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**Improved Hydraulic Fracturing Perforation
Efficiency Observed With Constant Entry Hole
and Constant Penetration Perforation**

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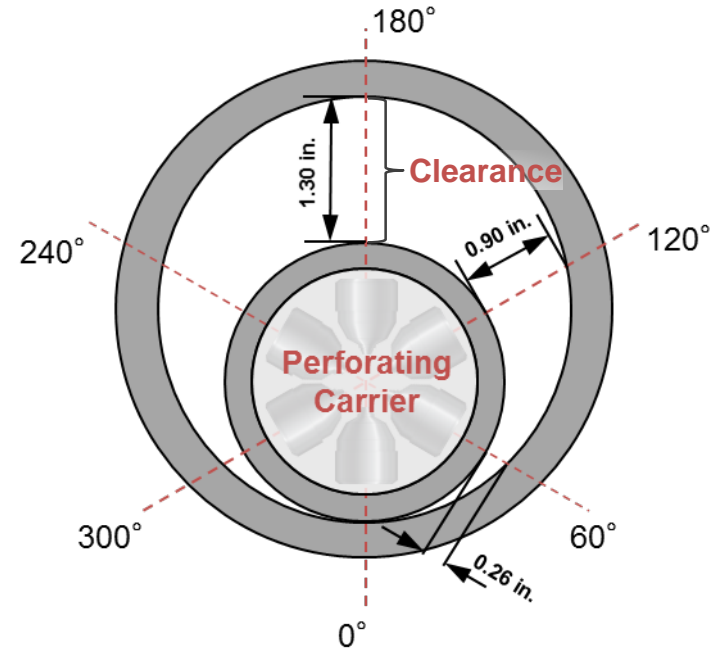


OUTLINE

- Conventional Perforating Systems
 - Entrance hole diameter
- Limited Entry Stimulation
 - The importance of entrance hole diameter
- New Perforating System
 - Constant Entry Hole & Constant Penetration
 - Carrier exit hole
- Impact on Hydraulic Fracturing Perforation Efficiency
 - Step rate test results
 - Comparing conventional and constant entry hole system
- Conclusions

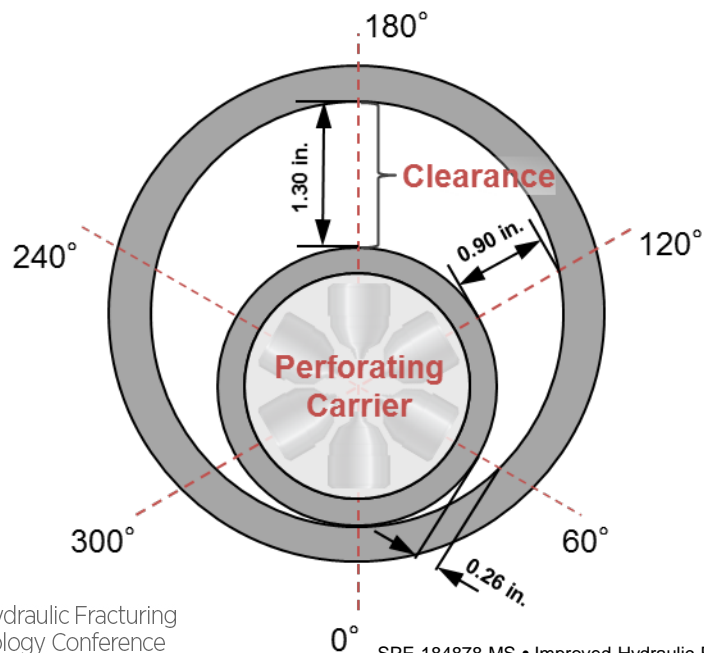
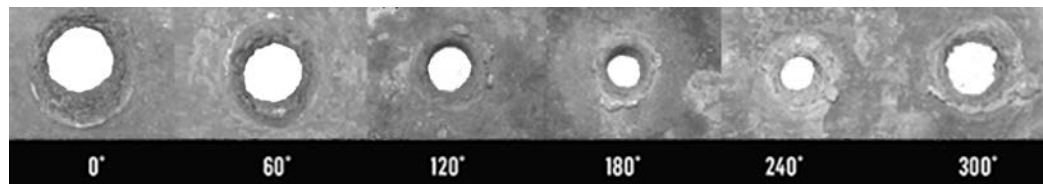
CONVENTIONAL PERFORATING SYSTEMS

