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

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INTERNATIONAL PERFORATING FORUM

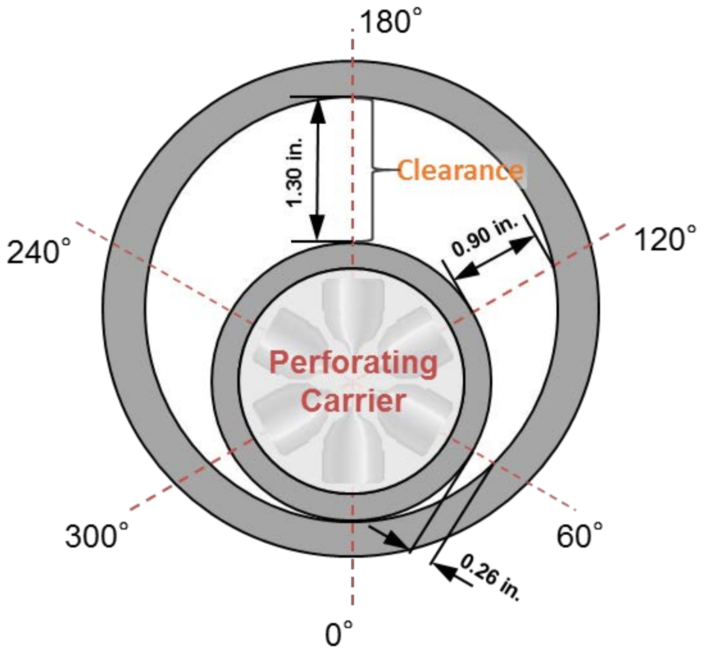
AGENDA

- Cluster Perforating for Limited Entry Stimulation
- Conventional Perforating Systems
- Constant Entry Hole & Constant Penetration
- Angled Perforating Systems
- Example
- Conclusions

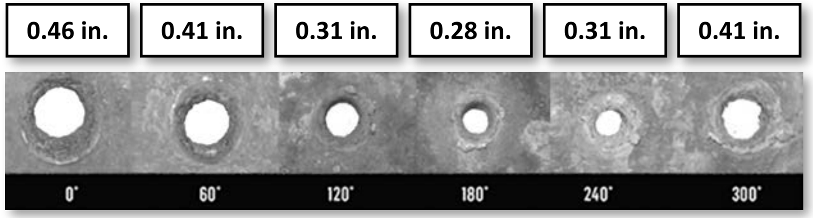
LIMITED ENTRY STIMULATION

- 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

- 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



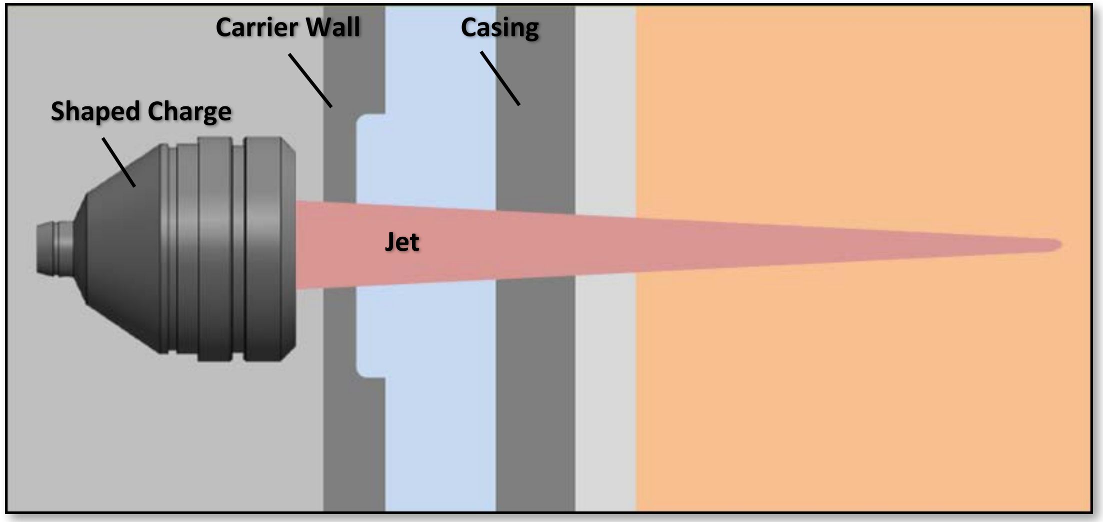
3-3/8 in. carrier in 5-1/2 in. 23lb/ft casing



