Primary funding is provided by

The SPE Foundation through member donations and a contribution from Offshore Europe

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Integrating Multiple Diagnostic Methods to Determine Limited Entry Treatment Effectiveness

Dave Cramer

ConocoPhillips

Society of Petroleum Engineers

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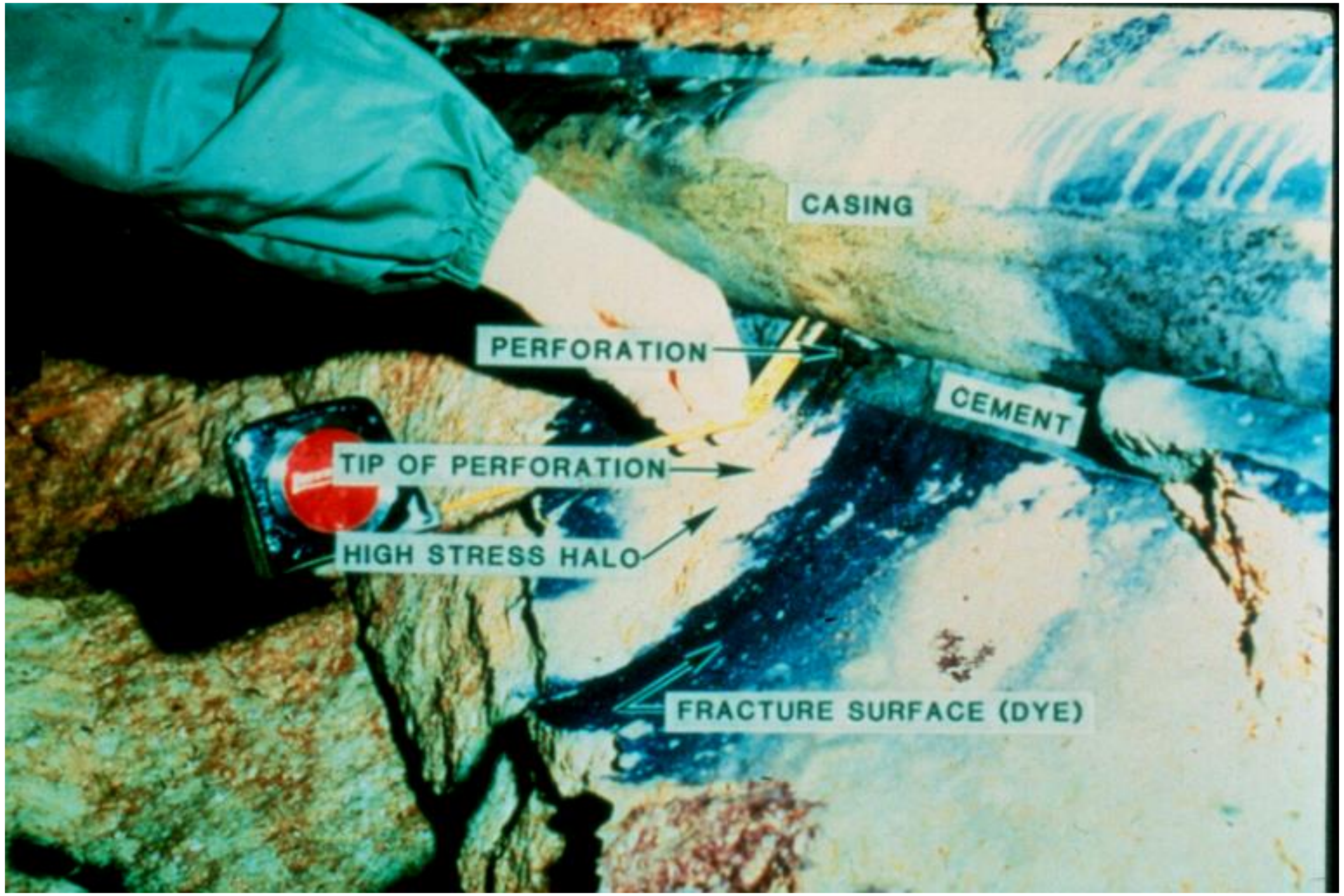
Agenda

- Limited entry treatment basics
- Perforation erosion dynamics
- Case study: limited entry treatments in an instrumented wellbore
- Key points

Limited Entry Treatment Technique

- Perforation entry holes in the casing string are used as a chokes when treating multiple intervals simultaneously.
- During the fracturing treatment, choked flow through a limited number of perforations produces backpressure.
- Backpressure reduces the impact of variable fracture propagation pressure among intervals, due to stress shadowing and other factors.
- Treatment distribution among intervals can be controlled - to a degree.

Mining Back the Near-Wellbore Region



Hydraulic fractures tended to avoid perforation tunnels (Warpinski, 1983). The portion of the perforation having a controllable impact on fracture initiation and propagation is the entry hole created in the casing.

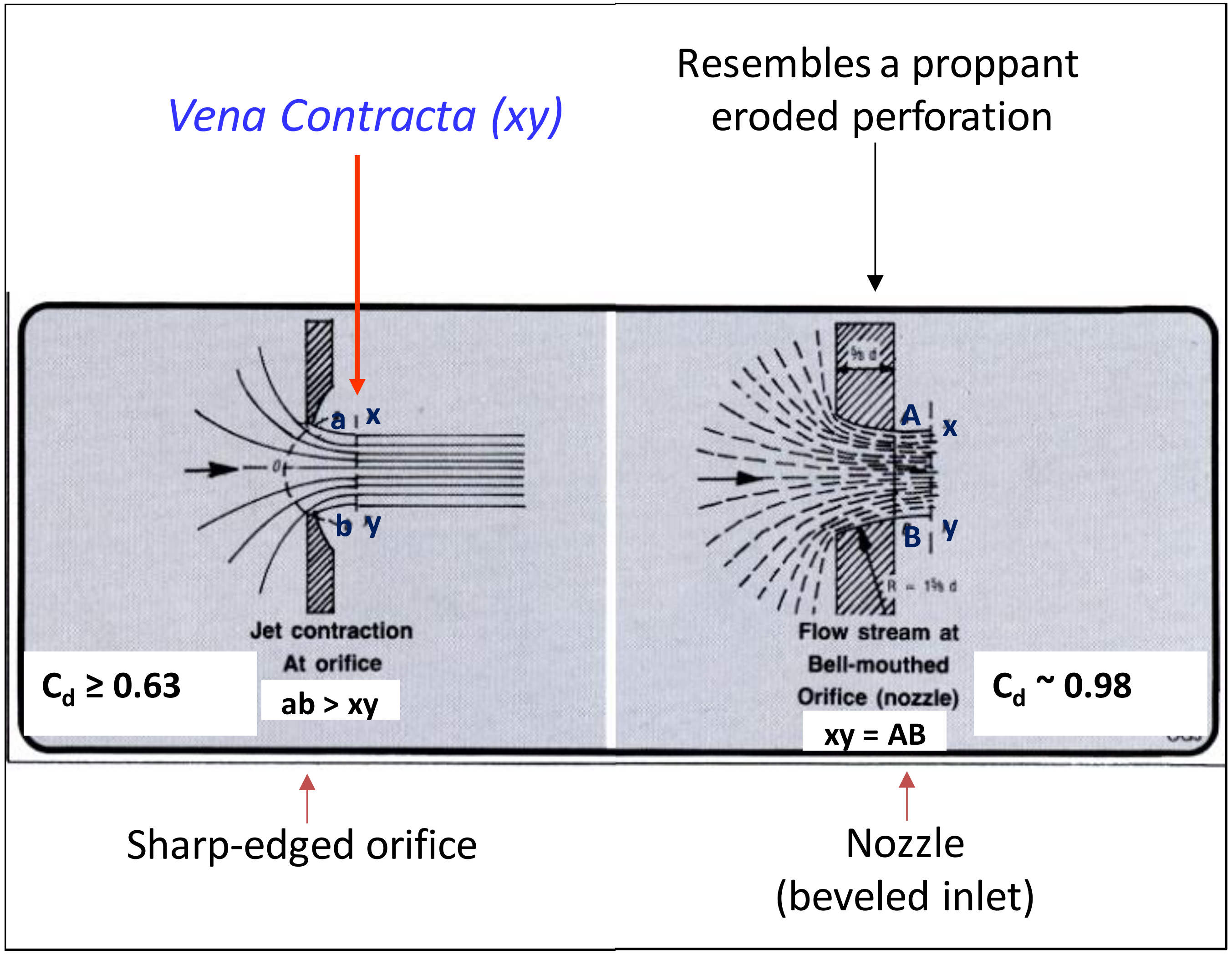
Predictive Equation for Pressure Drop Across a Perforation Entry Hole in Pipe

$$\Delta P_p = \frac{0.2369 \times Q^2 \times \rho}{C_d{}^2 \times N^2 \times D^4}$$

ΔP_p	= pressure drop across orifice/perforation, psi
Q	= injection rate, bbl/min
ρ (rho)	= fluid/slurry density, lb/gal
C_d	= discharge coefficient
N	= number of perforations
D	= orifice/ perforation diameter, in.

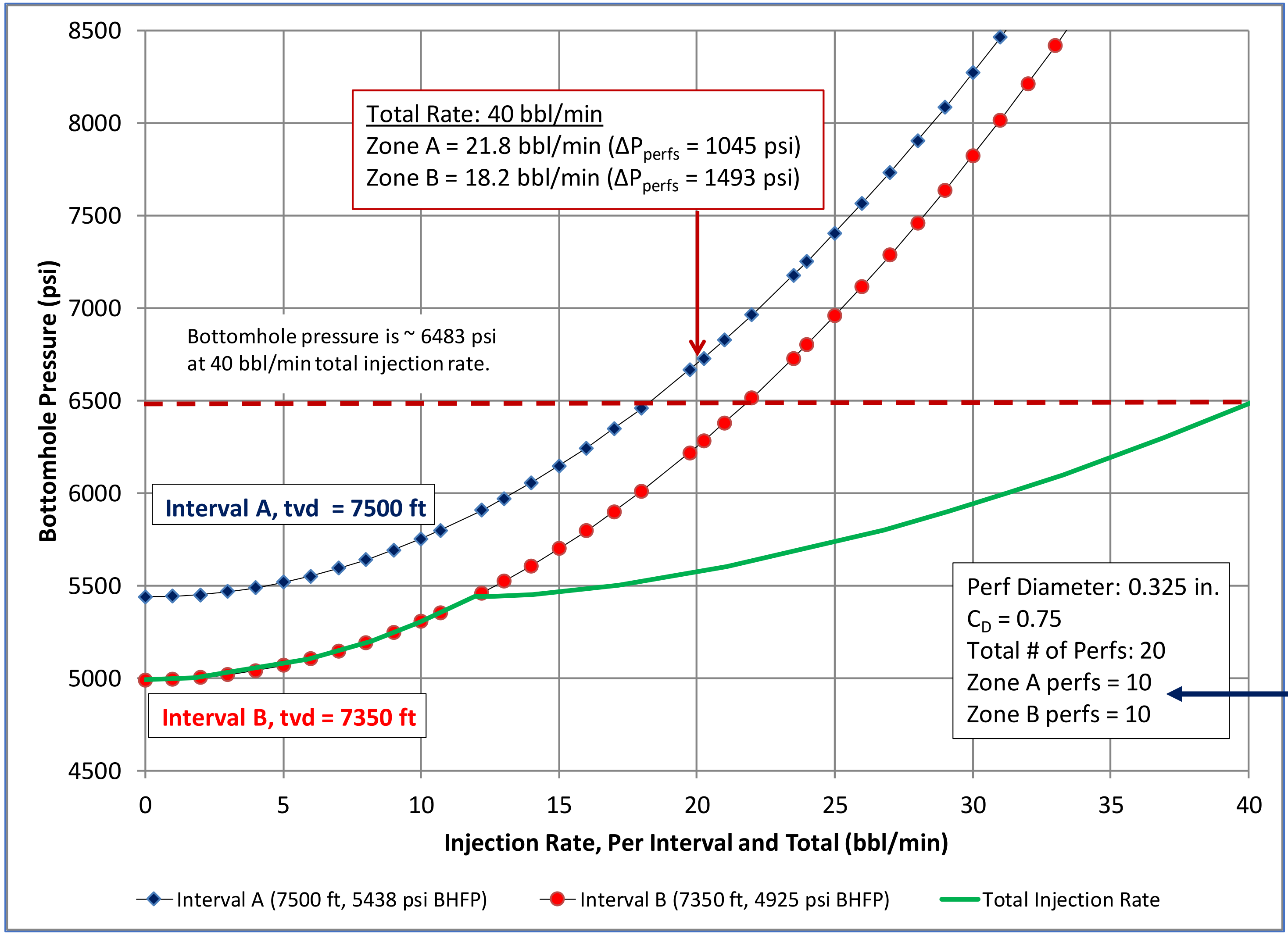
This equation is used to evaluate perforation friction pressure and is based on the Bernoulli theorem.

Flow Through an Orifice



Perforation inlet condition determines the discharge coefficient.

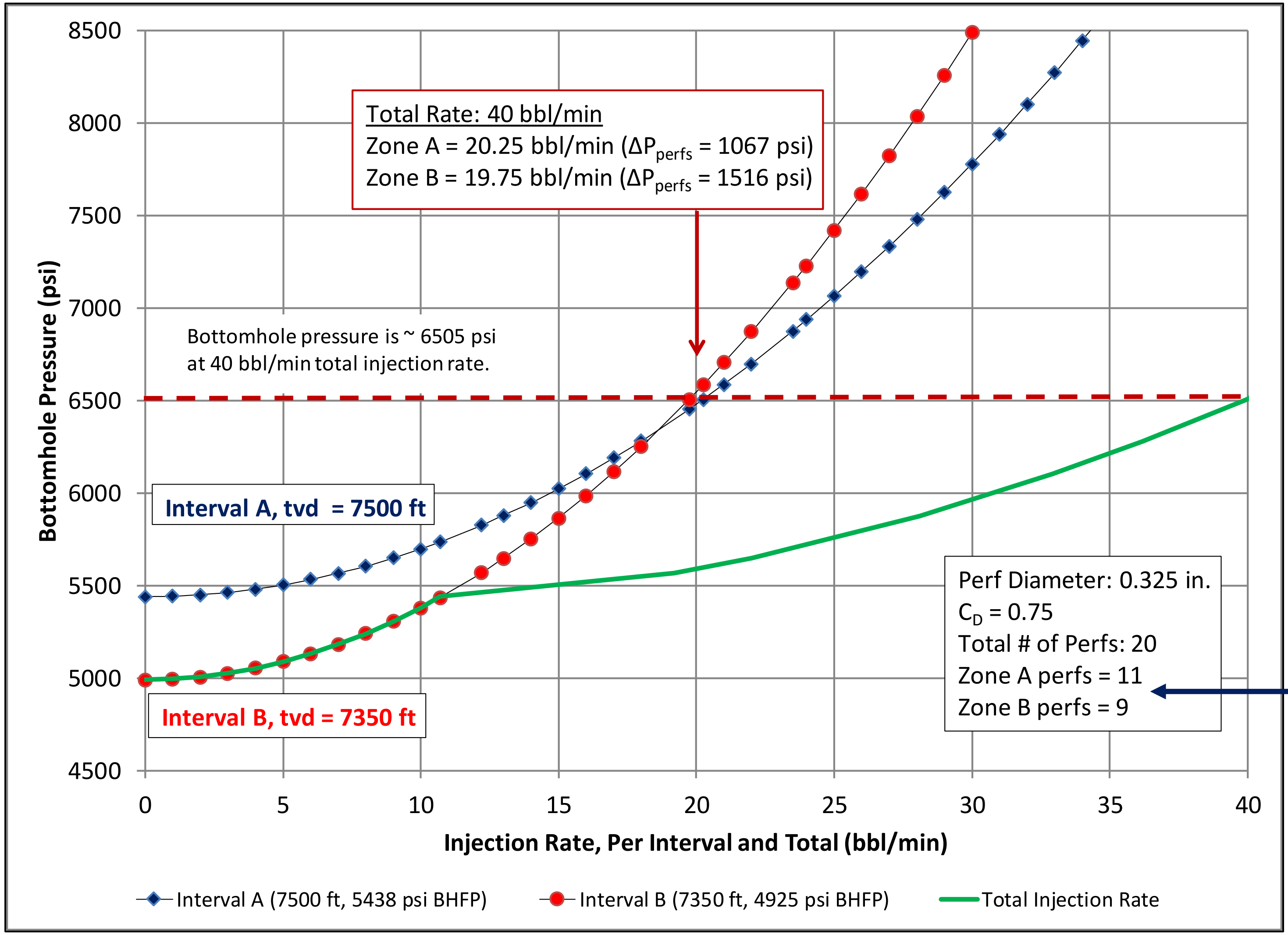
Conceptual Example of the Limited Entry Process



Equal weighting of perforations among intervals.

To achieve injection into all intervals during fracturing treatments, perforation friction must be greater than the maximum difference in fracturing pressure among intervals.

