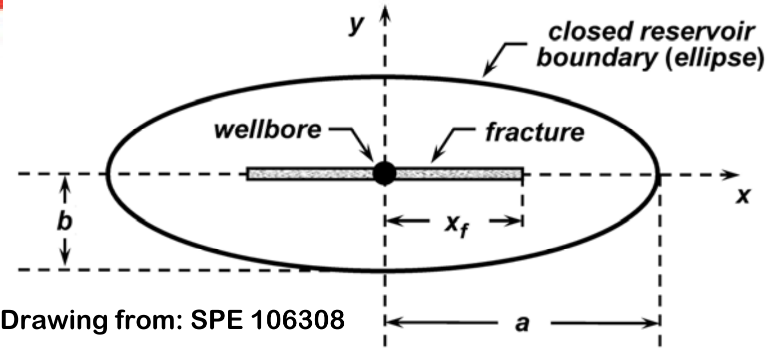
- Pseudo radial flow
  - Occurs in fractures of all conductivities, but it takes a long time to reach this pattern in TG reservoirs
  - Fracture appears to the reservoir as an expanded wellbore



Drawings from: Pressure Transient Response of a Transverse Finite Conductivity Fracture Intercepted by an Horizontal Well – Mohammed Saad Al-Kobaisi – MsC - OSU

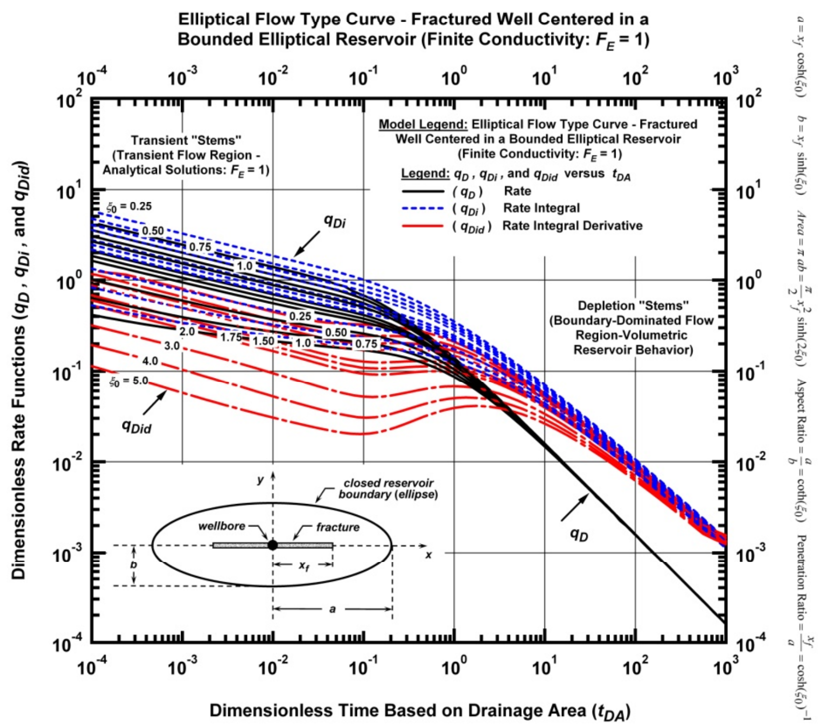
Elliptical Flow

- Impact on TG reservoirs
  - Can dominate the well performance
  - Also visible in anisotropic reservoirs
  - Reservoir properties begin to dominate well performance
  - It can last from months to years depending on perm and hydraulic fracture properties
- Math behind
  - Elliptical outer boundary has same length as fracture so a single parameter can be used to characterize many aspects of drainage area
  - Type curves obtained from an analytical solution. Curves are generated for different fracture conductivities and characterization parameter
- Utilization
  - Optimum well spacing and aspect ratio
  - Estimate drainage area
  - Fracture and reservoir properties



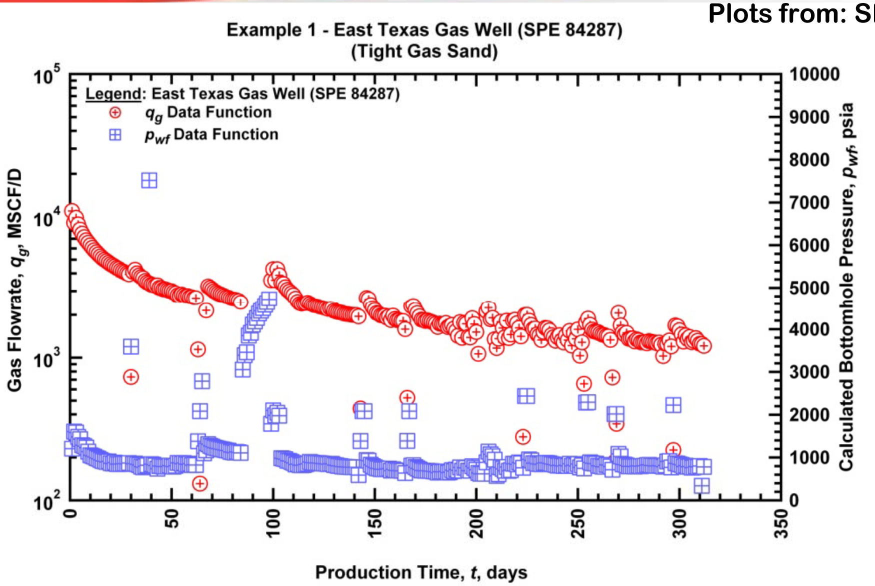
Drawing from: SPE 106308

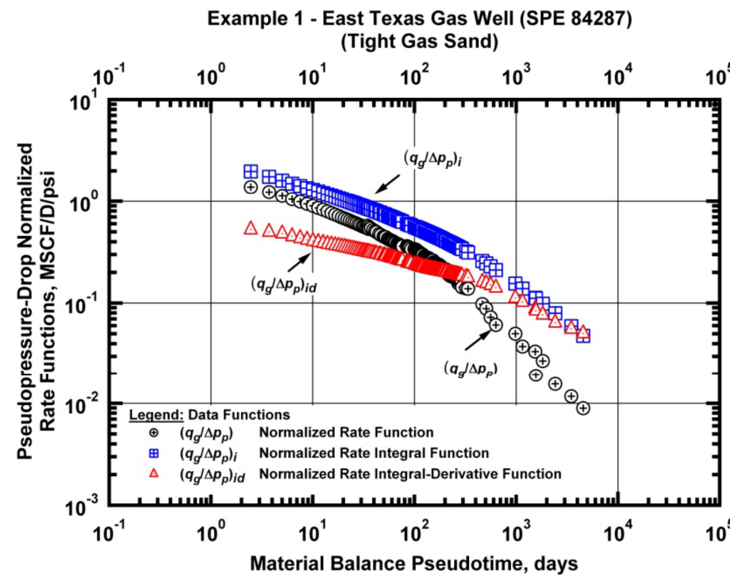
Cf= 1, 10, 100 and 1000

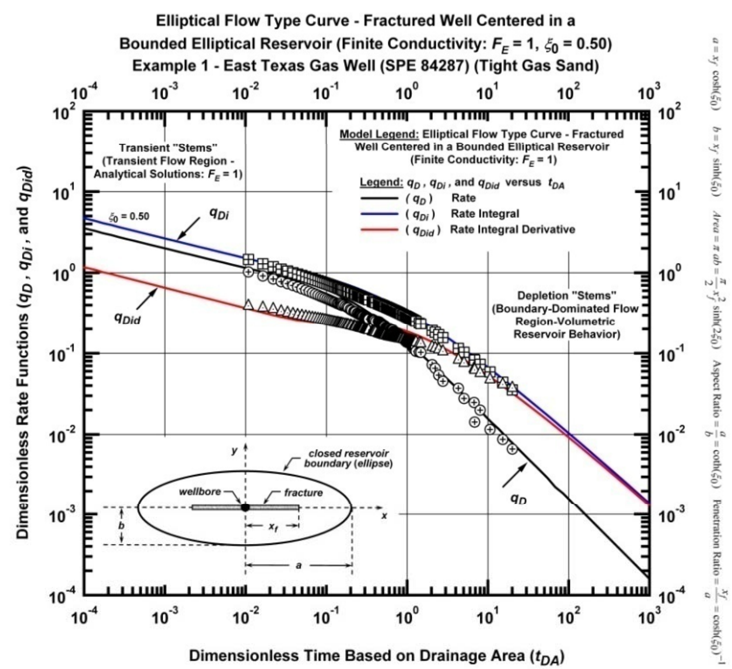


Elliptical Flow - Example

Plots from: SPE 106308







Solution: K= 0.006 mD, Xf= 300 ft, G= 1.6 Bscf

- Advantages
  - Easiness to match
  - Most of reservoir and fracture parameters are obtained
- Limitations
  - Analytical solution not suitable for common practice due to complex math and computational times associated