- Entrance hole diameter (EHD)
 - Varies widely with clearance
 - Published data is based on API testing which is averaged and is typically obtained in casing of lower grade and weight than is run in current multistage completions
 - EHD will be different in other casing size/weight/grade
- Penetration
 - Variation in clearance also has an impact on penetration

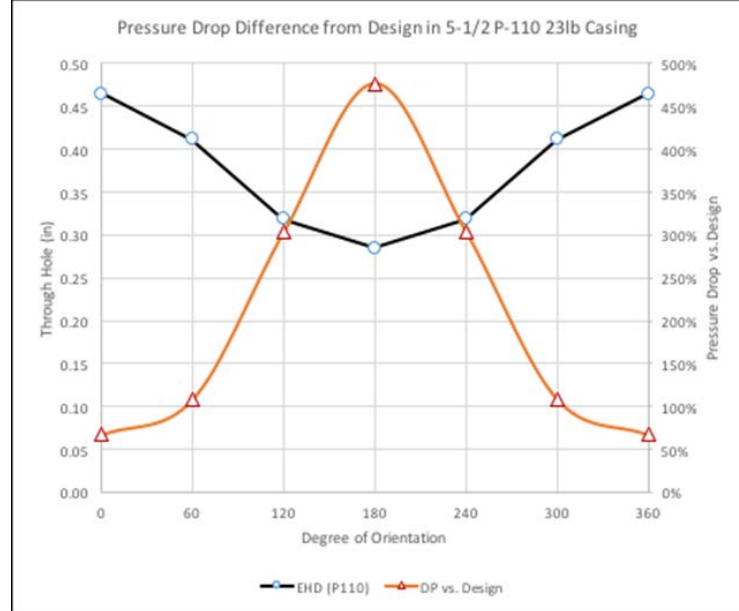


3-3/8 in. carrier in 5-1/2 in. 23lb/ft casing

CONVENTIONAL PERFORATING SYSTEMS

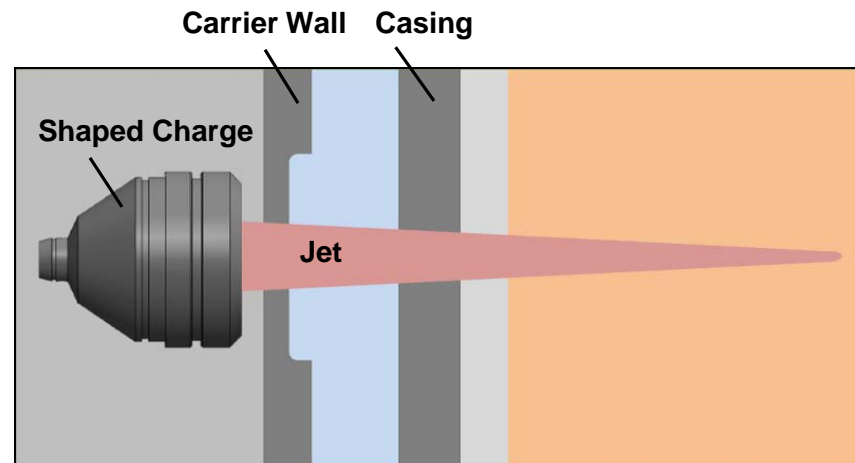


Shot No.	1	2	3	4	5	6	7
Phase	0	60	120	180	240	300	360
Clearance	0.00	0.26	0.90	1.30	0.90	0.26	0.00
API EHD	0.42	0.42	0.42	0.42	0.42	0.42	0.42
EHD (P110)	0.46	0.41	0.32	0.28	0.32	0.41	0.46
DP vs. Design	67%	109%	304%	477%	304%	109%	67%



CONVENTIONAL PERFORATING SYSTEMS

- The conventional shaped charge jet is designed to provide penetration
- Variation in the EHD at changing clearances is related to the shaped charge jet development
- Normally the diameter of the jet reduces at higher clearances
- When comparing different systems (eg. DP versus GH) – regardless of the charge type, typically the high side hole migrates to a diameter of about 0.3 inches



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
- Since the amount of perforation friction is critical for the success of this method an accurate and consistent estimate of the perforation EHD is important

LIMITED ENTRY STIMULATION

- The objective is to optimize the number of open perforations and perforation friction
- 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

