Laboratory Observations on Dynamic Effective Stress Associated with Dynamic Underbalance on Low and Moderate Strength Formations
Agenda

- Define Dynamic Effective Stress (DES) and note its importance
- Brief description of two test cases
- Review CT scan images for each test case and discuss the results
- Review fast gauge response charts from second test case
- Conclusions / Comments
What is DES and its importance?

- It is the transient stress around the perforation tunnel at perforating.
- It reaches a maximum immediately after charge detonation.
- Duration is typically between 0.25 and 1.50 seconds.
- It is a consequence of dynamic underbalance.
- It is significant for optimizing gravel pack and injection operations.
1. **Debris filled tunnel but with competent walls** – more common with big hole (BH) vs. deep penetrating (DP) charges

2. **Partial tunnel collapse** – usually when DP charges are used

3. **Failure with no tunnel walls** – occurs when a wellbore underbalance is combined with significant effective stress on a low UCS formation

SPE distinguished lecturer Dr. Ian Walton: “Shear failure occurs when effective stress exceeds 3 to 5 times the UCS of the formation depending on tunnel diameter”. SPE-90123-MS (2004) “A rock with strong cementation is more likely to support a competent cavity than a rock that is weakly consolidated. However, strength alone does not tell the whole story of how the rock will behave after being perforated. The capability of the virgin rock to support a perforation cavity is dependent on the compressive load, the UCS and on the diameter of the initial cavity. Based on Thick-wall cylinder tests, a model of tunnel stability was developed at SLB Cambridge Research Center. The model shows that shear failure occurs when the effective stress around the tunnel exceeds a certain multiple of the UCS. The multiple depends on the diameter of the tunnel and is most commonly in the range of 3 to 5 with narrow cavities being stronger than wider cavities.”

DES: mechanism that determines the condition of the perforation tunnel
Determine DES

Fast Gauge Chart of Wellbore Pressure during Perforating

Dynamic Effective Stress (DES) = (Overburden Stress - Formation Pressure) + Dynamic UB

Elapsed Time, seconds

Pressure, psi

Minimum Wellbore Pressure (Dynamic UB), point of max. Dynamic Effective Stress (DES)

Dynamic Underbalance (Dynamic UB): Formation Pressure - min. Wellbore Pressure

Peak DES

Overburden Stress

Wellbore Pressure

Formation Pressure
API RP 19B Section 4 Testing Apparatus Setup

- Overburden Stress to 25,000 psi
- Formation Pressure to 20,000 psi
- Temperature to 400°F
- Core Dia. to 12 in.
- Core Len. to 48 in.
## Test Setup and Conditions for Set 1 at Low Pressure

<table>
<thead>
<tr>
<th>Detail</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overburden pressure / Effective Stress (psi)</td>
<td>7,000 / (3,400 - 3,756)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation - estimated UCS (psi)</td>
<td>Castlegate sandstone (OMS-saturated) 2,200</td>
<td>Saltwash Red sandstone (dry) 890</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wellbore pressure (psi)</td>
<td>3,500</td>
<td>3,300</td>
<td>3,600</td>
<td>3,600</td>
</tr>
<tr>
<td>Formation (Pore) pressure (psi)</td>
<td>3,244</td>
<td>3,291</td>
<td>3,600</td>
<td>3,310</td>
</tr>
<tr>
<td>Per-charge free gun volume (cc)</td>
<td>240</td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Wellbore fluid</td>
<td>9-lbm/gal Brine</td>
<td>Odorless mineral spirits (OMS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>26.0</td>
<td>20.0 to 23.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeability (md)</td>
<td>1000</td>
<td>2000</td>
<td>1850</td>
<td></td>
</tr>
<tr>
<td>Static wellbore Pre-perf. condition (psi)</td>
<td>+256</td>
<td>Balanced</td>
<td>Balanced</td>
<td>+290</td>
</tr>
<tr>
<td>Charge</td>
<td>4 5/8-in. Steel-cased big hole HMX</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid gap (in.)</td>
<td>1.09</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Casing thickness (in.)</td>
<td>0.408 (4140 Steel)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Cement thickness (in.)</td>
<td>0.75 (Class A Portland)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Core diameter/length (in.)</td>
<td>7.0 (nominal) / 24.0 (nominal)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pore fluid</td>
<td>OMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (°F/°C)</td>
<td>77 / 25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Test 1

Wellbore: 3,500 psi, Pore Pressure: 3,244 psi, Static UB: 256 psi, Dynamic UB: 21 psi,

DES = 7,000 (Overburden) - 3,244 psi + 21 psi = 3,777 psi

Post–Flow CT image shows debris is removed and perforation tunnel is competent

Safe DES/UCS ratio is 3-5

With UCS of 2,200 psi the DES/UCS ratio = 1.7
Test 2

Wellbore: 3,300 psi, Pore Pressure: 3,291 psi, Static UB: 9 psi, Dynamic UB: 325 psi, 
DES = 7,000 (Overburden) - 3,291 psi + 325 psi = 4,034 psi

