Perforating High Stress Environments: Pushing the Limits, and Having Them Push Back

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The Woodlands

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Typical Field Characteristics

- Retrograde gas condensate
- Initial reservoir pressure ~ 11000-12000 psi
- ~ 14,000 ft TVDSS
- 350-375°F
- Sandstone - Relatively high rock strength
- 20-30 mD Permeability
Proposed Well Configuration

Cased & Perforated Completion

6.5” or 8.5” hole
5” or 5.5” P110 casing
0.75” or 1.75” cement

All reported Perf lengths are Core Penetration lengths
Perforating Requirements

Optimizing flow through perforations:

What perforation length do we need?
Importance of Lp on Productivity

Cased Hole Perforated Completion-gas
Pwf vs. Non-Darcy Rate
Kh=1.5 md; Kv=0.075 md; H=450 ft; Incl=0 deg; Dw=8.50 in; re=1665 ft; B=1.36 rb/stb
What length do we need?

Skin Evaluation: Perforation Geometry Effects

Increasing perf length provides greater skin improvement than increasing shot density

5” Lp: 12 spf/6 spf = 1, 5”/10” = 1.5
Beware!

Core Penetration Length Variability

2-7/8" gun, 4500 psi UCS rock strength, 7150 psi apparent effective stress

Test: Rock Penetration
Prediction: Rock Penetration
Section 1: Concrete Penetration
Perforating Requirements

Optimizing flow through perforations:

What skin damage can we live with?

What are the effects of:

- Overbalanced
- Underbalanced
- Mud? Brine? base oil?
Perforating Damage—Performance

- **Penetration, \( P \)**
- **Reduced permeability crushed zone, \( K_c \)**
- **Penetration, \( P \)**
- **Sand debris**
- **Damaged zone, \( K_d \)**
- **Undamaged formation, \( K \)**

**Poor skin**

**Fair skin**

**Good skin**
Importance of Skin on Productivity

Cased Hole Perforated Completion-gas

Pwf vs. Non-Darcy Rate

Kh=1.5 md; Kv=0.075 md; H=450 ft; Incl=0 deg; Dw=8.50 in; re=1665 ft; B=1.36 rb/stb

Lp = 14.5"
Competing Interests

Completion Group Best Practice
- Perforate Underbalanced in filtered fluids
- Run as large guns as possible – 3.5"

BU Desire
- Perforate overbalanced in mud
- Run 2-7/8” gun

Can the Trains meet?
Test all Scenarios

1. Flow Tests (skin damage):
   - Underbalanced
     - Static underbalance: 1500 psi
     - Dynamic underbalance: 3500 psi
   - Overbalanced
     - 500 psi
   - In mud
   - In base oil
   - 3-1/8” gun

2. Penetration Tests (length)
   - 2-7/8” gun
   - 3-1/8” gun
1. Flow Test

“Section 4”
Crushed Zone Permeability Measurement

- Undamaged Permeability Parallel to Bedding Planes, \( K \)
- Crushed Zone Permeability, \( K_c \)
- Crushed Zone Thickness
- Total Perforation Length

7"
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confinement:</td>
<td>5800 psia (13000 psia)</td>
</tr>
<tr>
<td>Pore Pressure:</td>
<td>4500 psia (11700 psia)</td>
</tr>
<tr>
<td>Wellbore Pressure:</td>
<td>3000-5000 psia</td>
</tr>
<tr>
<td>Temperature:</td>
<td>200°F (350°F)</td>
</tr>
<tr>
<td>Core Fluid:</td>
<td>Mineral Spirits (condensate)</td>
</tr>
</tbody>
</table>
Test Scenarios

Scenario A: Shoot overbalanced with mud, no DUB, kill
Scenario B: Shoot overbalanced with mud, 3500 psi DUB, kill
Scenario C: Shoot 1500 psi underbalanced in base oil, no DUB
Scenario D: Shoot balanced in base oil, 3500 psi DUB

<table>
<thead>
<tr>
<th>Number of Perforation Tests</th>
<th>Type of Fluid In Wellbore</th>
<th>Static Wellbore Pressure Prior to Perforating</th>
<th>Dynamic Underbalance Applied During Test</th>
<th>Post-Perforation Well Kill Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Tests</td>
<td>16.5 ppg OBM</td>
<td>500 psi Overbalance</td>
<td>3500 psi Dynamic Underbalance</td>
<td>Kill with OBM/Hold for 72 hrs</td>
</tr>
<tr>
<td>2 Tests</td>
<td>7.0 ppg Base Oil</td>
<td>50 psi Underbalance</td>
<td>3500 psi Dynamic Underbalance</td>
<td>Kill with Base Oil/No Hold</td>
</tr>
<tr>
<td>1 Test</td>
<td>7.0 ppg Base Oil</td>
<td>1500 psi Underbalance</td>
<td>No Dynamic Underbalance</td>
<td>Kill with Base Oil/No Hold</td>
</tr>
<tr>
<td>1 Test</td>
<td>16.5 ppg OBM</td>
<td>500 psi Overbalance</td>
<td>No Dynamic Underbalance</td>
<td>Kill with OBM/Hold for 72 hrs</td>
</tr>
</tbody>
</table>
Test 6: Mud, 500 psi Static Overbalance, no Dynamic Underbalance, OBM Kill
Test 4: Mud, 500 psi Static Overbalance, 3500 psi Dynamic Underbalance, OBM Kill
Rate vs Pressure Data

