Texas A&M University
PETE648 – Well Testing

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DFIT—The Unconventional Well Test: An Introduction

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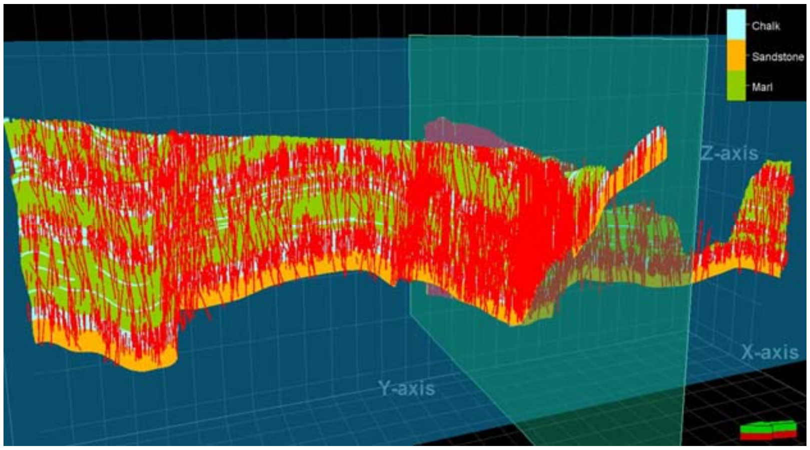
Subsurface Analysis in the Cloud
DFITpro

DFIT—The Unconventional Well Test
What We Need, What We Know, & Confidence

What We Need	What We Know	Confidence
Geology – *Stratigraphic Units, h* *Structure*	Vertical Wells & Outcrops Seismic & Outcrops	High
Hydrocarbon Pore Volume ϕ, S_w	Petrophysics - Correlations	High
PVT Properties p_b, R_s, B_o, γ_o, γ_g, z, μ_o, μ_g	Reservoir Fluid Studies	High
Reservoir Properties p_i, T	Well Testing, Including DFIT	High
Flow Properties Λp *or* p_{wf}	Bottomhole Gauges Before Artificial Lift After Artificial Lift	 High High
Hydraulic Fracture Properties $\boldsymbol{p_c}$, $\boldsymbol{\sigma_{min}}$, $\boldsymbol{C_L(t, \sigma)}$, $\boldsymbol{p_c}$, $\boldsymbol{n_f}$, $\boldsymbol{L_f(t, \sigma)}$, $\boldsymbol{k_f w_f(t, \sigma)}$	DFIT Microseismic, DTS Well Testing (Vertical Well) $L_f(t_p, \sigma)$, $k_f w_f(t_p, \sigma)$ Reservoir Simulation	High Low Med ?
Flow Capacity k_o, k_g, $\boldsymbol{k_r}$, k_m, k_{nf}, k_{eff}, $k_{nf}(p_n, t, \sigma)$	Outcrop Mapping, Image Log, Microseismic Core Well Testing Reservoir Simulation	? Med Med ?

DFIT—The Unconventional Well Test
Unconventional Reservoirs – Discontinuum Models – Defining Fracture Properties

- Unconventional Reservoirs
  - Inhomogeneous
  - Anisotropic
- Natural Fractures By Stratigraphic Unit
  - Sets
  - Density
  - Orientation
  - Length
  - Aperture
- Outcrop Mapping
- Image Logs
- Microseismic Data



Grechishnikova, A 2016. Discrete Fracture Network Model Developed from a High Resolution LIDAR Outcrop Survey of a Naturally Fractured Unconventional Niobrara Reservoir, Denver Basin. Presented at the Unconventional Resources Technology Conference, San Antonio, Texas, USA, 1-3 August 2016.

Unconventional reservoirs are inhomogeneous and anisotropic, and when we consider modeling production from such unconventional reservoirs, we must select continuum or discontinuum modeling approaches.

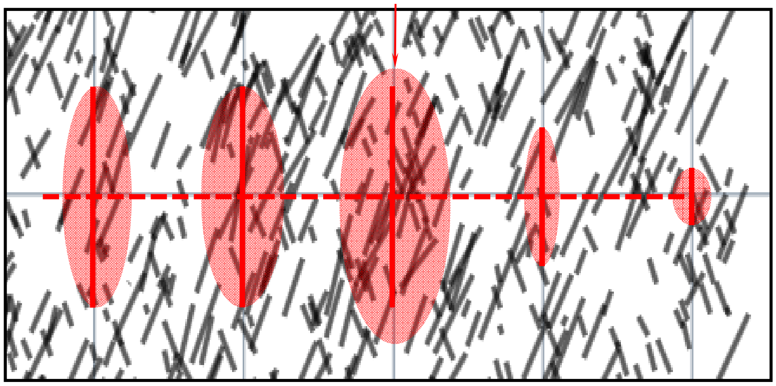
Here I show a discontinuum modeling approach where a discrete fracture network model was developed. The figure is from recent work by Grechishnikova showing a mapping of Codell-Niobrara fractures. To perform this type of modeling, we need to identify the different fracture sets, which are generally fractures with about ±10° in orientation, and for each fracture set, we need to know fracture density (or intensity), orientation, trace length, and aperture. This type of information can be collected from outcrop mapping, image logs, or even microseismic data.

For example, Gretchishnikova identified four fracture sets in the Codell-Niobrara sequence, and the figure shows one realization of two of the fracture sets. It’s one possible distribution of fractures that still fits the underlying statistics identified in the outcrop mapping.

Discontinuum modeling takes us into the world of stochastic models where results are expressed in probabilities. In my opinion, stochastic modeling has not been well accepted in our industry. For example, your boss or CEO asks, “what’s the EUR of the new Honkin shale wells?”

DFIT—The Unconventional Well Test
Unconventional Reservoirs – Continuum Models – Representative Elementary Volume

- Representative Elementary Volume
  - Smallest Volume Over Which A Measurement Will Yield A Value Representative Of The Whole
- Core Sample O(0.020 ft^3)
  - $k_{\text{CoreLab}} \neq k_{\text{Weatherford}}$
- Openhole Logs O(175,000 ft^3)
  - $k_{\text{calc}} \alpha k_{\text{CoreLab}} \neq k_{\text{Weatherford}}$
- Well Test O(1,000,000 ft^3)
  - $k = k_{\text{eff}} = k_m + k_{nf}$



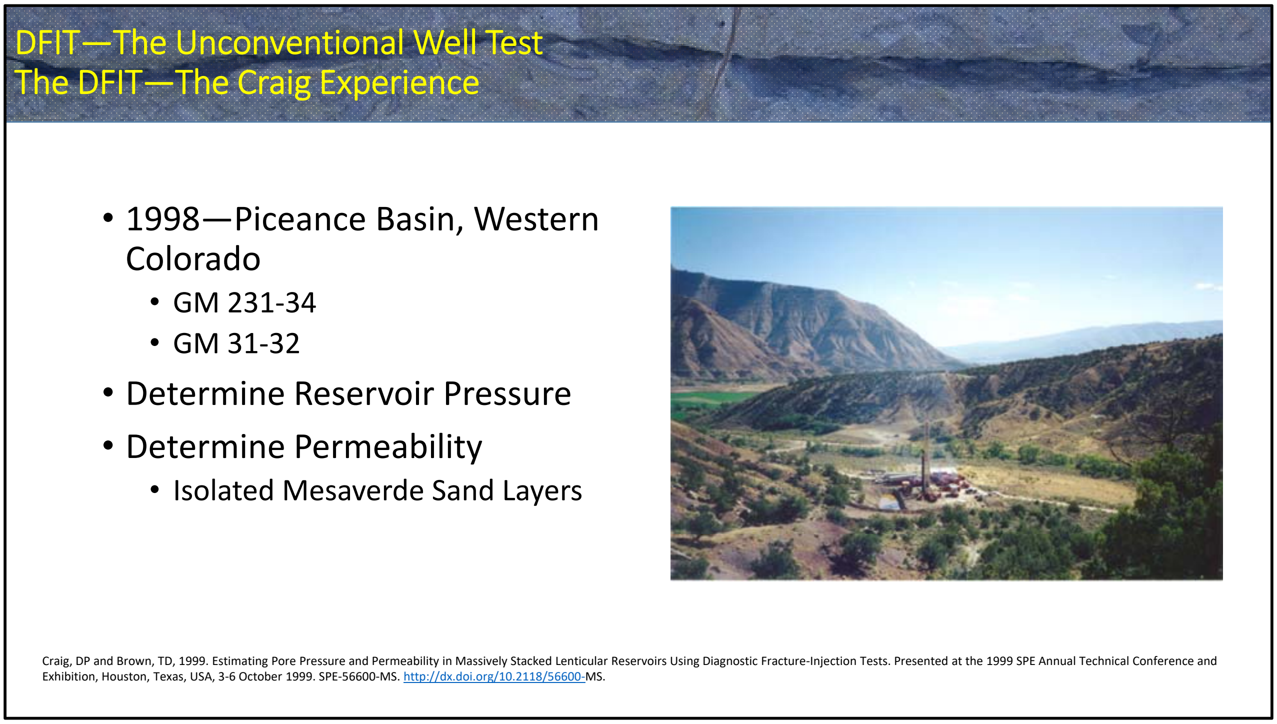
Continuum modeling is generally still the norm. In order to use continuum modeling, we need well testing to sample a representative elementary volume of the reservoir. The REV is the “smallest volume over which a measurement will yield a value representative of the whole.

Consider a core sample…it samples only 0.020 cubic feet of reservoir, and don’t get me started on the validity of crushed-core permeability.

Then we can use openhole logs, which in a horizontal well might sample 175,000 cubic feet or reservoir. However, the correlations are often built from core permeability.

Finally, a correctly designed well test can measure the effective permeability of both the matrix and natural fractures in a very large volume in excess of 1,000,000 cubic feet.

Every field is different, but the injection volume of a DFIT needs to insure that a sufficient volume of reservoir is sampled. In the first figure, the small DFIT samples virtually all matrix and not fractures; thus, the perm will not be representative. The second DFIT sample more fractures, but may still be too small to be representative. The third DFIT may be too large and sample too many fractures. The last two areas-of investigation look like they may have sampled a representative portion of the reservoir.



DFIT—The Unconventional Well Test
The DFIT—The Craig Experience

- 1998—Piceance Basin, Western Colorado
  - GM 231-34
  - GM 31-32
- Determine Reservoir Pressure
- Determine Permeability
  - Isolated Mesaverde Sand Layers

Craig, DP and Brown, TD, 1999. Estimating Pore Pressure and Permeability in Massively Stacked Lenticular Reservoirs Using Diagnostic Fracture-Injection Tests. Presented at the 1999 SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, 3-6 October 1999. SPE-56600-MS. http://dx.doi.org/10.2118/56600-MS.

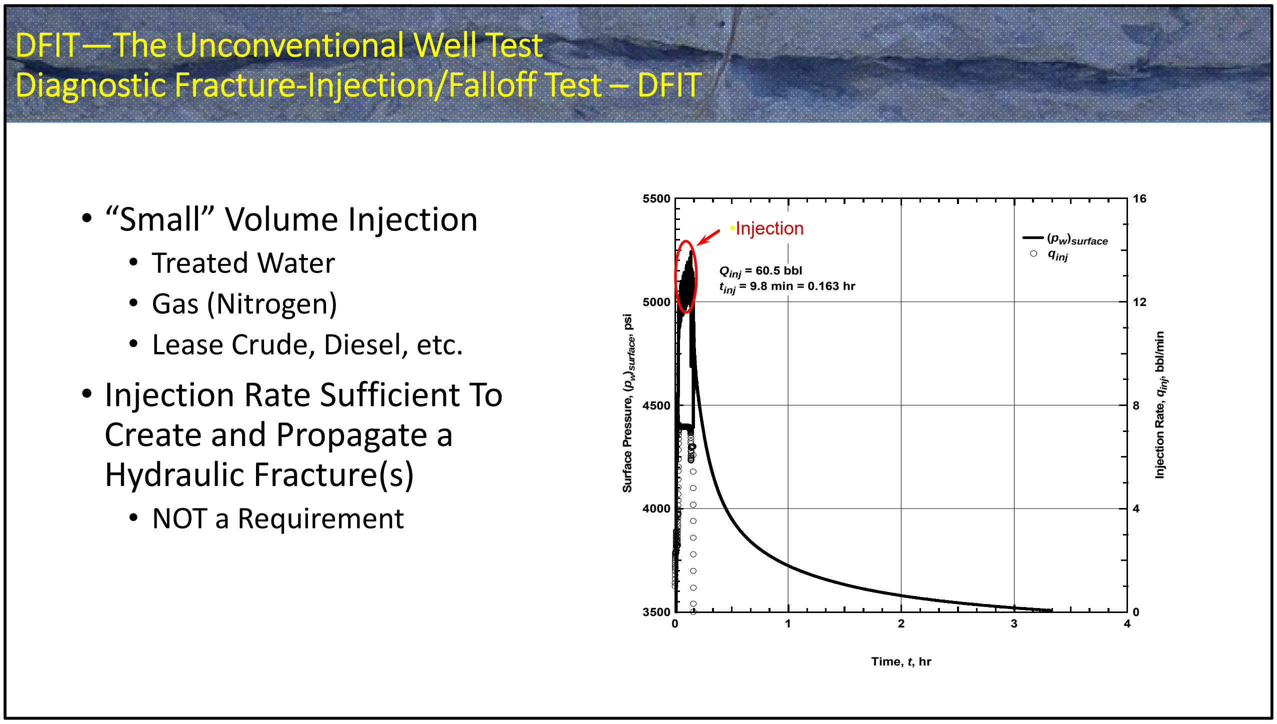
I began DFIT testing specifically to determine pressure and permeability in about July 1998. The first DFIT well is shown in the picture. Western Colorado's not a bad oilfield to work in, huh?

DFIT—The Unconventional Well Test
Pre-Frac Well Testing – Unconventional Wells

Pre-Frac	Measurable Flow YES	Measurable Flow NO	Under Pressured	Water Sensitive
Fracture Injection/Falloff	✓	✓	✓*	
Nitrogen Fracture Injection/Falloff	✓	✓	✓	✓
Pressure Buildup	✓		✓*	✓

* -Bottomhole Shut-in & Bottomhole Gauges

Tompkins, D., Persac, S., Craig, D.P., Birdwell, J.J. 2016. Nitrogen Fracture-Injection/Falloff Testing and Analysis in Underpressured Reservoirs. Presented at the Unconventional Resources Technology Conference, San Antonio, Texas, USA, 1-3 August. URTeC 2461218. http://dx.doi.org/10.15530-urtec-2016-2461218



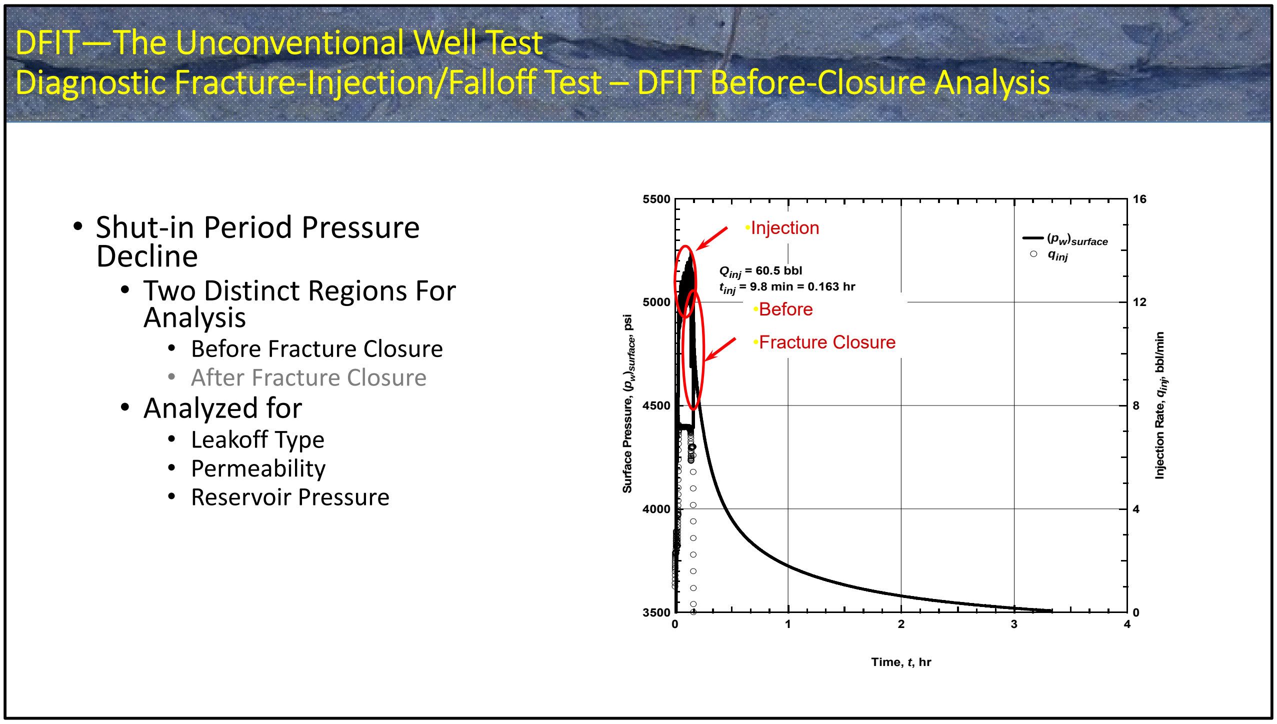
DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – DFIT

- “Small” Volume Injection
  - Treated Water
  - Gas (Nitrogen)
  - Lease Crude, Diesel, etc.
- Injection Rate Sufficient To Create and Propagate a Hydraulic Fracture(s)
  - NOT a Requirement

So, what is a DFIT? A DFIT is a diagnostic fracture-injection/falloff test. It consists of the injection of a small volume of water or gas at a rate sufficient to create and propagate a hydraulic fracture. In the example shown, a 60.5 bbl injection was pumped in 9.8 min.