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

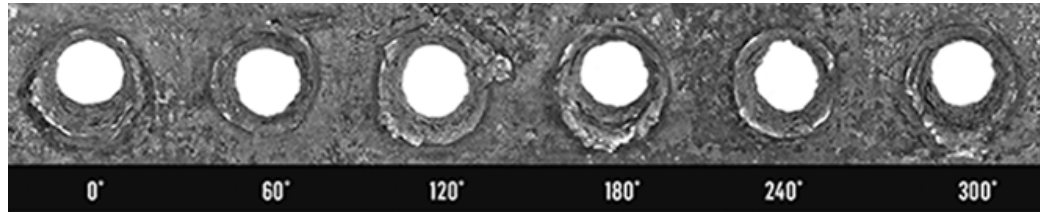
Where:

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)

NEW PERFORATING SYSTEM

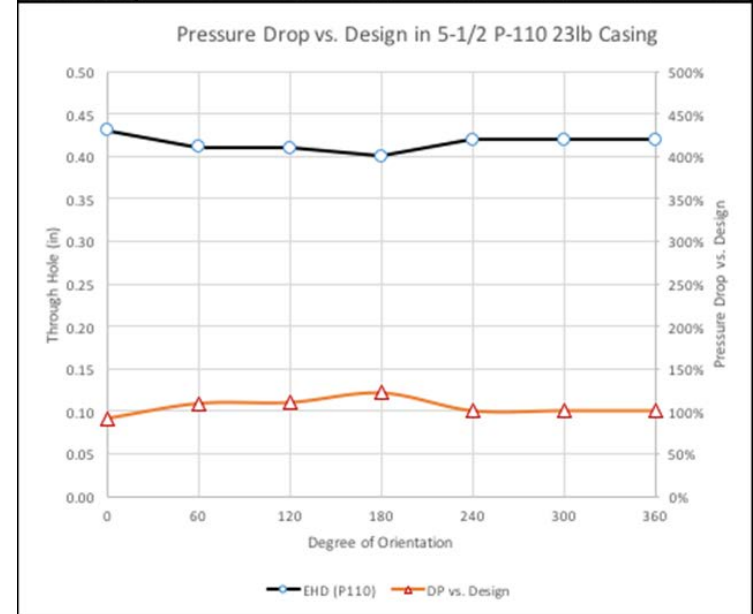
- A new perforating system offers a constant entry hole and constant penetration solution
- EHD and rock penetration is consistent even though the clearance between the carrier and inner wall of the casing varies
- Options are available with 0.30, 0.35, and 0.40 inch EHD

CONSISTENT PERFORATING SYSTEM



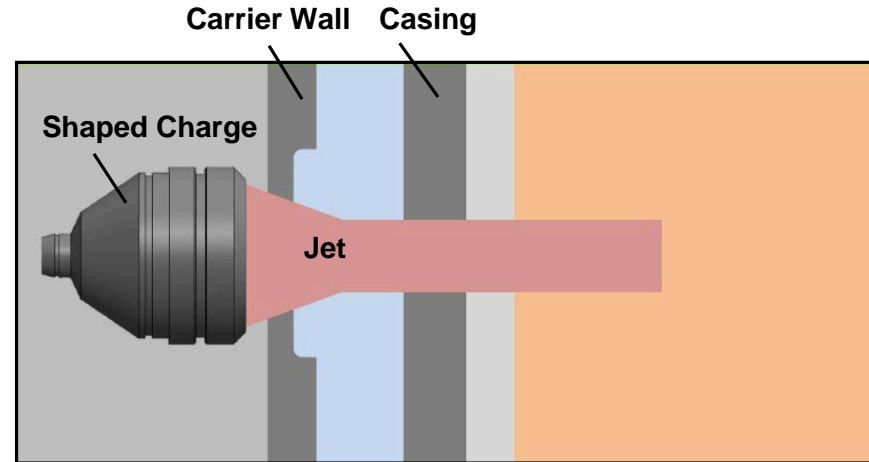
- Entrance hole diameter
 - Predictable and constant in a range of casing sizes, weights, and grades (eg. 4-1/2 – 5-1/2 P-110)
- Penetration
 - Variation in clearance does not impact the penetration

Shot No.	1	2	3	4	5	6	7
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Clearance	0.00	0.26	0.90	1.30	0.90	0.90	0.90
API EHD	0.42	0.42	0.42	0.42	0.42	0.42	0.42
EHD (P110)	0.43	0.41	0.41	0.40	0.42	0.42	0.42
DP vs. Design	91%	109%	110%	122%	100%	100%	100%



