Pre-frac Analysis
Observations and Best Practices

Robert Hawkes
Director of Completion Technologies

CSUR, March 13th, 2013
Measure twice – frac once

The Aberdeen section presentation on 23 April will focus on the use of pre-frac reservoir characterisation parameters that have the largest impact on the production performance obtained from any stimulation treatment. The most critical of these parameters are reservoir pressure, formation flow capacity (kh) and wellbore skin. Too often, it is not always clear whether poor post-frac production results are a result of a poor reservoir or a poor completion.

Robert began his career with Esso Resources, before joining Fekete Associates Inc. He is a recognised expert in the field of pressure transient analysis, reservoir characterisation and short-term pre-frac transient analysis. He graduated from the Southern Alberta Institute of Technology in 1979 with a diploma in Petroleum Engineering.
The Aberdeen section presentation on 23 April will focus on the use of pre-frac reservoir characterisation. The next Aberdeen section talk, ‘Measure twice – frac once; pre-frac reservoir characterisation from perforation inflow diagnostic (PID) testing’, will be delivered by Robert Hawkes, Reservoir Services team leader for BJ Services Canada. Robert will show that a properly designed and conducted closed-chamber perforation inflow diagnostic (PID) test is a cost-effective, safe and environmentally friendly method of obtaining critical pre-frac reservoir parameters.

In an effort to enhance the deliverability potential of a tight gas well, operators sometimes overlook the ‘missing link’ between stimulation design and the well’s post-frac production response. Robert’s talk will address this issue.

A review of the deliverability behaviour for tight gas parameters that have the largest impact on the production performance obtained from any stimulation treatment. The most critical of these parameters are reservoir pressure, formation flow capacity (kh) and wellbore skin. Too often, it is not always clear whether poor post-frac production results are a result of a poor reservoir or a poor completion.

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Ken Nolte pointed out in his keynote address in College Station (Feb 2007),

......the results from pre-frac testing determine practically every input and output of our fracture design process. They determine the expected frac geometry, conductivity, formation flow capacity and optimum frac design as well as means necessary to place the fracture treatment.

Bob Bachman, Taurus Reservoir Solutions Ltd

I am always looking for an excuse to re-analyze old mini-frac data. If one could determine an accurate permeability I think this would have immense benefit to any operator. In my opinion this is huge and allows us to make better production forecasts.
Bob Barree states in his most recent DFIT course notes (Jan 2013),

......because these parameters are so critical, it is imperative that the analysis is done correctly. In my personal experience, there are far too many self-avowed experts doing the analysis incorrectly and adding tremendous doubt and confusion to the fracturing industry, as well as casting doubt on the validity of the analysis methods and fracture modeling in general.
Motivation:

Deliverability Behavior

- Deliverability
  - COMPLETION EFFECTIVENESS
    - Flush Production
  - RESERVOIR CHARACTERISTICS
    - Stabilized Production

Although the completion controls *Flush* production, the reservoir controls *Stabilized* production
Motivation:

Multi-stage, Hz Well Production Performance Sensitivity

- **MONTNEY** British Columbia

  F. Hategan, Devon Energy

![Graph of MONTNEY (Actual vs Type Curve Models) Production](image)

<table>
<thead>
<tr>
<th>$kh$ [mDm]</th>
<th>20 Yrs. $\Delta G$ [Bscf]</th>
</tr>
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**What if the AFE was approved on 6.0 Bscf/well?**

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Pre-Frac Testing Review

- **DST Test**
  - First commercial DST in 1926

- **Wireline Formation Test**
  - In operation 1953
  - First RFT in 1975

- **PID Test**
  - McKinley (Exxon Research) 1970’s
  - Re-introduced in 2000 by BJ Services Canada

- **DFIT Test**
  - Early 90s
Pre-Frac Testing Review

- Perforation Inflow Diagnostic (PID) Test
  - Vertical Well: 3 Separate Tests

![Graph showing PID test results with WR Plug Failed, High Perm, and Low Perm indicated.](image-url)
Mini-frac Approach

Low Rate or High Rate?