Injection volumes considered “small” depend on the available shut-in time and desired sample-size of the reservoir rock. For example, DFIT with volumes up to 500 bbl have been pumped, but the shut-in period was in terms of weeks.

The injection volume controls the sample-size of the reservoir rock. A DFIT with a volume as small as 1-l can be pumped, but the test may not sample sufficient reservoir rock to be representative of the reservoir effective permeability and reservoir rock/fracture properties. There’s always a trade-off between an adequate injection volume to obtain representative reservoir properties and the available shut-in time.

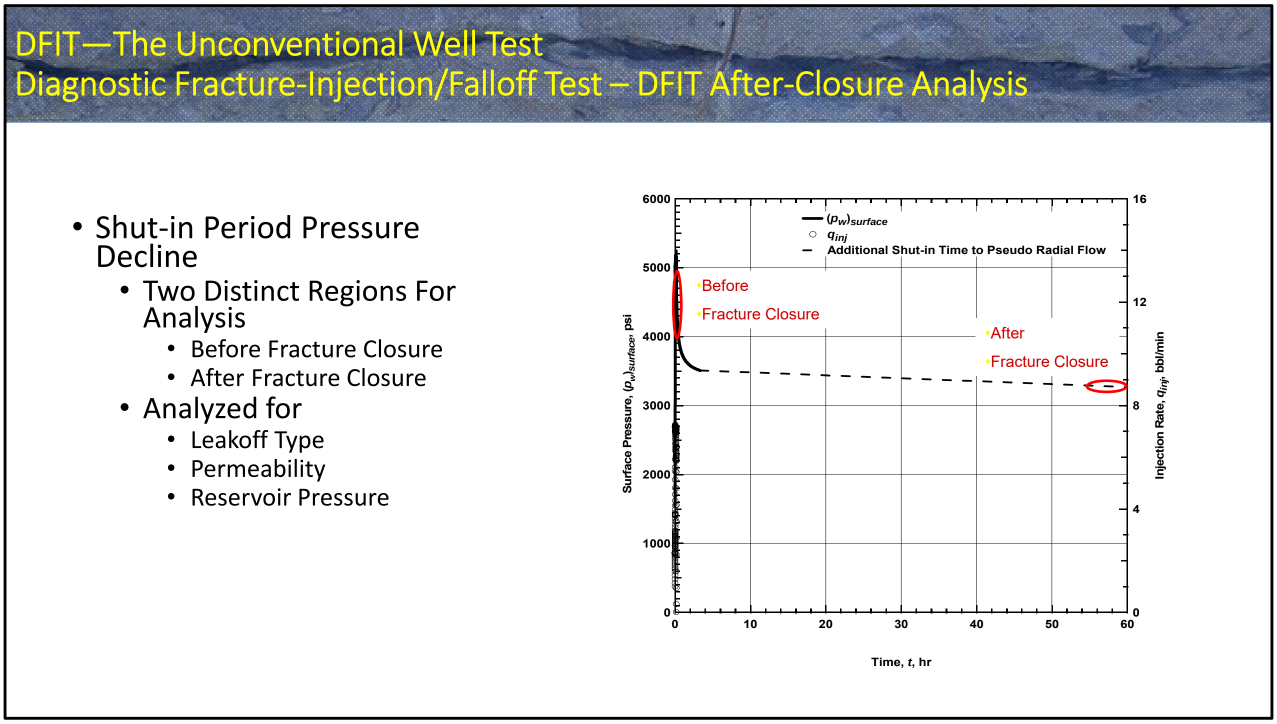


DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – DFIT Before-Closure Analysis

- Shut-in Period Pressure Decline
  - Two Distinct Regions For Analysis
    - Before Fracture Closure
    - After Fracture Closure
  - Analyzed for
    - Leakoff Type
    - Permeability
    - Reservoir Pressure

Following the injection, the well is shut-in for an extended falloff period. There are two distinct regions of falloff data that can be analyzed. The first is the before fracture closure data, which can be analyzed for leakoff type (pressure-dependent permeability, fracture height recession or transverse storage, fracture tip extension after closure, or normal), permeability, and reservoir pressure.

Of all the analysis methods for fracture-injection/falloff data, before-closure analysis has the **most uncertainty**.



DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – DFIT After-Closure Analysis

- Shut-in Period Pressure Decline
  - Two Distinct Regions For Analysis
    - Before Fracture Closure
    - After Fracture Closure
  - Analyzed for
    - Leakoff Type
    - Permeability
    - Reservoir Pressure

When sufficient falloff data is recorded, after-closure data can also be analyzed to determine permeability and reservoir pressure.

Conventional after-closure analysis, which was developed during the 1990s, uses straight-line methods in defined flow regimes to estimate reservoir parameters, for example, straight-line methods can be used when pseudolinear or pseudoradial flow are observed. A unique solution for permeability-thickness can be interpreted during pseudoradial flow, and the solution is NOT dependent on the created fracture half length. Calculating permeability-thickness during pseudolinear flow requires knowing fracture half length, but any estimate of fracture half length is highly uncertain.

Newer type curve methods can also be used to analyze all data, including before- and after-closure falloff.

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – List Of References

- Before-Closure Analysis
  - G-function Derivative Analysis
    - Nolte, K.G. 1979. Determination of Fracture Parameters from Fracturing Pressure Decline. https://doi.org/10.2118/8341-MS
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    - Barree, R.D. & Mukherjee, H. 1996. Determination of Pressure Dependent Leakoff and Its Effect on Fracture Geometry. https://doi.org/10.2118/36424-MS
    - Barree, R.D. 1998. Applications of Pre-Frac Injection/Falloff Tests in Fissured Reservoirs – Field Examples. https://doi.org/10.2118/39932-MS
  - General Closure Analysis
    - Barree, R.D., Barree, V.L., Craig, D.P. Holistic Fracture Diagnostics: Consistent Interpretation of Prefrac Injection Tests Using Multiple Analysis Methods. https://doi.org/10.2118/107877-PA
    - Liu, G. & Ehlig-Economides, C. 2016. Interpretation Methodology for Fracture Calibration Test Before-Closure Analysis of Normal and Abnormal Leakoff Mechanisms. https://doi.org/10.2118/179176-MS
    - McClure, M.W., Jung, H., Cramer, D.D., and Sharma, M.M. 2016. The Fracture-Compliance Method for Picking Closure Pressure From Diagnostic Fracture-Injection Tests. https://doi.org/10.2118/179725-PA
  - Permeability Analysis
    - Mayerhofer, M.J. & Economides, M.J. 1993. Permeability Estimation from Fracture Calibration Treatments. https://doi.org/10.2118/26039-MS
    - Mayerhofer, M.J., Ehlig-Economides, C.A., and Economides, M.J. 1995. Pressure-Transient Analysis of Fracture-Calibration Tests. https://doi.org/10.2118/26527-PA
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DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – List Of Excellent References

- After-Closure Analysis
  - Gu, H. *et al*. 1993. Formation Permeability Determination Using Impulse-Fracture Injection. https://doi.org/10.2118/25425-MS
  - Abousleiman, Y., Cheng, A. H-D, and Gu, H. 1994. *J. of Energy Resources Technology* (June 1994) 116, No. 6, 104
  - Soliman, M.Y. *et al*. 2005. After-Closure Analysis to Determine Formation Permeability, Reservoir Pressure, and Residual Fracture Properties. https://doi.org/10.2118/93419-MS
- New Type Curve Analysis 2006-Present
  - Craig, D.P. and Blasingame, T.A. 2006. Application of a New Fracture-Injection/Falloff Model Accounting for Propagating, Dilated, and Closing Hydraulic Fractures. https://doi.org/10.2118/100578-MS
  - Craig, D.P. 2014. New Type Curve Analysis Removes Limitations of Conventional After-Closure of DFIT Data. https://doi.org/10.2118/168988-MS
  - Craig, D.P. & Jackson, R.A. 2017 Calculating the Volume-of-Reservoir Investigated During a Fracture-Injection/Falloff Test DFIT. https://doi.org/10.2118/184820-MS

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – The *G*-Function & *G*-Function Analysis

- *G*-function – Nolte SPE 8341 (1979)
  - Pressure Decline Analysis Method
    - Relates Pressure To Leakoff Coefficient For Specific Fracture Geometries
  - Starts From Material Balance
  - Assumes Carter Equation For Leakoff
  - “Dimensionless Loss-Volume Function”
  - General Case (Hydraulic Fracture Mechanics, Valkó & Economides, pg. 213)

$$\Delta p_n = C_L E' \sqrt{t_e} G(\Delta t_D, \alpha_N) \begin{cases} h_f & \text{PKN} \\ 2L & \text{GDK} \\ (32/3\pi^2) R_f & \text{Radial} \end{cases}$$

$$G(\Delta t_D, \alpha_N) \equiv \frac{4}{\pi}\left[g(\Delta t_D, \alpha_N) - g_0(\alpha_N)\right]$$

$$g_0(\alpha) = \frac{\alpha\sqrt{\pi}\,\Gamma(\alpha)}{\Gamma\left(\frac{3}{2}+\alpha\right)}$$

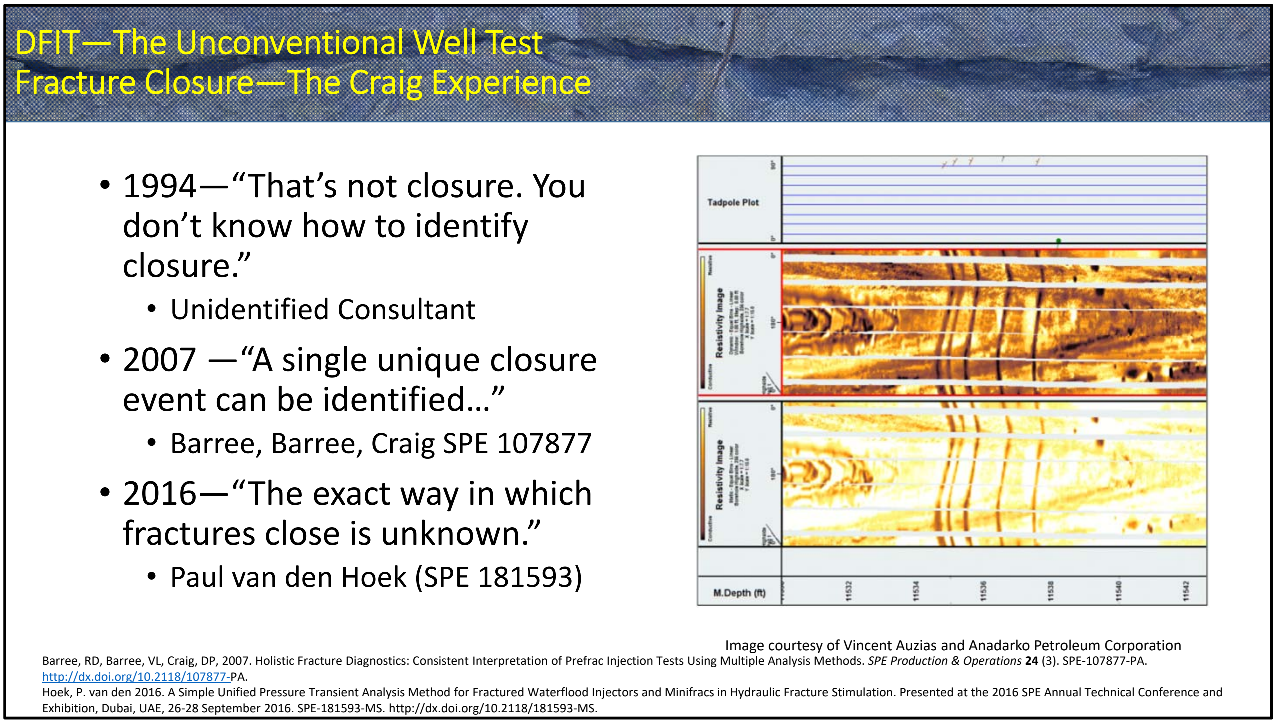
$$g\left(\Delta t_D, \alpha\right) = \frac{4\alpha\sqrt{\Delta t_D} + 2\sqrt{1+\Delta t_D} \times F\left[1/2, \alpha; 1+\alpha; \left(1+\Delta t_D\right)^{-1}\right]}{1+2\alpha}$$

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Power Model & *G*-Function Analysis

- *G*-function – Nolte SPE 8341 (1979)
  - Assumes Fracture Growth Function
    - Power model
  - Pressure Decline Relationship
    - Allows Fracture Closure Identification
    - Plot $p_w(t)$ vs. G
    - Only Works For “Normal” Leakoff
  - Castillo (1987)
    - Pressure-Dependent Leakoff
    - Added a plot of $dp_w(t)/dG$ vs. G
    - Didn’t Account for Tip Extension or Variable Storage
  - Barree & Mukherjee (1996)
    - Accounts for all Leakoff Types
    - Added a Plot of $G dp_w(t)/dG$ vs. G

$$\frac{A}{A_e} = \left(\frac{t}{t_e}\right)^{\alpha} \Rightarrow t = t_e\left(\frac{A}{A_e}\right)^{1/\alpha}$$

$$\Delta p_n = C_L E' \sqrt{t_e}\, G(\Delta t_D, \alpha_N) \begin{cases} h_f & \text{PKN} \\ 2L & \text{GDK} \\ (32/3\pi^2) R_f & \text{Radial} \end{cases}$$



DFIT—The Unconventional Well Test
Fracture Closure—The Craig Experience

- 1994—“That’s not closure. You don’t know how to identify closure.”
  - Unidentified Consultant
- 2007 —“A single unique closure event can be identified…”
  - Barree, Barree, Craig SPE 107877
- 2016—“The exact way in which fractures close is unknown.”
  - Paul van den Hoek (SPE 181593)

Image courtesy of Vincent Auzias and Anadarko Petroleum Corporation

Barree, RD, Barree, VL, Craig, DP, 2007. Holistic Fracture Diagnostics: Consistent Interpretation of Prefrac Injection Tests Using Multiple Analysis Methods. *SPE Production & Operations* **24** (3). SPE-107877-PA. http://dx.doi.org/10.2118/107877-PA.

