SPE DISTINGUISHED LECTURER

Primary funding is provided by

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

The Society is grateful to those companies that allow their professionals to serve as lecturers

Additional support provided by AIME

Society of Petroleum Engineers

Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl

SPE DISTINGUISHED LECTURER℠

Integrating Multiple Diagnostic Methods to Determine Limited Entry Treatment Effectiveness

Dave Cramer

ConocoPhillips

SPE International®
Society of Petroleum Engineers

Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl

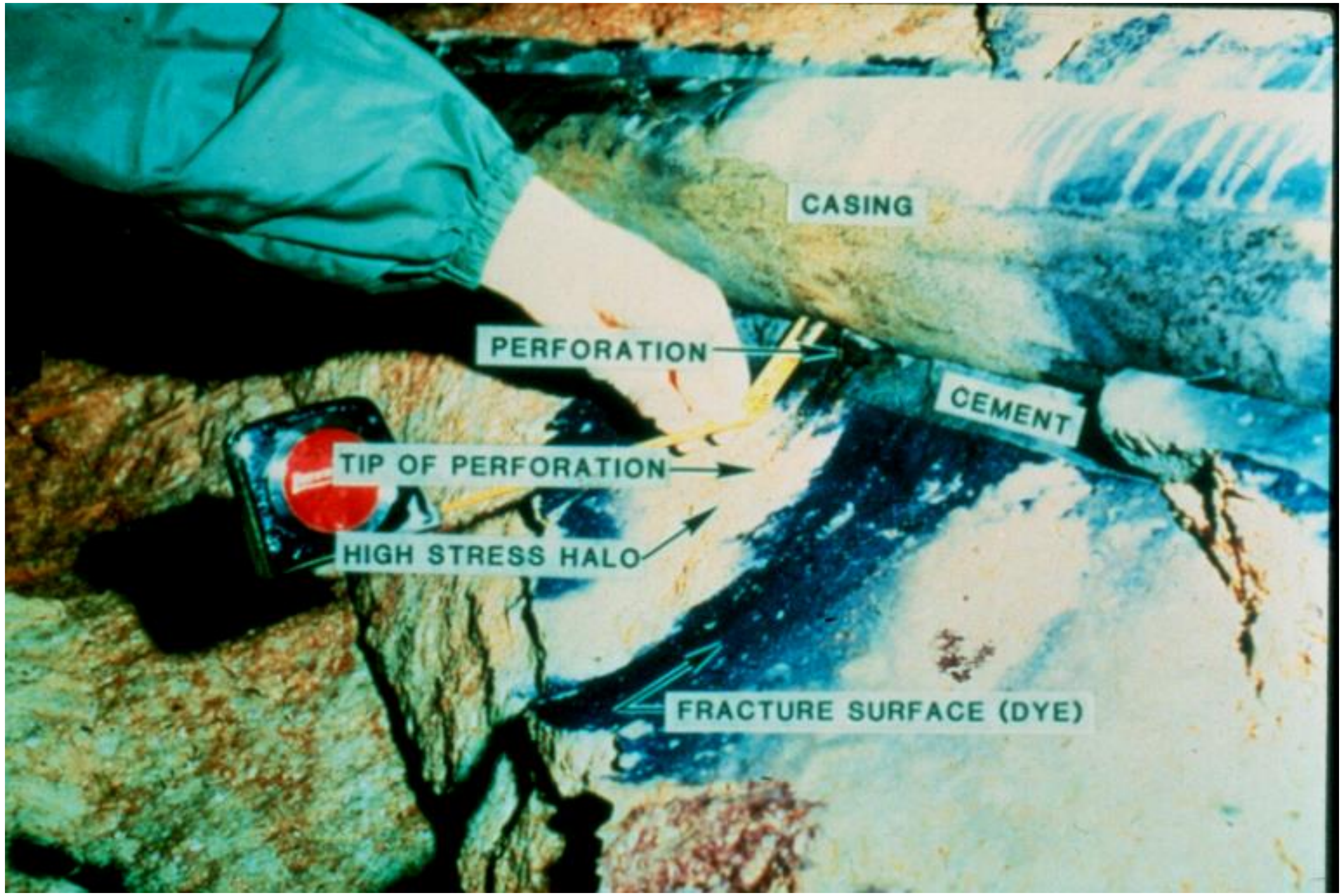
Agenda

- Limited entry treatment basics
- Perforation erosion dynamics
- Case study: limited entry treatments in an instrumented wellbore
- Case study: oriented perforating in Eagle Ford (time permitting)
- Summary of 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 differences in 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.

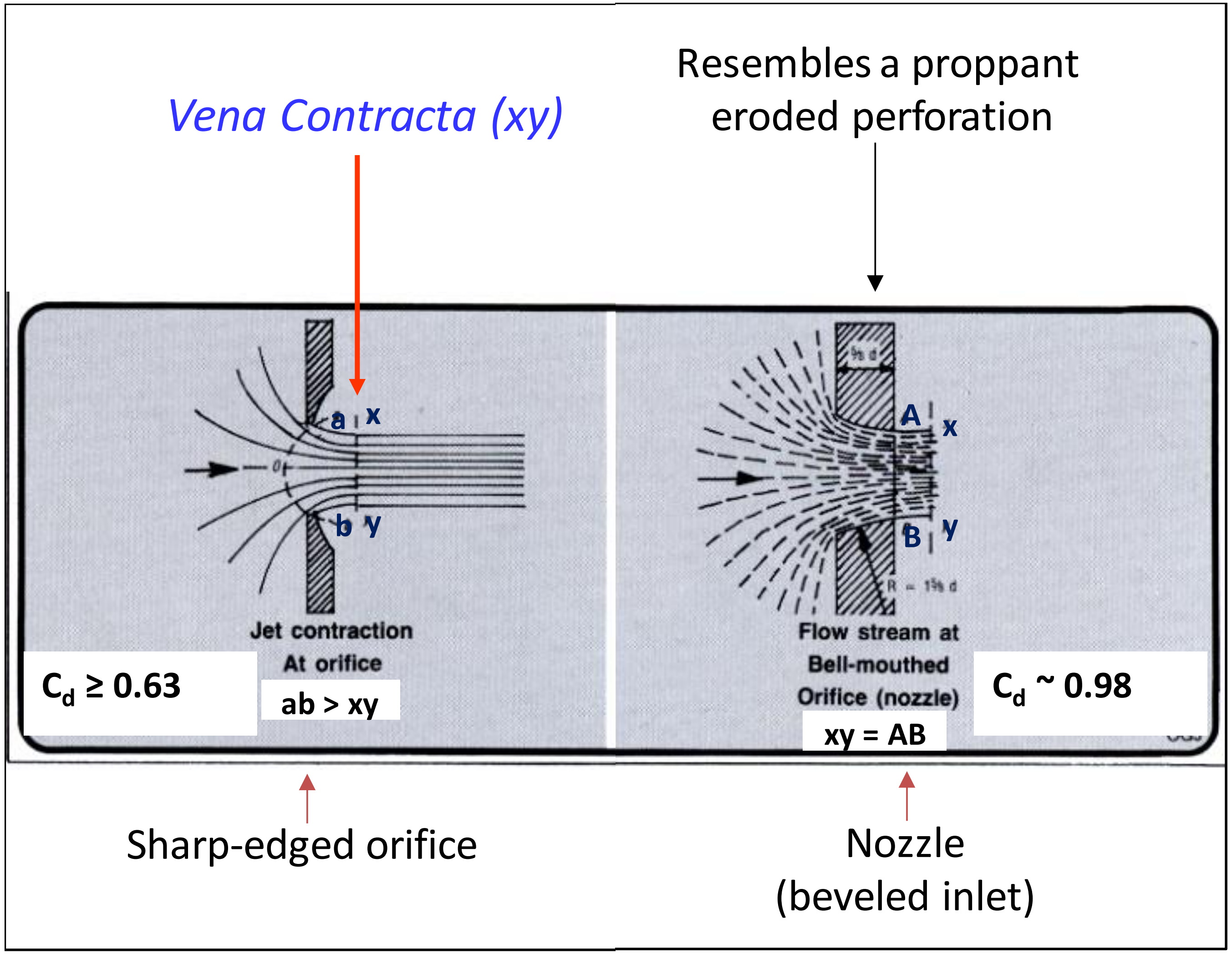
Predictive Equation for Pressure Drop Across a Perforation Entry Hole in Pipe

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

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



Vena Contracta (xy)

Resembles a proppant eroded perforation

$C_d \geq 0.63$

Jet contraction
At orifice

ab > xy

Flow stream at
Bell-mouthed
Orifice (nozzle)

xy = AB

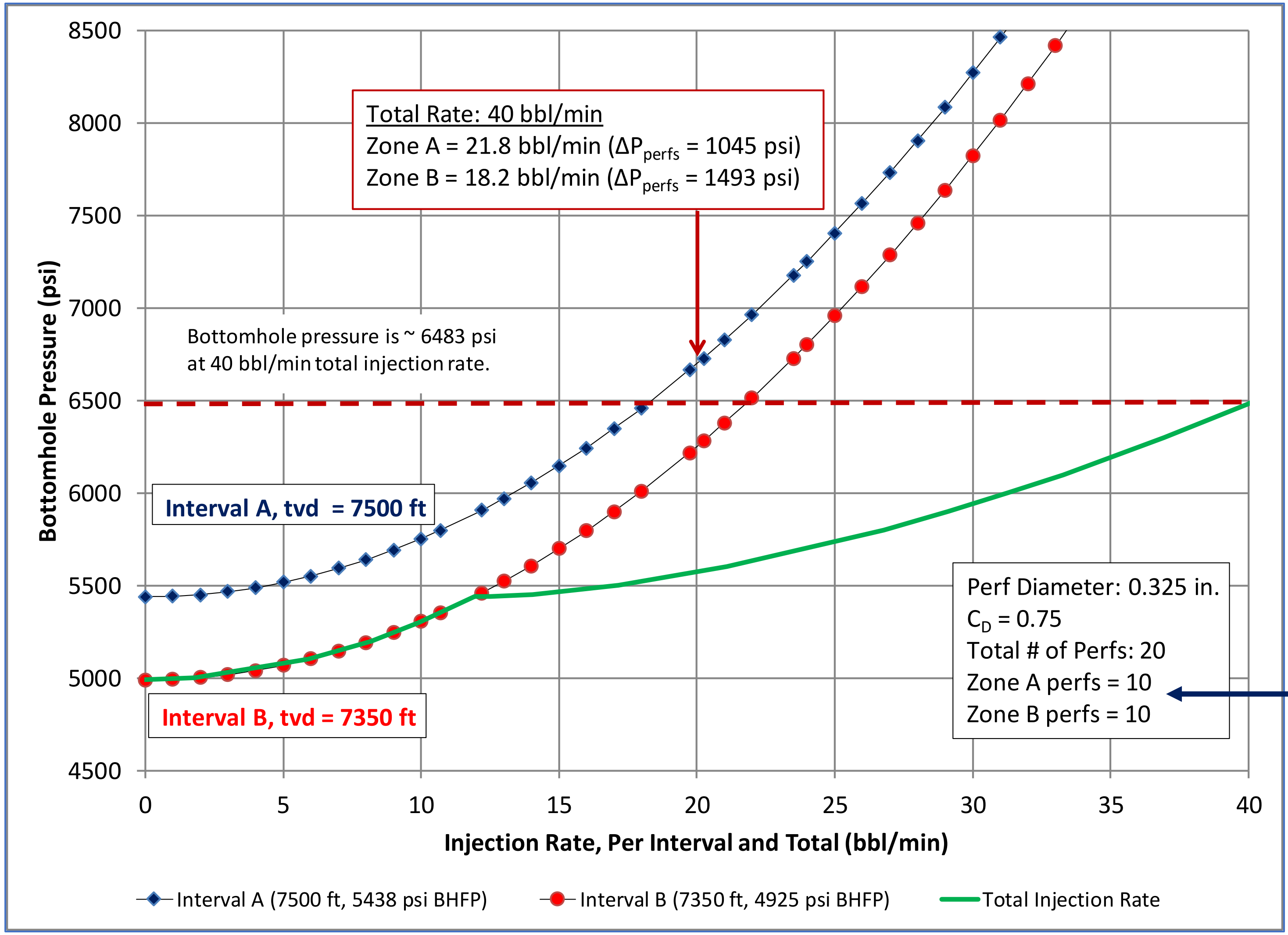
C_d ~ 0.98

Sharp-edged orifice

Nozzle
(beveled inlet)

Perforation inlet condition determines the discharge coefficient.

Conceptual Example of the Limited Entry Process



Total Rate: 40 bbl/min
Zone A = 21.8 bbl/min (ΔP_{perfs} = 1045 psi)
Zone B = 18.2 bbl/min (ΔP_{perfs} = 1493 psi)

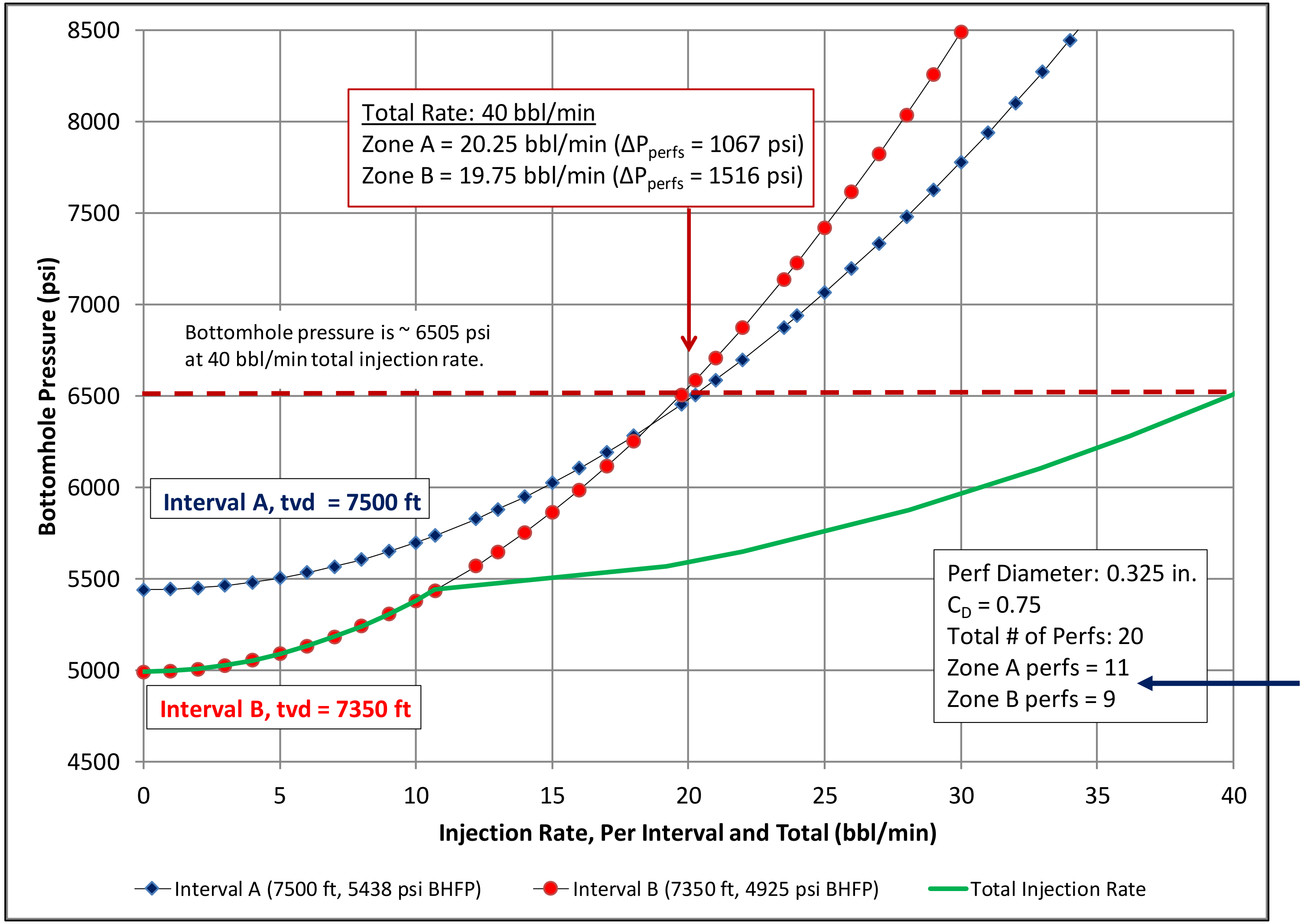
Bottomhole pressure is ~ 6483 psi
at 40 bbl/min total injection rate.

Perf Diameter: 0.325 in.
C_D = 0.75
Total # of Perfs: 20
Zone A perfs = 10
Zone B perfs = 10

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.

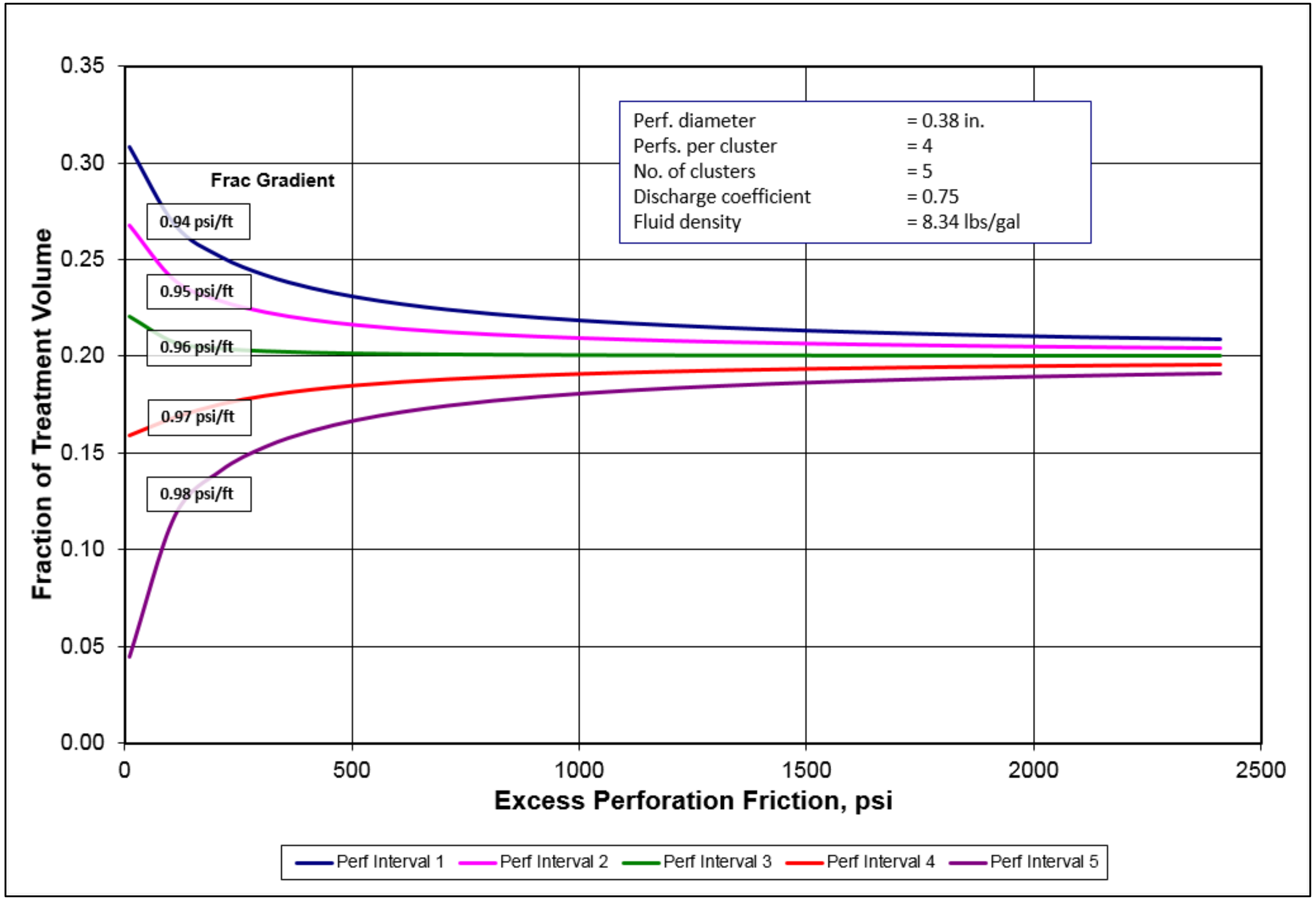
Conceptual Example of the Limited Entry Process



