Well Testing Fundamentals

What is a test?
Measurement of rate, time and pressure under controlled conditions.

Why test?

- Reservoir pressure
- Permeability
- Wellbore damage
- Deliverability
- Reservoir management
- Reservoir description
- Fluid samples
- Regulations

+ Well testing theory is based on constant rate Drawdown tests. Drawdown tests are not very practical (due to poor data quality). Buildup tests are more common.

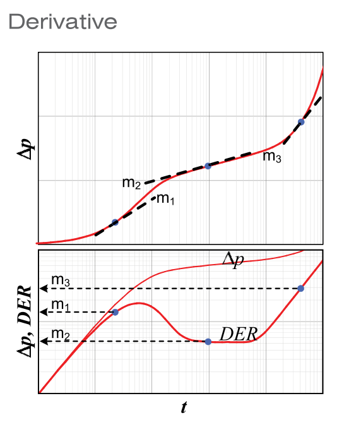
Transient Tests →	**Reservoir Characterization**
RFT®, WFT®, MDT® …	p_i, k, fluid samples
DST	p_i, k, fluid samples
Drawdown+ / Injection	k, s (often un-interpretable)
Buildup+ / Falloff	k, s, $\bar{p}_R$
Interference/Pulse	k, ϕc_t, lateral/vertical continuity
PITA, PID, Minifrac, CCT	p_i, k
Stabilized Tests →	**Deliverability Forecasting**
IPR	q_{stab}
AOF	q_{stab}

Derivative

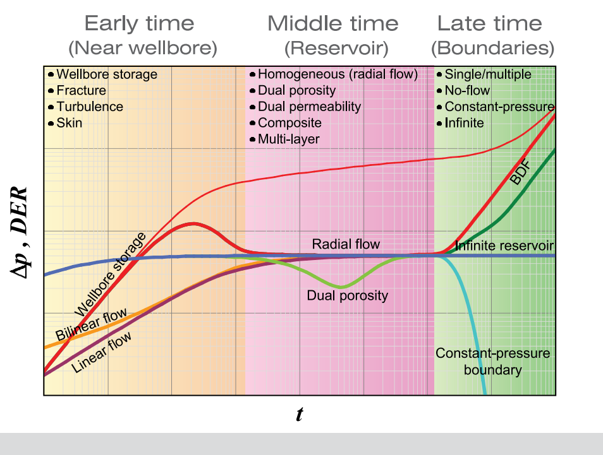
- Derivative (DER) is the slope of the semilog plot.

$$DER = \frac{d\Delta p}{d\ln t} = t\frac{d\Delta p}{dt}$$

- DER is usually plotted on log-log coordinates, combined with a plot of Δp.
- DER is used for flow regime diagnostics.



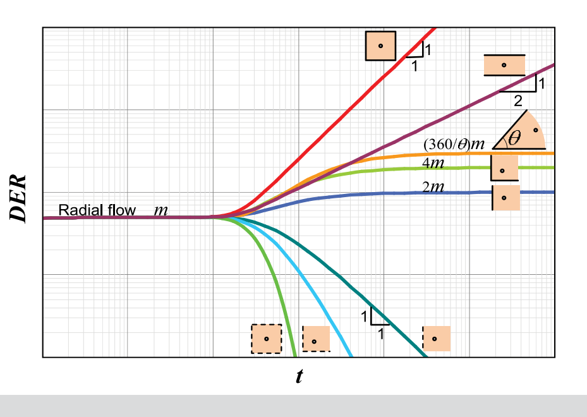
CONSTANT RATE FUNDAMENTALS



Flow regime		Derivative Slope	Time Function*	Result
Wellbore storage		1	t	C, C_D
Bilinear flow		1/4	$\sqrt[4]{t}$	$k^{1/4}\sqrt{k_f w}$
Linear flow	fracture	1/2	$\sqrt{t}$	$x_f\sqrt{k}$
	horiz. well			$L_e\sqrt{k_y}$
Spherical flow		-1/2	$1/\sqrt{t}$	$\sqrt[3]{k_x k_y k_z}$
Vertical radial flow in horizontal wells		0	$\log(t)$	$L_e\sqrt{k_y k_z}$
Radial flow (∞-acting)		0	$\log(t)$	kh
Linear flow – Channel		1/2	$\sqrt{t}$	$W\sqrt{k}$
Boundary-Dominated Flow		1	t	V_p

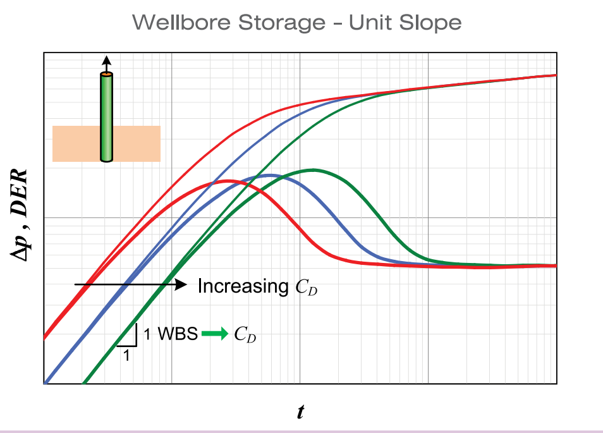
** x-axis of specialized plots.*

Boundaries



FLOW REGIMES

Wellbore Storage - Unit Slope



STORAGE

Storage Flow Regime is equivalent to emptying a tank

$$c = \frac{-1}{V}\frac{\Delta V}{\Delta p} = \frac{-1}{V}\frac{qt}{\Delta p}$$

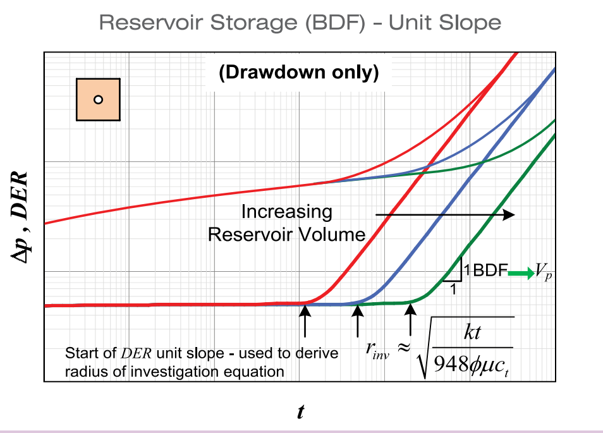
Early time: Wellbore Storage (WBS)