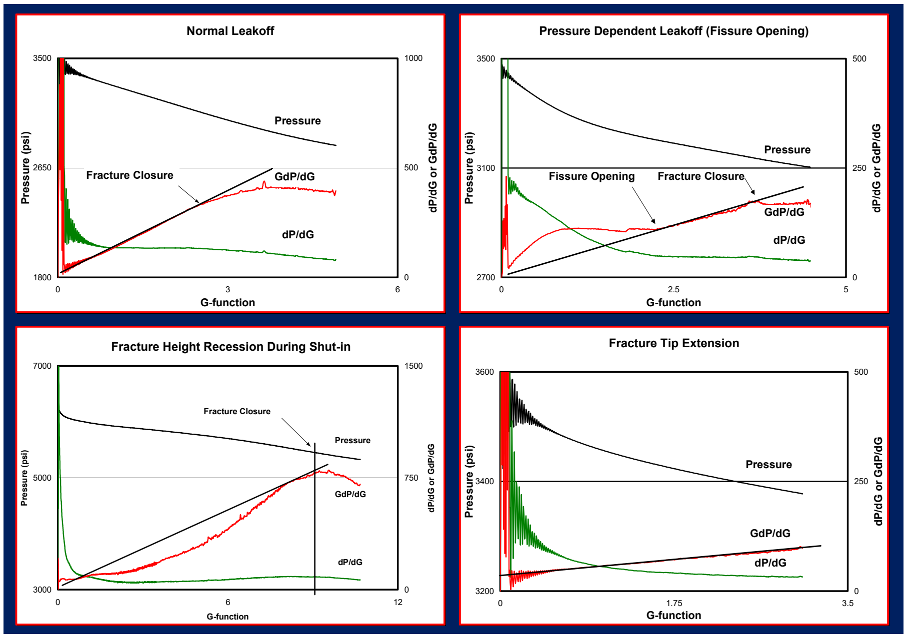
Hoek, P. van den 2016. A Simple Unified Pressure Transient Analysis Method for Fractured Waterflood Injectors and Minifracs in Hydraulic Fracture Stimulation. Presented at the 2016 SPE Annual Technical Conference and Exhibition, Dubai, UAE, 26-28 September 2016. SPE-181593-MS. http://dx.doi.org/10.2118/181593-MS.

At one of my early career post frac meetings, we were discussing a mini-frac, with disagreements about fracture closure. One of the seasoned engineers, looked across the conference table at me and said, “son, that’s not closure. You don’t know how to identify closure.”

After dedicating myself to fracture analysis for a decade, and finishing my PhD, I was fortunate to be a coauthor with Dr. Barree, where we stated, “a single closure event can be identified..” across multiple diagnostic plots. So at that time, we knew definitively how to identify closure.

After another decade, Paul van den Hoek, presents a paper expressing the common new belief that we don’t know how fractures close. So in the last 20 years, I feel like I’ve come full circle, and I’m right back to “son, that’s not closure.”

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Closure & Leakoff-Type Identification



Excerpt from SPE 60291 ...

The figure above contains the G-function derivative graphs for the four common leakoff types observed in low permeability “hard rock” sandstones.

The objective of the G-function derivative analysis is to identify the leakoff type and fracture closure stress. In most cases, the superposition derivative provides a definitive indication of hydraulic fracture closure when the data deviate downward from an extrapolated straight line through the period of normal leakoff.

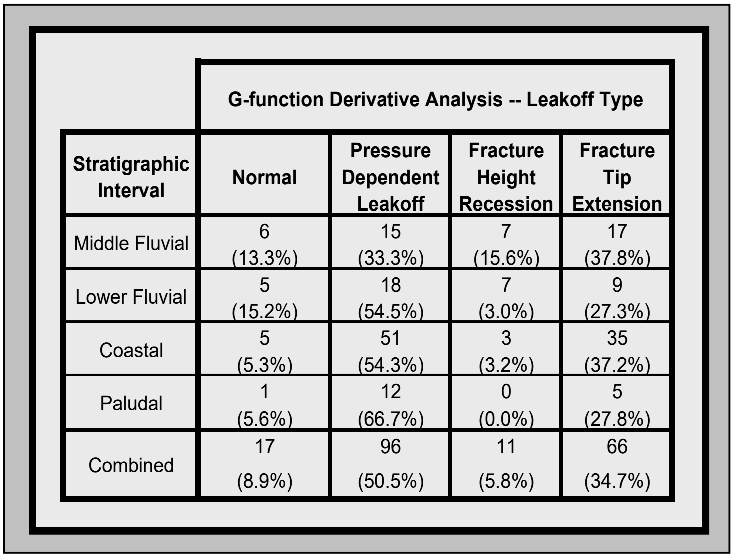
Normal leakoff behavior occurs when fracture area is constant during shut-in and leakoff is through a homogeneous rock matrix. With G-function derivative analysis, normal leakoff is indicated by a constant derivative and when the superposition derivative lies on a straight line through the origin. Fracture closure is identified when the superposition derivative data deviate downward from the straight line.

Pressure dependent leakoff from dilated fractures/fissures is indicated by a characteristic “hump” in the superposition derivative that lies above an extrapolated straight line through the normal leakoff data. The fissure opening pressure is identified at the end of the hump when the superposition derivative data meet the extrapolated straight line. A period of normal leakoff behavior is generally observed before fracture closure is identified when the superposition derivative data deviate downward from the extrapolated straight line.

Fracture height recession during shut-in is indicated by G-function derivative analysis when the superposition derivative data fall below a straight line extrapolated through the normal leakoff data. Fracture height recession is also indicated by a concave down pressure curve and an increasing pressure derivative. As previously noted, hydraulic fracture closure is identified when the superposition derivative data deviate downward from the straight line.

Fracture tip extension, which occurs when a fracture continues to grow after injection is stopped, is indicated when the superposition derivative data lie along a straight line that extrapolates above the origin.

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Leakoff-Types From Field Data



	G-function Derivative Analysis -- Leakoff Type			
Stratigraphic Interval	**Normal**	**Pressure Dependent Leakoff**	**Fracture Height Recession**	**Fracture Tip Extension**
Middle Fluvial	6 (13.3%)	15 (33.3%)	7 (15.6%)	17 (37.8%)
Lower Fluvial	5 (15.2%)	18 (54.5%)	7 (3.0%)	9 (27.3%)
Coastal	5 (5.3%)	51 (54.3%)	3 (3.2%)	35 (37.2%)
Paludal	1 (5.6%)	12 (66.7%)	0 (0.0%)	5 (27.8%)
Combined	17 (8.9%)	96 (50.5%)	11 (5.8%)	66 (34.7%)

Craig, DP, Odegard, CE, Pearson, WC, Schoeder, JE 2000. Case History: Observations From Diagnostic Injection Tests in Multiple Pay Sands of the Mamm Creek Field, Piceance Basin, Colorado. https://dx.doi.org/10.2118/60321-MS

Excerpt from SPE 60321 …

A total of 201 diagnostic fracture injection tests were pumped during the completion of 14 wells in the Mamm Creek Field (Piceance Basin). Of the 201 injection tests, 11 could not be analyzed because of mechanical problems, e.g., communication with other sands, surface or downhole leaks, or electronic problems. As a result, 190 tests were analyzed using G-function derivative analysis and the modified Mayerhofer permeability analysis.

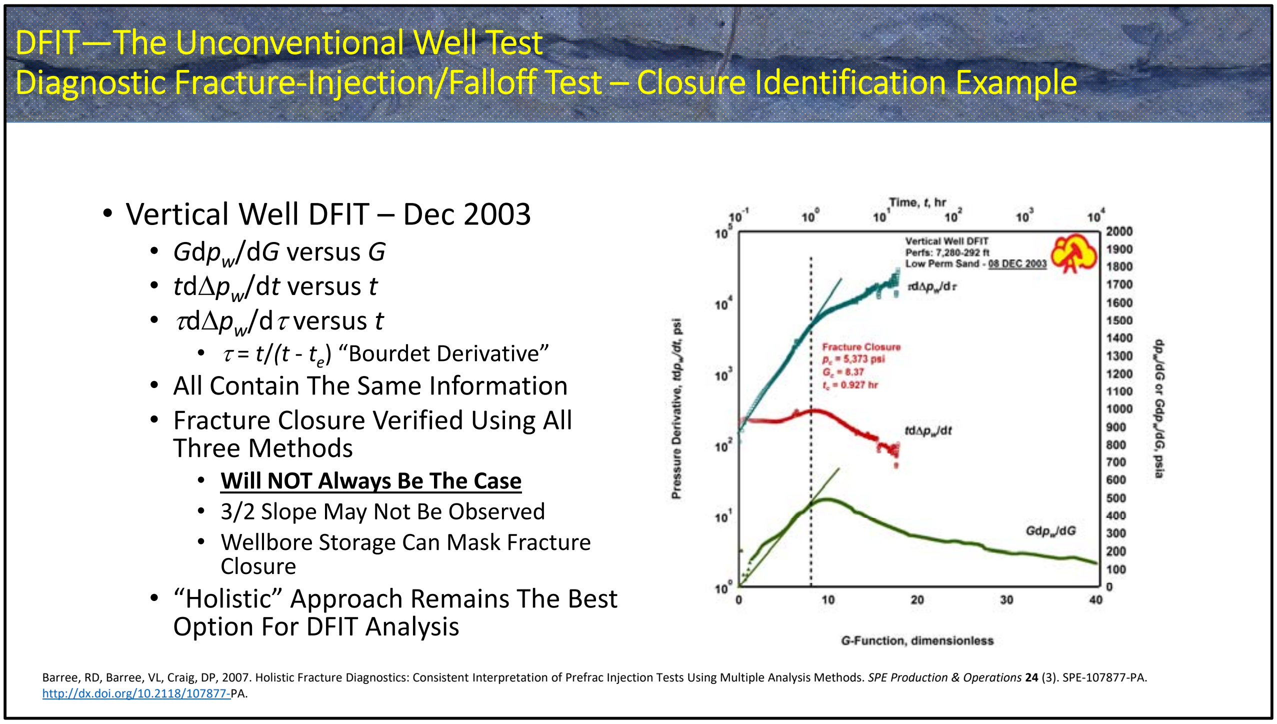
The results from different stratigraphic intervals were grouped for analysis and comparison with the data presented by Esphahanian and Storhaug. The stratigraphic intervals included the Middle Fluvial, Lower Fluvial, Coastal, and Paludal.

The table above contains the leakoff types identified by G-function derivative analysis for each stratigraphic interval. For all intervals, the most common leakoff types are pressure-dependent leakoff and fracture tip extension. Recall that pressure dependent leakoff suggests fractures/fissures were dilated during the injection test, and thus, results in a changing leakoff coefficient during the pressure falloff. Although the origin of the fractures/fissures cannot be determined, it is generally assumed pressure dependent leakoff in Mesaverde sandstones results from *natural* fractures. The table shows that pressure-dependent leakoff was identified in 50.5% of the diagnostic fracture injection tests. The Middle Fluvial interval had the lowest occurrence (33.3%) and the Paludal interval had the highest occurrence (66.7%) of pressure dependent leakoff.

The results from the G-function derivative analysis were not unexpected. Since the permeability in Mesaverde sands is largely a function of natural fractures, it was anticipated that a majority of the sands would indicate pressure dependent leakoff.

Fracture tip extension after shut-in was found in 34.7% of the diagnostic fracture injection tests. Fracture tip extension indicates the fracture is still growing after the injection stops because of low leakoff, and tip extension after shut-in has been shown to correlate with poor productivity. The highest occurrence of fracture tip extension was found for sands within the Middle Fluvial (37.8%) and Coastal (37.2%) intervals.

Esphahanian and Storhaug found that 28% of Mesaverde sands were producing less than 10 Mscf/D from production logs of 13 Mamm Creek wells. Qualitatively, the occurrence of tip extension after shut-in and the inferred poor productivity suggested by tip extension is consistent with the overall production distribution presented by Esphahanian and Storhaug. In other words, both production logs and pre-frac diagnostic fracture injection tests suggest essentially 30% of the Mesaverde sands are only marginally productive.



DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Closure Identification Example

- Vertical Well DFIT – Dec 2003
  - $G\mathrm{d}p_w/\mathrm{d}G$ versus G
  - $t\mathrm{d}\Delta p_w/\mathrm{d}t$ versus t
  - $\tau\mathrm{d}\Delta p_w/\mathrm{d}\tau$ versus t
    - $\tau = t/(t - t_e)$ "Bourdet Derivative"
  - All Contain The Same Information
  - Fracture Closure Verified Using All Three Methods
    - **Will NOT Always Be The Case**
    - 3/2 Slope May Not Be Observed
    - Wellbore Storage Can Mask Fracture Closure
  - "Holistic" Approach Remains The Best Option For DFIT Analysis

Barree, RD, Barree, VL, Craig, DP, 2007. Holistic Fracture Diagnostics: Consistent Interpretation of Prefrac Injection Tests Using Multiple Analysis Methods. *SPE Production & Operations* **24** (3). SPE-107877-PA. http://dx.doi.org/10.2118/107877-PA.

Recall that fracture closure is a storage phenomenon. The above plot compares all three typical closure identification curves for the same falloff. On top is the so called Bourdet derivative, which I believe is a misnomer because it implies a well-test analysis basis, but the origins of the plotting function is Nolte's low-permeability, high-efficiency limiting-case solution for the *G*-function and not well testing superposition solutions.

In any case, closure is shown by the vertical line, and closure is consistently identified using all three curves. That will NOT always be the case. In many cases the 3/2 slope will not "fit" the Bourdet derivative, and it's also possible for wellbore storage in the semilog derivative to mask fracture closure in high permeability reservoirs.

The holistic approach remains the best option for DFIT analysis and closure identification, and the classical G-function plot remains the gold standard. Consider the following examples…

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Estimating Reservoir Pressure From Closure

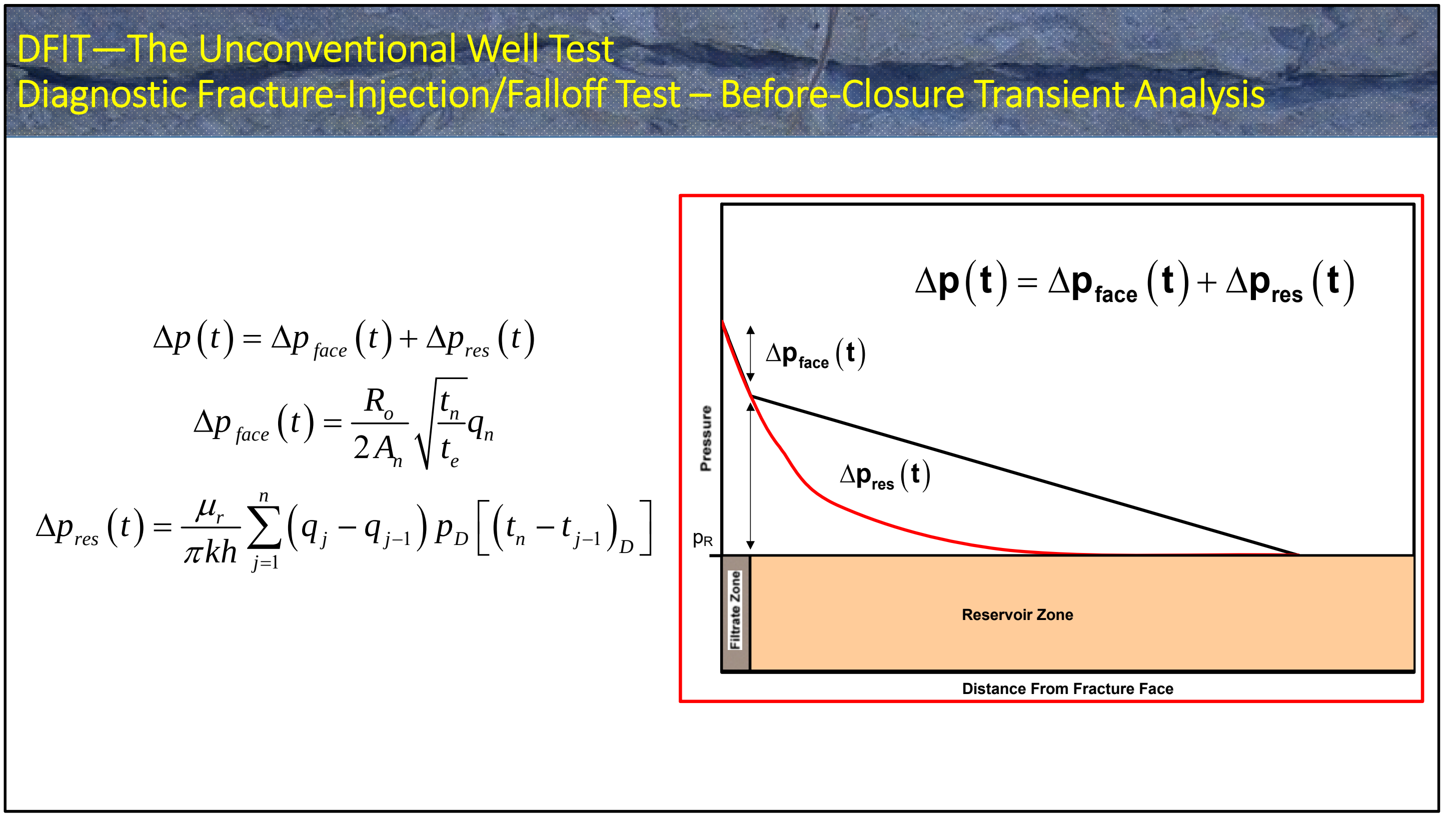
- “Stress Log Equation”

$$\sigma_{\min} = \left[\frac{\upsilon}{1-\upsilon}\right]\left[\sigma_z - \alpha_1 p_r\right] + \alpha_2 p_r + \sigma_{ext}$$