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

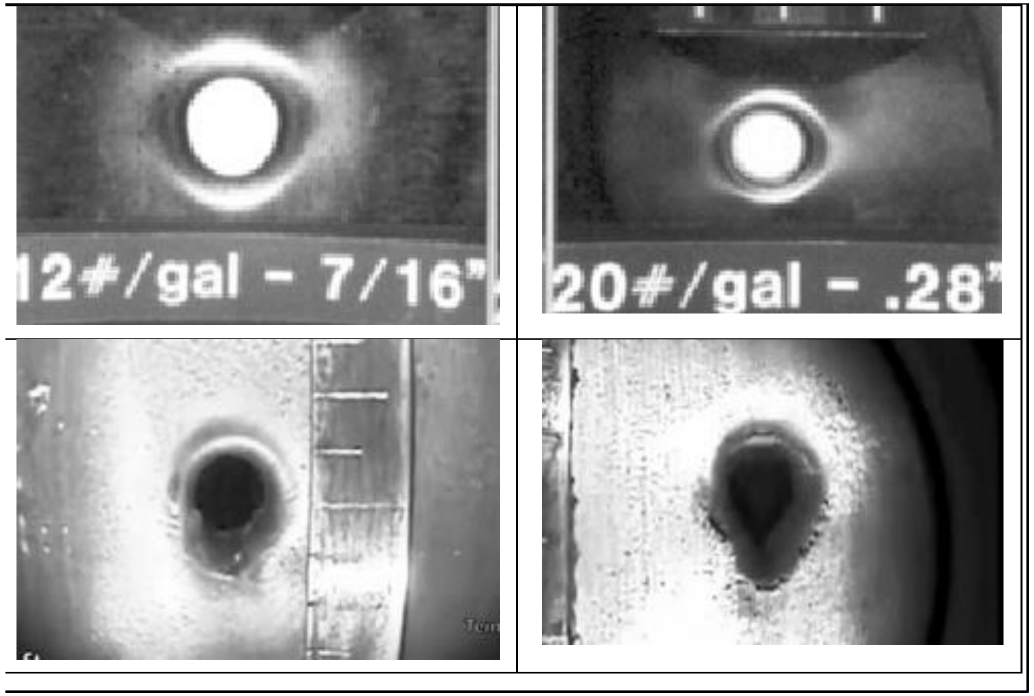


from IPS presentation: Cramer (2010)

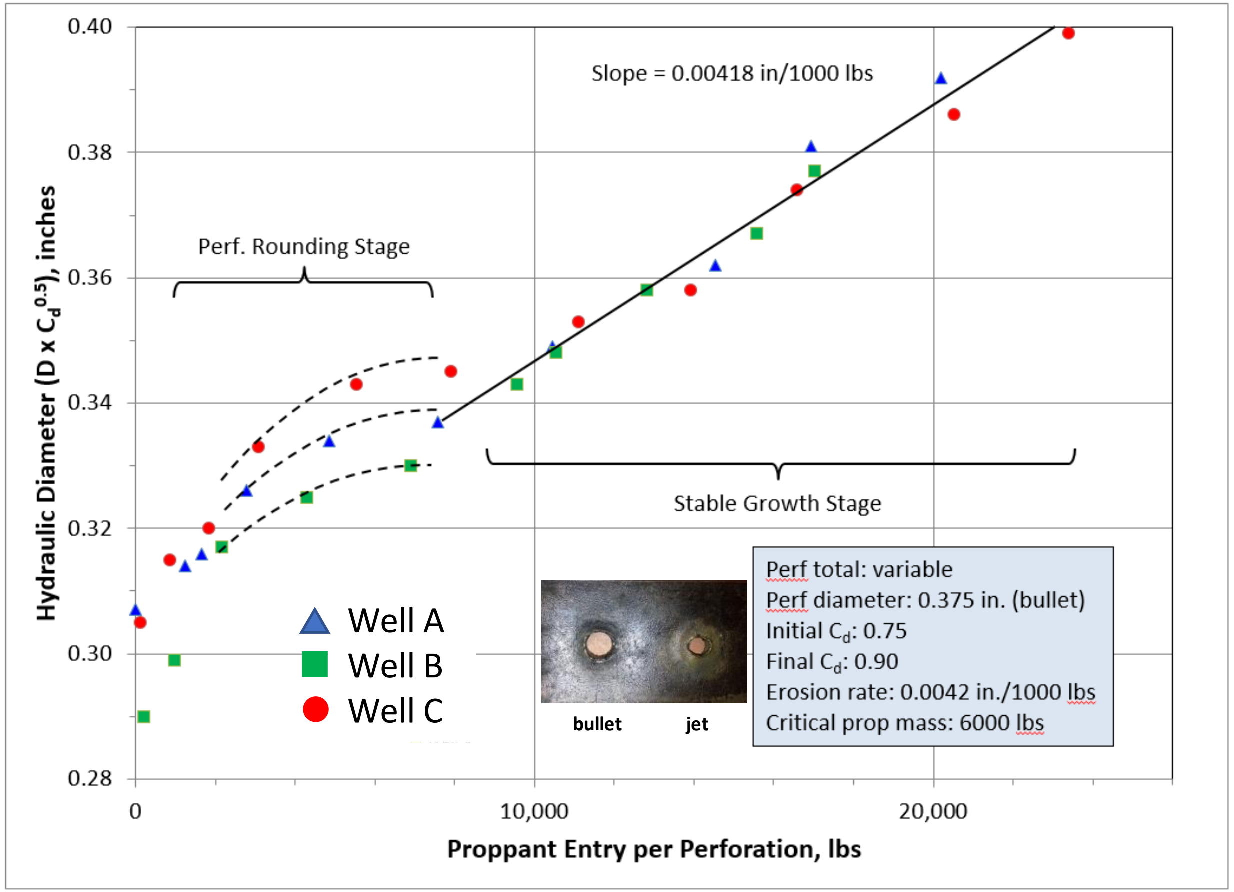
Excess perforation friction is additional to the pressure difference between intervals with the highest and lowest fracture propagation pressures. It improves the treatment distribution among intervals with dissimilar fracture propagation pressures.

Perforations Erode in a Two-Step Process

From SPE 15474: Crump, Conway (1988)



From SPE 194334: Cramer et al (2019)

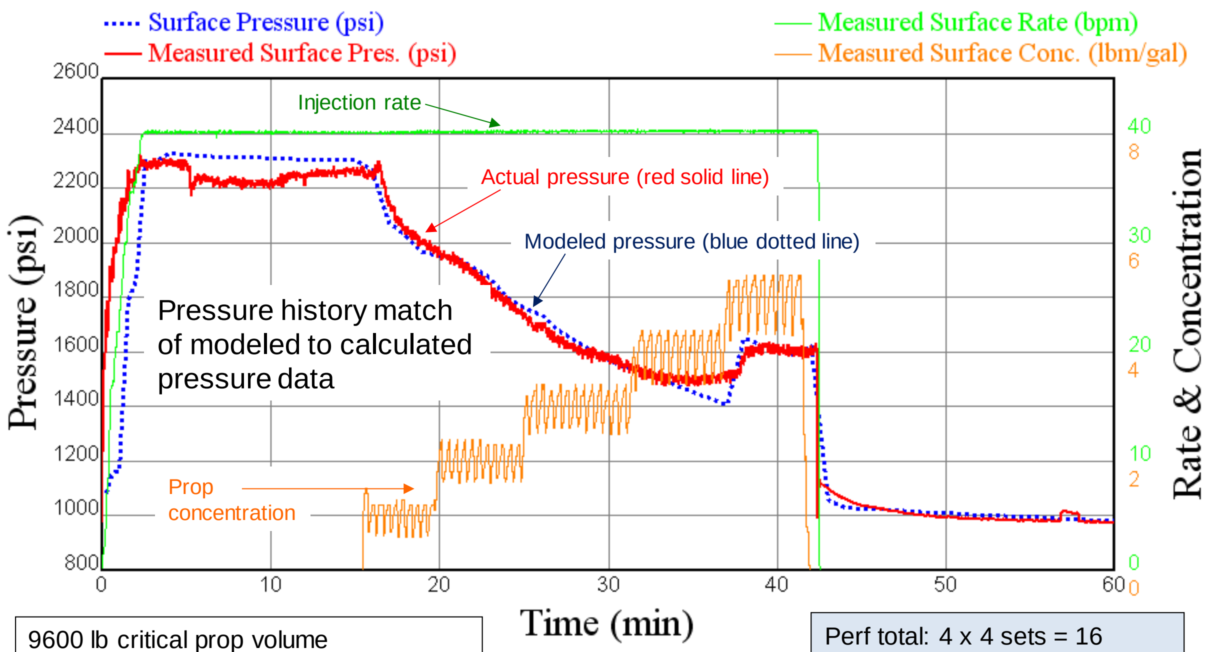


Perf total: variable
Perf diameter: 0.375 in. (bullet)
Initial C_d: 0.75
Final C_d: 0.90
Erosion rate: 0.0042 in./1000 lbs
Critical prop mass: 6000 lbs

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.

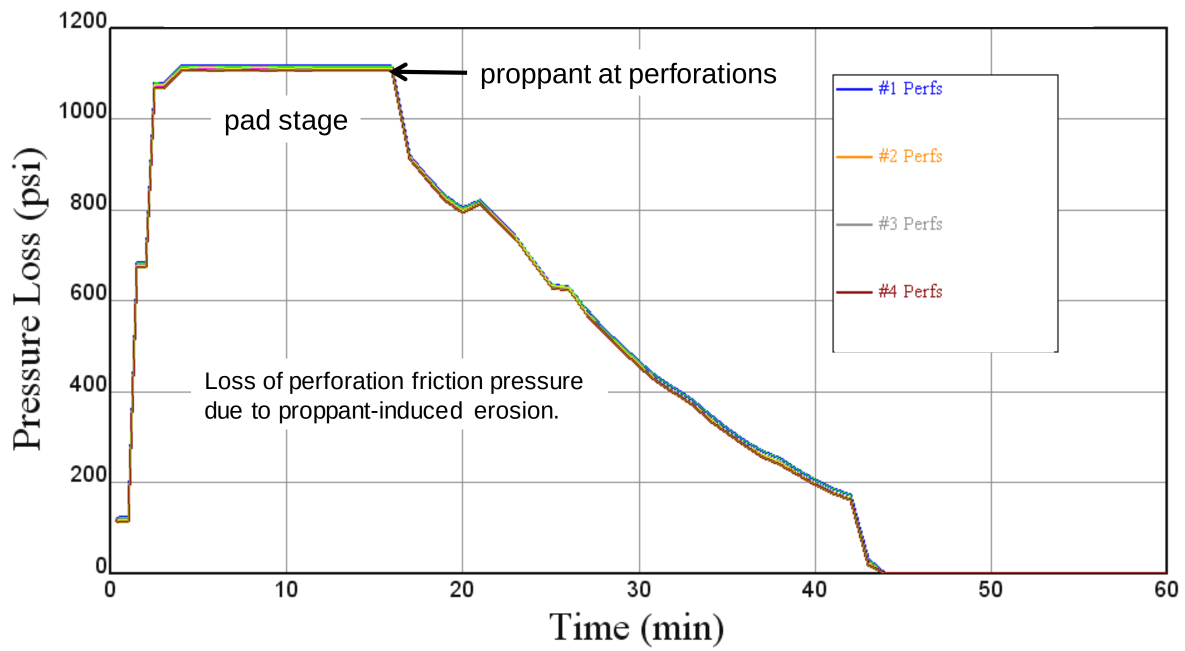
Modeling Limited Entry Treatments and Perforation Erosion



Pressure history match of modeled to calculated pressure data

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

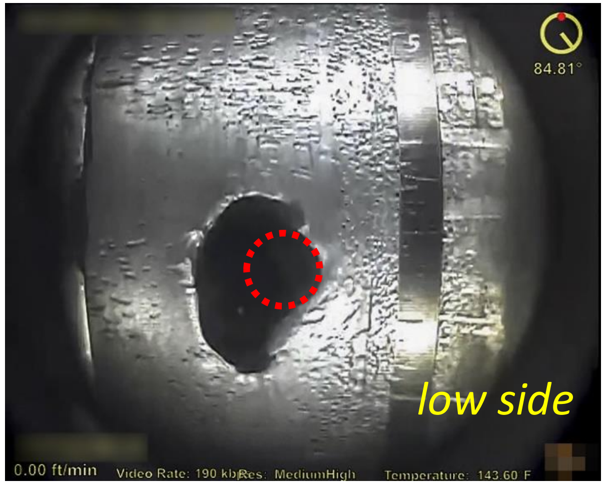


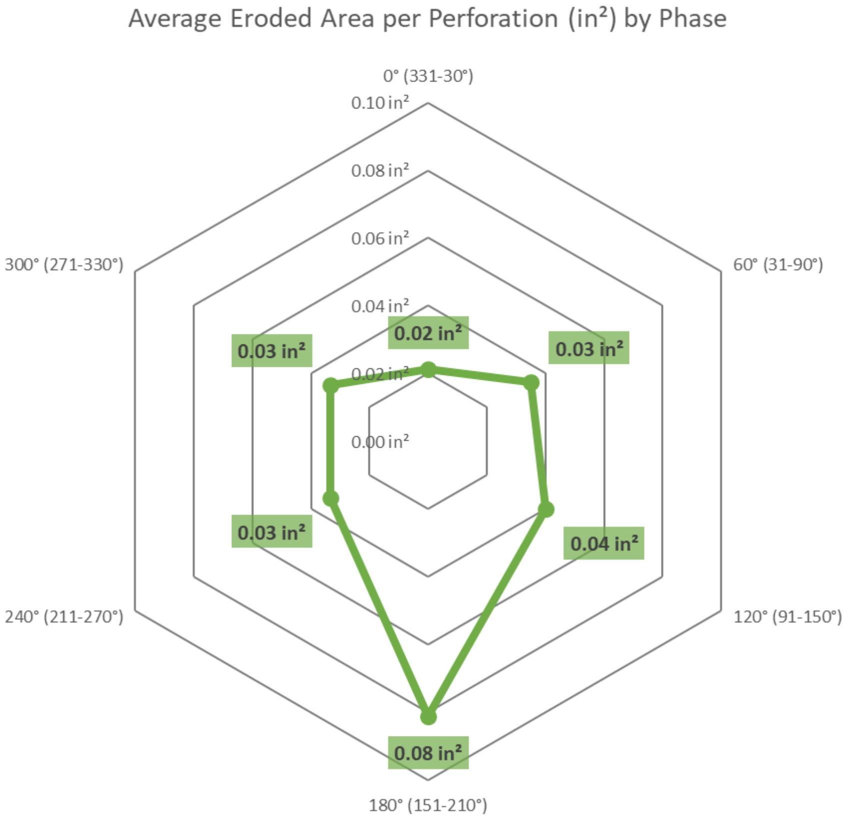
Loss of perforation friction pressure due to proppant-induced erosion.

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

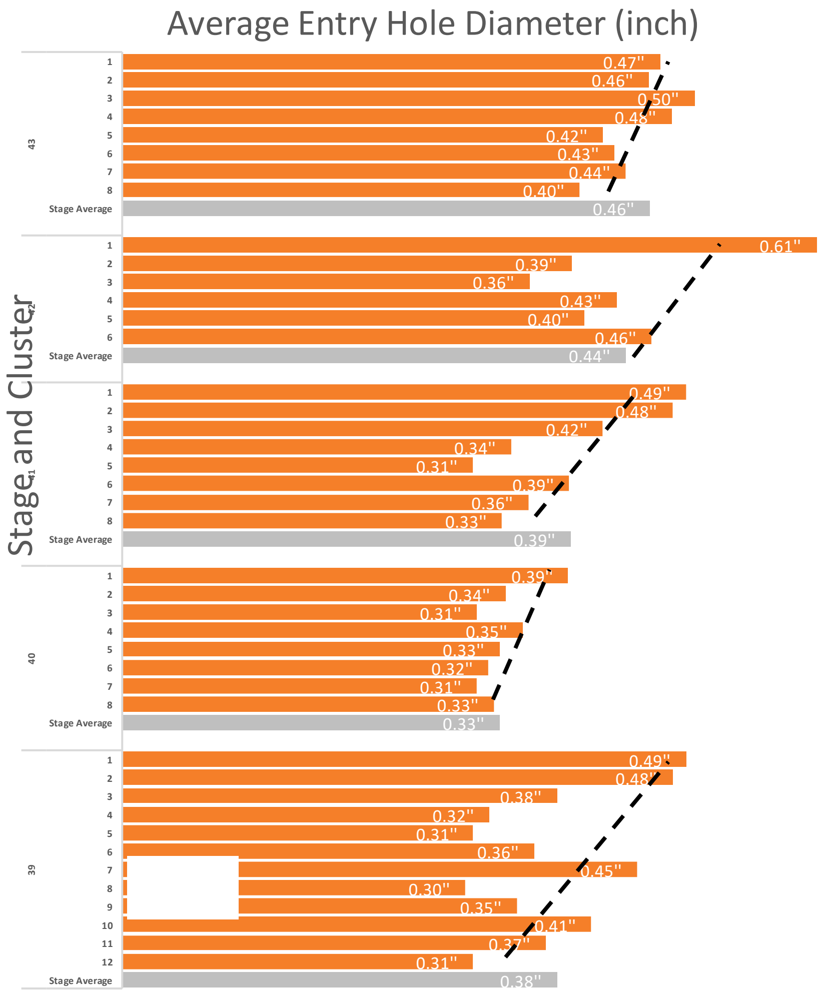
Perforation erosion can lead to loss of control in limited entry treatments.

Post-Treatment Imaging Reveals Phase and Heel Bias





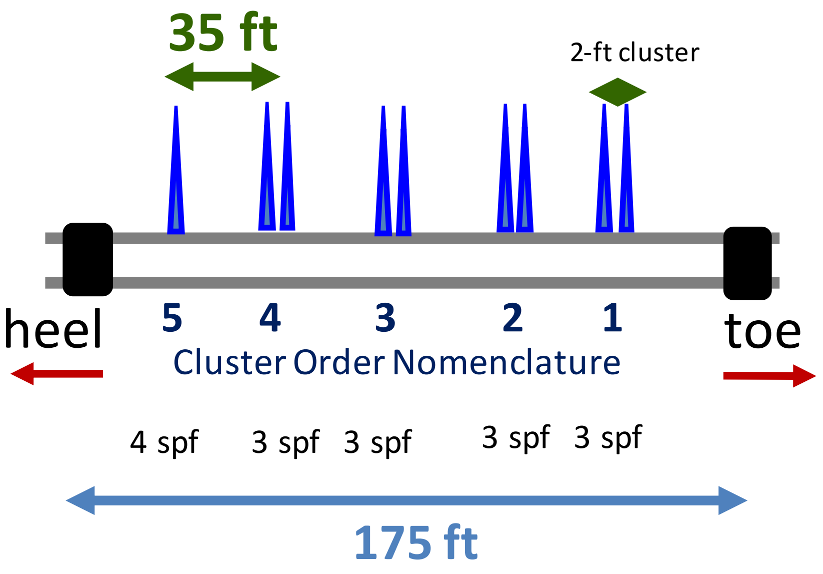
from paper SPE 194334



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

Zero phase



35 ft

2-ft cluster

heel

5 4 3 2 1

Cluster Order Nomenclature

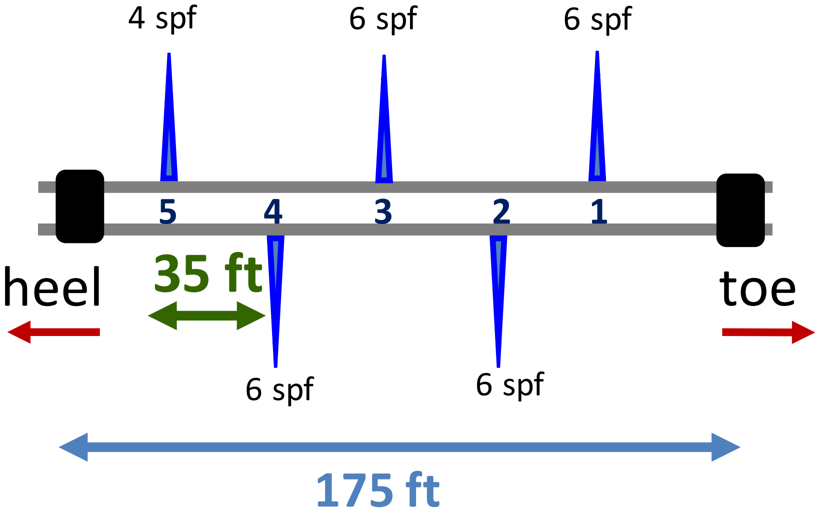
toe

4 spf 3 spf 3 spf 3 spf 3 spf

175 ft

Well A

60° (helical) phasing



4 spf 6 spf 6 spf

5 4 3 2 1

heel

35 ft

toe

6 spf 6 spf

175 ft

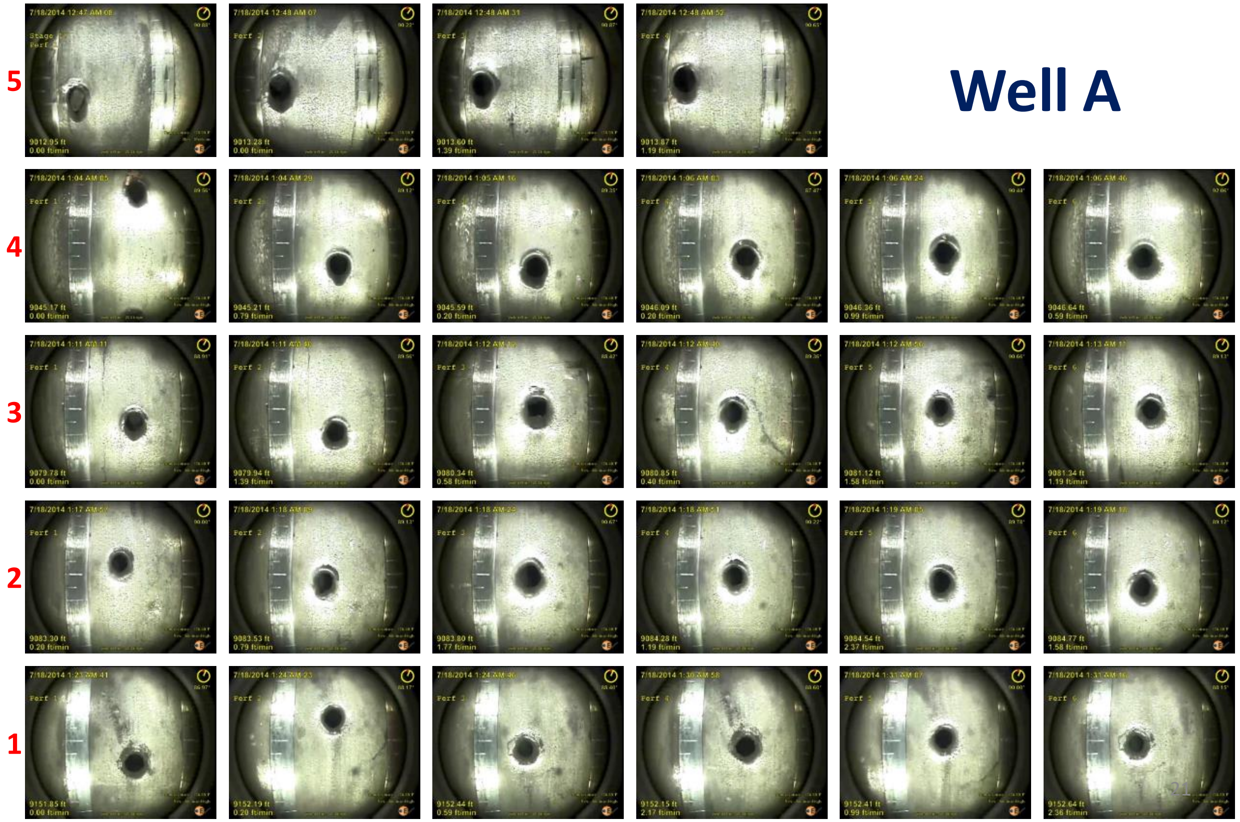
Well B

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.