- Pressure and derivative have unit slope

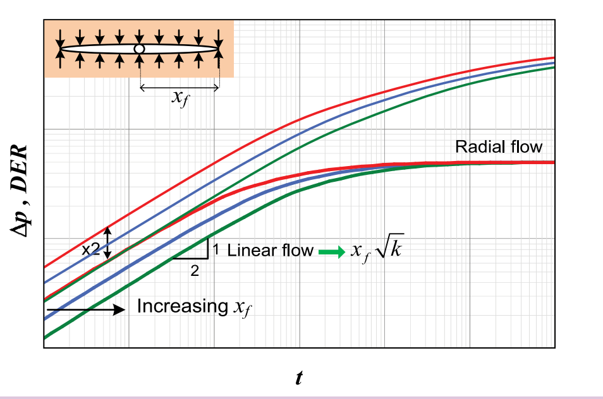
Late time: Boundary-Dominated Flow (BDF)

- Also known as:
  - Pseudo-steady state
  - Stabilized
  - Tank-type behavior
- Applies to Drawdown only – **NOT Buildup**
- Derivative unit slope occurs much earlier than pressure unit slope

Reservoir Storage (BDF) - Unit Slope



Reservoir Linear Flow (Fracture) – Half Slope



LINEAR FLOW

Early Time → fracture

- Infinite conductivity fracture
- Pressure and derivative have slope of ½ (Separated by a factor of 2)
- Equivalent to negative skin

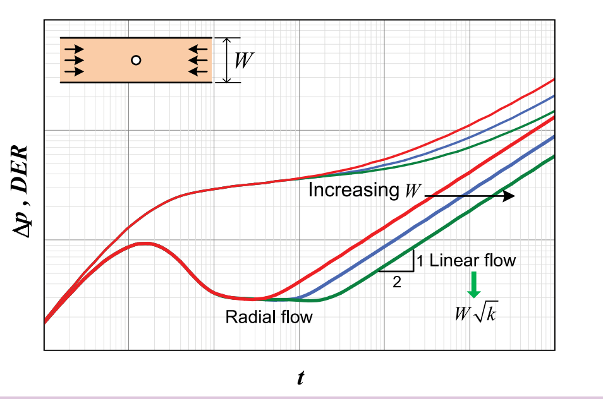
$$r_{wa} = \frac{x_f}{2} \Rightarrow s = \ln\left(\frac{2r_w}{x_f}\right)$$

- Fracture effectiveness may be reduced by:
  - Skin on fracture face
  - Choke skin
  - Finite conductivity within the fracture

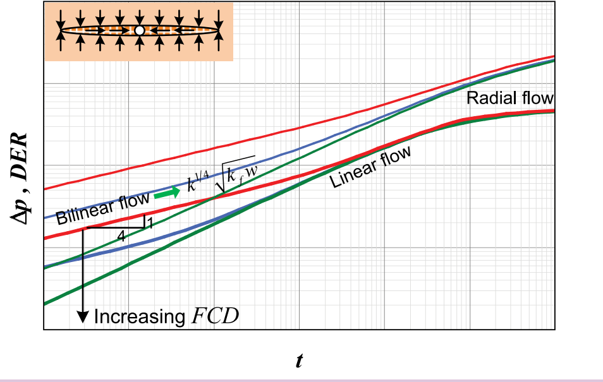
Late Time → channel (parallel boundaries)

- Derivative has slope of ½

Reservoir Linear Flow (Channel) – Half Slope



Bilinear Flow – Quarter Slope (Finite Conductivity Fracture)



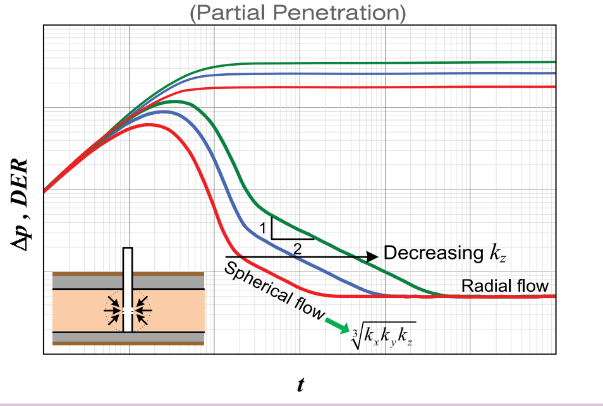
BILINEAR FLOW

- Finite conductivity fracture
- Dimensionless Fracture Conductivity $FCD = \frac{k_f w}{k x_f}$
- Bilinear flow regime precedes linear flow
- $FCD > 100$ → infinite conductivity fracture

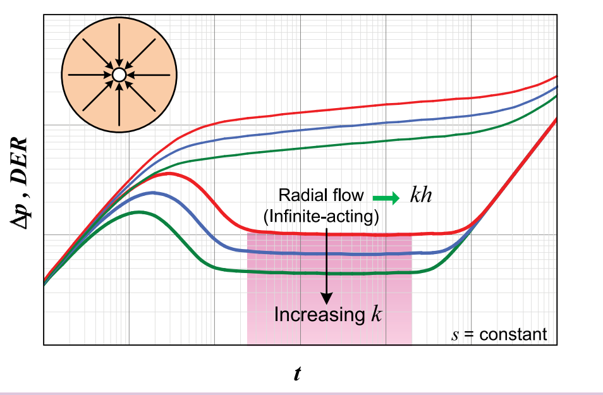
SPHERICAL FLOW

- Partial Penetration or limited perforations
- Slope of derivative is -½
- Component of total skin
- Magnitude of skin depends on vertical permeability and perforation interval
- Radial flow from completed interval may be observed before spherical flow

