Extreme Hard Rock Perforating: Penetration Challenges and Limits

Hanaey Ibrahim
Mohd Shafie Jumaat
Brenden Grove
David Atwood

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Introduction

- Khulud field in Oman has deep vertical 4.5’ monobore wells drilled for tight gas. Multi-stage hydraulic fracturing performed.
- Rock strength = ~20,000 psi to ~55,000 psi
- Porosity + ~5%, $K = ~1$ mD
- Formation breakdown has been a problem.
- SPE-152458 for Khulud: Explosive perforating and abrasive jetting perforating used. Lower breakdown pressure achieved with abrasive jetting by average 1180psi.
- Need to understand explosive perforating performance in very strong rock.
Fig. 25: Khulud West preferred structural model and fault-seal concept
Production Casing 9-7/8" 68.8# SM 955 VAM TOP x 9-5/8" 53.5# P-110 VAM TOP SE
Burr Rating 2.02 psi
Collapse Rating 1695 psi
Diff: 0.37", nom: ID 8.47"
Top of 7" Liner 3,991 m

9-7/8" Casing Shoe @ Base of Ghurf 4,104 m

Drilling Liner 7" 35#/SM 955 VAM TOP
Burr Rating 10.53 psi
Collapse Rating 1898 psi
Diff: 0.52", nom: ID 6.50"
Top of 4-1/2" Liner 4,600 m

Production Liner 4-1/2" 17#/SM 20CR-125 VAM TOP
Burr Rating 6.34 psi
Collapse Rating 9,342 psi
Diff: 0.31", nom: ID 3.74"
A MIN/NMHR 16.1 kPa/lm
Wellbores perforating guns: Wells
TD 5-7/8" Hole 5,328 m

Production Tubing 4-1/2" 17#/SM 130x110 VAM TOP
Burr Rating 6.02 psi
Collapse Rating 1,069 psi
Diff: 0.16", nom: ID 1.74"
Liner Top Rucker ZIP

Seal Bore Locates 4-1/2" 17#/Encorel 718 VAM TOP 39 ft (min. ID 3.74", 18 ft up/12 ft down n/a)
Polished Bore Rework 30 ft (seal bore ID: 5.000")
Liner Top Rucker 4-1/2" ZIP

177.6 °C
2-7/8" HMR
2.616 kPa/m

Total 108.6 °C
Khulud formations in Oman with UCS in the range 20,000 to 50,000psi. What is the performance?
Penetration Lower Limit

- To confirm the penetration lower limit (DoPmin) proposed in SPE-151846
- Khulud cores UCS range
5 x 1m cores from the following wells were sent to laboratory for perforating shot tests:

<table>
<thead>
<tr>
<th>Khulud-5</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Box #</td>
<td>Top depth</td>
<td>Bottom depth</td>
<td>Core #</td>
</tr>
<tr>
<td>22</td>
<td>4791.16</td>
<td>4792.16</td>
<td>2</td>
</tr>
<tr>
<td>35</td>
<td>4831.7</td>
<td>4832.7</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>4886.2</td>
<td>4887.2</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Khulud-6</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Box #</td>
<td>Top depth</td>
<td>Bottom depth</td>
<td>Core #</td>
</tr>
<tr>
<td>17</td>
<td>5083.3</td>
<td>5084.3</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>5100</td>
<td>5101</td>
<td>3</td>
</tr>
</tbody>
</table>
Test Procedure

