1. Design and Limited Entry
2. Diagnostics
3. Perforation Technology
4. Case Histories
5. Fluid and Proppant Transport
“All I need is a hole in the pipe”
“What perforation hole size am I getting”
“Can I obtain a consistent perf diameter without centralizing the gun system”
“I don’t need a deep penetrating perforation charge, the frac doesn’t propagate out the end of (conventional) perf tunnels anyway”
“We routinely pump frac stages through toe sleeves”
“I want fewer perforations per cluster”
“How can I increase my cluster efficiency”
“What perforation pressure drop do I need to achieve limited entry”
Use Pump Rate to maintain Pressure Drop to simultaneously treat multiple clusters in a frac stage

**18 to 24 months ago**
- 6 to 8 clusters
- 4 to 6 perfs per cluster
- ~1,200 psi differential pressure
- 100 BPM / 8 clusters = 12.5 BPM/cluster

**Today**
- 12 to 30 clusters
- 1 to 4 perfs per cluster
- ~2,400 psi differential pressure
- 100 BPM / 20 clusters = 5 BPM/cluster

Same hydraulic fracture geometry?
Pressure Drop is a function of Injection Rate per Perforation and the Perforation Hole Size raised to the 4\(^{th}\) Power

\[
\Delta P_{\text{perf}} = \frac{0.237 \rho Q^2}{D^4 C^2}
\]

Where: \(\Delta P_{\text{perf}}\) = Total perforation friction, psi
\(Q\) = Flow rate through each perforation, BPM/perf
\(D\) = Diameter of perforation, in.
\(C\) = Perforation discharge coefficient (0.9 for round perforation)
\(\rho\) = Fluid density, lbs./gal
10 clusters, 3 perfs per cluster

<table>
<thead>
<tr>
<th></th>
<th>EEH 35 Initial Breakdown</th>
<th>EEH 35 Proppant Erosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole Size</td>
<td>0.35 inch dia.</td>
<td>0.37 inch dia.</td>
</tr>
<tr>
<td><strong>ESTIMATED</strong> Cv Factor</td>
<td>0.70</td>
<td>0.90</td>
</tr>
<tr>
<td>Injection Rate</td>
<td>80 BPM</td>
<td>80 BPM</td>
</tr>
<tr>
<td>Number of Perfs</td>
<td>30 perfs</td>
<td>30 perfs</td>
</tr>
<tr>
<td>Rate per Perf @ 100% Efficiency</td>
<td>2.67 BPM/Perf</td>
<td>2.67 BPM/Perf</td>
</tr>
<tr>
<td>Perf Friction @ 100% Efficiency</td>
<td>1,925 psi</td>
<td>933 psi</td>
</tr>
<tr>
<td>Perf Friction @ 95% Efficiency</td>
<td>2,133 psi</td>
<td>1,033 psi</td>
</tr>
<tr>
<td>Perf Friction @ 90% Efficiency</td>
<td>2,377 psi</td>
<td>1,151 psi</td>
</tr>
<tr>
<td>Perf Friction @ 85% Efficiency</td>
<td>2,665 psi</td>
<td>1,291 psi</td>
</tr>
<tr>
<td>Perf Friction @ 80% Efficiency</td>
<td>3,008 psi</td>
<td>1,457 psi</td>
</tr>
<tr>
<td>Perf Friction @ 75% Efficiency</td>
<td>3,423 psi</td>
<td>1,658 psi</td>
</tr>
<tr>
<td>Perf Friction @ 70% Efficiency</td>
<td>3,929 psi</td>
<td>1,903 psi</td>
</tr>
</tbody>
</table>
### Equal Entry Hole - Design 2