Spherical Flow – Negative Half Slope (Partial Penetration)



Permeability



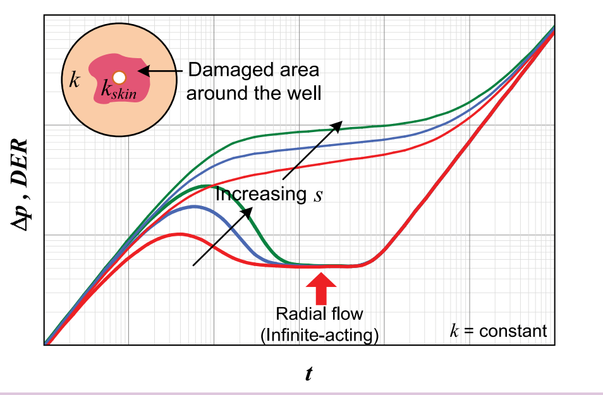
RADIAL FLOW (INFINITE-ACTING)

- Derivative has a slope of zero
- Used to obtain permeability

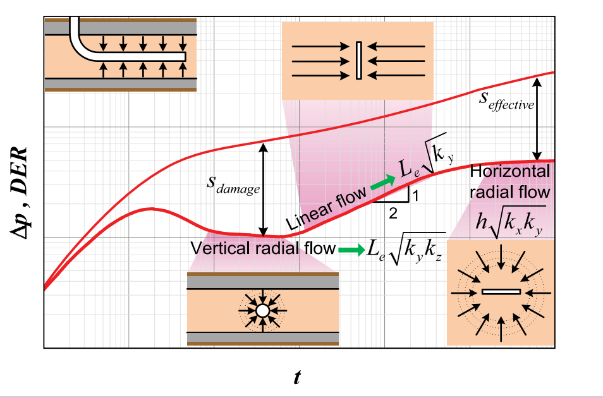
SKIN

- $\Delta p|_{skin}$ = difference between ideal and measured flowing pressure
- $s = \Delta p|_{skin}$ expressed in dimensionless form
- Skin $s = \left(\frac{k}{k_{skin}} - 1\right)\ln\frac{r_{skin}}{r_w}$
- Apparent wellbore radius $r_{wa} = r_w e^{-s}$; $s = \ln\frac{r_w}{r_{wa}}$
- Total skin, $s' = s_{damage} + s_{turbulence} + s_{partial\ penetration} + s_{geometry} + s_{fracture} + \ldots$

Skin



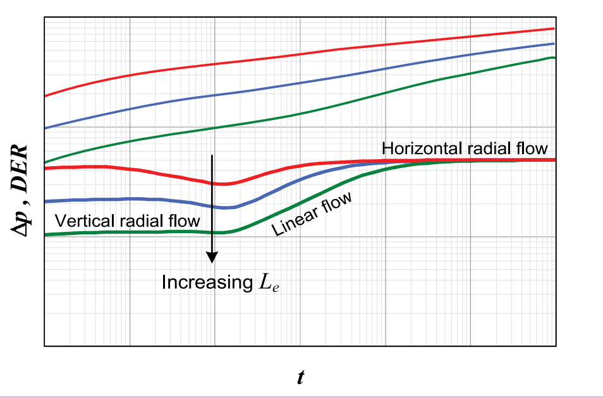
Horizontal Well



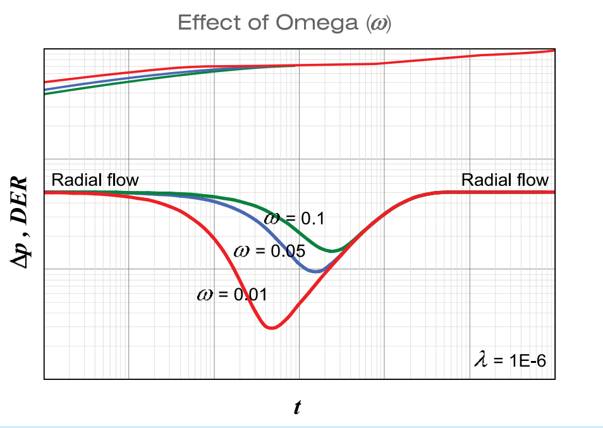
HORIZONTAL WELL FLOW REGIMES

- Vertical radial flow → vertical permeability, $\sqrt{k_y k_z}$ skin around wellbore, s_{damage}
- Linear flow → k_y or effective wellbore length, L_e
- Once linear flow is reached, horizontal well is similar to vertical fractured well + $s_{convergence}$
- Horizontal radial flow → horizontal permeability, $\sqrt{k_x k_y}$, and skin equivalent to vertical well, $s_{effective}$

Effective Well Length



Effect of Omega (ω)



DUAL POROSITY / PERMEABILITY

- Storativity ratio (ω) gives an indication of the fraction of the hydrocarbons stored in the fissures (porosity 1)

$$\omega = \frac{(\phi c_t h)_1}{(\phi c_t h)_1 + (\phi c_t h)_2}, \text{ typically } 0.01 \text{ to } 0.1$$

- Interporosity Flow Coefficient (λ) reflects the contrast between matrix and fracture permeability; it also depends on matrix size and geometry

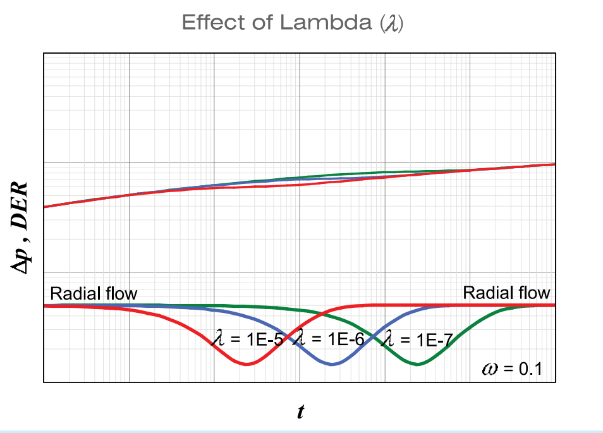
$$\lambda = \alpha\frac{k_2}{k_1}, \text{ typically } 10^{-4} \text{ to } 10^{-8}$$