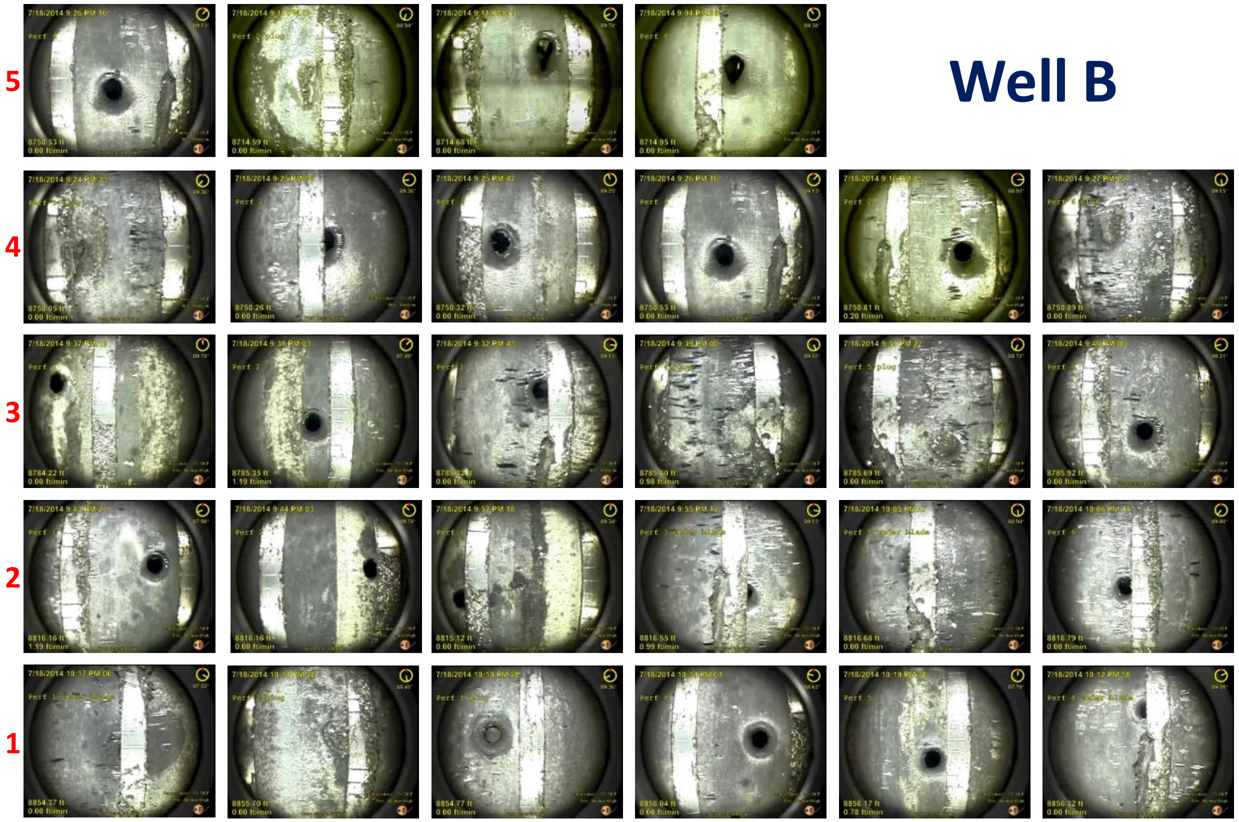
Case Study Treatment Basics

- 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

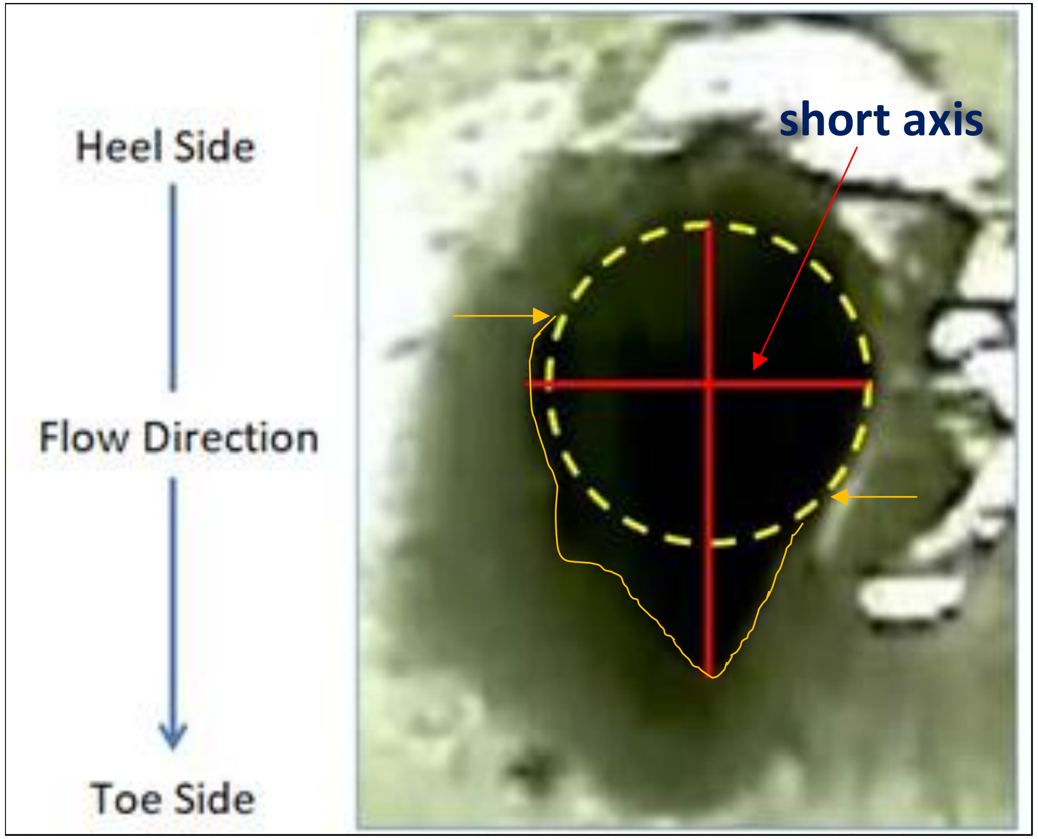


60° phasing, helical distribution around the well

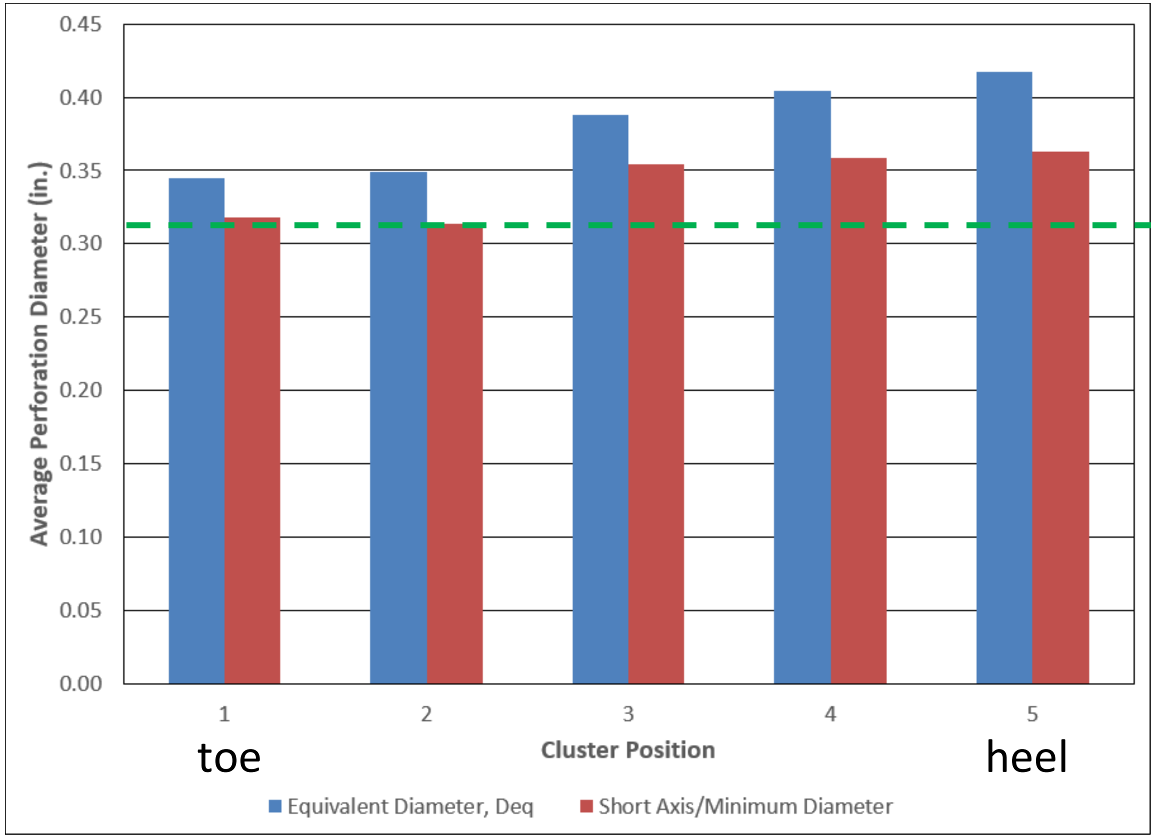
Cluster numerical ordering is from toe to heel (1 to 5). Oriented zero-phase perforating to the high-side of the wellbore provided superior visibility for video-based imaging and more uniform entry-hole size.

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

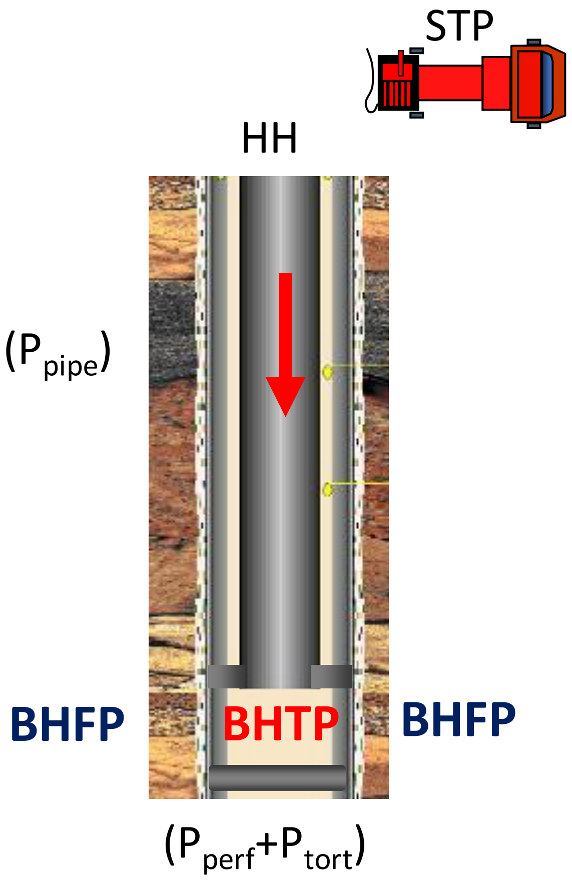


Difference between D_{eq} and initial hole size indicates erosion

Treating Pressure Components

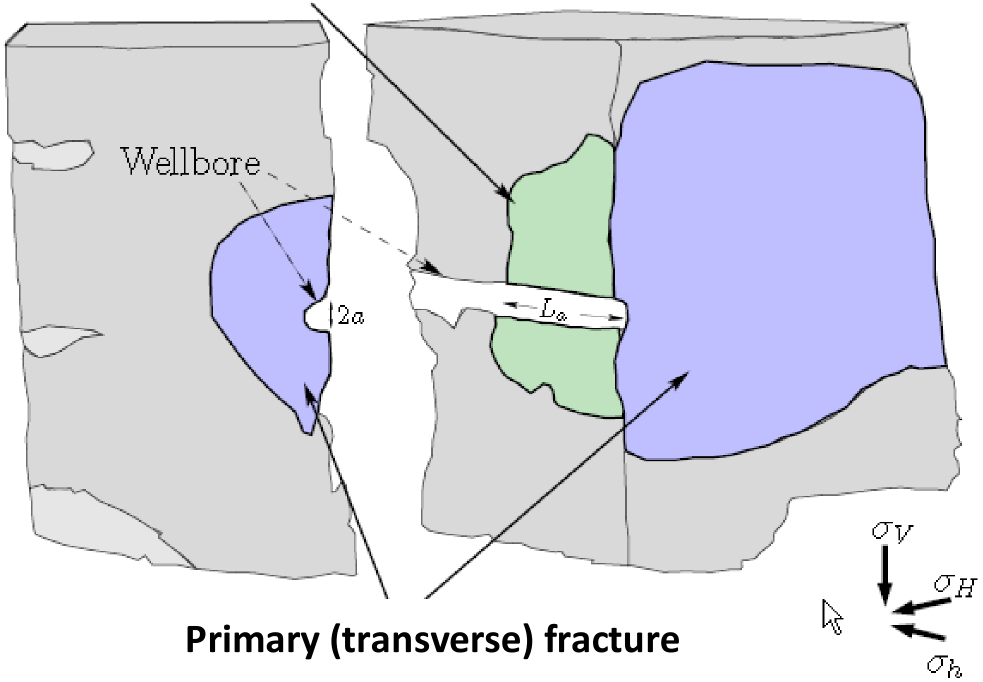
- BHTP = STP + HH – P_{pipe}
- BHFP = STP + HH – P_{pipe} **– P_{perf} – P_{tort}**
- BHFP = ISIP + HH

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



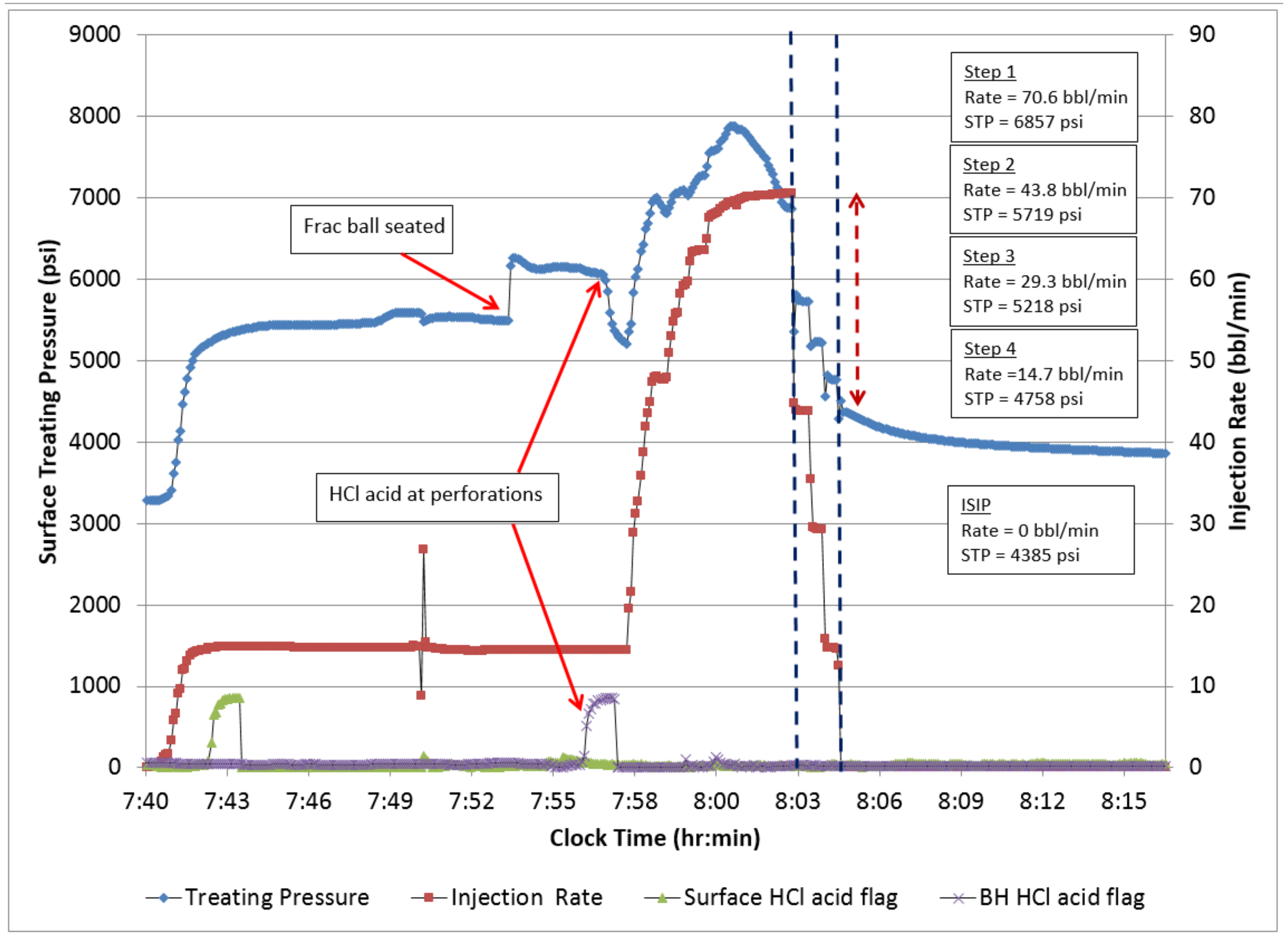
Starter (axial) fracture

Primary (transverse) fracture

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



Frac ball seated

HCl acid at perforations

Step 1
Rate = 70.6 bbl/min
STP = 6857 psi

Step 2
Rate = 43.8 bbl/min
STP = 5719 psi

Step 3
Rate = 29.3 bbl/min
STP = 5218 psi

Step 4
Rate =14.7 bbl/min
STP = 4758 psi

ISIP
Rate = 0 bbl/min
STP = 4385 psi

Equations:

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

$ISIP = BHFP – HH$

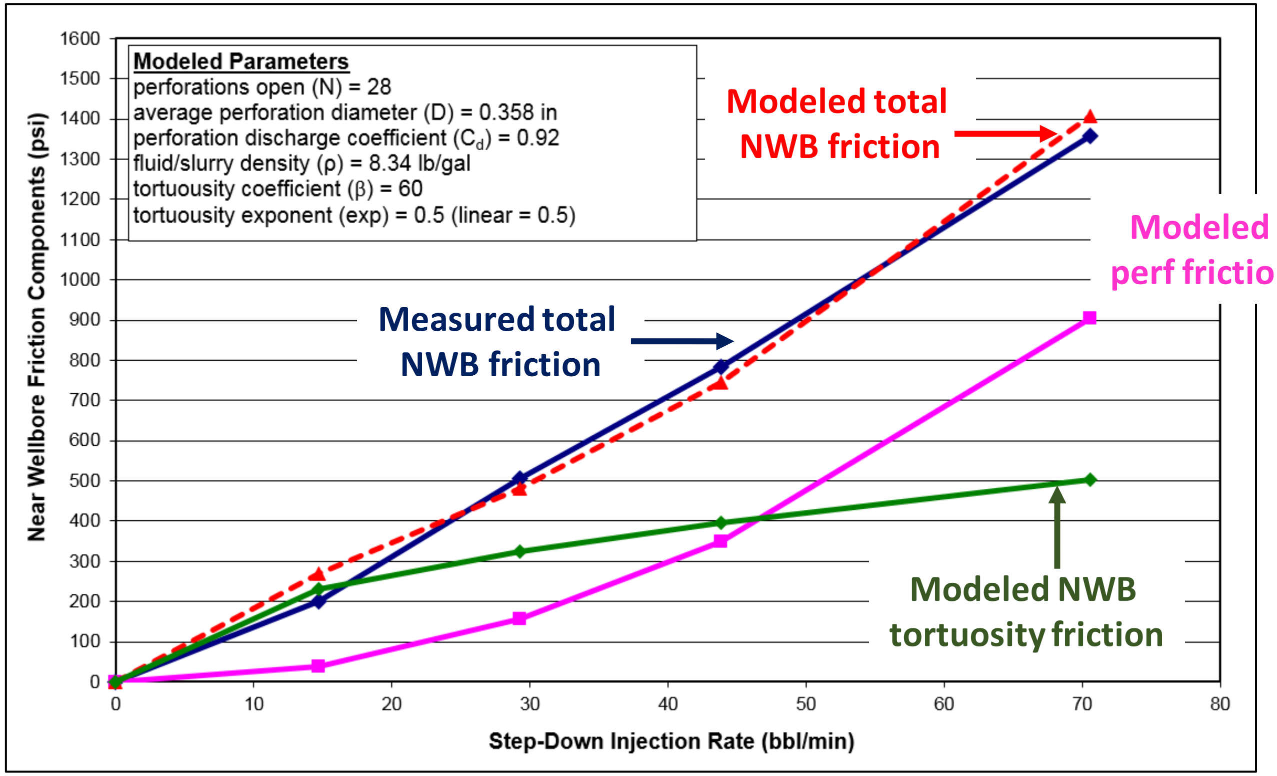
$BHTP = BHFP + P_{NWF}$

$P_{NWF} = STP - ISIP – P_{pipe}$

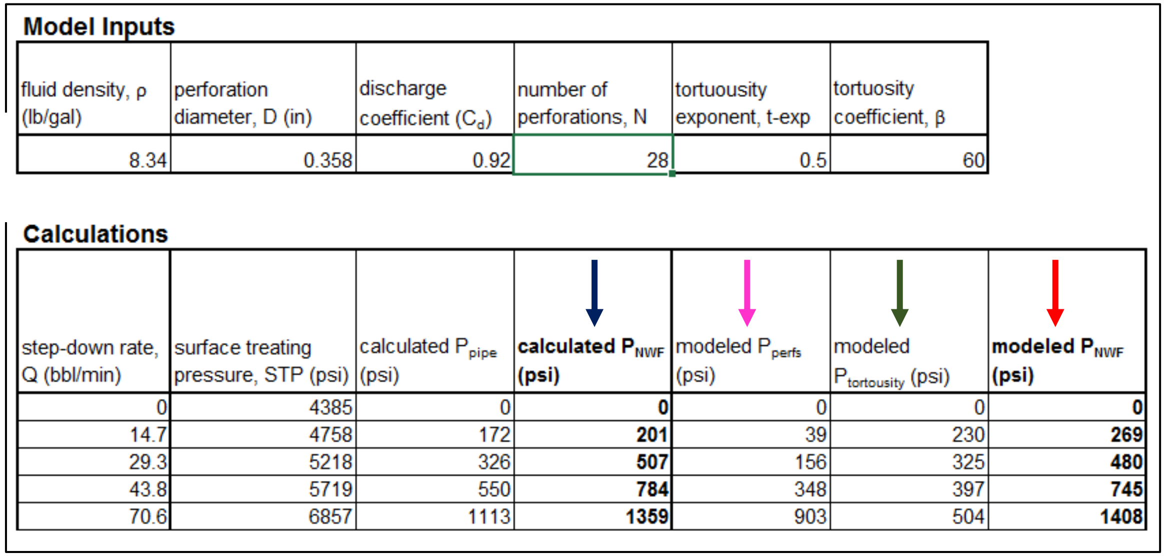
$P_{NWF} = P_{Perf} + P_{Tort}$

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

Step Rate Test Analysis Results



Modeled Parameters
perforations open (N) = 28
average perforation diameter (D) = 0.358 in
perforation discharge coefficient (C_d) = 0.92
fluid/slurry density (ρ) = 8.34 lb/gal
tortuousity coefficient (β) = 60
tortuousity exponent (exp) = 0.5 (linear = 0.5)



Model Inputs

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

Calculations

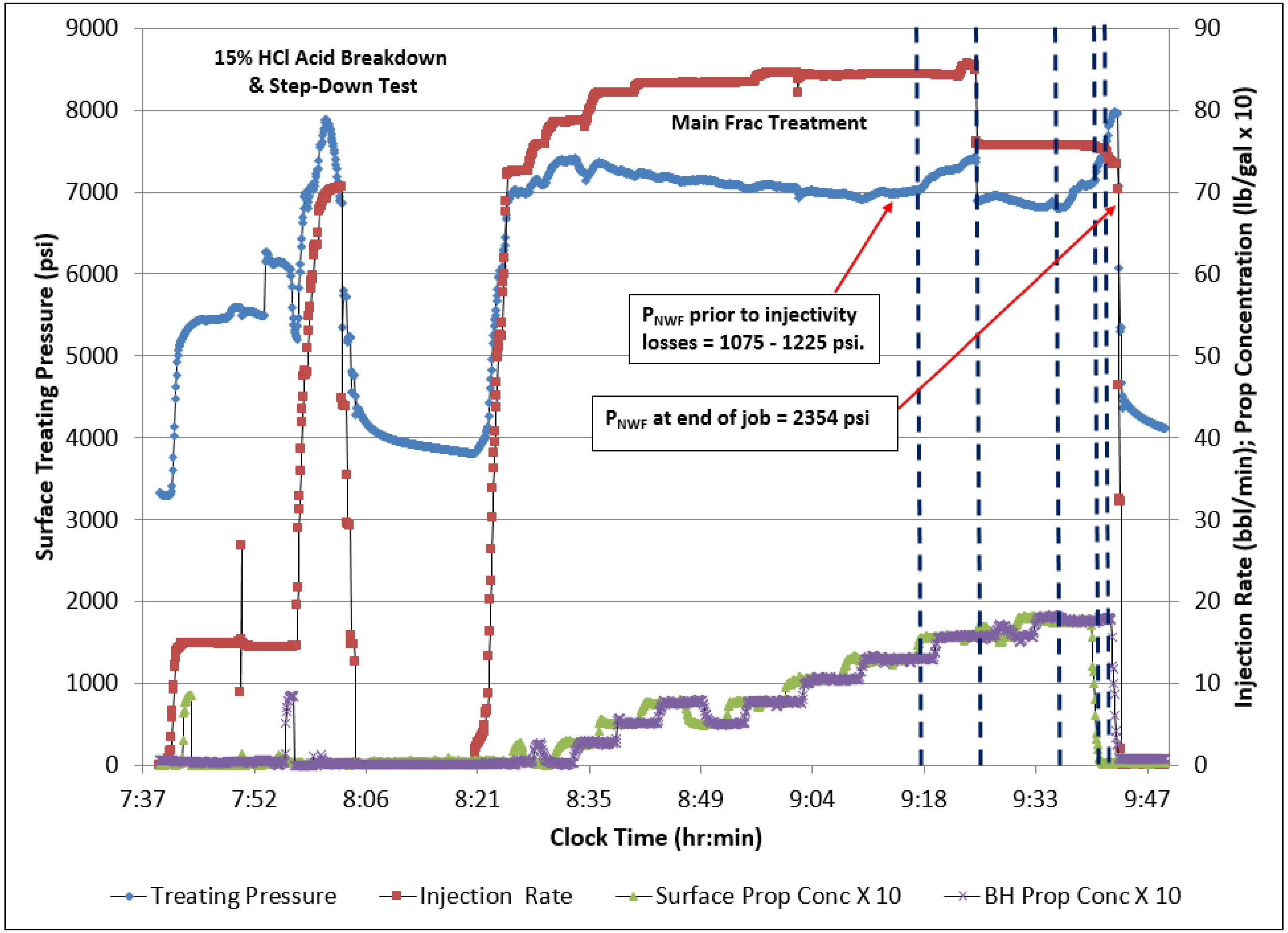
step-down rate, Q (bbl/min)	surface treating pressure, STP (psi)	calculated P_{pipe} (psi)	**calculated P_{NWF} (psi)**	modeled P_{perfs} (psi)	modeled $P_{tortousity}$ (psi)	**modeled P_{NWF} (psi)**
0	4385	0	**0**	0	0	**0**
14.7	4758	172	**201**	39	230	**269**
29.3	5218	326	**507**	156	325	**480**
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 $Q^{t\text{-}exp}$

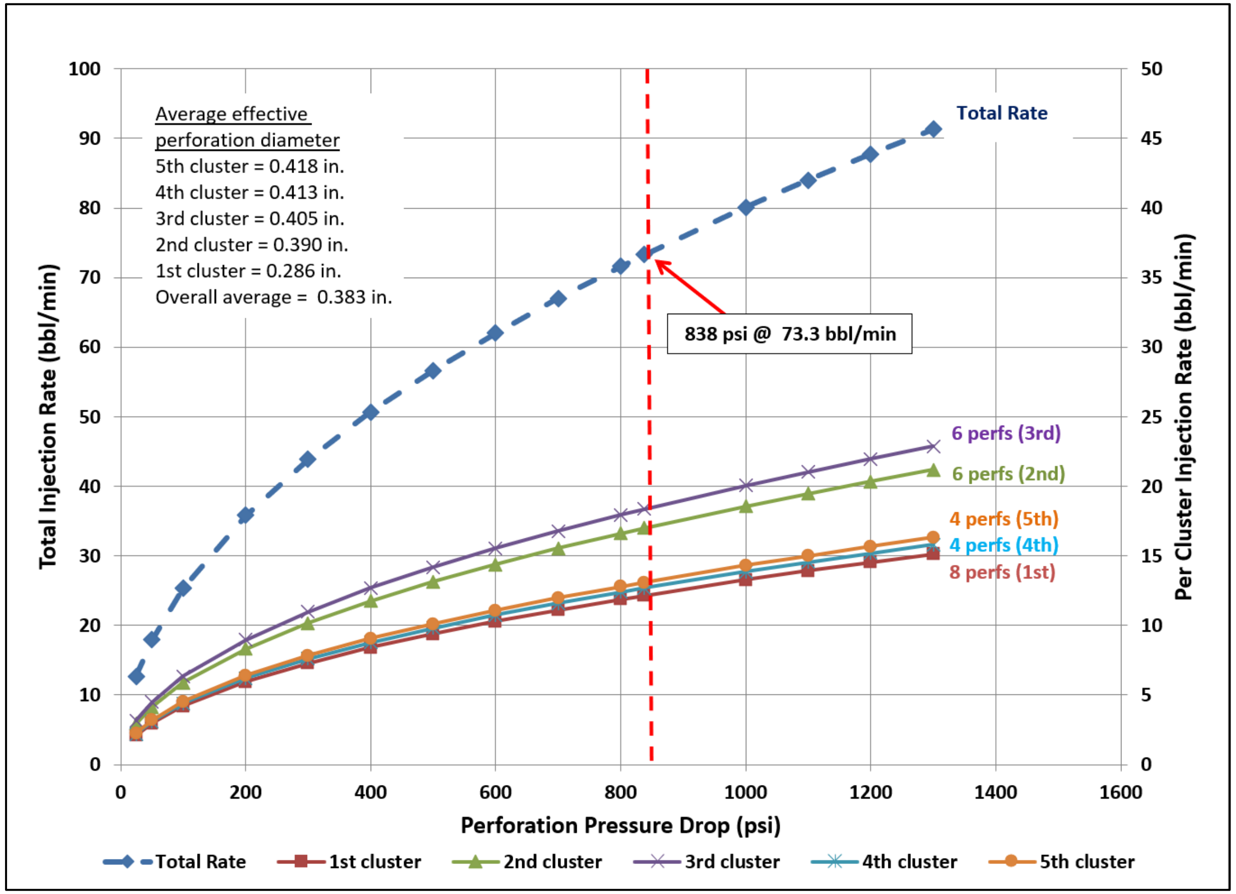
Well A, Stage 21: best-fit history match of modeled with calculated (actual) total near-wellbore friction

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

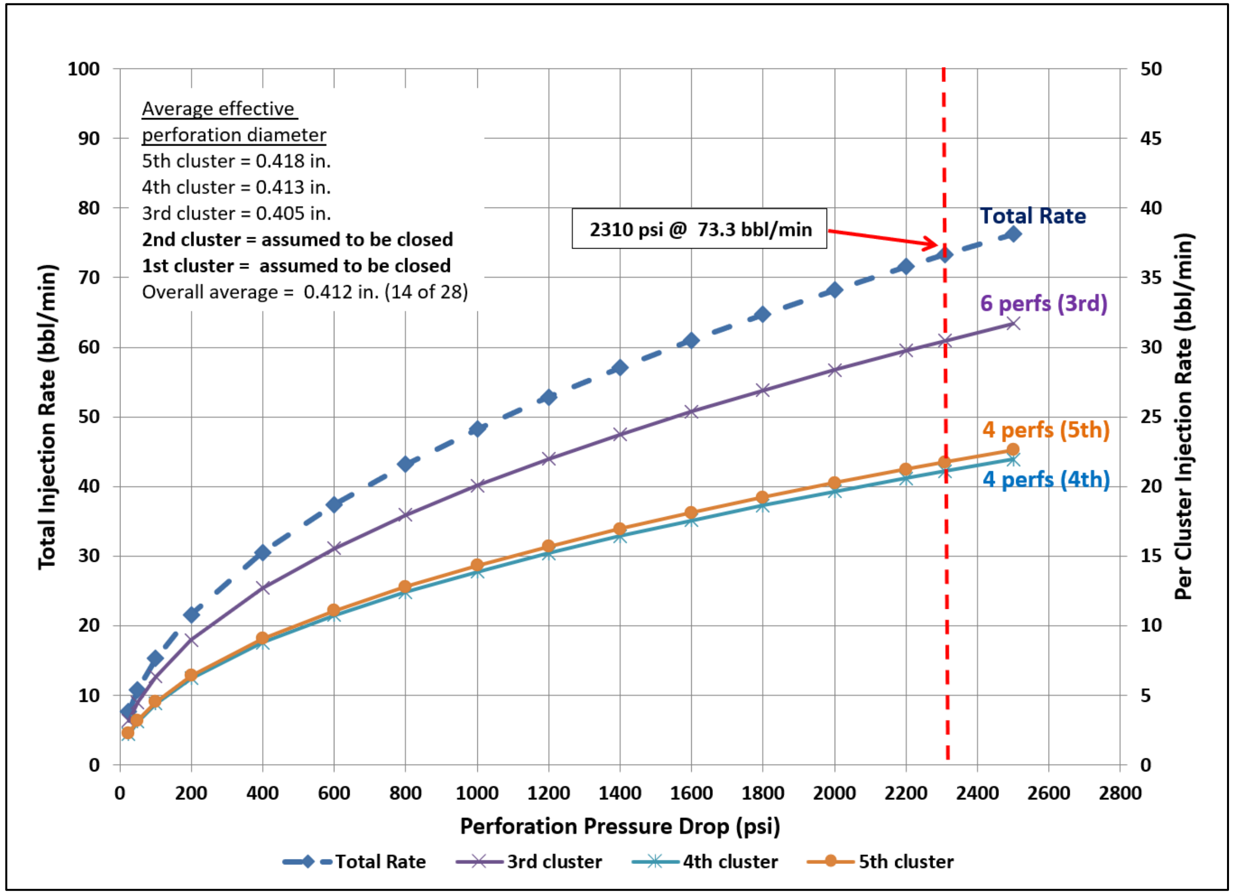


Average effective perforation diameter
5th cluster = 0.418 in.
4th cluster = 0.413 in.
3rd cluster = 0.405 in.
2nd cluster = 0.390 in.
1st cluster = 0.286 in.
Overall average = 0.383 in.

838 psi @ 73.3 bbl/min

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).



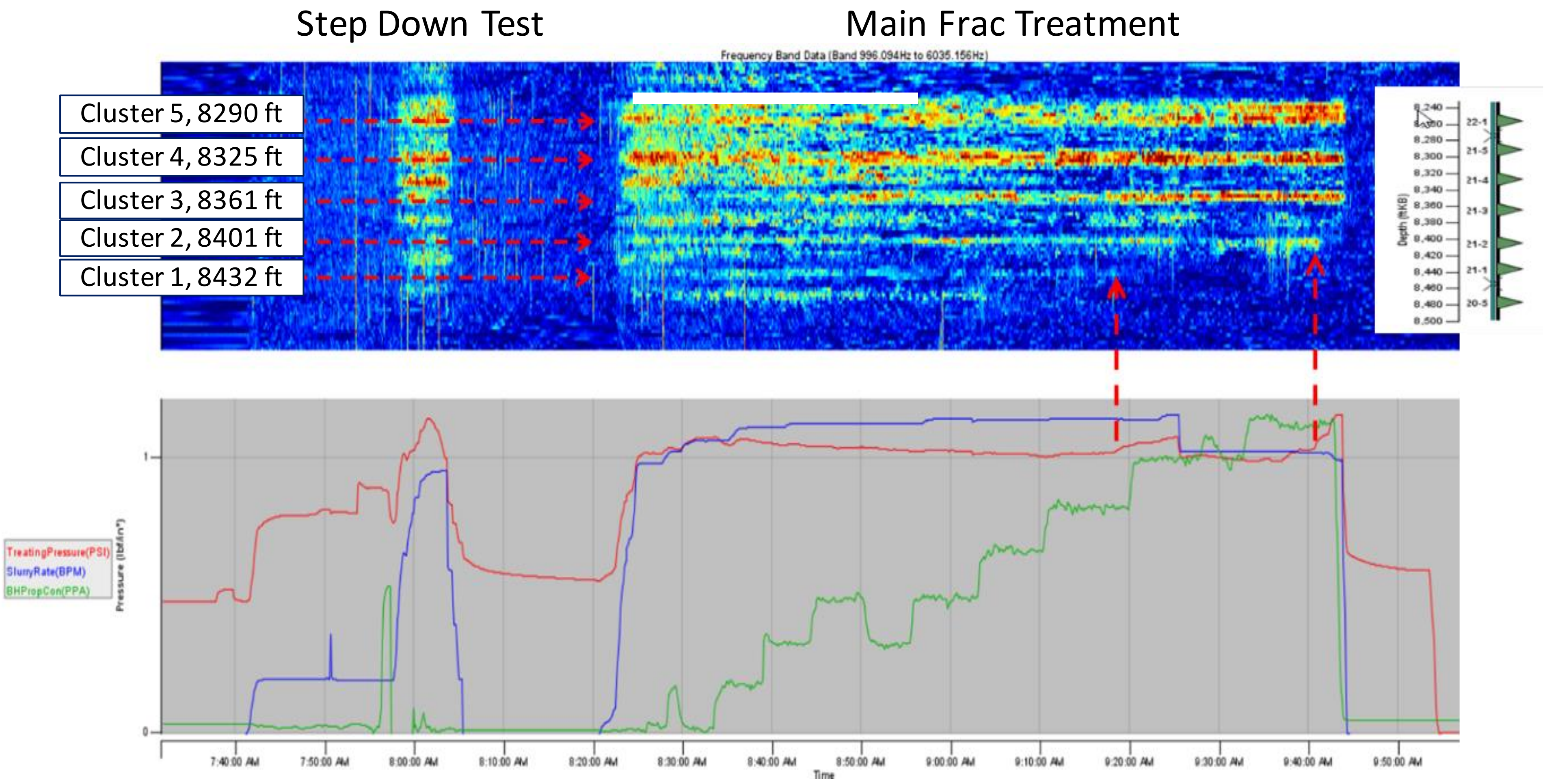
Average effective perforation diameter
5th cluster = 0.418 in.
4th cluster = 0.413 in.
3rd cluster = 0.405 in.
2nd cluster = assumed to be closed
1st cluster = assumed to be closed
Overall average = 0.412 in. (14 of 28)