ISIP

Closure Identification
Flow Regime Identification
Specialized Plots
Completion Considerations

LT = http://petrowiki.org/Building_geomechanical_models

LT = Limit test
LOP = Leakoff test
FIT = Formation integrity test
FBP = Formation breakdown pressure
FPP = Fracture propagation pressure
ISIP = Instantaneous shut-in pressure
FCP = Fracture closure pressure

Pressure Volume
Fracture orientation is determined by relationship of principal stresses.
Stress Orientation

\[ \sigma_2 \]
My axe is stuck!!
My axe is stuck!!

Much easier to split........
even if you miss.
Understanding the stress regime is critical to fracture growth, geometry, and treating pressures.
Some Basic Principles
The least principal stress (closure pressure) is taken to be the pressure at which the transition in flow regime occurs.
Mini-frac Approach

SPE 107877  
Barree et al, 2007

SPE 93419  
Soliman et al, 2005

SPE 160169  
Bachman et al, 2012

SPE 140136  
Mohamed et al, 2011

G-Time Scale  
Log Time Scale

Closure  
Linear/Radial Flow

Pressure  
Time
Post Shut-In: What is G-function Analysis?

- Post shut-in pressure decline analysis using dimensionless function
- Extends the analysis through use of the first derivative and semi-log derivative of BHP (dP/dG and GdP/dG)
- Also uses the characteristic shapes of derivative curves to locate specific modes of pressure decline
- Extension to After-Closure Analysis (ACA) to define reservoir linear and pseudo-radial flow
Normal Leakoff G-Function
Fracture closure is expressed as a change in storage phenomena, and so when there is a change in slope by the pressure derivative (positive to negative), this is picked as closure.
Flow Regime: Before Closure

Linear Flow
\[ m = \frac{1}{2} \]

Carter Linear Flow
\[ m = 1 \]
Flow Regime: After Closure

Linear Flow
\[ m = -\frac{1}{2} \]

Bi-linear Flow
\[ m = -\frac{3}{4} \]

Radial Flow
\[ m = -1.0 \]
Flow Regime: After Closure

Linear Flow
\[ m = -\frac{1}{2} \]

Bi-linear Flow
\[ m = -\frac{3}{4} \]

Radial Flow
\[ m = -1.0 \]
Log-Log Plot

User Beware: this plotting technique has issues!
Some Basic Principles

Linear Flow Model

$m = 1/2$
Some Basic Principles

Linear Flow Model

* closure signature may be an artefact of the time function (see Slide 7)
Some Basic Principles

Copy of Slide 7

Delta-Time

BH ISIP = 9998 psi

ΔP vs. Δt

ΔtΔP/dΔt vs. Δt

Radial Flow

Fracture Closure

??

PureEnergy

Providing Superior Value
Some Basic Principles

Linear Flow Model

Agarwal Time

\[ tp \Delta t \]

\[ tp + \Delta t \]
Tip #1: For a detailed understanding of Time Plotting Functions and their slopes, read Bachman SPE 160169.
Flow Regime: Before Closure

Fracture Linear Flow

\[ m = \frac{1}{2} \]

Carter Linear Flow

\[ m = \frac{3}{2} \]

Tip #2: Focus on the leak-off mechanism and the transition of flow regimes.
Case Example 1

If my well goes on vacuum during the fall-off test, should I be concerned even though I ran bottom-hole pressure recorders?
Case Example 1
Bttm Hole Pressure Data

Hydraulic port opened $P = 49827$ kPa

End of Job Injection
Pressure (EOJ) = 33602 kPa
Case Example 1
Bttm Hole Pressure Data
Case Example 1
Bttm Hole Pressure Data

Fracture Closure
- t: 40.76 min
- P: 22069 Pa (a)

Slope = 1/2

What’s going on over here…
Case Example 1

Bttm Hole Pressure Data

Overburden Gradient = 22.62 kPa/m (1.0 psi/ft)

Normal Pressure Gradient = 9.8 kPa/m (0.433 psi/ft)

Hydraulic Port Opens.