- α is a shape factor that depends on the size and geometry of the matrix
- $\lambda = 0$ → No crossflow in the reservoir
- Flow Capacity Ratio (κ) is the contribution of the high permeability layer with respect to the total

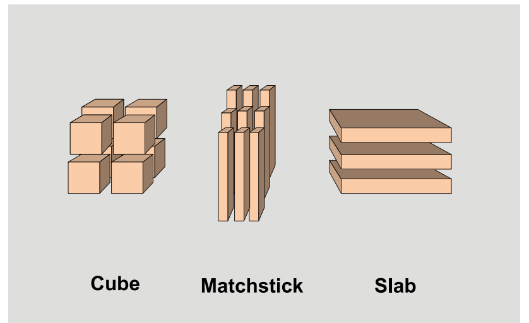
$$\kappa = \frac{k_1 h_1}{k_1 h_1 + k_2 h_2}$$

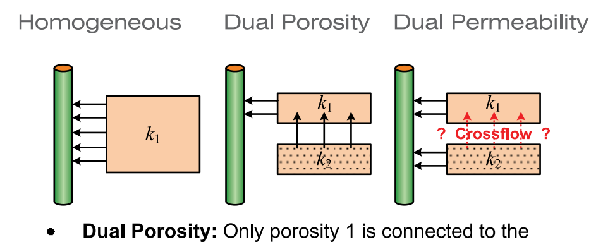
- $k_2 \to 0,\ \kappa \approx 1$ → dual porosity

Effect of Lambda (λ)



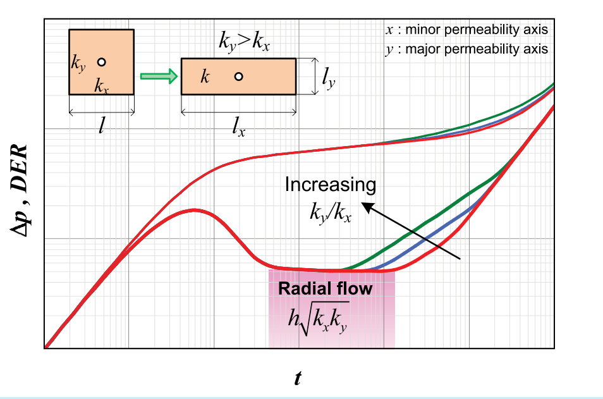
Matrix Element Shapes





- **Dual Porosity:** Only porosity 1 is connected to the well, and porosity 2 acts like a source. Example: naturally fractured reservoir: fissures (1); matrix (2)
- **Dual Permeability:** Each porosity is connected to the well. Example: two layers commingled at the well. Crossflow in the reservoir may or may not exist

Vertical Well - Horizontal Anisotropy



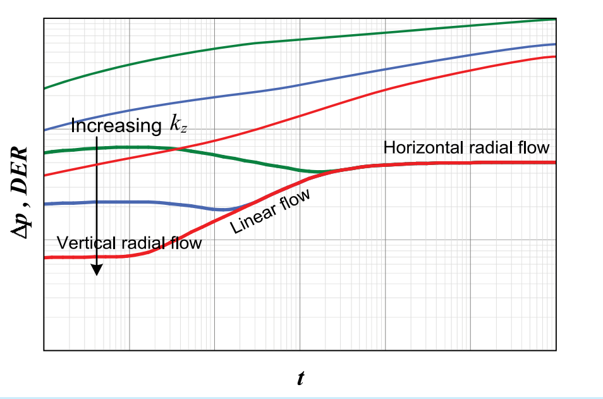
ANISOTROPY

- Anisotropy affects the drainage pattern
- It creates elliptical iso-potentials
- Coordinate transformation converts anisotropic reservoir models to equivalent isotropic ones of different dimensions

$$l_x = l\sqrt{k/k_x} \qquad k = \sqrt{k_x k_y}$$
$$l_y = l\sqrt{k/k_y}$$

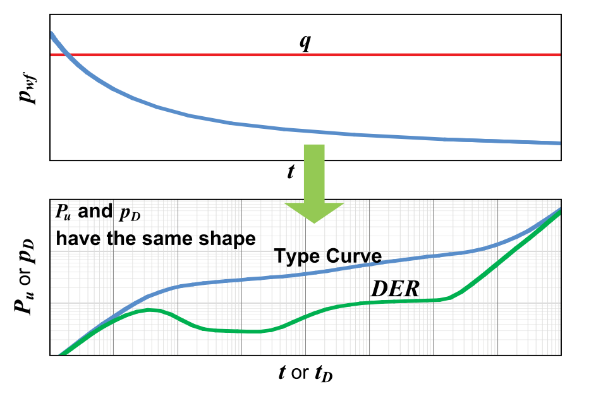
- Horizontal anisotropy is important in certain depositional environments; such as naturally fractured reservoirs or coals
- Vertical anisotropy is common and affects skin whenever there is flow in the vertical direction, such as partial penetration

Horizontal Well - Vertical Anisotropy



SUPERPOSITION

Unit Rate Function



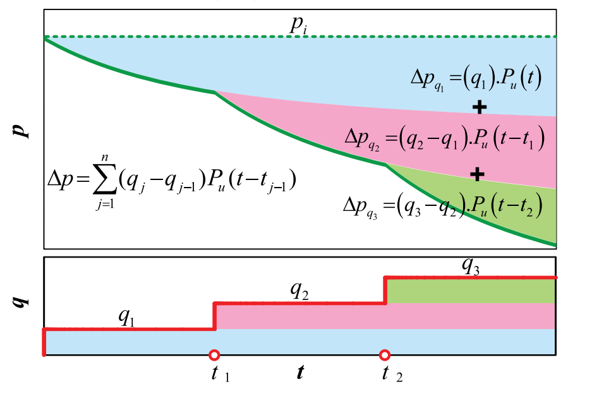
UNIT RATE FUNCTION

- Unit Rate Function, P_u, is defined as the pressure drop per unit constant flow rate : $P_u = (\Delta p/q)$
- It is the fundamental solution of the Diffusivity Equation used in Well Test Interpretation
- P_u is often expressed in dimensionless form