$\sigma_{\min}$ - **Minimum Horizontal Stress [psi] (Closure Pressure)**
υ - **Poisson’s Ratio (Sand ~ 0.20)**
σ_z - **Overburden Stress [1.00-psi/ft (OH Log)]**
α_1, α_2 - **Biot’s Poroelastic Constant (1.00)**
σ_{ext} - **External (Tectonic) Stress**

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – *G*-Function Analysis Output

- G-function Derivative Analysis Provides
  - Hydraulic Fracture Closure Stress
  - Leakoff Type Identification
    - Normal
    - Pressure Dependent Leakoff
      - Fissure Opening Pressure
    - Fracture Height Recession/Transverse Storage/Variable Storage
    - Fracture Tip Extension
- Pore Pressure Estimate can be Calculated from the Closure Stress and the Uniaxial Strain Relationship



DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Before-Closure Transient Analysis

$$\Delta p(t) = \Delta p_{face}(t) + \Delta p_{res}(t)$$

$$\Delta p_{face}(t) = \frac{R_o}{2A_n}\sqrt{\frac{t_n}{t_e}}\,q_n$$

$$\Delta p_{res}(t) = \frac{\mu_r}{\pi kh}\sum_{j=1}^{n}\left(q_j - q_{j-1}\right)p_D\left[\left(t_n - t_{j-1}\right)_D\right]$$

Pressure-transient analysis of the pressure decline is different. Mayerhofer and Economides borrowed from established pressure-transient analysis methods to formulate a new pressure decline model.

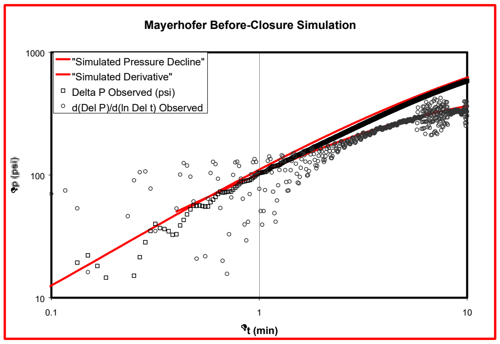
The basis of the model is the pressure transient method of Cinco-Ley and Samaniego (SPE 10179). The Cinco-Ley and Samaniego model desribes flow from a finite conductivity vertical fracture with fracture face damage caused by fluid loss. During a linear flow period, Cinco-Ley and Samaniego's model of the pressure drop includes a component for the flow from an infinite conductivity fracture combined with a fracture face skin to account for fluid loss damage.

The figure above shows the Mayerhofer and Economides conceptual model of the filtrate zone and the reservoir zone. The figure shows that the total pressure drop between the fracture and the reservoir at any time, $\Delta p(t)$, is the sum of the pressure drop in the filtrate zone, $\Delta p_{face}(t)$, and the pressure drop in the reservoir zone, $\Delta p_{res}(t)$. Although conceptually similar to the conventional model, the Mayerhofer model differs because it accounts for unsteady state flow in the reservoir, that is, the pressure decline is a function of time.

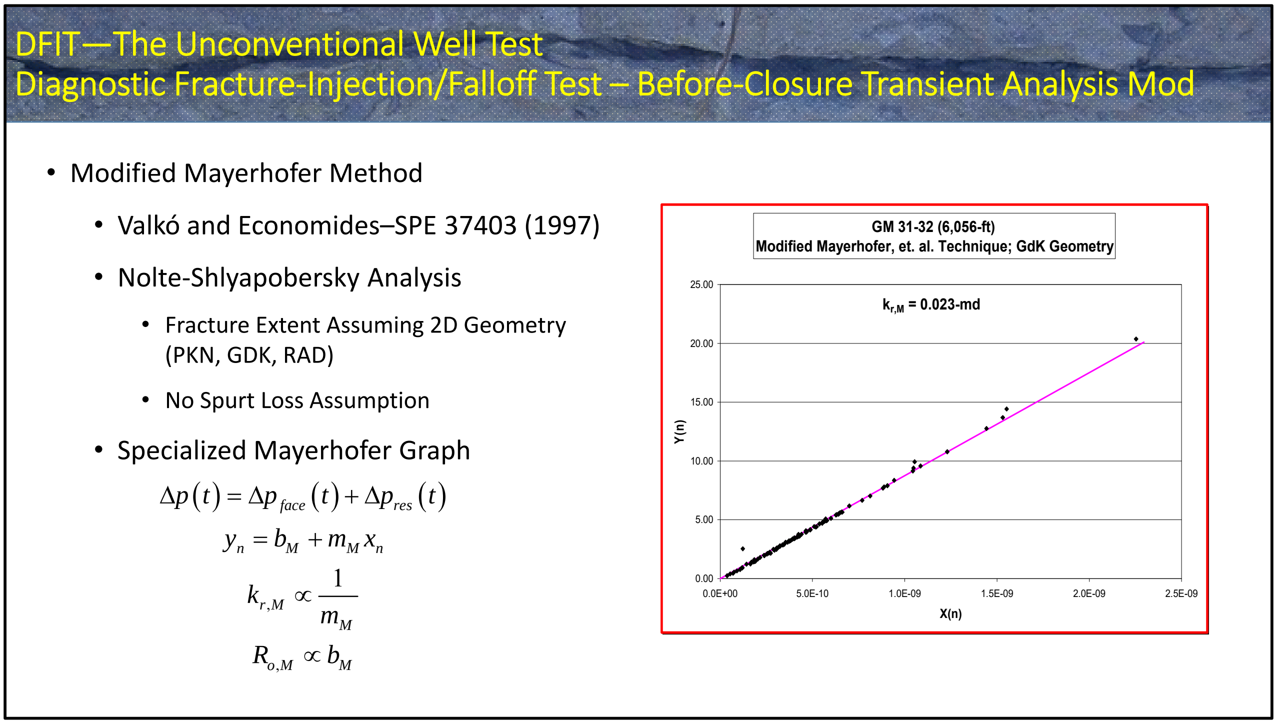
Additionally, the Mayerhofer model is formulated as formation linear flow from an infinite conductivity vertical fracture with a rate dependent skin to account for the pressure decline in the filtrate zone, thus the connection with Cinco-Ley and Samaniego's established pressure transient analysis method.

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Before-Closure Transient Analysis Example

- Before-Closure Permeability Analysis
  - Mayerhofer, Economides, Ehlig-Economides–SPE 26527 (1994)
  - History-Matching (Iterative) Technique
    - Permeability
    - Pore Pressure
    - Fracture Area



Log-Log history-match using Mayerhofer, Economides, and Ehlig-Economides method. Matches observed pressure and pressure derivative with simulated values.



DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Before-Closure Transient Analysis Mod

- Modified Mayerhofer Method
  - Valkó and Economides–SPE 37403 (1997)
  - Nolte-Shlyapobersky Analysis
    - Fracture Extent Assuming 2D Geometry (PKN, GDK, RAD)
    - No Spurt Loss Assumption
  - Specialized Mayerhofer Graph

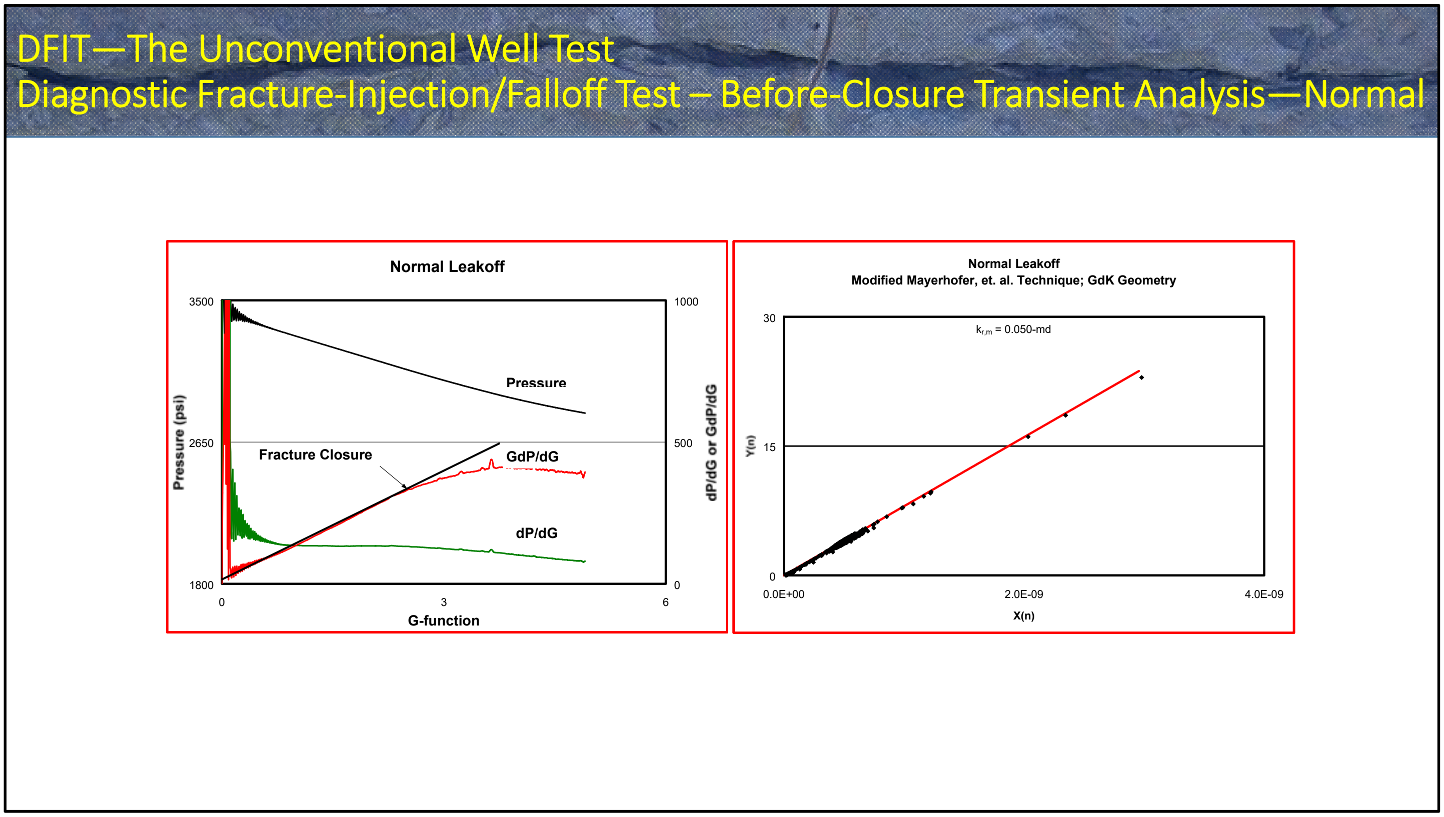
$$\Delta p(t) = \Delta p_{face}(t) + \Delta p_{res}(t)$$

$$y_n = b_M + m_M x_n$$

$$k_{r,M} \propto \frac{1}{m_M}$$

$$R_{o,M} \propto b_M$$

The Mayerhofer method was modified by Valko & Economides in 1997, hence the name modified Mayerhofer method. Valko & Economides include Nolte-Shlyapobersky analysis to estimate fracture extent (half-length), thus the modified Mayerhofer method does not require a history-matching routine. The disadvantage, however, is the no spurt loss assumuption of Nolte-Shlyapobersky analysis.

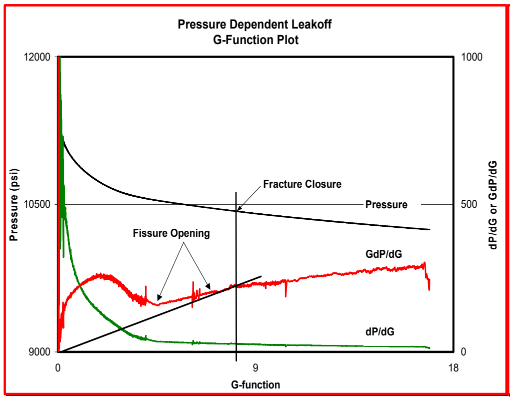


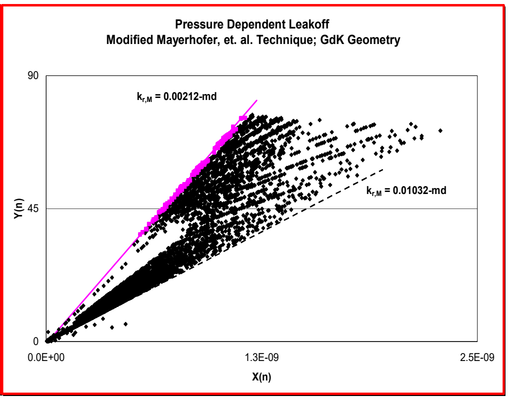
DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Before-Closure Transient Analysis—Normal

The objective of the G-function derivative analysis is to identify the leakoff type and fracture closure stress. In most cases, the superposition derivative provides a definitive indication of hydraulic fracture closure when the data deviate from an extrapolated straight line through a period of normal leakoff.

<u>Normal leakoff</u> behavior occurs when fracture area is constant during shut-in and leakoff is through a homogeneous rock matrix. With G-function derivative analysis, normal leakoff is indicated by a constant derivative and when the superposition derivative lies on a straight line through the origin. Fracture closure is identified when the superposition derivative data deviate from the straight line.

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Before-Closure Transient Analysis—PDL


Pressure Dependent Leakoff
G-Function Plot


Pressure Dependent Leakoff
Modified Mayerhofer, et. al. Technique; GdK Geometry

Excerpt from SPE 60291 …

The above figure contains the G-function derivative analysis for a diagnostic fracture injection test that exhibits pressure dependent leakoff. Pressure dependent leakoff is indicated by the large “hump” in the superposition derivative that lies above a line through the normal leakoff data prior to hydraulic fracture closure.

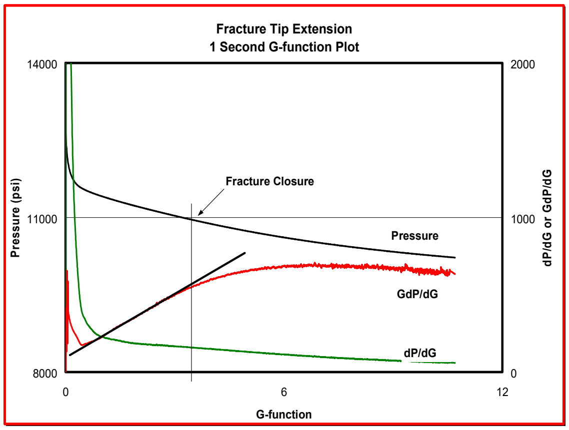
Pressure dependent leakoff is the result of fractures/fissures that were dilated by the injection test. As the pressure declines during the falloff, the fractures/fissures constrict until closure at the fissure opening pressure. The result of the dilation/constriction sequence is variable leakoff during closure, and can be an indication of a heterogeneous dual-porosity reservoir.