**12 clusters, 2 perfs per cluster**

<table>
<thead>
<tr>
<th></th>
<th>EEH 40 Initial Breakdown</th>
<th>EEH 40 Proppant Erosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole Size</td>
<td>0.4 inch dia.</td>
<td>0.42 inch dia.</td>
</tr>
<tr>
<td><strong>ESTIMATED</strong> Cv Factor</td>
<td>0.70</td>
<td>0.90</td>
</tr>
<tr>
<td>Injection Rate</td>
<td>90 BPM</td>
<td>90 BPM</td>
</tr>
<tr>
<td>Number of Perfs</td>
<td>24 perfs</td>
<td>24 perfs</td>
</tr>
<tr>
<td>Rate per Perf @ 100% Efficiency</td>
<td>3.75 BPM/Perf</td>
<td>3.75 BPM/Perf</td>
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<tr>
<td>Perf Friction @ 100% Efficiency</td>
<td>2,232 psi</td>
<td>1,111 psi</td>
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<tr>
<td>Perf Friction @ 95% Efficiency</td>
<td>2,473 psi</td>
<td>1,231 psi</td>
</tr>
<tr>
<td>Perf Friction @ 90% Efficiency</td>
<td>2,755 psi</td>
<td>1,371 psi</td>
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<td>Perf Friction @ 85% Efficiency</td>
<td>3,089 psi</td>
<td>1,537 psi</td>
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<td>Perf Friction @ 80% Efficiency</td>
<td>3,487 psi</td>
<td>1,736 psi</td>
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<td>Perf Friction @ 75% Efficiency</td>
<td>3,968 psi</td>
<td>1,975 psi</td>
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<tr>
<td>Perf Friction @ 70% Efficiency</td>
<td>4,555 psi</td>
<td>2,267 psi</td>
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</tbody>
</table>
Observations

From Over 2,500 Step Down Test Analyses

- Shallow penetration charges work well
- Geology and rock stress still matter
- Higher confidence level on analyses with Equal Entry Hole perforations
- Perforation phasing not a big a factor
- Less tortuosity with shallow penetration charges
- Conventional deep penetration charges of varying hole size are difficult to analyze (lower confidence level on analyses) and generally indicate higher tortuosity
- Performing a Step Down Test every 5 to 10 frac stages has value
- Many operators appear to shoot too many holes
- Higher perforation differential pressure diversion works
- We do not understand fluid and proppant transport; and perforation erosion as well as we would like
Equal Entry Hole (EEH) Shape Charges

1. Consistent hole size charge
2. Enables Limited Entry design for diversion
3. Shorter, equal penetration, regardless of water gap or casing
4. Engineered for maximum consistency
5. For use with diverter products
6. Improves perf cluster efficiency
7. Shape charge technology engineered for current unconventional casing, size, weight and grade
8. Customized entry hole selection
Angled Equal Entry Hole (AEEH) Shape Charges

2nd Generation Equal Entry – Angled Charge for Proppant Transport

1. Consistent hole size charge
2. Provides an “off ramp” for more efficient proppant placement
3. Perforating tunnels are tilted in direction of fluid flow
4. Enables Limited Entry design for diversion
Spiral Pattern vs Single Plane

Which design would be better for fracture initiation and reducing tortuosity?
Single Plane Equal Entry Hole (SPEEH) Shape Charges

70% Shorter Gun

Field Trials at 100 BPM

64 holes, 4 perfs per cluster, Spiral

vs.

48 holes, 3 perfs per cluster, SPEEH

~ 1,000 psi lower surface treating pressure with SPEEH
Well A  Wolfcamp, 6 perfs/cluster, 5 clusters

Well B  Wolfcamp, 6 perfs/cluster, 5 clusters

Note  - All Step Down Test analyses were performed by the Operator and the results were shared with GEODynamics by the Operator
* Conventional (Conv)
  Stages 1-4 and 15-19 (9 stages)

* Equal Entry Hole (EEH)
  Stages 5-9 and 20-24 (10 stages)

* Angled Equal Entry Hole (AEEH)
  Stages 10-14 and 25-28 (9 stages)

<table>
<thead>
<tr>
<th>Average</th>
<th>Conv</th>
<th>EEH</th>
<th>AEEH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Perfs</td>
<td>21</td>
<td>24</td>
<td>27</td>
</tr>
<tr>
<td>Perf Efficiency %</td>
<td>70</td>
<td>80</td>
<td>90</td>
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<tr>
<td>Tortuosity (psi/BPM^0.5)</td>
<td>57</td>
<td>53</td>
<td>30</td>
</tr>
</tbody>
</table>

* No valid Step Down Tests for Stages 1, 2 and 21
Well A

Perf Eff %, Tortuosity

Conv  EEH  AEEH  Conv  EEH  AEEH

Perf Eff %  Tortuosity (psi/BPM^0.5)
• Conventional (Conv)  
  Stages 1-5 and 16-19 (9 stages)

• Equal Entry Hole (EEH)  
  Stages 6-10 and 20-23 (9 stages)