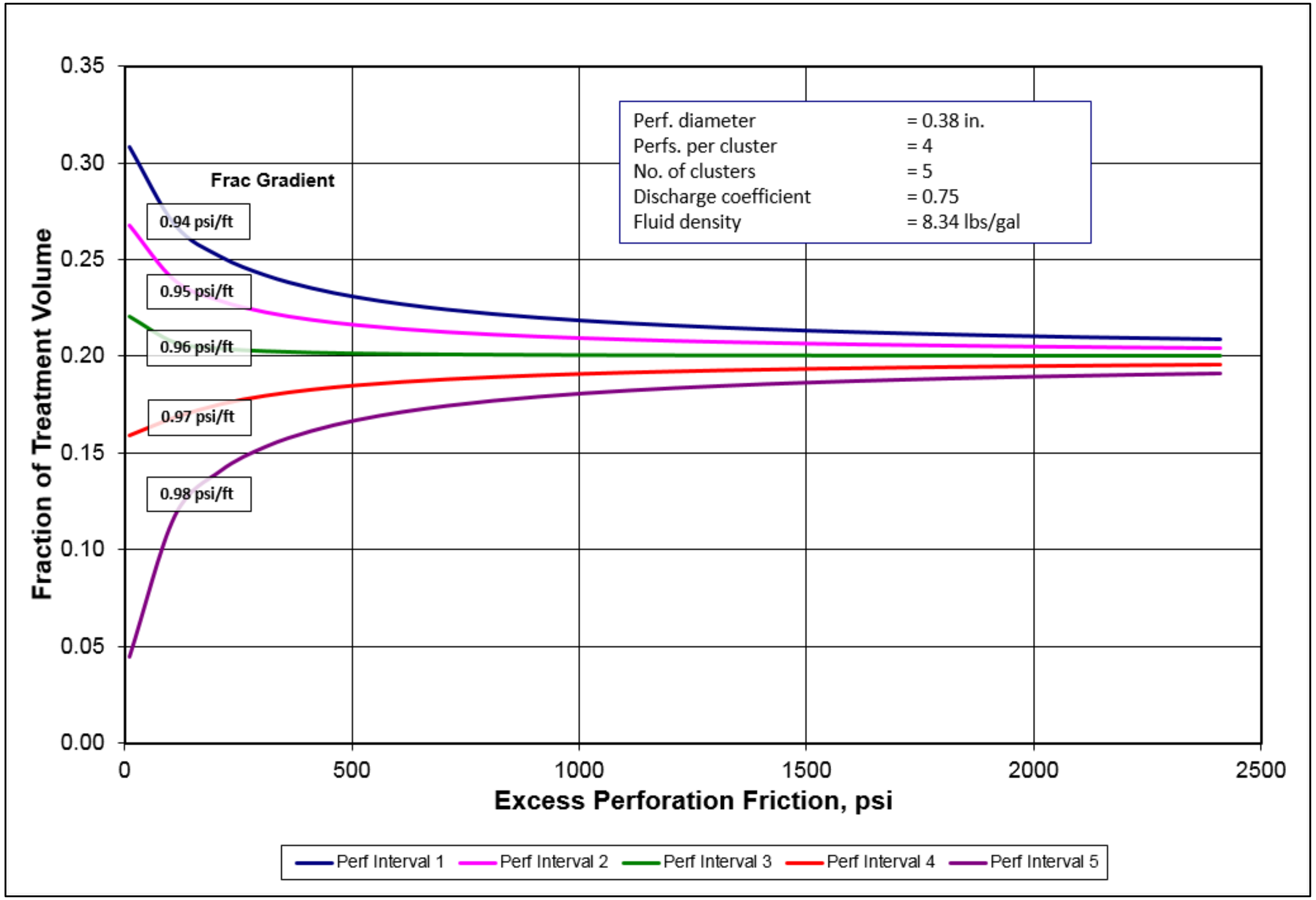
Conceptual Example of the Limited Entry Process



Unequal weighting of perforations among intervals.

Adjusting the number of perforations among intervals can lead to more uniform treatment distribution – if the difference in bottomhole fracturing pressure is known with certainty.

Excess Perforation Friction Pressure Enhances Treatment Control

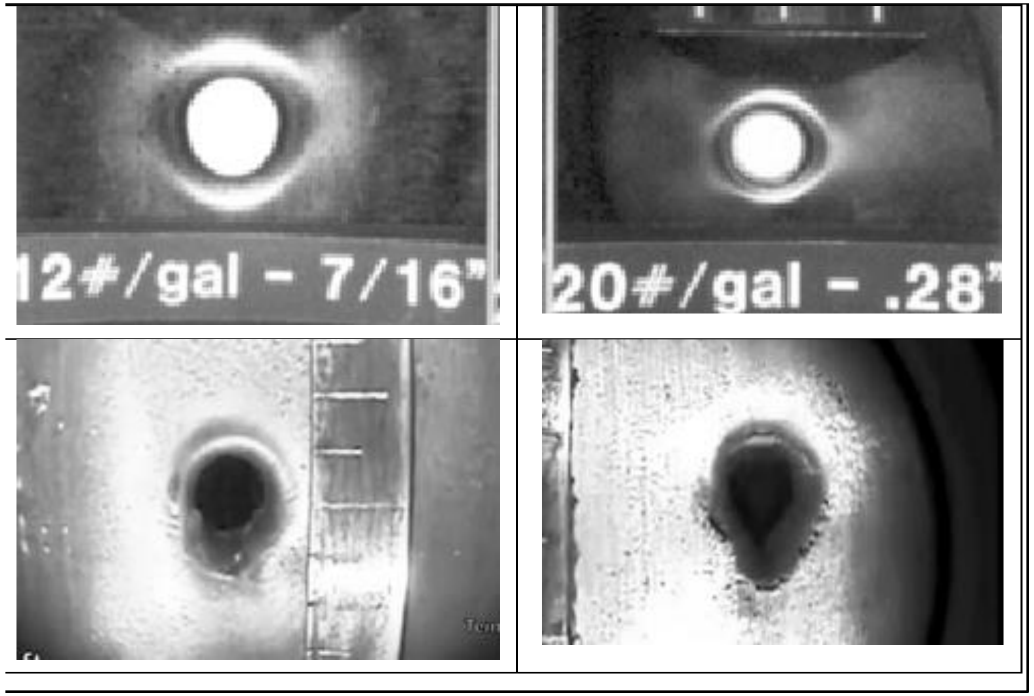


from paper SPE 194334

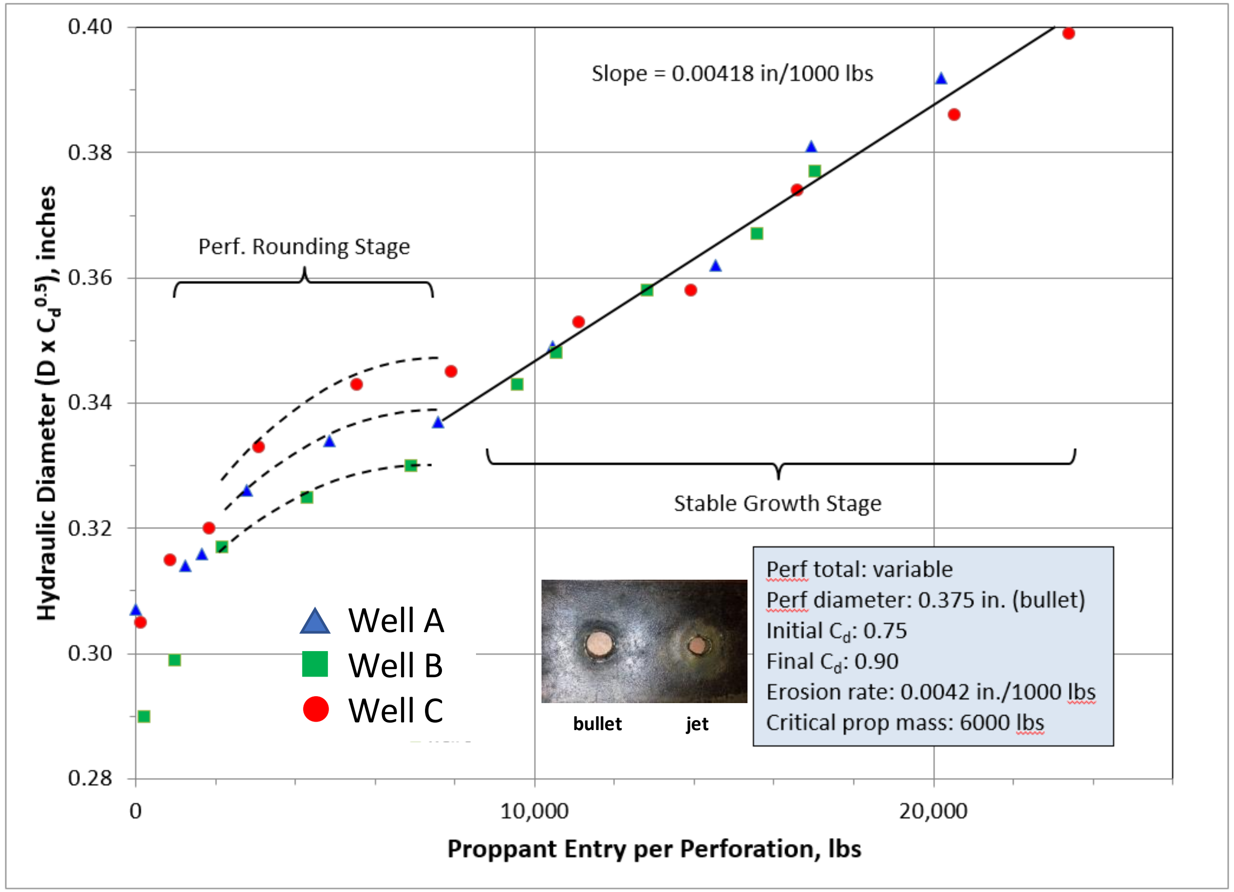
Excess perforation friction is additional to the pressure difference between intervals with the highest and lowest fracture propagation pressures. It improves the treatment distribution among intervals with dissimilar fracture propagation pressures.

Perforations Erode in a Two-Step Process

From SPE 15474: Crump, Conway (1988)



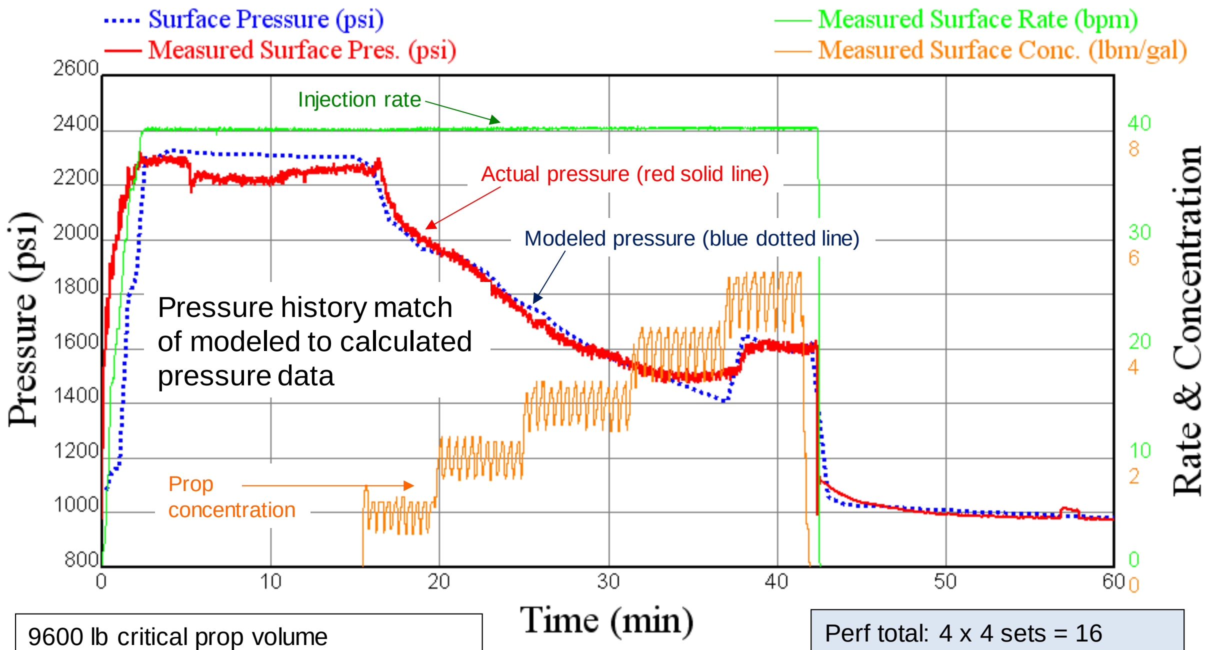
From SPE 194334: Cramer et al (2019)



From SPE 16189: Cramer (1987)

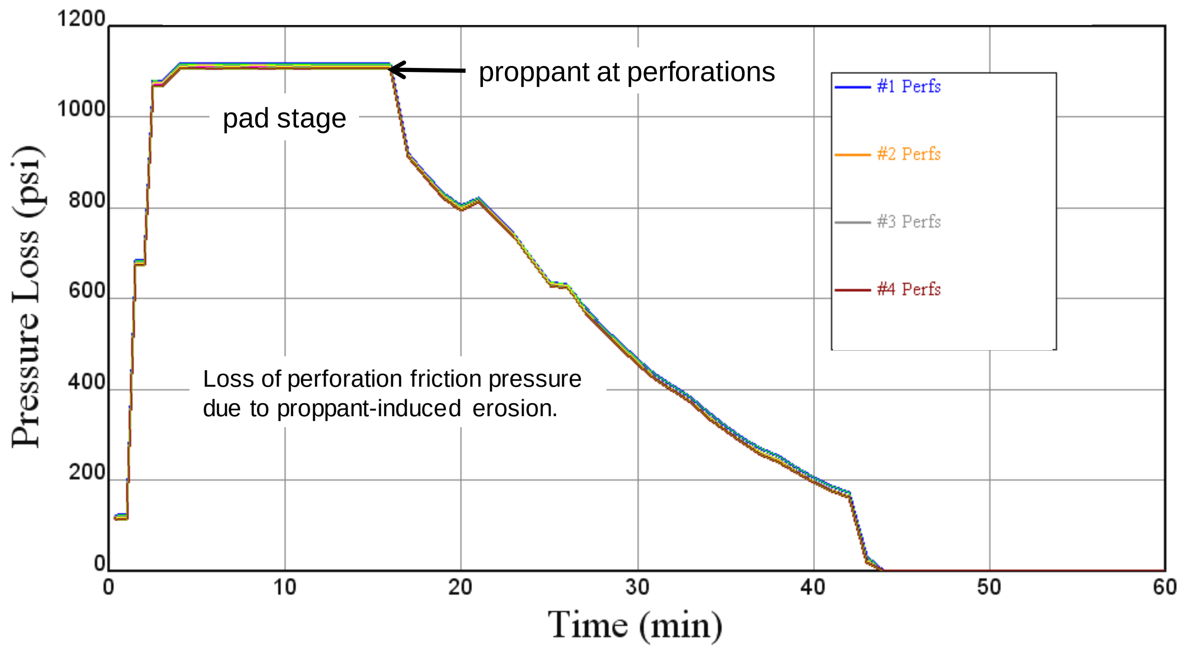
This is a finding from a case study in the DJ Basin and has been verified by post-treatment video-based imaging of perforations. The gain in hydraulic perforation (entry hole) diameter results in a loss of perforation friction. Case study pipe and proppant types: 4-1/2 in., 11.5 lb. N-80 casing and 20/40 mesh Northern sand.

Modeling Limited Entry Treatments and Perforation Erosion



9600 lb critical prop volume
6275 lb/perf during erosion phase
Estimated EOJ perf diameter = 0.57 in.