2310 psi @ 73.3 bbl/min

14 open perforations

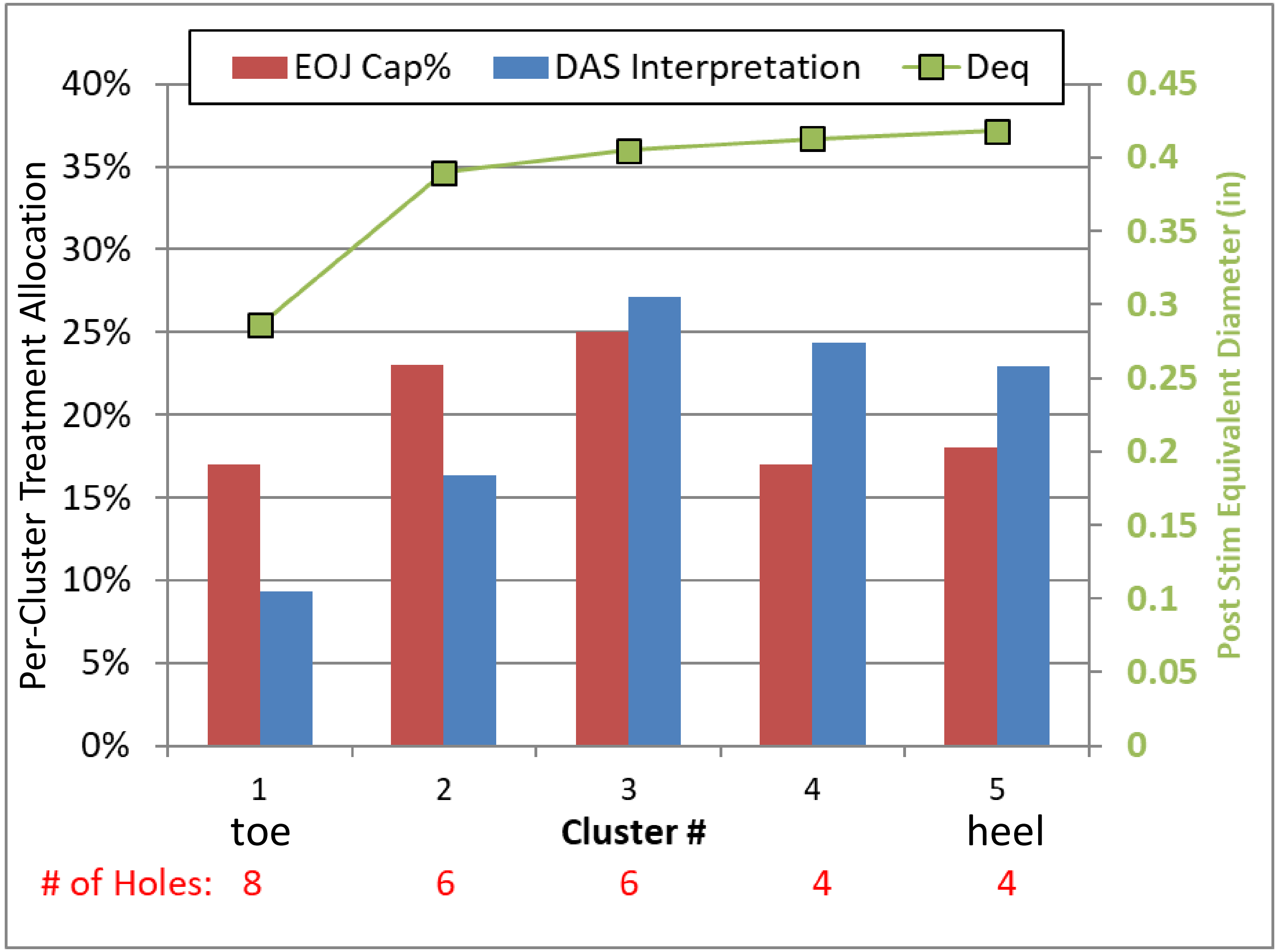
Reduced number of open perforations, leading to good agreement with measured and modeled perforation friction. This analysis was supported by the DAS data.

DAS Waterfall Plot: Well A, Stage 21



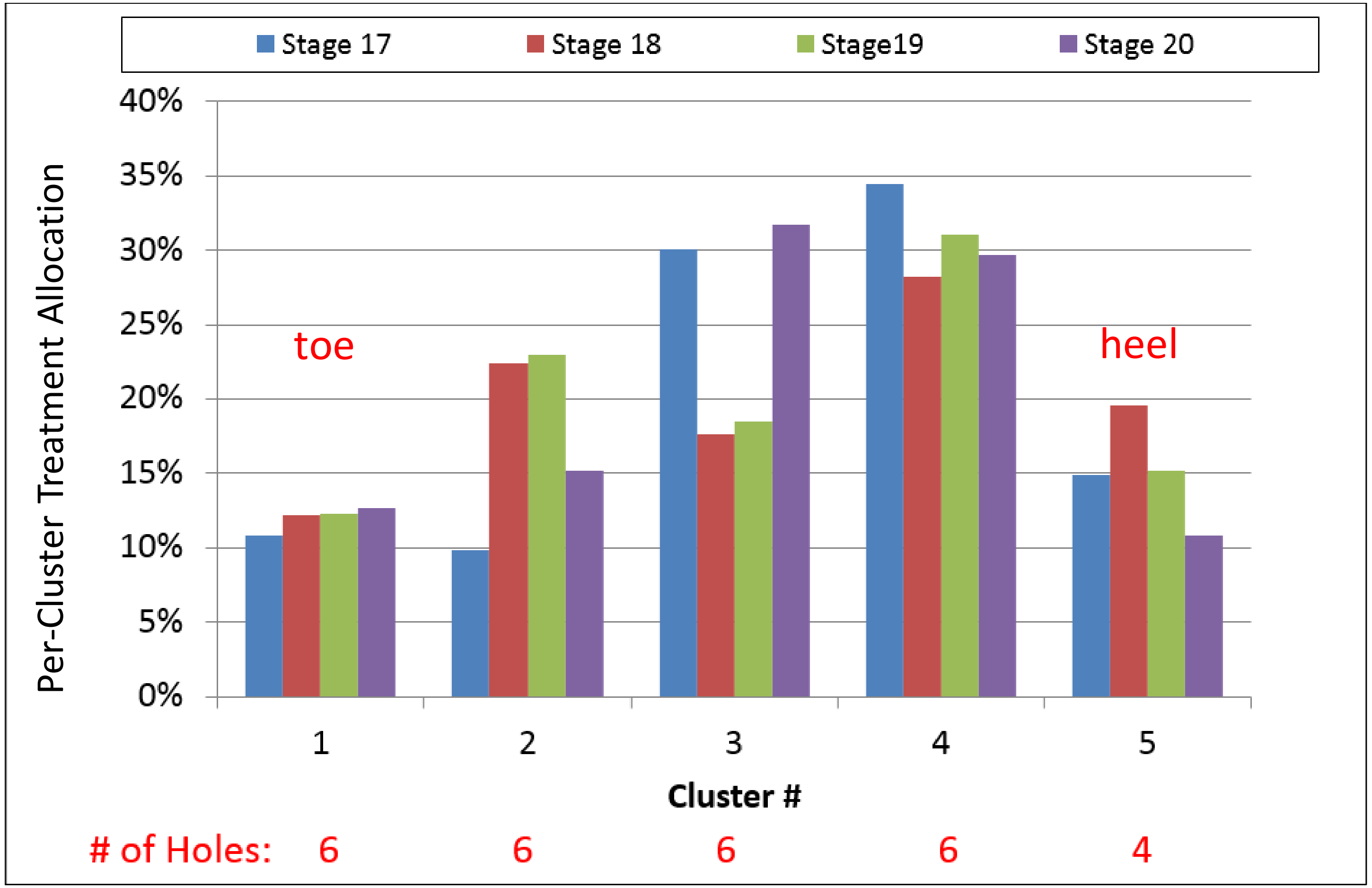
Termination in DAS signal in two of the five clusters corresponded with two rapid treating pressure increases, suggesting screenouts in Clusters 1 and 2.

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.

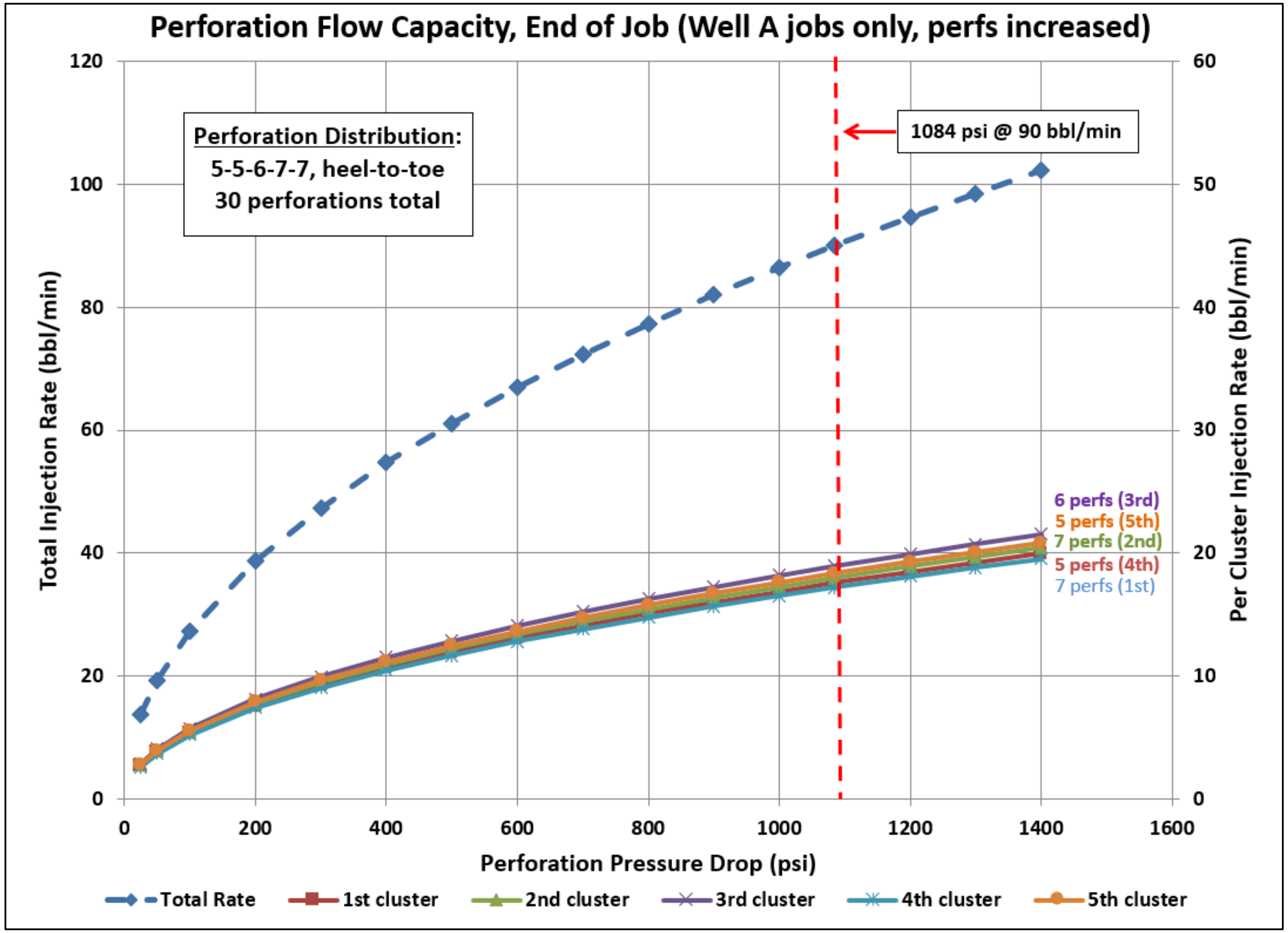
Hypothetical Perforation Redesign

Average Effective Entry Hole Diameter

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.

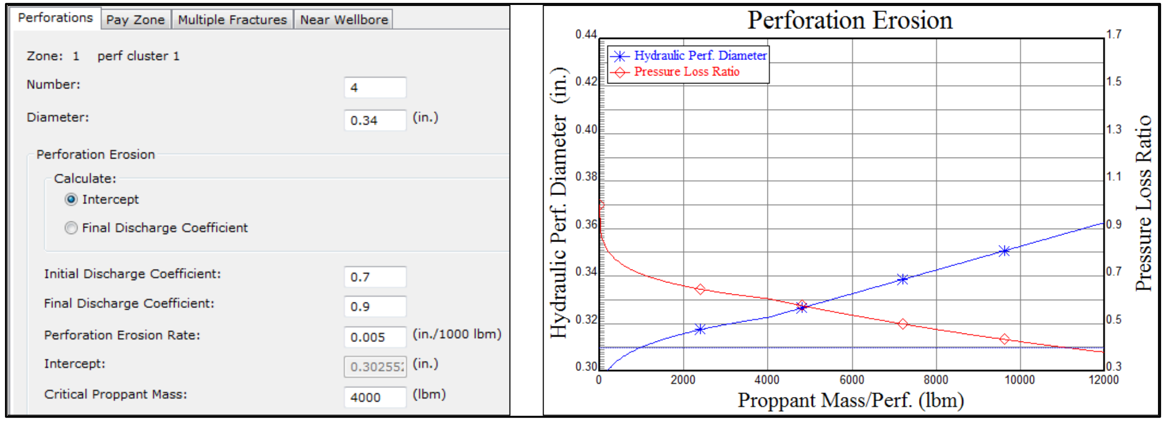
Injection Rate

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



Zone: 1 perf cluster 1

Number: 4

Diameter: 0.34 (in.)

Perforation Erosion

Calculate:

● Intercept

○ Final Discharge Coefficient

Initial Discharge Coefficient: 0.7

Final Discharge Coefficient: 0.9

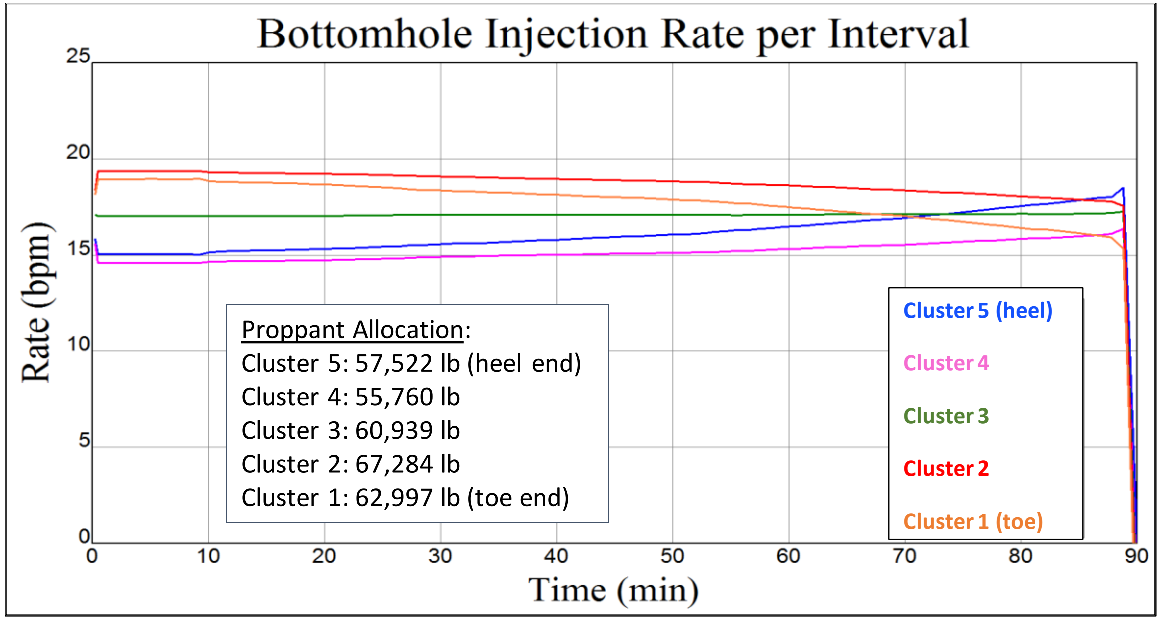
Perforation Erosion Rate: 0.005 (in./1000 lbm)

Intercept: 0.30255 (in.)

Critical Proppant Mass: 4000 (lbm)

Interactive perforation erosion module

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



Proppant Allocation:

Cluster 5: 57,522 lb (heel end)

Cluster 4: 55,760 lb

Cluster 3: 60,939 lb

Cluster 2: 67,284 lb

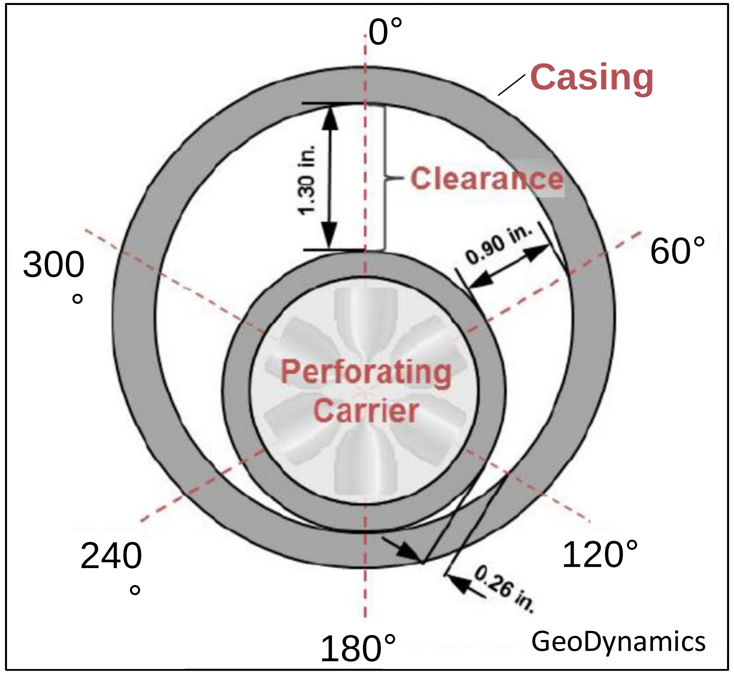
Cluster 1: 62,997 lb (toe end)

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.

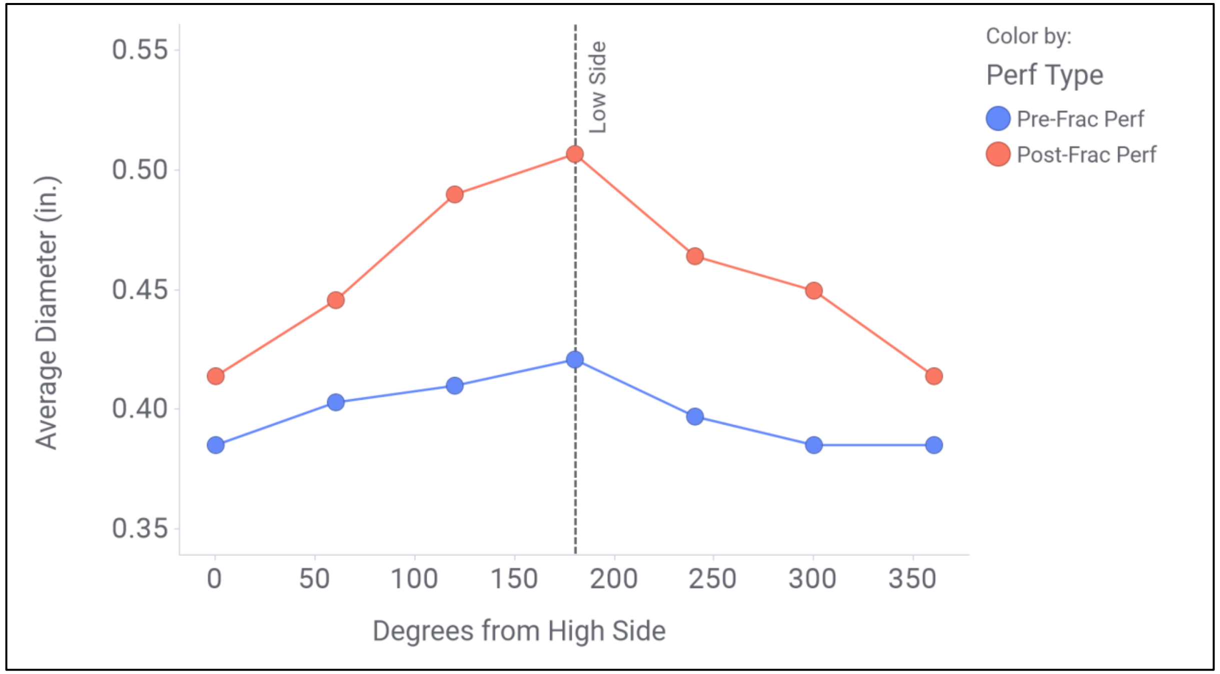
South Texas Case Study: Limited Entry and Perforating Gun Phasing

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**



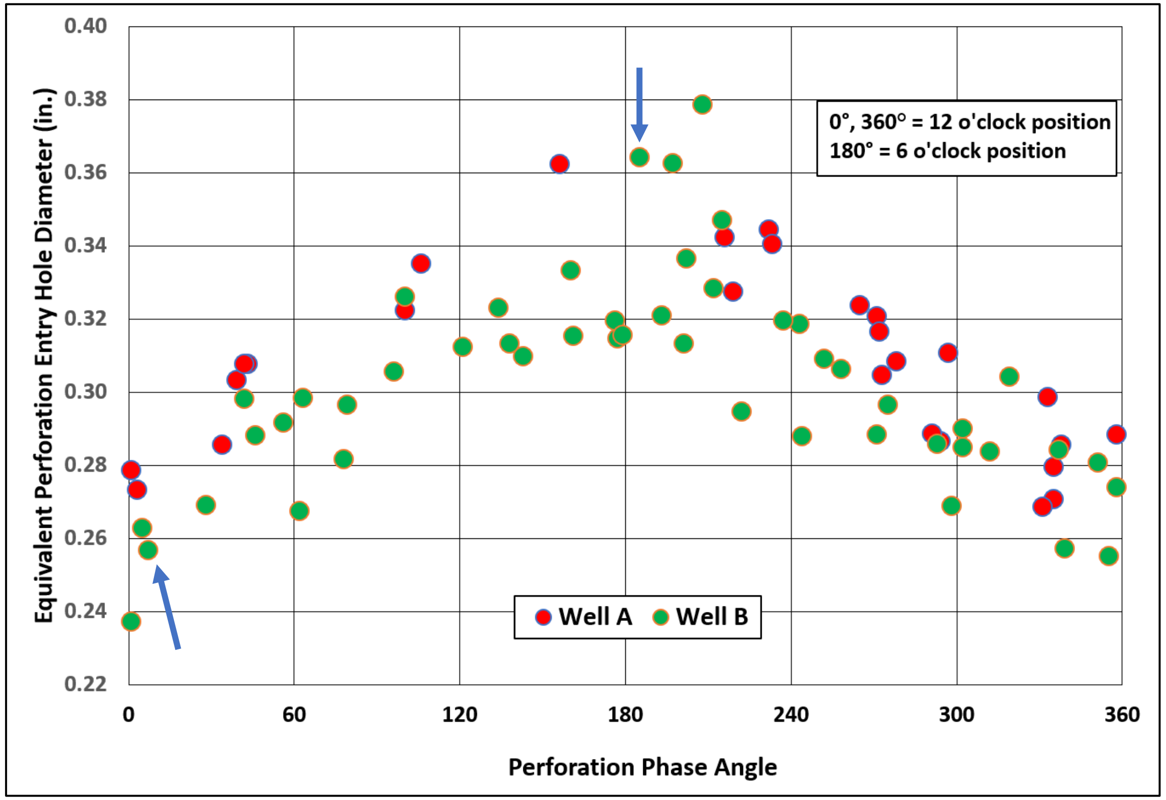
Cross-Section of Perf Gun Inside Casing



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.

