Fekete

SOFTWARE TRAINING
COURSE

Mini-frac (DFIT)Analysis for Unconventional Reservoirs using F.A.S.T. WellTest™

fastwelltest

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Course Outline

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  - Why Perform a Mini-frac Test?
- Mini-frac Test Overview
- Analysis
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- Radial Flow Example
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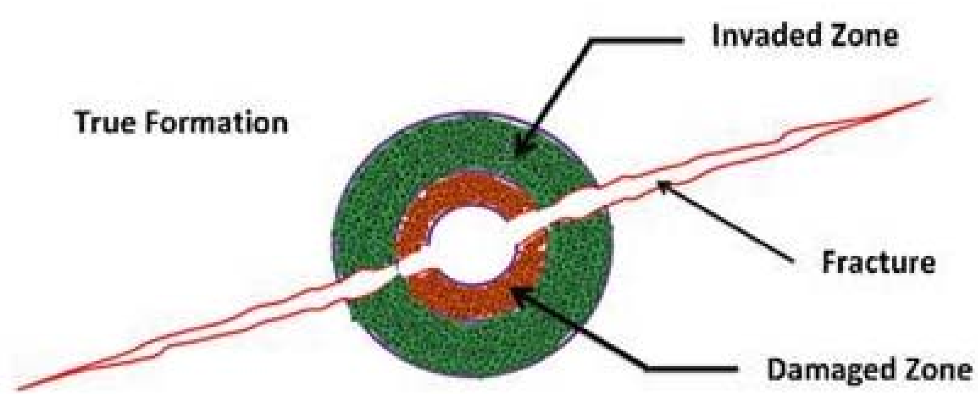
What is a Mini-frac Test?

- A mini-frac test is an injection/falloff diagnostic test performed without proppant before a main fracture stimulation treatment
- The intent is to break down the formation to create a short fracture during the injection period, and then to observe closure of the fracture system during the ensuing falloff period.

What is a Mini-frac Test?



Fracture cut through the near wellbore damaged zone

- The created fracture can cut through near-wellbore damage, and provide better communication between the wellbore and true formation.

- A mini-frac test is capable of providing better results than a closed chamber test performed on a formation where fluid inflow is severely restricted by formation damage.

Why Perform a Mini-frac Test?

- Determine initial formation pressure (P_i) & effective permeability (k) to:
  - Assist production/pressure data analysis
  - Provide initial inputs for reservoir models
  - Assess stimulation effectiveness
  - Help quantify reserves

- Estimate fracture design parameters such as:
  - Fracture gradient
  - Closure pressure (minimum horizontal stress)
  - Leak-off coefficients

Why Perform a Mini-frac Test?

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For Shale/Tight Formations:

Effective Permeability (k) is very low

- Matrix permeability of a few nanodarcies to a few microdarcies (when natural fractures exist) render conventional tests impractical before stimulation

Horizontal Multi-Frac Wells

- Massive hydraulic fracture treatments
- Multiple fracture stages
- Multiple perforation clusters per fracture stage
- Numerous fracture networks created
- Difficult to quantify effective formation permeability and pressure after stimulation

Why Perform a Mini-frac Test?

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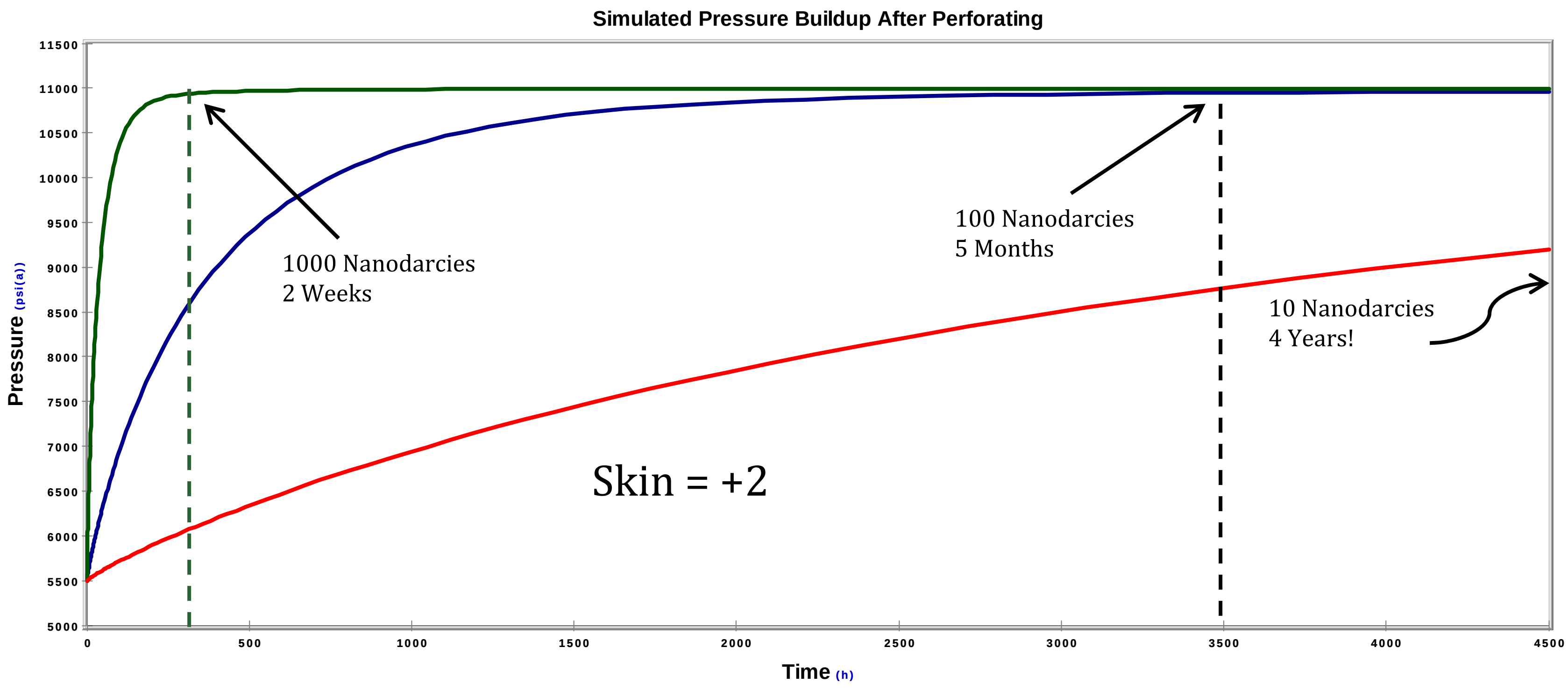
Shut-in Time Required to Estimate P_i & k (After Perforating)

Based on Haynesville Shale Properties



Why Perform a Mini-frac Test?

Shut-in Time Required to Estimate P_i & k (After Perforating)

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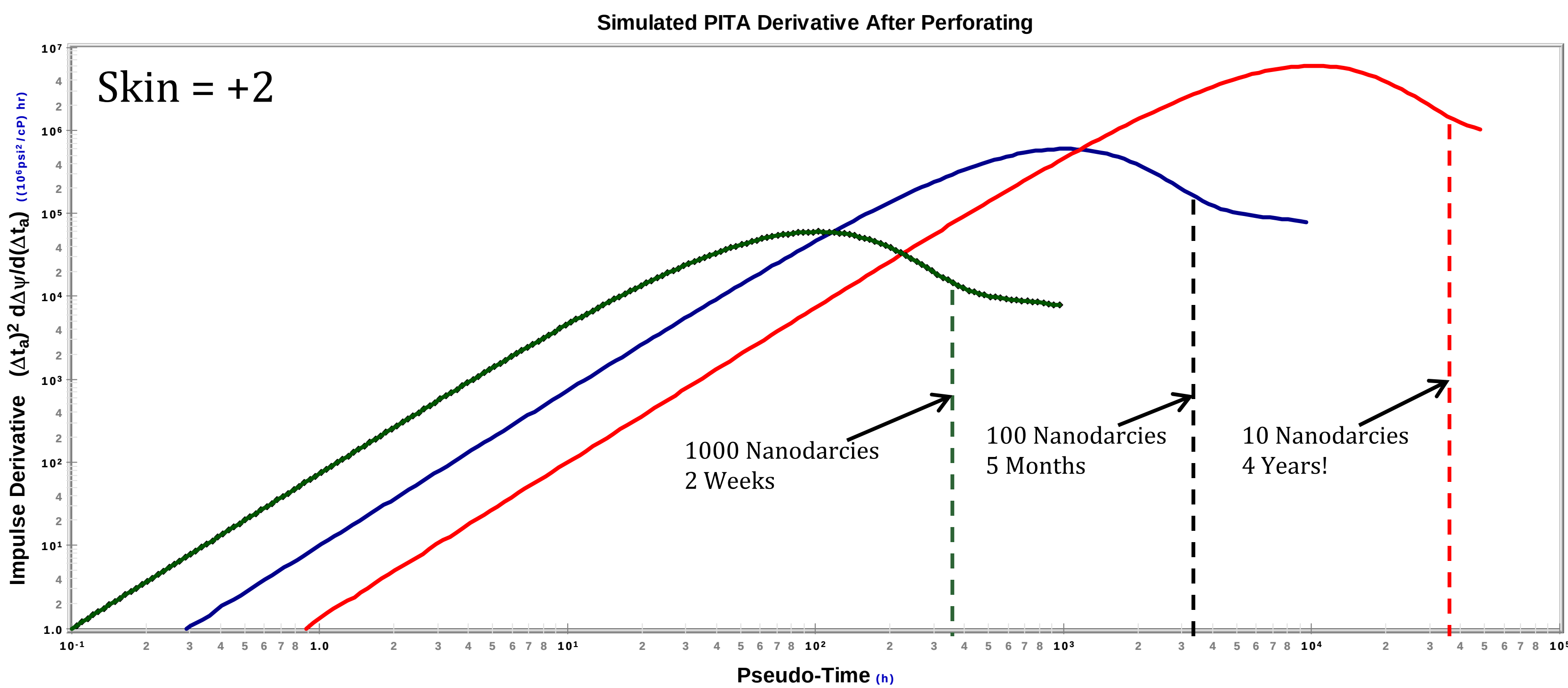

Why Perform a Mini-frac Test?

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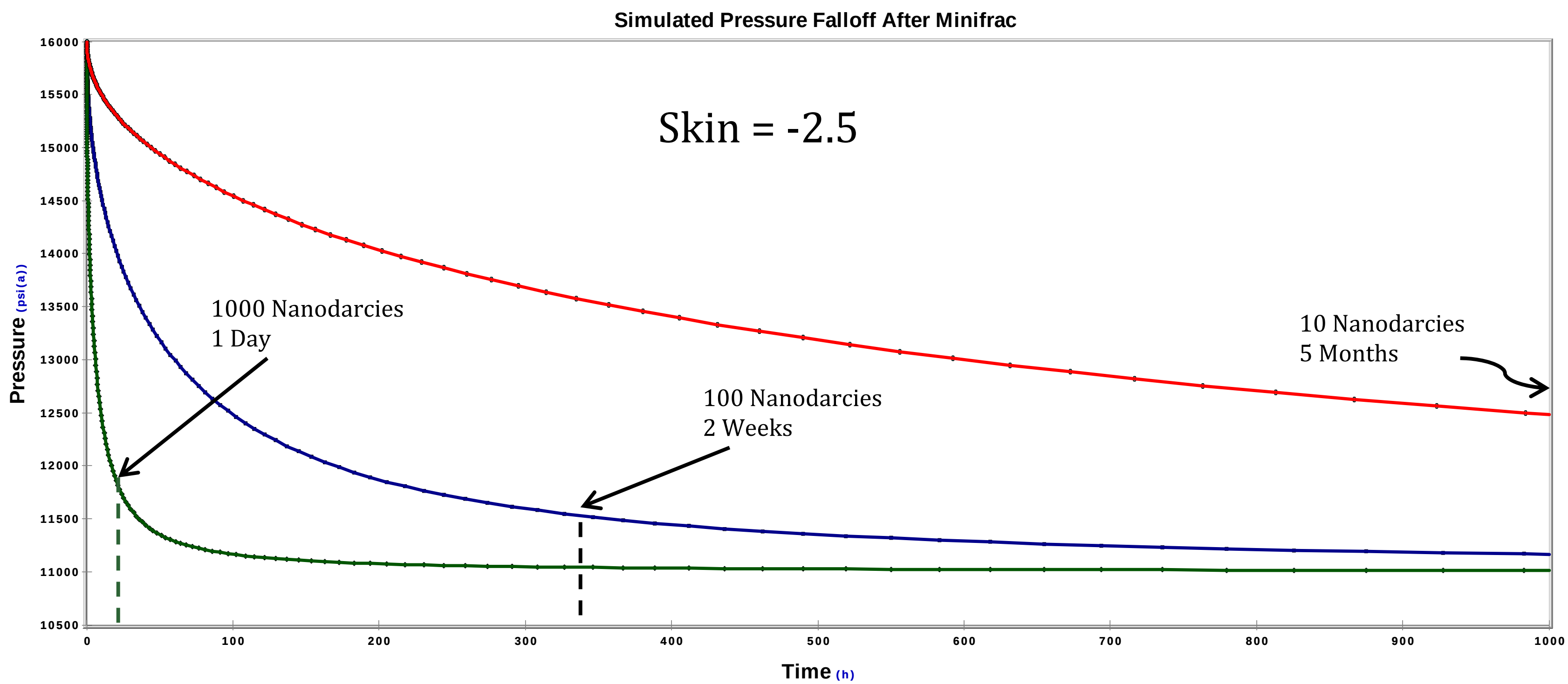
Shut-in Time Required to Estimate P_i & K (After Mini-frac)