Multi Fractured Horizontal Wells in Conventional Reservoirs

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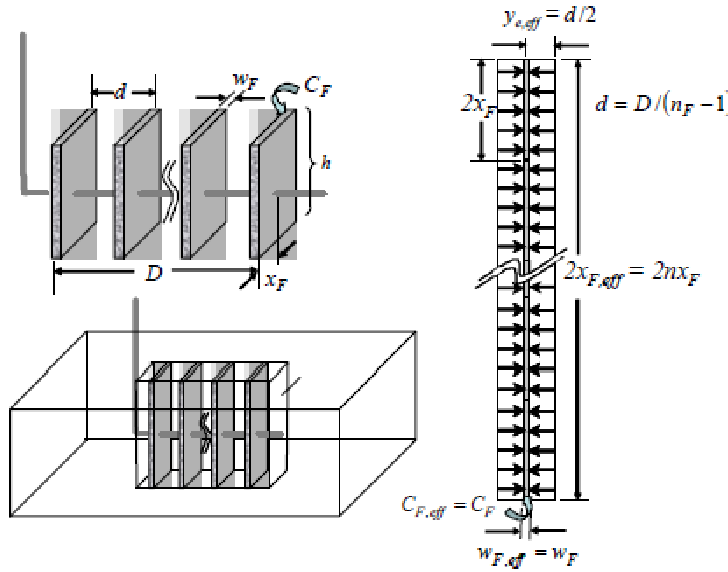
- Characteristics
  - The purpose of an horizontal well is to create a system such that the long time performance of the horizontal well will be equivalent to that of a fractured well with a specific conductivity (preferably infinite) and a fracture length equal to the distance between the two outermost fractures

Diagrams from: SPE 121290



  - Equivalent fracture length = aggregate length of the individual hydraulic fractures
  - Conductivity equivalent fracture = average of the conductivities of the individual fractures
  - Long term performance function of the effective fracture conductivity and fracture half-length
  - Effective conductivity depends on the reservoir permeability, number, distance between and conductivities of each individual fracture
  - The drainage area around the equivalent fracture is a parallelepiped with the length of the equivalent fracture and the with equal to the average hydraulic fracture spacing
  - All of this only valid if performance is governed by the long term productivity of the reservoir beyond the tips of the fractures. Pseudo-radial flow must develop around the system otherwise the concept of effective wellbore radius can not be used

Multi Fractured Horizontal Wells

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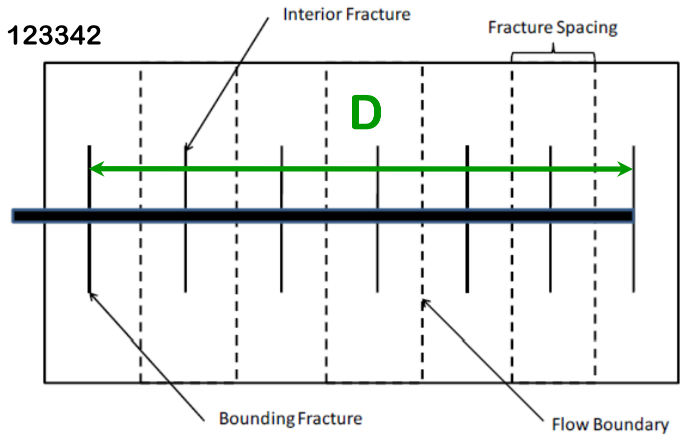
Drawing from: SPE 123342



- Transverse fractures (TF)
  - Numerous studies prove TF are best option to drain horizontal wells in TG reservoirs
  - Not all fractures contribute equal
  - Small area of contact at wellbore (choked flow)
  - Q: How many hydraulic fractures ?
- Composite system behavior
  - Time for the start of pseudo-radial flow is even larger than for vertical wells
  - Quite different flow geometry (3D) when compared to vertical well (1D)
  - Performance highly influenced by partial penetration and formation anisotropy
  - Wellbore storage is much more significant and can mask other flow regimes
  - Q: How long the horizontal section should be ?
  - Pressure drop inside the wellbore
  - Interaction of well, hydraulic fractures and natural fractures
  - Productivity is governed by linear flow perpendicular to the fracture faces confined to the stimulated volume between fractures

$$t \geq \frac{1.14\times 10^{4}\,\phi c_t \mu x_F^2}{k}$$

But Xf,eff= D/2

Transverse Fractures Behavior

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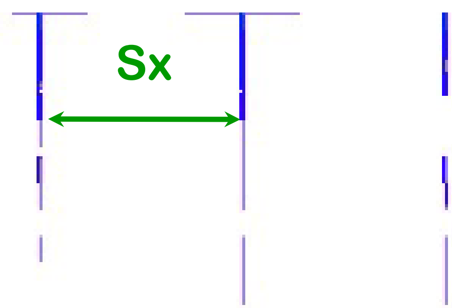
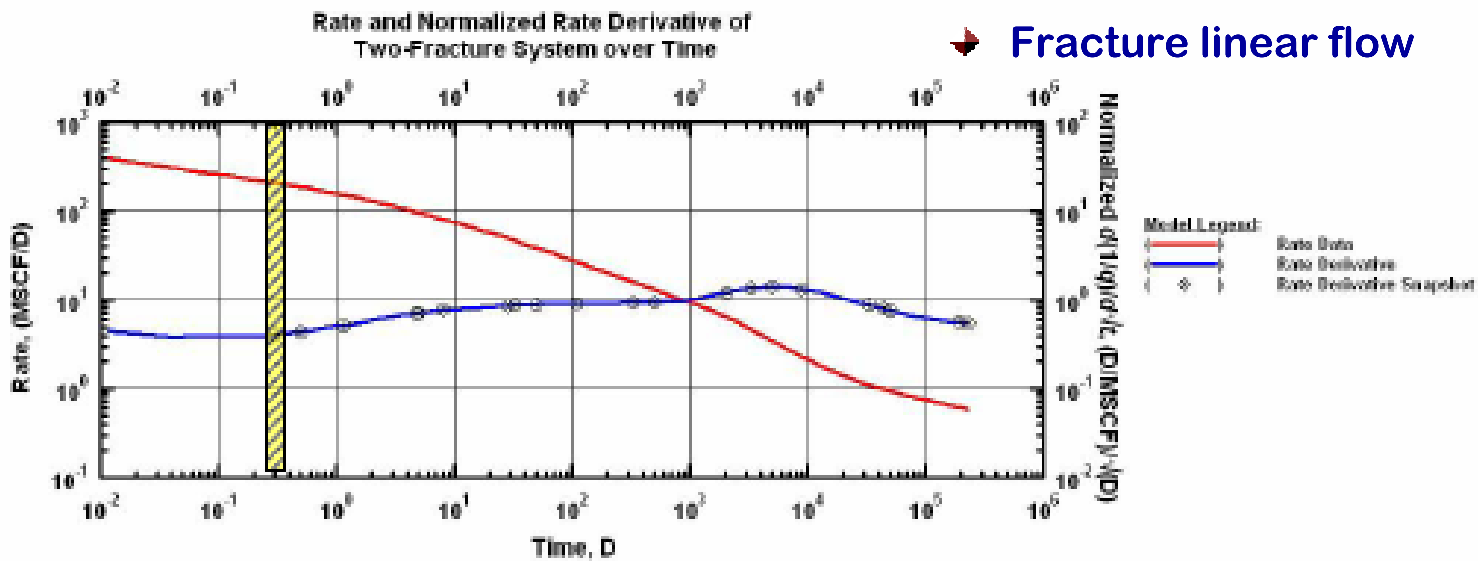
System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 0.3 days



- **Physical effect**
  - Individual fractures start cleaning up
  - Each one acts individually
  - Effective length evolves in time as fracture cleans up
- **Transient behavior**
  - Early time
  - Fracture linear flow



Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

Transverse Fractures Behavior

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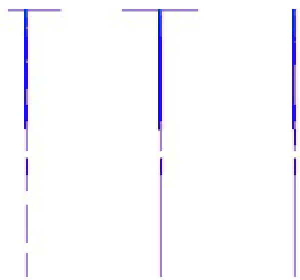
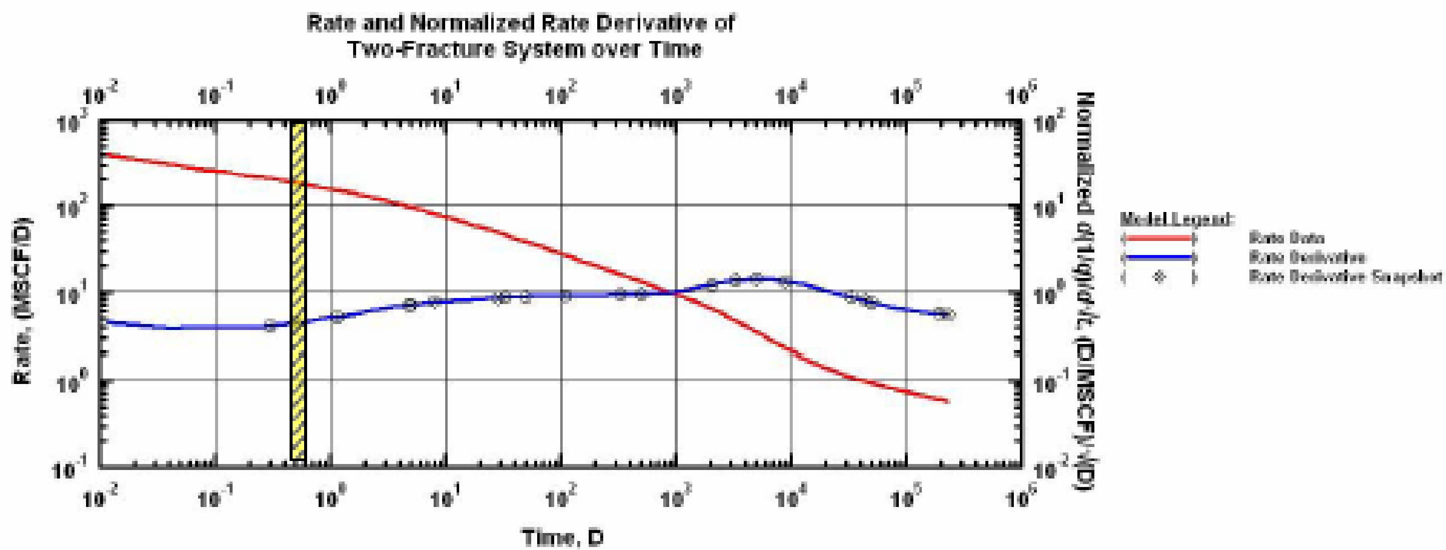
System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 0.5 days



- Physical effect
  - Fractures continue cleaning up
  - Individual behavior
- Transient behavior
  - Early time
  - Some fracture linear flow
  - Onset of formation bilinear flow

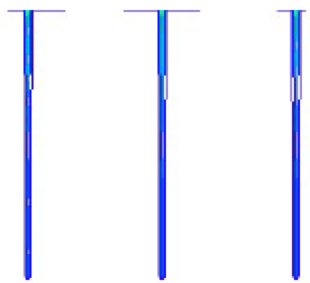


Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

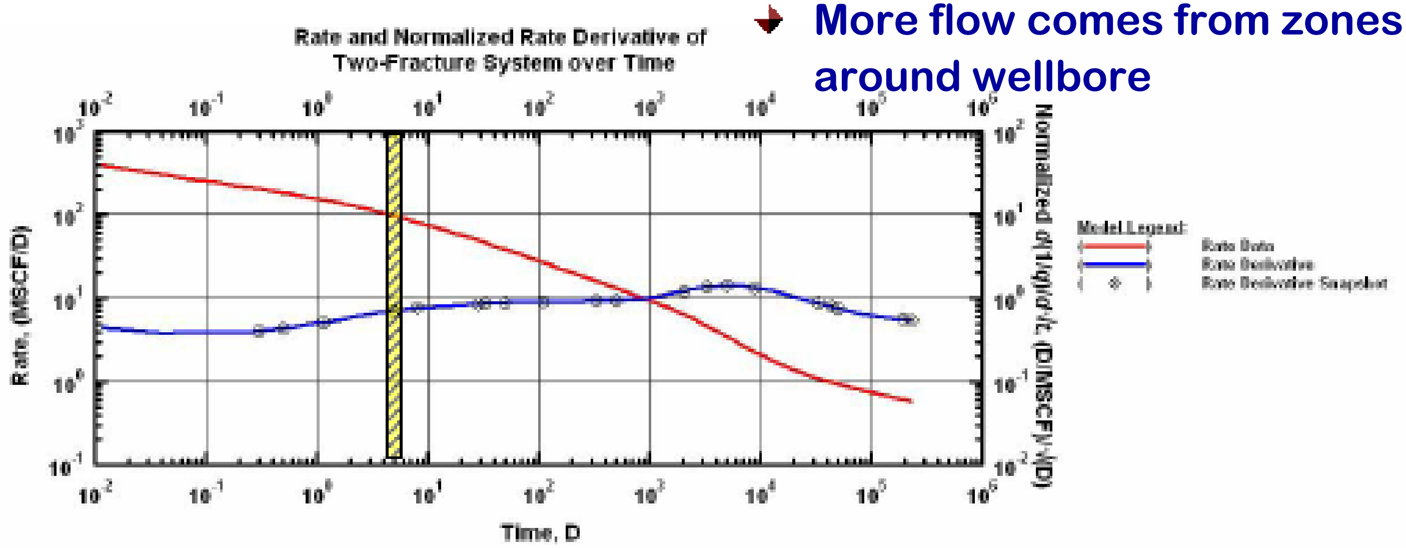
Transverse Fractures Behavior

Pan American ENERGY

System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 5 days



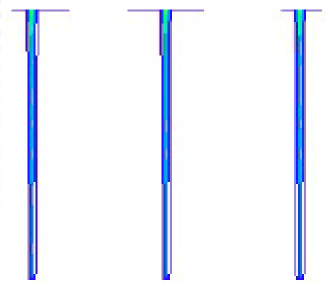
- **Physical effect**
  - Clean up ends. Effective fracture length fully developed
  - Individual behavior
- **Transient Behavior**
  - Early time
  - Formation bilinear flow
  - More flow comes from zones around wellbore



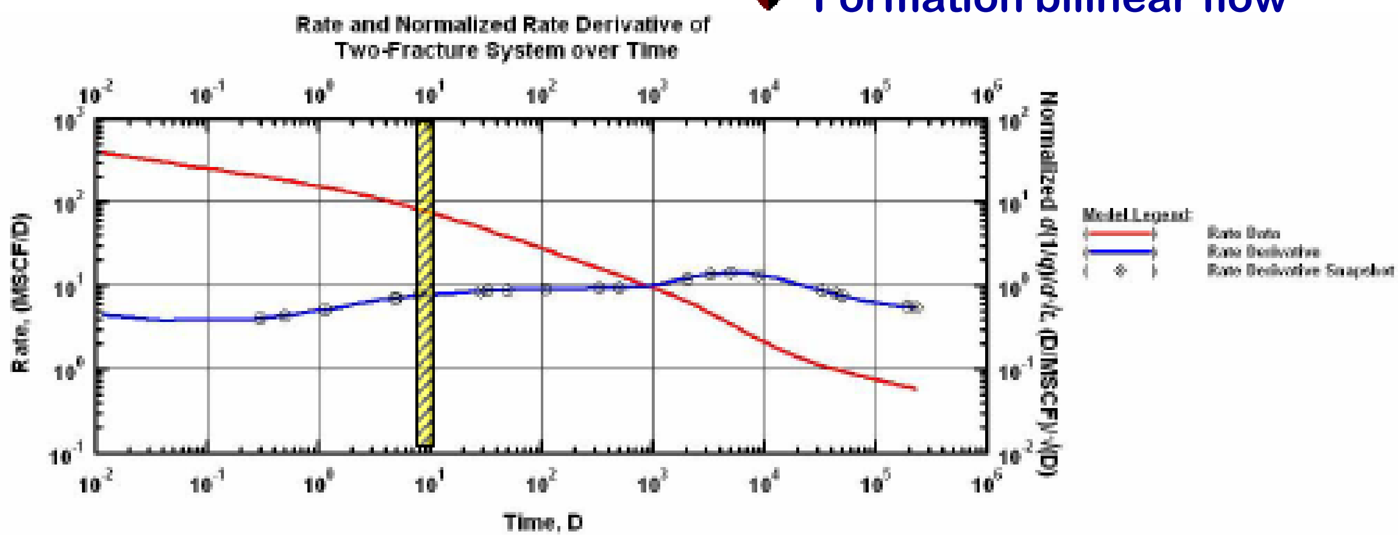
Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

Transverse Fractures Behavior

System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 8 days



- Physical effect
  - Flow from reservoir in front of fracture faces
  - Each fractures behaves individually
- Transient Behavior
  - Early time
  - Formation bilinear flow



Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

Transverse Fractures Behavior

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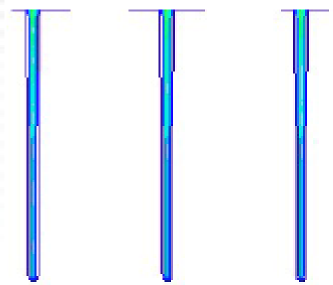
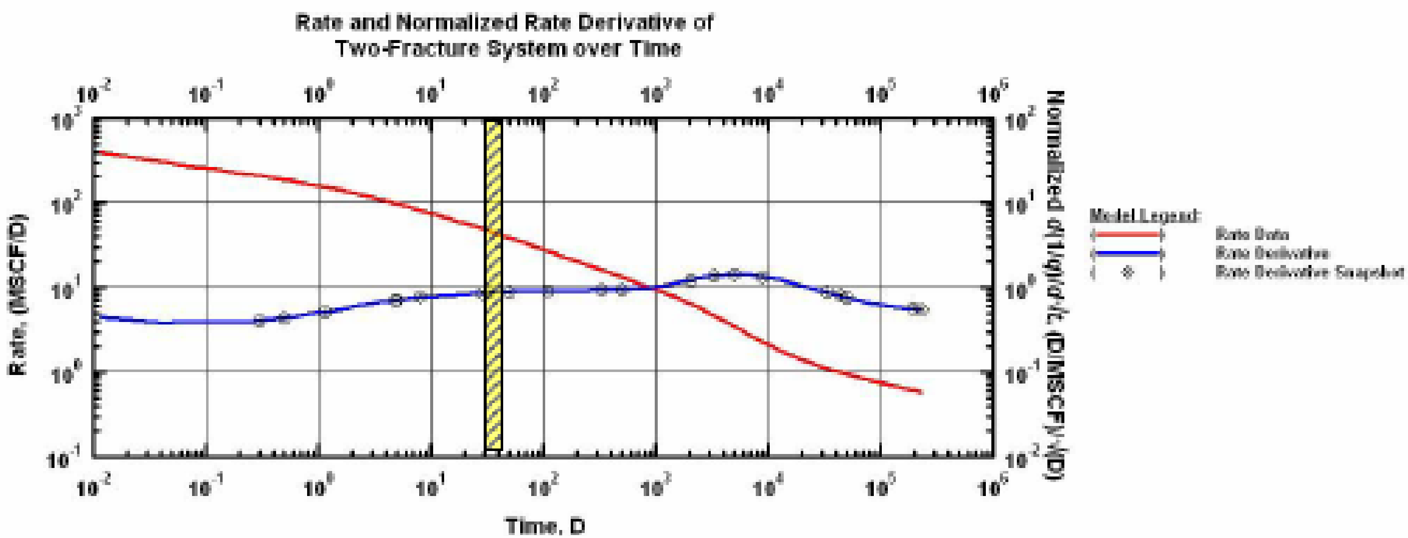
System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 33 days



- **Physical effect**
  - Flow comes mainly from zones in front of fracture faces
  - Still fractures acts a sole one
- **Transient Behavior**
  - Early time
  - Bilinear flow



Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

Transverse Fractures Behavior

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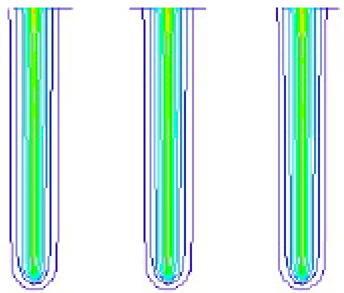
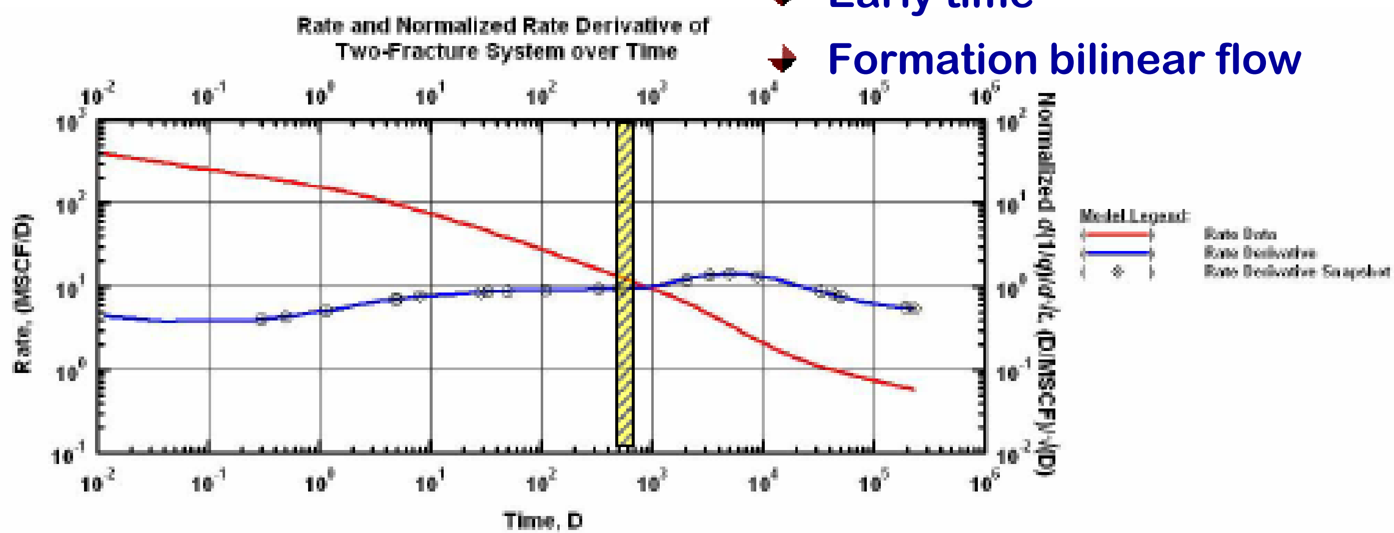
System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 500 days



- **Physical effect**
  - Flow comes mainly from zones in front of fracture faces
  - Pressure profile developed around fractures
  - Individual behavior of fractures
- **Transient Behavior**
  - Early time
  - Formation bilinear flow



Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

Transverse Fractures Behavior

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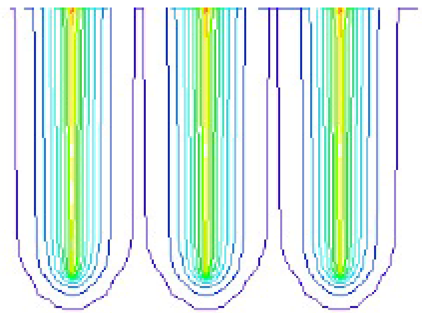
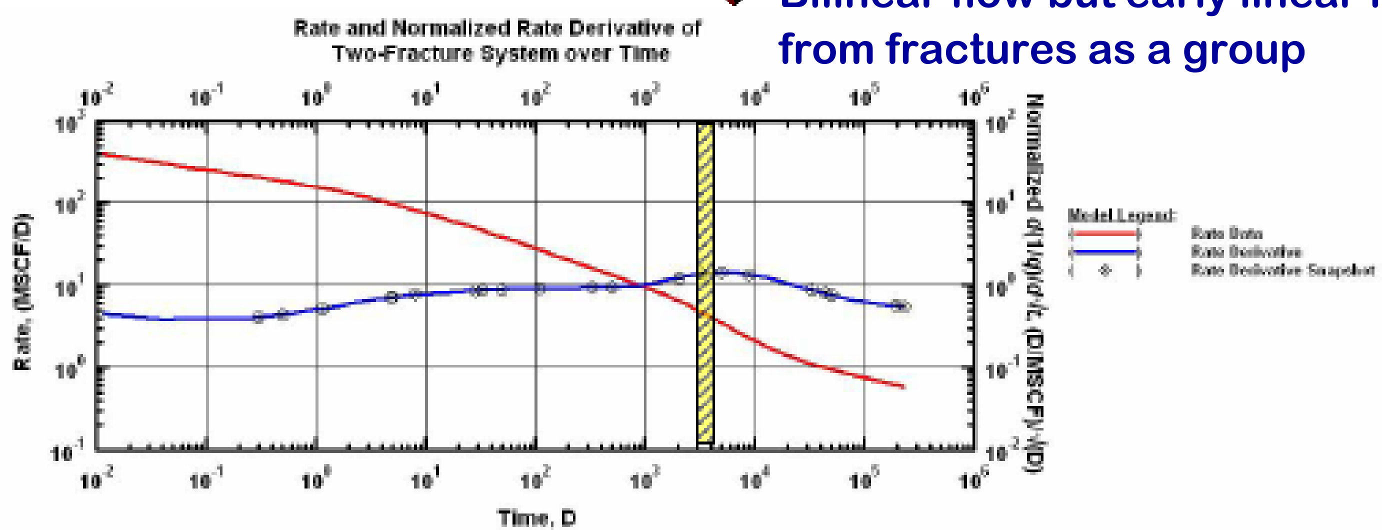
System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 9 years



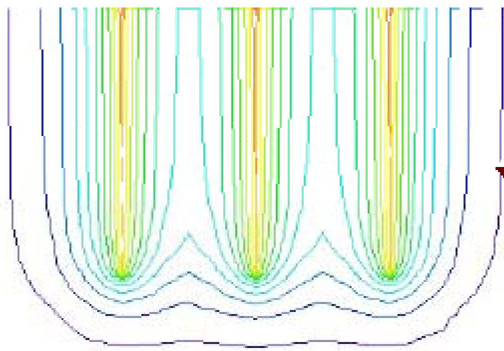
- Physical effect
  - Pressure envelope of each fracture is close enough to each other, excluding bounding fractures
  - Onset of interference
  - Fractures starts acting as a whole
- Transient Behavior
  - Bilinear flow but early linear flow from fractures as a group