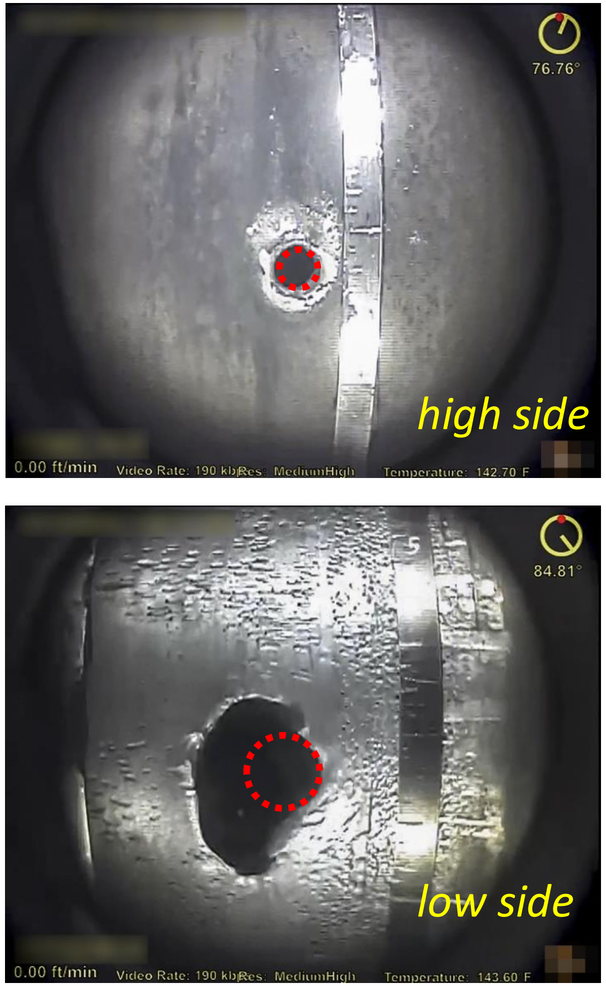
Perf total: 4 x 4 sets = 16
Perf diameter: 0.38
Initial discharge coef: 0.75
Final discharge coef: 0.93
Erosion rate: 0.03 in/1000 lbs
Critical prop mass: 600 lbs

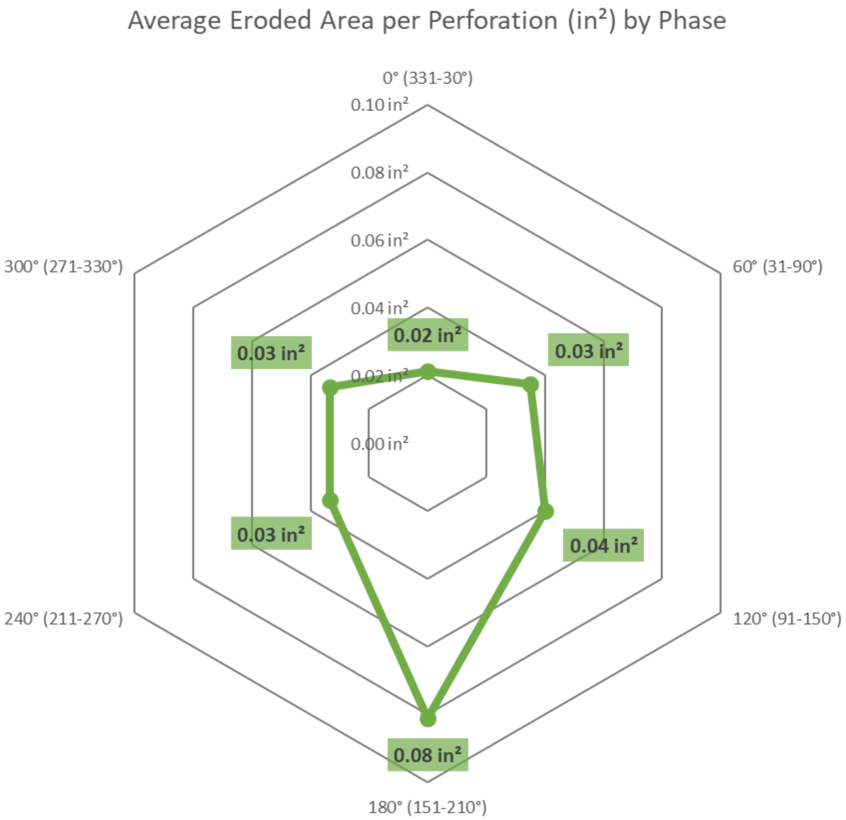


pipe: 7 in., 23 lb J-55 casing
proppant type: 12/20 mesh resin coated ceramic

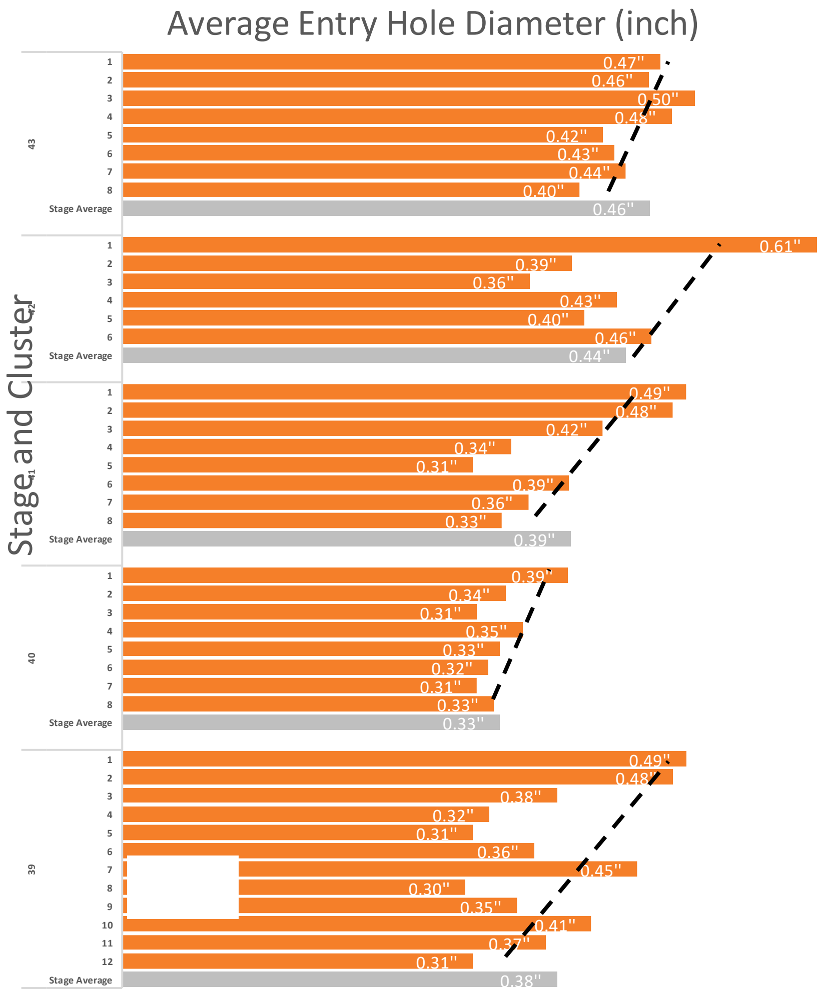
Perforation erosion can lead to loss of control in limited entry treatments.

Post-Treatment Imaging Reveals Phase and Heel Bias



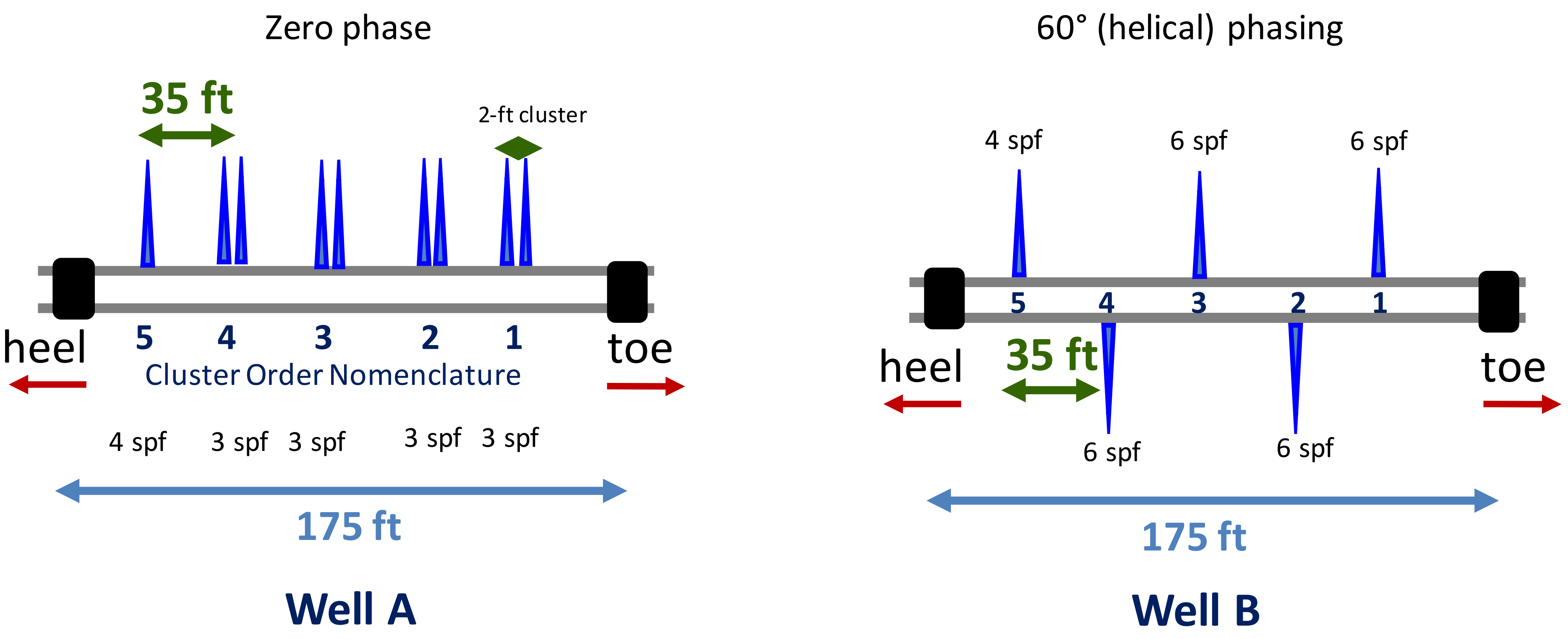


from paper SPE 194334



Estimated pre-erosion flow area of low side perforation was more than 3-fold greater than high side perforation.
Chart of average entry hole diameter by stage and cluster shows heel bias, possibly caused by stress shadowing.

Case Study: Limited Entry Treatments in a Well Spacing Pilot Project

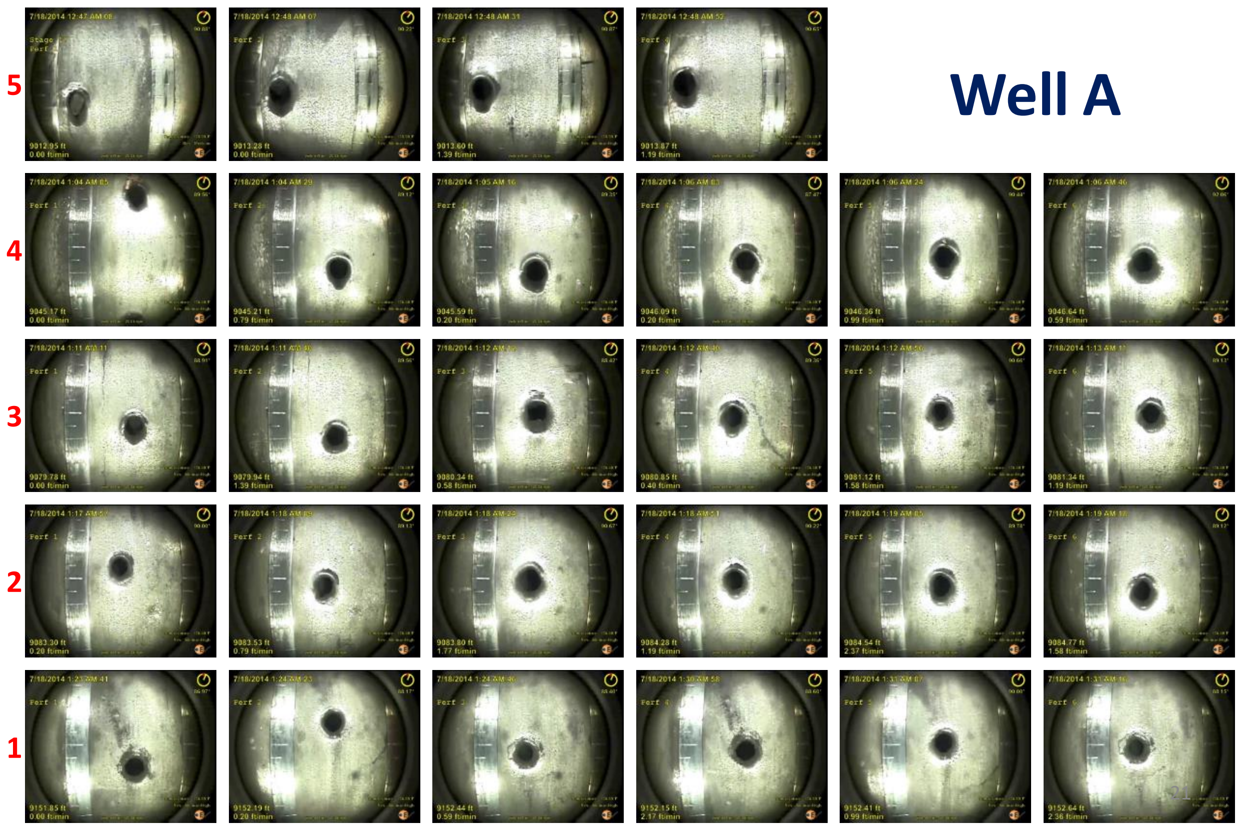


Standard frac stage configuration for case study wells A and B. Fiber enabling DAS and DTS measurements during hydraulic fracturing treatments was cemented in place along the bottom of the lateral in Well A.

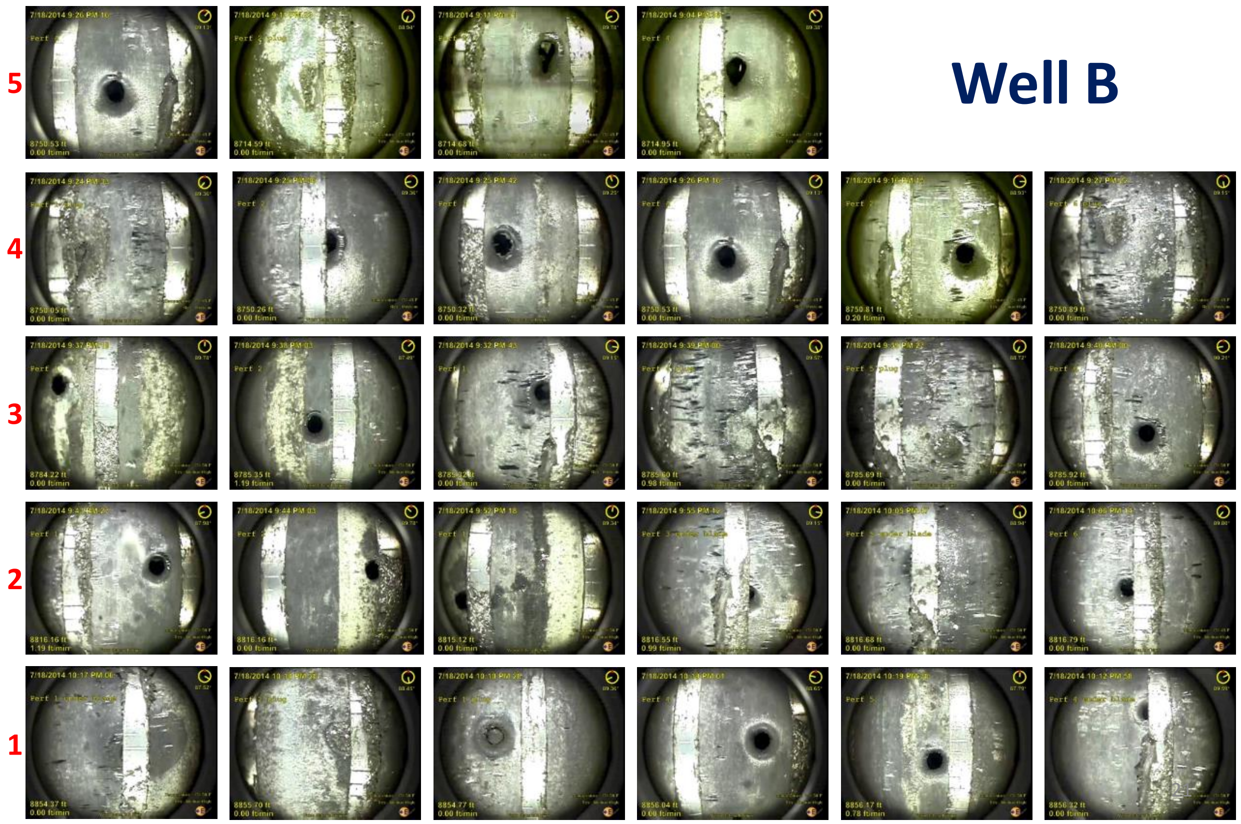
Case Study Treatment Basics

- Fracturing fluid: slick water
- Maximum injection rate: 85 bbl/min.
- Proppant concentration: up to 2.5 lb/gal.
- Frac stage volumes: 4000 gallons of 15% HCl acid + 319,000 gallons of slicked water + 350,000 lbs of proppant (100 mesh sand, 40/70 mesh sand, 40/70 mesh curable resin coated sand).
- Average treatment volumes per cluster: 63,000 gallons of slicked water + 70,000 lbs of proppant with an average injection rate of 17 bbl/min per cluster.
- The volume of proppant per perforation averaged 12,500 lbs.

