Pre-frac Reservoir Characterization from Perforation Inflow Diagnostic (PID) Testing

“Measure Twice – Frac Once”

Robert Hawkes
Team Leader, Reservoir Services
BJ Services Company Canada
SPE DISTINGUISHED LECTURER SERIES

is funded principally through a grant of the SPE FOUNDATION

The Society gratefully acknowledges those companies that support the program by allowing their professionals to participate as Lecturers.

And special thanks to The American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) for their contribution to the program.
EXECUTIVE SUMMARY

- **Initial** post-frac welltest analysis **OVER-ESTIMATE** most tight gas well production performances.

- **Take the time** (money) to obtain initial reservoir pressure (pi) prior to your fracture treatment.

- **Closed chamber testing** is an *overlooked* pre-frac testing technique.
Problem

- We have completed our hydraulic fracture treatment program with *most* wells on production.

- Post frac pressure buildup analysis are finished.

- Initial production results are less than what we predicted.

- Please review the frac treatment reports and the well test analysis to determine re-frac candidates!
General PTA Theory

LINEAR FLOW IN THE FRACTURE (a)

BILINEAR FLOW (b)

LINEAR FLOW IN THE FORMATION (c)

PSEUDO-RADIAL FLOW (d)
Where the end of linear flow from a fracture is defined as $t_{Dxf} = 0.016$

$$t_{Dxf} = \frac{0.000264kt}{\phi(\mu c_t) \cdot x_f^2}$$

$t = \text{hours}$

$k = 0.1 \text{ mD} \quad x_f = 100\text{m} \quad t = 36\text{ h (1.5 d)}$

$k = 0.01 \text{ mD} \quad x_f = 100\text{m} \quad t = 360\text{ h (15 d)}$
The Fetkovich plot is to production analysis what the log-log derivative is to the well test analysis.
Post-frac Flow and Buildup Test

ENCANA CORPORATION
ECA SMOKY 7-21-59-4W6

Total Test

UPPER BELLY RIVER : 2087.5 - 2092.5 m KB.
2005/06/13 TO 2005/06/18.

\[ \Delta t = 107.54 \text{ h} \]
\[ \Delta P_{\text{data}} = 17916 \text{ kPa(a)} \]

30 Tonnes, 20/40 Ottawa Type Sand
92 m\(^3\) Gelled Hydro-Carbon, 15 m\(^3\) CO2
Max sand concentration 900 kg/m\(^3\)
Frac gradient ~ 14.8 kPa/m
Post-frac Flow and Buildup Test

ENCANA CORPORATION.
ECA SMOKY 7-21-59-4W6

Log log Plot

Upper Belly River: 2087.5 - 2092.5 m KB.
2005/06/13 TO 2005/06/18.

$\Delta \psi/\text{Derivative}, 10^6 \text{kPa}^2/\mu\text{Pa.s}$

False Radial Flow.
Where’s the Frac?!!
Note the very early flattening of the pressure derivative (1.0 h).
**Post-frac Flow and Buildup Test**

ENCANA CORPORATION.
ECA SMOKY 7-21-59-4W6

UPPER BELLY RIVER: 2087.5 - 2092.5 m KB.
2005/06/13 TO 2005/06/18.

**Results:**
- \( p_r = 18585 \text{ kPa} \)
- \( k_h = 0.9 \text{ mD} \cdot \text{m} \)
- \( s = -2.9 \)

**Horner Plot**

- \( \Delta t = 105.92 \text{ h} \)
- \( p = 17906 \text{ kPa(a)} \)
An Idealized View Of A Propped Fracture Showing Trapped Fluid Due To High Capillary End Effects

Trapped injected fluid
Good Tests Cost Money; Bad Tests Cost MORE

We’ll test it after the frac
The completion controls *Flush* production, whereas the reservoir controls *Stabilized* production.
Flush Production: controlled by Reservoir Pressure ($p_i$), flow capacity ($k_h$) and completion effectiveness ($x_f$).

Long Term Production: controlled by flow capacity ($k_h$), drainage area and shape ($A$).
Reservoir Characteristics

- **Flow Capacity (kh)**
  - biggest impact on a well’s deliverability
  - system kh?

- **Net Pay (h)**
  - a moving target.
  - storage driven?
  - deliverability driven?