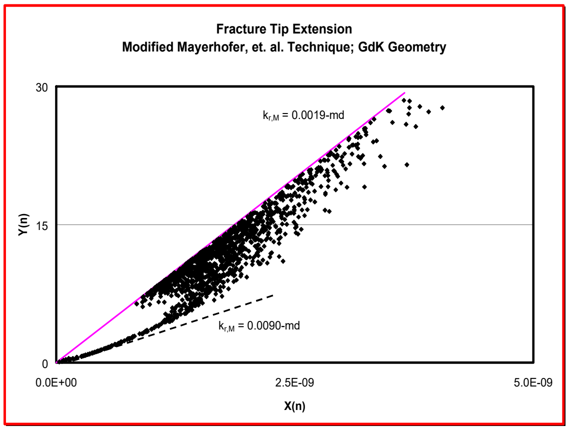
Ehlig-Economides, Fan, and Economides [SPE 28690] extended the theoretical development of the Mayerhofer method to naturally fractured reservoirs and found that application of the Mayerhofer method in dual-porosity reservoirs will provide an estimate of $k_{fb}\omega$ (the product of bulk permeability of the natural fracture system and fracture storativity ratio). Unfortunately, dual-porosity behavior results in a non-linear specialized Mayerhofer plot.

The above figure also contains the specialized Mayerhofer plot for the pressure falloff data. The plot demonstrates that the data are non-linear and “sweep” across the plot. As a result, $k_{fb}\omega$ varies from 0.010-md with a line through the early-time data, and 0.002-md with a line through the late-time data. In other words, the specialized Mayerhofer plot suggests permeability is decreasing with time during fracture closure, which is consistent with a dilated fracture system constricting during closure.

Ehlig-Economides, *et al.*,[7] also note that reasonable estimates of $k_{fb}\omega$ and fracture face resistance are possible if a portion of the specialized plot is straight. The straight portion of the data correspond to the normal leakoff data from the G-function derivative analysis, thus the G-function plot can be used to locate the straight line on the specialized Mayerhofer plot. For example the straight line through the late-time data in the specialized Mayerhofer plot ($k_{fb}\omega$ = 0.002-md), represent the normal leakoff data shown in the G-function derivative graph between fissure opening and fracture closure pressure.

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Before-Closure Transient – Tip Extension





- Increasing Fracture Area
- Permeability Overestimated

Excerpt from SPE 60291 …

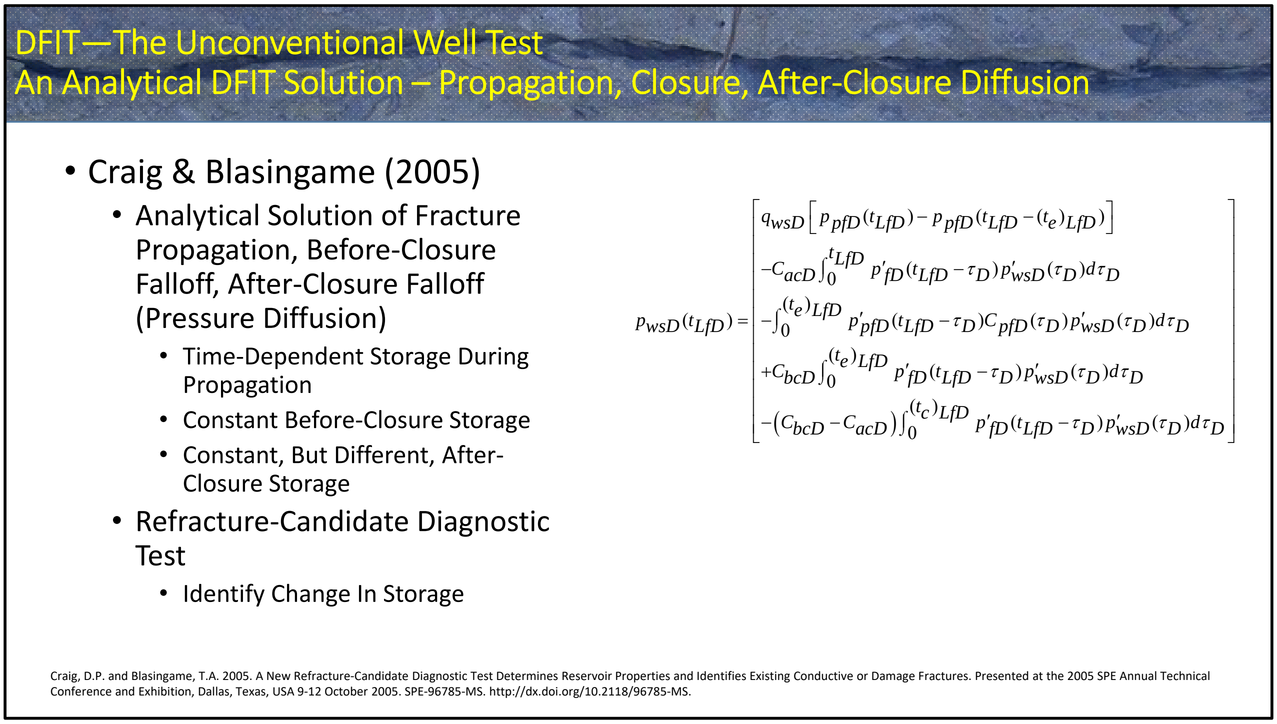
Fracture tip extension after shut-in is the result of extremely low leakoff. Physically, fracture tip extension occurs when the energy from the injection test cannot be released through leakoff and is dissipated through fracture growth. Fracture tip extension typically occurs in very low permeability reservoirs, and has been shown to correlate with poor production [SPE 39953].

The above figure contains the G-function derivative analysis and the specialized Mayerhofer plot for a zone exhibiting fracture tip extension after shut-in. Similar to the pressure dependent leakoff example, the data on the specialized Mayerhofer plot are non-linear and sweep across the graph. Since the fracture continues to grow after shut-in, the assumption of constant fracture area during closure is violated, and the permeability will be overestimated using the modified Mayerhofer method. The above figure contains two estimates of permeability using the early-time data ($k_{r,M}$ = 0.009-md) and the late-time data ($k_{r,M}$ = 0.0019-md). As the shut-in time increases, the leakoff rate and the calculated permeability “appear” to decrease until fracture closure. Although the late-time data during fracture tip extension is recommended for estimating permeability from the specialized plot, permeability will still be overestimated since the fracture continues to grow during closure.

DFIT—The Unconventional Well Test
Diagnostic Fracture-Injection/Falloff Test – Before-Closure Analysis Output

- G-function Derivative Analysis Provides
  - Hydraulic Fracture Closure Stress
  - Leakoff Type Identification
    - Normal
    - Pressure Dependent Leakoff
      - Fissure Opening Pressure
    - Fracture Height Recession/Transverse Storage/Variable Storage
    - Fracture Tip Extension
- Pore Pressure Estimate can be Calculated from the Closure Stress and the Uniaxial Strain Relationship
- Permeability to the Mobile Reservoir Fluid

Caution – Highly Uncertain – Fracture Geometry Unknown – Uniaxial Strain Relationship Can Fail



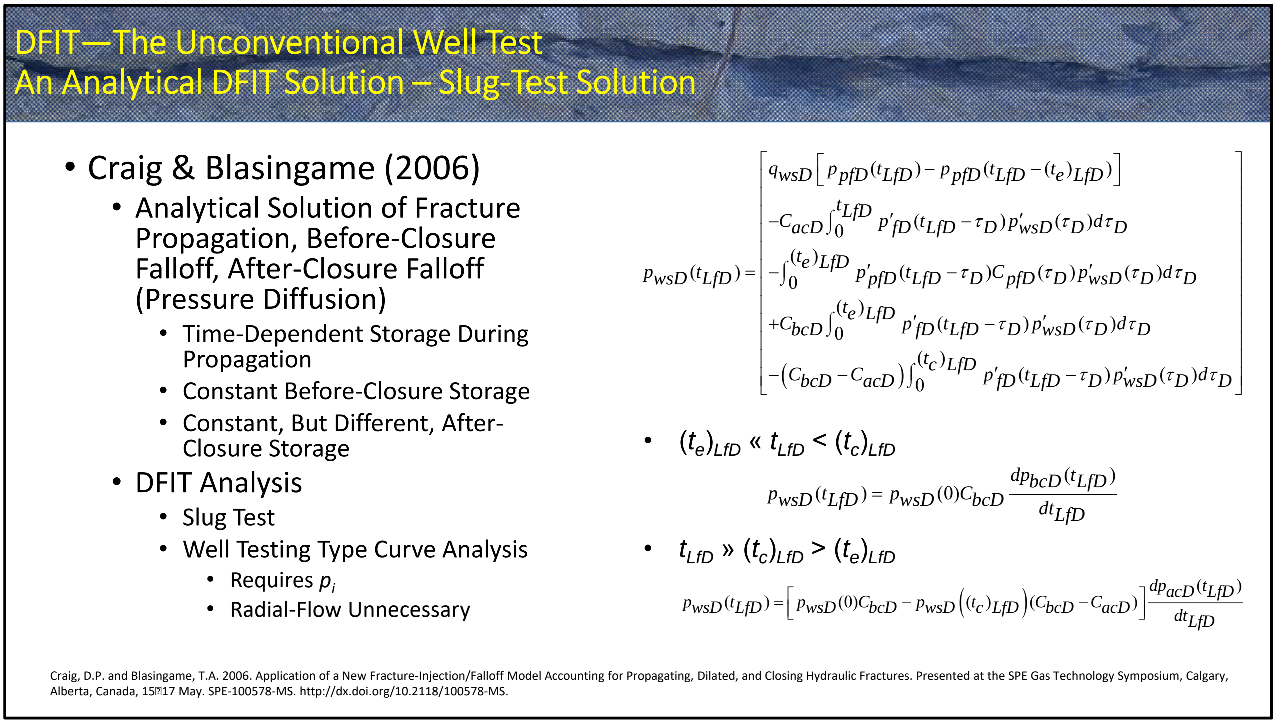
DFIT—The Unconventional Well Test
An Analytical DFIT Solution – Propagation, Closure, After-Closure Diffusion

- Craig & Blasingame (2005)
  - Analytical Solution of Fracture Propagation, Before-Closure Falloff, After-Closure Falloff (Pressure Diffusion)
    - Time-Dependent Storage During Propagation
    - Constant Before-Closure Storage
    - Constant, But Different, After-Closure Storage
  - Refracture-Candidate Diagnostic Test
    - Identify Change In Storage

$$p_{wsD}(t_{LfD}) = \begin{bmatrix} q_{wsD}\left[p_{pfD}(t_{LfD}) - p_{pfD}(t_{LfD} - (t_e)_{LfD})\right] \\ -C_{acD}\int_0^{t_{LfD}} p'_{fD}(t_{LfD} - \tau_D)p'_{wsD}(\tau_D)d\tau_D \\ -\int_0^{(t_e)_{LfD}} p'_{pfD}(t_{LfD} - \tau_D)C_{pfD}(\tau_D)p'_{wsD}(\tau_D)d\tau_D \\ +C_{bcD}\int_0^{(t_e)_{LfD}} p'_{fD}(t_{LfD} - \tau_D)p'_{wsD}(\tau_D)d\tau_D \\ -\left(C_{bcD} - C_{acD}\right)\int_0^{(t_c)_{LfD}} p'_{fD}(t_{LfD} - \tau_D)p'_{wsD}(\tau_D)d\tau_D \end{bmatrix}$$

Craig, D.P. and Blasingame, T.A. 2005. A New Refracture-Candidate Diagnostic Test Determines Reservoir Properties and Identifies Existing Conductive or Damage Fractures. Presented at the 2005 SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA 9-12 October 2005. SPE-96785-MS. http://dx.doi.org/10.2118/96785-MS.

In 2005, I presented an analytical solution of the entire process—fracture propagation, fracture closure, and after closure diffusion. The initial solution was prepared for developing a refracture-candidate diagnostic, but in 2006…



DFIT—The Unconventional Well Test
An Analytical DFIT Solution – Slug-Test Solution

- Craig & Blasingame (2006)
  - Analytical Solution of Fracture Propagation, Before-Closure Falloff, After-Closure Falloff (Pressure Diffusion)
    - Time-Dependent Storage During Propagation
    - Constant Before-Closure Storage
    - Constant, But Different, After-Closure Storage
  - DFIT Analysis
    - Slug Test
    - Well Testing Type Curve Analysis
      - Requires p_i
      - Radial-Flow Unnecessary

$$p_{wsD}(t_{LfD}) = \begin{bmatrix} q_{wsD}\left[p_{pfD}(t_{LfD}) - p_{pfD}(t_{LfD} - (t_e)_{LfD})\right] \\ -C_{acD}\int_0^{t_{LfD}} p'_{fD}(t_{LfD} - \tau_D)p'_{wsD}(\tau_D)d\tau_D \\ -\int_0^{(t_e)_{LfD}} p'_{pfD}(t_{LfD} - \tau_D)C_{pfD}(\tau_D)p'_{wsD}(\tau_D)d\tau_D \\ +C_{bcD}\int_0^{(t_e)_{LfD}} p'_{fD}(t_{LfD} - \tau_D)p'_{wsD}(\tau_D)d\tau_D \\ -\left(C_{bcD} - C_{acD}\right)\int_0^{(t_c)_{LfD}} p'_{fD}(t_{LfD} - \tau_D)p'_{wsD}(\tau_D)d\tau_D \end{bmatrix}$$

- $(t_e)_{LfD} \ll t_{LfD} < (t_c)_{LfD}$

$$p_{wsD}(t_{LfD}) = p_{wsD}(0)C_{bcD}\frac{dp_{bcD}(t_{LfD})}{dt_{LfD}}$$

- $t_{LfD} \gg (t_c)_{LfD} > (t_e)_{LfD}$

$$p_{wsD}(t_{LfD}) = \left[p_{wsD}(0)C_{bcD} - p_{wsD}\left((t_c)_{LfD}\right)(C_{bcD} - C_{acD})\right]\frac{dp_{acD}(t_{LfD})}{dt_{LfD}}$$

Craig, D.P. and Blasingame, T.A. 2006. Application of a New Fracture-Injection/Falloff Model Accounting for Propagating, Dilated, and Closing Hydraulic Fractures. Presented at the SPE Gas Technology Symposium, Calgary, Alberta, Canada, 15–17 May. SPE-100578-MS. http://dx.doi.org/10.2118/100578-MS.

Dr. Blasingame and I extended the solution to DFIT analysis, and we demonstrated that the solution could be reduced to a variable-storage slug test solution. Slug tests were not new. Agarwal and Ramey published slug test solutions in 1972, so it was a known well test analysis methodology; however, matching DFIT data to well testing solutions required knowing reservoir pressure, which could not always be interpreted from the DFIT data.