• Angled Equal Entry Hole (AEEH)  
  Stages 11-15 and 24-27 (9 stages)

<table>
<thead>
<tr>
<th>Average</th>
<th>Conv</th>
<th>EEH</th>
<th>AEEH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Perfs</td>
<td>22</td>
<td>22</td>
<td>24</td>
</tr>
<tr>
<td>Perf Efficiency %</td>
<td>73</td>
<td>73</td>
<td>80</td>
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<tr>
<td>Tortuosity (psi/BPM^0.5)</td>
<td>35</td>
<td>42</td>
<td>35</td>
</tr>
</tbody>
</table>

* No valid Step Down Tests for Stages 1, 21 and 24
Well B

Perf Eff %, Tortuosity

Perf Eff %  Tortuosity (psi/BPM^0.5)

<table>
<thead>
<tr>
<th></th>
<th>Perf Eff %</th>
<th>Tortuosity (psi/BPM^0.5)</th>
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<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>27</td>
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</tr>
</tbody>
</table>
Equal Entry Hole (EEH) = 0.42 inch EHD

- 10 clusters, 3 perfs per cluster
- Average number of perfs open (30 perfs shot) = 29 perfs
- Average perf efficiency = 95%
- Average Tortuosity = 38 (psi/sqrt(BPM))
- Average Tortuosity at 90 BPM = 361 psi
- Average Rate = 86.1 BPM
- Average STP = 7,501 psi

- 12 out of 15 stages with SDT had 100% perforation efficiency
- 13 out of 15 stages with SDT had tortuosity
- Ave Rate was flat (Stages 3 and 24 were less than 74 BPM)
- Ave STP decreased from Stage 3 to 45
Equal Entry Hole Well

Perf Efficiency, Tortuosity

Perf Eff (%)  Tortuosity (psi/BPM^0.5)
Equal Entry Hole Well

Ave Rate (BPM)  Ave STP (psi)
Single Plane Equal Entry Hole (SPEEH) = 0.32 inch EHD

10 clusters, 3 perfs per cluster
Average number of perfs open (30 perfs shot) = 30 perfs
Average perf efficiency = 100%
Average Tortuosity = 13 (psi/sqrt(BPM))
Average Tortuosity at 90 BPM = 123 psi
Average Rate = 88.2 BPM
Average STP = 7,725 psi

• 13 out of 13 stages with SDT had 100% perforation efficiency
• 6 out of 13 stages with SDT had tortuosity
• Ave Rate was flat (all Stages were greater than 84 BPM)
• Ave STP decreased from Stage 3 to 45
Single Plane Equal Entry Hole Well

Perf Efficiency, Tortuosity

- Perf Eff (%)
- Tortuosity (psi/BPM^0.5)
Single Plane Equal Entry Hole Well

Ave STP

Ave Rate

Ave Rate (BPM)  Ave STP (psi)
Perforating and Hydraulic Fracturing

Well Design
Perforation System, Number of Perforations, Clusters and Frac Stages

Design Changes
Maximize Well Performance and Economics

Step Down Tests
Quick, Easy and Economically Justified every 4 to 6 Frac Stages

Data Analysis
Perforation Efficiency, Tortuosity, Fracture Diagnostics, Ops/Geology Review, Production Analysis

Design Changes
Maximize Well Performance and Economics

Step Down Tests
Quick, Easy and Economically Justified every 4 to 6 Frac Stages

Data Analysis
Perforation Efficiency, Tortuosity, Fracture Diagnostics, Ops/Geology Review, Production Analysis
Final Thoughts

• Calculate limited entry perforation pressure drop for the initial injection with slickwater and after pumping a few thousand pounds of proppant (discharge coefficient increase and perforation erosion)

• Specify the perforating system that you ran your design calculations with and ensure that the system is delivered to the wellsite and run without improper substitution

• Perform fracture diagnostics – Step Down Tests, downhole camera, downhole imaging, etc. to evaluate perforation designs

• What effect does changing the pump rate per cluster have on the created fracture geometry?
What makes you think proppant moves uniformly with the fluid?

Does proppant placement vary as a function of proppant size?

• This could have many implications:
  • Erosion
  • Screen-outs
  • Well Productivity
  • Fracture Conductivity
  • Frac Hits
  • Proppant Flowback
THANK YOU
Q&A AND DISCUSSION

Steve Baumgartner and Phil Snider