Average EHD = 0.36 inches

CONVENTIONAL PERFORATING SYSTEMS

- 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



EHD & LIMITED ENTRY STIMULATION

- 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

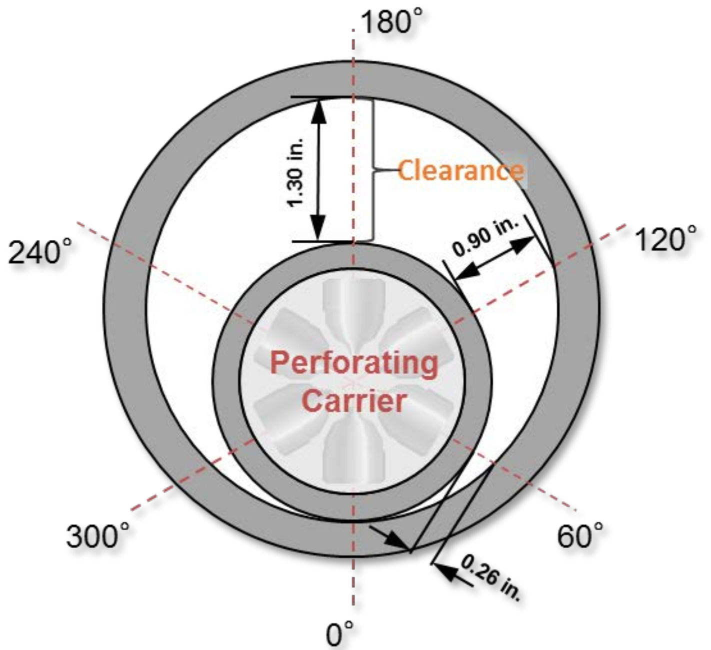
$$P_{pf} = \frac{1.975 q^2 \rho_f}{C_D^2 N_p^2 d_p^4}$$

Where:

P_{pf}	=	Perforation friction pressure (psi)
q	=	Total pump rate (bpm)
ρ_f	=	Slurry density (g/cm^3)
C_D	=	Perforation discharge coefficient
N_p	=	Number of open perforations
d_p	=	Perforation diameter (in)

CONSISTENT PERFORATING SYSTEM

- 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



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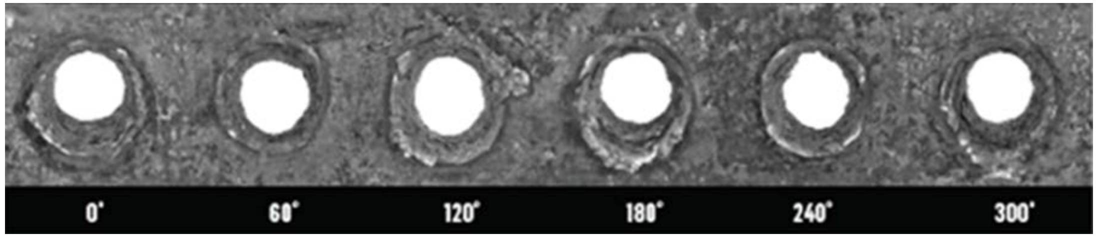
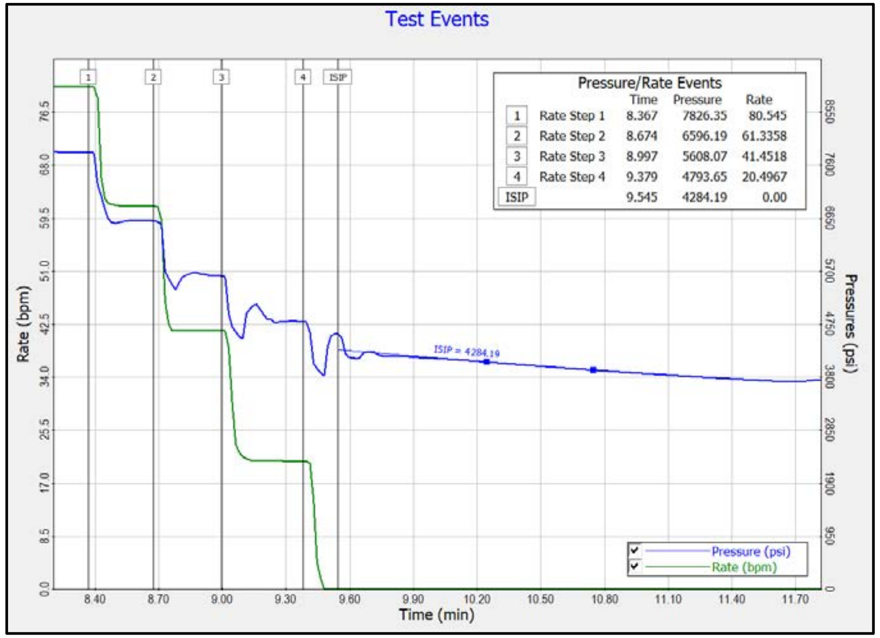
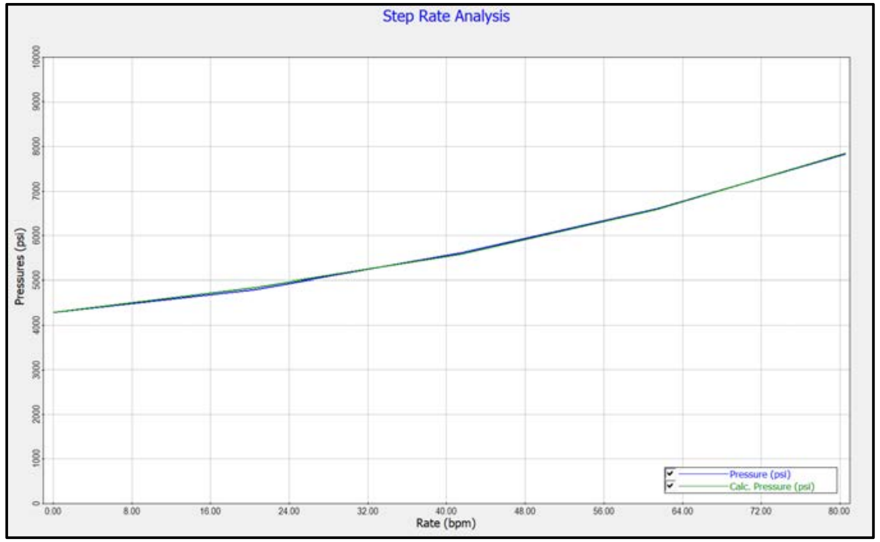