DFIT—The Unconventional Well Test
An Analytical DFIT Solution – Radial Flow Solution

- Radial Flow Impulse Solution Assuming $p_{wsD}(0) = 0$

$$p_{wD}(t_{LfD}) = \frac{1}{2}\frac{(t_e)_{LfD}}{t_{LfD}}$$

- Complete Radial Flow Impulse Solution

$$p_w - p_i = \frac{141.2(24)}{2}\frac{\mu}{kh}\left(Q_t + p_{wsD}(0)C_{ac}(p_0 - p_i)\right)\left(\frac{1}{t_e + \Delta t}\right)$$

- Plot

$$p_w \text{ vs. } \left(\frac{1}{t_e + \Delta t}\right)$$

- Extrapolate Straight Line Through Pseudoradial Data

$$p_i = \text{intercept}$$

$$\frac{kh}{\mu} = \frac{141.2(24)}{2}\frac{\left(Q_t + p_{wsD}(0)C_{ac}(p_0 - p_i)\right)}{m_{acpr}}$$

Gu, *et al.*: “Formation Permeability Determination Using…,”SPE 25425 (1993)

DFIT—The Unconventional Well Test
An Analytical DFIT Solution – Linear Flow Solution

- Linear Flow Impulse Solution Assuming $p_{wsD}(0) = 0$

$$p_{wD}(t_{LfD}) = \frac{\sqrt{\pi}}{2}\frac{(t_e)_{LfD}}{\sqrt{t_{LfD}}}$$

- Complete Linear Flow Impulse Solution

$$p_w - p_i = \frac{141.2(24)\sqrt{\pi}\sqrt{0.0002637}}{2}\frac{1}{hL_f}\left(\frac{\mu}{\phi c_t k}\right)^{1/2}\left(Q_t + p_{wsD}(0)C_{ac}(p_0 - p_i)\right)\left(\frac{1}{t_e + \Delta t}\right)^{1/2}$$

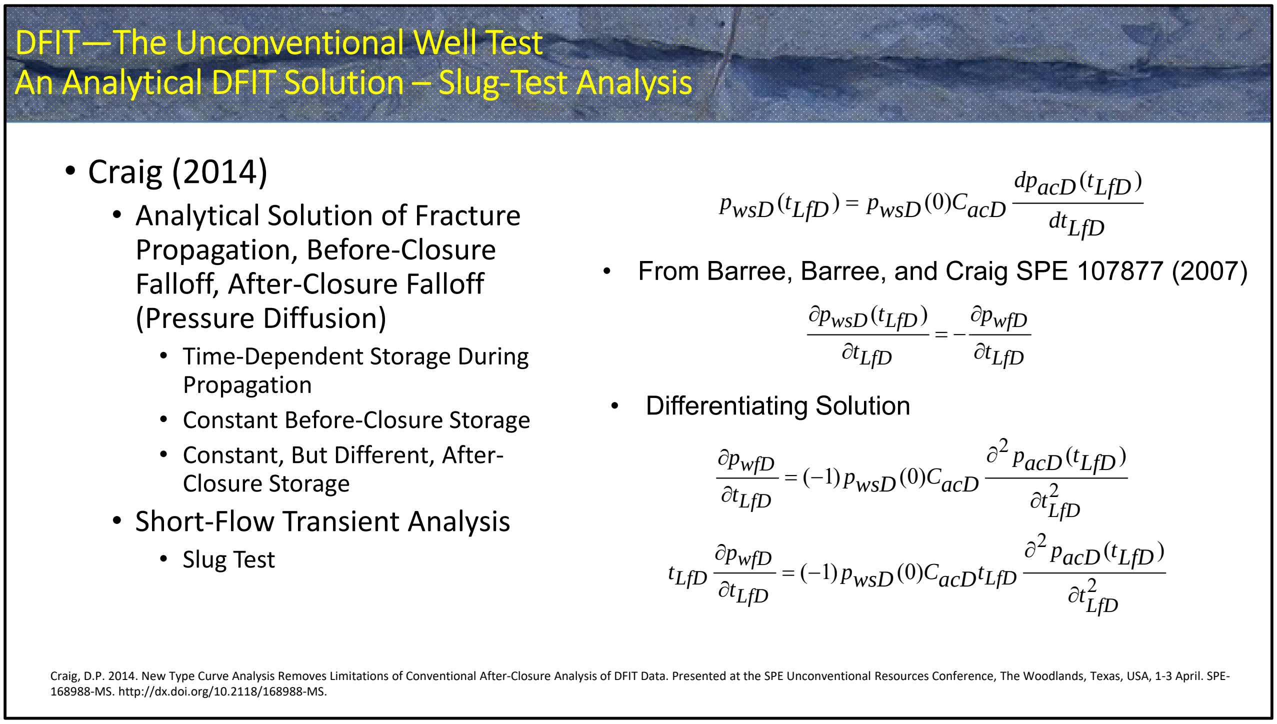
- Plot

$$p_w \text{ vs. } \left(\frac{1}{t_e + \Delta t}\right)^{1/2}$$

- Extrapolate Straight Line Through Pseudolinear Data

$$p_i = \text{intercept}$$

$$\frac{kh}{\mu} = \left[\frac{141.2(24)\sqrt{\pi}\sqrt{0.0002637}}{2}\frac{\left(Q_t + p_{wsD}(0)C_{ac}(p_0 - p_i)\right)}{hL_f m_{acpl}}\left(\frac{\mu}{\phi c_t}\right)^{1/2}\right]^2$$



DFIT—The Unconventional Well Test
An Analytical DFIT Solution – Slug-Test Analysis

- Craig (2014)
  - Analytical Solution of Fracture Propagation, Before-Closure Falloff, After-Closure Falloff (Pressure Diffusion)
    - Time-Dependent Storage During Propagation
    - Constant Before-Closure Storage
    - Constant, But Different, After-Closure Storage
  - Short-Flow Transient Analysis
    - Slug Test

$$p_{wsD}(t_{LfD}) = p_{wsD}(0)C_{acD}\frac{dp_{acD}(t_{LfD})}{dt_{LfD}}$$

- From Barree, Barree, and Craig SPE 107877 (2007)

$$\frac{\partial p_{wsD}(t_{LfD})}{\partial t_{LfD}} = -\frac{\partial p_{wfD}}{\partial t_{LfD}}$$

- Differentiating Solution

$$\frac{\partial p_{wfD}}{\partial t_{LfD}} = (-1)\,p_{wsD}(0)C_{acD}\frac{\partial^2 p_{acD}(t_{LfD})}{\partial t_{LfD}^2}$$

$$t_{LfD}\frac{\partial p_{wfD}}{\partial t_{LfD}} = (-1)\,p_{wsD}(0)C_{acD}t_{LfD}\frac{\partial^2 p_{acD}(t_{LfD})}{\partial t_{LfD}^2}$$

Craig, D.P. 2014. New Type Curve Analysis Removes Limitations of Conventional After-Closure Analysis of DFIT Data. Presented at the SPE Unconventional Resources Conference, The Woodlands, Texas, USA, 1-3 April. SPE-168988-MS. http://dx.doi.org/10.2118/168988-MS.

In 2008, I differentiated the slug test solution, and with a derivative substitution and after multiplying by dimensionless time, a new solution with another derivative is introduced.

DFIT—The Unconventional Well Test
An Analytical DFIT Solution – A DFIT Is Analyzed As A Well Test

- Craig (2014)
  - Analytical Solution of Fracture Propagation, Before-Closure Falloff, After-Closure Falloff (Pressure Diffusion)
    - Time-Dependent Storage During Propagation
    - Constant Before-Closure Storage
    - Constant, But Different, After-Closure Storage
  - Short-Flow Transient Analysis
    - Slug Test
    - Well Testing Type Curve Analysis
      - Pressure, p_i, From Match Point
      - Radial-Flow Unnecessary

$$p_{wsD}(t_{LfD}) = p_{wsD}(0)C_{acD}\frac{dp_{acD}(t_{LfD})}{dt_{LfD}}$$

- From Barree, Barree, and Craig SPE 107877 (2007)

$$\frac{\partial p_{wsD}(t_{LfD})}{\partial t_{LfD}} = -\frac{\partial p_{wfD}}{\partial t_{LfD}}$$

- Differentiating Solution

$$\frac{\partial p_{wfD}}{\partial t_{LfD}} = (-1)p_{wsD}(0)C_{acD}\frac{\partial^2 p_{acD}(t_{LfD})}{\partial t_{LfD}^2}$$

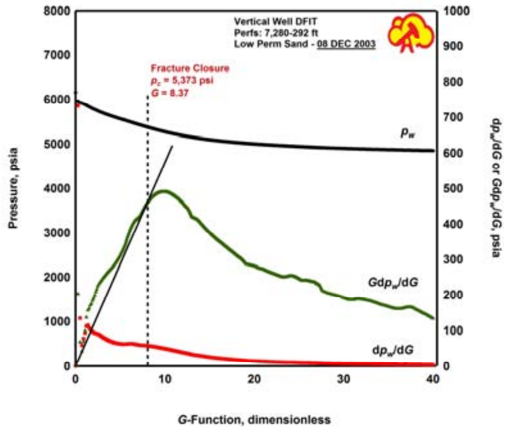
$$\boxed{t_{LfD}\frac{\partial p_{wfD}}{\partial t_{LfD}} = (-1)p_{wsD}(0)C_{acD}t_{LfD}\frac{\partial^2 p_{acD}(t_{LfD})}{\partial t_{LfD}^2}}$$

Craig, D.P. 2014. New Type Curve Analysis Removes Limitations of Conventional After-Closure Analysis of DFIT Data. Presented at the SPE Unconventional Resources Conference, The Woodlands, Texas, USA, 1-3 April. SPE-168988-MS. http://dx.doi.org/10.2118/168988-MS.

While it may not look clear, the new solution is extremely powerful. It means the same semilog derivative used in the Barree holistic analysis method can be matched to a well-testing type curve. From the match point reservoir pressure can be determined. With this new match, the well testing type curve analysis methodology was complete, and all DFIT could be analyzed by well testing methods. So let’s look at an example…

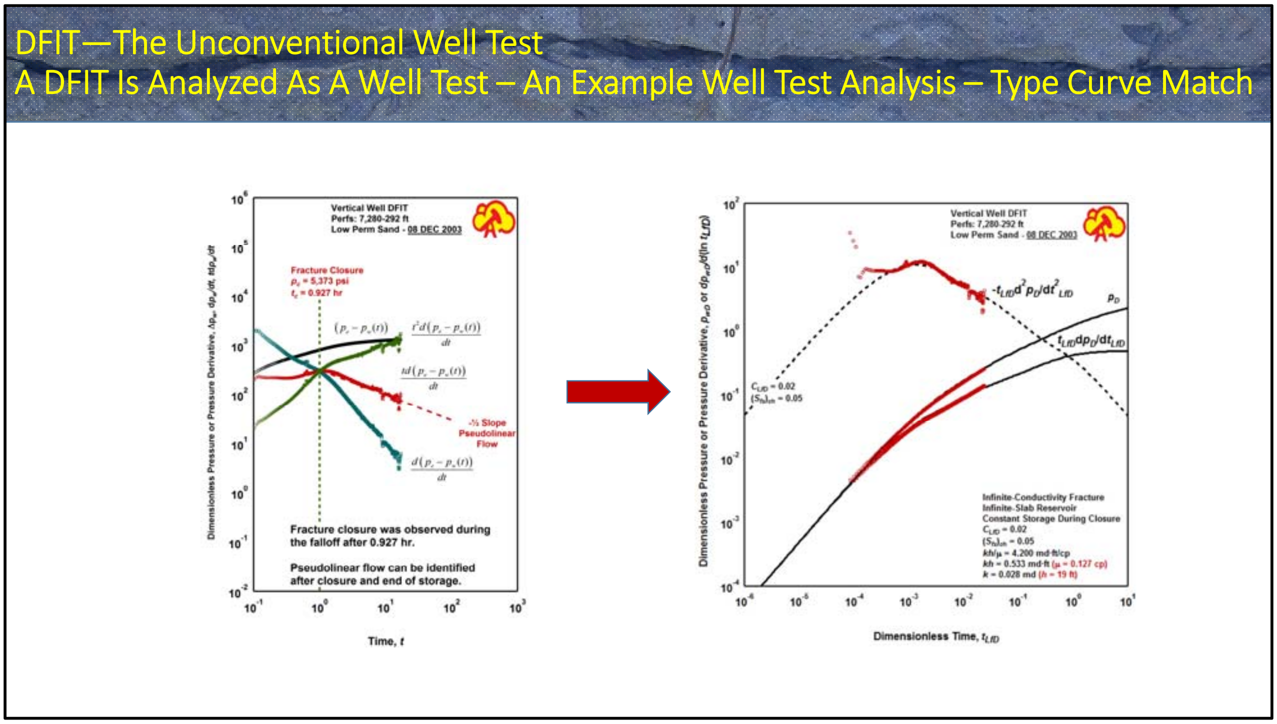
DFIT—The Unconventional Well Test
A DFIT Is Analyzed As A Well Test – An Example Well Test Analysis – Vertical Well

- Vertical Well DFIT – Dec 2003
- Pressure Dependent Leakoff
  - Closure, p_c = 5,373 psi
  - Closure, G = 8.37



Here we have a vertical well, and we are looking at the standard G-function plot. The superposition derivative, Gdp/dG, shows pressure-dependent leakoff, and fracture closure at G = 8.37 and a pressure of 5,373 psi.

Remember, the holistic methodology also requires a log-log diagnostic plot…

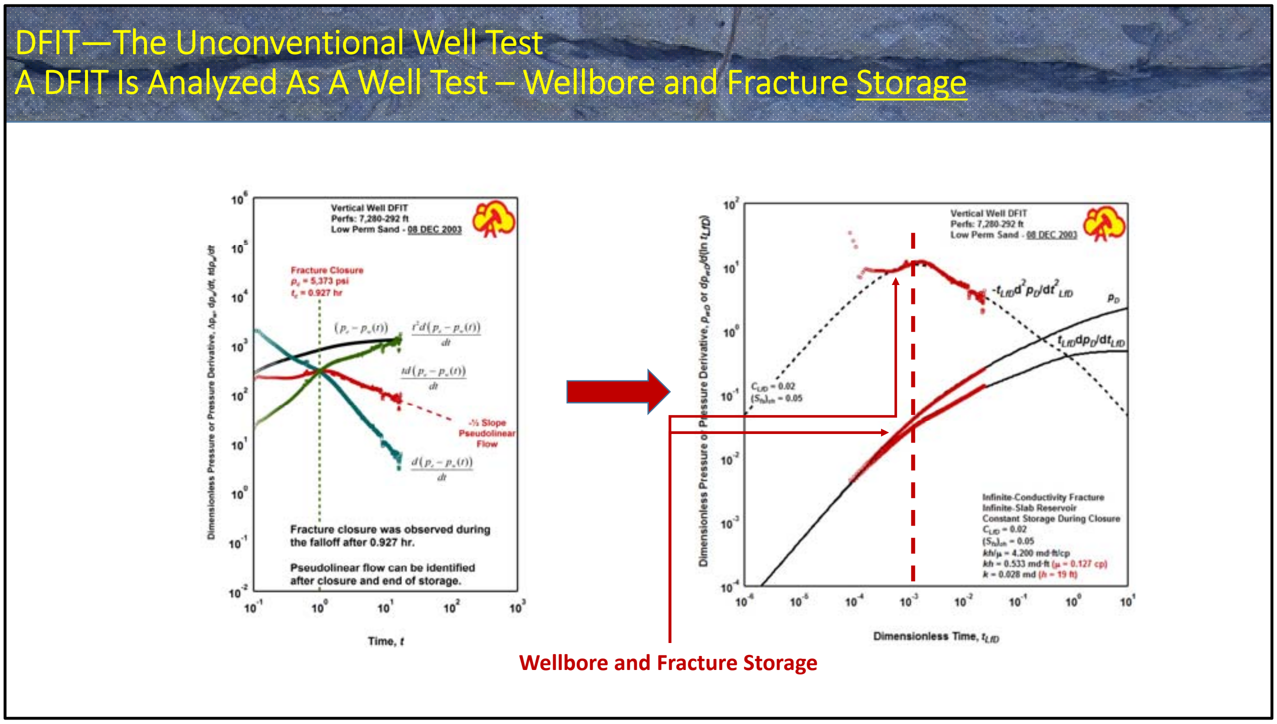


DFIT—The Unconventional Well Test
A DFIT Is Analyzed As A Well Test – An Example Well Test Analysis – Type Curve Match

…which is shown in the graph on the left. The red curve is the semilog derivative, which is the derivative of the observed pressure difference multiplied by time. That same curve is shown in the second figure matched to an analytical solution for an infinite-conductivity fracture with dimensionless storage of *C*D = 0.02 and a choked-fracture skin, S = 0.02. Pressure is calculated from the dimensionless pressure match point, and transmissibility can be determined from a type curve match point of the integrated reservoir pressure difference.

The match is non-unique. With the data matching three type curves, there is a relatively small range of possible solutions. In many cases, the transmissibility can vary by a factor of about 3, but it is different for every problem analyzed.