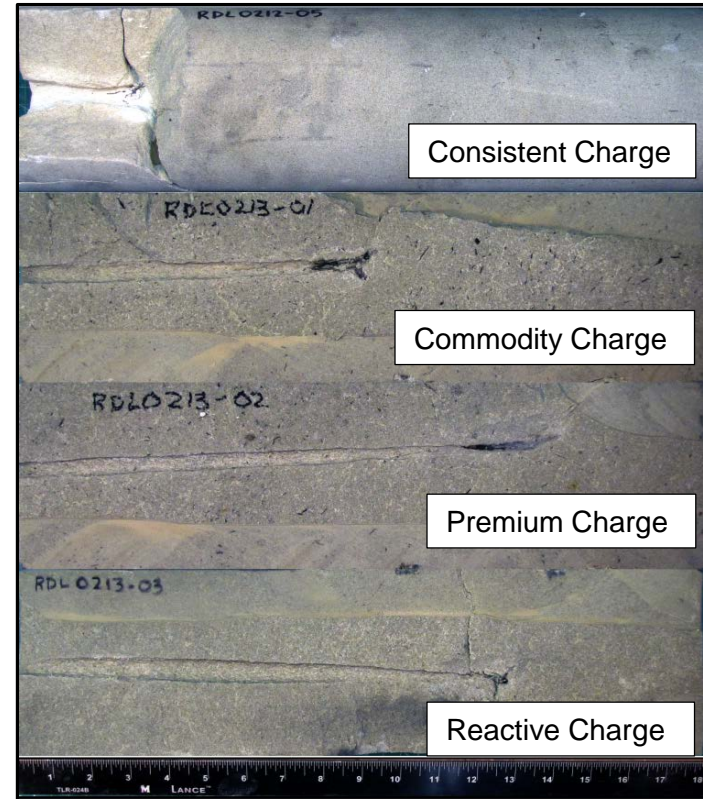
CONSISTENT PERFORATING SYSTEM

- 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.
- The diameter of the jet in the initial (jet formation) region is larger than the diameter after it has been fully developed.
- The gun carrier wall interacts with the jet to improve the precision of the created holes in the casing



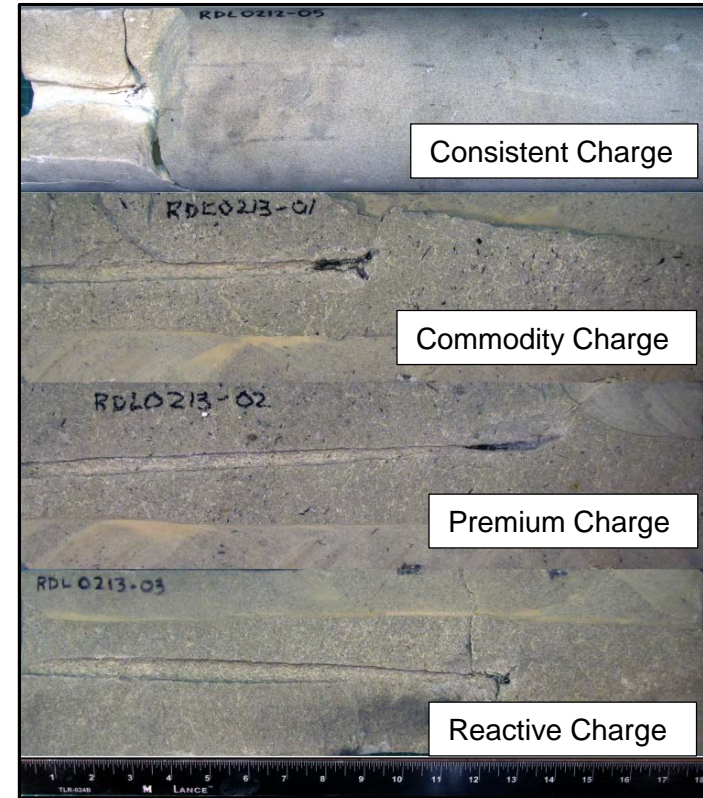
CONSISTENT PENETRATION

- Lab testing as per API 19B Section II & IV in stressed rock has demonstrated that formation penetration is also consistent at all phase orientations
- To obtain a consistent EHD, formation tunnel length is somewhat reduced as compared to a conventional deep penetrating charge of similar configuration