Video-based Perforation Imaging Results



Zero-phase perforating, oriented to the high side of the well

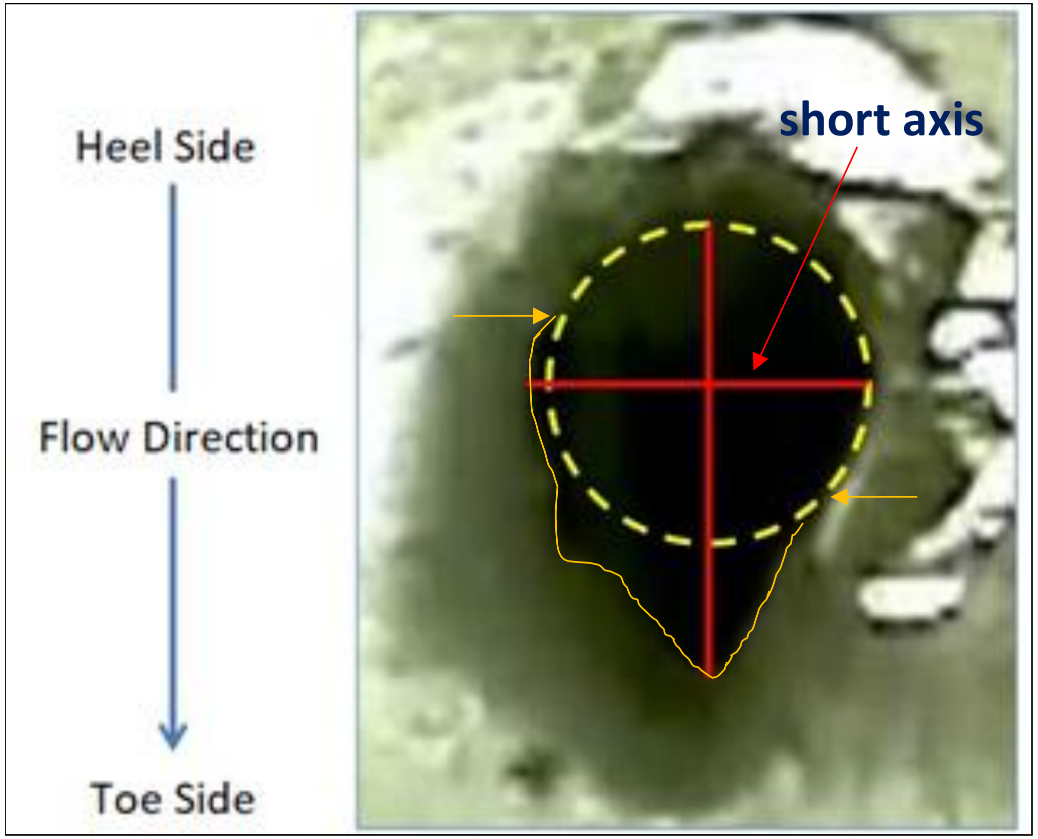


60° phasing, helical distribution around the well

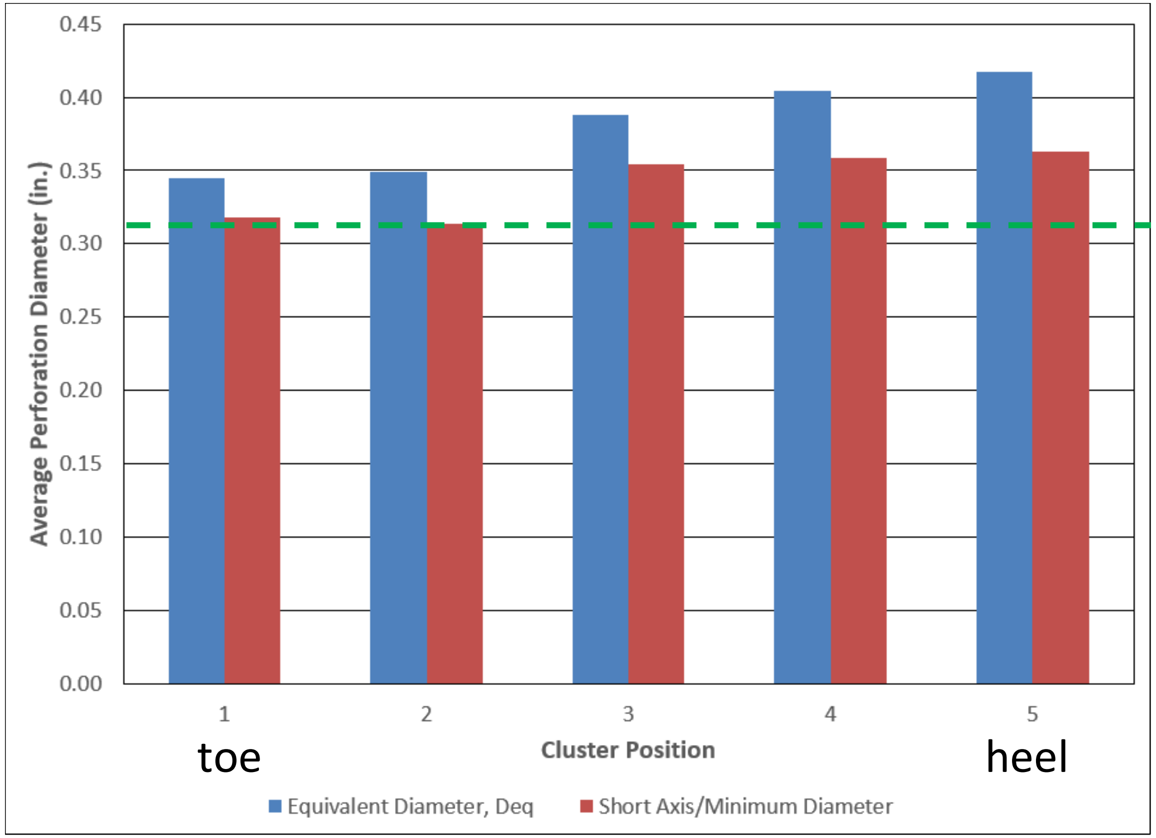
Cluster numerical ordering is from toe to heel (1 to 5). Oriented zero-phase perforating to the high-side of the wellbore provided superior visibility for video-based imaging and more uniform entry-hole size.

Erosion by Cluster, Well A

Ending versus initial perforation diameter



Short axis diameter of uneroded part of the exit hole used for estimating the initial perforation diameter

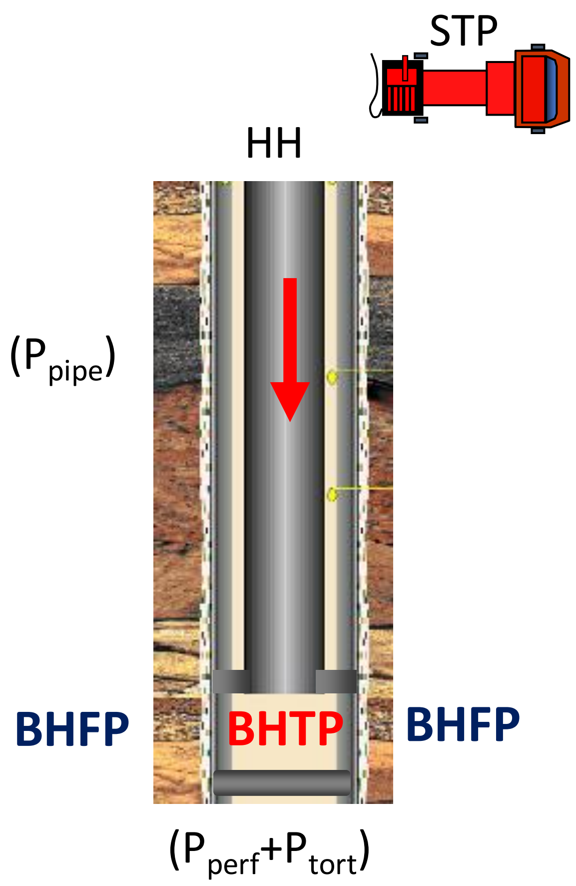


Difference between D_{eq} and initial hole size indicates erosion

Treating Pressure Components

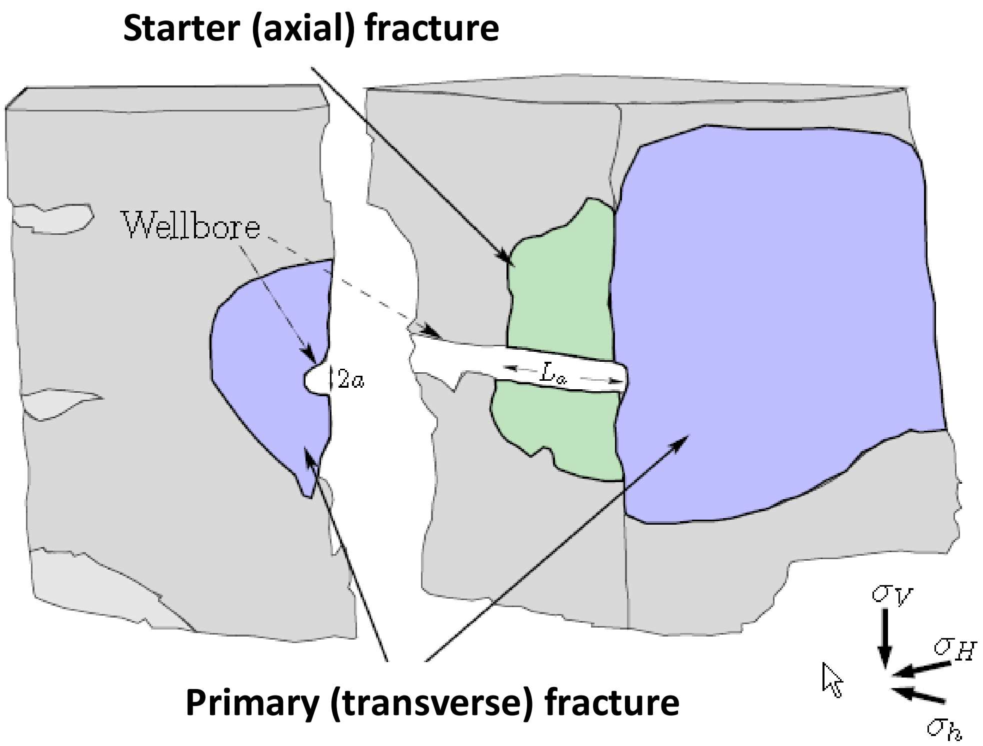
- $BHTP = STP + HH - P_{pipe}$
- $BHFP = STP + HH - P_{pipe} - P_{perf} - P_{tort}$
- $BHFP = ISIP + HH$

BHTP	= Bottomhole pressure in wellbore
BHFP	= Bottomhole pressure in fracture
STP	= Wellhead treating pressure
HH	= Hydrostatic head/pressure
ISIP	= Instantaneous shut in pressure
P_{pipe}	= Pipe friction
P_{perf}	= Perforation entry hole friction
P_{tort}	= Tortuosity (friction from perforations to fracture)



Pressure is typically measured near the wellhead. Rate/friction pressure correlations and tracking software are used to calculate downhole pressure within and just outside of the wellbore.

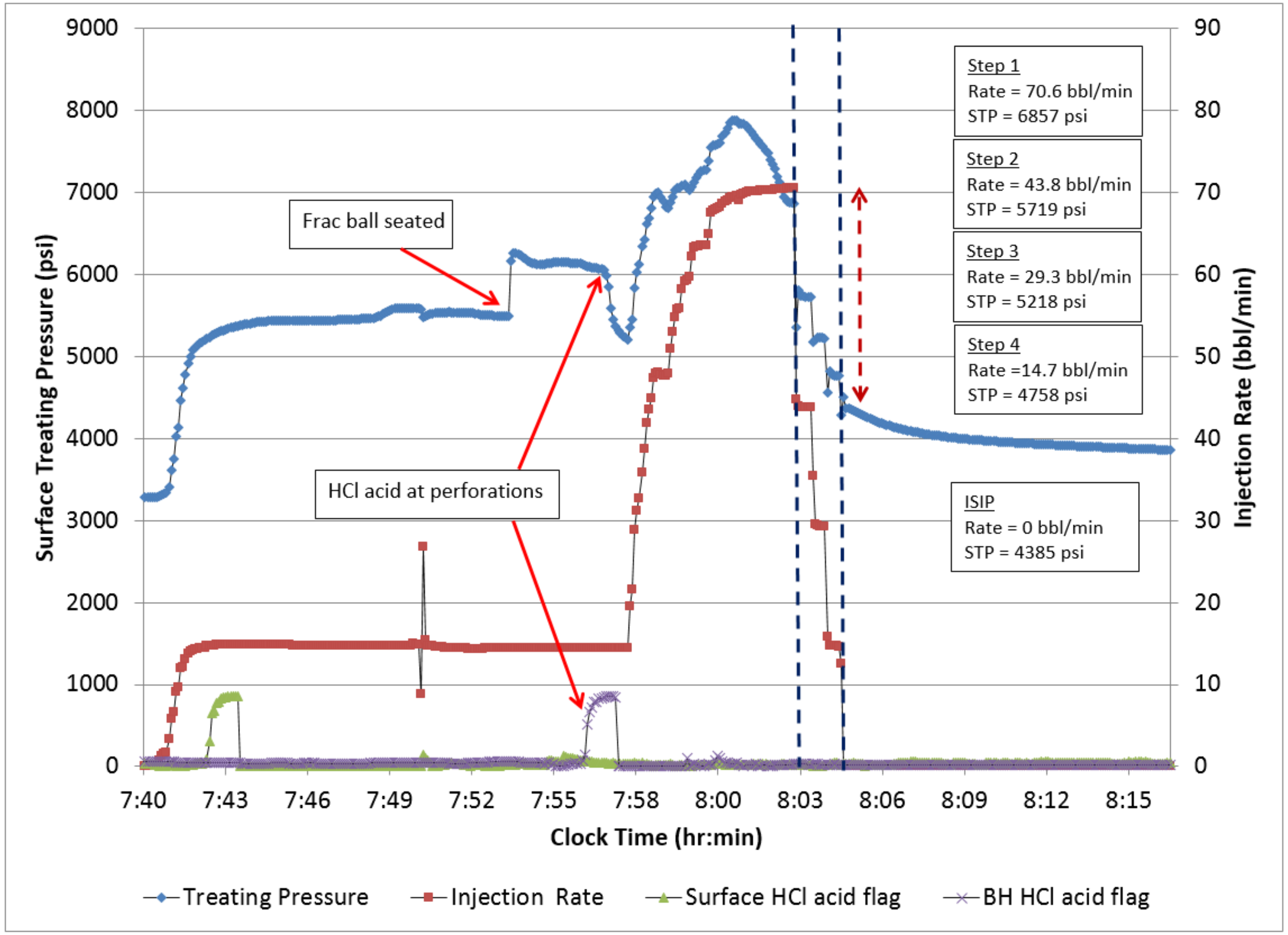
Axial and Transverse Fracture Components in a Horizontal Borehole



Weijers et al, 1994

Dislocation between perforations and primary fracture can initially result in significant friction pressure (P_{tort}).

Step Rate Test for Evaluating Near Wellbore Friction



Equations:

$STP = BHFP - HH + P_{Pipe} + P_{NWF}$

$ISIP = BHFP - HH$

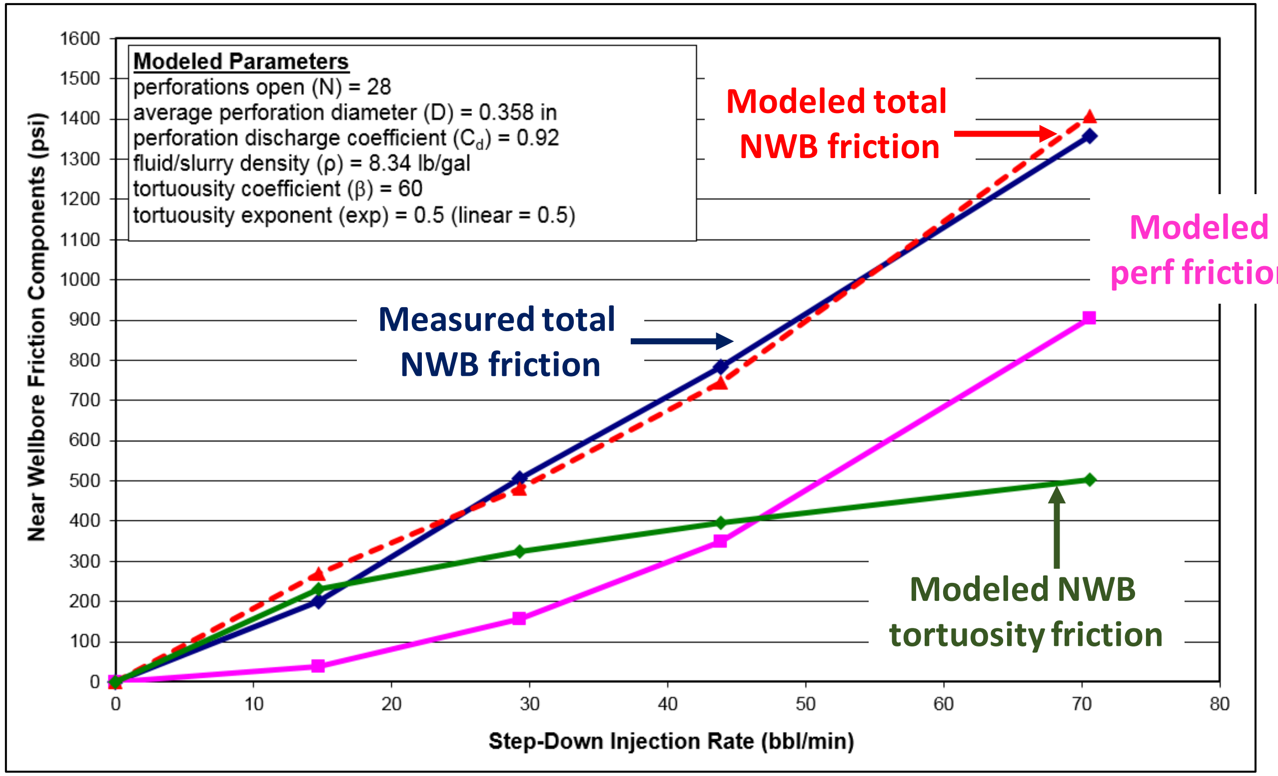
$BHTP = BHFP + P_{NWF}$

$P_{NWF} = STP - ISIP - P_{pipe}$

$P_{NWF} = P_{Perf} + P_{Tort}$

Surface treating pressure (STP) – pipe friction (P_{pipe}) – instantaneous shut in pressure (ISIP) = near wellbore friction (P_{NWF})

Step Rate Test Analysis Results



Model Inputs

fluid density, ρ (lb/gal)	perforation diameter, D (in)	discharge coefficient (C_d)	number of perforations, N	tortuosity exponent, t-exp	tortuosity coefficient, β
8.34	0.358	0.92	28	0.5	60