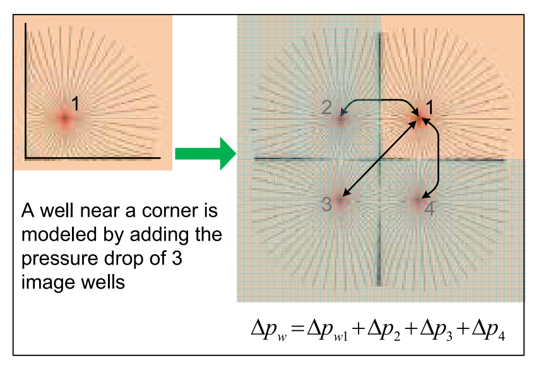
$$p_D = \frac{\Delta pkh}{141.2qB\mu} \qquad t_D = \frac{2.637E-4\ kt}{\phi\mu c_t r_w^2}$$

- It is called a Type Curve when plotted on log-log coordinates, and is usually presented with the semilog derivative $DER = d(p_D)/d(\ln t_D)$
- Every reservoir has its own Unit Rate Function; the shape of its derivative reflects the reservoir model

Superposition-in-Time



Superposition-in-Space



A well near a corner is modeled by adding the pressure drop of 3 image wells

$$\Delta p_w = \Delta p_{w1} + \Delta p_2 + \Delta p_3 + \Delta p_4$$

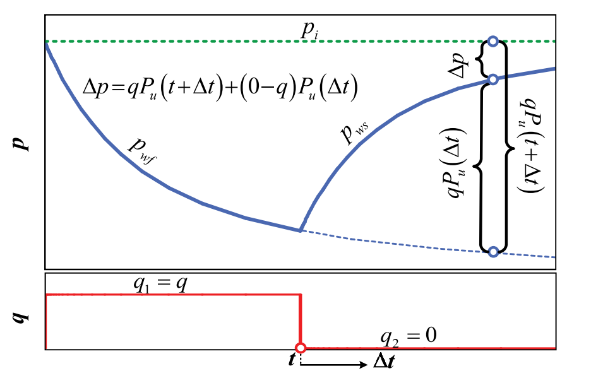
CONVOLUTION

- Superposition is also known as Convolution
- In simple terms, the Principle of Superposition states that the total pressure drop is simply the summation of the individual pressure drops
- It is applied ***in time*** to account for rate changes, and ***in space*** to account for multiple wells and boundaries

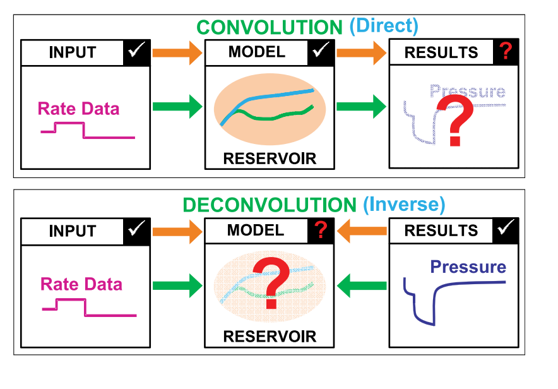
SUPERPOSITION-IN-TIME

- Superposition-in-time is used to convert the constant rate solution (Pu) to a multi-rate solution
- The rate used for each step is the difference between the current rate and the previous rate
- A rate changing from q_1 to q_2 at time t_1, is treated as q_1 continuing forever plus (q_2-q_1) starting at t_1

Buildup as Example of Superposition



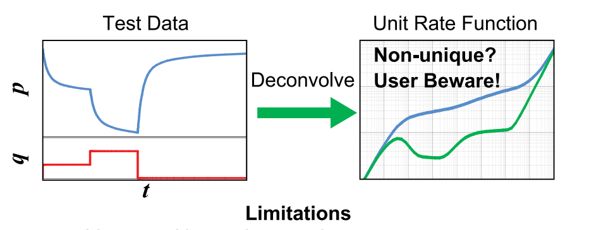
Direct and Inverse Processes



DECONVOLUTION

- Deconvolution is the reverse of superposition
- Its purpose is to extract the Unit Rate Function from pressure data in multi-rate tests
- This Unit Rate Function is in fact the reservoir Type Curve; it facilitates identification of the reservoir model
- It does NOT require a pre-conceived reservoir model; rather, it is used to determine what the reservoir model might be
- It is used to convert buildup or multi-rate data into the corresponding constant rate Drawdown Type Curve

Deconvolution

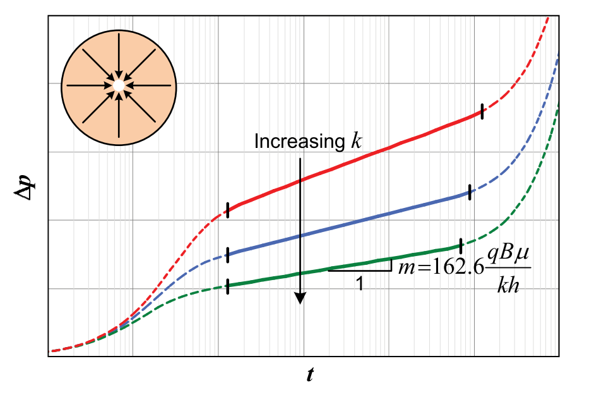


Limitations

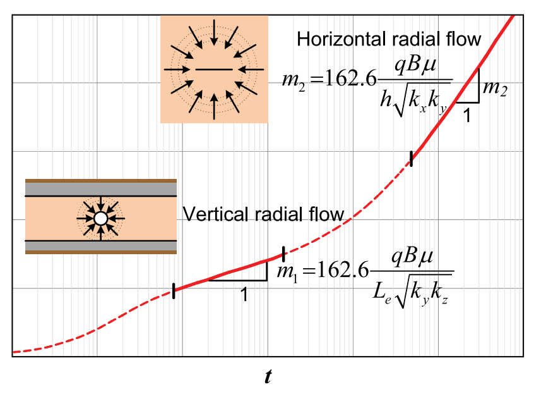
- Very sensitive to data quality
- Changing skin, changing wellbore storage, missing/ incorrect initial pressure and gaps in data can have a significant effect on the shape of the deconvolved Type Curve