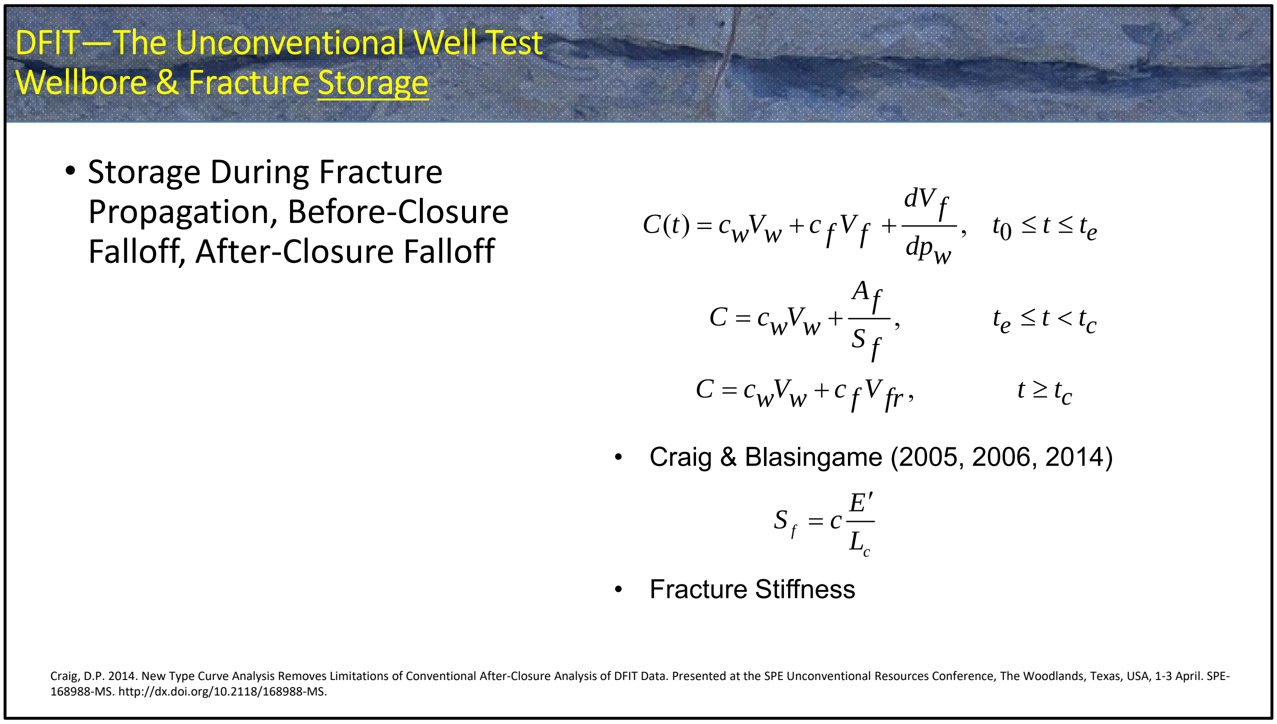
Here the transmissibility, kh/μ, is 4.20 md ft/cp, the *kh* is 0.533 md ft, and with an interval thickness of 19 ft, the permeability is 0.026 md.



DFIT—The Unconventional Well Test
A DFIT Is Analyzed As A Well Test – Wellbore and Fracture Storage

Wellbore and Fracture Storage

One issue that I would like to call your attention to is the data before the vertical dashed line. As you may recall from your reservoir engineering courses, the unit-slope line means that storage is distorting the reservoir response. Looking upwards to the semilog derivative curve, you can see that the increasing semilog derivative corresponds to storage. In other words, fracture closure is a wellbore storage phenomenon.



DFIT—The Unconventional Well Test
Wellbore & Fracture Storage

- Storage During Fracture Propagation, Before-Closure Falloff, After-Closure Falloff

$$C(t) = c_w V_w + c_f V_f + \frac{dV_f}{dp_w}, \quad t_0 \le t \le t_e$$

$$C = c_w V_w + \frac{A_f}{S_f}, \quad t_e \le t < t_c$$

$$C = c_w V_w + c_f V_{fr}, \quad t \ge t_c$$

- Craig & Blasingame (2005, 2006, 2014)

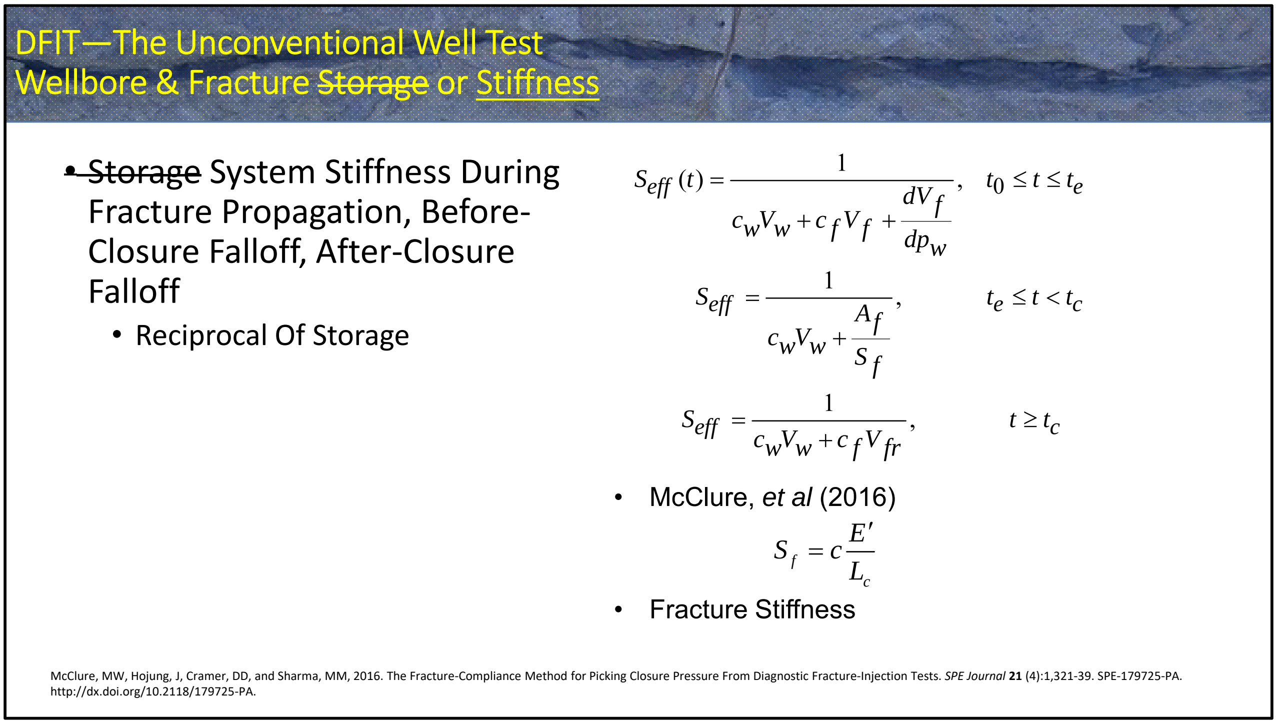
$$S_f = c\frac{E'}{L_c}$$

- Fracture Stiffness

Craig, D.P. 2014. New Type Curve Analysis Removes Limitations of Conventional After-Closure Analysis of DFIT Data. Presented at the SPE Unconventional Resources Conference, The Woodlands, Texas, USA, 1-3 April. SPE-168988-MS. http://dx.doi.org/10.2118/168988-MS.

In the original Craig and Blasingame solution, the DFIT process is modeled as a changing storage problem with increasing storage during propagation, constant storage during closure, and a constant, but different storage during after-closure diffusion.

Several new papers have written about changing “stiffness” or changing “compliance” during a DFIT…



DFIT—The Unconventional Well Test
Wellbore & Fracture ~~Storage~~ or Stiffness

- ~~Storage~~ System Stiffness During Fracture Propagation, Before-Closure Falloff, After-Closure Falloff
  - Reciprocal Of Storage

$$S_{eff}(t) = \frac{1}{c_w V_w + c_f V_f + \frac{dV_f}{dp_w}}, \quad t_0 \le t \le t_e$$

$$S_{eff} = \frac{1}{c_w V_w + \frac{A_f}{S_f}}, \quad t_e \le t < t_c$$

$$S_{eff} = \frac{1}{c_w V_w + c_f V_{fr}}, \quad t \ge t_c$$

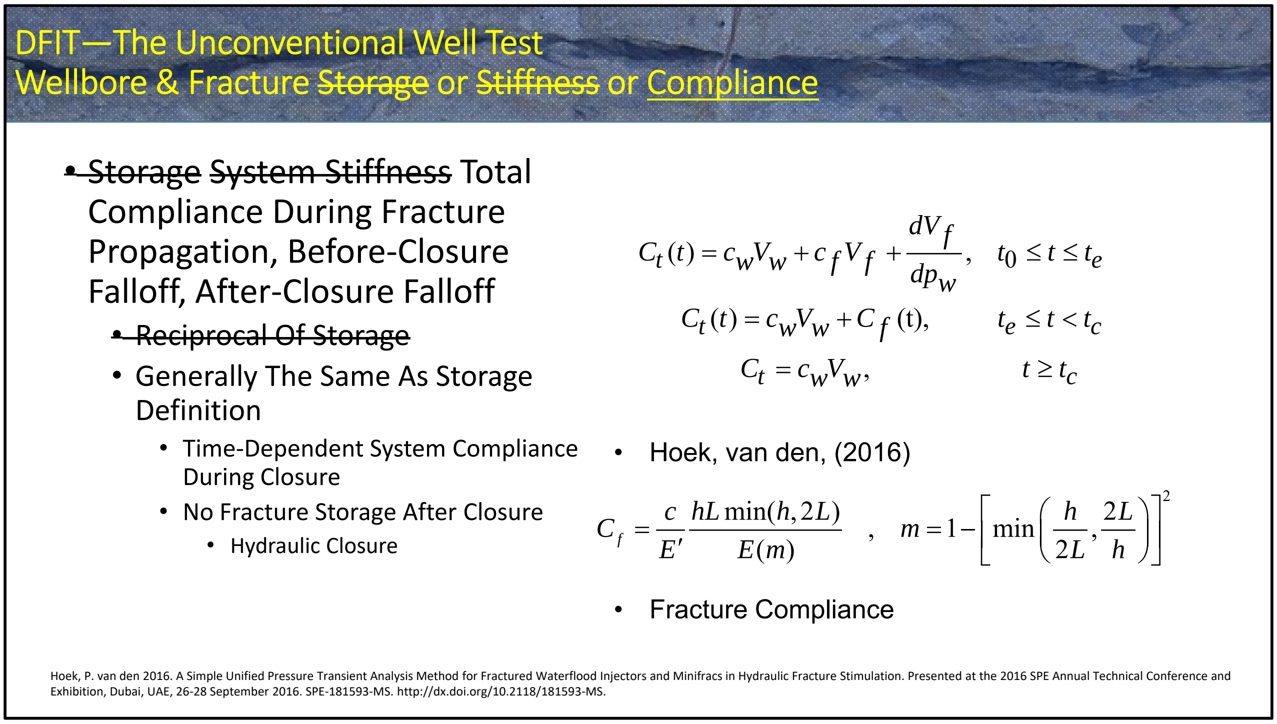
- McClure, *et al* (2016)

$$S_f = c\frac{E'}{L_c}$$

- Fracture Stiffness

McClure, MW, Hojung, J, Cramer, DD, and Sharma, MM, 2016. The Fracture-Compliance Method for Picking Closure Pressure From Diagnostic Fracture-Injection Tests. *SPE Journal* **21** (4):1,321-39. SPE-179725-PA. http://dx.doi.org/10.2118/179725-PA.

Here I show that system stiffness is simply the reciprocal of storage as defined by Craig and Blasingame. “System stiffness” is also defined in terms of “fracture stiffness,” so that can also add some confusion. Just to make certain that we aren’t completely confused, fracture stiffness is the reciprocal of fracture compliance.



DFIT—The Unconventional Well Test
Wellbore & Fracture ~~Storage~~ or ~~Stiffness~~ or Compliance

- ~~Storage System Stiffness~~ Total Compliance During Fracture Propagation, Before-Closure Falloff, After-Closure Falloff
  - ~~Reciprocal Of Storage~~
  - Generally The Same As Storage Definition
    - Time-Dependent System Compliance During Closure
    - No Fracture Storage After Closure
      - Hydraulic Closure

$$C_t(t) = c_w V_w + c_f V_f + \frac{dV_f}{dp_w}, \qquad t_0 \le t \le t_e$$

$$C_t(t) = c_w V_w + C_f(\mathrm{t}), \qquad t_e \le t < t_c$$

$$C_t = c_w V_w, \qquad t \ge t_c$$

- Hoek, van den, (2016)

$$C_f = \frac{c}{E'}\frac{hL\min(h,2L)}{E(m)} \quad , \quad m = 1 - \left[\min\left(\frac{h}{2L},\frac{2L}{h}\right)\right]^2$$

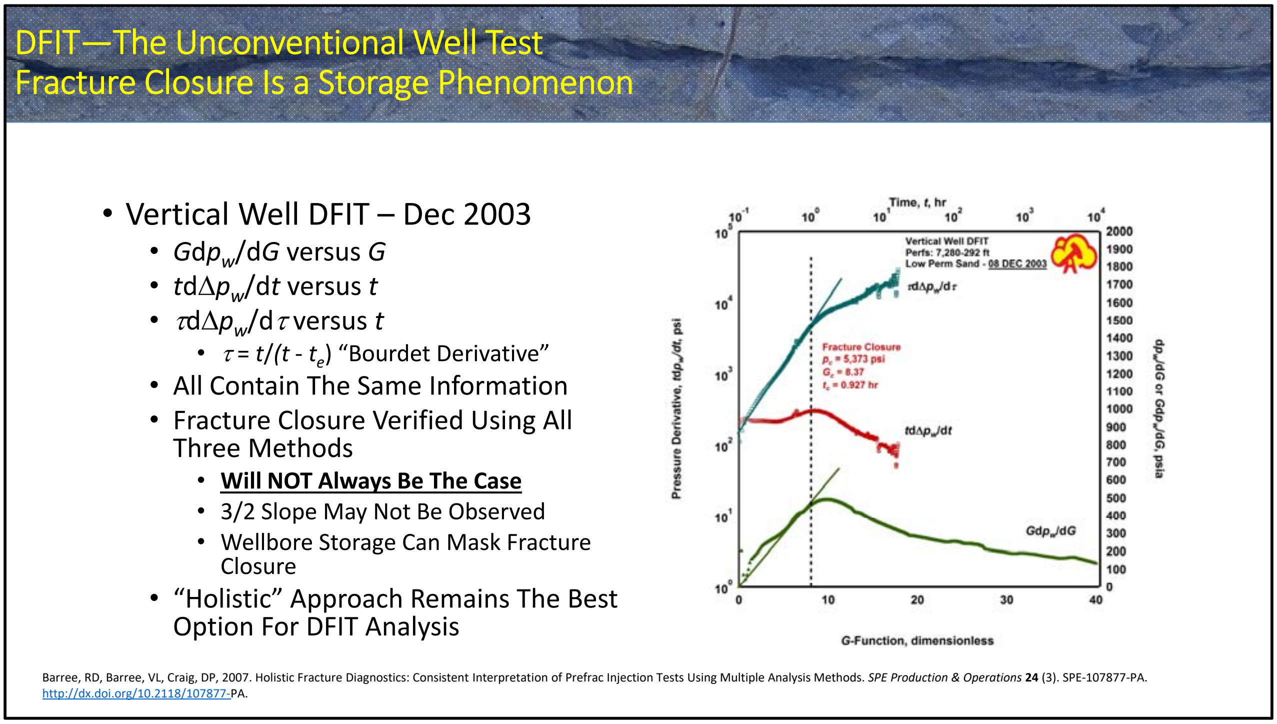
- Fracture Compliance

Hoek, P. van den 2016. A Simple Unified Pressure Transient Analysis Method for Fractured Waterflood Injectors and Minifracs in Hydraulic Fracture Stimulation. Presented at the 2016 SPE Annual Technical Conference and Exhibition, Dubai, UAE, 26-28 September 2016. SPE-181593-MS. http://dx.doi.org/10.2118/181593-MS.