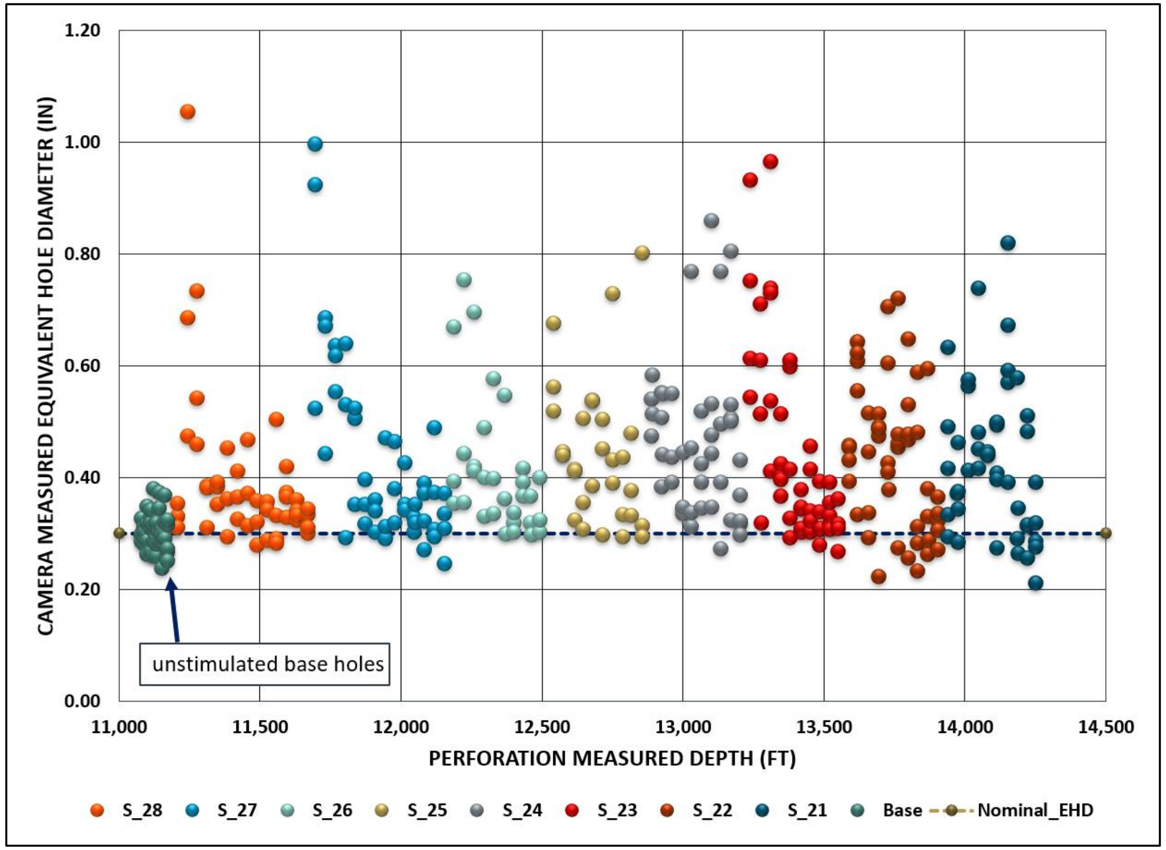
Perforation Entry Hole Size is Significantly Affected by Gun Clearance



0°, 360° = 12 o'clock position
180° = 6 o'clock position

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

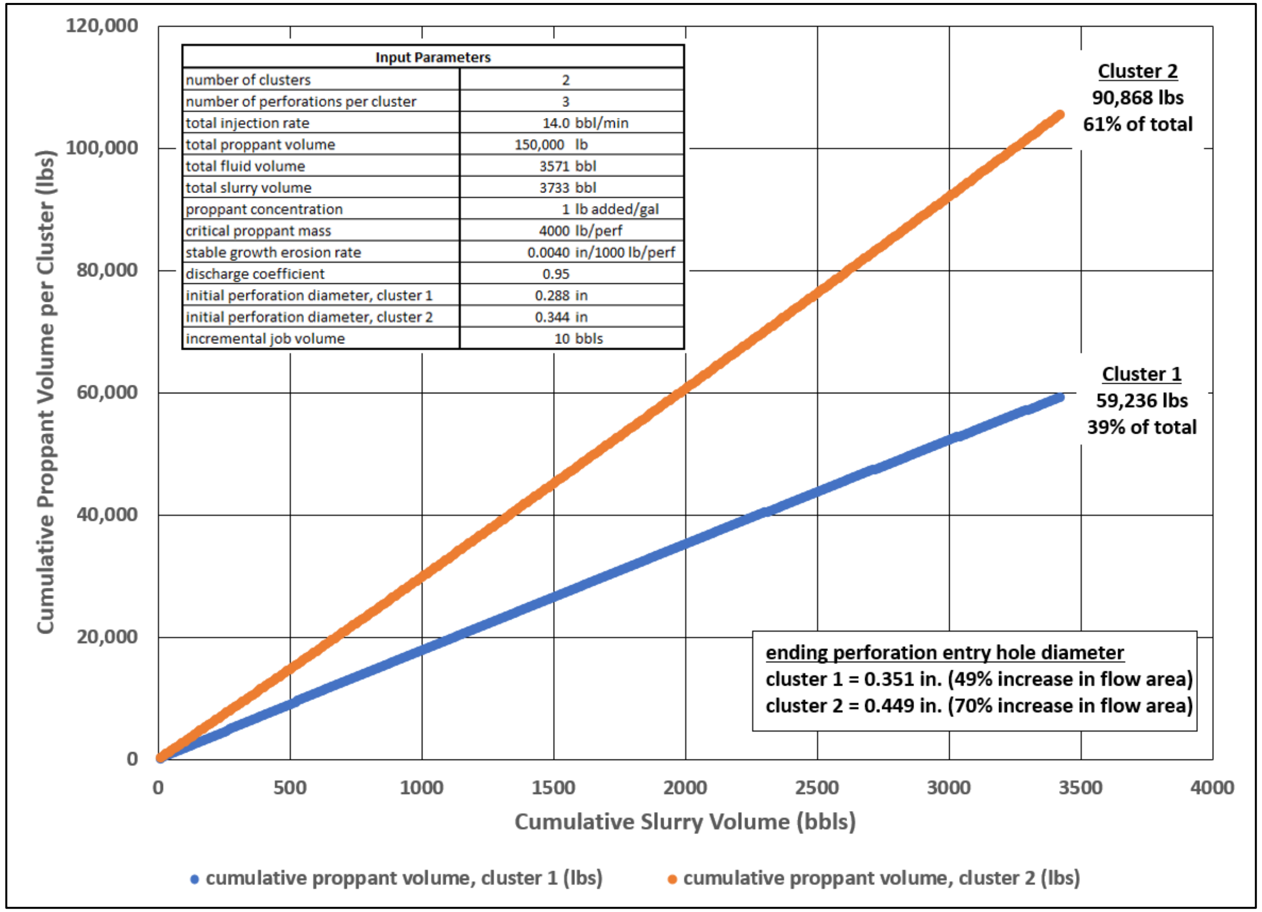


unstimulated base holes

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



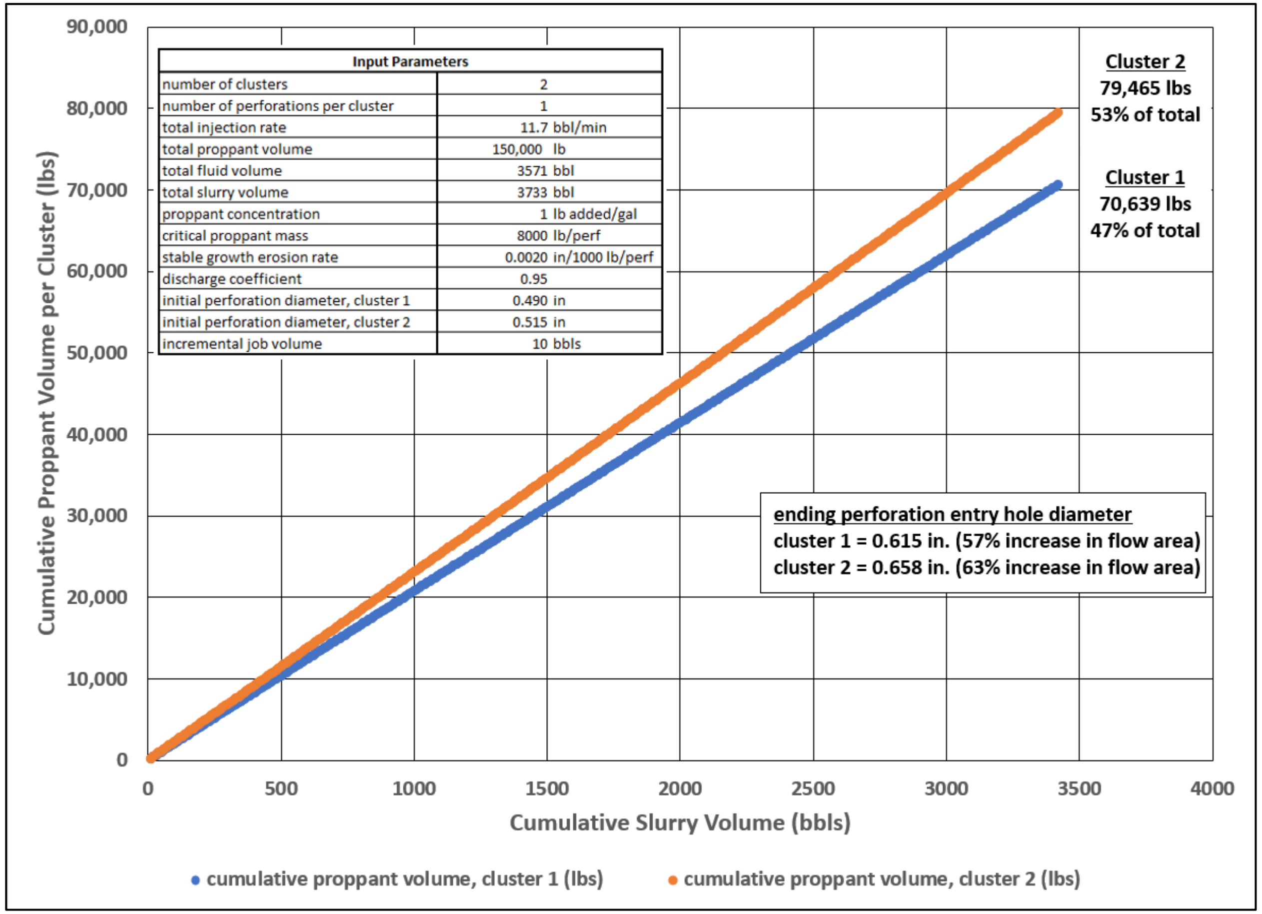
Input Parameters	
number of clusters	2
number of perforations per cluster	3
total injection rate	14.0 bbl/min
total proppant volume	150,000 lb
total fluid volume	3571 bbl
total slurry volume	3733 bbl
proppant concentration	1 lb added/gal
critical proppant mass	4000 lb/perf
stable growth erosion rate	0.0040 in/1000 lb/perf
discharge coefficient	0.95
initial perforation diameter, cluster 1	0.288 in
initial perforation diameter, cluster 2	0.344 in
incremental job volume	10 bbls

Cluster 2
90,868 lbs
61% of total

Cluster 1
59,236 lbs
39% of total

ending perforation entry hole diameter
cluster 1 = 0.351 in. (49% increase in flow area)
cluster 2 = 0.449 in. (70% increase in flow area)

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



Input Parameters	
number of clusters	2
number of perforations per cluster	1
total injection rate	11.7 bbl/min
total proppant volume	150,000 lb
total fluid volume	3571 bbl
total slurry volume	3733 bbl
proppant concentration	1 lb added/gal
critical proppant mass	8000 lb/perf
stable growth erosion rate	0.0020 in/1000 lb/perf
discharge coefficient	0.95
initial perforation diameter, cluster 1	0.490 in
initial perforation diameter, cluster 2	0.515 in
incremental job volume	10 bbls

Cluster 2
79,465 lbs
53% of total

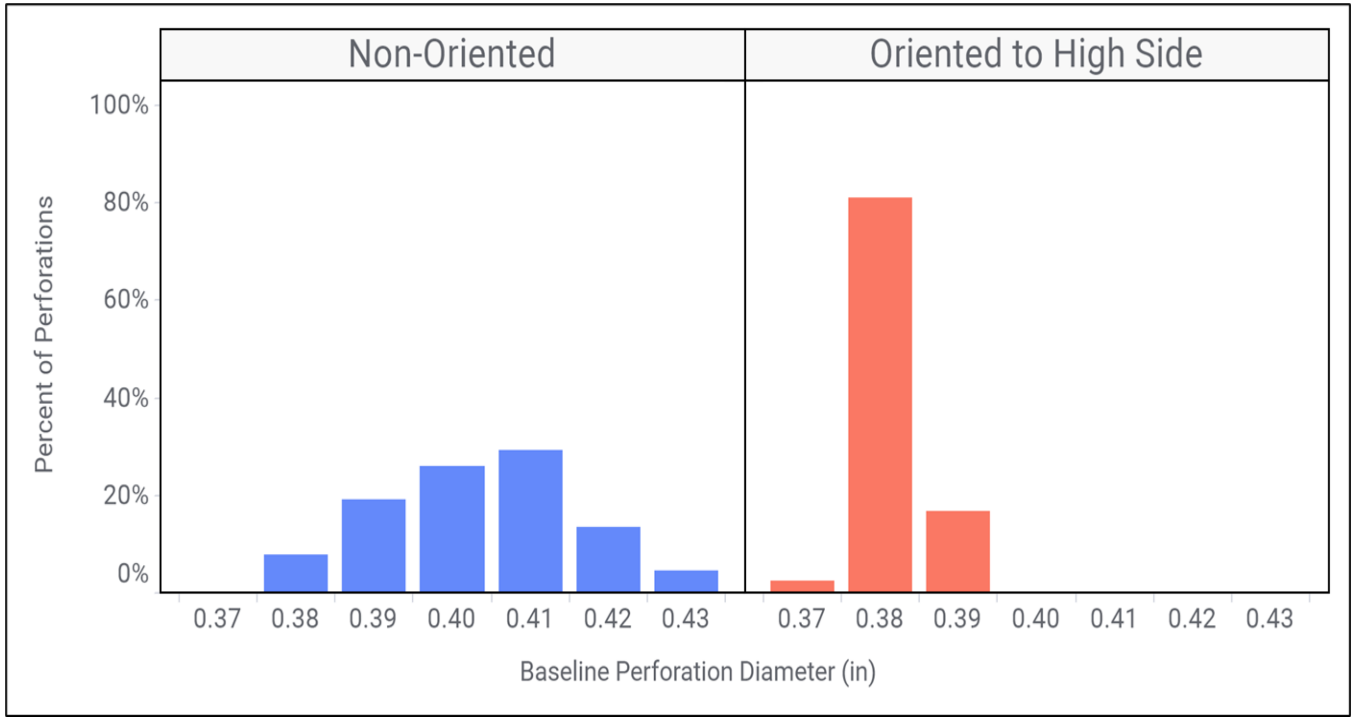
Cluster 1
70,639 lbs
47% of total

ending perforation entry hole diameter
cluster 1 = 0.615 in. (57% increase in flow area)
cluster 2 = 0.658 in. (63% increase in flow area)