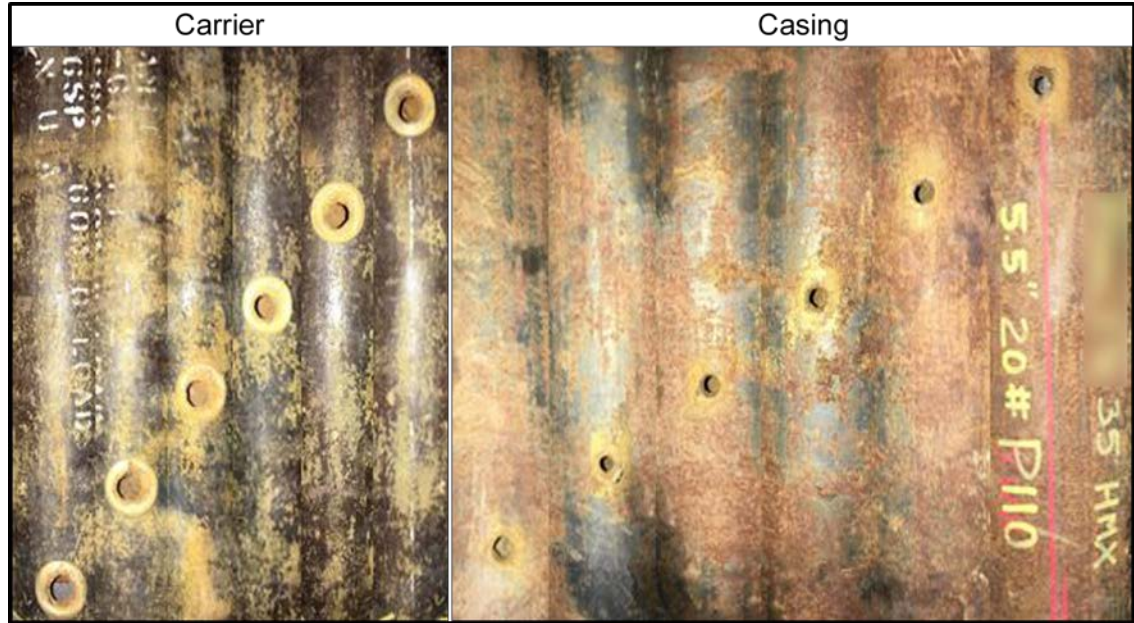
CONSISTENT PENETRATION

- Some authors indicate that a reduction in penetration may not adversely affect the completion since less penetration may also result in less formation compaction within the tunnel
 - For a hydraulically fractured completion, break down and treating pressure may be reduced due to a more effective perforation flow path



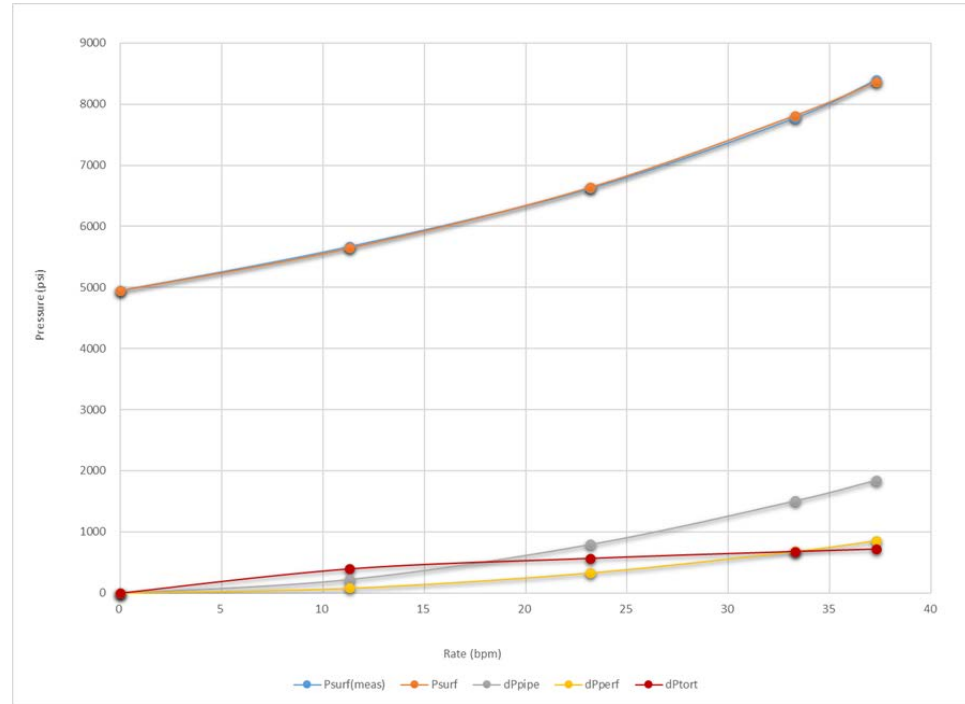
CARRIER EXIT HOLE

- In order to get consistent performance the exit hole on the carrier is larger
- Larger exit hole diameters on the carrier do not translate to larger entrance holes in the casing
- Strategies have been development to ensure that charge debris is larger than with conventional system
 - Debris release can be reduced



