Perforating Design for HTHP Completion: Rigorous Testing to Maximize Well Productivity

SPE 159920
Optimized Cased and Perforated Completion Designs Through The Use of API RP-19B Laboratory Testing to Maximize Well Productivity

Alex Procyk, ConocoPhillips, David Atwood, Schlumberger

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Typical Field Characteristics

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

Cased & Perforated Completion
Why are we looking into the perforating process so closely?…..

……A real world example from a similar field, with similar completion design and similar conditions
**Initial Perf job:**
- Perforated 1000 psi overbalanced in oil based mud
- Poor Well Response from first perf Job Compared to Benchmark well perforated underbalanced

**Reperf Job:**
- 3 years after first perf job
- UB (live well)
- During the perforating operations the shut-in tubing pressure increased from 3,649 to 5,001 psi.
Perforating Design Goal

- Design perfs to achieve desired skin, the first time!
- Get full production across entire perforated zone
Perforating Requirements

Perforation Geometry:
- Density
- Phasing
- Diameter
- Length

Perforation Damage:
- Perforation Fill
- Crushed Zone Permeability
Perforating Requirements

What perforation length do we need?
WHAT PERFORATION LENGTH DO WE NEED?

Evaluation of Perforation Geometry and Damage Effects

$K_h=10\; md,\; K_h/K_v=1,\; H=500\; ft\; TVT,\; b=H_p/H=1,\; Incl=0\; deg,\; K_mf/K_r=0.5,\; r_mf=r_w+1\; ft\; and\; r_w=0.354\; ft\; for\; all\; cases$

Increasing perforation length provides more skin improvement than increasing shot density

$5''\; L_p: 12\; spf/6\; spf = 1,\; 5''/10'' = 1.5$
Core Penetration Length Variability

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

Core Penetration Length (in.)

- Test: Rock Penetration
- Prediction: Rock Penetration
- Section 1: Concrete Penetration

Beware!
Perforating Requirements

What perforation conditions do we need?

How should we perforate?

• Overbalanced
• Underbalanced
• In Mud?
• In Brine?
Perforating Damage—Performance

**Poor skin**
- Reduced permeability crushed zone, $K_c$
- Dmg depth, Damaged zone, $K_d$
- Undamaged formation, $K$
- Sand debris

**Fair skin**
- Dmg depth, Damaged zone, $K_d$
- Undamaged formation, $K$
- Sand debris

**Good skin**
- Dmg depth, Damaged zone, $K_d$
- Undamaged formation, $K$
Perforation Design: Competing Interests

Best Practice for Completions
- Perforate Underbalanced in filtered brine
- Run as large guns as possible – 3.5”

Best Practice for Operations
- Perforate overbalanced in mud
- Run 2-7/8” gun

Can the Two Competing Interests meet?
Test all Scenarios

1. Flow Tests (skin):
   - Underbalanced
     - Static underbalance: 1500 psi
     - Dynamic underbalance: 3500 psi
   - Overbalanced
     - 500 psi
   - In mud (per fluid)
   - 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 Thickness
- Crushed Zone Permeability, Kc
- Total Perforation Length
- 7”
Section 4 test not rated for actual conditions

Confinement: 5800 psia (13000 psia)

Pore Pressure: 4500 psia (11700 psia)

Wellbore Pressure: 3000-5000 psia

Temperature: 200°F (350°F)

Core Fluid: Mineral Spirits (condensate)
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>
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</table>
Test 6: Mud, 500 psi Static Overbalance,  no Dynamic Underbalance, OBM Kill
SECTION 4 TEST PROGRAM RESULTS

Test 4: Mud, 500 psi Static Overbalance, 3500 psi Dynamic Underbalance, OBM Kill
Test 3: Base Oil, 1500 psi Static Underbalance, no Dynamic Underbalance, Base Oil kill
SECTION 4 TEST PROGRAM RESULTS

Test 5: Base Oil, 50 PSI Underbalanced, Dynamic Underbalance, Base Oil kill
SECTION 4 TEST PROGRAM RESULTS

CFE Comparison

- Test 1: 500 psi SOB, 3500 psi DUB, Mud
- Test 2: 50 psi SUB, 3500 psi DUB, Base oil
- Test 3: 1500 psi SUB, no DUB, base oil (test 2 repeat)
- Test 4: 50 psi SOB, 3500 psi DUB, mud (repeat test 1)
- Test 5: 50 psi OB, no SUB, No DUB, mud

Legend:
- Red: No underbalance
- Blue: 1500 psi SUB
- Green: 3500 psi DUB

CFE

0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70
## Kc/K Summary

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

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>Kc/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 6</td>
<td>500 psi OB, no SUB, No DUB, mud</td>
<td>0.00</td>
</tr>
<tr>
<td>Test 3</td>
<td>1500 psi SUB, no DUB, base oil</td>
<td>0.20</td>
</tr>
<tr>
<td>Test 5</td>
<td>50 psi SUB, 3500 psi DUB, base oil (test 2 repeat)</td>
<td>0.30</td>
</tr>
<tr>
<td>Test 4</td>
<td>500 psi SOB, 3500 psi DUB, mud (repeat test 1)</td>
<td>0.50</td>
</tr>
<tr>
<td>Test 2</td>
<td>50 psi SUB, 3500 psi DUB, Base oil</td>
<td>0.40</td>
</tr>
<tr>
<td>Test 1</td>
<td>500 psi SOB, 3500 psi DUB, Mud</td>
<td>0.70</td>
</tr>
</tbody>
</table>

- Red: no underbalance
- Blue: 1500 psi SUB
- Green: 3500 psi DUB

**Notes:**
- Crush zone thickness is calculated as the difference between the scrubbed radius \( r_{\text{scrubbed}} \) and the jetted radius \( r_{\text{jet}} \).
- The jet thickness \( d_{\text{jet}} \) is 0.15".
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 us!