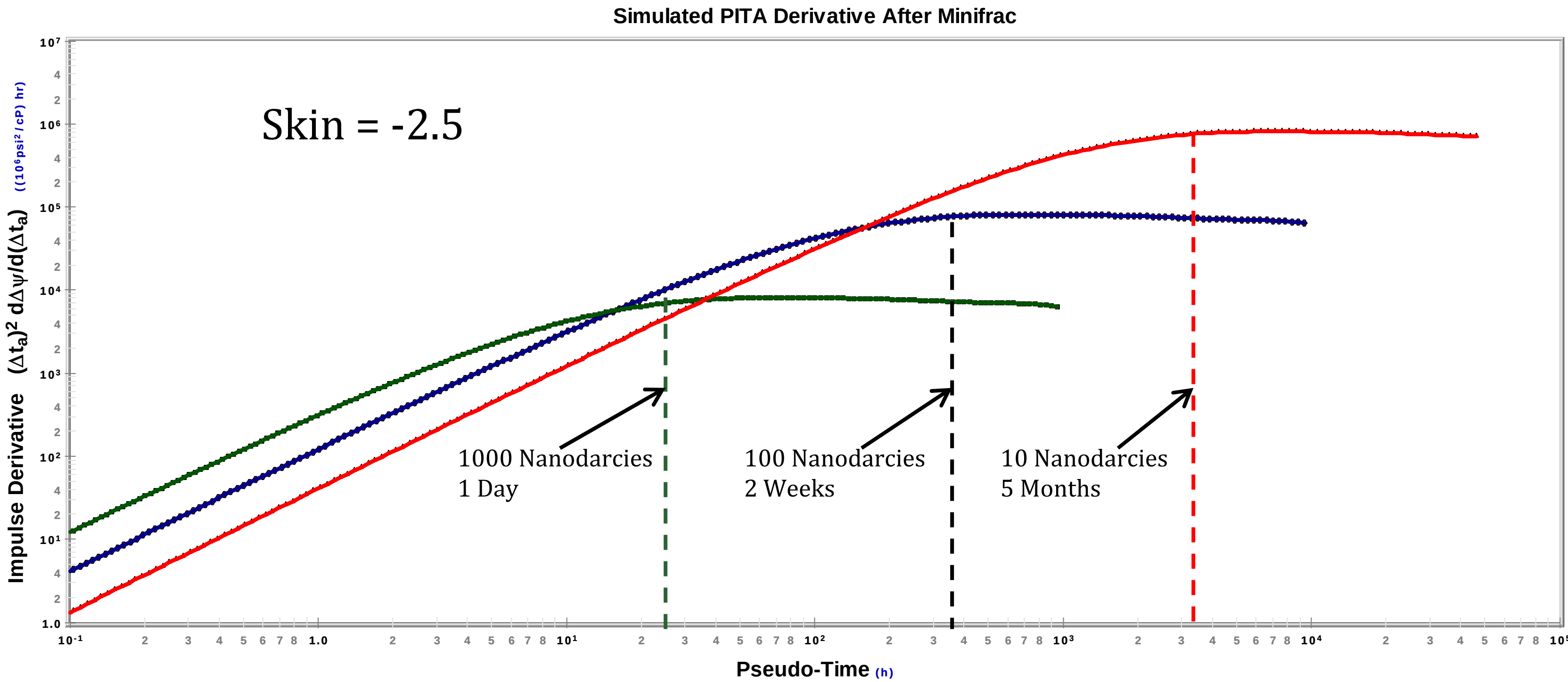
Based on Haynesville Shale Properties



Why Perform a Mini-frac Test?

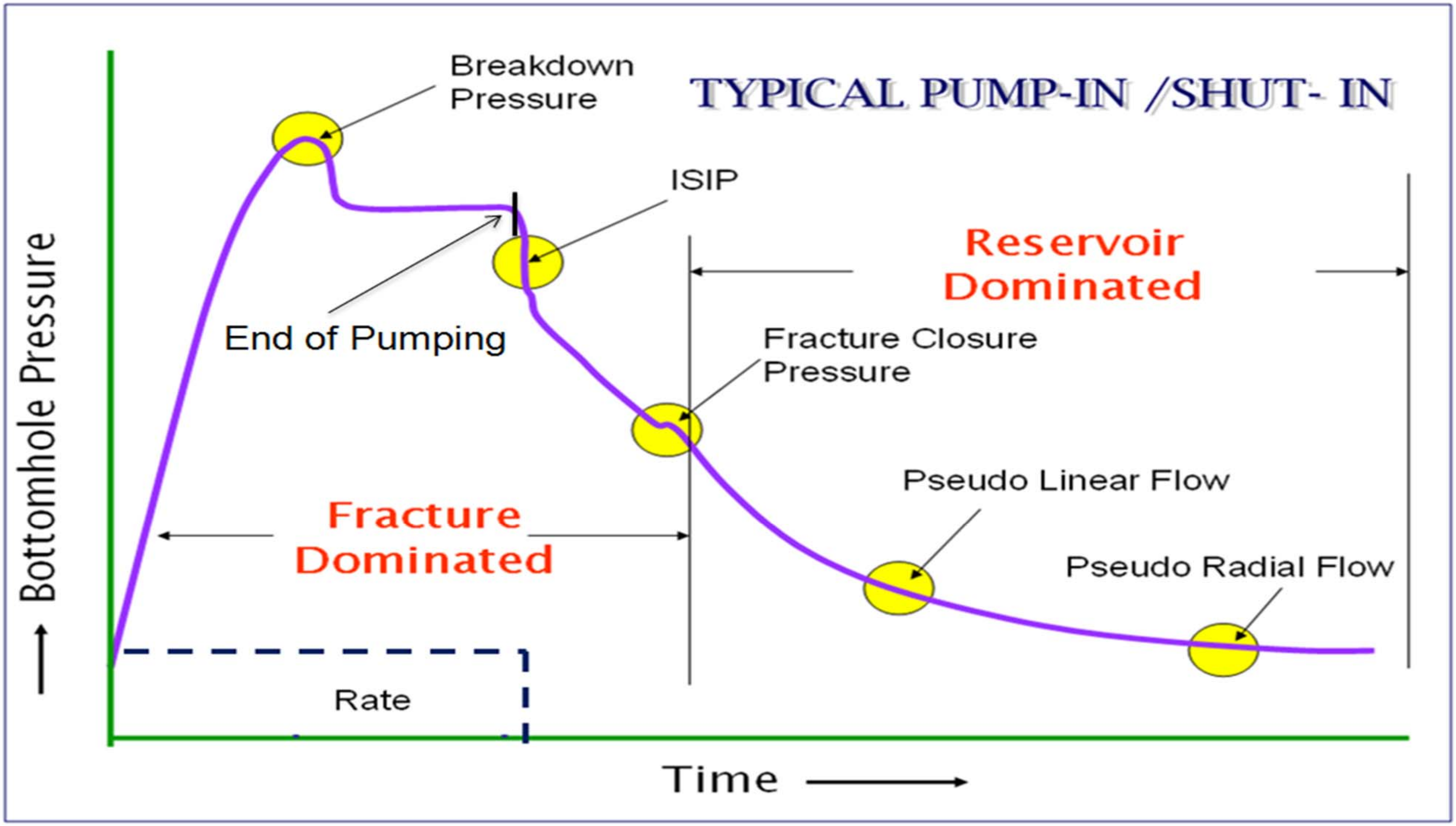
Shut-in Time Required to Estimate Pi & K (After Mini-frac)

Based on Haynesville Shale Properties



Mini-frac Test Overview

Typical Fracture Injection Tests



Mini-frac Analysis

Mini-frac Test Analysis is conducted in two steps:

- **Pre-Closure Analysis (PCA)**
  - Uses special derivatives and time functions (G-Function, √t)
  - Indentify leak-off behaviour and closure pressure
- **After-Closure Analysis (ACA)**
  - Similar workflow to traditional pressure transient analysis
  - Uses "impulse" solution to establish formation permeability (k) and pressure (P_i)

PCA: Parameters

The following parameters are determined from the Pre-Closure Analysis (PCA):

- Fracture Closure Pressure (p_c)

  p_c = Minimum Horizontal Stress

- Instantaneous Shut-In Pressure (ISIP)/Propagation Pressure

  ISIP = Final Bottomhole Injection Pressure - Friction Component

- Fracture Gradient

  Fracture Gradient = ISIP / Formation Depth

- Net Fracture Pressure (Δp_{net})

  Δp_{net} = ISIP – Closure Pressure

- Fluid Efficiency: the ratio of the stored volume within the fracture to the total fluid injected

$$Fluid\ Efficiency = \frac{G_c}{2 + G_c} \qquad G_c \text{ is the } G - Function\ time\ at\ fracture\ closure$$

PCA: G-Function

The G-function is a dimensionless time function relating shut-in time (t) to total pumping time (t_p) at an assumed constant rate and are based on the following equations:

$$G(\Delta t_D) = \frac{4}{\pi}\left(g(\Delta t_D) - g_0\right)$$

$$g(\Delta t_D) = \frac{4}{3}\left((1 + \Delta t_D)^{1.5} - \Delta t_D^{1.5}\right) \qquad for\ \alpha = 1$$

$$g(\Delta t_D) = (1 + \Delta t_D)\sin^{-1}\left((1 + \Delta t_D)^{-0.5}\right) + \Delta t_D{}^{0.5} \qquad for\ \alpha = 0.5$$

$$\Delta t_D = \frac{(t - t_p)}{t_p}$$

$$g_0 = \frac{\pi}{2} \quad for\ \alpha = 0.5 \qquad\qquad g_0 = \frac{4}{3} \quad for\ \alpha = 1$$

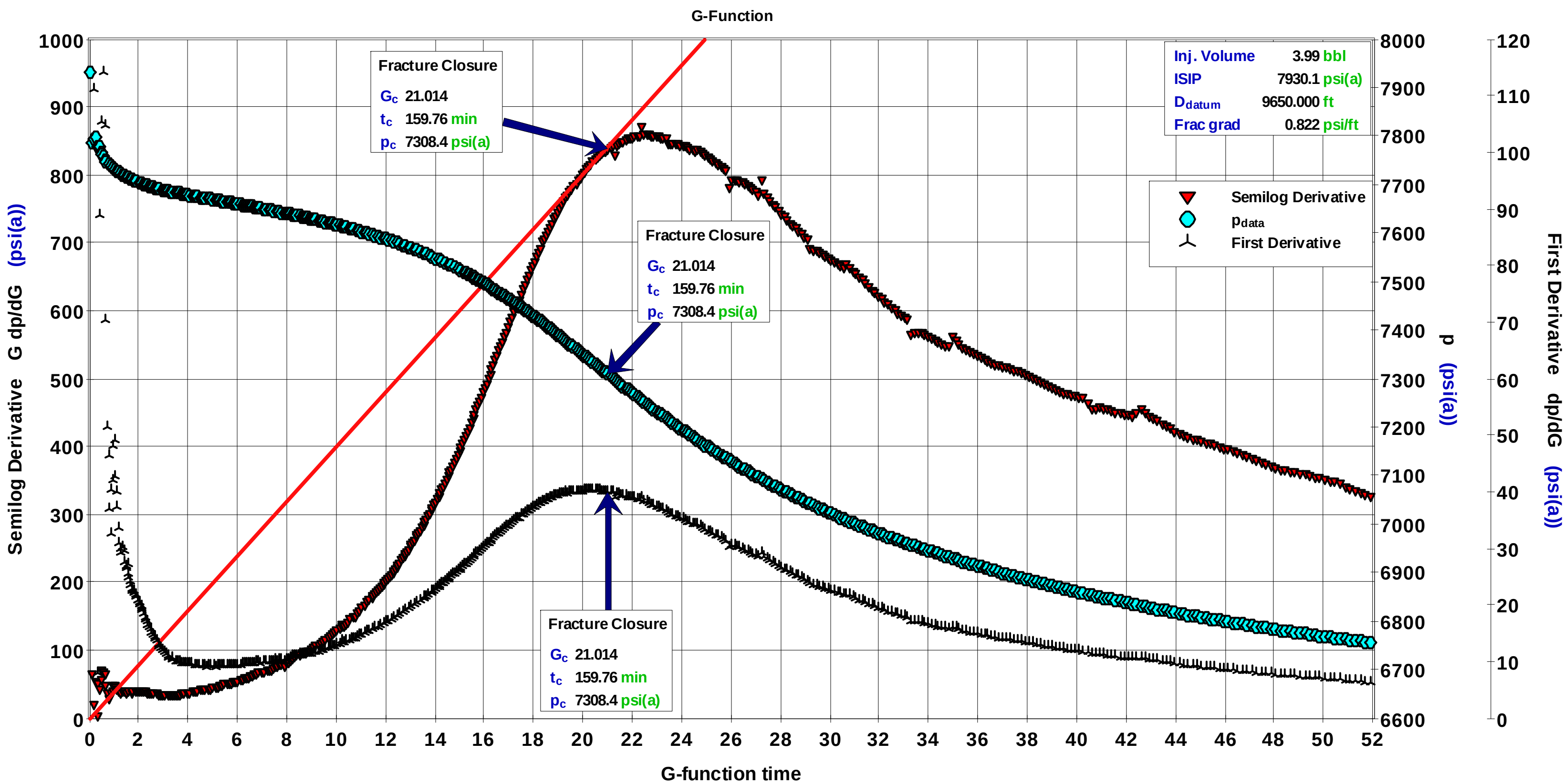
Two limiting cases for the G-function are shown here:

α = 1.0 is for low leak-off

α = 0.5 is for high leak-off

The value of g_0 is the computed value of g at shut-in.