0.40 in. – all phases/clearances

IMPACT OF CONSISTENT PERFORATING SYSTEM

- 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





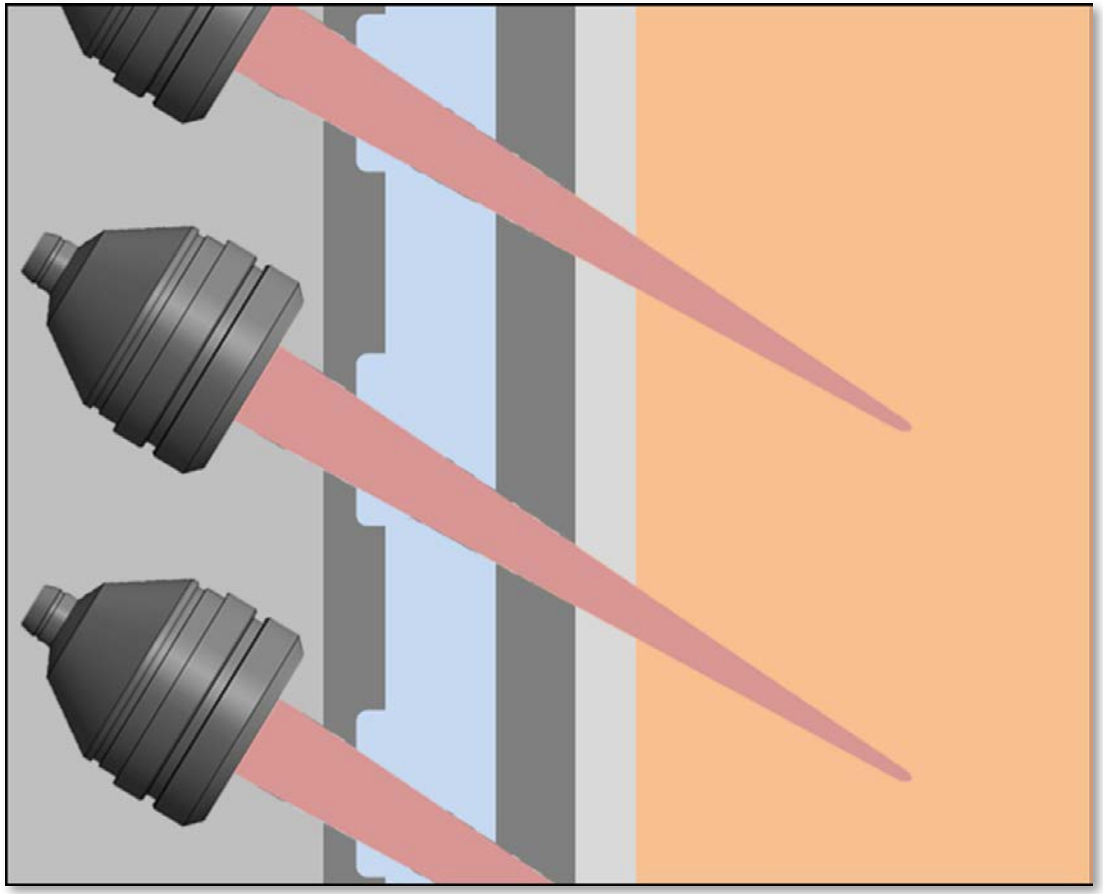
ANGLED PERFORATING SYSTEMS

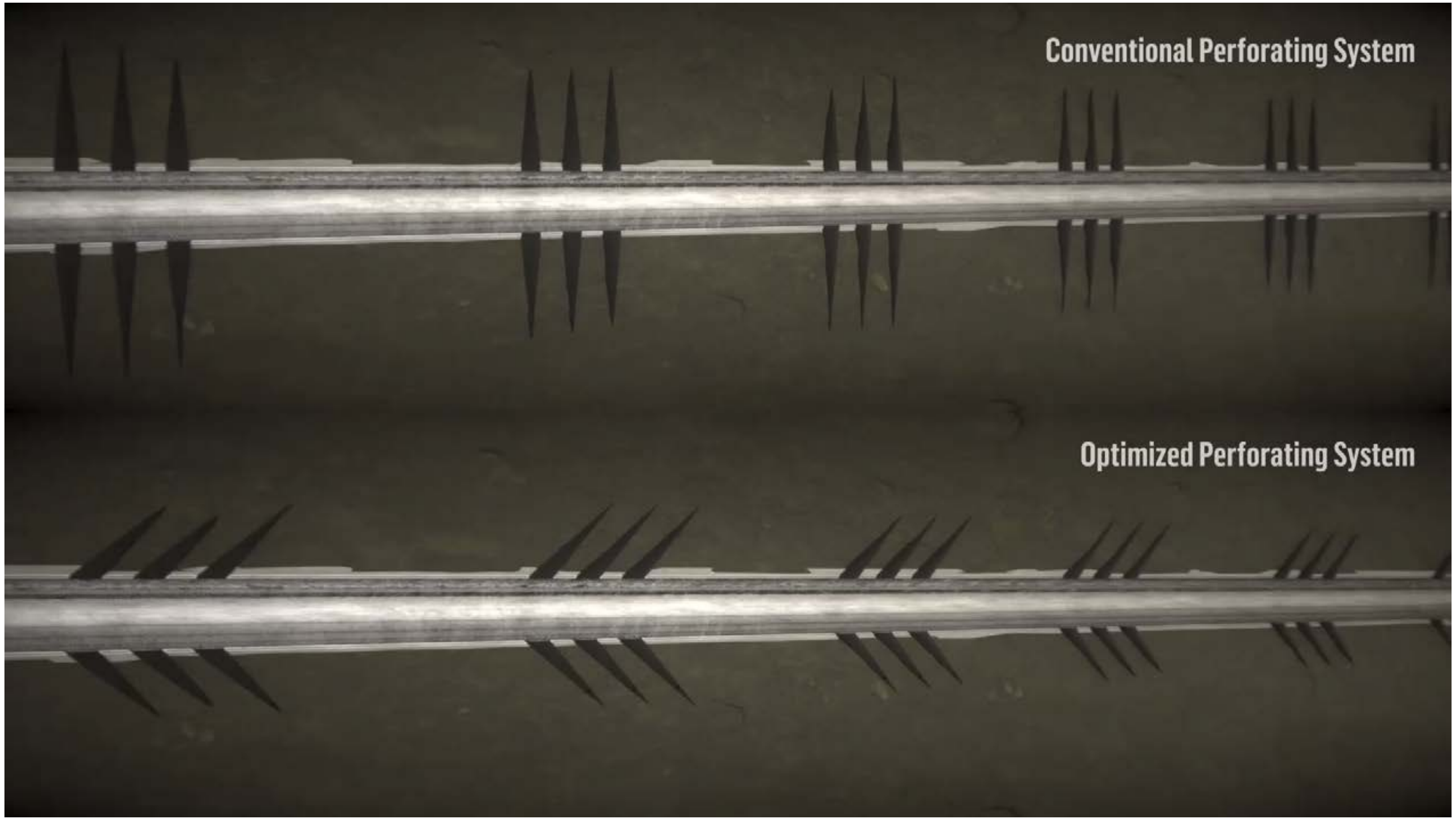
- "What if the tunnel was angled in the direction of flow?"
- Consistent entry hole charge but with tunnel and entrance hole angled
- Provides an "off ramp" for more efficient diversion of proppant
- Perforating tunnels are tilted in direction of fluid flow
- Constant entry hole size in eccentered conditions