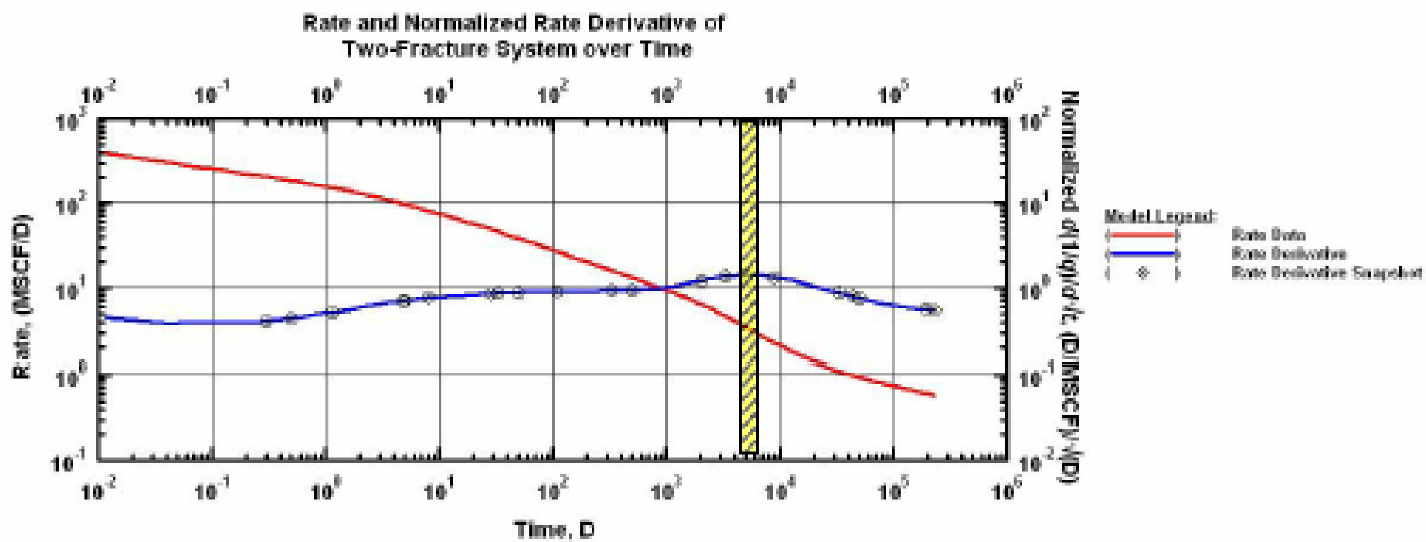
Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

Transverse Fractures Behavior

System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 14 years



- Physical effect
  - Fractures act as a package
  - Pressure front moves forward from line of fracture tips
- Transient Behavior
  - Middle time
  - Inflow is linear



Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

Transverse Fractures Behavior

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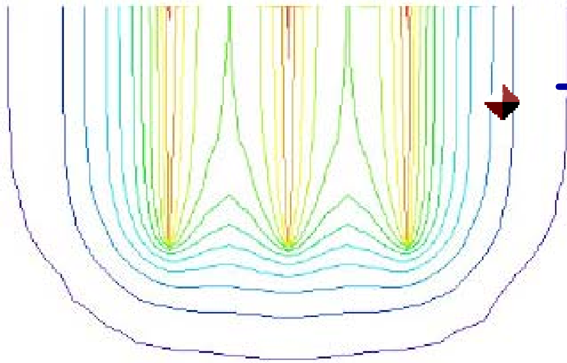
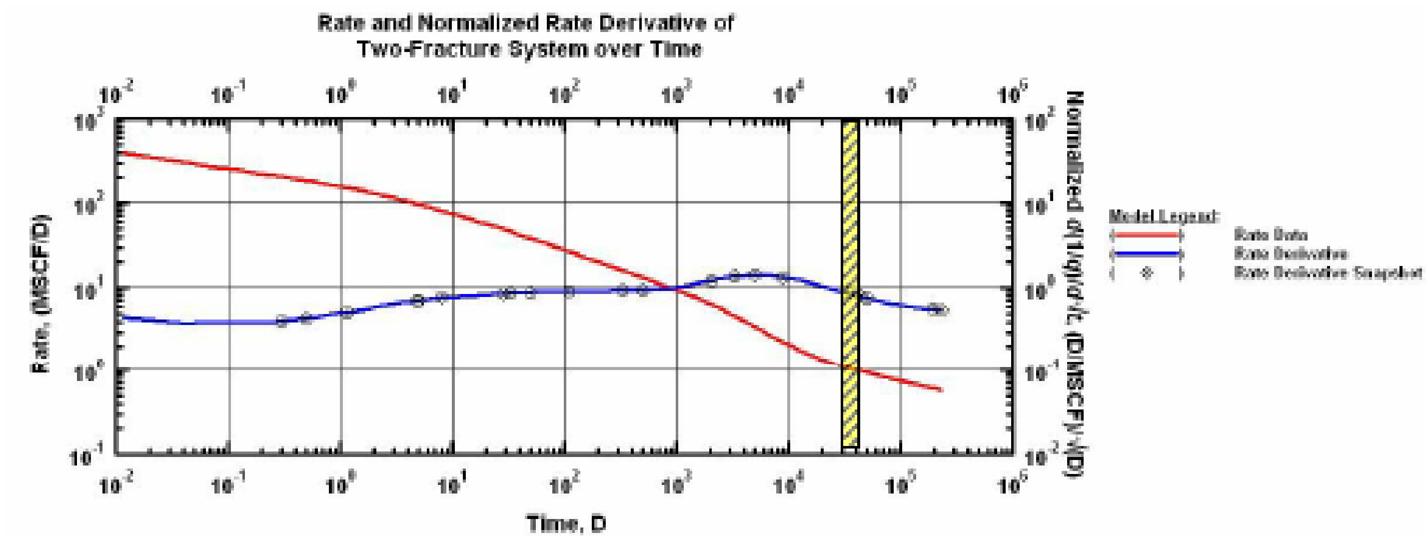
System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 90 years



- Physical effect
  - Pressure wave continue evolving around the fracture package
- Transient Behavior
  - Onset of late time
  - Onset of elliptical flow



Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

Transverse Fractures Behavior

System:
K= 100 nD= 0.0001 mD
Sx= 25 m
t= 120 years

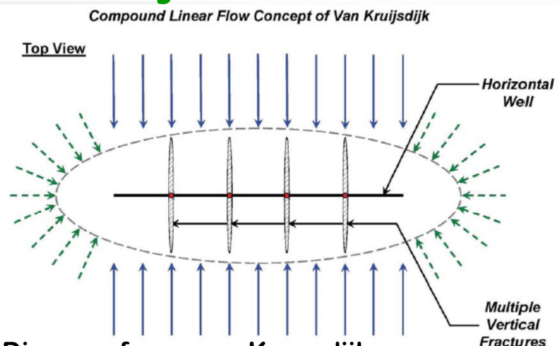
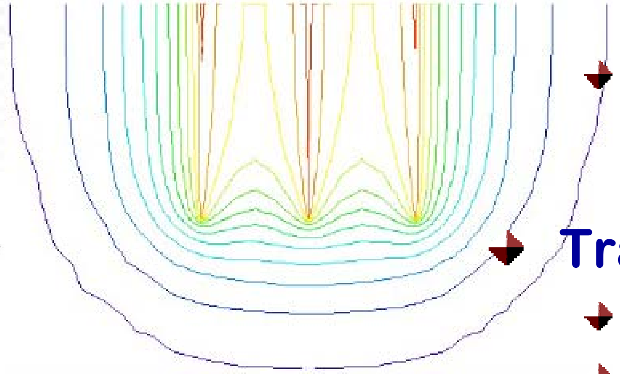
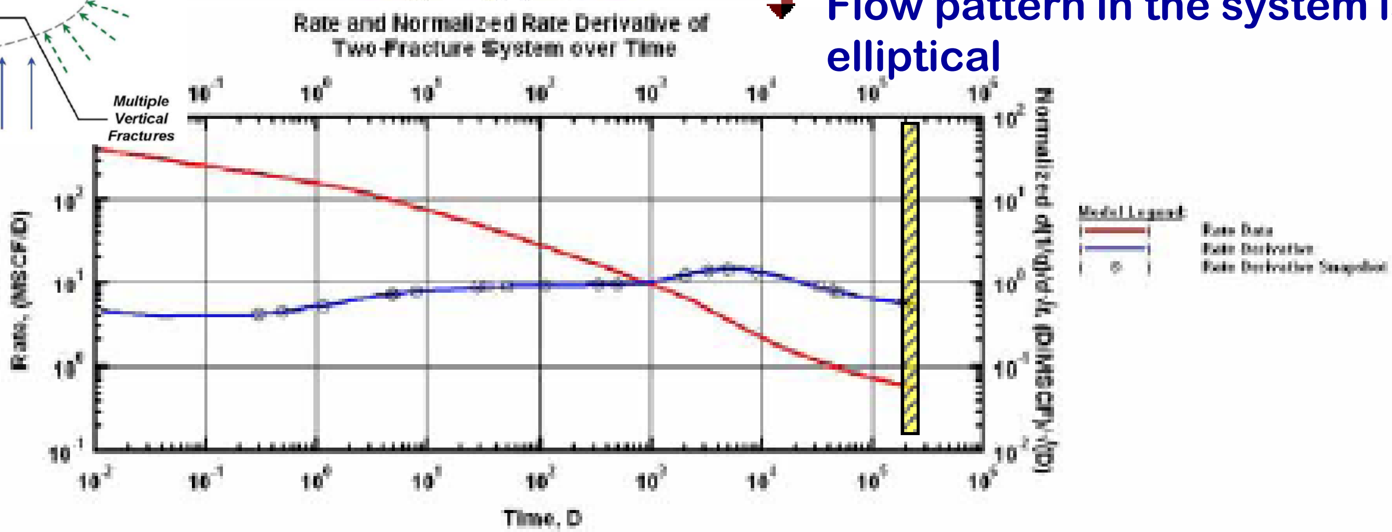