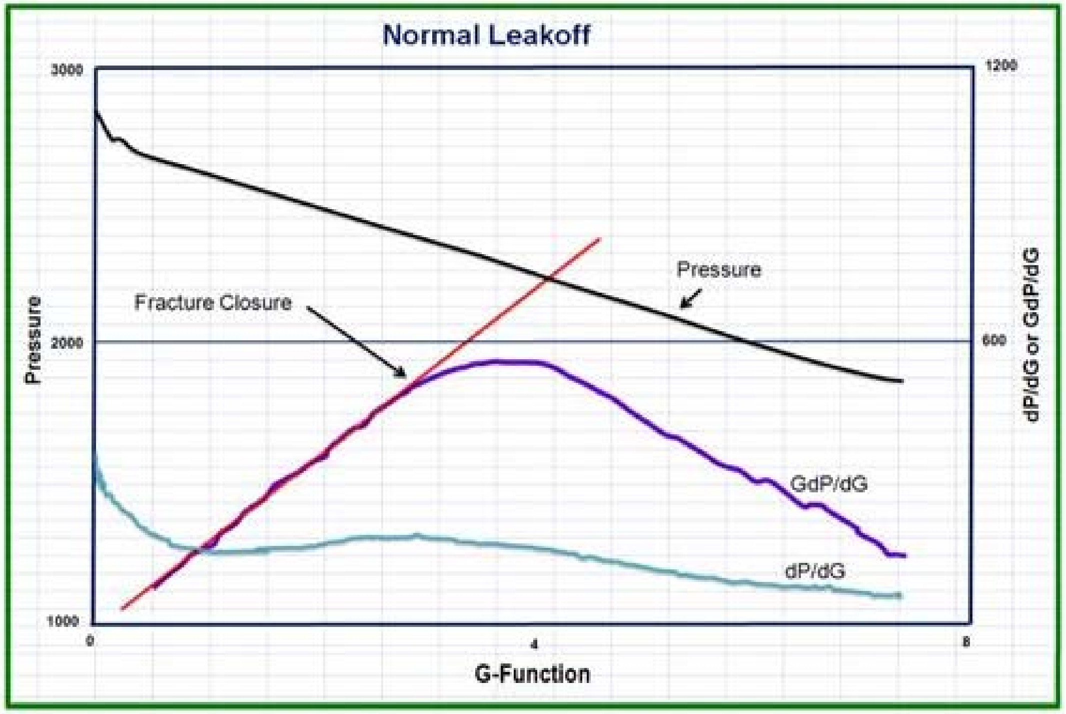
PCA: G-Function Analysis



Fracture closure is identified as the point where the G-Function derivative starts to deviate downward from the straight line

PCA: Leak-Off Types

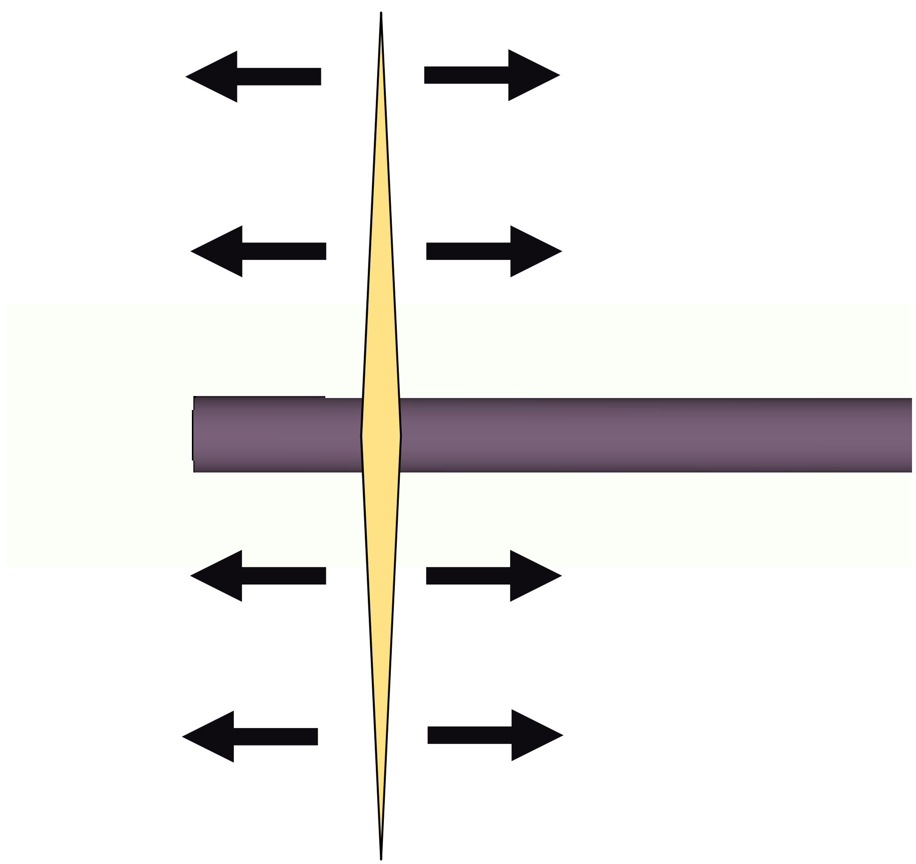
Normal Leak-off: occurs when the fracture area is constant during shut-in and the leak-off occurs through a homogeneous rock matrix

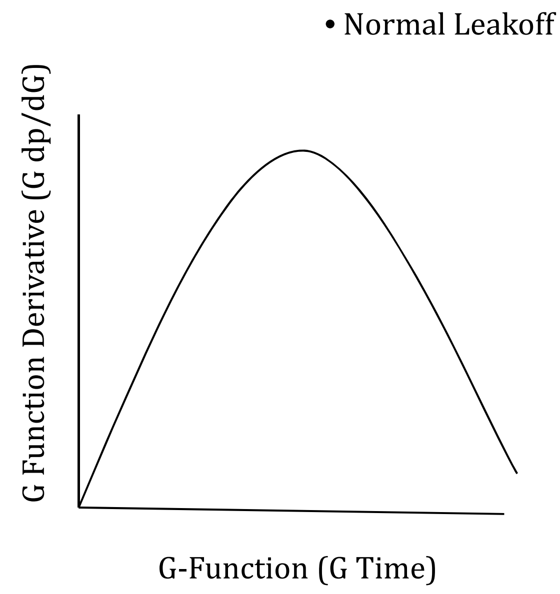


The characteristic signatures of normal leak-off are :

1. A constant pressure derivative (dP/dG) during fracture closure.
2. The G-Function derivative (G dP/dG) lies on a straight line that passes through the origin

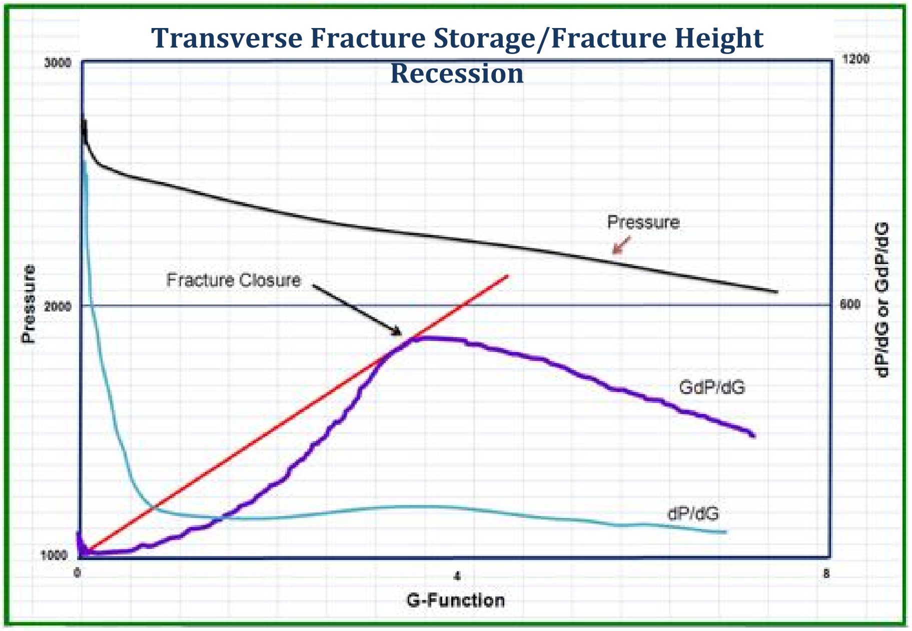
Normal Leakoff





PCA: Leak-Off Types

Transverse Fracture Storage/Fracture Height Recession is indicated when the G-Function derivative G dP/dG falls below a straight line that extrapolates through the normal leak-off data, and exhibits a concave up trend

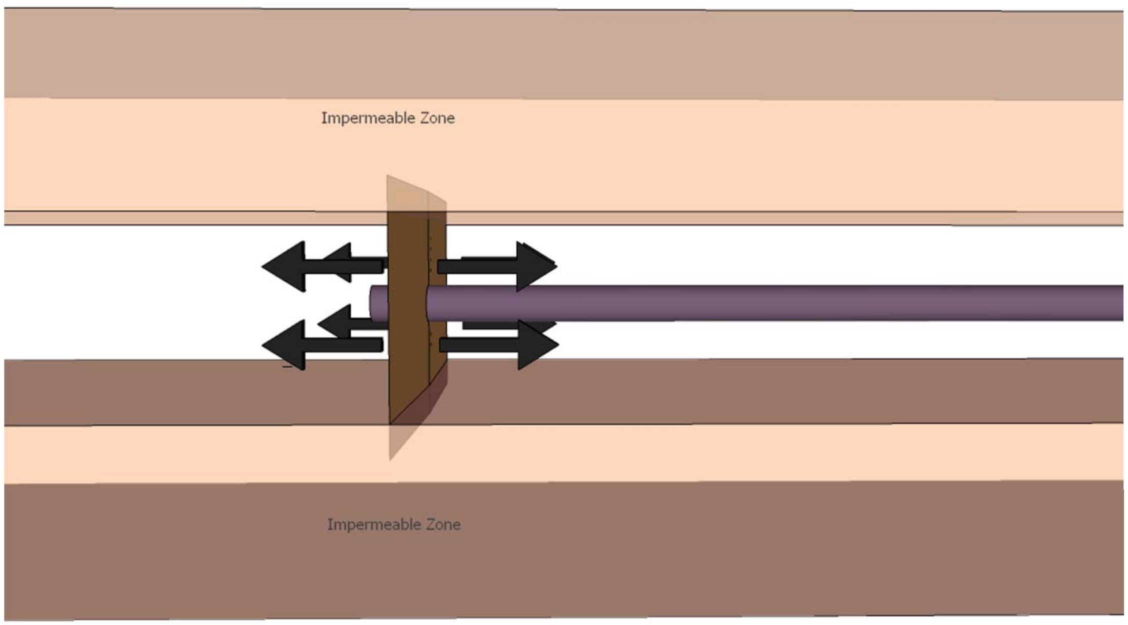


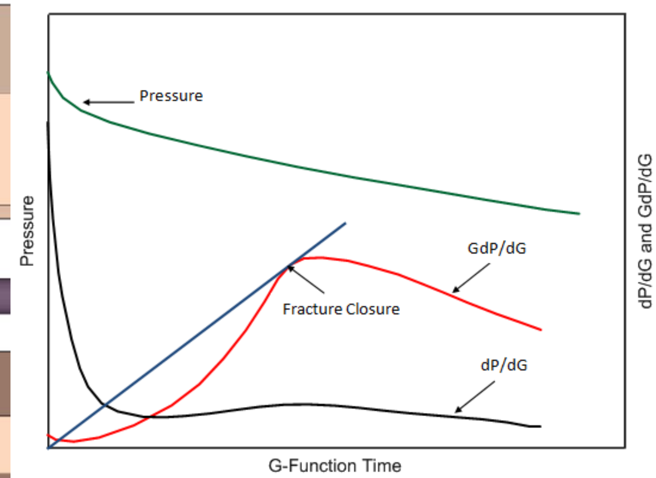
Two characteristics are visible on the G-function curve:

1. The G-Function derivative G dP/dG lies below a straight line extrapolated through the normal leak-off data.
2. The G-Function derivative G dP/dG exhibits a concave up trend.
3. The First Derivative dP/dG also exhibits a concave up trend.