Round 1 to Operations
2. Core Penetration Tests
Confirm Actual Penetration with Testing

- Perform tests at realistic conditions
- Compare against predictions
- Select deepest penetrating charge
Pore Pressure: 11700 psi

Confinement pressure: 13000 psi

Wellbore pressure: 12000 psi

Temperature: 350° F

Net stress: 1300 psi

Apparent net stress: ~9000 psi
Perf Length – High Expectations

Predicted Formation Penetration
2-7/8” and 3-1/8” Guns

Rock UCS = 7000 psi

Expected apparent net stress

Apparent Net Stress = \( \sigma_c - \alpha P_p \)
Perforation Created By 23 g HNS Charge At HPHT Conditions
TEST 6: Mud, 500 psi Static Overbalance, no Dynamic Underbalance, OBM Kill

Apparent net stress = 4400 psi
Perforation Created By 19 g HNS Charge At HPHT Conditions
Post Shot - Perf Test Photo's

- Test Core 2B = 6.75 inch
- Test Core 3T = 5.2 inch
- Test Core 4B = 6.38 inch
- Test Core 5T = 6.56 inch
- Test Core 6B = 4.6 inch
- Test Core 7T = 5.81 inch
Core Penetration: Predicted vs. Actual

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

Company

A

A

B

B

C

C

Core Penetration (in.)

- Solid: Predicted
- Shaded: Actual
Skin Evaluation Incorporating Section-2 and Section-4 Test Results

- Initial Screening Case: SPF=6, Dp=0.25", Phasing=60 deg and Kc/K=0.4 for UB Perforating with Kmf=0.50
- Modified Screening Case: SPF=6, Dp=0.25", Phasing=60 deg and Kc/K=0.4 for UB Best Practices with Kmf=0.75
- Design Case with Section-2 and Section-4 Results: SPF=6, Dp=0.85", Phasing=60 deg and Kc/K=0.4 for DUB with Kmf=0.75
- Best Laboratory Test Case: SPF=6, Dp=0.85", Phasing=60 deg and Kc/K=0.7 for DUB with Kmf=0.75

Initial Skin = +1.9 with Lp=12" and Dp=0.25"
Final Skin = +1.0 with Lp=6.75" and Dp=0.85"

Expected skin @ 12" penetration, 0.25" diameter

Perf Geometry much different than expected, but yields roughly the same skin due to huge diameter (= flow area)
Some things to think about

- Perforation characteristics: “Carrot Shape” (Short & Dumpy) –
  - Is this an HNS artifact?
  - What effect does the saturating fluid play?
  - Is the carrot shape indicative to the lower rock strength only. What happens in higher rock strength?

Is Short and Fat still acceptable with a low perm mud filtrate invaded zone?
Pushing Testing Further

• How do we encourage the industry to cut larger ID core in actual HPHT rock to advance testing further..........(UK & Norway) are the main user of this HPHT perf technology..

• How do we improve analogue rock selection, is synthetic rock a option? where are we with this technology?

• Testing in Brine. Tests resulted in vastly improved penetration. "Reality" future testing requires accurate saturation of the core to demonstrate if improvement associated with rock saturation.
Gun design for 2 7/8” HPHT Guns (Central Grabben Type Formation use 2 7/8” due to 5” Tubing /Liners ) has **probably** reached its limit. There has to be quantum leap in technology to make any difference and this does not seem to be available today.

**DUB:** Cannot actually measure the event in real time due to limitations of gauge technology (temp) both in the lab and in the field.
Acknowledgements / Thank You / Questions

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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
Perf Length Test Results

- Charges shot shorter than expected in HPHT Tests
- Charges had larger perforation diameters in HPHT Tests
- Perf Geometry depended upon saturating fluid (OMS vs brine)
- 3-1/8” did not shoot significantly deeper than 2-7/8”, at least settling that argument
- DUB and perf geometry should be sufficient for our skin goals (stay tuned)
Length vs Total Skin
Well 3

Initial Perf job:
- Perforated overbalanced in oil based mud
- Poor Well Response from first perf Job Compared to Benchmark well perforated underbalanced

Reperf Job:
- 3 years after first perf job
- UB (live well)
Well 4 Backpressure Plot

- 2002-2005 Production Data
- 2006-2007 Production Data
- 2008-2009 Production Data
- 2010-2011 Production Data
- Data in IPR Graph
- Production model

Original Completion

After Reperf

P*2 - Pwf*2 (psia^2)

Rate (mmscf/d)
Well 3 Backpressure Plot

- Original Completion
- After Reperf

Rate (mmcf/d)

$P^*^2 - P_{wf}^2$ (psia^2)

- 2002-2004
- 2005-2006
- 2007-2009
- 2010

Data in PR Graph

Production Model, $S = 12.5$