- **Effective Porosity (φ)**
  - all pores are NOT created equal

- **Logs (static)**
- **Cores (needs to be corrected)**
- **Welltest (dynamic)**
- **Production (ground truth?)**

- **Cut-off (???)**
- **Permeability or storage?**
- **Gas saturation**
- **Porosity**

- **Logs**
- **Cores (mineralogy!!)**
- **Material balance**
Completion Effectiveness

\[ F_{CD} = \frac{k_f \cdot W_f}{k_m \cdot x_f} \]

- An \( F_{cd} \) of 1.6, is the optimum for ANY reservoir, well, and proppant.

- In low permeability formations, this requirement results in a long and narrow fracture.

- In high permeability formations, a short and wide fracture provides the same \( F_{cd} \).


- \( k_f \) frac perm
- \( w_f \) frac width
- \( k_m \) matrix perm
- \( x_f \) frac half-length
An accurate knowledge of the formation permeability is essential
- More important than anything else

Unfortunately, fracture permeability \( k_f \) is not constant for gas wells
- Non-Darcy flow effects
- Multiphase flow effects

Therefore design for \( F_{cd} \) of 20
**PRODUCTION DIAGNOSTICS**

- **GIP = 14.0 E3 m3**
- **Pr = 23,000 kPa**
- **kh = 0.55 mD.m**

Well: 01-27

Well: 02-27

Frac Model (S = -5.7)
PRODUCTION DIAGNOSTICS

GIP = 14.0 E3 m³
Pr = 23,000 kPa
kh = 0.55 mD.m

Well: 01-27
Well: 02-27
Frac Model (S = -2.3)
PRODUCTION DIAGNOSTICS

Well: 01-27
Frac Model: -5.7
GIP: 14.0 E3 m3
Pr: 23,000 kPa
kh: 0.55 mD.m

Well: 02-27
KH Model

SPEDL Series
Sensitivity of Production Forecast

% Error in Cum Gas Forecast

30% error in \( kh \) estimate results in a 26% error in cum gas forecast.

30% error in frac length is only 7% error in cum gas forecast.
Productivity Index \( (J) \) can be expressed in the following terms:

\[
J = \frac{kh}{1422T(\ln \frac{r_e}{r_w} - \frac{3}{4} + s)} = \frac{q}{m(p_{avg}) - m(p_{wf})}
\]

In its simplified form, it can be expressed as:

\[
J = \frac{kh}{8 + s}
\]

\[
q_a = \left[\frac{8 + s_b}{8 + s_a}\right] \times [qb]
\]

In the *rule of eights*, \( s_b \) and \( s_a \) represent the skin effects before and after fracture treatment, respectively. Similarly \( q_b \) and \( q_a \) represent the boundary-dominated flow rates before and after fracture treatment, where:

\[
r_w' = \frac{1}{2} x_f
\]

or

\[
r_w' = r_w e^{-s}
\]

\[
s = -\ln(r_w'/r_w)
\]
What is PID testing?

- Perforation Inflow Diagnostics (PID).
- Pre-frac reservoir test.
- Underbalanced perforating procedures.
- Application of closed chamber testing.
3 Month Window for Drilling and Completions in Canada

December 30th

March 30th
$q_w = 24 \ C(p_w) \frac{d}{dt} p_w$
◆ PID Testing for Shallow Gas

- Cost effective.
- Rigless.
- Evacuated wellbore.
- Electronic surface recorders.
- multi-zone reservoirs.
Shallow Gas Operation
Closed Chamber Theory

Ellerslie perforations: 1265.0-1269.5 mKB
Surface pressures converted to sandface

\[ q_w = 24 C(p_w) \frac{dp_w}{dt} \]
SPEDL Series

0.001 0.01 0.1 1 10 100

Pseudo Time

Pseudo Pressure and Derivative

Log-log Derivative Plot

Storage

Pseudo Pressure

Derivative

-1 slope

Ellerslie perforations: 1265.0-1269.5 mKB

Log-Log--log Derivative Plot

Pseudo Pressure

t = 2.1 hrs

Pseudo Time
Inverse Time Plot

Ellerslie perforations: 1265.0-1269.5 mKB

\( p^* = 3431 \text{ kPa} \)

\( t = 2.1 \text{ hrs} \)
SPEDL Series

1700 1900 2100 2300 2500 2700 2900 3100 3300 3500

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40

Rate Conv. Fn.