Fracture Height Recession

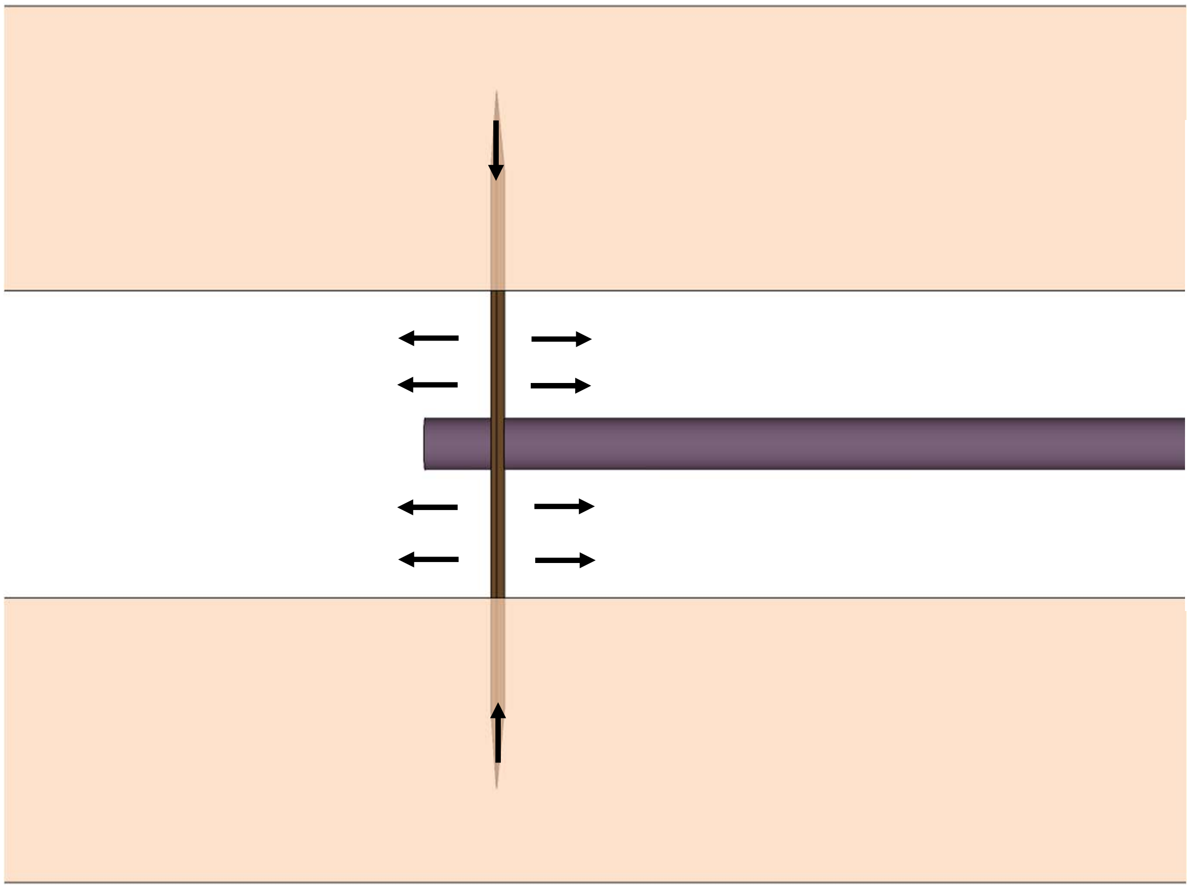
- Fracture penetrates impermeable zone

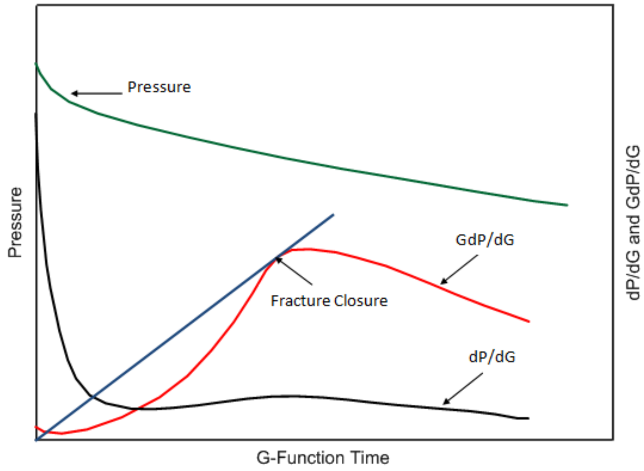




Fracture Height Recession

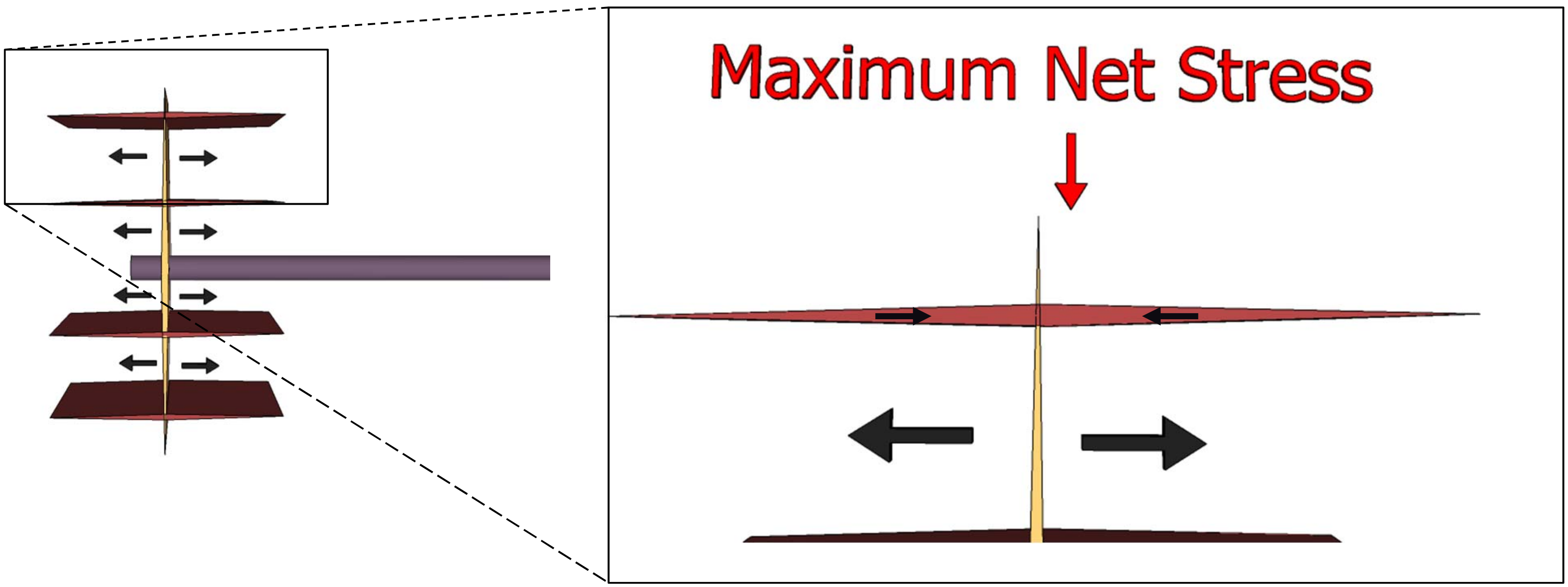
- Fracture penetrates impermeable zone





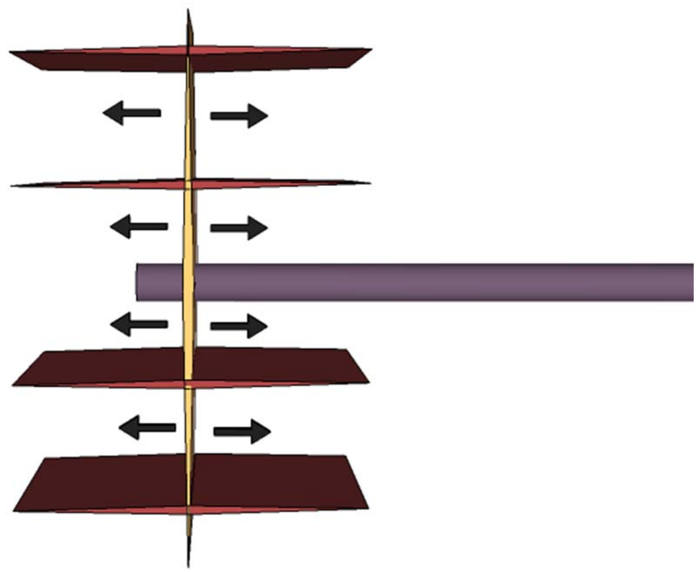
Transverse Storage

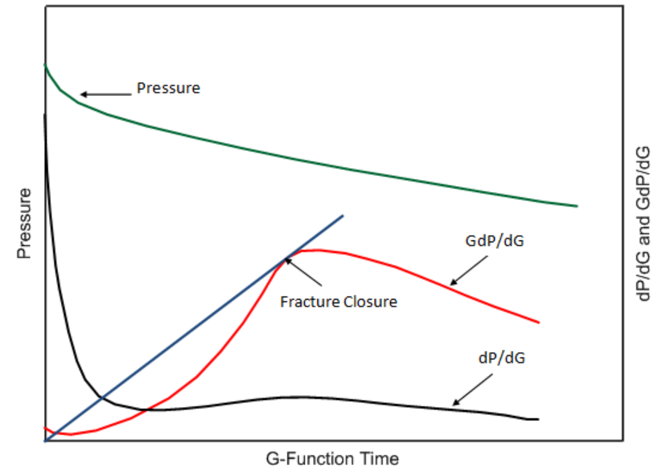
- Early Time – Secondary fractures open



Transverse Storage

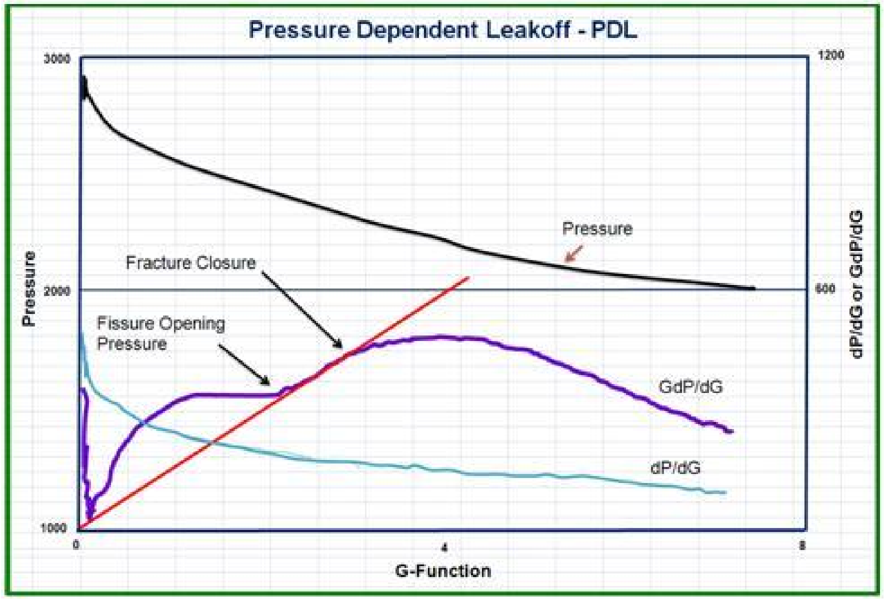
- Late Time – Secondary fractures close





PCA: Leak-Off Types

Pressure Dependent Leak-off (PDL): indicates the existence of secondary fractures intersecting the main fracture, and is identified by a characteristic "hump" in the G- Function derivative that lies above the straight line fit through the normal leak-off data.

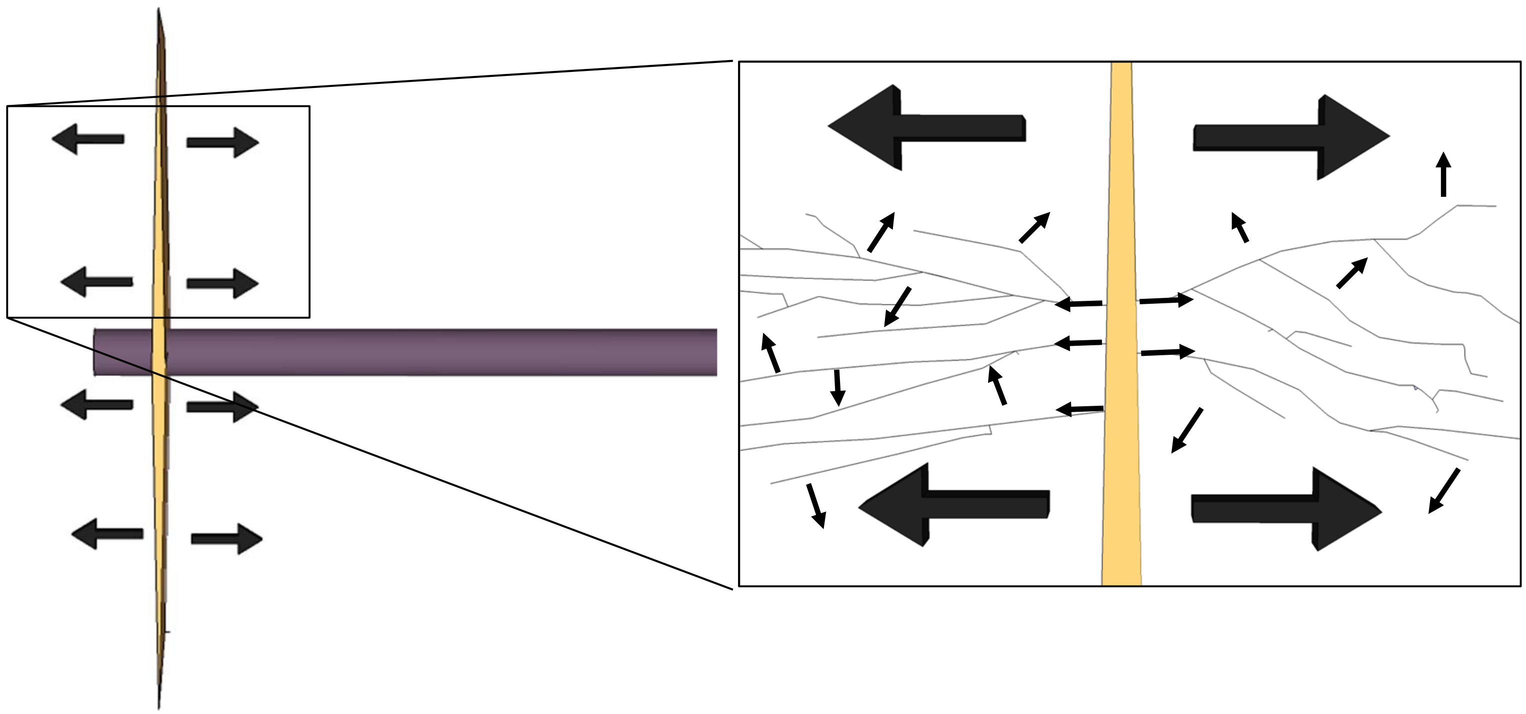


The characteristic signatures of pressure dependent leak-off are:

1. A characteristic large "hump" in the G-Function derivative G dP/dG lies above the straight line that passes through the origin..
2. Subsequent to the hump, the pressure decline exhibits normal leak-off.
3. The portion of the normal leak-off lies on a straight line passing through the origin.
4. The end of the hump is identified as "fissure opening pressure".