…and van den Hoek refers to changing total compliance during a DFIT. The big difference here is that he allows fracture half-length to decrease during closure.

Undoubtedly, you will hear much about storage, compliance, and stiffness in the near future, but keep in mind that changing storage, changing stiffness, and changing compliance all refer to the same thing.

From a reservoir engineering standpoint, it simply indicates the fracture is still creating after-flow into the reservoir and distorting the true pressure falloff response of the reservoir. Commonly referred to as wellbore and fracture storage distortion.



DFIT—The Unconventional Well Test
Fracture Closure Is a Storage Phenomenon

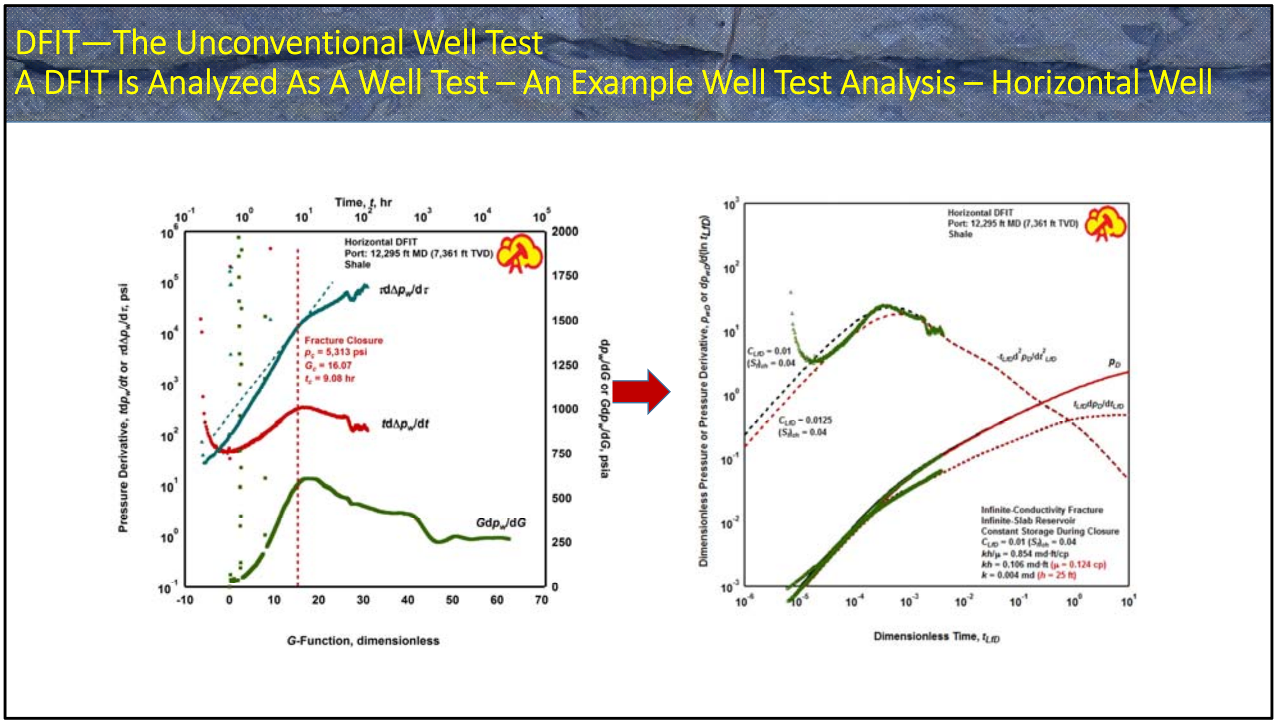
- Vertical Well DFIT – Dec 2003
  - $G\mathrm{d}p_w/\mathrm{d}G$ versus G
  - $t\mathrm{d}\Delta p_w/\mathrm{d}t$ versus t
  - $\tau\mathrm{d}\Delta p_w/\mathrm{d}\tau$ versus t
    - $\tau = t/(t - t_e)$ "Bourdet Derivative"
  - All Contain The Same Information
  - Fracture Closure Verified Using All Three Methods
    - **Will NOT Always Be The Case**
    - 3/2 Slope May Not Be Observed
    - Wellbore Storage Can Mask Fracture Closure
  - "Holistic" Approach Remains The Best Option For DFIT Analysis

Barree, RD, Barree, VL, Craig, DP, 2007. Holistic Fracture Diagnostics: Consistent Interpretation of Prefrac Injection Tests Using Multiple Analysis Methods. *SPE Production & Operations* **24** (3). SPE-107877-PA. http://dx.doi.org/10.2118/107877-PA.

Recall that fracture closure is a storage phenomenon. The above plot compares all three typical closure identification curves for the same falloff. On top is the so called Bourdet derivative, which I believe is a misnomer because it implies a well-test analysis basis, but the origins of the plotting function is Nolte's low-permeability, high-efficiency limiting-case solution for the *G*-function and not well testing superposition solutions.

In any case, closure is shown by the vertical line, and closure is consistently identified using all three curves. That will NOT always be the case. In many cases the 3/2 slope will not "fit" the Bourdet derivative, and it's also possible for wellbore storage in the semilog derivative to mask fracture closure in high permeability reservoirs.

The holistic approach remains the best option for DFIT analysis and closure identification, and the classical G-function plot remains the gold standard. Consider the following examples…



DFIT—The Unconventional Well Test
A DFIT Is Analyzed As A Well Test – An Example Well Test Analysis – Horizontal Well

There are questions in regard to the correct closure pick. Generally, the magnitude of the difference in closure pressure is small. Whenever vertical well DFIT can be compared with horizontal well DFIT, the consistent interpretation is the traditional approach, which is at the end of fracture-height recession/transverse storage.

All of that storage, stiffness, compliance stuff doesn't matter for pressure and transmissibility calculations if you use the well testing analysis approach which was derived assuming variable storage during closure and after-closure falloff. The data can still be analyzed for reservoir pressure and transmissibility, permeability-thickness, and permeability.

DFIT—The Unconventional Well Test
Volume of Investigation From DFIT

- Radial Flow

$$r_D = \sqrt{4t_D} \Rightarrow r_i = \sqrt{\frac{kt}{948\phi\mu c_t}}$$

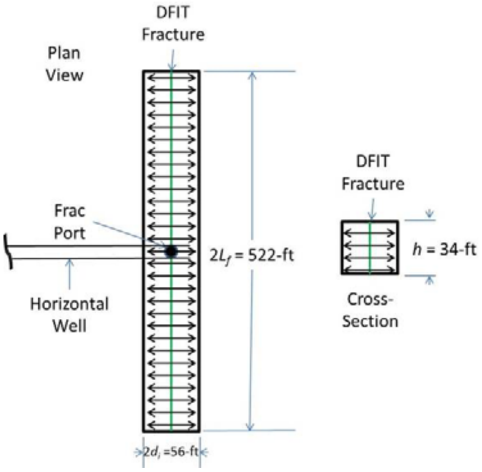
$$A_i = \pi r_i^2 \qquad V_i = hA_i$$

- Linear Flow

$$y_D = \sqrt{2t_{LfD}} \Rightarrow y_i = \sqrt{\frac{kt}{1896\phi\mu c_t}}$$

$$A_i = 2y_i * 2L_f$$

$$V_i = hA_i$$

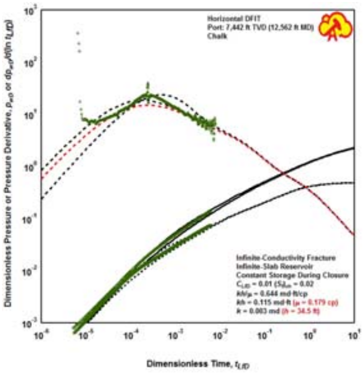


The depth of investigation for a DFIT is easily calculated from known impulse solutions. For radial flow, the permeability and the time at the end of the radial flow period is used to calculate the radius of investigation. The area-of-investigation is calculated from the radius of investigation, and if the fracture height is known, the volume-of-investigation is calculated.

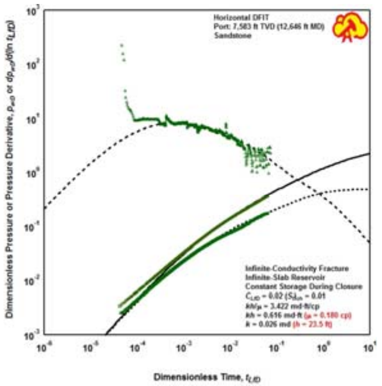
For a fractured well, and specifically, a well with a linear flow period, the depth of investigation is calculated from the permeability and the time at the end of the linear flow period. Calculating the area-of-investigation requires knowing the fracture half-length, and once again, the volume-of-investigation requires knowing the fracture height.

DFIT—The Unconventional Well Test
Volume of Investigation From DFIT – Two Low Permeability Examples

- Chalk
  - 93.2 bbl DFIT
  - k_{eff} = 0.003 md
- Sandstone
  - 88.1 bbl DFIT
  - k_{eff} = 0.026 md



$$L_f = \sqrt{\frac{0.0002637k}{\phi \mu c_t}\left(\frac{t}{t_{LfD}}\right)_M} = 261 \text{ ft}$$



$$L_f = \sqrt{\frac{0.0002637k}{\phi \mu c_t}\left(\frac{t}{t_{LfD}}\right)_M} = 215 \text{ ft}$$

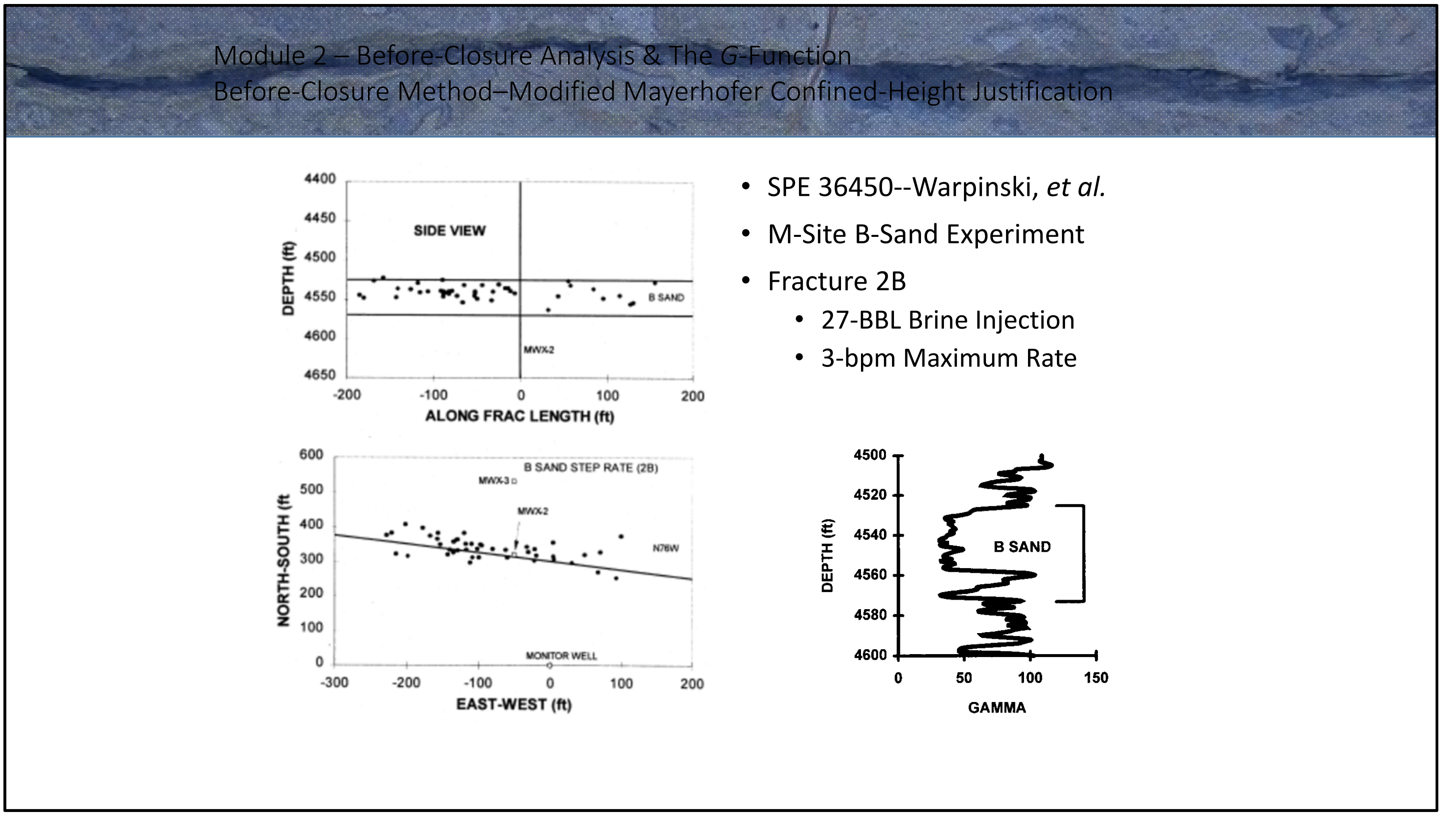
Formation	Depth of Investigation	Area of Investigation	Volume of Investigation
Chalk (*k* = 0.003 md)	28 ft	29,232 ft^2	1,008,504 ft^3
Sandstone (*k* = 0.026 md)	77 ft	66,220 ft^2	1,556,170 ft^3

If DFIT are analyzed as a well test, the fracture half length can be calculated from the type curve match. In the Chalk example, the permeability is calculated from the dimensionless pressure match point, and the fracture half-length is calculated from the dimensionless time match point. So the depth of investigation in a 0.003 md reservoir was 28 ft along a fracture half-length of 261 ft, which results in an area of investigation of 29,232 ft2.

The sandstone is an order-of-magnitude higher permeability, so the depth-of-investigation increases to 77 ft, and the created fractured half-length decreases to 215 ft. The area-of investigation of 66,220 ft2, and the volume-of-investigation is 1,556,170 cubic feet. In this field the volume-of-investigation is a representative elementary volume and the permeability can be used with confidence to predict and model production.

DFIT—The Unconventional Well Test
Summary

- A DFIT Is A Well Test And Can Be Analyzed As A Short-Flow Transient Test
  - Uses ALL Data From End Of Injection Through The End Of Falloff
  - General Solution – Infinite-Conductivity, Finite-Conductivity, Dual Porosity, Radial Flow, etc. Can All Be Used As Necessary
  - Observed Data, $t d\Delta p_w / dt$, Fits Directly To Derivative Type Curve
  - Does Not Require Radial Flow
- Variable Storage Accounted For In Well Testing Solution
  - In Unconventional Reservoirs, The End of Storage Distortion Coincides With Hydraulic Fracture Closure
- DFIT Should Sample A Representative Elementary Volume Of Reservoir
  - Small Volume DFIT May Not Produce Representative Permeability Estimates
- Volume-Of-Investigation Can Be Calculated From Well Test Analysis Results



Module 2 – Before-Closure Analysis & The *G*-Function
Before-Closure Method–Modified Mayerhofer Confined-Height Justification

- SPE 36450--Warpinski*, et al.*
- M-Site B-Sand Experiment
- Fracture 2B
  - 27-BBL Brine Injection
  - 3-bpm Maximum Rate

The modified Mayerhofer method is formulated with 2D fracture models, which we have long suspected provide unrealistic estimates of created geometry. For low volume, low rate brine injections; however, the 2D models provide an adequate description of fracture dimensions.

The M-Site, which is located in the Piceance Basin of Western Colorado, provides the justification for using 2D fracture models. The figures shown are from SPE 35450, which discussed the results of microseismic monitoring of hydraulic fracture growth in Mesaverde sands. Specifically, I have shown the microseismic results from Injection 2B, which was a 27-bbl (~1,000-gals) injection of 2% KCl at 3-bpm maximum rate. As shown in the figures, the recorded microseisms were confined to the main body of the B-Sand and extended some ~150-ft from the wellbore.

If the Nolte-Shlyapobersky method is used to estimate fracture dimensions, the results are ~135-ft for PKN geometry, which is reasonably close to the length indicated by the measured microseisms during the injection.