Angling the Perforation Tunnel Geometry of Constant Entry Hole Perforating Charges Results in Further Improvements in Hydraulic Fracturing Efficiency
AGENDA

• Cluster Perforating for Limited Entry Stimulation
• Conventional Perforating Systems
• Constant Entry Hole & Constant Penetration
• Angled Perforating Systems
• Example
• Conclusions
LIMITED ENTRY STIMULATION

• Limited entry stimulation is a hydraulic fracturing technique in which the number of perforations available for fracturing fluids to enter the formation are “limited”

• Commonly used in multi-stage plug and perforate horizontal applications – wells will have many stages with each stage consisting of a number of clusters of perforations spaced at predetermined distances

• A higher pressure drop across the perforations (perforation friction) is desirable to encourage distribution of the stimulation treatment to all perforation clusters within the stage
CONVENTIONAL PERFORATING SYSTEMS

- Entrance hole dia. (EHD)
  - Varies widely with clearance
  - Published data is averaged from API testing in lower grade and weight casing

- Penetration
  - Variation in clearance also has an impact on penetration

Average EHD = 0.36 inches
• The conventional shaped charge jet is designed to provide penetration

• Normally the diameter of the jet reduces at higher clearances - typically the high side hole migrates to a diameter of about 0.3 inches

• The jet is intended to enter the formation perpendicular to the casing
• The objective is to optimize the number of open perforations and perforation friction in order to direct the stimulation to all clusters.

• If the EHD varies circumferentially then radial distribution of the stimulation can be further compromised as perforation friction through each perforation will be different.

• If the quoted average entrance hole is used then the cumulative pressure drop cannot be easily predicted.
PERFORATION FRICTION

• Perforation friction calculation shows the importance of the EHD term ($d_p$)

• Small changes in EHD have a significant impact on perforation friction

• Accurate perforation diameter estimates are critical to the design of the stimulation

• Determining the number of perforations which are open and the corresponding pressure drop is difficult if EHD not consistent

$$P_{pf} = \frac{1.975q^2\rho_f}{C_D N_p^2 d_p^4}$$

Where:
- $P_{pf}$ = Perforation friction pressure (psi)
- $q$ = Total pump rate (bpm)
- $\rho_f$ = Slurry density (g/cm$^3$)
- $C_D$ = Perforation discharge coefficient
- $N_p$ = Number of open perforations
- $d_p$ = Perforation diameter (in)
• Provides consistent entry hole diameter and penetration at all phases
• Consistent even though the clearance between the carrier and inner wall of the casing varies
• System options are available with 0.25 – 0.50 inch EHD
• Charges are uniquely designed and engineered to form a constant diameter fully developed jet
• The formation of the jet occurs in the charge case and near the inside wall of the gun carrier behind the scallop/spotface
• Step rate testing and analysis has been used to evaluate consistent entry hole charges

• Results have demonstrated perforation efficiencies of about 80 percent

• Reliability of EHD ensures frac design objectives can be met – extreme limited entry frac design
ANGLED PERFORATING SYSTEMS

• “What if the tunnel was angled in the direction of flow?”
• Consistent entry hole charge but with tunnel and entrance hole angled
• Provides an “off ramp” for more efficient diversion of proppant
• Perforating tunnels are tilted in direction of fluid flow
• Constant entry hole size in eccentric conditions

• Angled holes are engineered to create a physical diversion on toe side of casing for proppant to naturally flow into the formation
• More uniform placement of proppant in all perf clusters within the stage
Angling the Perforation Tunnel Geometry
• Perforation friction calculation shows the importance of the EHD term \( d_p \)

• Step rate test analysis indicates that the discharge coefficient \( C_D \) is increased compared to conventionally oriented perforations – an indication that fluid flow is more efficient

• At the same friction pressure a higher rate is achievable

\[
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- \( d_p \) = Perforation diameter (in)
Comparing Conventional, Consistent, and Angled system

- Bakken well; 4-1/2 in., 13.5 lb/ft, P-110 casing; 10,500 ftTVD
- 31 stages completed at 2, 3, 5, 8, & 13 shots per cluster
- Evaluation of 4 wells/system (total of 12)
- Target pump rate was 85 bpm
Comparing Conventional, Consistent, and Angled system

• Using Conventional shaped charges only able to obtain a rate of 60 bpm

• Transitioned to a Consistent perforating charge and pump rate increased to 70 bpm

• Angled perforating system with Consistent perforating charges – obtain pump rates >85 bpm

• Operator now standardized to Angled/Consistent system for all future Three Forks and Bakken wells
CONCLUSIONS

• A consistent EHD perforation permits optimization of limited entry stimulations since all perforations have the same EHD and can equally contribute to the stimulation

• If proppant selection is based off the average perforation EHD then the holes which are smaller than this average diameter may actually screen out

• Consistent EHD charges provide higher perforation efficiency compared to conventional perforating charges run on the same well

• Angled perforating systems tilt the perforation tunnels in the direction of fluid flow allowing proppant to more naturally flow into the formation

• Able to maintain higher pump rates