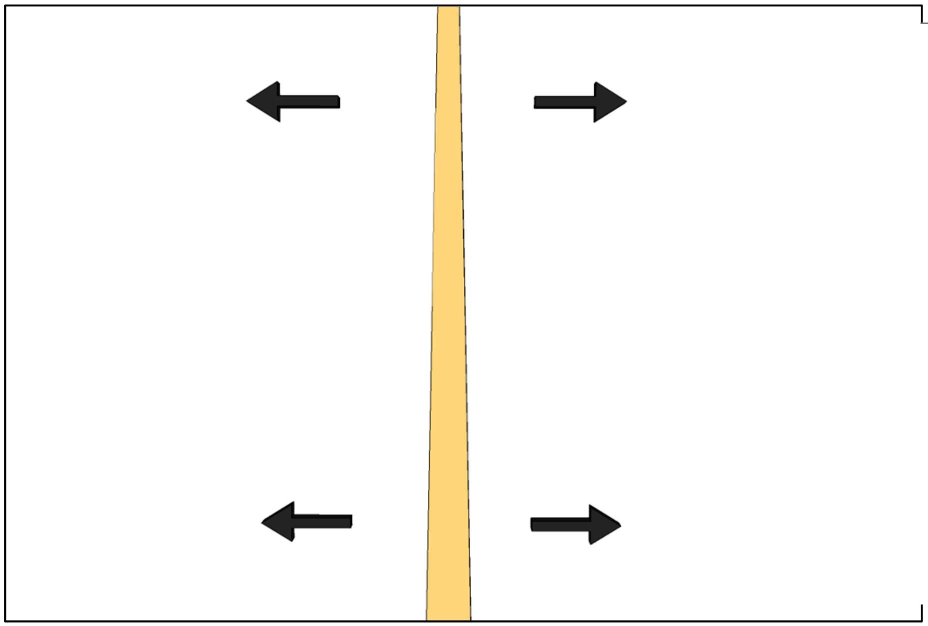
Pressure Dependant Leak-off

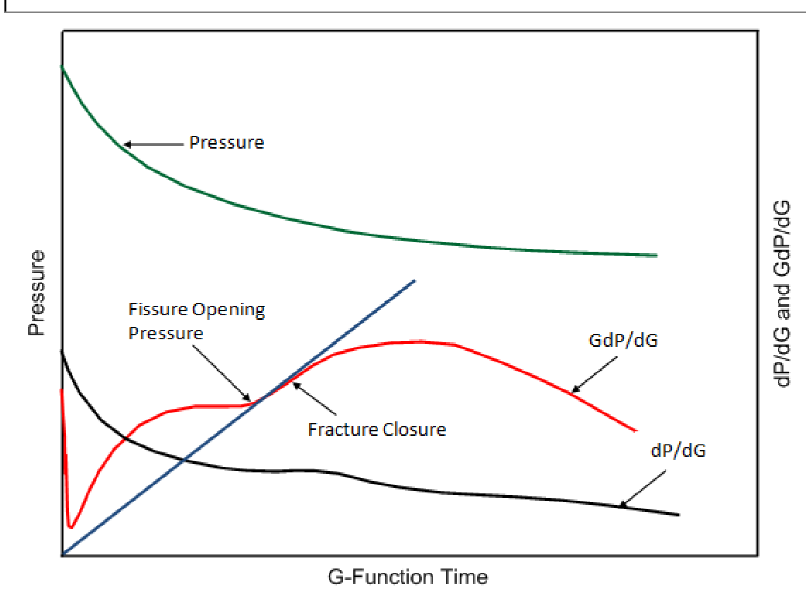
- Early Time - Extra leak-off from microfractures at high pressure/early time



Pressure Dependant Leak-off

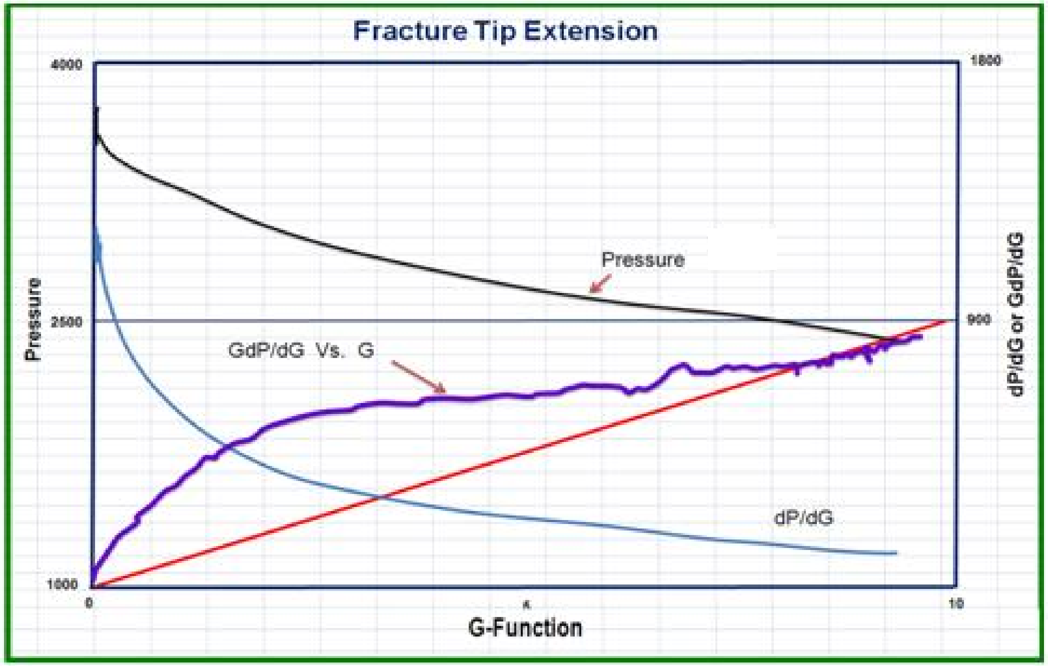
- Late Time- Microfractures close, normal leak-off resumes





PCA: Leak-Off Types

Fracture Tip Extension occurs when a fracture continues to grow even after injection is stopped and the well is shut-in. It is a phenomenon that occurs in very low permeability reservoirs, as the energy which normally would be released through leak-off is transferred to the ends of the fracture.

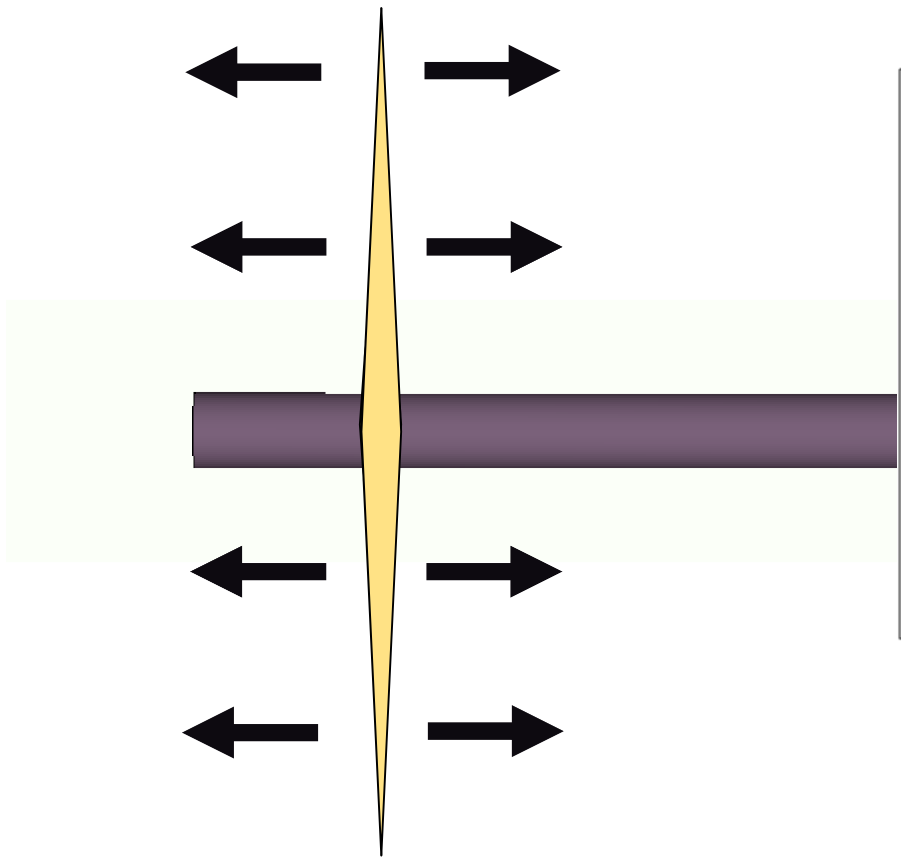


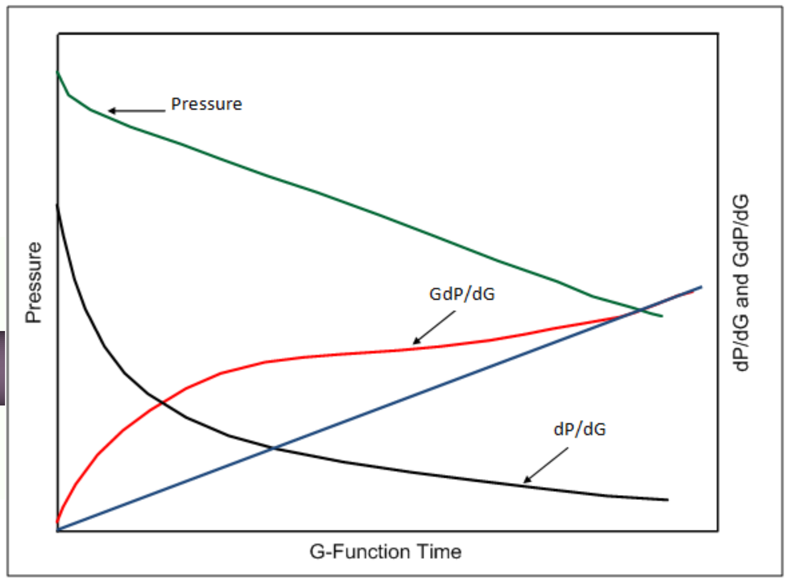
The characteristic signatures of fracture tip extension are:

1. The G-Function derivative G dP/dG initially exhibits a large positive slope that continues to decrease with shut-in time, yielding a concave-down curvature.
2. Any straight line fit through the G-Function derivative G dP/dG intersects the y-axis above the origin.

Fracture Tip Extension

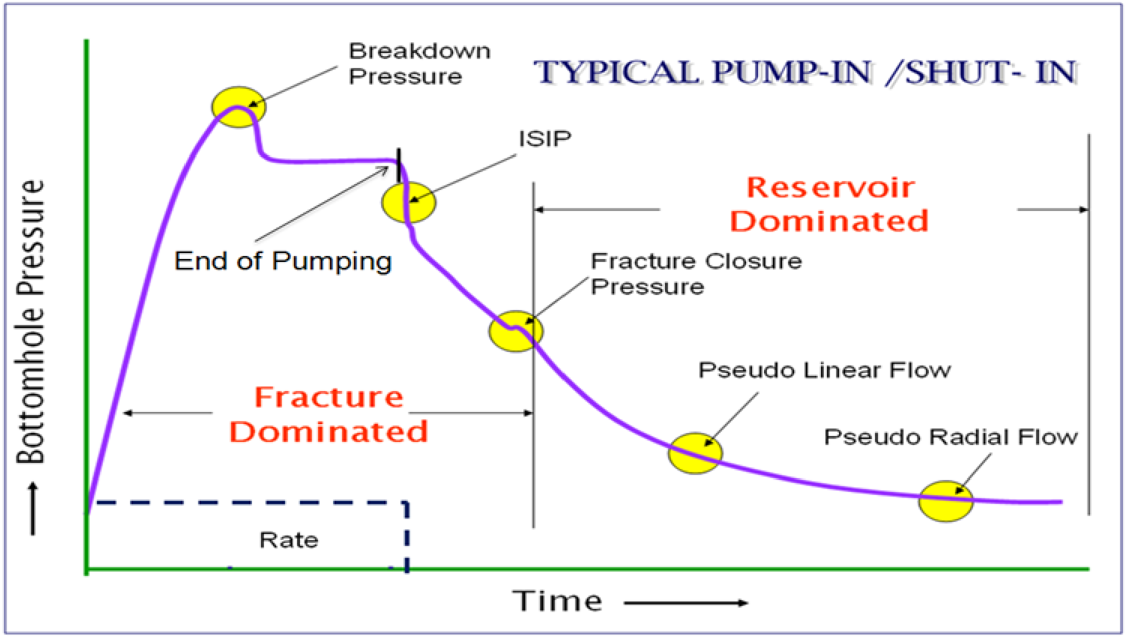
- Fracture Tip Extension Provides Extra Leak-Off