Diagram from: van Kruysdijk and Dullaert



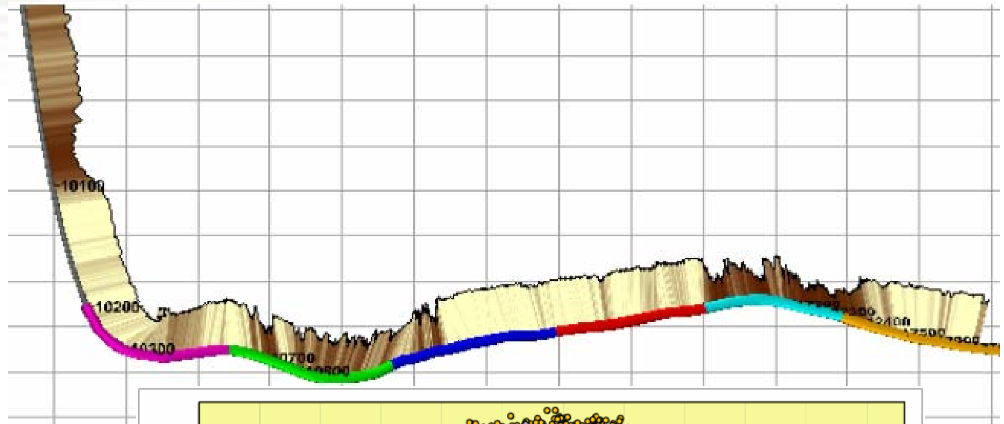
- Physical effect
  - Group of fractures act as a single fracture
  - Contribution from the reservoir beyond the stimulated area is negligible
- Transient Behavior
  - Late time
  - Flow pattern in the system is elliptical

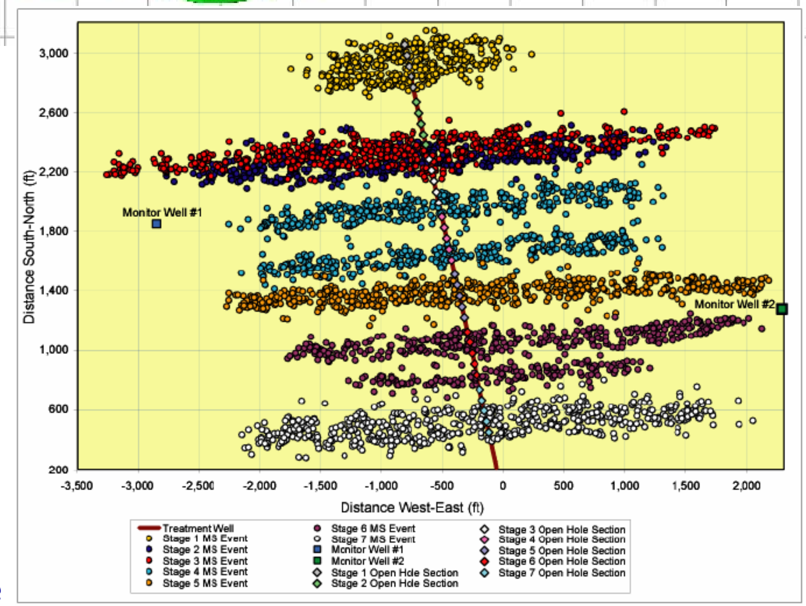


Graphs from: Well Performance Analysis – Shale Gas Reservoirs. Tom Blasingame.

Horizontal Wells and Fractures: The Real World

Graphs from: SPE 110067



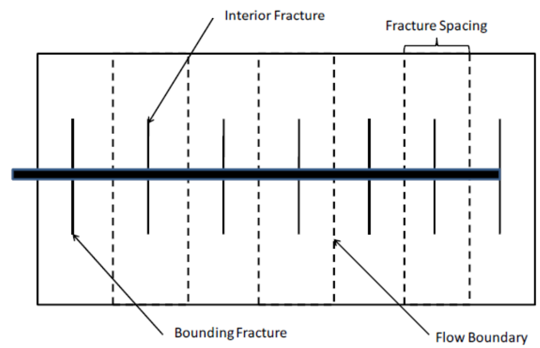


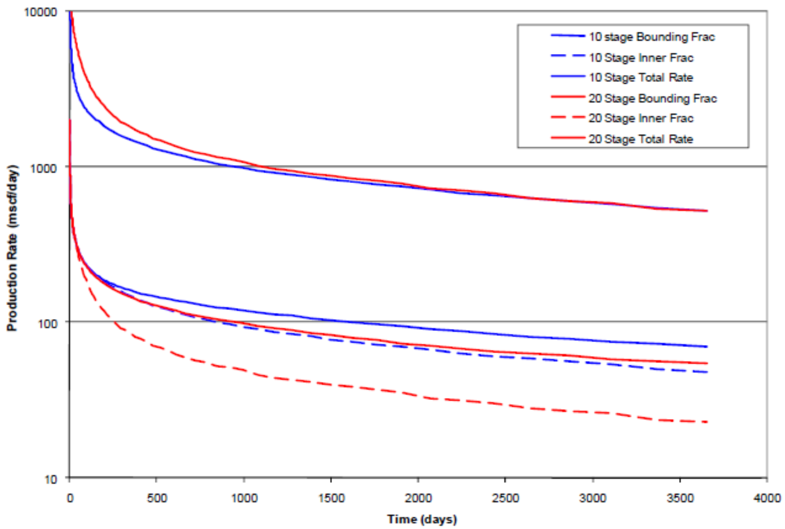
- **Reservoir**
  - Heterogeneous
  - Zones with different rock properties
  - Pay zone height is variable along wellbore
- **Wellbore**
  - Crooked rather than straight
  - It has roughness and for instance there is a pressure drop inside it
  - Transverse flowing area is not constant
- **Fractures**
  - Different fracture design
  - Spacing between fractures is variable
- **Well & fractures performance**
  - Productivity index for pseudo steady state flow. Pressure drop along the wellbore is not considered. Overestimation of PI.
  - For practical purposes multi-fractured horizontal wells do not drain the region beyond the tips of the hydraulic fractures
  - Most of the well life, flow is transient. Economics dictate strategy

Horizontal Wells and Fractures: The Real World

Pan American ENERGY

- **Fracture spacing**
  - Primary factors that govern are formation permeability and the time to interference of the production transients between the inner fractures
  - The outer reservoir boundaries impact the performance of outer fractures and define the length of the drainage area of internal fractures
- **Number of fractures**
  - Adding more fractures to the same horizontal length provides more initial rate but at the same time interference is reached sooner and rate from inner fractures will be reduced
  - Total reserves or ultimate recovery are not enhanced placing more fractures
  - Drainage area of internal fractures is determined by their spacing and by the length of the drainage channel that can be contacted
  - Drainage area of external fractures is controlled by reservoir architecture





From: SPE 123342

Fracture Effectiveness and Spacing

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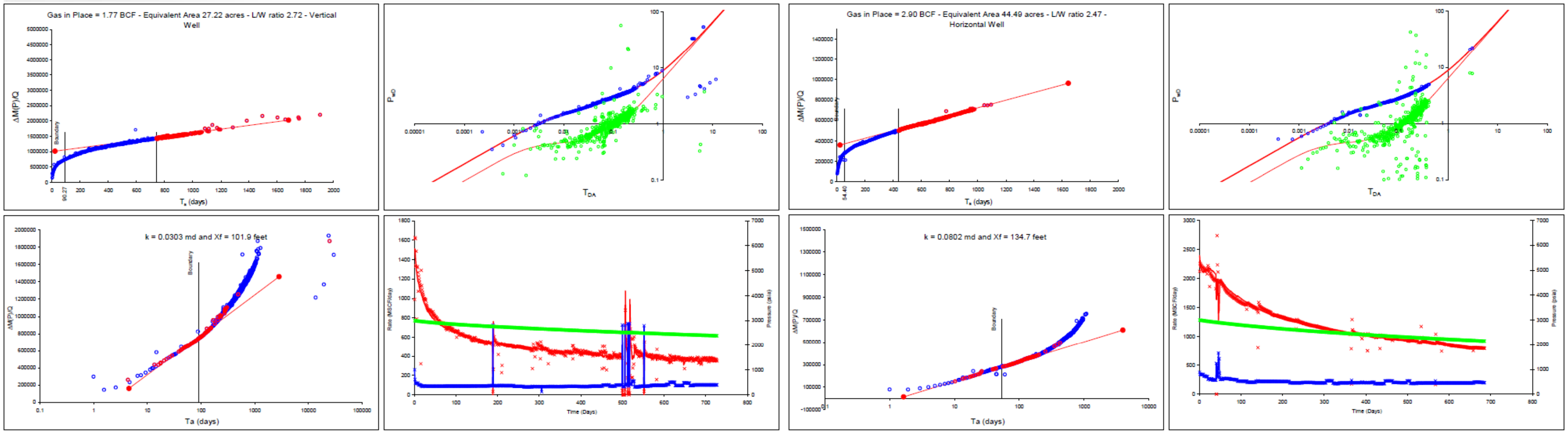
- **Key strategy for developing**
  - **Drill a couple of vertical wells to gather as much information as possible for reservoir engineering purposes and fracture design. It will save you nightmares with horizontals**

$$\text{Fracture Efficiency} = \frac{(kh)_{horizontal}}{n\,(kh)_{vertical}}$$

Graphs from: SPE 123342



Vertical well

OGIP= 1.77 Bscf
Drainage area= 28 acres
Aspect ratio= 2.7:1
K= 0.03 mD; K-h=2.4 mD-ft; Xf= 102 ft