Calculations

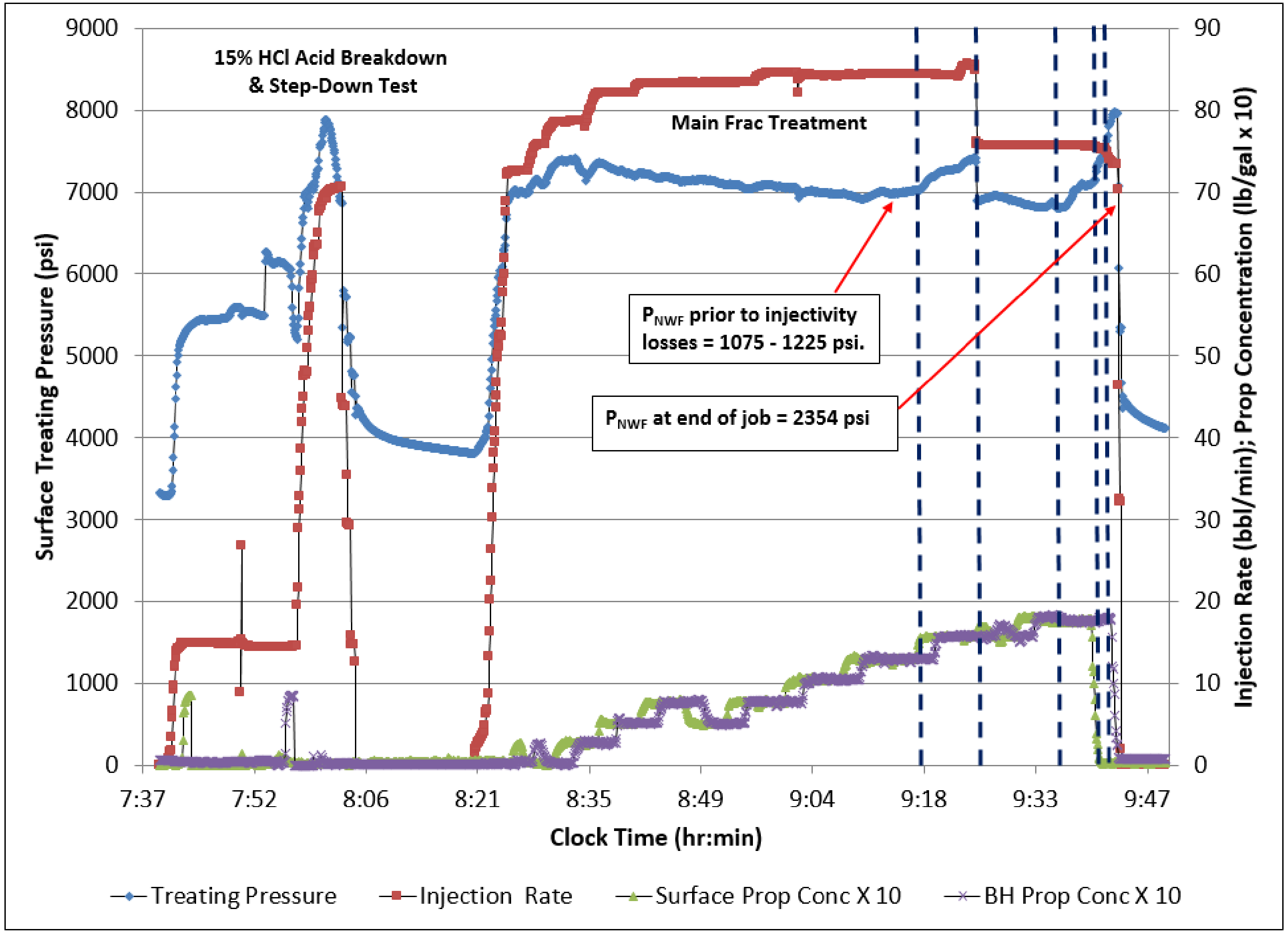
step-down rate, Q (bbl/min)	surface treating pressure, STP (psi)	calculated P_{pipe} (psi)	**calculated P_{NWF} (psi)**	modeled P_{perfs} (psi)	modeled $P_{tortousity}$ (psi)	**modeled P_{NWF} (psi)**
0	4385	0	**0**	0	0	**0**
14.7	4758	172	**201**	39	230	**269**
29.3	5218	326	**507**	156	325	**480**
43.8	5719	550	**784**	348	397	**745**
70.6	6857	1113	**1359**	903	504	**1408**

$$P_p = \frac{0.2369 \ x \ Q^2 \ x \ \rho}{C_d{}^2 \ x \ N^2 \ x \ D^4}$$

NWB tortuousity = tortuousity coefficient (β) x $Q^{t\text{-}exp}$

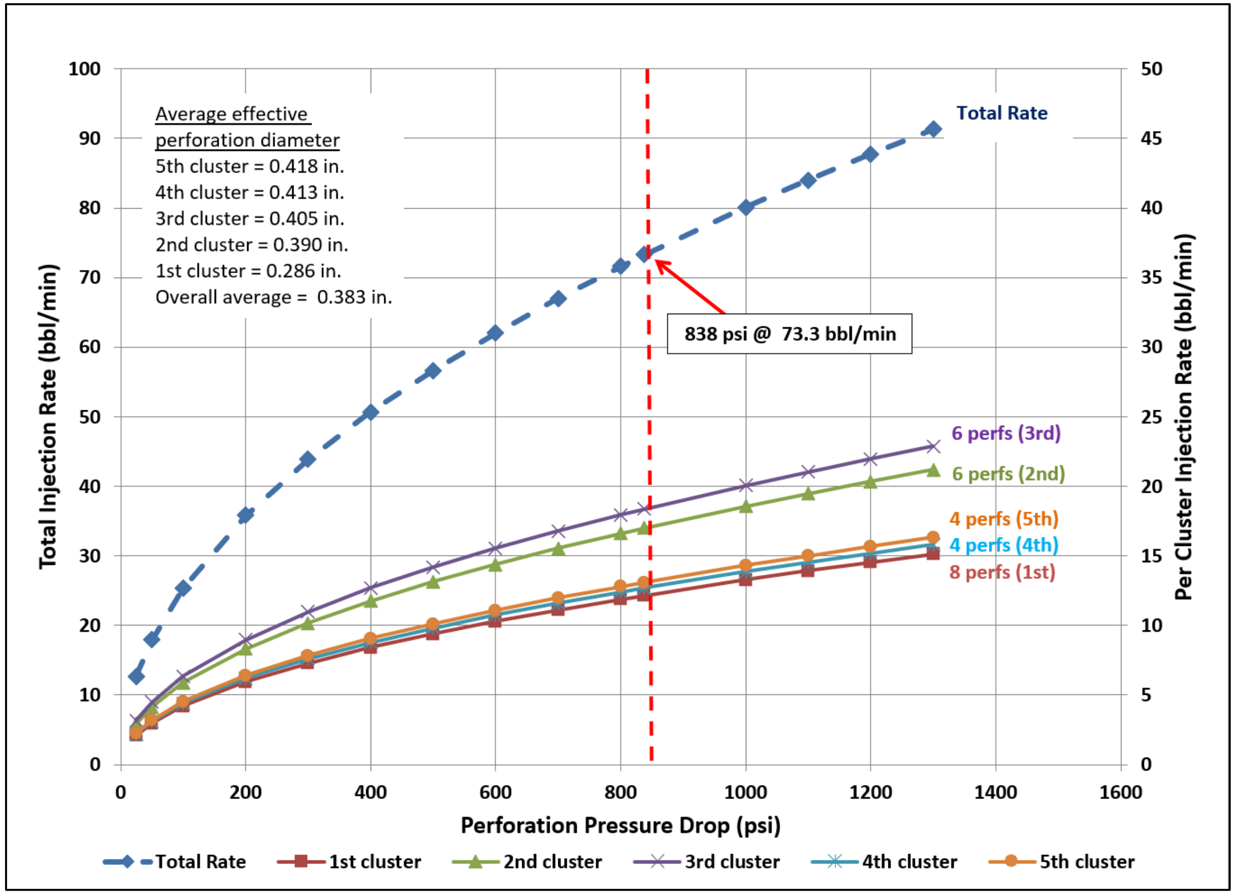
Well A, Stage 21: best-fit history match of modeled with calculated (actual) total near-wellbore friction

Treatment Parameter Plot: Well A, Stage 21



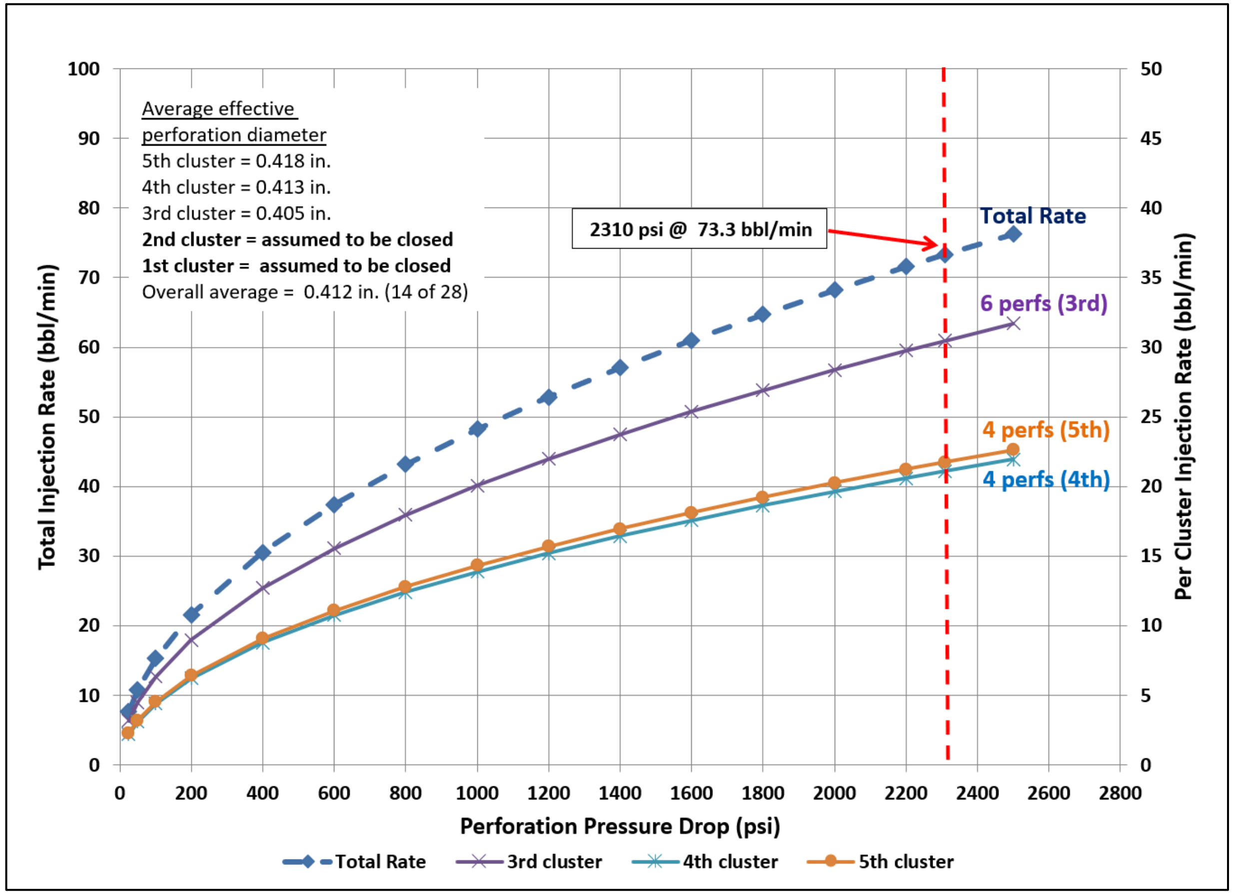
Vertical blue dashed lines indicate potential losses of injectivity into perforations (4-6 episodes).

Calculated Perforation Friction at End of Job: Well A, Stage 21



28 open perforations

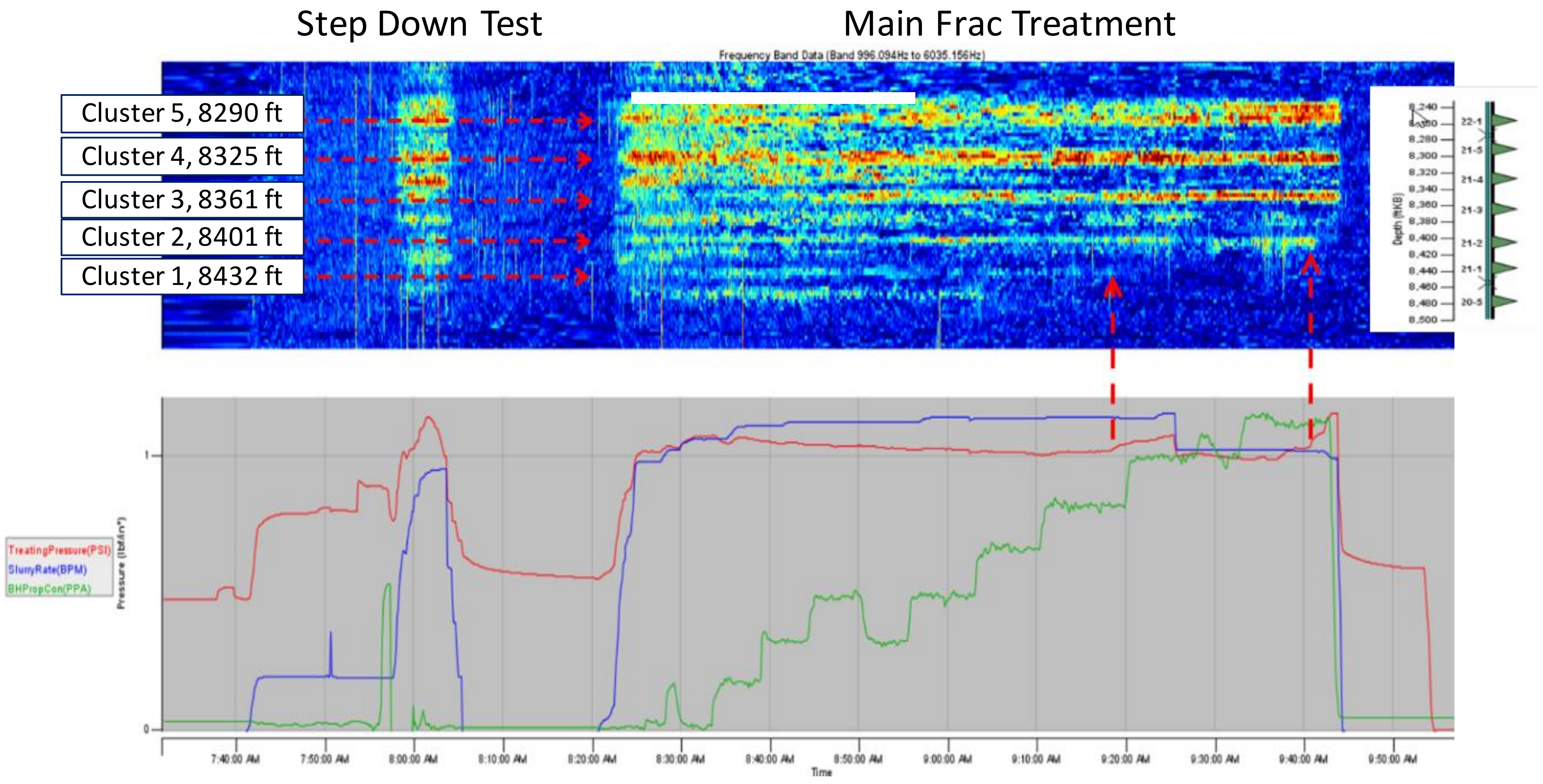
All perforations are assumed to be open. There is a large discrepancy between measured (2354 psi) and calculated/ modeled perforation/near-wellbore friction (838 psi).



