Variable Rate Fracturing – A Step Change in Hydraulic Fracturing

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Problem: Low perf efficiency hinders well performance

1. Perforation breakdown efficiency is low, <60%
   • Centralization: Cement thickness
   • Variations in rock composition
   • Variations in stresses

2. Few tools effectively address it
   • Ball sealing: low controllability, increased time, challenging in horizontals
   • Engineered perforations: concentrating on good pay doesn’t address perforation breakdown
   • Specialized perf guns: perf pattern and gun placement don’t guarantee perf opening

Variations in perforation breakdown pressures can exceed 1000’s psi*

*Perforation breakdown pressures at various horizontal stress anisotropies and pore pressures.
Breakthrough – Patented* Variable Rate Fracturing (VRF) Technology
A step change (literally) for improved perforation efficiency

- VRF uses engineered rate changes throughout fracturing treatment to:
  - Induce pressure pulses which travel up and down the wellbore
  - Pressure pulses combined with original limited entry fracturing pressure can be much higher, thus exceeding breakdown pressure of non-open perforations
- Enhances both perforation opening and fracture complexity (branching)

(*) US Patents 9,581,004 & 9,879,514, 9,982,523 + others pending
Marcellus field test – VRF in odd frac stages

- Very rapid engineered change of pump rate in pad
- No additional equipment or materials needed
- 19% higher average production
Permian field test – VRF on complete well in Wolfcamp

Production comparison after 14 months

<table>
<thead>
<tr>
<th>Well</th>
<th>Prod. Increase</th>
<th>Proppant Loading (klbs/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset 1</td>
<td>11%</td>
<td>1.8</td>
</tr>
<tr>
<td>VRF Well</td>
<td>-</td>
<td>1.1</td>
</tr>
<tr>
<td>Offset 2</td>
<td>26%</td>
<td>1.1</td>
</tr>
<tr>
<td>Offset 3</td>
<td>23%</td>
<td>1.1</td>
</tr>
<tr>
<td>Offset 4</td>
<td>14%</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Workflow and toolbox enables design and optimization of VRF treatments—Example of workflow

- Using control data design VRF and predict improvement
- Monitor in real time and optimize
- Establish created fracture volume and verify actual production performance with predicted
Design VRF treatment

• For a desired pressure pulse magnitude determine magnitude and time interval for the initial rate drop \( \Delta Q_1 \) & \( \Delta T_1 \)
• & Determine the duration of the rate pulse \( \Delta T_2 \).

\[ Q_{\text{2}} = Q_{\text{1}} - \Delta Q_{\text{1}} \]
Optimize in real time

- Novel perforation efficiency analysis using classical and proprietary techniques enables:
  - Determination of initially open perforations (baseline stepdown)
  - Effectiveness of each engineered rate pulse
  - Progression of # of open-perforations during treatment (bound solution, lower uncertainty)
  - Optimization of subsequent rate pulses
Calculate fracture volume and production

• Using pressure transient data we calculate fracture volume

• Compare fracture volume with production

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Summary

• Low perforation efficiency is the main cause for poor horizontal shale well performance
• VRF significantly increases perforation efficiency
• Improved perforation efficiency leads to improved stimulation efficiency by creating more fractures
• Field tests have shown consistent improvement in opening of additional perforations in many wells and shale formations
• Significant uplift in average well production, as high as 30% noted
• Proprietary workflow and toolbox enables design and optimization of VRF treatments
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