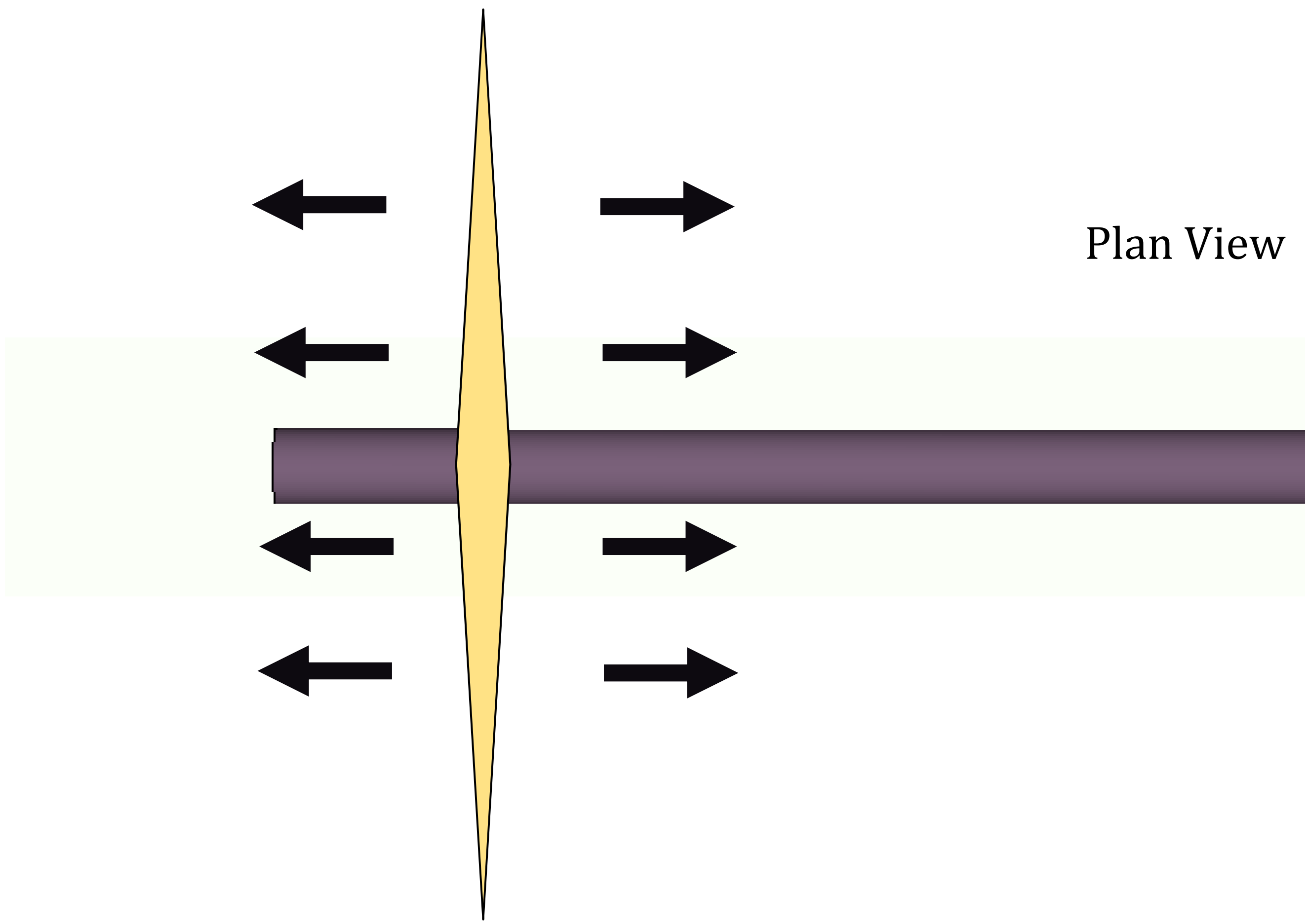
After-Closure Analysis (ACA)

- ACA is performed on falloff data collected after fracture closure
- Similar workflow to traditional pressure transient analysis



- Traditional PTA founded on the “constant-rate solution”
- Main ACA techniques are founded on the “impulse solution”
- The “constant-rate solution” hinges on the flow rate prior to SI
- The “impulse solution” hinges on a “defined volume”

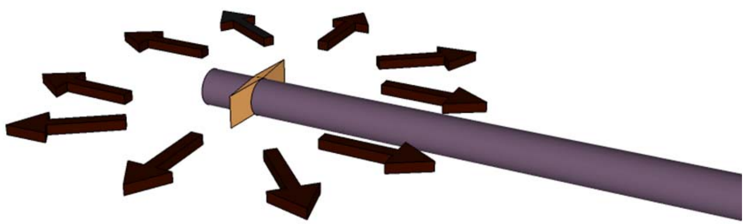
After Closure – Linear Flow



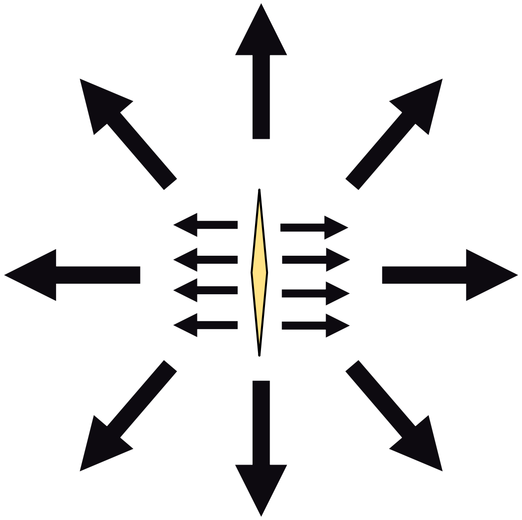
After Closure – Radial Flow

- Radial Flow in Horizontal Plane
  - If linear flow is observed before radial flow, can use fracture model

3D



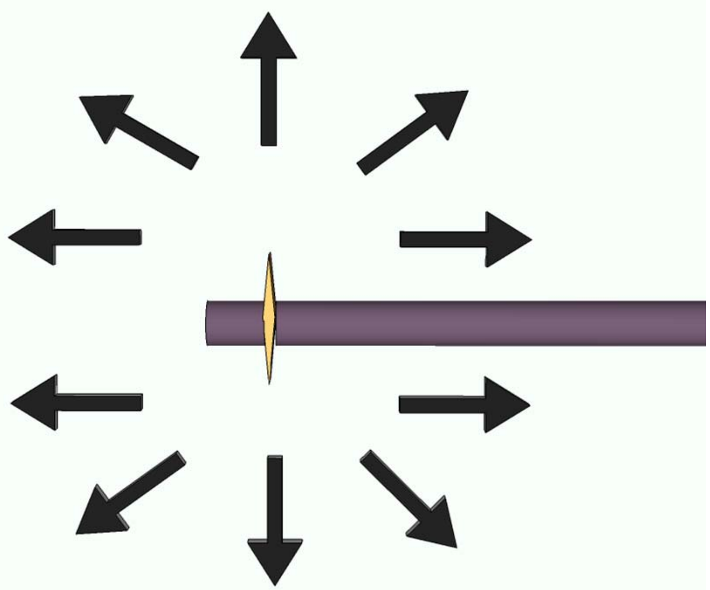
Plan View – Vertical Model with Fracture



After Closure

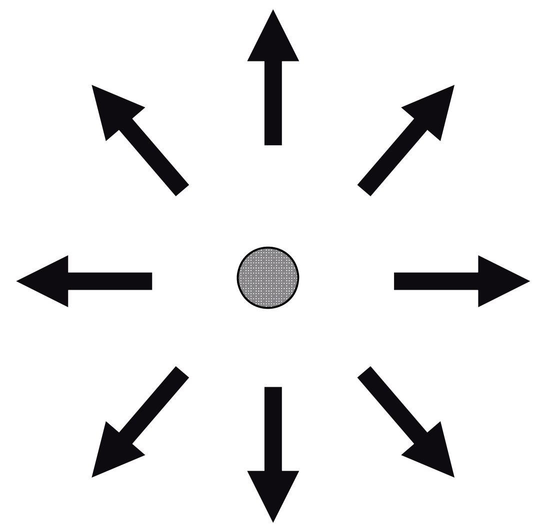
- Radial Flow in Horizontal Plane
  - If only radial flow is observed, can be modelled as vertical with negative skin

Conceptual Model



Vertical Model

Plan View



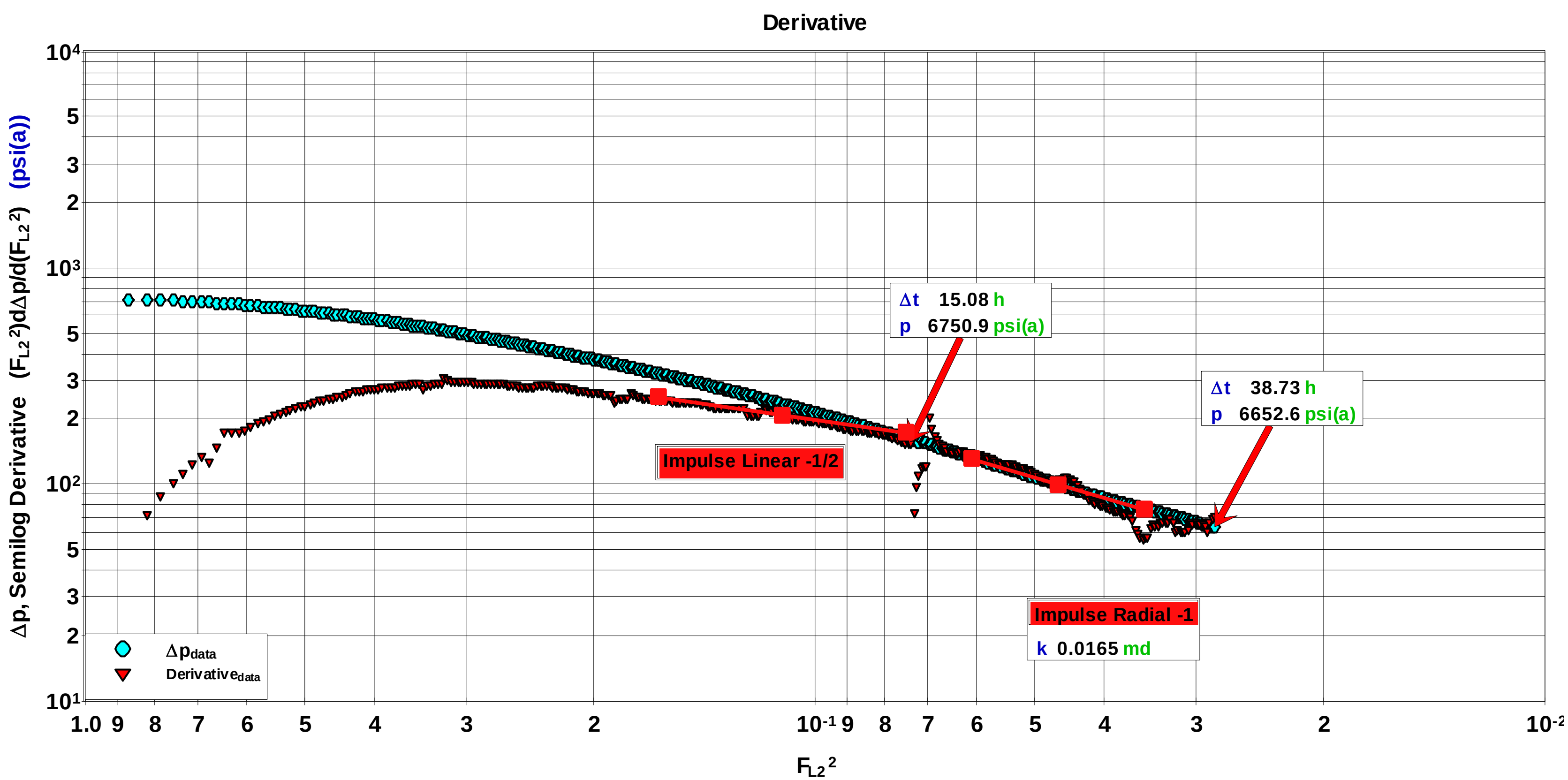
After-Closure Analysis (ACA)

- After-Closure Analysis (ACA) is performed on falloff data collected after fracture closure.
- Similar workflow to traditional pressure transient analysis.
- Traditional PTA founded on the “constant-rate solution”; Mini-Frac ACA techniques are founded on the “impulse solution”.
- The “constant-rate solution” hinges on the flow rate prior to the analyzed shut-in period whereas the “impulse solution” hinges on a “defined volume”.
- Impulse solutions are used because of the short injection period and assume the entire injected volume is injected instantaneously.
- There are two ACA techniques available in F.A.S.T. WellTest™ (Nolte and Soliman/Craig).

Nolte ACA

- This after-closure analysis method is based on the work of K.G. Nolte[8], and expanded on by R.D. Barree[4].
- Based on the solution of a constant pressure injection followed by a falloff.
- The impulse equations are obtained by approximating the injection duration as very small.
- Uses injected volume as the impulse volume and the falloff begins at fracture closure.
- Characteristic slopes of the semi-log derivative when plotted on the log-log derivative plot differ from traditional PTA:
    - Impulse Linear flow has a slope of -1/2.
    - Impulse Radial flow has a slope of -1.