Safe DES/UCS ratio is 3-5

With UCS of 2,200 psi the 
DES/UCS ratio = 1.83
Test 3 and Test 4

Wellbore: 3,557 psi, Pore Pressure: 3,267 psi  
Dynamic UB: 10 psi  
DES = 7,000 (Overburden) - 3,267 psi + 10 psi = 3,743 psi

With UCS of 890 psi the DES/UCS ratio = 4.2

Safe DES/UCS ratio is 3-5

Wellbore: 3,293 psi, Pore Pressure: 3,326 psi  
Dynamic UB: 284 psi  
DES = 7,000 (Overburden) - 3,326 psi + 284 psi = 3,958 psi

With UCS of 890 psi the DES/UCS ratio = 4.4
### Test Setup and Conditions for Set 2 at High Pressure

<table>
<thead>
<tr>
<th>Detail</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target DUB / DES (psi)</td>
<td>6,000 / 16,000</td>
<td>10,500 / 20,400</td>
<td>8,000 / 18,000</td>
</tr>
<tr>
<td>Overburden pressure / Effective stress (psi)</td>
<td>26,000 / 10,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation - estimated UCS (psi)</td>
<td>Kansas sandstone (3,600 TerraTek 2014) (OMS-saturated)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation (Pore) pressure (psi)</td>
<td>16,000</td>
<td>16,000</td>
<td>16,000</td>
</tr>
<tr>
<td>Wellbore pressure (psi)</td>
<td>16,200</td>
<td>16,200</td>
<td>16,200</td>
</tr>
<tr>
<td>Wellbore fluid</td>
<td>OMS</td>
<td>OMS</td>
<td>OMS</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>20.1</td>
<td>24.6</td>
<td>19.9</td>
</tr>
<tr>
<td>Permeability (md)</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Static condition (psi)</td>
<td>+200</td>
<td>+200</td>
<td>+200</td>
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<tr>
<td>Charge (in.)</td>
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<tr>
<td>Fluid gap (in.)</td>
<td>1.480</td>
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<tr>
<td>Casing thickness (in.)</td>
<td>0.650 (17-4 Stainless Steel)</td>
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</tr>
<tr>
<td>Cement thickness (in.)</td>
<td>1.19 (Class A Portland)</td>
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<td></td>
</tr>
<tr>
<td>Core diameter/length (in.)</td>
<td>9.00 / 18.00 (nominal)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pore fluid</td>
<td>OMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (°F/°C)</td>
<td>77 / 25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Wellbore: 16,200 psi, Pore Pressure: 16,000 psi Dynamic UB: 6,506 psi
DES = 26,000 (Overburden) - 16,000 psi + 6,506 psi = 16,506 psi

Safe DES/UCS ratio is 3-5

With UCS of 3,600 psi the DES/UCS ratio = 4.6
DES effect seen by hemispherical fracture banding contained within the BH impact zone.

Wellbore: 16,200 psi, Pore Pressure: 16,000 psi  
Dynamic UB: 14,100 psi  
DES = 26,000 (Overburden) - 16,000 psi + 14,100 psi = 24,100 psi

Safe DES/UCS ratio is 3-5

With UCS of 3,600 psi the DES/UCS ratio = 6.7
Wellbore: 16,200 psi, Pore Pressure: 16,000 psi  
Dynamic UB: 7,553 psi

DES = 26,000 (Overburden) - 16,000 psi + 7,553 psi = 17,553 psi

Safe DES/UCS ratio is 3-5

With UCS of 3,600 psi the DES/UCS ratio = 4.9
Fast Gauge Data For Test 1

Test No. 1

Fast Gauge Wellbore Pressure Response

- Static OB (+)/UB (-) = +200 psi
- Peak DUB = -6,506 psi
- $p^i_p = 16,000$ psi
- $p^{max}_{wb} = 9,494$ psi
- $p^{i}_{wb} = 16,200$ psi

Elapsed Time, seconds
Fast Gauge Data For Test 2

Test No. 2

Fast Gauge Wellbore Pressure Response

Static OB(+) / UB(-) = +200 psi

- $p_{wb}^{0} = 16,200$ psi
- $p_{p}^{f} = 16,000$ psi

Peak DUH = -14,108 psi

$P_{wb}^{min} = 1,892$ psi

Elapsed Time, seconds
Fast Gauge Data For Test 3

Test No. 3

Fast Gauge Wellbore Pressure Response

Static OB(+)/UB(-) = +200 psi

$p_{wfr}^i = 16,200$ psi

$p_{pi}^f = 16,000$ psi

Peak DUB = -7,553 psi

$p_{wfr}^{min} = 8,447$ psi

Elapsed Time, seconds
Conclusions/Comments

- Dynamic effective stress is the by-product of the dynamic underbalance and should be considered in dynamic underbalance design.

- It is the determinant for perforation tunnel collapse because that is the stress that can lead to failure, tensile and shear.

- Lower viscosity is favorable for avoiding collapse in terms of reducing the peak of DES and time exposure to high DES.

- Based on CT images from a similar HP testing project, DES effects on limestones should be considered separately, mainly due to narrower tunnels.

- DES can be modeled in shock hydro simulations with a modified rate-dependent strength model, a future plan.
Acknowledgements

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QUESTIONS? THANK YOU

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