SPECIALIZED PLOTS

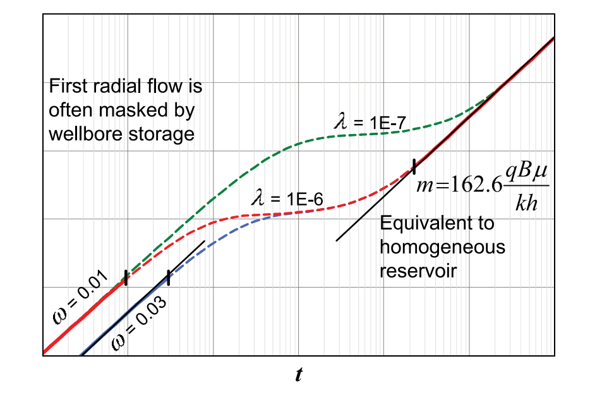
Radial Flow



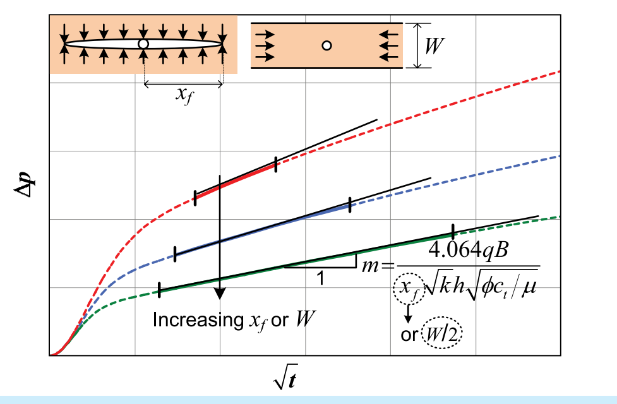
Radial Flow - Horizontal Well



Radial Flow - Dual Porosity



Reservoir Linear Flow - Fracture or Channel

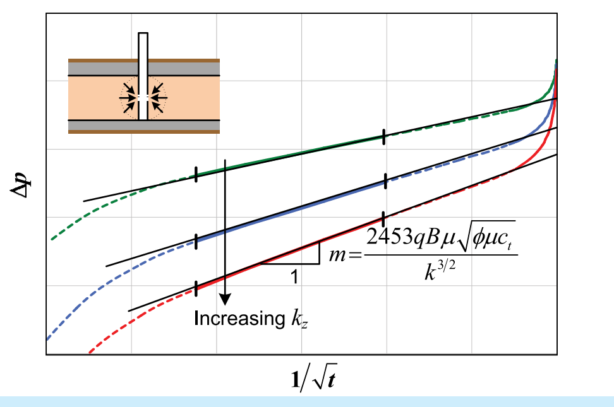


- A specialized plot is a plot of the pressure data on a time axis that is specific to a particular flow regime:

Flow Regime	X-Axis
Radial flow (horizontal)	$\log(t)$
Radial flow (vertical)	$\log(t)$
Linear flow (fracture)	$\sqrt{t}$
Linear flow (channel)	$\sqrt{t}$
Bilinear flow	$\sqrt[4]{t}$
Spherical flow	$1/\sqrt{t}$
Wellbore storage (afterflow)	t
Boundary-dominated flow	t

- It exhibits a straight line during that flow regime
- The slope of the line gives the result of interest

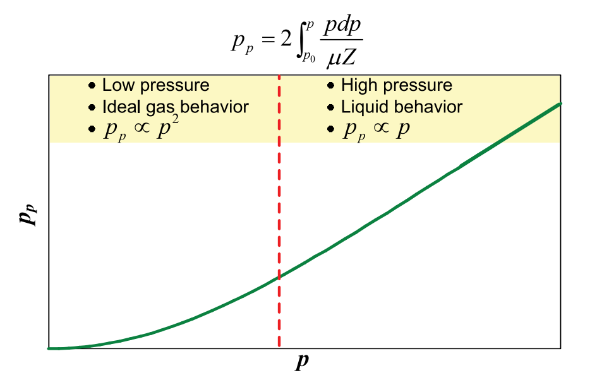
Spherical Flow



GAS CONSIDERATIONS

Pseudo-Pressure

$$p_p = 2\int_{p_0}^{p}\frac{pdp}{\mu Z}$$



PSEUDO-PRESSURE (p_p)

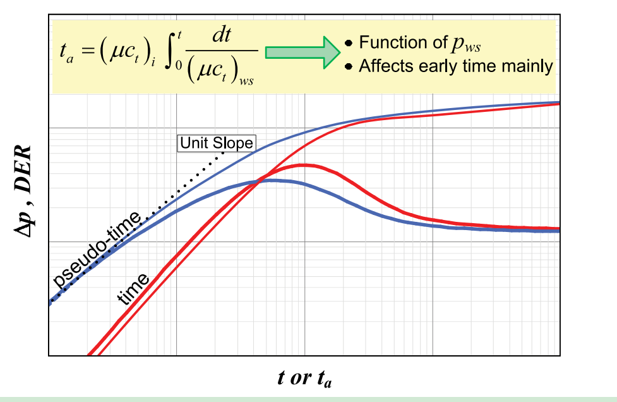
- Welltest equations are based on liquid flow equations:
  - Constant μ
  - Constant c
- Gas properties (μ, c and Z) vary with pressure
- Pseudo-pressure accounts for variations of μ and Z
- Pseudo-pressure is an **exact** transformation
- Replacing p by p_p makes Darcy's Law applicable to gas (when expressed in terms of flow rate at standard conditions)
- p_p does **NOT** account for variation in gas compressibility (c_g) with pressure (see pseudo-time)

