LIMITED ENTRY CLUSTER PERFORATING SYSTEM IMPROVES FRACTURING EFFICIENCY IN HORIZONTAL WELLS

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INTRODUCTION

In conventional usage, well known vertical well perforating tools have been successfully adapted to horizontal wireline plug and perforation applications

- Initially limited entry meant 4 shot clusters
- Wells were 4 – 12 stages
- Cluster spacing was greater than 500 ft apart
- Wells were completed with TCP at the toe

New learnings have pushed operators to new techniques

- (2-3) shot, 6 shot, or 12 shot clusters predominatly
- Wells are 20-40 stages
- Cluster spacing is 250 ft or less
- Valves at the toe stage dramatically lower cost

Why? And does this mean something for perforating tools?
NEW TOOLS FOR NEW TECHNIQUES - CHARGES

<table>
<thead>
<tr>
<th>Charge Type</th>
<th>Sandstone</th>
<th>Carbonate</th>
<th>Shale</th>
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<tbody>
<tr>
<td>Constant EHD Charge</td>
<td><img src="sandbox.png" alt="Image" /></td>
<td><img src="carbonate.png" alt="Image" /></td>
<td><img src="shale.png" alt="Image" /></td>
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<td>Commodity Charge</td>
<td><img src="sandbox2.png" alt="Image" /></td>
<td><img src="carbonate2.png" alt="Image" /></td>
<td><img src="shale2.png" alt="Image" /></td>
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<td>Premium Charge</td>
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<td><img src="carbonate3.png" alt="Image" /></td>
<td><img src="shale3.png" alt="Image" /></td>
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<td>Reactive Charge</td>
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<td><img src="carbonate4.png" alt="Image" /></td>
<td><img src="shale4.png" alt="Image" /></td>
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SYSTEM DESIGN FOR HORIZONTAL UNCONVENTIONAL WELLS

- Do Only the Holes Matter?

- Industry Standards Through Trial and Error: Why?
  - 6 Shot per Foot (SPF) Clusters in US Unconventional
  - Alternate: Multiple clusters at 180 degrees (not oriented!)

- Operators are finding the exceptions in Well Design!
EXAMPLE 1 – REDUCED TREATING PRESSURE

- Comparison between conventional and new cluster perforation system
- Both wells perforated with the same reactive perforating charge
- Wolfcamp B formation; Midland County, TX
- TVD 9650 ft
- Treating pressure reduced on average approximately 1000 psi – at increased pump rates
**EXAMPLE 2**

- Number of horizontal wells in the same pad perforated with both conventional and cluster based perforating systems
- RELIABLY IMPROVED PERF FRICTION without ACID

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Charge Type</th>
<th>Avg Treating Pressure</th>
<th>Avg Treating Rate</th>
<th>Avg Max Rate</th>
<th>Avg Hyd HP</th>
<th>Acid Volume / Well</th>
<th>Avg FR Volume</th>
<th>Avg Gel Volume</th>
<th>Calc’d Perf Friction</th>
<th>Avg Stage Pump Time</th>
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<tbody>
<tr>
<td>East 16H</td>
<td>Conventional</td>
<td>8278</td>
<td>95.5</td>
<td>100.8</td>
<td>20452</td>
<td>192</td>
<td>162</td>
<td>580</td>
<td>938</td>
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<td>East 17H</td>
<td>Conventional</td>
<td>8155</td>
<td>95.5</td>
<td>99.9</td>
<td>19668</td>
<td>45</td>
<td>173</td>
<td>568</td>
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<td>100.8</td>
<td>19654</td>
<td>186</td>
<td>142</td>
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<td>1293</td>
<td>1:55</td>
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<tr>
<td>East 18H</td>
<td>Angled</td>
<td>8257</td>
<td>95</td>
<td>99</td>
<td>20115</td>
<td>93</td>
<td>161</td>
<td>543</td>
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<tr>
<td>East 19H</td>
<td>Angled</td>
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<td>101</td>
<td>19452</td>
<td>0</td>
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<td>550</td>
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**Delta**

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<th>Average</th>
<th>7888</th>
<th>99</th>
<th>101</th>
<th>19482</th>
<th>0</th>
<th>140</th>
<th>546</th>
<th>981</th>
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<tbody>
<tr>
<td>Delta</td>
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<td>-1</td>
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- % change: %
- $ Value: $ Value