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

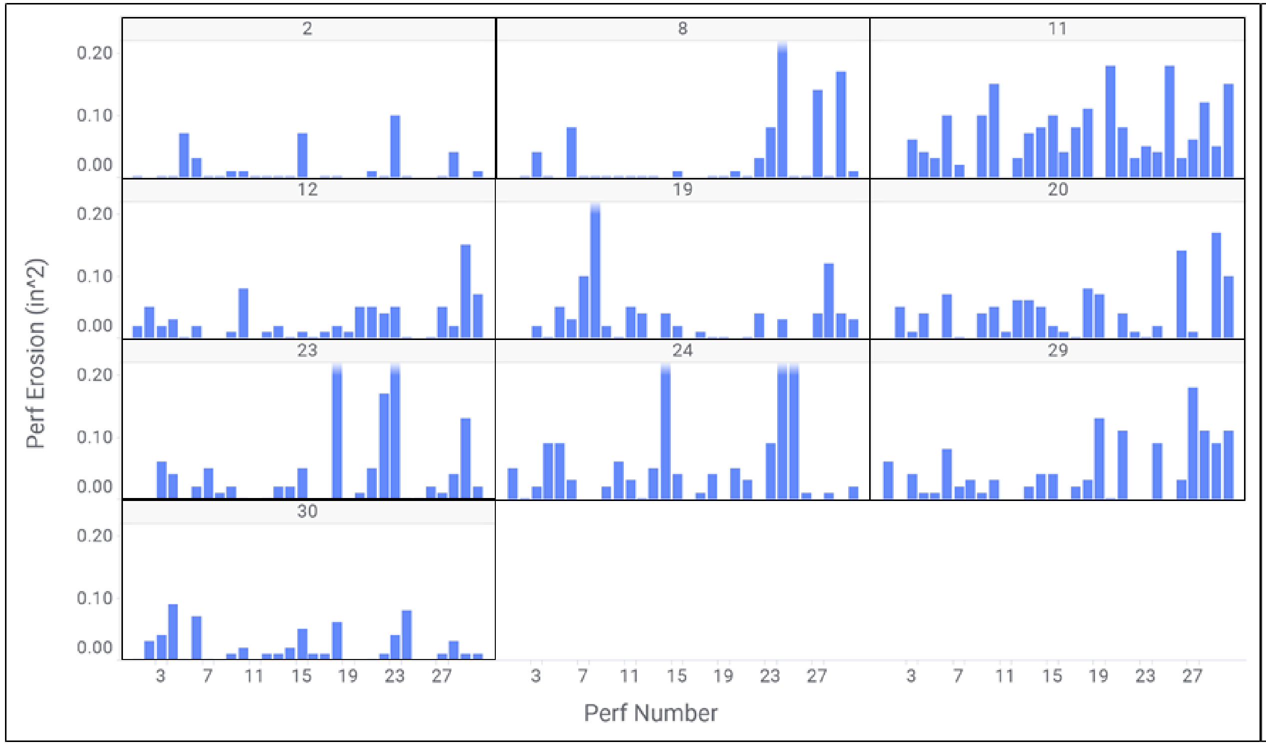
Initial Entry Hole Sizes

Non-Oriented versus Oriented

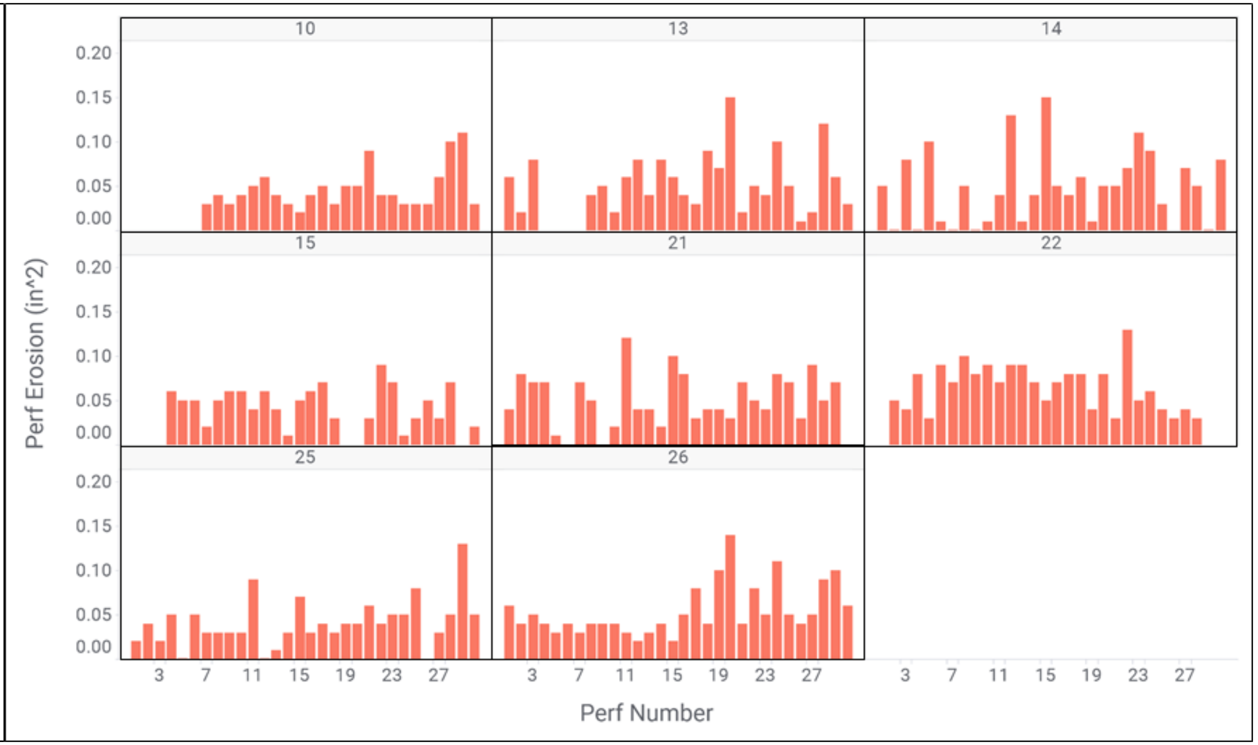


Histogram of baseline perforation diameter by orientation method

Erosional Characteristics of Limited Entry Perforations: Video-based Imaging



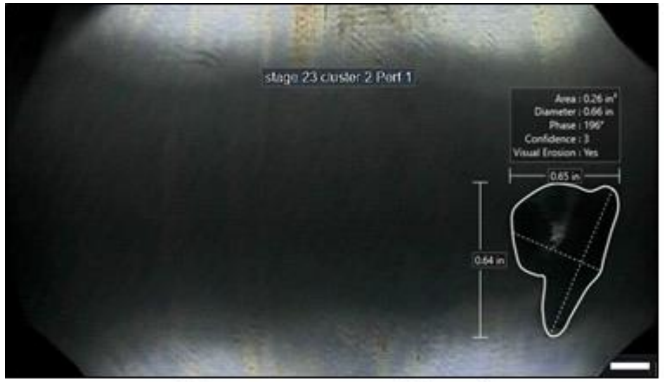
Non-Oriented Stages



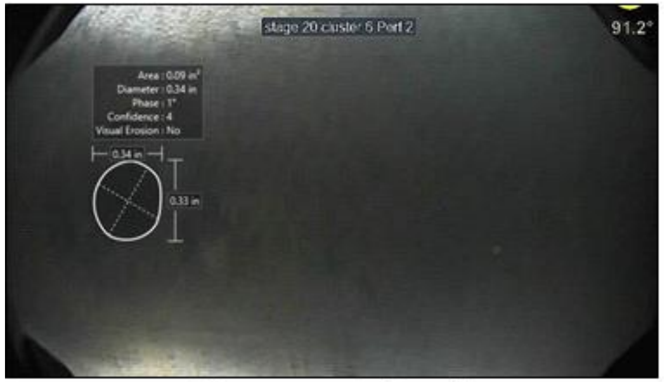
Oriented Stages

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.

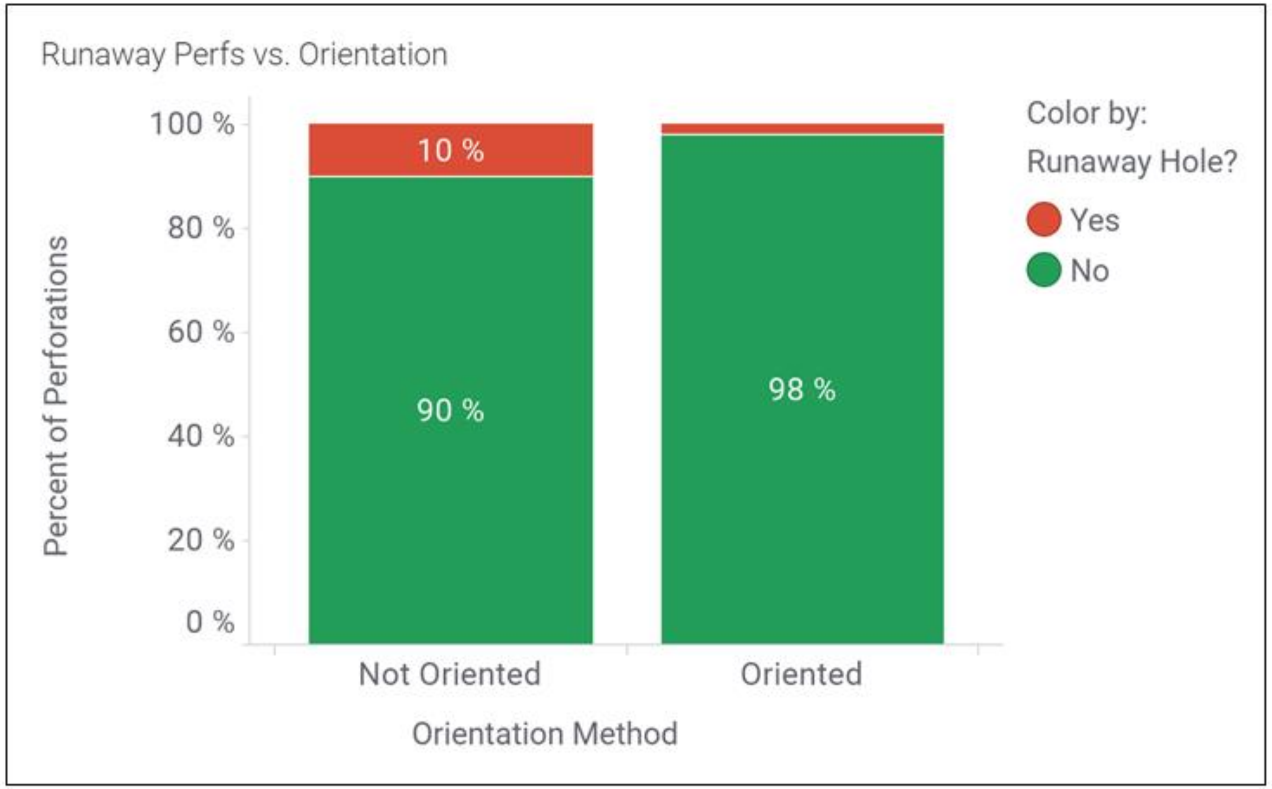
Limited Entry Perforating: Erosional Severity



Runaway Perf



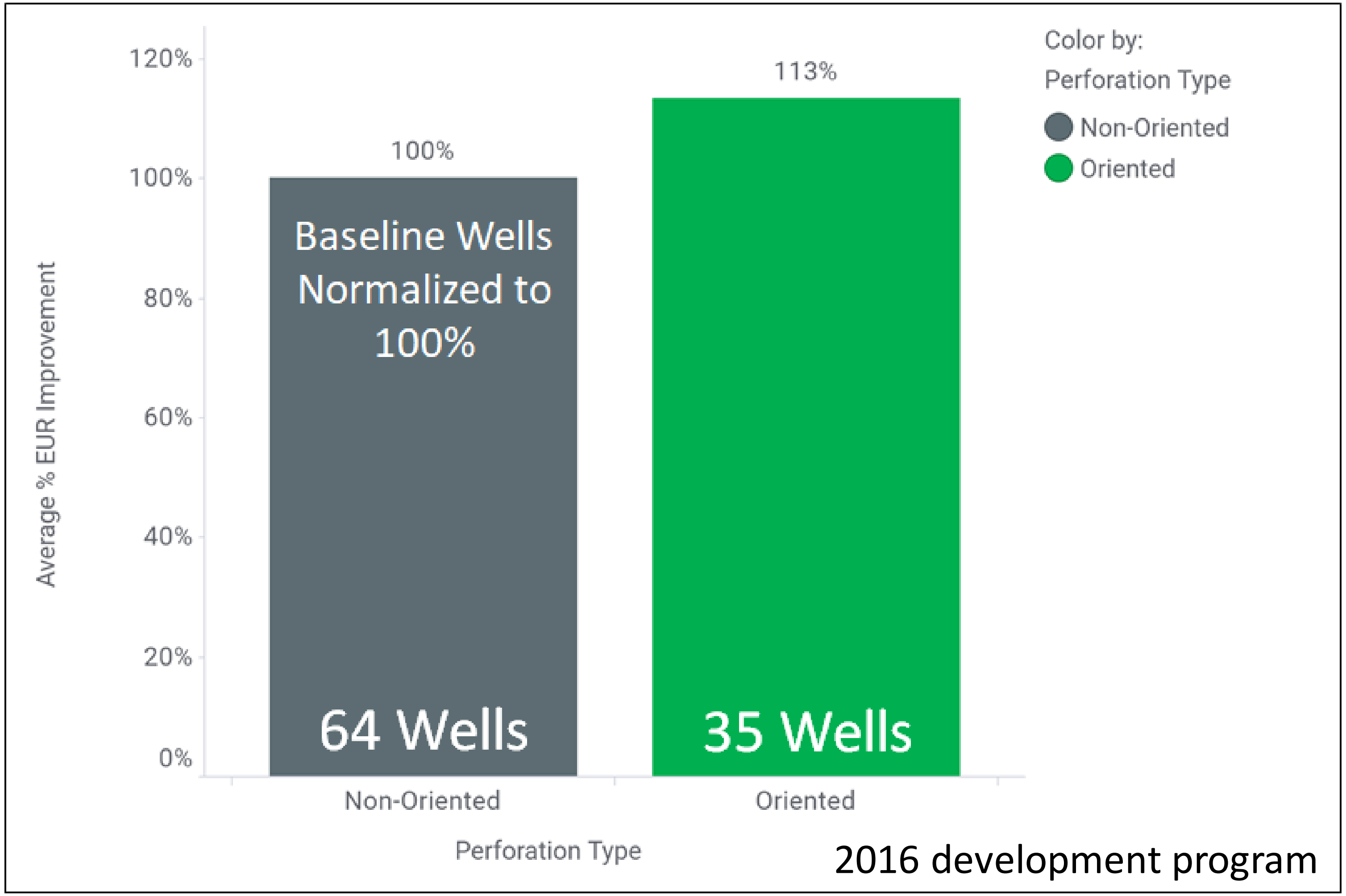
Normal Perf



***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



2016 development program

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.

Your Feedback is Important

Enter your section in the DL Evaluation Contest by completing the evaluation form for this presentation

Visit SPE.org/dl

#SPEDL

Society of Petroleum Engineers

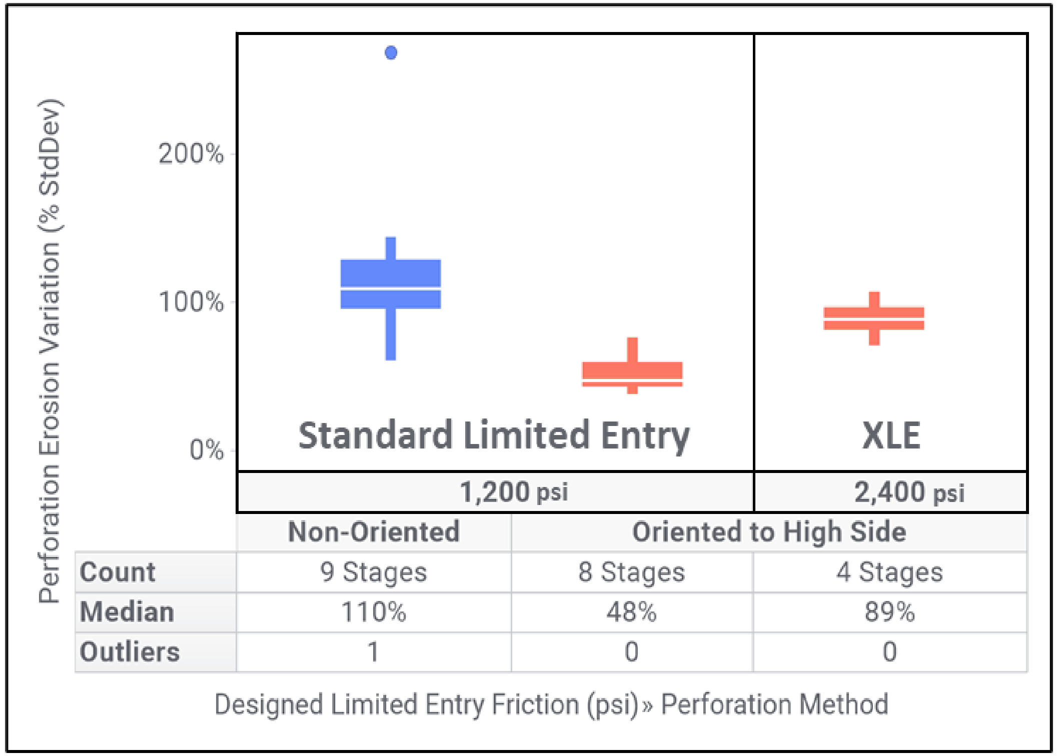
Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl

Extra Slides

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.
- Lookback study indicated wells utilizing oriented perforating exhibited significantly greater normalized 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.**
- 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.

Entry Hole Orientation and Initial Size

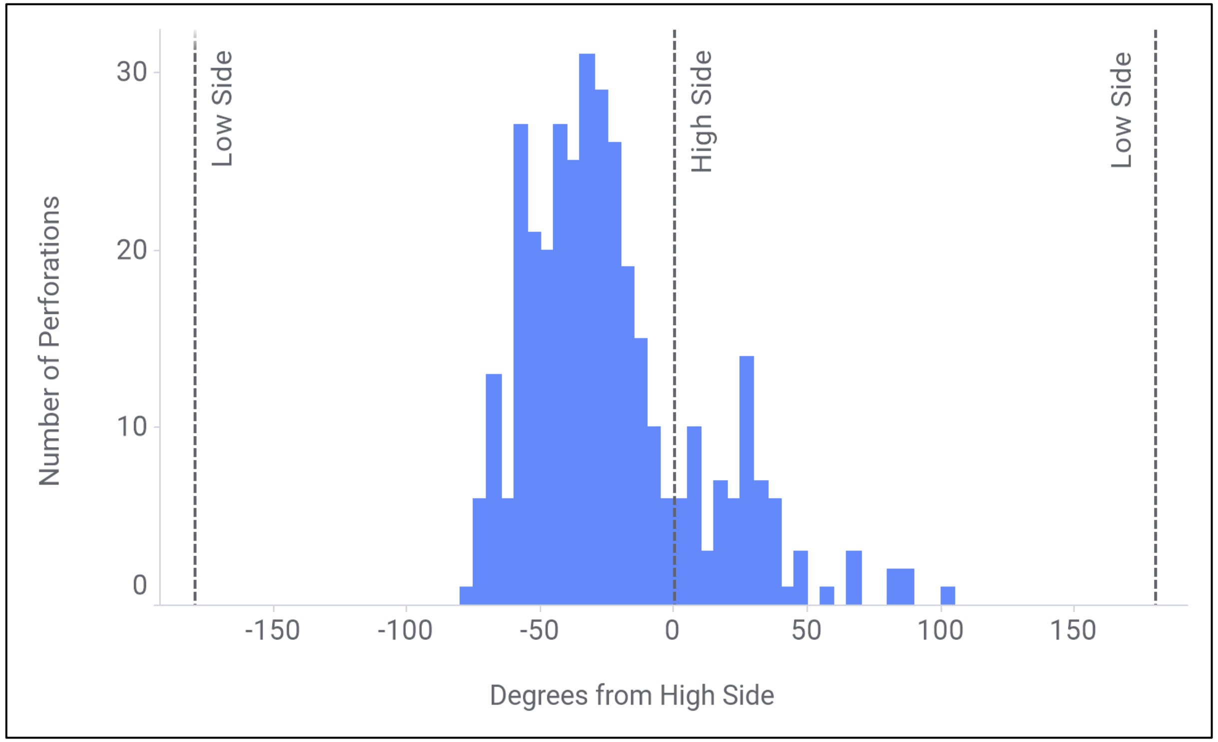


	1,200 psi		2,400 psi
	Non-Oriented	Oriented to High Side	
Count	9 Stages	8 Stages	4 Stages
Median	110%	48%	89%
Outliers	1	0	0

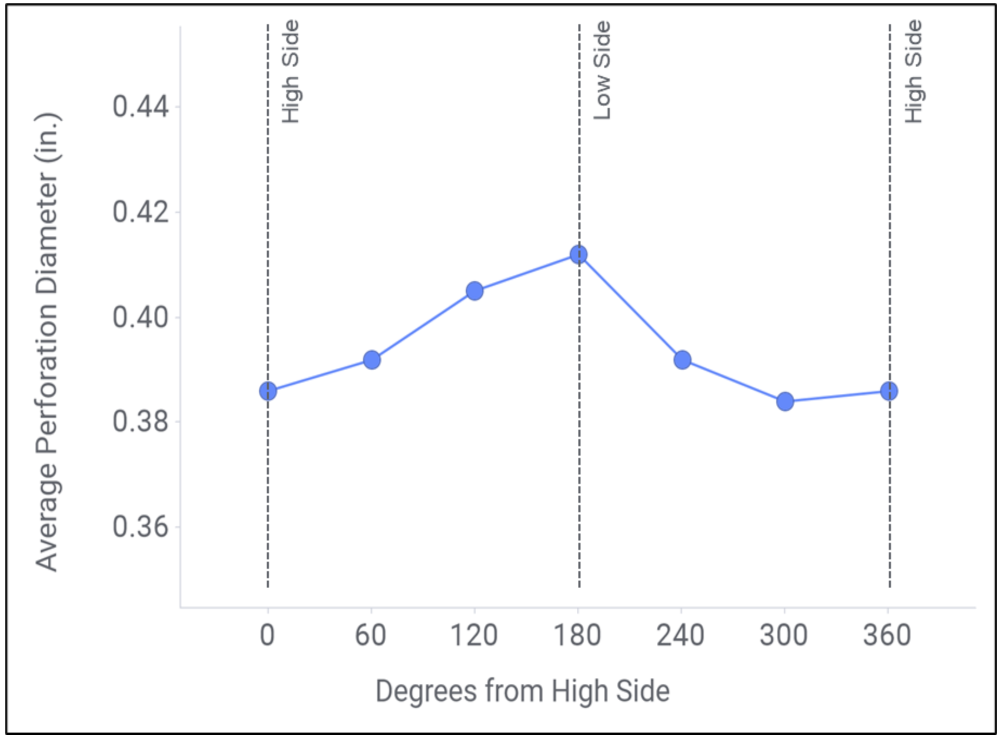
Paper SPE-204203-MS

Perforation erosion variation by orientation method and by limited entry perforation friction. Standard limited entry design with oriented perforating yielded the best result.