Gas: Replace	pressure p → pseudo-pressure p_p time t → pseudo-time t_a

	Liquid	Gas
p_D	$(p_i - p_{wf})\frac{kh}{141.2qB\mu}$	$(p_{p\,i} - p_{p\,wf})\frac{kh}{1.417E6qT}$
t_D	$\frac{0.0002637kt}{\phi\mu c_t r_w^2}$	$\frac{0.0002637kt_a}{\phi(\mu c_t)_i r_w^2}$
c_t	constant $S_{gi}c_{gi} + S_{oi}c_{oi} + S_{wi}c_{wi} + c_f$	Varies with pressure $S_g c_g + S_o c_o + S_w c_w + c_f + c_d^{**}$

**CBM desorption compressibility, $c_d = \frac{\rho_B B_g V_L}{\phi}\frac{p_L}{(p_L + p)^2}$

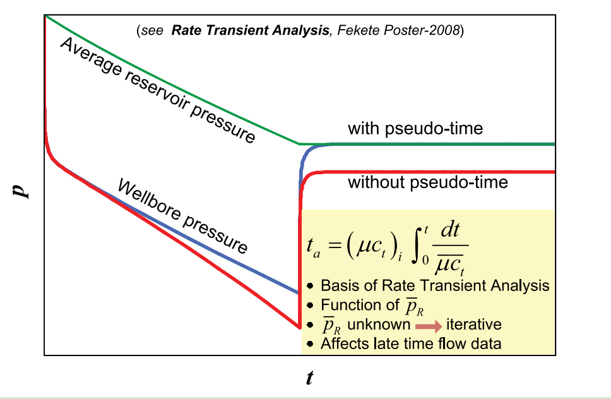
Buildup Pseudo-Time



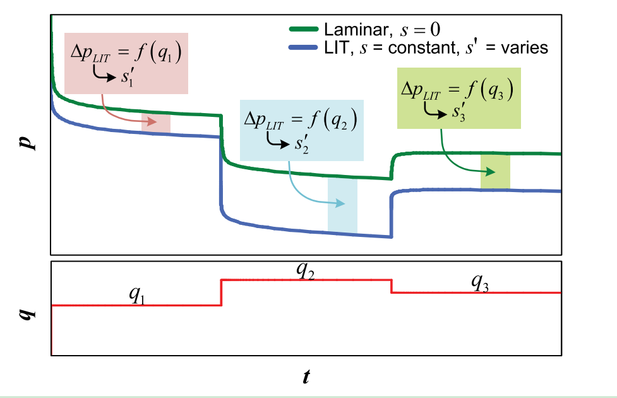
PSEUDO-TIME (t_a)

- Pseudo-time (t_a) corrects for variation of gas viscosity (μ_g) and compressibility (c_g) with pressure
- At low pressure c_g varies significantly → $c_g \approx \frac{1}{p}$
- Pseudo-time transformation is **not exact**
- Pseudo-time is defined **DIFFERENTLY** for drawdown and buildup
  - In well testing (buildup analysis) pseudo-time is defined in terms of pressure at the **wellbore**
  - For analysis of production data (long drawdowns) pseudo-time is defined in terms of the **average reservoir pressure** NOT the wellbore pressure

Drawdown Pseudo-Time



Pressure Drop due to Turbulence



TURBULENCE
(HIGH VELOCITY NON-DARCY FLOW)

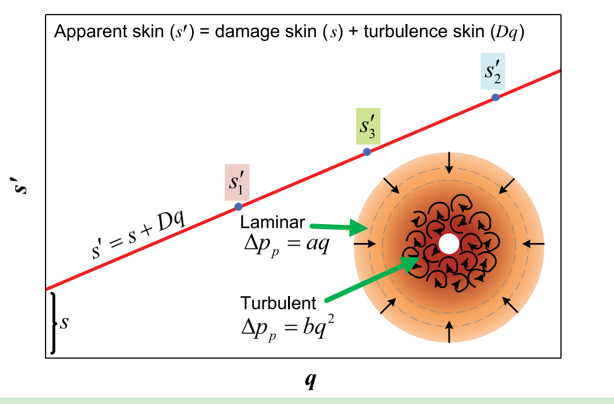
- Gas flow within the reservoir can be laminar or turbulent
- Velocity increases as the wellbore is approached
- Turbulence near the wellbore area causes an additional pressure drop that is treated as skin
- Skin due to turbulence is rate-dependent
- Multiple rates are required to quantify turbulence
- Positive skin usually means damage; however it could represent a stimulated well with turbulence

LAMINAR-INERTIAL-TURBULENT (LIT) FLOW

(Forchheimer or Houpeurt Equation)

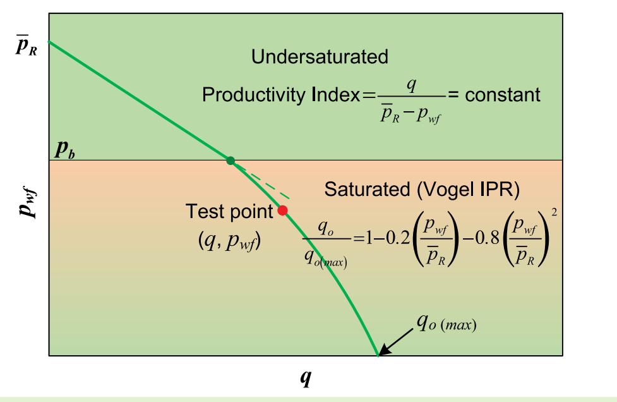
$$\Delta p_p = aq + bq^2 \text{ or sometimes } \Delta p^2 \approx a'q + b'q^2$$

Turbulence Factor D



STABILIZED TESTS

Inflow Performance Relationship (IPR) - Oil

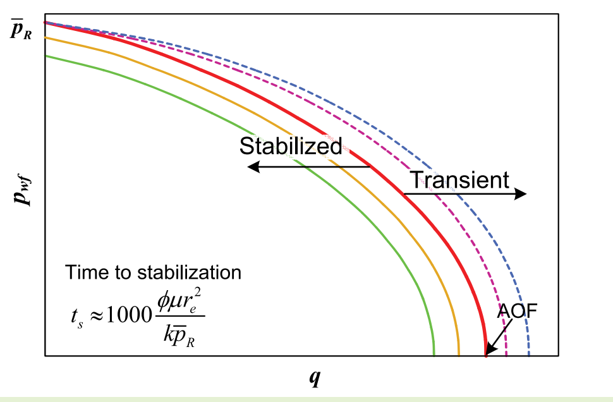


IPR FOR OIL …. AOF FOR GAS

Deliverability Tests : Evaluate deliverability, **NOT** reservoir characteristics