$P_i - P_{ws} = m \left( \log(t) + \sum_n + \frac{q(t)s}{q_{ref}} \right)$

$kh = 7.5 \text{ mD.m}$

$S = +3.0$

Ellerslie perforations: 1265.0-1269.5 mKB

t = 2.1 hrs

t = 0.7 hrs

S = 0.5
S = 3
S = 5.5

Slope
Radius of Investigation with respect to PID Testing

- **if** Cores investigate “inches”,
- Logs investigate “feet”,
- Well Tests investigates “hundreds of feet”,
- as long as you can measure a change in pressure, you are effectively flowing the well.
- Radius of Investigation \( (r_i) \) is based on time \( (t) \) and permeability \( (k) \), not flow rate.

\[
r_i = \sqrt{\frac{k \times t}{6944 \times \Phi \times \mu \times c_t}}
\]
Recorders on Perf Gun Operation
Both surface and BHP gauges were used to monitor the inflow response after perforating the well.
The expanded scale of this plot shows a 4 minute delay in gas inflow after perforating the Vikng.

ERHSC 86.0 mm
25 gr SDP
5 SPF 60°
Gas rates was calculated using the closed chamber technique based on a gas chamber volume of 5.3 m³.

AOF = 3.5 \times 10^3 m^3/d
The inverse slope (n) of 1.0 is characteristic of dry gas (laminar) inflow.
PID Testing for Deep, Tight Gas

- Cost effective, safe.
- Electronic downhole recorders
- Downhole shut-in
- Two days rig time
Tight Gas PID Test

Plug w/recorders

Downhole Gauge

Perforation

Build up

dp/dt

Set Csg Plug

Pressure

Time

SPEDL Series
PID Test

Raw Downhole Data

RRD @2070.0 mkB

ENCANA CORPORATION
1000 21-059-04W6-0
Start Test Date: 2005/06/10
Final Test Date: 2005/06/11

Formation: UPPER BELLY RIVER: 2087.5 - 2092.5 mkB

Gauge 1 Pressure: p (psi)
Gauge 2 Temperature: °C

t = 1.2083
p = 15975.79
2005/06/10 17:12:30
Set Plug with recorders

Gauge 1 Time

t = 10.5467
Temp = 61.17

RRD @2070.0 mkB

t = 18.4250
p = 18743.44
2005/06/11 10:25:30
End of Test
The derivative response of -1 reflects radial flow.
**ENCANA CORPORATION.**
**ECA SMOKY 7-21-59-4W6**
**UPPER BELLY RIVER 2087.5 - 2092.5 m KB.**
**2005/06/10 to 2005/06/11.**

**PID Test – Inverse Time Plot**

- **Analysis 1**
- $p^* = 19174 \text{kPa}$
- $\Delta t = 11.05 \text{h}$
- $p = 18456 \text{kPa}$

**RRD @2070.0 mKB.**

Expanded scale of the Impulse Plot

**SPEDL Series**
If we honour the reservoir pressure obtained from the PID test:

\( p^* \) increases by 3%

\( kh \) reduces by 55%
## Importance of Initial Reservoir Pressure

### CASE HISTORY*

<table>
<thead>
<tr>
<th></th>
<th>14 Day Buildup</th>
<th>240 Day Buildup</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_i$ [kPa]</td>
<td>19041</td>
<td>19293</td>
<td>1.3</td>
</tr>
<tr>
<td>$k$ [mD]</td>
<td>0.05</td>
<td>0.02</td>
<td>150</td>
</tr>
<tr>
<td>$x_f$ [m]</td>
<td>40.1</td>
<td>66.2</td>
<td>39</td>
</tr>
<tr>
<td>$k_f w$ [mD.m]</td>
<td>280</td>
<td>470</td>
<td>40</td>
</tr>
<tr>
<td>5 yrs. $\Delta G$ [MMscf]</td>
<td>100</td>
<td>65</td>
<td>54</td>
</tr>
</tbody>
</table>

* Hategan and Hawkes, 2006
Conclusions

- Initial post-frac buildup analysis OVER-ESTIMATE most tight gas well production performances.

- Perforation Inflow Diagnostic (PID) Analysis gives us the ability to peer through the wellbore region and determine the quality of the reservoir rock lurking behind.
Conclusions

- **Closed chamber testing** during underbalanced perforating is an *overlooked* pre-frac testing technique to determine initial reservoir pressure and in-situ permeability.

- In tight gas reservoirs, *reservoir pressure* is a critical parameter for hydraulic fracturing treatments and evaluation.
“It is a capital mistake to theorize before one has data. Insensibly one begins to *twist* facts to suit theories, instead of theories to suit facts”

Sherlock Holmes