Patents: US7044225, US9038521, US9562421 and Patents Pending

ANGLED PERFORATING SYSTEMS

- 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




Conventional Perforating System
Optimized Perforating System

PERFORATION FRICTION – ANGLED

- 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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MEETING TARGET PUMP RATES

NAPS 2018 NORTH AMERICA PERFORATING SYMPOSIUM

Comparing Conventional, Consistent, and Angled system

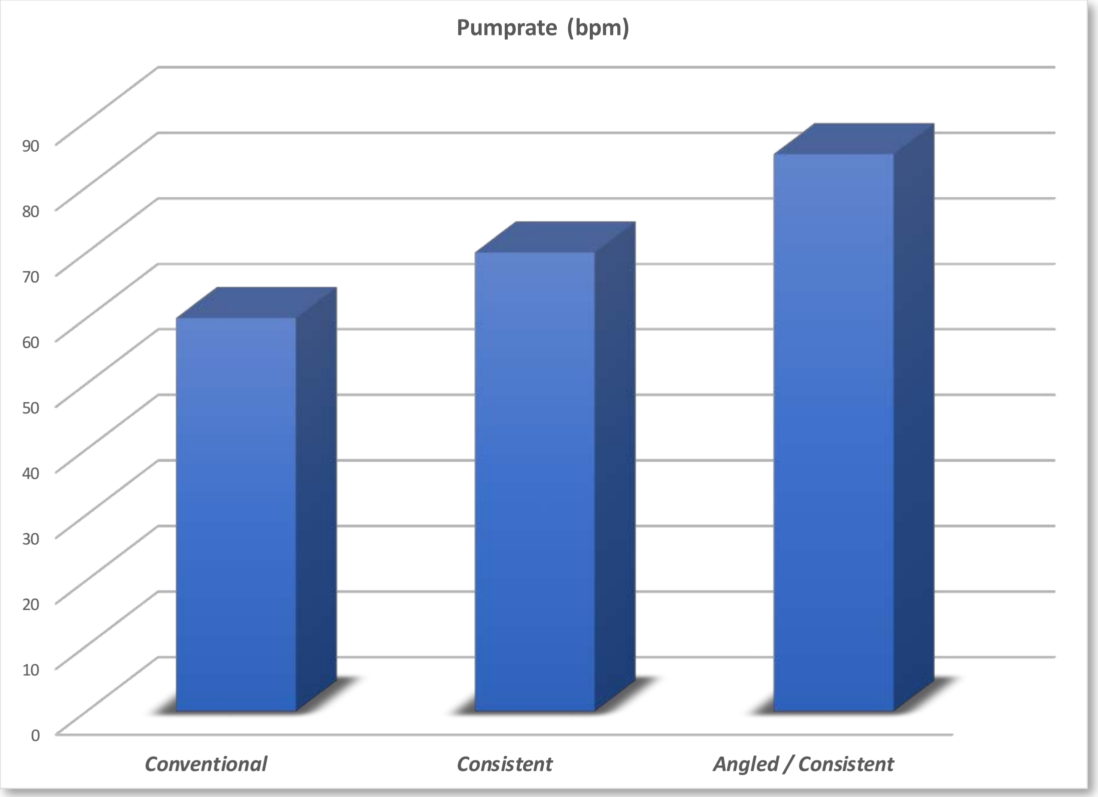
- Bakken well; 4-1/2 in., 13.5 lb/ft, P-110 casing; 10,500 ftTVD
- 31 stages completed at 2, 3, 5, 8, & 13 shots per cluster
- Evaluation of 4 wells/system (total of 12)
- Target pump rate was 85 bpm

MEETING TARGET PUMP RATES

NAPS 2018 NORTH AMERICA PERFORATING SYMPOSIUM

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

Questions?

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