Perforation Design for Well Stimulation

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Typical Shaped Charge

- Primer charge
- Main explosive charge
- Case or container
- Detonating cord groove ¾ point of initiation
- Liner
Approximate Jet Velocities and Pressures

Pressure on target - \( P_1 = 15 \times 10^6 \) psi
Lateral pressure (at \( \frac{1}{2} \) in.) - \( P_2 = 100,000 \) psi
Velocity forward jet - \( V_1 = 30,000 \) ft/sec.
Velocity rear jet - \( V_2 = 15,000 \) ft/sec.
Typical Perforation Damage

- Reduced Permeability Zone
- Plastically Compacted Zone
- Pulverized Compacted Zone
- Perforation Tunnel
“Stress Cage” Formation in Sandia Mine-Back Experiment
Poor Perforation Breakdown - Caused by “Stress Cage”
Compaction Damage is Related to Charge Design

- "Big Hole" charges are focused to create large diameter entry holes
  - More radial deformation
  - More stress-cage effect
  - Less penetration
- "Deep Penetrating" charges are focused for maximum depth of penetration
  - Usually less radial deformation
  - Smaller stress-cage effect
  - Lower breakdown pressure
Proper Perforating Techniques Can Minimize Damage

In soft rocks perforation charge size can affect breakdown pressure.

Perforation diameter is more important than penetration.

More holes are better than deeper penetration.
Step-rate Analysis for Conventional Perfs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>D_tub (m)</td>
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<tr>
<td>D_perf (in)</td>
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<td>L_pipe (ft)</td>
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<td>TVD (ft)</td>
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<td>Cd</td>
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<tr>
<td>n</td>
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<td>k</td>
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<td>Number perf’s</td>
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<td>CS_exp</td>
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<td>WH-ISIP (psi)</td>
<td>5015</td>
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</table>

Hydraulic Fracture Step-Rate Diagnostics

<table>
<thead>
<tr>
<th>Q (bpm)</th>
<th>Psurf (meas)</th>
<th>PPG @surf</th>
<th>BHP</th>
<th>dPfr (psi)</th>
<th>dPperf</th>
<th>dPtot</th>
<th>Psurf</th>
<th>Phyd</th>
<th>Calc BHP</th>
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<td>4373.30</td>
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</table>

54 holes shot, Perf’d twice
Impact of Poor Perforations on Job Performance
Avoiding Plastic Compaction and Stress Cage in Perforating

• Bullet-guns avoid plastic compaction and may generate fracturing and perm enhancement

• Hydrojetting (abrasive sand-jetting) can cut deep, efficient holes with minimal mechanical damage
  – Avoid jetting for long times as this can generate fines and emulsions
  – Hydrojetting can provide penetration up to 12 inches or more
Fractures Radiate from Bullet-Formed Perforation
Wellhead/Platform Leg Removal (Lab Test)

successful cut

unsuccessful cut
Step-Rate Analysis for Hydro-Jet Holes: No measurable DP

<table>
<thead>
<tr>
<th>Q(bpm)</th>
<th>Psurf(meas)</th>
<th>PPG@surf</th>
<th>BHP</th>
<th>dPfr(psi)</th>
<th>dPerf</th>
<th>dPfert</th>
<th>Psurf</th>
<th>Phydr</th>
<th>Calc BHP</th>
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<td>3875.35</td>
<td>9175.35</td>
</tr>
</tbody>
</table>

![Graph showing pressure versus rate with various data points and lines representing different parameters.](Image)
Case 1: 100% of Perfs Open for Low Density Perforating

Hydraulic Fracture Step-Rate Diagnostics

30 holes shot, 180 deg
Minimum Perforation Sizes for Sand Bridging

- Perforation diameters of 6x the prop diameter assure no bridging.

<table>
<thead>
<tr>
<th>Proppant Size (mesh)</th>
<th>Recommended Perf Diameter (inches)</th>
</tr>
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<tbody>
<tr>
<td>6/12</td>
<td>0.80</td>
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<td>8/16</td>
<td>0.56</td>
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<td>12/20</td>
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<td>16/30</td>
<td>0.28</td>
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<td>20/40</td>
<td>0.20</td>
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<td>30/50</td>
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<tr>
<td>40/70</td>
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</table>
Minimum Required Perf Diameter Depends on Concentration

### Table of Proppant Concentration and Diameter

<table>
<thead>
<tr>
<th>Concentration (lb/gal)</th>
<th>8/12 mesh</th>
<th>10/20 mesh</th>
<th>20/40 mesh</th>
<th>40/60 mesh</th>
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</thead>
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<tr>
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<td>0.5</td>
<td>0.7</td>
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<td>0.70</td>
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</table>
Fractures Rarely Initiate at Perf Tunnels
Tortuosity Caused by Poor Perf Orientation and Poor Cement