Horizontal well

OGIP= 2.90 Bscf
Drainage area= 44.5 acres
L= 4000 ft; Frac's= 12; Spacing= 363 ft
K-h= 6.32 mD; Xf= 135 ft

- **FE= 21.9 %. Only 2.6 fractures would be necessary to drain this reservoir !**

Multi Fractured Horizontal Wells in Unconventional Reservoirs

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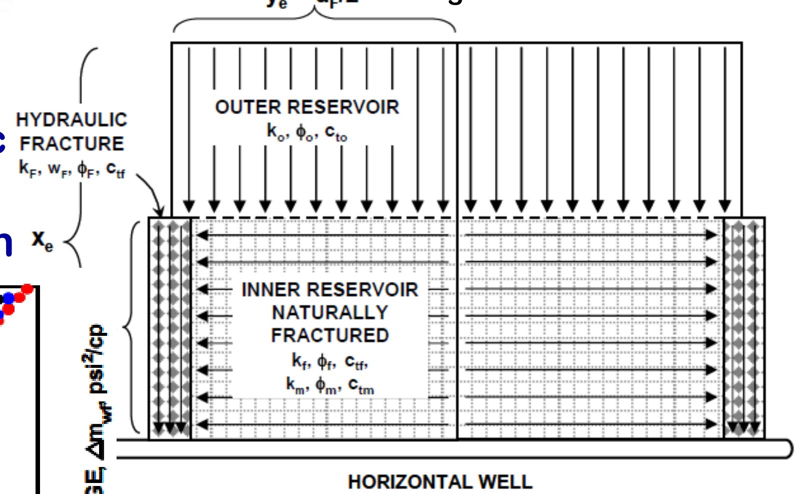
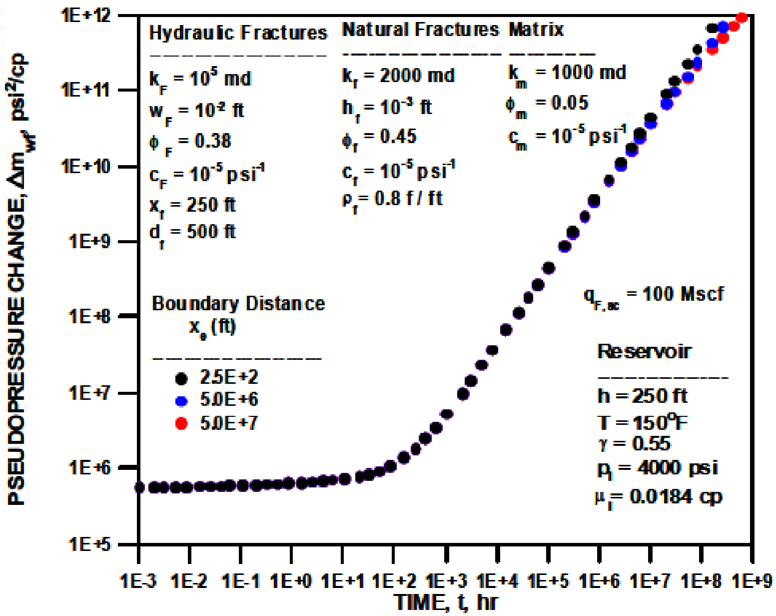
Diagram from: SPE 121290



- **Characteristics**
  - The system is made up of transverse hydraulic fractures, natural fracture network between hydraulic fractures and an outer reservoir with matrix flow

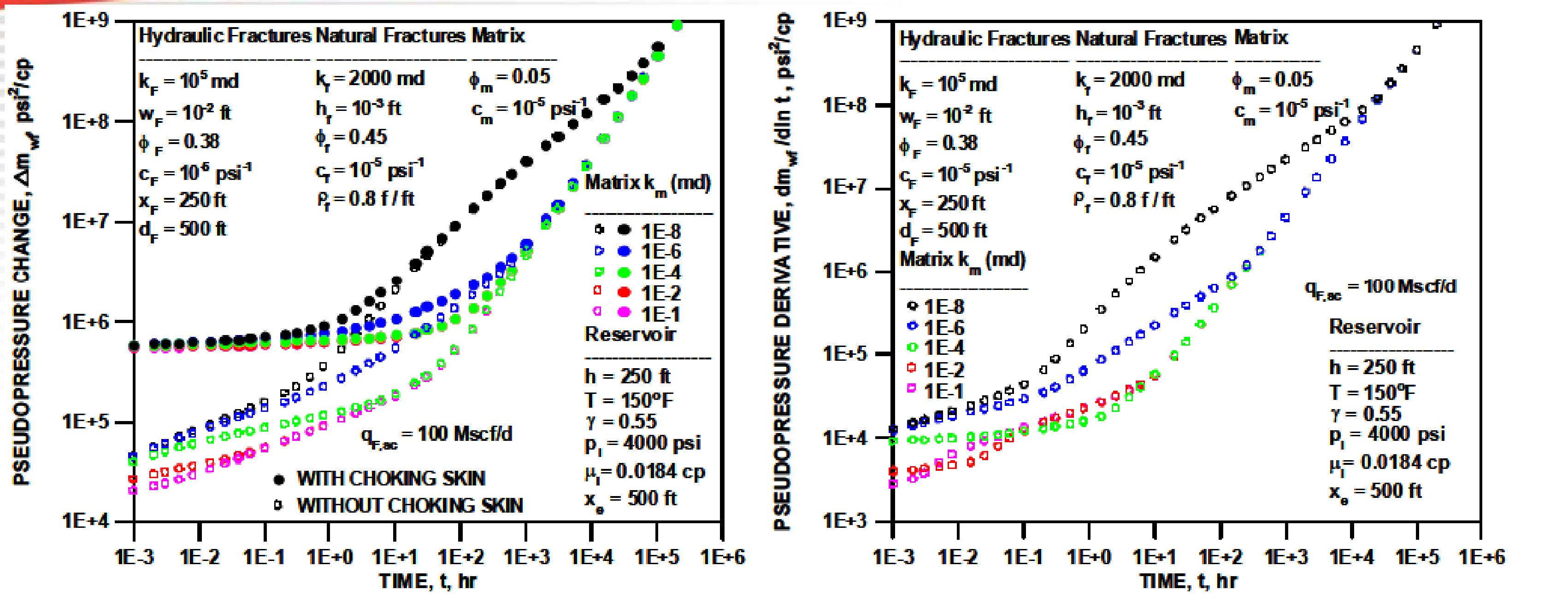


A – k_f = 2000 md

- **Conclusions**
  - Support from outer reservoir becomes evident after 100 years !
  - This behavior supports the common practice of small well spacing to efficiently drain tight gas reservoirs with multi-fractured horizontal wells
  - For practical matrix permeabilities, MFHW does not drain beyond fracture tips