Differential Pressure (psi) vs Rate (ml/min)

- Test 1: SOB, DUB, Mud
- Test 4: SOB, DUB, Mud
- Test 2: SUB, DUB, Base Oil
- Test 5: SUB, DUB, Base Oil
- Test 3: SUB, Base Oil
- Test 6: SOB, no DUB, Mud
Core Flow Efficiency Comparisons

<table>
<thead>
<tr>
<th>Test</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50 psi SUB, 3500 psi DUB, Base oil</td>
</tr>
<tr>
<td>2</td>
<td>50 psi SUB, 3500 psi DUB, Mud</td>
</tr>
<tr>
<td>3</td>
<td>1500 psi SUB, No DUB, Base oil</td>
</tr>
<tr>
<td>4</td>
<td>50 psi SUB, 3500 psi DUB, Base oil</td>
</tr>
<tr>
<td>5</td>
<td>50 psi SUB, 3500 psi DUB, Base oil</td>
</tr>
<tr>
<td>6</td>
<td>50 psi OB, No SUB, No DUB, Mud</td>
</tr>
<tr>
<td>7</td>
<td>50 psi SUB, 3500 psi DUB, Base oil</td>
</tr>
<tr>
<td>8</td>
<td>50 psi OB, No SUB, No DUB, Mud</td>
</tr>
</tbody>
</table>

- **3500 psi DUB**
- **1500 psi SUB**
- **No underbalance**
Crushed Zone Permeability

### Kc/K Summary

Crush zone thickness = \( r_{\text{scrubbed}} - r_{\text{jet}}; d_{\text{jet}} = 0.15'' \)

<table>
<thead>
<tr>
<th>Test</th>
<th>Conditions</th>
<th>Kc/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>500 psi SOB, 3500 psi DUB, Mud</td>
<td>0.70</td>
</tr>
<tr>
<td>2</td>
<td>50 psi SUB, 3500 psi DUB, Base oil</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>50 psi SUB, 3500 psi DUB, mud (repeat test 1)</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>1500 psi SUB, no DUB, base oil</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>500 psi SOB, 3500 psi DUB, mud (repeat test 1)</td>
<td>0.50</td>
</tr>
<tr>
<td>5</td>
<td>50 psi SUB, 3500 psi DUB, base oil (test 2 repeat)</td>
<td>0.40</td>
</tr>
<tr>
<td>6</td>
<td>500 psi OB, no SUB, No DUB, mud</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Legend:
- **3500 psi**
- **1500 psi SUB**
- **no underbalance**
Flow Results

- Perforating in mud without underbalance very bad
  no surprise

- Dynamic underbalance most important
  moderate surprise

- Perforating and killing in mud with dynamic underbalance is OK
  Surprise to COP!
2. Core Penetration Tests
What length do we need?

Skin Evaluation: Perforation Geometry Effects

$K_h=10 \text{ md, } K_h/K_v=1, H=500 \text{ ft TVT, } b=H_p/H=1, \text{ Inc}=0 \text{ deg, } K_m/K_r=0.8, \text{ mf}=\text{ nr}=1 \text{ ft, and } 0.354 \text{ ft for all cases}$

Increasing perf length provides greater skin improvement than increasing shot density

$5'' \text{ Lp: 12 spf/6 spf } = 1, 5''/10'' = 1.5$
Perf Length Expectations

A Predicted Formation Penetration

2-7/8\" and 3-1/8\" Guns

Rock UCS = 7000 psi

Net Stress (psi)

Penetration (in.)

Expected apparent stress

\[ \sigma = \sigma_c - \alpha P_p \]
HPHT Test Apparatus

Section 2

Pore Pressure: 11700 psi

Confinement pressure: 13000 psi

Wellbore pressure: 12000 psi

Temperature: 350°F
Perf Length Results

Core Penetration: Predicted vs. Actual
2-7/8" gun, 4500 psi UCS rock strength, 7150 psi apparent net stress

3-1/8" gun Lpt = 7"

Solid: Predicted
White: Total
Shaded: Open
Core Penetration
7/17/2011, After perf test #2

[Image of a core sample with measurements and markings]
Skin Evaluation: Perforation Damage Effects

$K_r = 10 \text{ md}, \frac{K_H}{K_v} = 1, H = 500 \text{ ft TVT}, \theta = H_p / H = 1, \text{Inc} = 0 \text{ deg}, K_m / K_r = 0.8, r_m = r_w = 1 \text{ ft}, SPF = 5, D_p = 0.35'' \text{ and } r_w = 0.354 \text{ ft for all cases}$

- $K_o / K = 0.02$ for Overbalanced Perforating in Mud
- $K_o / K = 0.09$ for DUB + Frac with Mud
- $K_o / K = 0.30$ for Static Underbalance Perforating in Base Oil
- $K_o / K = 0.40$ for Dynamic Underbalance Perforating in Base Oil
- $K_o / K = 0.50$ for Dynamic Underbalance Perforating + Low Pressure Kill
- $K_o / K = 0.70$ for Best Dynamic Underbalance Results Seen in Tests

**Where we are**

- **Real Lp estimate**
- **Target we are shooting for**
Perf Length Test Results

- Charges shot shorter than expected in HPHT Tests
- Charges had larger perforation diameters in HPHT Tests
- 3-1/8” did not shoot significantly deeper than 2-7/8”, at least settling that argument
“And that’s all I got to say about Perforating”