Perforation Orientation

Restricted Cement Annulus

Fluid Flows through Annular Gap to Fracture

Annular flow restrictions cause high fluid shear, high pressure drops, and early screenouts.
Near-Wellbore Pressure Loss

- Stress halo around perf
- Flow around cement micro-annulus
- Perforation interference
- Narrow fracture width
- Fracture turning and branching (multiples)
- Off-vertical fractures
- Pulverized cement debris
- Charge debris
- Leakoff into drilling and perf induced fracs
Recommendations for Successful Perforating for Stimulation

- Perf underbalanced, flow back and clean up perfs
- Use aggressive cleanup procedures
- Large enough diameter to accept proppant
- Sufficient number and diameter to allow fluid entry at desired pressure
- Determine optimum phasing to minimize entry friction
- Don’t shoot more holes than you need
- If a screenout occurs consider reperforating before re-fracturing
Aggressive Perforation Cleanup Techniques Should Be Used

- Perforation Breakdowns
  - Injection of non-damaging fluids
  - May not open all perforations
- Acid or Brine Ballouts
  - Small perforated intervals
  - May not contact all perfs
- Perforation Surging and Washing
- Perforation Isolation Tools
- Acid Soaks
  - Maintain drawdown over a long time period
- Extreme Overbalance Perforating
- Stress Frac Treatments
Conventional Perfs After Ballout: Does it help?

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<th>Phydr</th>
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</tr>
</tbody>
</table>

72 holes shot (6 spf)
Underbalance Perforating
Removes Perforation Damage

• Underbalance provides surge of fluid into the wellbore for cleanup.
• Excess underbalance may cause collapsed casing, formation breakdown and damage from fines movement.
• Underbalance requirement is indicated by field data:
  – No improvement from acidizing indicates clean perforations
  – Underbalance is determined by reservoir permeability
  – At low permeability, may be associated with insufficient flow for cleanup irrespective of pressure differential.
Underbalance Perforating in Oil Wells

Recommended Underbalance

Perm, md

Total Underbalance, psi

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Underbalance Perforating in Gas Wells

Recommended Underbalance

Stuck Packer

Casing collapse

Data from George King
Effect of Acid on Sandstone
Summary of Perforating Recommendations

- One size does NOT fit all
  - What works GREAT! In one area may not work in another
  - Find the optimum strategy for your reservoir and stress state
- In general fewer holes shot means higher perf efficiency and less near-well damage
  - I do not favor cluster perforating
  - I do like low shot density to avoid overlapping stress cages
- If you don’t know the stress field orientation, phasing can be inconclusive
- In deviated holes and highly anisotropic stresses, try to shoot in the direction of minimum near-well compression
  - For highly deviated and horizontal holes, that is top and bottom
- Depth of penetration is meaningless in a well that must be fractured to produce commercially
- Get a hole through the pipe that is big enough for the proppant
Limited Entry Frac Designs

• Force fluid into more than one zone
  – use perf restriction as flow orifice
  – high shear and treating pressure
  – possible fluid damage
  – perforation erosion concerns
  – maximum sustained pressure drop is uncertain
Perforation Restriction Causes a Large Pressure Drop

\[ P_{pf} = \frac{1.975 q^2 \rho_f}{C_D N_p^2 d_p^4}; \text{ psi} \]

where

- \( q \) = the total pump rate, bpm
- \( \rho_f \) = the slurry density, g/cc
- \( C_D \) = the perforation coefficient
- \( N_p \) = the number of open perforations
- \( d_p \) = the perf diameter, inches
Crump/Conway Study of Perf Erosion

Crump & Conway, SPE 15474
Final Perf Geometry in Crump/Conway Study
Perforation $\Delta P$ in Limited Entry Treatments

Perforation $dP$ at 1 bpm/perf, 4 ppa

- $Cd$
- diam
- $dP_{perf}$

Pumping Time, minutes

Perf Diameter and Cd

Perf $dP$, psi
Post Frac Logs - LE Frac in OK

Post Frac Production = 29 MMCD/D

Frac 1       Frac2       Frac3       Perf Only
Prop Concentration After LE Frac Compared to Model
Fracture Geometry in Multi-Zone Treatments

- Effect of different extension and closure stresses in multiple zones
- Distribution of injected fluid
- Excessive perf erosion
- Damage to fluid through high shear
- Effects of proppant on mobility and slurry placement
- Effects of crossflow during closure