Nolte ACA

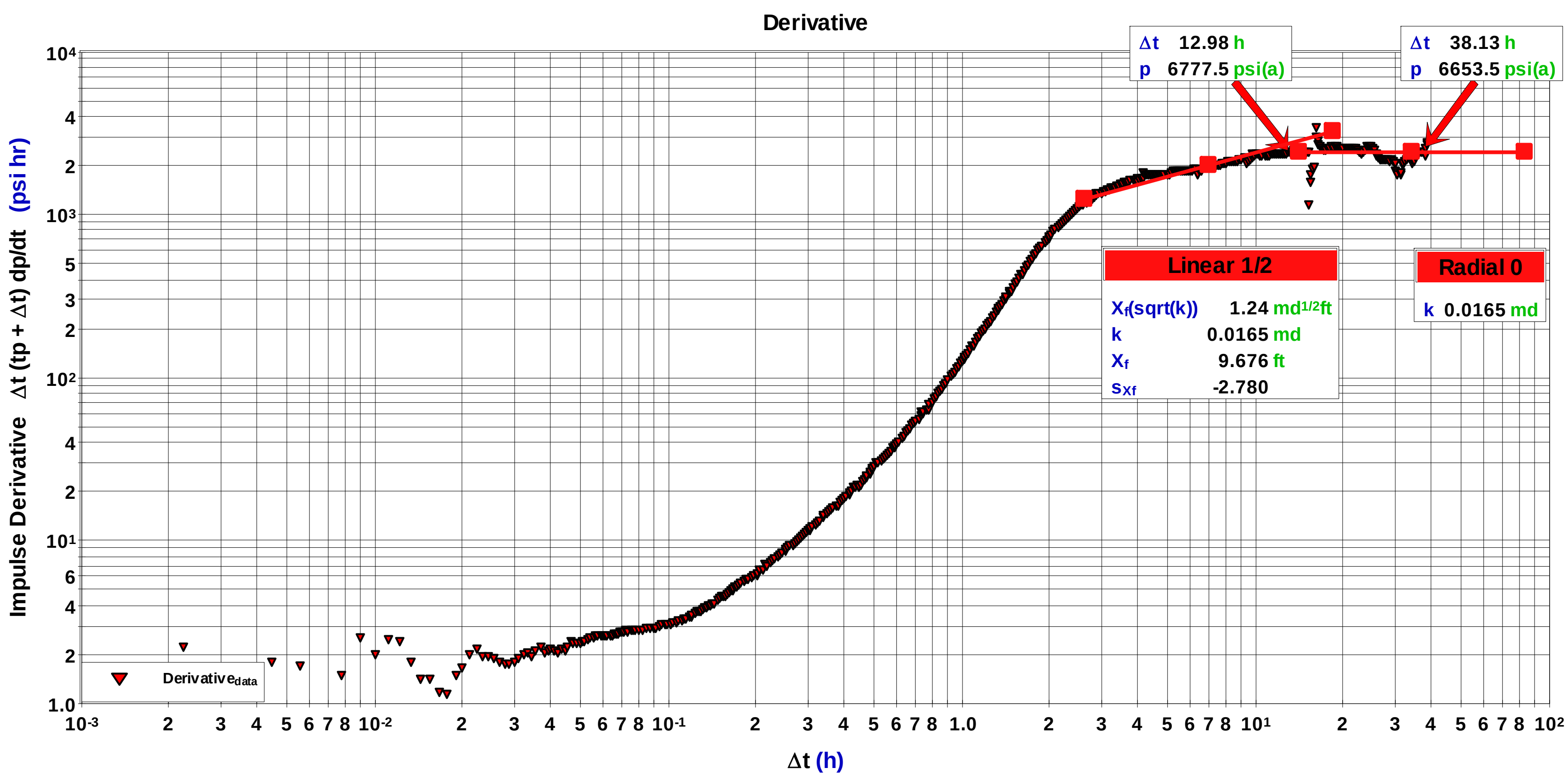


Derivative
Δp, Semilog Derivative (F_L2 ²)dΔp/d(F_L2 ²) (psi(a))
10⁴
5
3
2
10³
5
3
2
10²
5
3
2
10¹
1.0 9 8 7 6 5 4 3 2 10⁻¹ 9 8 7 6 5 4 3 2 10⁻²
F_L2 ²
Δt 15.08 h
p 6750.9 psi(a)
Δt 38.73 h
p 6652.6 psi(a)
Impulse Linear -1/2
Impulse Radial -1
k 0.0165 md
Δp_data
Derivative_data

Soliman/Craig ACA

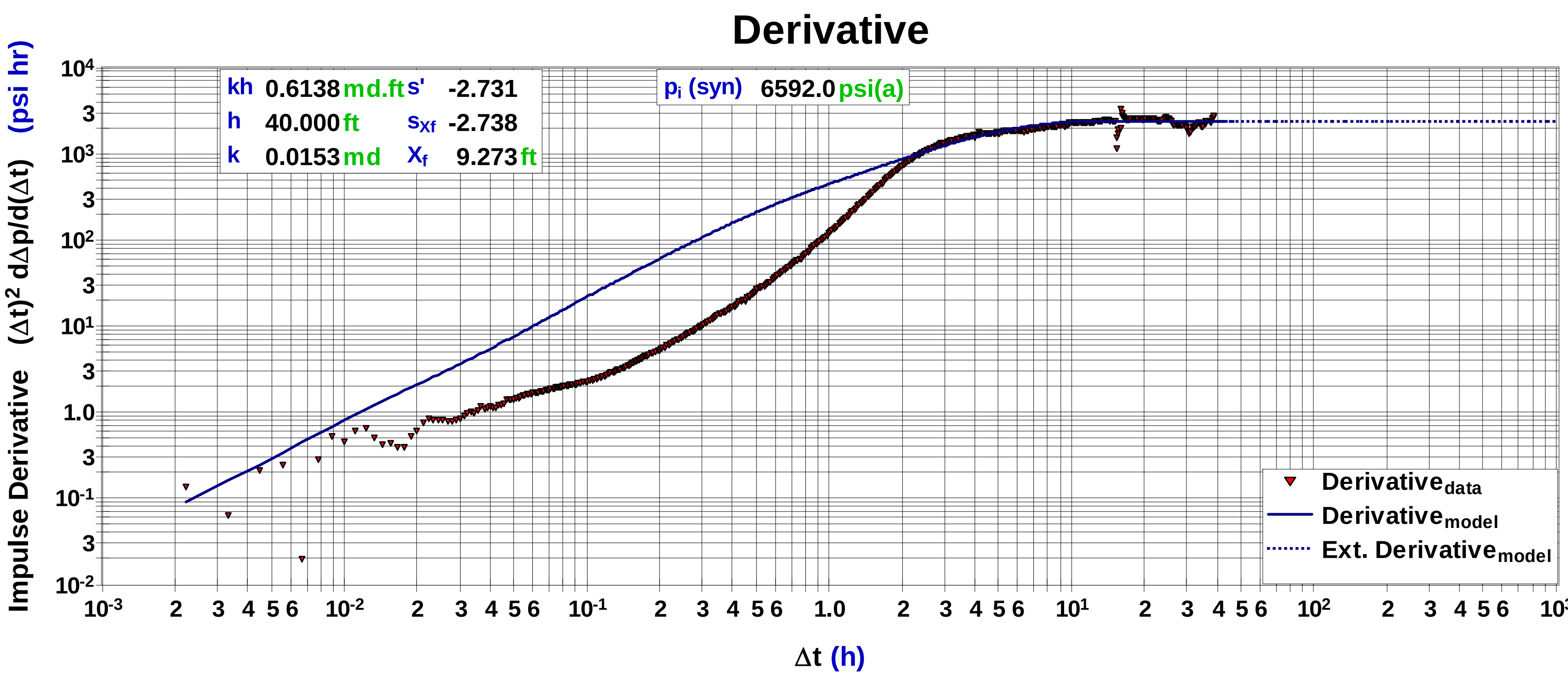
- This after-closure analysis method is based on the combined works of M.Y. Soliman and D. Craig[1].
- Soliman's solution is based on a constant rate injection followed by a long falloff[2].
- Soliman applied superposition in Laplace space to obtain a single equation and then took the late-time approximation to obtain impulse equations (for bilinear, linear and radial flow).
- D. Craig developed an analytical model which accounts for fracture growth, leak-off, closure and after-closure[3].
- The late-time approximation of Craig's model produced impulse equations that are consistent with Soliman's solutions.
- Uses injected volume as the impulse volume.
- Characteristic slopes of the impulse derivative when plotted on the log-log derivative plot are identical to those of traditional PTA.
- Soliman/Craig's solutions facilitate the use of analytical models in F.A.S.T. WellTest™.

Soliman/Craig ACA



ACA - Modelling

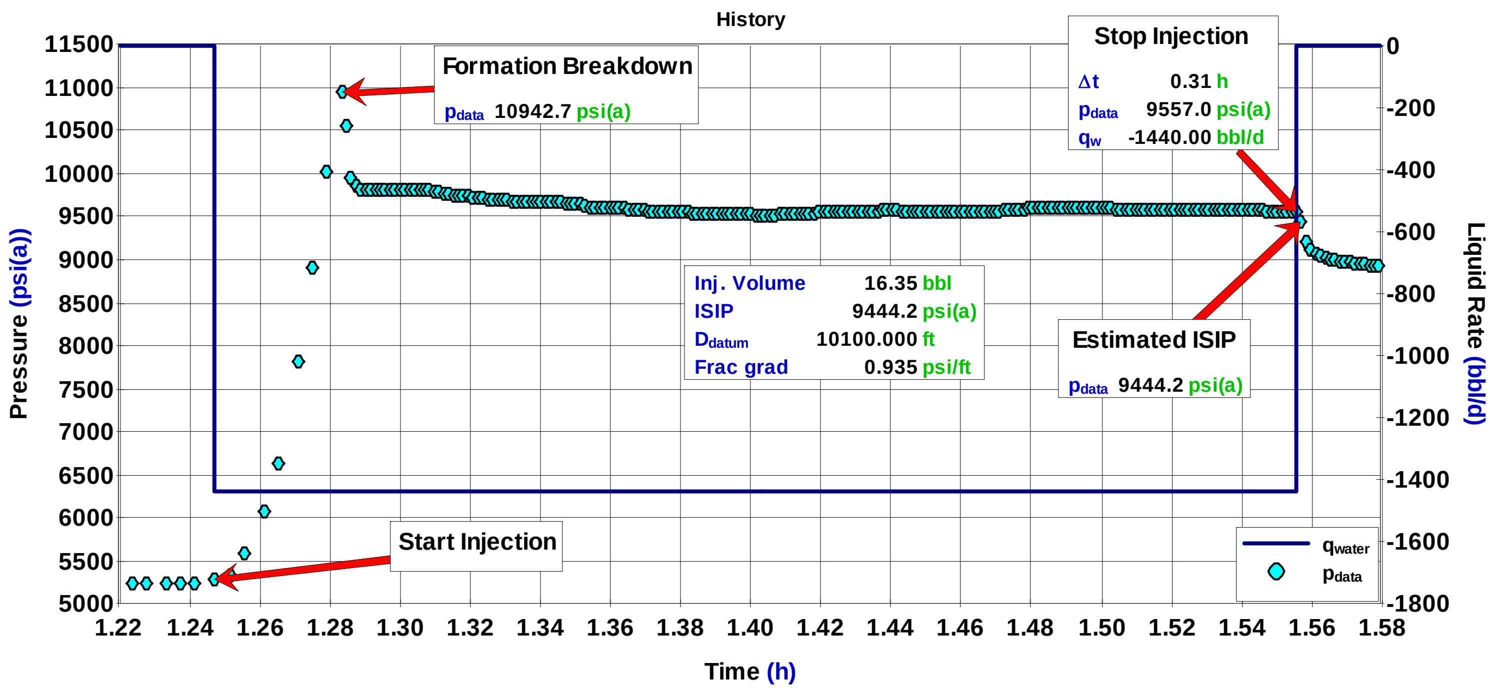
- Once the initial reservoir pressure (P_i) and permeability (k) are estimated, a model is generated (Soliman/Craig)to confirm these estimates. Note that the existing model does not account for the change in storage that occurs while the induced fracture is closing, and the analysis is focused on the after-closure data.



- This is especially critical when reservoir dominated (radial) flow is not achieved within a test period, or when data scatter aggravates the analysis.

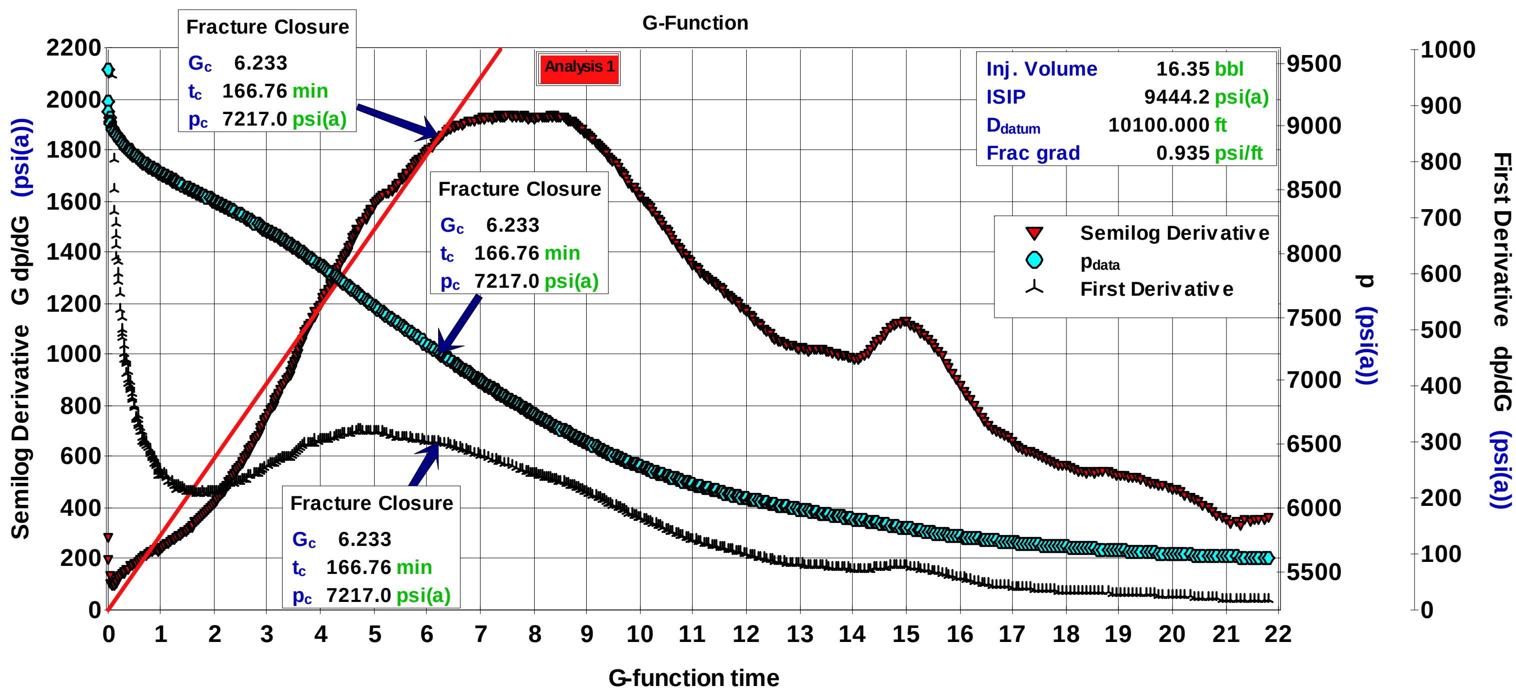
Mini-frac Observations from Real Data

- An example of a Mini-frac test conducted on a vertical well at a formation depth of 10,000 ft analyzed using F.A.S.T. WellTest™ is depicted in the following slides.