14 open perforations

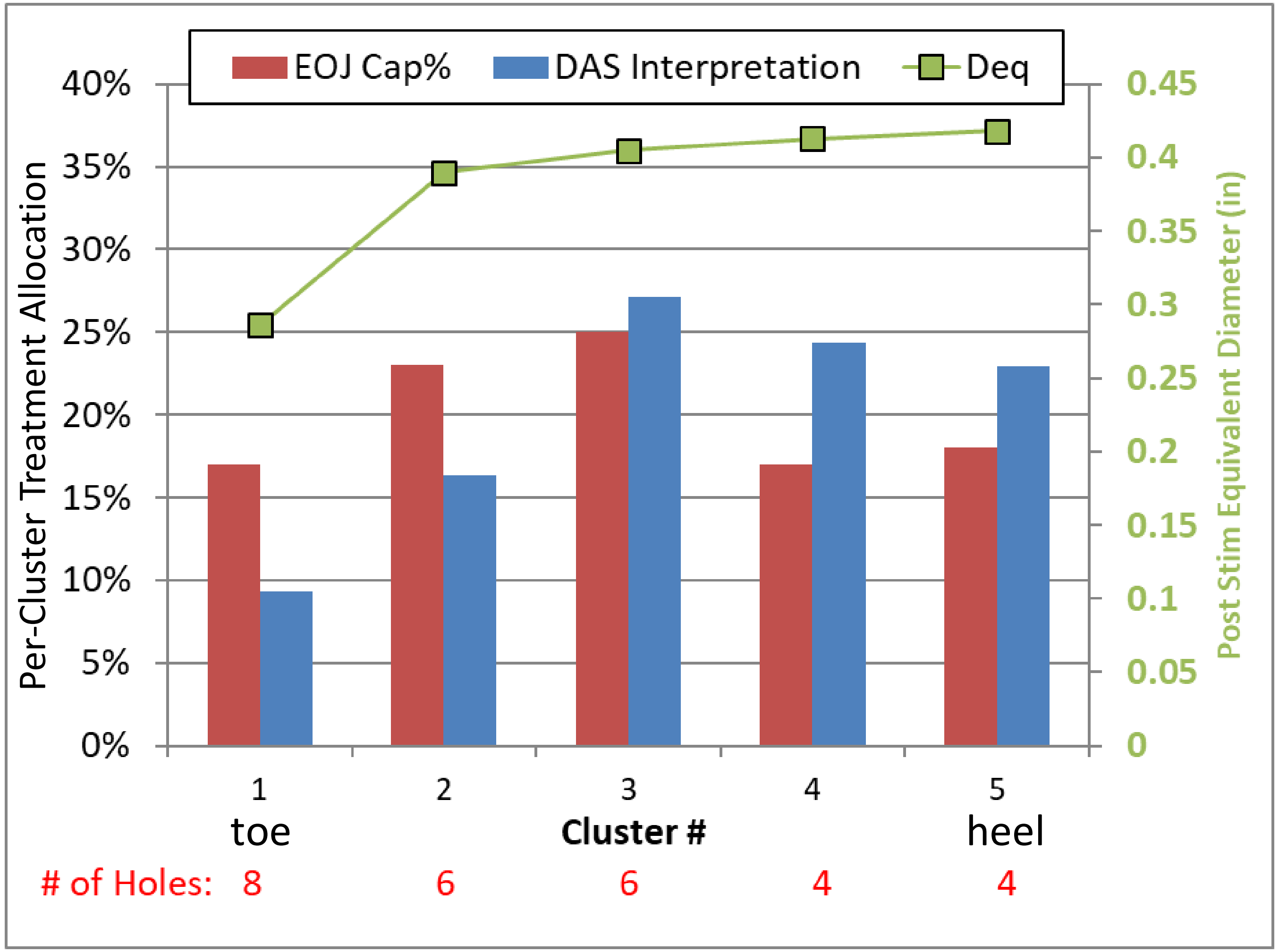
Reduced number of open perforations, leading to good agreement with measured and modeled perforation friction. This analysis was supported by the DAS data.

DAS Waterfall Plot: Well A, Stage 21



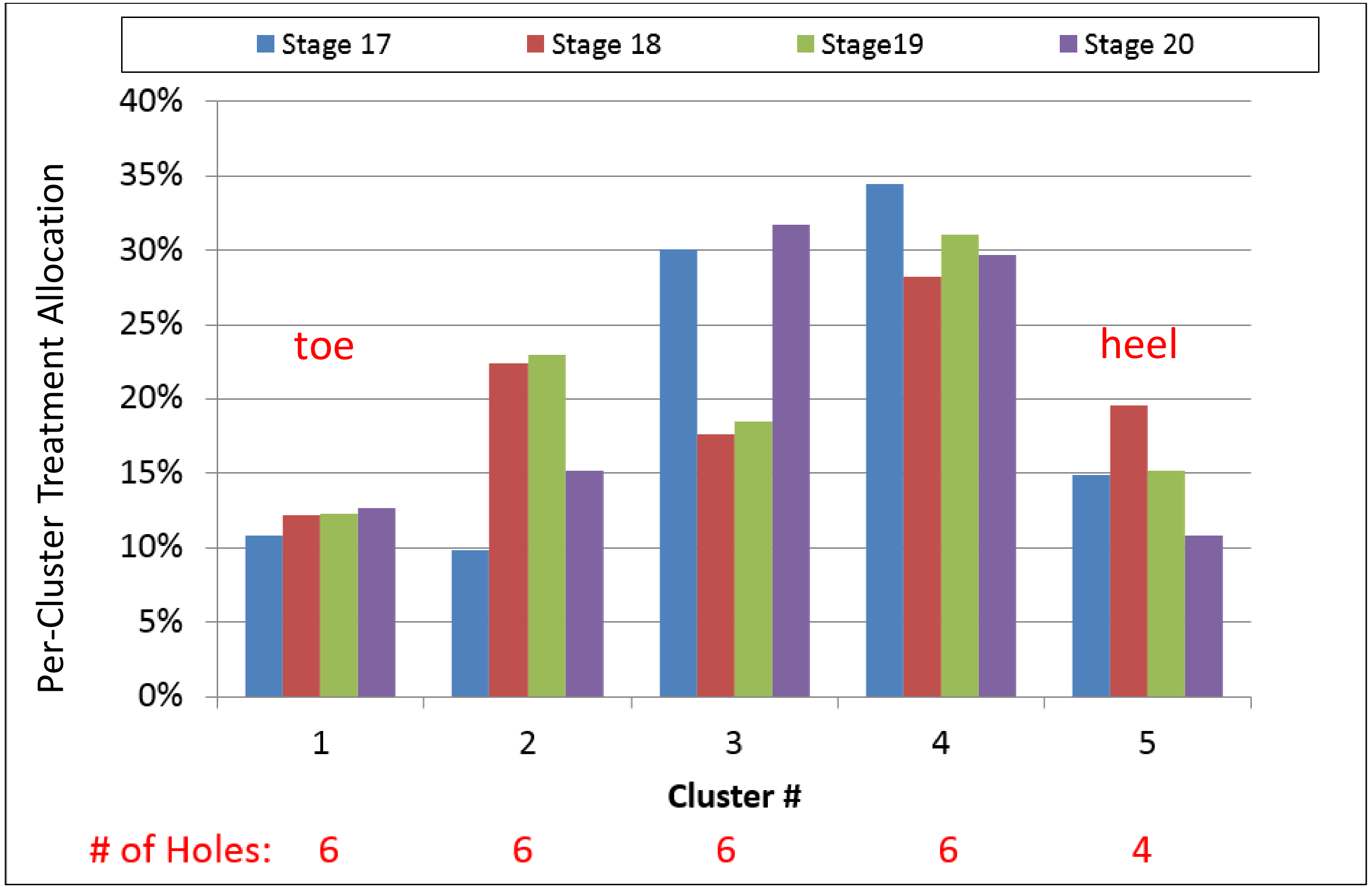
Termination in DAS signal in two of the five clusters corresponded with two rapid treating pressure increases, suggesting screenouts in Clusters 1 and 2.

Comparison of Treatment Allocation Methods: Well A, Stage 21



Significantly undersized perforations led to under-treatment of Cluster 1

DAS-Based Treatment Allocation, Standard Perforation Distribution



Significantly reduced perforation density in Cluster 5 led to over-correction of heel bias.

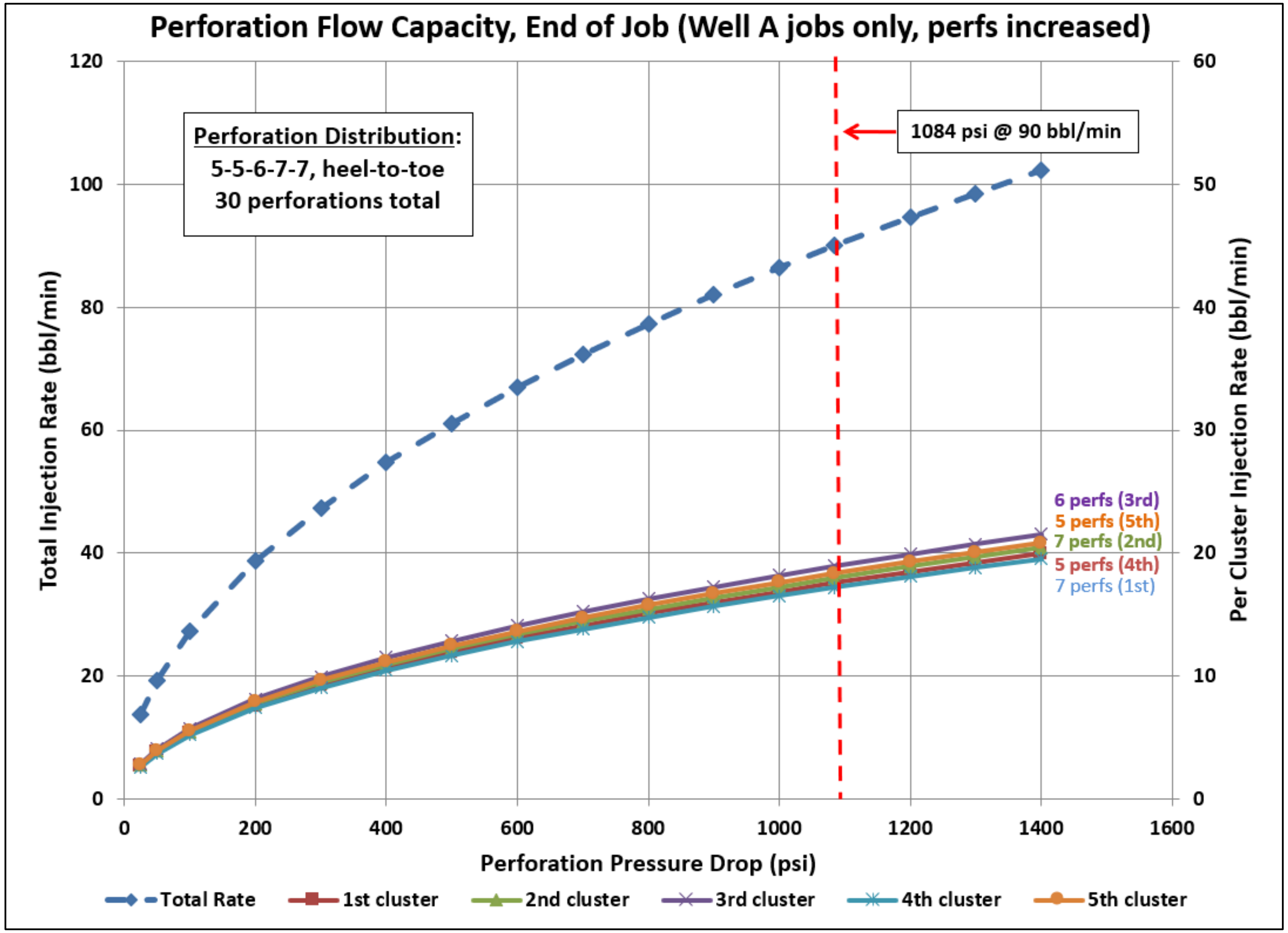
Hypothetical Perforation Redesign

<u>Average Effective Entry Hole Diameter</u>

Cluster 5 = 0.417 in.
Cluster 4 = 0.404 in.
Cluster 3 = 0.387 in.
Cluster 2 = 0.349 in.
Cluster 1 = 0.345 in.

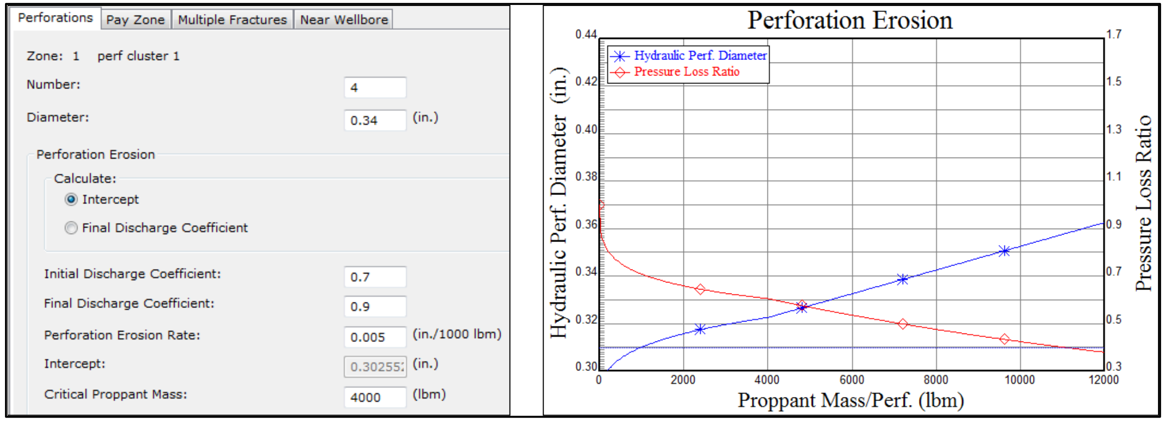
<u>Injection Rate</u>

Cluster 5 = 18.3 bbl/min
Cluster 4 = 17.2 bbl/min
Cluster 3 = 18.9 bbl/min
Cluster 2 = 18.0 bbl/min
Cluster 1 = 17.6 bbl/min



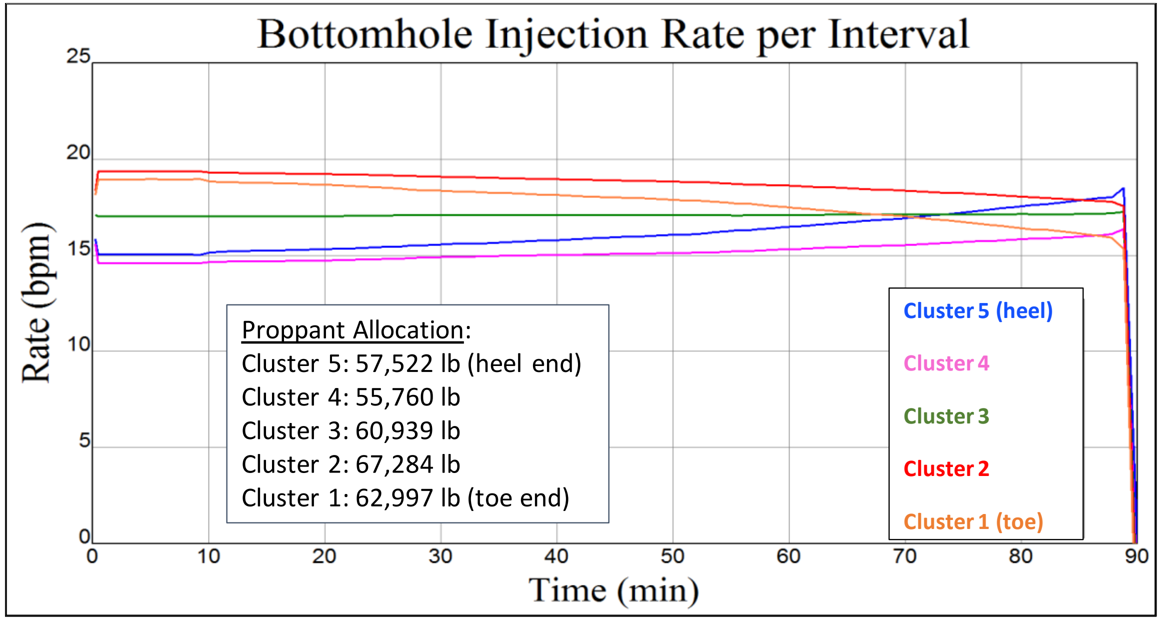
Using the average end-of-job equivalent entry hole diameter for the case study as a starting point, perforations were distributed to provide a nearly-uniform injection rate among clusters.

Forward Modeling of Redesigned Perforation Scheme



Interactive perforation erosion module

Incremental stress from previous fracture stage ~ 400 psi in toe-cluster region, decreasing toward the heel cluster



Perforation distribution of 5-5-6-7-7, heel to toe, led to improved treatment allocation.
This result was dependent upon achieving an equivalent diameter for all perforations.

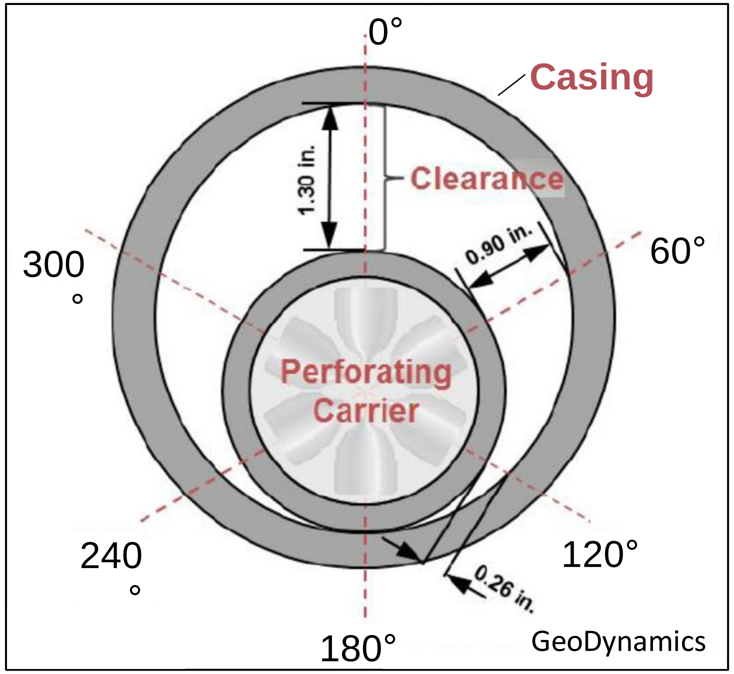
Eagle Ford Experience

- South Texas, large scale development program, normal faulting environment: $\sigma_V > \sigma_{H\text{-}max} > \sigma_{h\text{-}min}$.
- Oriented perforating was first applied 4-5 years ago based on changes in job design leading to 4 perforations or fewer per cluster. Operational problems with orienting system and claims of consistent diameter charges by perforating vendors led to discontinuation.
- Lookback study indicated wells utilizing oriented perforating exhibited significantly greater normalized EUR (actual EUR divided by "type curve" EUR) as compared to same-vintage wells utilizing non-oriented perforating.
- Did a single-well trial in 2019 comparing oriented and non-oriented perforating. This case was documented in Snyder, J., Cramer, D., White, M. *Improved Treatment Distribution Through Oriented Perforating*. **Paper SPE-204203-MS.** It was a keynote presentation at the 2021 SPE Hydraulic Fracturing Conference in May.
- Highlights from that study are shown in the following slides. Perforation entry hole dimensions were derived by analyzing images obtained in a post-treatment video-based wellbore survey.

