Keynote Presentation
Fracture Diagnostics for Well Design

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Statistical Approach

• Drill 1000 or more wells, and use statistics as a guide for well design.
• Never mind about collecting good data.
• Never mind about formation characteristics or well design.
• Just use trendology to minimize uncertainty.
Recovery Factor Relation to EUR

- EUR is forecast recovery to abandonment rate or pressure
- Recovery factor – RF – is fraction of hydrocarbon in place
  - For conventional reservoir RF relates to IOIP or IGIP
  - If done on a resource basis instead of a well drainage (SRV) basis, the RF could be much smaller
Target Well Design
What Makes a Good Well

• Sweet spot
• Drilling execution
• Hydraulic fracture execution
Sweet Spot

bbl/month

0 – 2000
2000 – 4000
4000 – 8000
8000 – 16000
16000 - 100000
Sweet Spot

- Black Oil Wells
- Volatile Oil Wells
- Gas Condensate Wells
- Dry Gas Wells
Sweet Spot
Total Organic Carbon (TOC)

from geochemical logs

from core samples

If \( U_{\text{ppm}} > 4 \text{ ppm} \)

\[
C_{\text{TOC}} = C_{\text{measured}} - C_{\text{calcite}} - C_{\text{dolomite}} - C_{\text{siderite}}
\]

Pemper et al., 2009

www.nationalpetrographic.com
Drilling Execution

Potential Landing Zones Identification

- Zone A: Secondary siliceous interval, 6-8% porosity, higher resistivity, lower in-situ stresses, good steerable markers.
- Zone B: Primary siliceous interval 6-8% porosity, thicker pay interval, lower in-situ stresses.
Radial flow assumption implies wrong permeability and pore pressure
## Fracture Calibration Injection Fall-off Test

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISIP, psi</td>
<td>8770</td>
</tr>
<tr>
<td>Minimum propagation pressure ($p_{p,\text{min}}$), psi</td>
<td>6647</td>
</tr>
<tr>
<td>Fracture initial radius, ft</td>
<td>41.0</td>
</tr>
<tr>
<td>Fracture final radius after tip extension, ft</td>
<td>62.85</td>
</tr>
<tr>
<td>Main fracture leakoff coefficient ($C_{Lm}$), $\times 10^{-4}$ ft/\sqrt{\text{min}}</td>
<td>4.155</td>
</tr>
<tr>
<td>Natural fracture closure pressure ($p_{fo}$), psi</td>
<td>6624</td>
</tr>
<tr>
<td>Main fracture closure pressure ($p_c$), psi</td>
<td>5732</td>
</tr>
<tr>
<td>Fluid efficiency ($\eta$)</td>
<td>0.879</td>
</tr>
<tr>
<td>Permeability from linear flow ($k_{\text{linear}}$), nd</td>
<td>40.6</td>
</tr>
<tr>
<td>Interporosity flow coefficient ($\lambda$)</td>
<td>40</td>
</tr>
<tr>
<td>Storativity ratio ($\omega$)</td>
<td>0.4</td>
</tr>
<tr>
<td>Permeability from history match ($k$), nd</td>
<td>130</td>
</tr>
<tr>
<td>Formation pressure ($p_i$), psi</td>
<td>4424</td>
</tr>
</tbody>
</table>

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**Slide 12**

SPE-181856
Hydraulic Fracture Execution

- Mechanical Specific Energy (MSE) from drilling measurements and mud motor parameters
- Facies-based cluster positions to enable uniform breakdown pressure
Hydraulic fracture planes propagate perpendicular to minimum stress independent of the horizontal well direction.