STEP RATE TESTING

- Step rate testing was used to evaluate the impact of consistent entrance hole perforating on fracturing operation
- Involves pumping fluid at several distinct rates while measuring pump pressure
 - Can predict near-wellbore pressure losses, perforation friction, and the number of open perforations for each stage
 - Predicted surface pump pressure is compared to the actual measured pressure
 - Calculated surface pressure is adjusted by varying the number of perforations open and the tortuosity to match the measured surface pressure



COMPARING PERFORATION EFFICIENCY

Example 1

- Williston Basin – Bakken formation (approx. 10,728 ft TVD)
- Well completed with 43 perforated stages
- 4-1/2 inch 13.5 lb/ft, P-110 casing
- Both conventional systems and Consistent EHD perforating systems were assessed (2-7/8 and 3-1/8 inch systems)
- In each case the number of perforations shot per stage/cluster was adjusted to provide approximately the same area open to flow for each stage based on the supplied/predicted entrance hole diameter

COMPARING PERFORATION EFFICIENCY

Example 1

- Step rate tests were conducted pre-acid, post-acid, and post-frac for each stage.
- Analysis of post-acid data determined that stages completed with a conventional charge showed perforation efficiency (the ratio of the number of holes open to the total number holes per stage) ranged from 44-70 percent
- The Consistent EHD system perforation efficiency exceeded 80 percent
- Near wellbore tortuosity was consistently low with each perforating system

COMPARING PERFORATION EFFICIENCY

Example 2

- Williston Basin – Three Forks formation (approx. 10,778 ftTVD)
- Well completed with 39 perforated stages
- 4-1/2 inch 13.5 lb/ft, P-110 casing
- As with Example 1 - different conventional systems were used in alternating stages with a Consistent EHD perforating system

COMPARING PERFORATION EFFICIENCY

Example 2

- Step rate tests were conducted pre-acid, post-acid, and post-frac for each stage.
- Perforation efficiency for the conventional system ranged from 51-66 percent
- Perforation efficiency for the Consistent system averaged 80 percent
- Near wellbore tortuosity was consistently low with each perforating system

COMPARING PERFORATION EFFICIENCY

Example 3 – Well to Well Comparison

Well 1 - Conventional System

- EHD 0.42 in. average
- Permian – Wolfcamp A
- TVD 9,000 ft
- Casing: 5-1/2 in. 20 lb/ft P110
- Number of Stages: 43
- Carrier Size: 3-1/8 in. 6spf 60° 40 shots/stage, 5 gun clusters
- Perforation Efficiency for conventional system ranged from 44 – 55%
- Average Treating Rate: 65bbl/min
- Average of frac designed pumped/stage: 77%

Well 2 – Consistent System

- EHD 0.40 in.
- Permian – Wolfcamp A
- TVD: 9,000 ft
- Casing: 5-1/2 in. 20 lb/ft P110
- Number of Stages: 42
- Carrier Size: 3-1/8 in. 6spf 60° 40 shots/stage, 5 gun clusters
- Perforation Efficiency for Consistent system ranged from 75 – 85%
- Average Treating Rate: 90bbl/min
- Average of frac designed pumped/stage: 95%

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
- A design based off a conventional perforation system can provide misleading results - if proppant selection is based off the average perforation EHD then the holes which are smaller than this average diameter may actually screen out
- Accurate step rate testing allows for future optimization of the completion and treatment plan
- Consistent EHD charges provide higher perforation efficiency compared to conventional perforating charges run on the same well

CONCLUSIONS

- This new perforating system eliminates the variable EHD of conventional systems and has the potential to provide even flow distribution and velocity through all open perforations since the diameter, erosion, and penetration will be consistent
- All perforations have an equal chance of accepting stimulation since the pressure drop across any single perforation is the same

Acknowledgements / Thank You / Questions

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