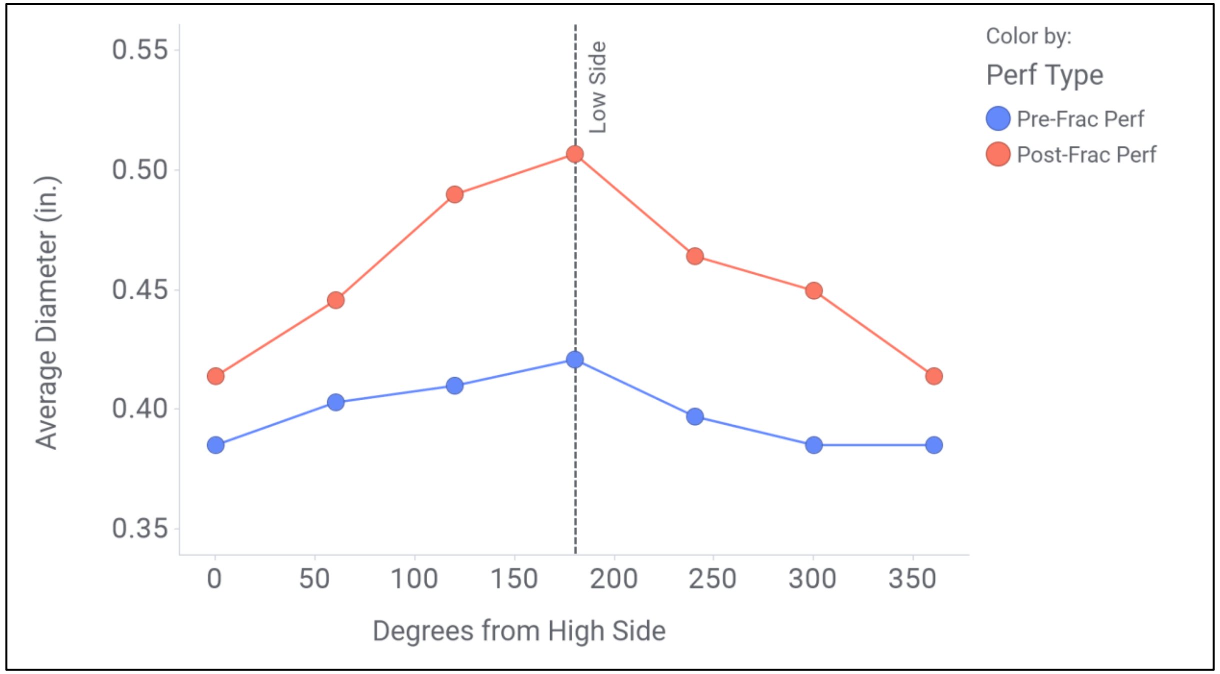
South Texas Case Study: Limited Entry and Perforating Gun Phasing

Reasons for evaluating:

1. Perforating creates **larger holes on bottom** and smaller holes on top
2. Gravity segregation causes **proppant to preferentially go to holes on the bottom**
3. Larger holes will take more flow rate and **erode faster**



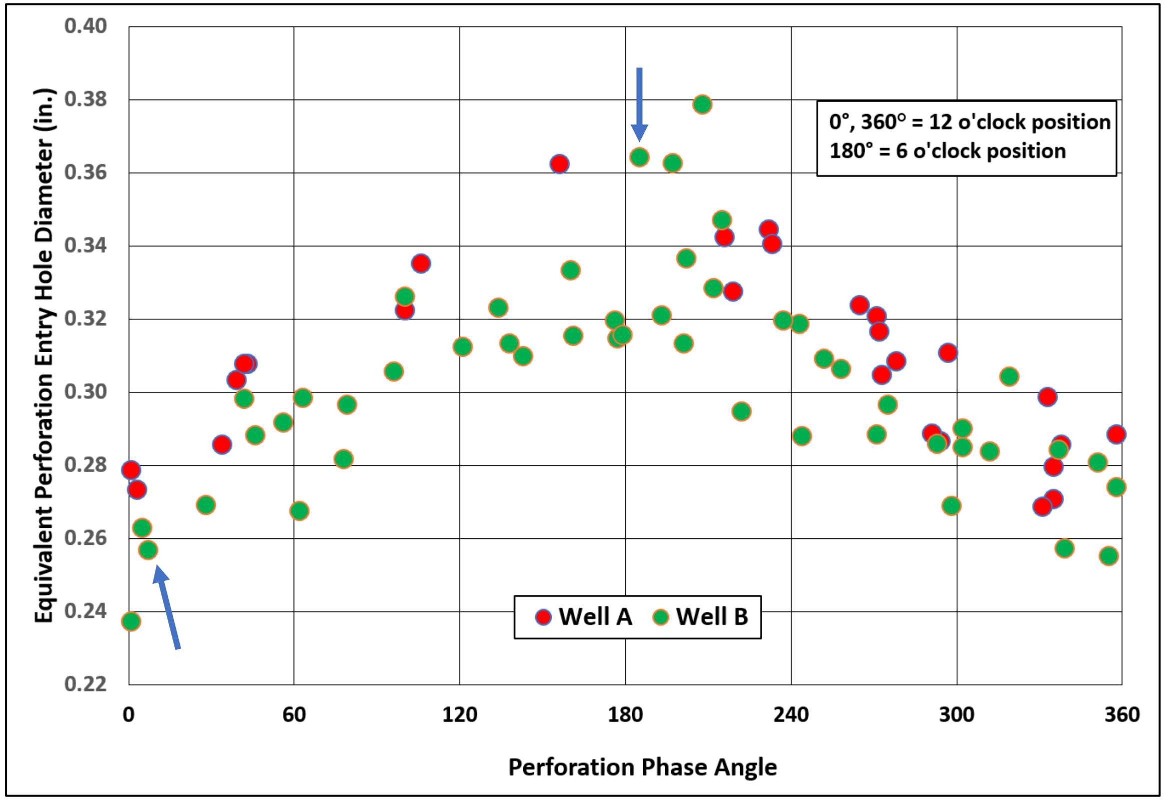
Cross-Section of Perf Gun Inside Casing



Perf Diameter by Orientation

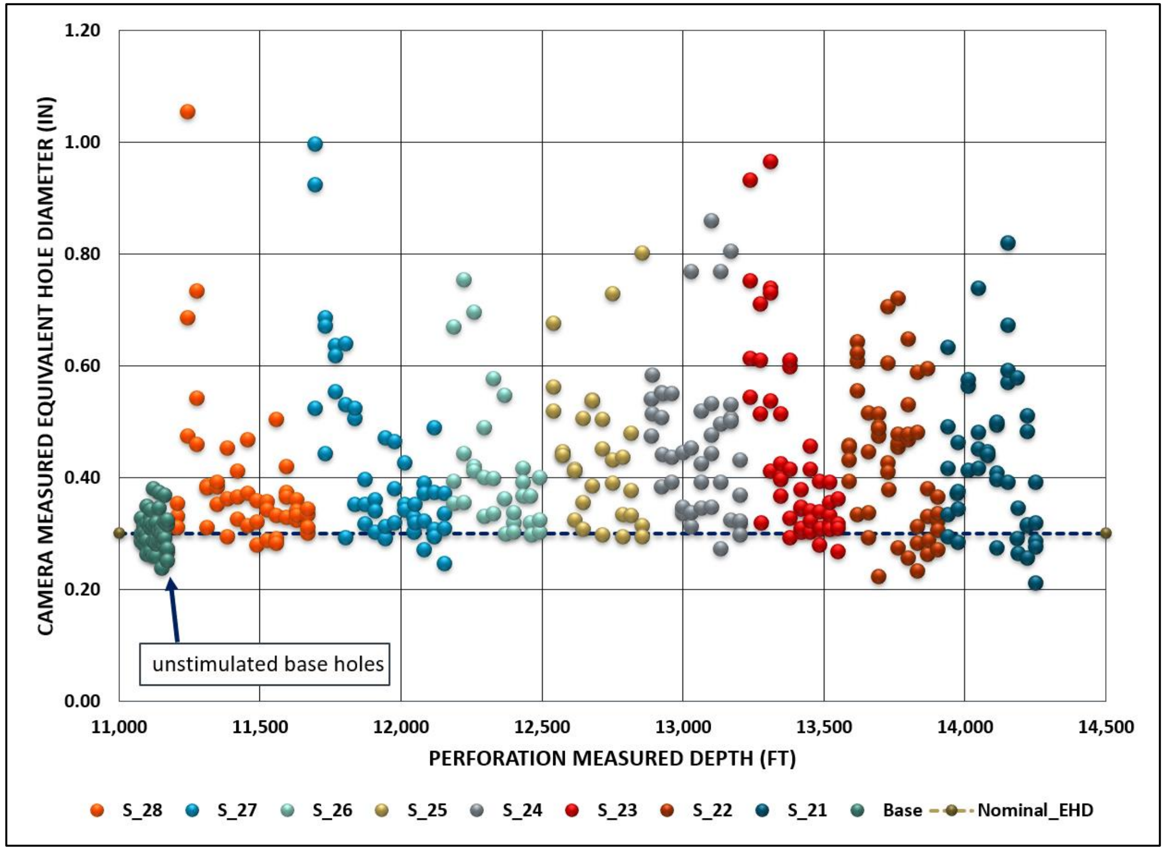
This was part of a multi-variable field study of limited entry perforating in a South Texas Business Unit (BU), coordinated by Jon Snyder, ConocoPhillips.

Perforation Entry Hole Size is Significantly Affected by Gun Clearance



wellbore segment	average equivalent perforation diameter (in.)		injection rate differential	
	Well A	Well B	Well A	Well B
upper third	0.288	0.276	1.00	1.00
middle third	0.312	0.296	1.18	1.14
lower third	0.344	0.328	1.43	1.41

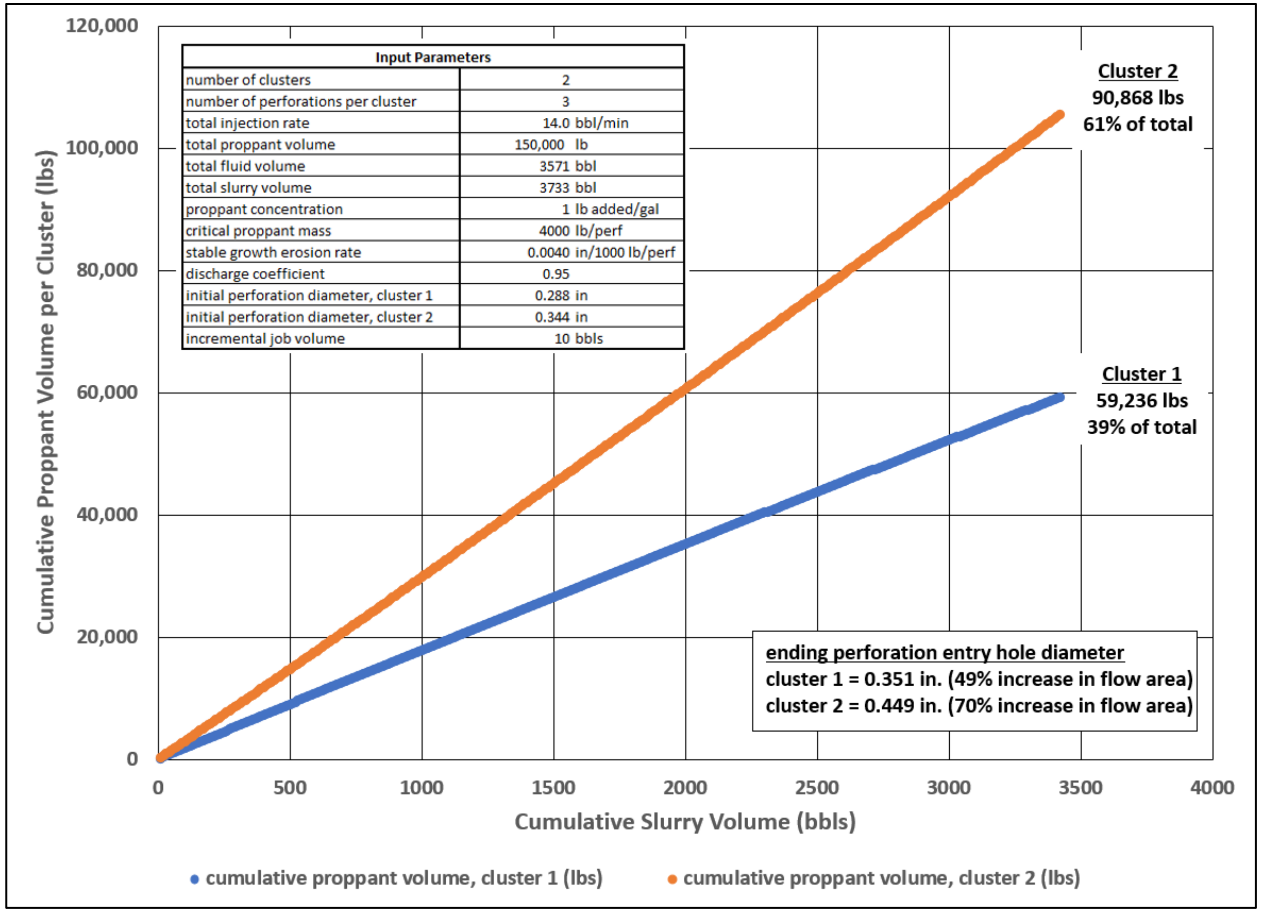
Untreated (base) perforation entry hole dimensions derived from video-based imaging



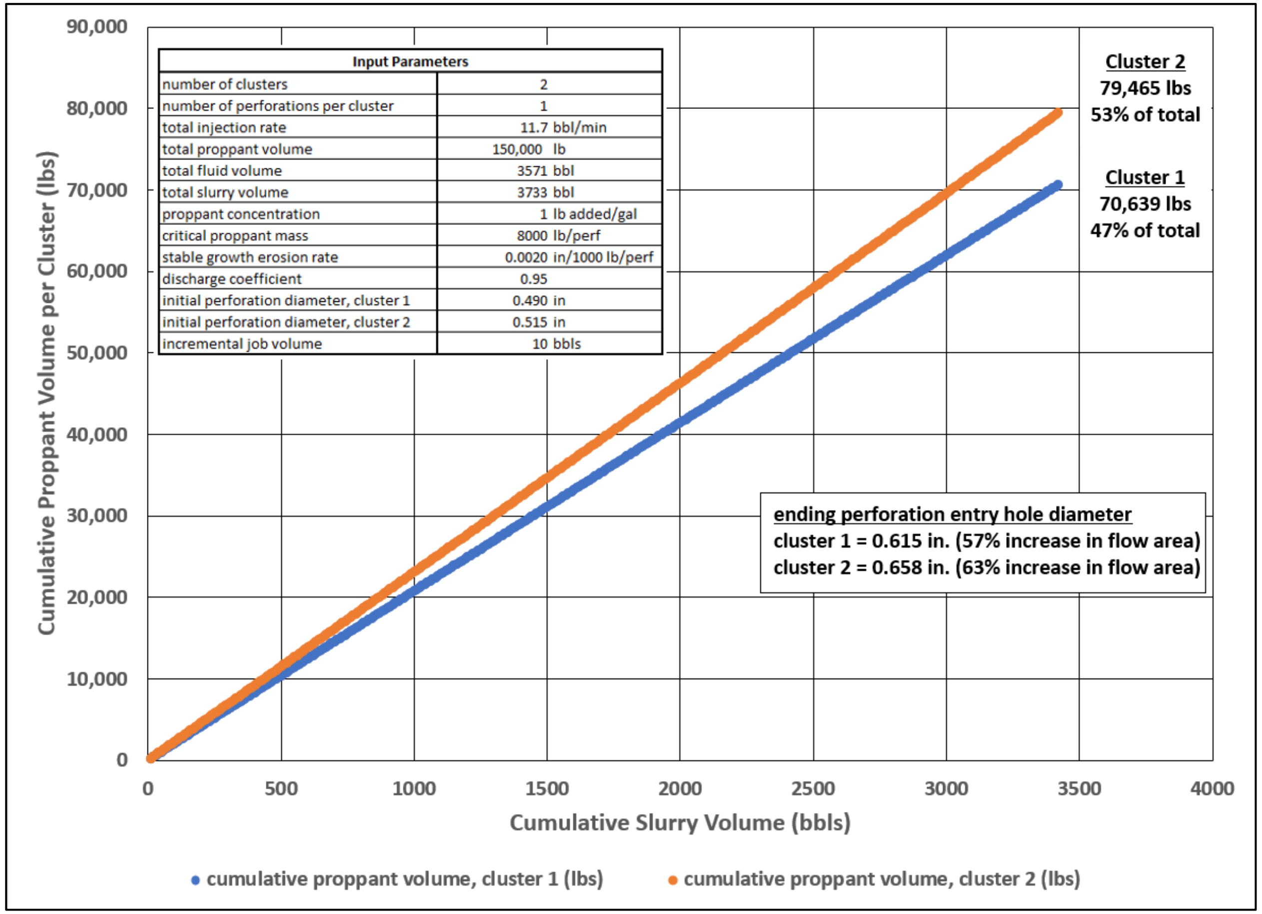
Post-treatment perforation measurements in Well B, derived from video-based imaging