Operators frequently drill horizontal wells in other directions.
Hydraulic Fracture Execution

Montney Shale Gas Wells

Well Direction

Well Performance

SPE Asia Pacific
Hydraulic Fracturing Conference

ARMA 13-289

Fracture Diagnostics and Well Design – C. Ehlig-Economides
Fracture Diagnostics

- Microseismic
- Production Data
Microseismic Survey

Baihly et al., 2007, SPE 110067
Microseismic SRV

Baihly et al., 2007, SPE 110067
Microseismic SRV

Baihly et al., 2007, SPE 110067
Propped SRV

Based on reported 600 ft well spacing

Baihly et al., 2007, SPE 110067
Productive SRV
Continuum Model from Production Data

Volume from PDA

Baihly et al., 2007, SPE 110067
Alternative Productive SRV
Isolated Fracture Model from Production Data

Volume from PDA

Baihly et al., 2007, SPE 110067
Produced Volume from BDF

Continuum

Modified from Baihly et al., 2007, SPE 110067

Isolated Fractures

Modified from Baihly et al., 2007, SPE 110067

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Production Data – Isolated Well

Match with Pressure Dependent Permeability Model

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SPE 166152 Vera
Production Data

Sequential BU Analysis

![Graph showing Sequential BU Analysis](image)

- **BU1**
- **BU2**
- **BU3**

Gas Potential, psF/µp

Elapsed time, hr

10^6, 10^7, 10^8, 10^9, 10^10

0.01, 0.1, 1, 10, 100
Production Data – Pilot Wells
Wells with Different Model Matches (after 6-12 mo on production)

- **Boundary Homo**
- **Boundary Dual**
- **Water Production**
- **Pressure Support**
Production Data

Well 8-2 Model Match with Small Apparent Fracture Length

Model: homogenous formation with boundary
Fracture half length: 87m   Permeability: 800nd
SRV (pore volume): 0.448 × 10^6 m^3
Well 8-3 fracturing interference with Well 8-2

Production Data

Interference while Fracturing

Well 8-3 starts fracturing

Well 8-3 starts production

Critical rate: $12 \times 10^4$ m$^3$
Production Data

Barnett Shale Gas Well Interference Example

Layout of Primary and Infill for Pad A

Production Data from Well 1

SPE 152224
Production Data

High Salinity Flowback Water

Ghanbari et al. (2013)

Zolfaghari et al. (2014)
Production Data – Drawdown Management

Petrohawk Red River Shale Example

Sample Well Comparison
Red River Parish – Rate vs. Cumulative Production

Well on 24/64” Choke
Well on 14/64” Choke

Sample Well Comparison
Red River Parish – Pressure vs. Cumulative Production

Well on 14/64” Choke
Well on 24/64” Choke
Production Data – Drawdown Management

Haynesville Shale Productivity Loss

- Well “S” @ 460 days
- Well “S” @ 295 days

$X_f \cdot k$

Drawdown [%]

SPE 154692
Production Data – Drawdown Management

Choke Effect on Eagle Ford Shale Well

- MSCFD
- BOPD
- FTP (PSI)
- Choke

Choke change due to facility issues
Reduced choke from 16/64" to 12/64"

Prior to choke reduction:
- Rapid decline in FTP
- Liquid loading forecast @ 300 days

After choke reduction:
- Stabilized FTP, extended stable flow
- Increased EUR
Fracture Diagnostics and Well Design

• Production data require time.
• Wells have been drilled and completed without definitive diagnostics.
Play Development

- Factory Drilling
- Recovery Factor
- Enhanced Oil Recovery
Factory Drilling

Stacked Lateral Completions with Pad Drilling

- Horizontal well length
- Spacing between horizontal wells
  - Lateral
  - Vertical
- Spacing between hydraulic fractures
Enhanced Oil Recovery

Bakken Waterflood Pilot

Production in Offset-East Well

SPE-180270

Fracture Diagnostics and Well Design – C. Ehlig-Economides
Enhanced Oil Recovery

Lower Shaunavon shale pilot waterflood

Thomas et al. (2014)
Enhanced Oil Recovery

Modified Zipper Fracture Waterflood Well Pattern

SPE 167056
Enhanced Oil Recovery

- Current pattern wells
  - Preclude displacement processes
  - Huff and puff possible
- Proposed infill injection well pattern using existing well

Vertical lines are hydraulic fracture planes; blue for injection wells, green for production wells

Wells drilled in minimum stress direction

Wells not drilled in minimum stress direction

\( \sigma_{\text{min}} \)
Thank You / Questions