Multi Fractured Horizontal Wells in Unconventional Reservoirs

Diagram from: SPE 121290



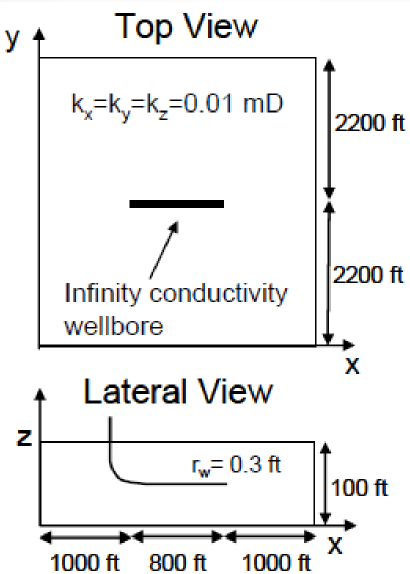
A – PSEUDOPRESSURE VS. TIME

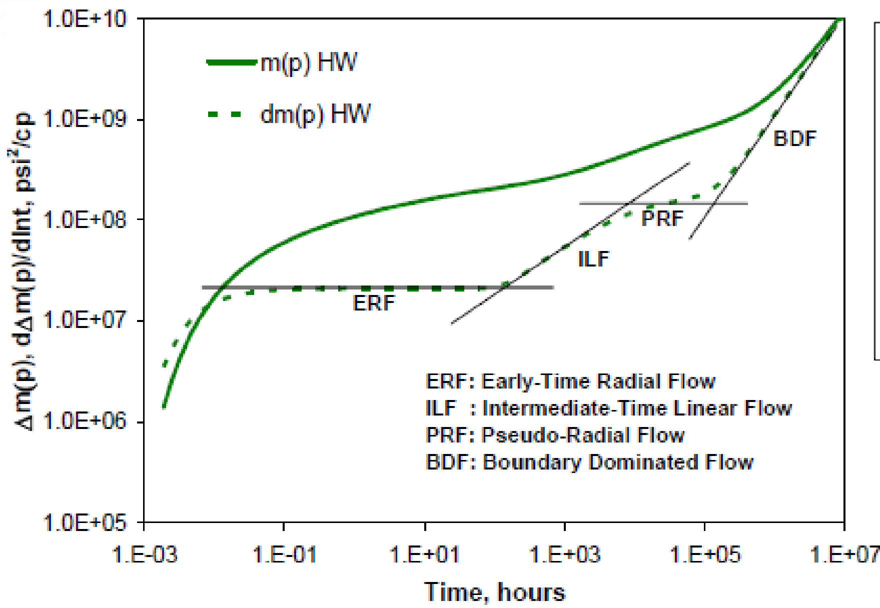
B – LOG-DERIVATIVE VS. TIME

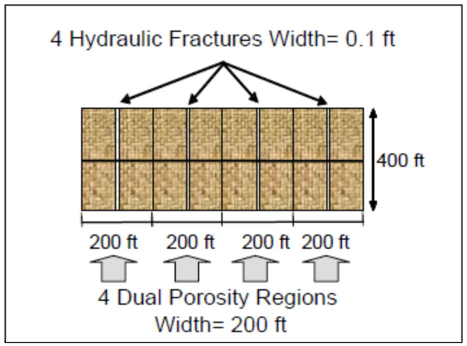
- **Conclusions**
  - Dense fracture network required to get sufficient effective permeability
  - Choking effect skin masks early time behavior. Derivative response is not influenced, so it must be used for flow identification and analysis
  - When maximum flow capacity of natural fractures is reached, additional productivity form the matrix can not utilized. This emphasizes the importance of holding or improving the flow capacity of natural fractures
  - Density of natural fractures instead of natural fractures permeability is what impacts productivity

Natural & Hydraulic Fractures and Horizontal Wells's Fraternity

- Impact of natural fractures in TG reservoirs
  - If hydraulic fractures affect stress distribution whether creating or activating natural fractures around wellbore, productivity is significantly improved
  - But if there is no too much contrast between hydraulic and natural fractures, the impact of hydraulic fractures on well productivity will be negligible







Early radial flow (ERF): 4 days
Intermediate linear flow (ILF): 5 months (slope ½)
Pseudo-radial flow: 10 years
Boundary dominated flow (BDF): starts after 11.5 years (slope 1) – well in transient flow

Diagram and graph from: SPE 108110

Natural & Hydraulic Fractures and Horizontal Wells's Fraternity

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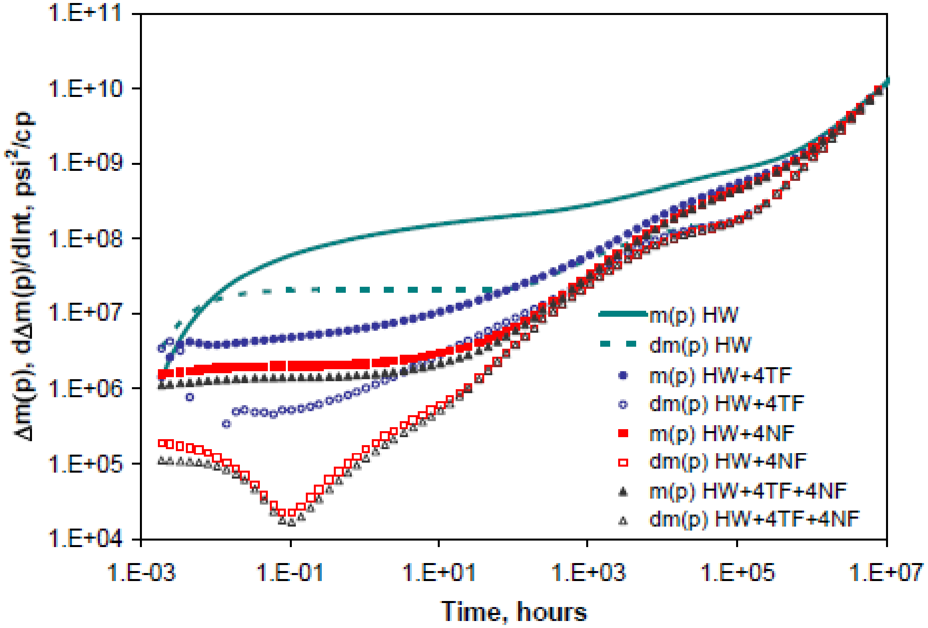

Graph from: SPE 108110

Early radial linear flow (ERLF): flat derivative behavior. Radial flow in the fracture and linear flow in the reservoir

Intermediate linear flow (ILF): derivative (slope ½)

Pseudo-radial flow: masked by fracture interference and horizontal well behavior.

Boundary dominated flow (BDF): derivative (slope 1). Similar to the unfractured well behavior

- Conclusions
  - During the early time period (transient flow), productivity of the fractured well is better than that of the unfractured well
  - After the BDF begins the productivities of both cases are essentially the same as differences in pressure an derivative behavior became insignificant

Natural & Hydraulic Fractures and Horizontal Wells's Fraternity

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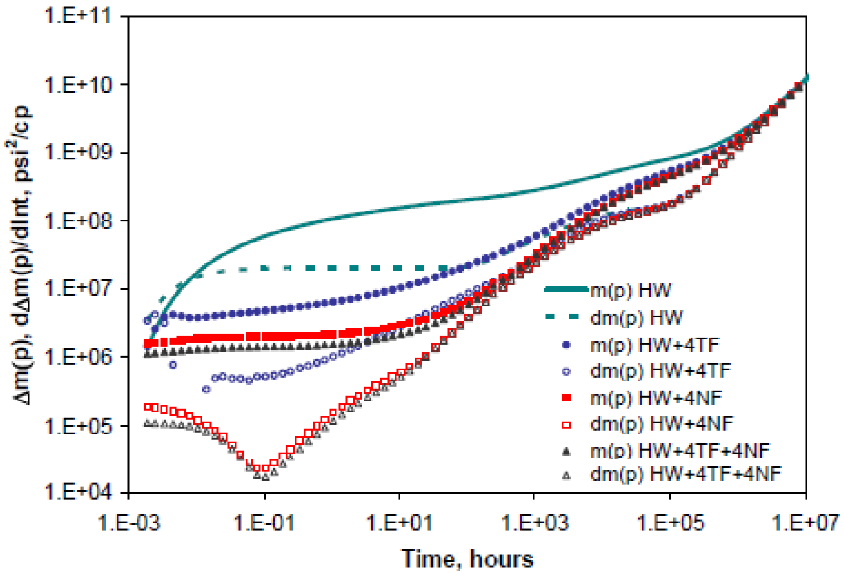
Graph from: SPE 108110



Early radial linear flow (ERLF): flat derivative behavior. Radial flow in the fracture and linear flow in the natural fractures. Also characteristics dip of dual porosity systems

Transitional flow

Pseudo-radial flow: in the reservoir. Derivative (slope 1)

Pseudo-radial flow: all flows are similar as those for an unfractured well

- **Conclusions**
  - Except during the early time period (transient flow), productivity of the fractured well is similar to that of the unfractured well
  - Productivity of the well with fractures surrounded by natural fractures is better than the other previous cases
  - Despite transverse fractures do not substantially contribute to well productivity, they are required to activate o create natural fractures
  - Fracture design must focus on creating or improving the natural fracture network. If natural fractures have high permeability, addition of hydraulic fractures will not provide significant improvement of well productivity

Remarkable Conclusions

"…unconventional reservoirs behave well different compared to conventional ones…"

"…limitations of every method before applying it must be well understood, otherwise unexpected results may arise and wrong decisions could be taken…"

"…NEVER use a single methodology to estimate reservoir or / and hydraulic fractures properties as such methodology is near impossible to provide sufficient strength in its physics, ALWAYS use an integrated approach to validate results from different methods…"

Referents In TG Reservoir Analysis

Pan American ENERGY

- Blasingame, Tom
  - Texas A&M University
- Kazemi, Hossein
  - Colorado School of Mines
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Q&A

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