- UCS Scratch Test
- Cut cores into 8” samples based on measured UCS
- Select the samples to use for the proposed explosive charge
- Shoot the samples in API-19B Section 2 Setup
- Retrieve the shot core, cut and measure the penetration
UCS Scratch Test Result (Core 5-2)
UCS Scratch Test Result (Core 5-3)
UCS Scratch Test Result (Core 5-5)
UCS Scratch Test Result (Core 6-2)
UCS Scratch Test Result (Core 6-3)
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Taken From Core #</th>
<th>Dry Bulk Density</th>
<th>Effective Compressive Strength</th>
<th>Quasi-Static Young’s Modulus</th>
<th>Quasi-Static Poisson’s Ratio</th>
<th>Approximate Scratch UCS Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-P-1</td>
<td>KHDL 5-5</td>
<td>2.660</td>
<td>31520</td>
<td>5817500</td>
<td>0.26</td>
<td>30 ksi to 34 ksi</td>
</tr>
<tr>
<td>P-P-2</td>
<td>KHDL 5-5</td>
<td>2.654</td>
<td>28920</td>
<td>5701700</td>
<td>0.35</td>
<td>30 ksi to 34 ksi</td>
</tr>
<tr>
<td>P-PL-1</td>
<td>KHDL 5-5</td>
<td>2.653</td>
<td>24110</td>
<td>5761600</td>
<td>0.14</td>
<td>30 ksi to 34 ksi</td>
</tr>
<tr>
<td>P-PL-2</td>
<td>KHDL 5-5</td>
<td>2.660</td>
<td>26505</td>
<td>5096600</td>
<td>0.16</td>
<td>30 ksi to 34 ksi</td>
</tr>
<tr>
<td>S-P-1</td>
<td>KHDL 5-2</td>
<td>2.591</td>
<td>32345</td>
<td>5624100</td>
<td>0.22</td>
<td>30 ksi to 40 ksi</td>
</tr>
<tr>
<td>S-P-2</td>
<td>KHDL 5-2</td>
<td>2.585</td>
<td>29450</td>
<td>5925000</td>
<td>0.25</td>
<td>30 ksi to 40 ksi</td>
</tr>
<tr>
<td>S-PL-1</td>
<td>KHDL 5-2</td>
<td>2.551</td>
<td>27880</td>
<td>6033100</td>
<td>0.31</td>
<td>30 ksi to 40 ksi</td>
</tr>
<tr>
<td>S-PL-2</td>
<td>KHDL 5-2</td>
<td>2.593</td>
<td>31325</td>
<td>5488300</td>
<td>0.25</td>
<td>30 ksi to 40 ksi</td>
</tr>
<tr>
<td>U-P-1</td>
<td>KHDL 6-2</td>
<td>2.594</td>
<td>22275</td>
<td>3504500</td>
<td>0.21</td>
<td>25 ksi to 31 ksi</td>
</tr>
<tr>
<td>U-P-2</td>
<td>KHDL 6-2</td>
<td>2.599</td>
<td>29380</td>
<td>5088600</td>
<td>0.09</td>
<td>25 ksi to 30 ksi</td>
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<tr>
<td>U-PL-1</td>
<td>KHDL 6-2</td>
<td>2.594</td>
<td>24805</td>
<td>4816800</td>
<td>0.30</td>
<td>25 ksi to 30 ksi</td>
</tr>
<tr>
<td>U-PL-2</td>
<td>KHDL 6-2</td>
<td>2.599</td>
<td>37510</td>
<td>5999000</td>
<td>0.20</td>
<td>35 ksi to 42 ksi</td>
</tr>
<tr>
<td>V-P-1</td>
<td>KHDL 6-3</td>
<td>2.610</td>
<td>32535</td>
<td>5617300</td>
<td>0.21</td>
<td>28 ksi</td>
</tr>
<tr>
<td>V-PL-1</td>
<td>KHDL 6-3</td>
<td>2.594</td>
<td>32330</td>
<td>5249600</td>
<td>0.21</td>
<td>25 ksi to 29 ksi</td>
</tr>
<tr>
<td>Z-P-1</td>
<td>KHDL 5-3</td>
<td>2.614</td>
<td>(Note 1)</td>
<td>(Note 1)</td>
<td>(Note 1)</td>
<td>53 ksi</td>
</tr>
<tr>
<td>Z-PL-1</td>
<td>KHDL 5-3</td>
<td>2.620</td>
<td>52360</td>
<td>8536400</td>
<td>0.13</td>
<td></td>
</tr>
</tbody>
</table>

(Note 1) This sample "failed" the UCS test apparatus being used, when the sample exploded at a load that would indicate a UCS in excess of 60ksi.
F_{bi} from UCS and Stress (SPE-151846)

- UCS range from the cores for the tests: 20,000 to 50,000psi
Test Setup

- API-19B Section 2 Test
- Apply 10,000 radial and confinement stress
- 0 pore pressure with residual pore fluid
- Standard end-cap with cement sheath
- Standard gun carrier with scallop and 0.5” water standoff
The Tests