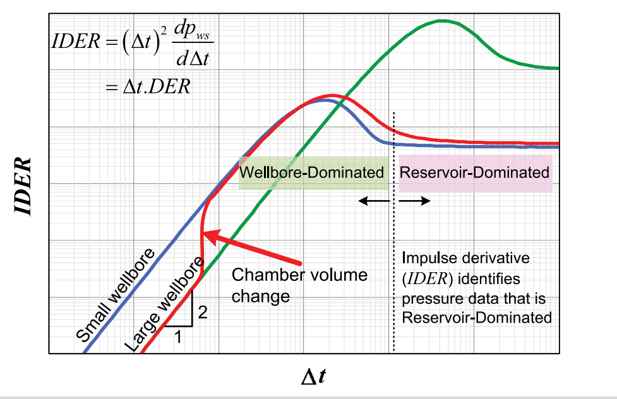
- **IPR :** Inflow Performance Relationship
  - Flow potential of a well at any sandface pressure
  - Single point test
- **AOF :** Absolute Open Flow
  - Maximum rate of a gas well when back pressure at sandface is zero
  - Multiple rates required to evaluate turbulence

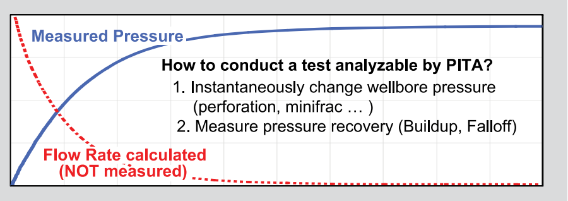
Absolute Open Flow (AOF) - Gas



PERFORATION INFLOW TEST ANALYSIS (PITA)

Impulse Derivative (IDER)

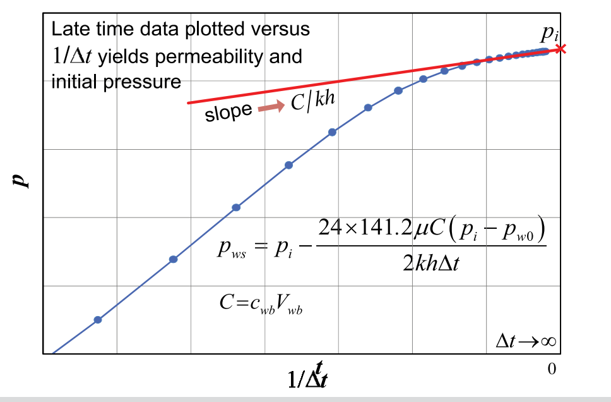




How to conduct a test analyzable by PITA?
1. Instantaneously change wellbore pressure (perforation, minifrac …)
2. Measure pressure recovery (Buildup, Falloff)

- Pre-frac test
- Useful for determining initial pressure and permeability of low permeability reservoirs
- PITA is similar to other tests:
  Slug, Surge®, Impulse®, Perforation Inflow Diagnostic (PID), Closed Chamber Test (CCT), Flow Rate Tester (FRT®), DFIT®, Minifrac, After-Closure-Analysis (ACA), ...

PITA – Late Time Analysis



NOMENCLATURE

a, a'	constant in LIT equation
b, b'	constant in LIT equation
B	formation volume factor
c	compressibility
c_d	desorption compressibility
c_f	formation compressibility
c_t	total compressibility
c_{wb}	compressibility of wellbore fluids
C	wellbore storage
D	turbulence factor
DER	semilog derivative for drawdown
h	formation thickness
k	permeability
k_f	permeability in fracture
k_x	permeability in x direction
k_y	permeability in y direction
k_z	permeability in z direction
l	reservoir length
l_x	transformed reservoir length in x direction
l_y	transformed reservoir length in y direction
L_e	effective length of a horizontal well
m	slope of the straight line on specialized plots
p	pressure
p_0	reference pressure
p_b	bubble point pressure
p_P	pseudo-pressure
$\bar{p}_R$	average reservoir pressure
p_{w0}	perforation cushion pressure
P_L	Langmuir pressure
P_u	unit rate function
q	flow rate
$q_{o(max)}$	maximum oil flow rate
q_{stab}	stabilized flow rate
r_e	external reservoir radius
r_{inv}	radius of investigation
r_w	wellbore radius
r_{wa}	apparent wellbore radius
s	skin
s'	total skin
S	saturation
t	time
t_a	pseudo-time
t_s	time to stabilization
T	temperature
V	volume
V_L	Langmuir volume
V_p	pore volume
V_{wb}	wellbore volume
w	fracture width
W	channel width
x_f	fracture half length
Z	compressibility factor
Δt	shut-in time

Equations - oil field units

Greek symbols

α	shape factor
Δ	difference
ϕ	porosity
κ	flow capacity ratio
λ	interporosity flow coefficient
μ	viscosity
θ	wedge angle
ρ_B	bulk density
ω	storativity ratio

Subscripts

D	dimensionless
g	gas
i	initial
j,n	variable counter
o	oil
$turb$	turbulence
w	water
wf	flowing well
ws	shut-in well

Abbreviations

ACA	after closure analysis
AOF	absolute open flow
BDF	boundary-dominated flow
CCT	closed chamber test
DFIT®	diagnostic fracture injection test
DST	drill stem test
FCD	dimensionless fracture conductivity
FRT®	flow rate tester
IDER	impulse derivative
IPR	inflow performance relationship
MDT®	modular formation dynamic tester
PID	perforation inflow diagnostic
PITA	perforation inflow test analysis
RFT®	repeat formation tester
WBS	wellbore storage
WFT	wireline formation tester

IHS Markit™

Well Testing Fundamentals

All analyses described can be performed using IHS Markit's Well Testing software WellTest.