Mini-frac Observations from Real Data

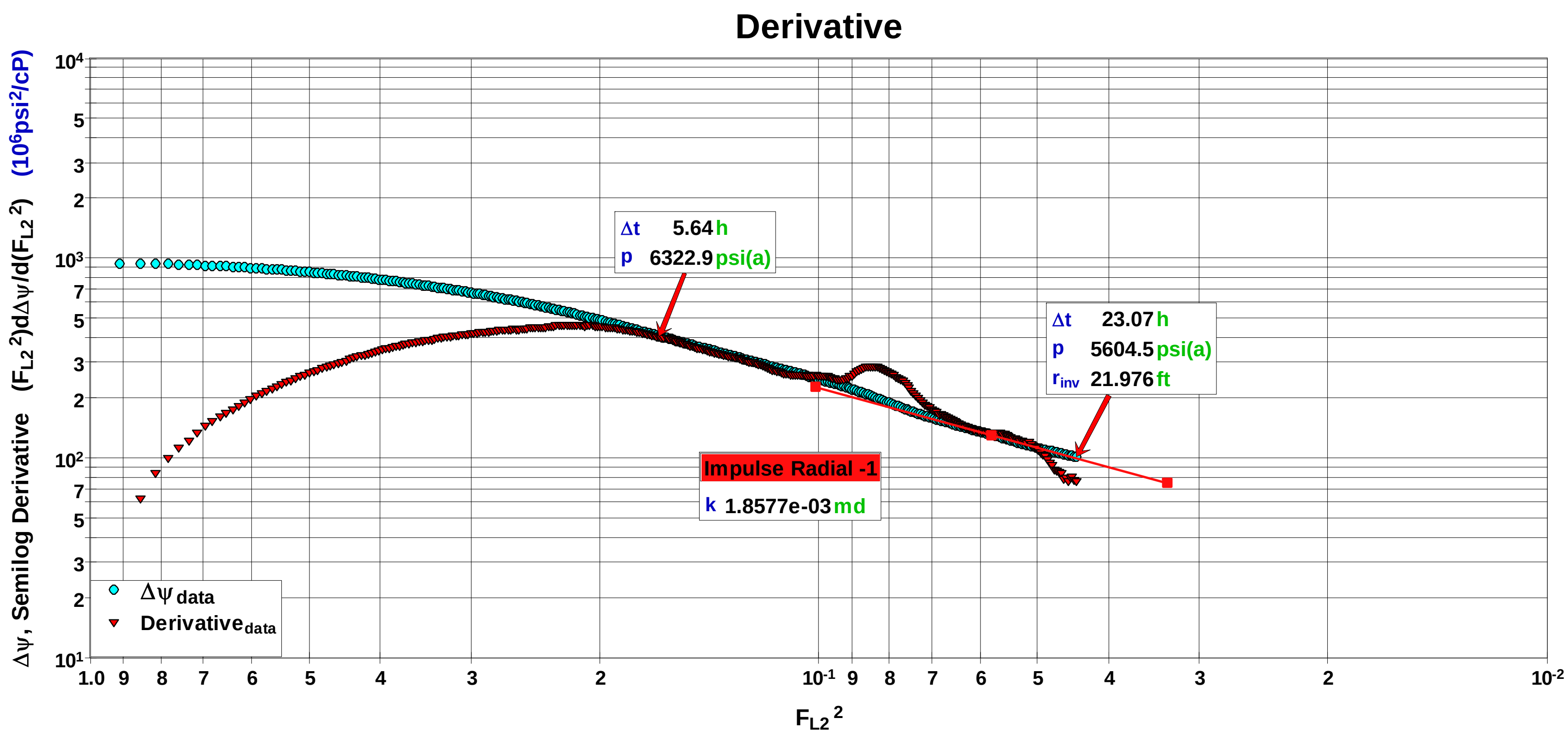
- The pre-closure analysis using the semi-log and first derivative corresponding to G-function time is shown below:



- From this plot, fracture closure is identified within the initial 3-hours of the falloff period

Mini-frac Observations from Real Data

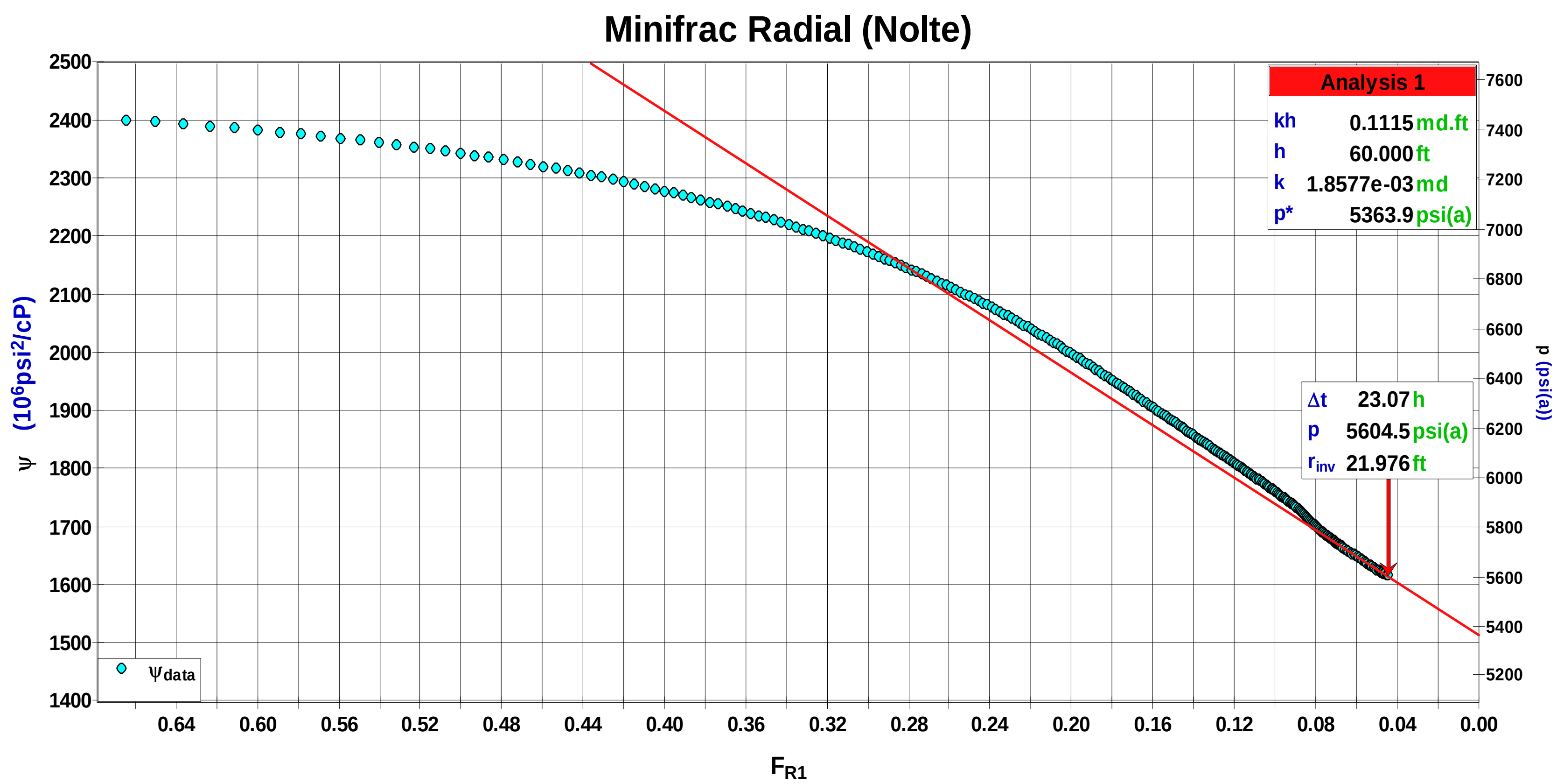
- The Nolte ACA log-log diagnostic plot is shown below:



- The semi-log derivative, calculated with respect to closure time, exhibits a slope of -1 after 5.64 hours, suggesting that radial flow has developed.
- The fluctuations in the derivative slope can be attributed to gas-entry that is not accounted for with the bottomhole pressure calculations.

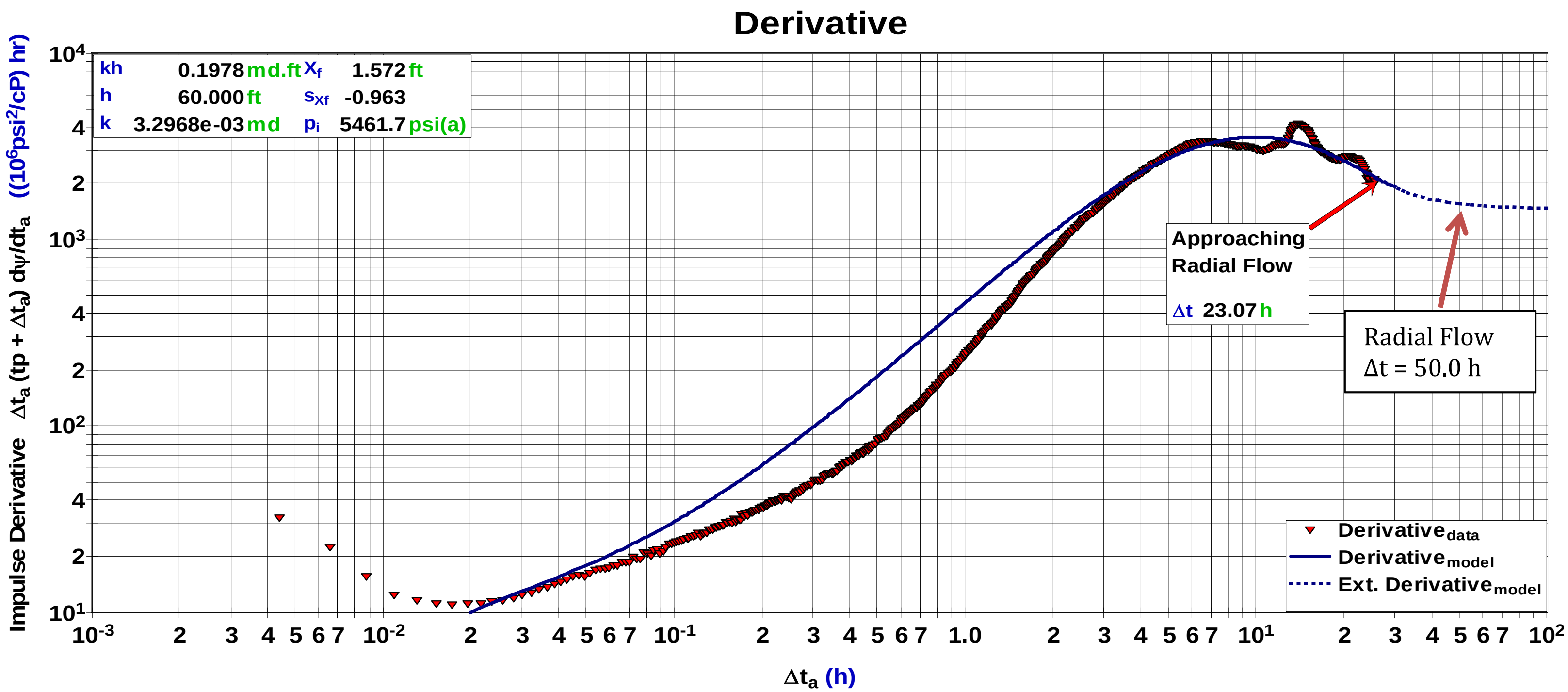
Mini-frac Observations from Real Data

- The falloff data plotted with the Nolte ACA radial time function FR2 is shown below:



Mini-frac Observations from Real Data

- The log-log plot of the derivative used in the Soliman/Craig impulse solution shows the match obtained with the model:



- The model suggests radial flow was not quite achieved during the test period, and would likely develop after ~50 hours of shut-in.
- In this case, the transition to radial flow is sufficiently developed to yield reliable estimates of formation pressure and permeability.

Mini-Frac Test Design

- Short duration injection period, followed by extended falloff period.
- Water commonly used for injection.
- Optimum injection rate/duration:
  - 1 – 2 bpm (1500 – 3000 bbld)
  - 2 – 3 minute injection (after wellbore fill-up)
  - sufficient to breakdown formation, while minimizing fracture growth and closure time
- Falloff duration controlled by permeability (k) and rock properties:
  - minimum 2 days for k > 0.001 md (1000 Nanodarcies)
  - minimum 2 weeks for k < 0.001 md (1000 Nanodarcies)

References

1. "New Method for Determination of Formation Permeability, Reservoir Pressure, and Fracture Properties from a Minifrac Test", Soliman, M.Y., Craig D., Barko, K., Rahim Z., Ansah J., and Adams D., Paper ARMA/USRMS 05-658, 2005
2. "Analysis of Buildup Tests With Short Producing Times", M. Y. Soliman, SPE, Halliburton Services Research Center, Paper SPE 11083 August 1986.
3. "Application of a New Fracture-Injection/Falloff Model Accounting for Propagating, Dilated, and Closing Hydraulic Fractures, D. P. Craig, Haliburton, and T. A. Blasingame, Texas A&M University, Paper SPE 100578, 2006.
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