- Per stage Savings:
  - $9,419.00
  - $11,718.00
  - $629.92
  - $(84.55)
  - $495.72
  - $616.74
  - $33.15
  - $(4.45)
NEW DESIGN ELEMENTS FOR PERFORATING SYSTEMS

- Each gun is designed for an individual cluster
- The arrangement of charges is tuned so that
  - An additional charge in a cluster provides maximum benefit
  - A subtracted charge in a cluster yields minimum loss
- Systems are not constant phase or shot density, but target probability of placement with a given number of shots in a cluster
- For example: 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, and 14 shot designs.
- Where lower number of shots are desired, orientation may be used, which impacts system design
NEW PERFORATING SYSTEM

- Uses angled perforations arranged in banks to place fracture initiation points on the same plane near wellbore.
- By connecting transversely to the fracture planes, every hole feeds the fracture, and variations due to hole size are minimized.
- Shot configurations available: 2, 3, 4, 5, 6, 7, 8, 10, 12, and 14 shot designs.
- This system is optimized to be run without orientation.
NEW PERFORATING SYSTEM

- For Formation Reach, Carbonates, Difficult to Break Formations, and Operational Advantage:

Guns

Reactive Liner Charges

US9038521 and Patents Pending
DOMINANT HOLES

- Operators Report: Downhole cameras have shown a single dominant hole in many clusters.
- The dominant hole is obvious due to preferential erosion of that hole vs. the remaining holes.
- The eroded hole is often more 2-3 times the original diameter.
DOMINANT HOLE DISTRIBUTION AND WELLBORE STRESS

- With Conventional Phasing, dominant holes are distributed statistically:
  - Downward 30 deg arc: 70%
  - Upward 30 deg arc: 20%
  - Either remaining side: 10%

- Conceptually, this can be accounted for due to stress distribution around the casing and the variation in hole sizes.
For a 6 shot, 6 SPF, 60 deg Gun, the chance of placing a perforation hole in the preferred stress arc of the wellbore (up or down) is 50%.

The fully loaded 6 shot 60 deg cluster has the highest chance of any conventional fixed phase, fixed density system, which may explain the popularity of this system.
DOMINANT HOLES: DOWNLOADING

- The breakdown pressure of each cluster will vary with this statistic, like the flip of a coin: high or low.
- Downloading the 6 shot gun to 5 shots will affect the statistical chance of placing a shot appropriately, and increase the chance of variation from cluster to cluster.

68%

- It doesn’t matter how you download.
DOMINANT HOLES: UPLOADING

- Adding a shot to a constant phase system will not improve the chances.
- The seventh shot has a 16% chance to be in the top or bottom arc of interest.
- It doesn’t matter how you upload.
- The additional shot may further unbalance the clusters, if it moves more dominant holes to the low side.
CLUSTER BASED PERFORATING SYSTEMS

- Converging System and Non Converging System Available
- Designed to be run without orientation
- Phasing to improve perforation placement

6 Shot  
U=50%

8 Shot  
U=33%

12 Shot  
U=0%

US9038521 and Patents Pending
CLUSTER BASED PERFORATING SYSTEMS

- Dual bank design groups opposing charges for best planar performance
- Converging charges offset hole size variation (Every perforation feeds a planar frac)
- Converging system allows strategic arrangement of tip fractures

8 Shot End

8 Shot Side

8 Shot 3D

US9038521 and Patents Pending
PERFORATION SYSTEMS FOR CLUSTERS

- **Application:**
  - Limited Entry Perforating Systems

- **Benefits:**
  - Arranges perforations for statistical placement
  - Available in 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, or 14 shot per cluster configurations, in 3-1/8” Guns

- **Opportunities to treat more clusters:**
  - Enables Advanced Limited Entry Frac Design
  - Balance injection between clusters through stage design with new tools
  - Break down troublesome wells
  - Achieve higher rates at lower pressures
  - Reduce pumping cycle time
NEW TOOLS ENABLE NEW TECHNIQUES FOR WELL COMPLETION

- Cluster based perforation guns combined with charge options can enable
  - Extended reach into the well
  - Arrangement of initiation points
  - Rescue for difficult to break down formations

- Effective holes improve reliability and repeatability
- Mix hole sizes in a single stage
- Mix shaped charge family types in a single stage
- Change design as you work up the well – (Charge – Gun – Cluster)
- Mix charge and system types in a single cluster with orientation

- Also – in conjunction with precision hole size systems: Advantageous Cement Squeeze
Well Design will Never be the Same