Key Point: The initial imbalance in entry hole size increases exponentially due to proppant-induced erosion

Treatment Allocation, Multi-Phase vs Zero-Phase Perforating Design



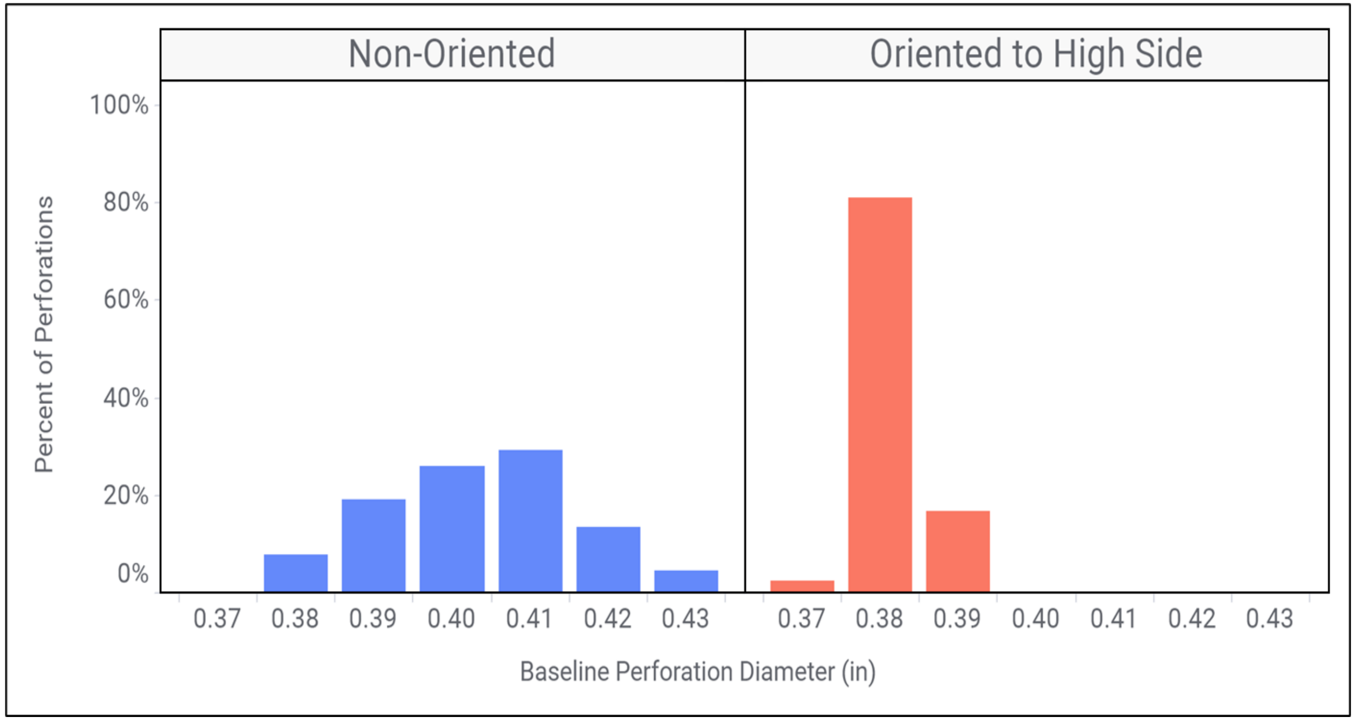
Well A Base Holes, high side and low side entry-hole averages
Initial diameters = 0.288 in. (upper third), 0.344 in. (lower third)



Big Hole Charge Surface Test, High Side, Zero-Phase Orientation
Initial diameters = 0.490 in. (smallest) to 0.515 in. (largest)

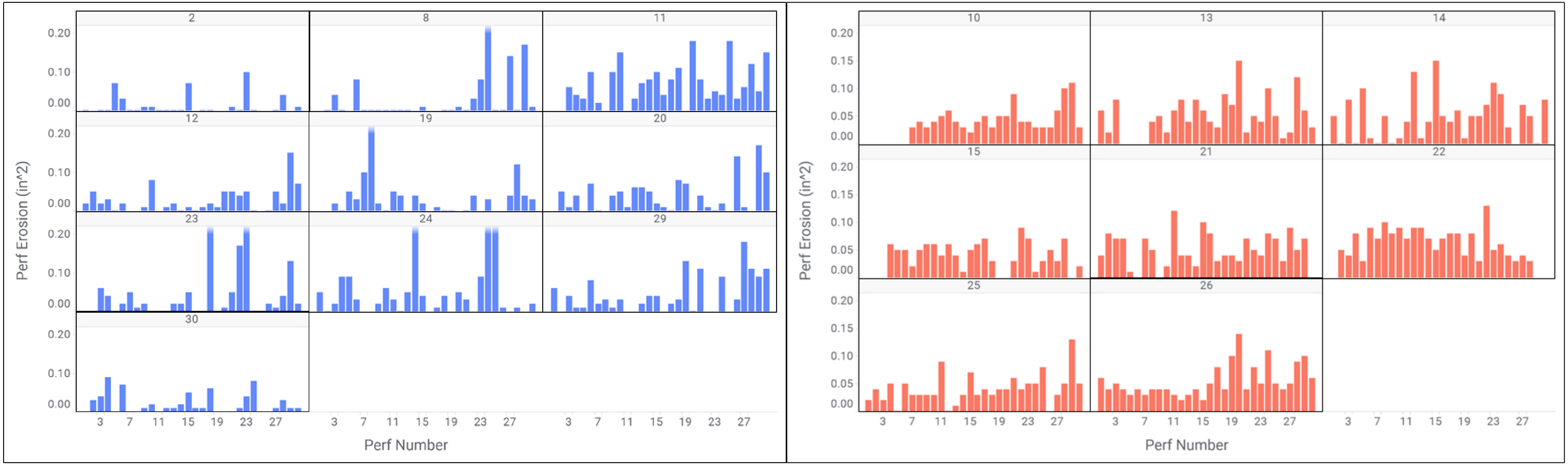
Initial Entry Hole Sizes

Non-Oriented versus Oriented



Histogram of baseline perforation diameter by orientation method

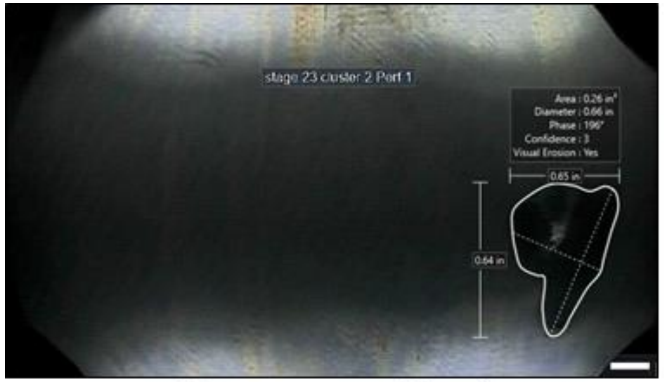
Erosional Characteristics of Limited Entry Perforations: Video-based Imaging



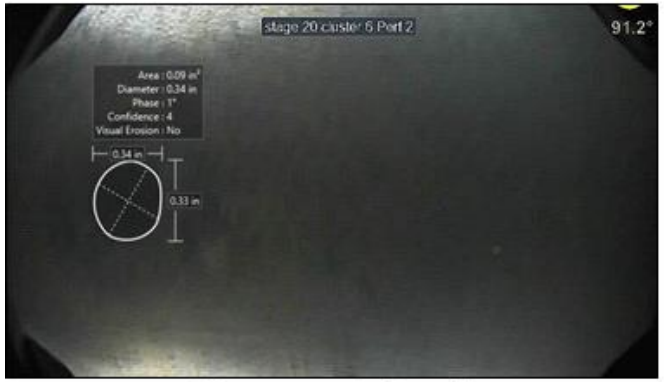
Non-Oriented Stages **Oriented Stages**

As evidenced by erosion characteristics, treatment distribution among clusters was much more uniform when orienting the perforations to the 12 o'clock position in the wellbore. Targeted perforation friction was 1300 psi.

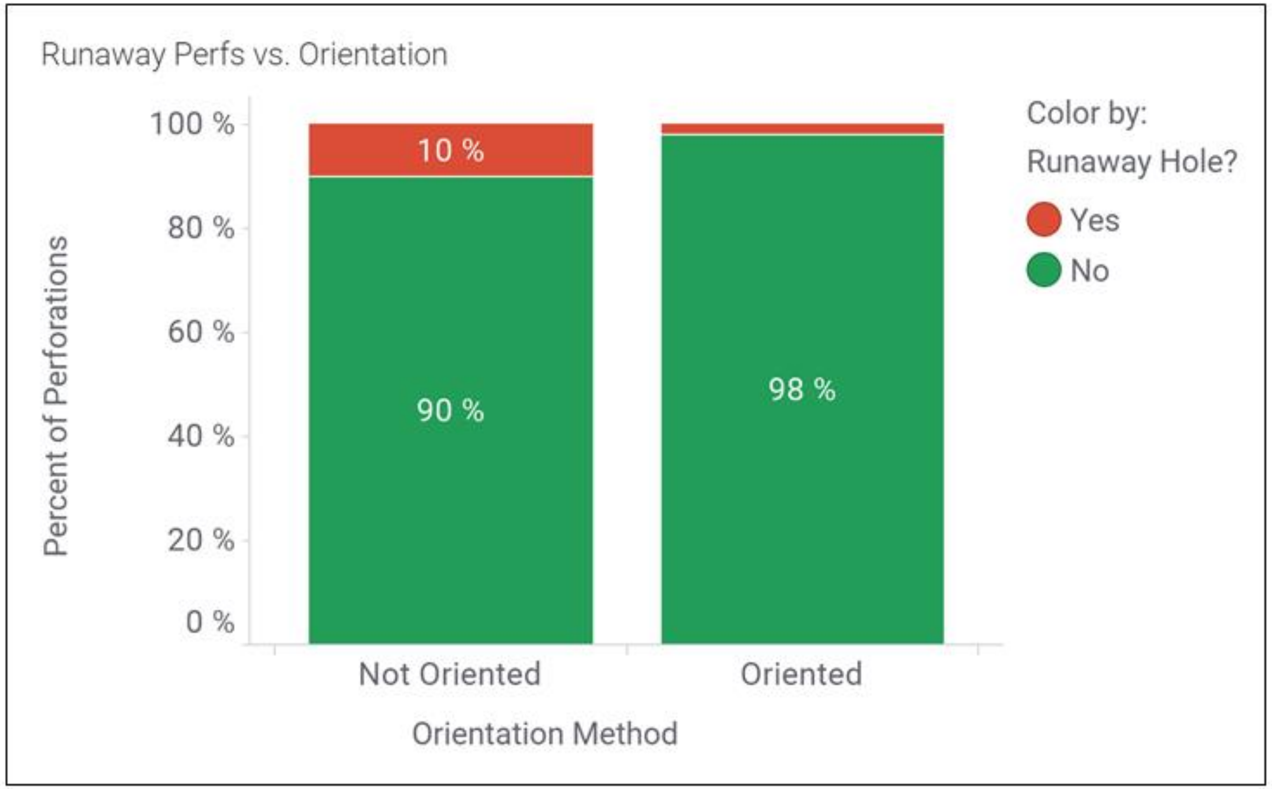
Limited Entry Perforating: Erosional Severity



Runaway Perf



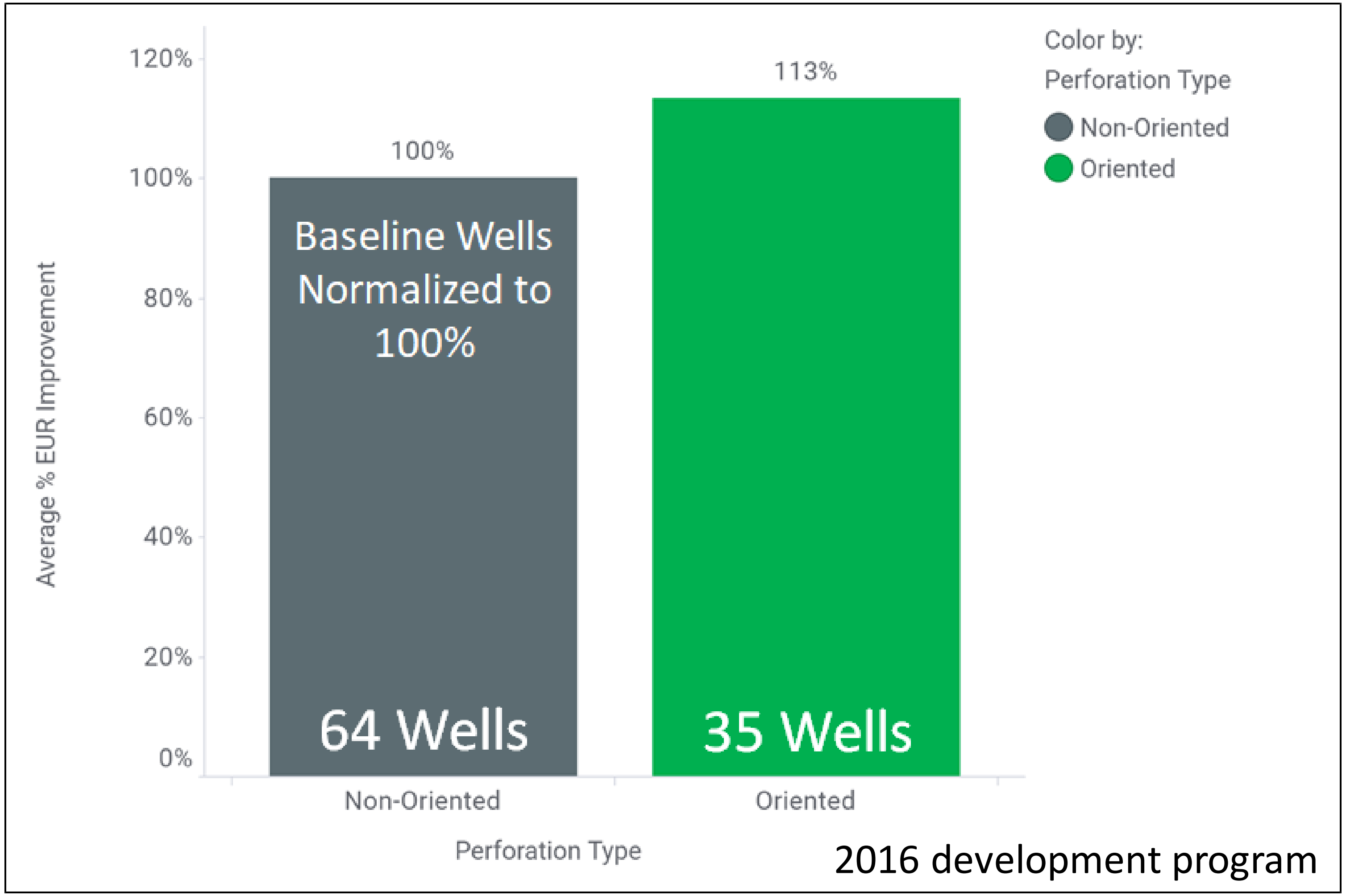
Normal Perf



Definition of Runaway Perf: *End of stage diameter is 40% larger than average baseline perf diameter*

Oriented perforating reduced instances of outsized or runaway perforations as a result of proppant-induced erosion.

Effect of Oriented Perforating on Well Productivity



Based on production lookback and video-based imaging results, the BU has standardized on orientation going forward.

Key Points

- The limited entry technique can lessen but not eliminate the consequences of unequal stress distribution along the lateral. The goal is to minimize the effect.
- Perforation erosion is a significant component of limited entry dynamics.
- Achieving excess perforation friction is important for mitigating the impact of variable stress and tortuosity along laterals but can lead to accelerated erosion.
- To achieve the best results from the limited entry technique, it is important to achieve minimal variation in entry-hole dimensions.
- Refer to SPE-16189-MS, SPE-194334-PA, SPE-204203-MS and SPE-205003-PA for detailed information on limited entry treatment methodology.

Summary

1. Field and laboratory tests demonstrate that the **tunnel formed within the reservoir rock during the perforation process does not participate in the fracture initiation process**. Hydraulic fractures grow from the base of the perforation or more commonly, a plane coincident with the cement-sheath and drilled-hole that is normal to the least stress.
2. When the diameter of the initial entry hole varies among perforations in a fracturing stage, the larger entry holes receive more fluid and proppant, and are eroded at a greater rate than the smaller entry holes. This leads to **progressively greater flow and enlargement of the larger entry holes** at the expense of the smaller entry holes.
3. Critical steps in optimizing limited entry treatment results are to make concerted efforts to achieve **equivalent entry hole dimensions** for all perforations. The commonly used **jet perforators are particularly challenged** in meeting this requirement.
4. The circumferential location of perforations in the wellbore (high side to low side) can affect the initial entry hole diameter, in turn effecting proppant-induced erosion patterns. **Gravity** can accentuate low side perforation erosion via proppant.
5. Findings from ConocoPhillips field tests support using perforation systems oriented to the high side of the wellbore for improving treatment distribution among all perforations within a stage.
6. **Zero-phase oriented perforating is now a standard practice** in all plug and perf applications performed by ConocoPhillips in the United States and Canada.

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