Injection Pressure.

2012/10/05 08:40:36
15946.4 kPa
95.476 hrs
A fall-off test will go on vacuum when pore pressure is less than hydrostatic weight of the injected liquid.

Since compressibility of gas (Cg) is decades larger than the compressibility of water (Cw), the fall-off pressure response changes significantly once fluid drops below surface…..and for practical purposes, the test is over.
Case Example 1
Bttm Hole Pressure Data

Minifrac Radial Flow Plot

Pressure, kPa
Radial Flow Time Function

9.8 kPa/m
8.2 kPa/m

Analysis 2
$P^* = 14925$ kPa(a)

Analysis 1
$P^* = 15219$ kPa(a)

$\Delta t = 1.36$ h
$P = 17975$ kPa(a)
**Case Example 1**

**Btm Hole Pressure Data**

**Tip #3:** Run downhole shut-in tools if there is any chance of a depleted zone.

**Tip #4:** If well goes on vacuum (without a downhole shut-in), keep it shut in as long as possible to obtain a reasonable estimate of Reservoir Pressure.

**Tip #5:** If well goes on vacuum (without a downhole shut-in), you have no hope in determining Reservoir Permeability.

**Tip #6:** Pore pressure is related to closure pressure, therefore, the lower the pore pressure – the lower the closure pressure ($sh_{min}$).
Often we don’t see radial flow after-closure, is my reservoir pressure determination still valid?
6-Well Pad Montney Formation Case Study

58-L Pad Plan View; Farrell Creek, N.E. British Columbia

- Cemented Liners
- Plug & Perf
- Hydraulic Port in the Toe
Hz Well F
Did the frac close?

EOJ = 30.56 kPa/m (1.4 psi/ft)

20.0 kPa/m (0.9 psi/ft)
Case Example 2

PPD

21.8 dy

Slope = 3/2

Slope = 1

20.1 kPa/m
(0.9 psi/ft)
Case Example 2

P* Radial: 39.4 Mpa
P* Linear: 37.3 MPa
\[ 2,100 \text{ kPa (5%)} \]
Even back in the 80’s it was recognized that when the use of a *radial* flow regime analysis technique was used to analyze *linear* flow dominated data, it would result in an OPTIMISTIC estimate of permeability (200%) – while the extrapolated pressure (p*) was reasonable (2-3%)

Laird, Mattar (1985)
I’m rounding third and heading for home....

Vertical Well D

Case Example 3
SPE 163825
Why is Flow Regime Identification Important?
Case Example 3

Slope = 0 = RADIAL FLOW
Slope = 3/2 = CARTER FLOW

24.0 kPa/m (1.1 psi/ft)
21.0 kPa/m (0.9 psi/ft)
Based on the density logs, the overburden gradient is \(~25.3 \text{ kPa/m}\)
21.0 kPa/m (0.9 psi/ft)
• **Reservoir Pressure**
  - Errors in reservoir pressure tend to be small, even when unsure of after-closure flow regime.
  - Can be validated *after-the-frac*.

• **Reservoir Permeability ($k$)**
  - We are still challenged in this exercise and your best hope is *pre-frac*.

• **....are we wasting our time ?**
  - If your results are used to understand your post-frac expectations......then NO.
• **Closure Pressure**  
  – *Still needs a holistic approach* (........and more work)

• **Leak-off Behaviour**  
  – *Understanding the flow regime during a mini-frac, provides information on your fracture geometry.*

• **After Closure Analysis**  
  – Welltest Theory  
  – *HOWEVER, be careful how you impose a flow regime on the data.*
Acknowledgement

Florin Hategan, Devon Energy

Bob Bachman, Taurus Reservoir Solutions
A Quandary
not
a
Conundrum

.......any further improvement in interpretation technology can only come from significant improvements in the identification and validation steps (Gringarten, 2008).