- 2-7/8” guns Charge-A
The Tests

- 2-7/8” gun charge-B
The Tests

- 3.5” gun Charge-C
The Tests

- 3-3/8” gun charge-D
The Tests

- 2’’ gun charge-E
### Test Results

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Test Sample ID</th>
<th>Source</th>
<th>Over Perforated</th>
<th>Scratch UCS Charge</th>
<th>Shaped Charge</th>
<th>Water</th>
<th>Rock</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>One</td>
<td>KLD5-2</td>
<td>22.6 ksi</td>
<td>2-7/8&quot; Charge-A</td>
<td>0.5</td>
<td>4.75</td>
<td>T to B</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Nine</td>
<td>KLD5-5</td>
<td>42.7 ksi</td>
<td>2-7/8&quot; Charge-A</td>
<td>0.5</td>
<td>4.00</td>
<td>T to B</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Six</td>
<td>KLD5-3</td>
<td>31.4 ksi</td>
<td>2-7/8&quot; Charge-A</td>
<td>0.5</td>
<td>4.00</td>
<td>B to T</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Three</td>
<td>KLD5-2</td>
<td>22.5 ksi</td>
<td>2-7/8&quot; Charge-B</td>
<td>0.5</td>
<td>3.25</td>
<td>T to B</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Ten</td>
<td>KLD5-5</td>
<td>38.7 ksi</td>
<td>2-7/8&quot; Charge-B</td>
<td>0.5</td>
<td>2.75</td>
<td>T to B</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Seven</td>
<td>KLD5-3</td>
<td>28.7 ksi</td>
<td>2-7/8&quot; Charge-B</td>
<td>0.5</td>
<td>2.75</td>
<td>T to B</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Eighteen</td>
<td>KLD6-2</td>
<td>29.7 ksi</td>
<td>3.5&quot; Charge-C</td>
<td>0.5</td>
<td>4.62</td>
<td>T to B</td>
<td></td>
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<tr>
<td>8</td>
<td>Five</td>
<td>KLD5-3</td>
<td>27.7 ksi</td>
<td>3.5&quot; Charge-C</td>
<td>0.5</td>
<td>6.00</td>
<td>T to B</td>
<td></td>
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<tr>
<td>9</td>
<td>Seventeen</td>
<td>KLD6-2</td>
<td>41.0 ksi</td>
<td>3.5&quot; Charge-C</td>
<td>0.5</td>
<td>5.12</td>
<td>T to B</td>
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</tr>
<tr>
<td>10</td>
<td>Seven (back end)</td>
<td>KLD5-5</td>
<td>28.6 ksi</td>
<td>2&quot; Charge-E</td>
<td>0.5</td>
<td>2.75</td>
<td>T to B; using remains of core from Test 6</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Ten (back end)</td>
<td>KLD5-3</td>
<td>32.8 ksi</td>
<td>2&quot; Charge-E</td>
<td>0.5</td>
<td>3.00</td>
<td>B to T; using remains of core from Test 5</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Thirteen</td>
<td>KLD6-3</td>
<td>22.0 ksi</td>
<td>3-3/8&quot; Charge-D</td>
<td>0.5</td>
<td>6.00</td>
<td>B to T</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Fourteen</td>
<td>KLD6-3</td>
<td>25.2 ksi</td>
<td>3-3/8&quot; Charge-D</td>
<td>0.5</td>
<td>5.88</td>
<td>B to T</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Four</td>
<td>KLD5-2</td>
<td>27.6 ksi</td>
<td>2&quot; Charge-E</td>
<td>0.5</td>
<td>3.50</td>
<td>T to B</td>
<td></td>
</tr>
</tbody>
</table>
Observation-1

- The penetration does not diminish towards zero, confirming the asymptote (DoPmin)
Observation-2

- Crossover of Charge-A vs Charge-B based on **extrapolation** of experimental data at UCS<20,000 psi does not occur.
**Observation-3**

- 3-3/8” gun Charge-D matches the performance of 3.5” gun Charge-C at high UCS.
Observation-4

- 2" gun Charge-E matches the performance of 2-7/8" gun Charge-B at high UCS.
Way Forward

- Charge-A has deeper penetration than Charge-B in the test:
  - For hydraulic fracturing in Khulud field: trial will be done in 3 wells to see if that is beneficial.

- Based on these characterization, these 5 charges can be selected for Khulud (completion size) and other fields depending on:
  - Rock strength
  - Application (normal unstimulated completion or pre-stimulation perforating)

- PDO Charge A trials:
  - Two wells have been perforated using Charge A and production logging interpretation is on going for evaluation.
  - Third well will be perforated this week using charges A and B followed by acid stimulation and PLT to measure charge A performance.