Entry Hole Orientation and Initial Size as Determined From Post-Treatment Video-Based Imaging Survey

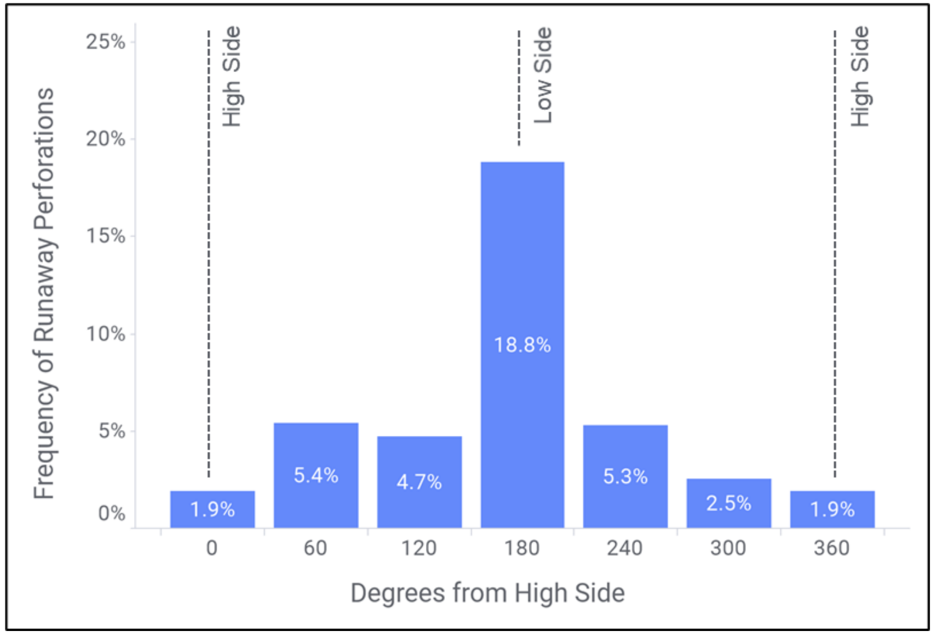


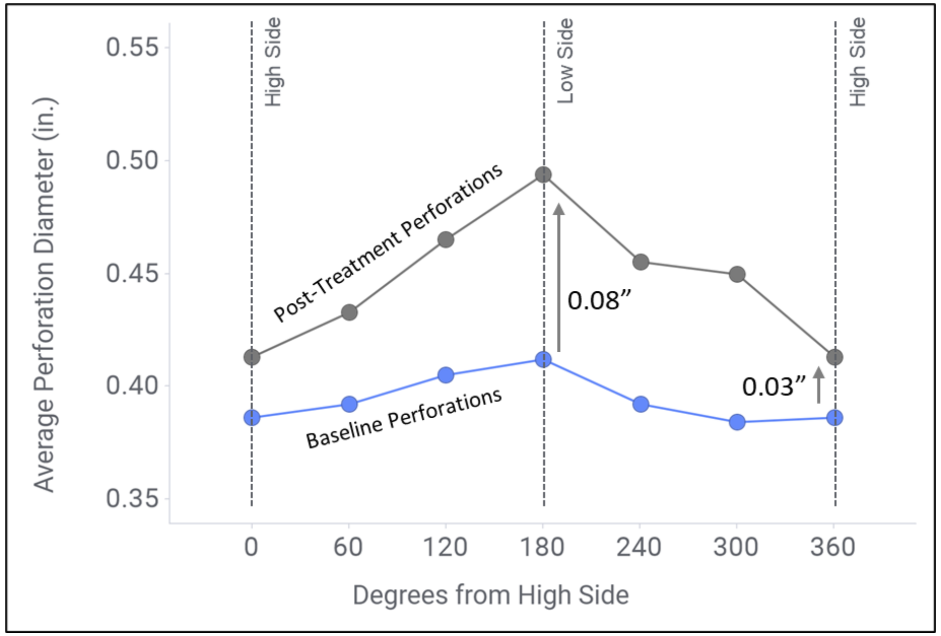
Histogram of perforation orientation for all stages that were oriented to the high side



Average diameters from baseline (untreated) perforations

Excessively Eroded Entry Holes as a Function of Gun Phasing



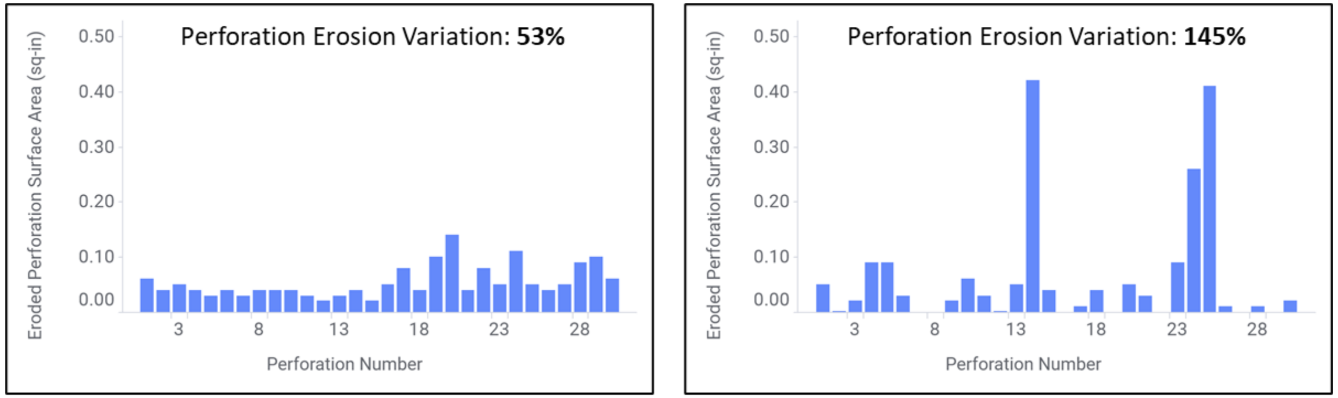


Paper SPE-204203-MS

Frequency of runaway perforations versus perforation phase angle

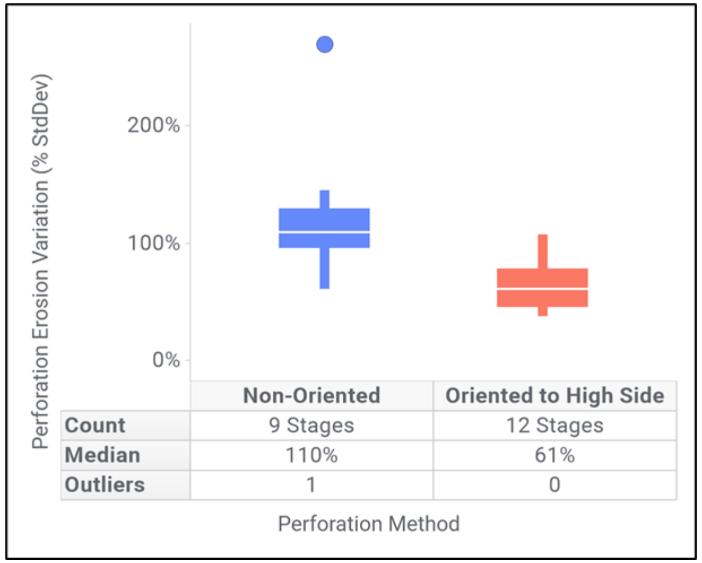
Average diameters from baseline perforations (blue) and post-treatment perforations (dark gray).

Variation of Entry Hole Orientation and Initial Size



(a) **(b)**

Example of a stage with low perforation erosion variance (a) and a stage with high perforation erosion variance (b).

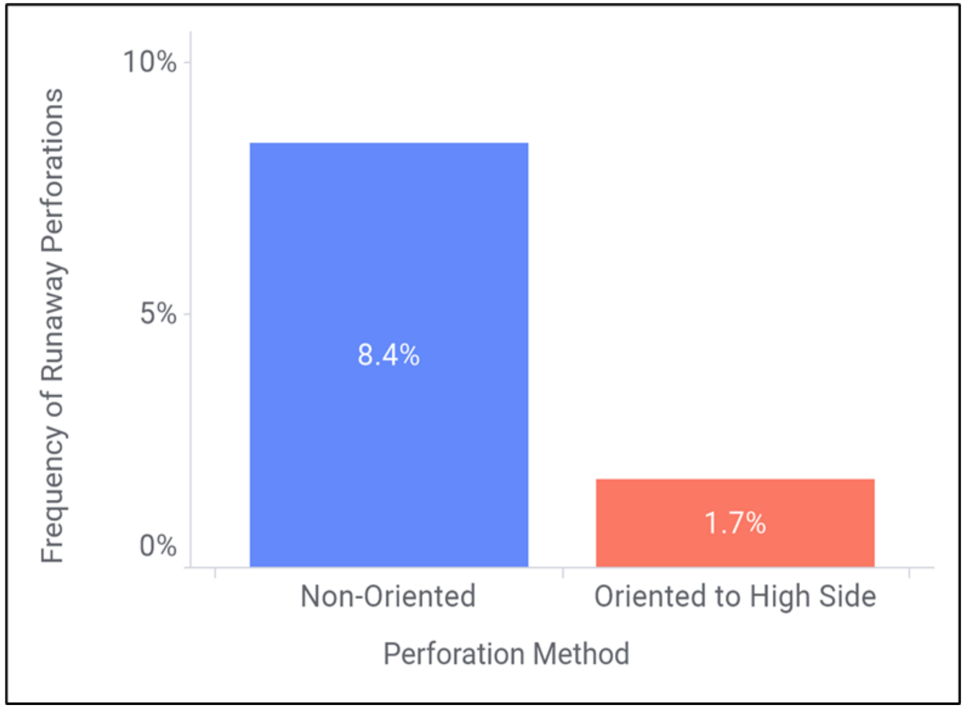


	Non-Oriented	Oriented to High Side
Count	9 Stages	12 Stages
Median	110%	61%
Outliers	1	0

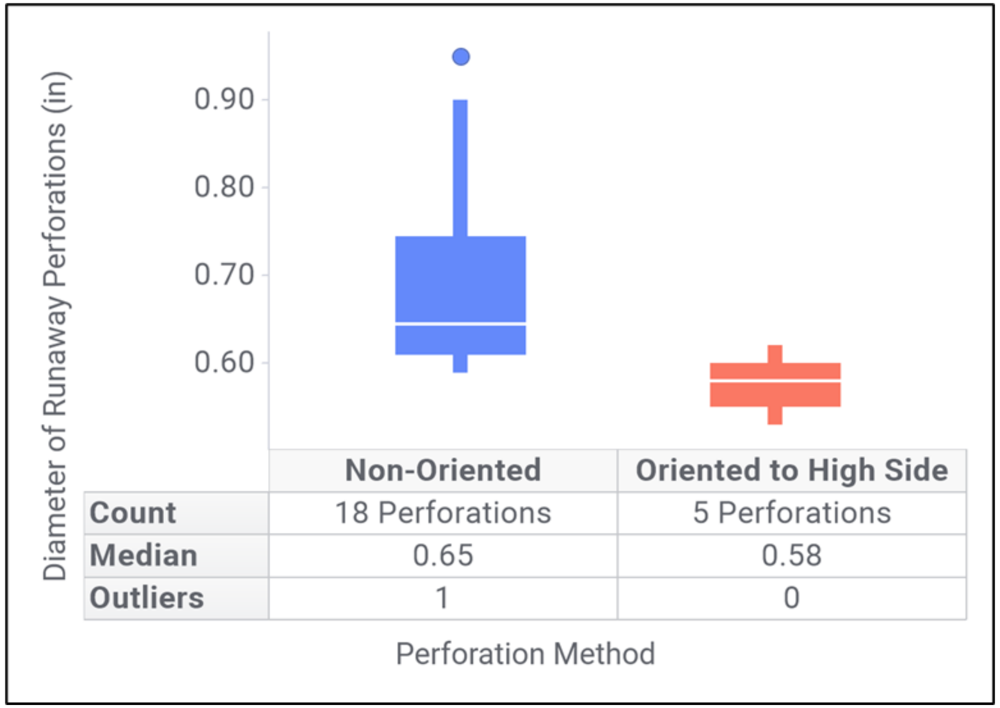
Perforation erosion variation by orientation method

Paper SPE-204203-MS

Incidences of Runaway (Excessively Eroded) Perforation Entry Holes



Frequency of runaway perforations by orientation method

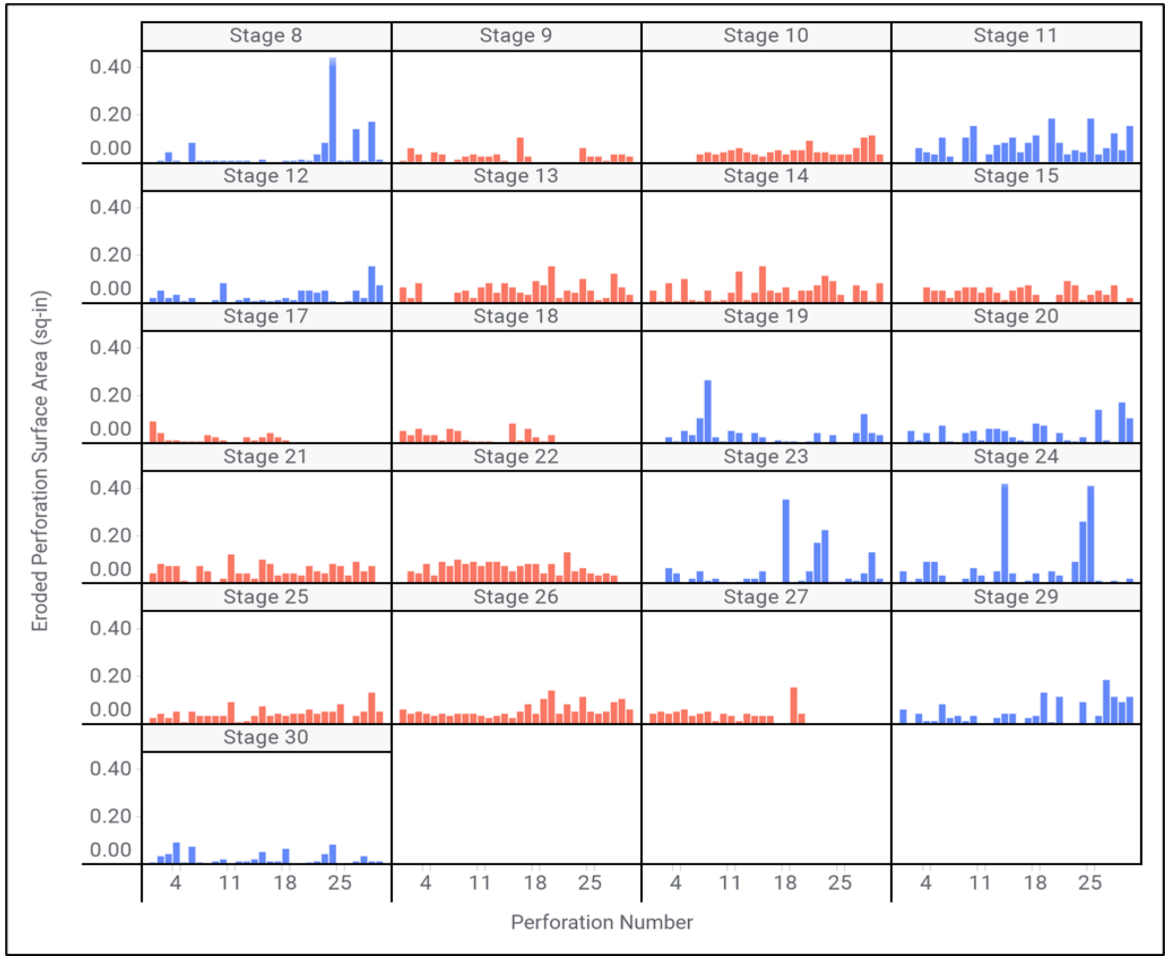


	Non-Oriented	Oriented to High Side
Count	18 Perforations	5 Perforations
Median	0.65	0.58
Outliers	1	0

Size of runaway perforations by orientation method

Paper SPE-204203-MS

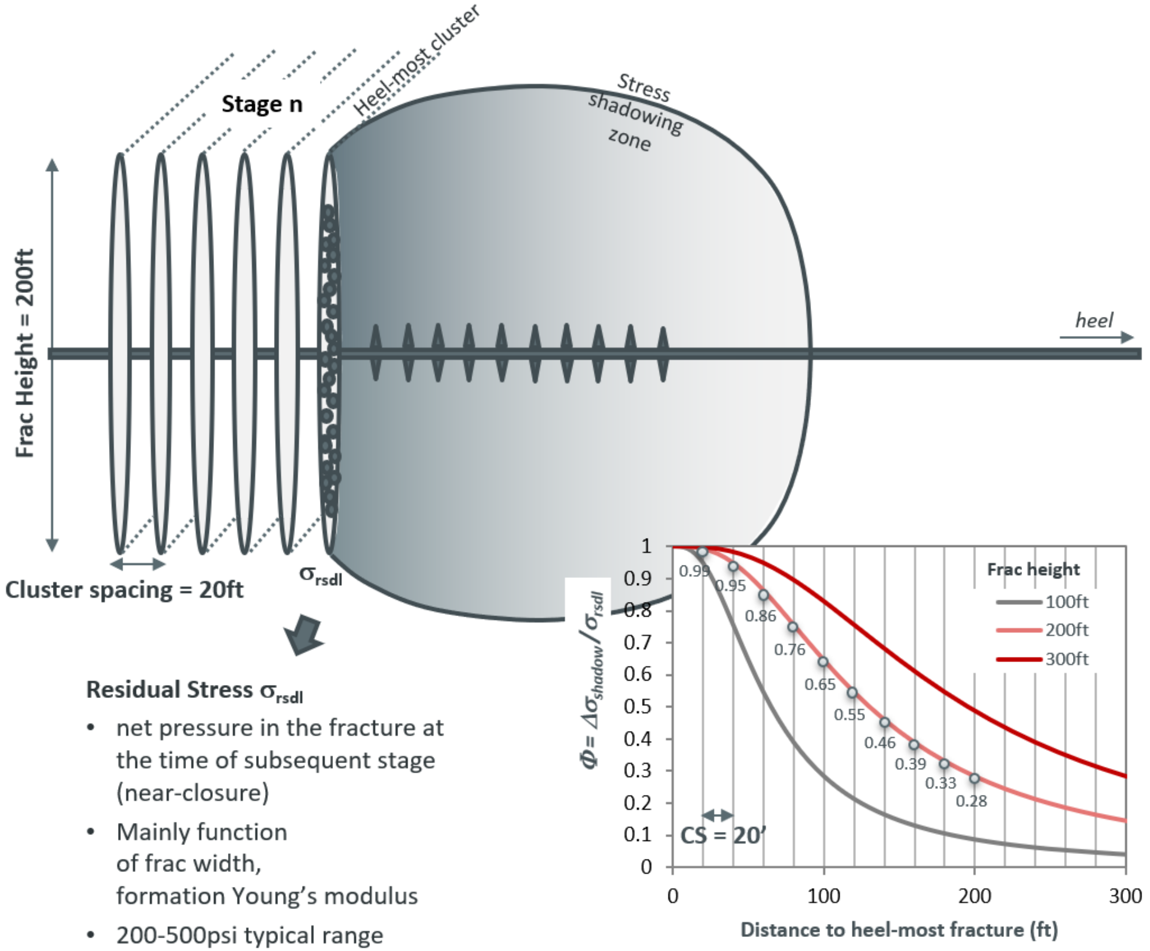
Entry Hole Orientation and Initial Size



Paper SPE-204203-MS

Calculated perforation erosion at each perforation for non-oriented stages (blue) and stages oriented to the high side (red)

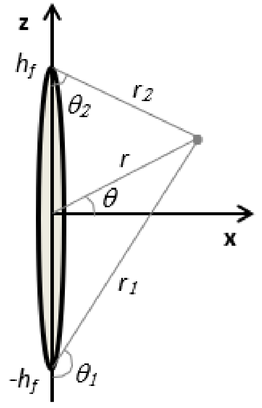
Stress Shadowing Basics

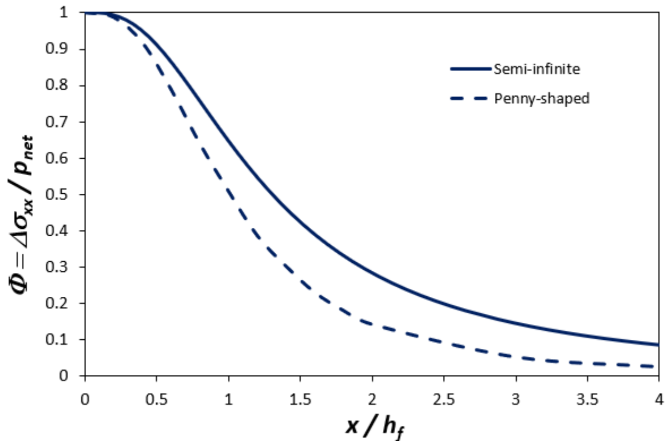


Residual Stress σ_{rsdl}

- net pressure in the fracture at the time of subsequent stage (near-closure)
- Mainly function of frac width, formation Young's modulus
- 200-500psi typical range

$$p_{net} = \frac{w_f E}{4(1-\nu^2)h_f} \qquad \Phi_{penny-shaped} = \frac{2}{\pi}\left[\frac{x}{h_f}\frac{\left(x^2-h_f^2\right)^2}{\left(x^2+h_f^2\right)^2} - \tan^{-1}\left(\frac{h_f}{x}\right)\right] \qquad \Phi_{semi-infinite} = 1-\left(\frac{x}{h_f}\right)^3\left[1+\left(\frac{x}{h_f}\right)^2\right]^{-3/2}$$



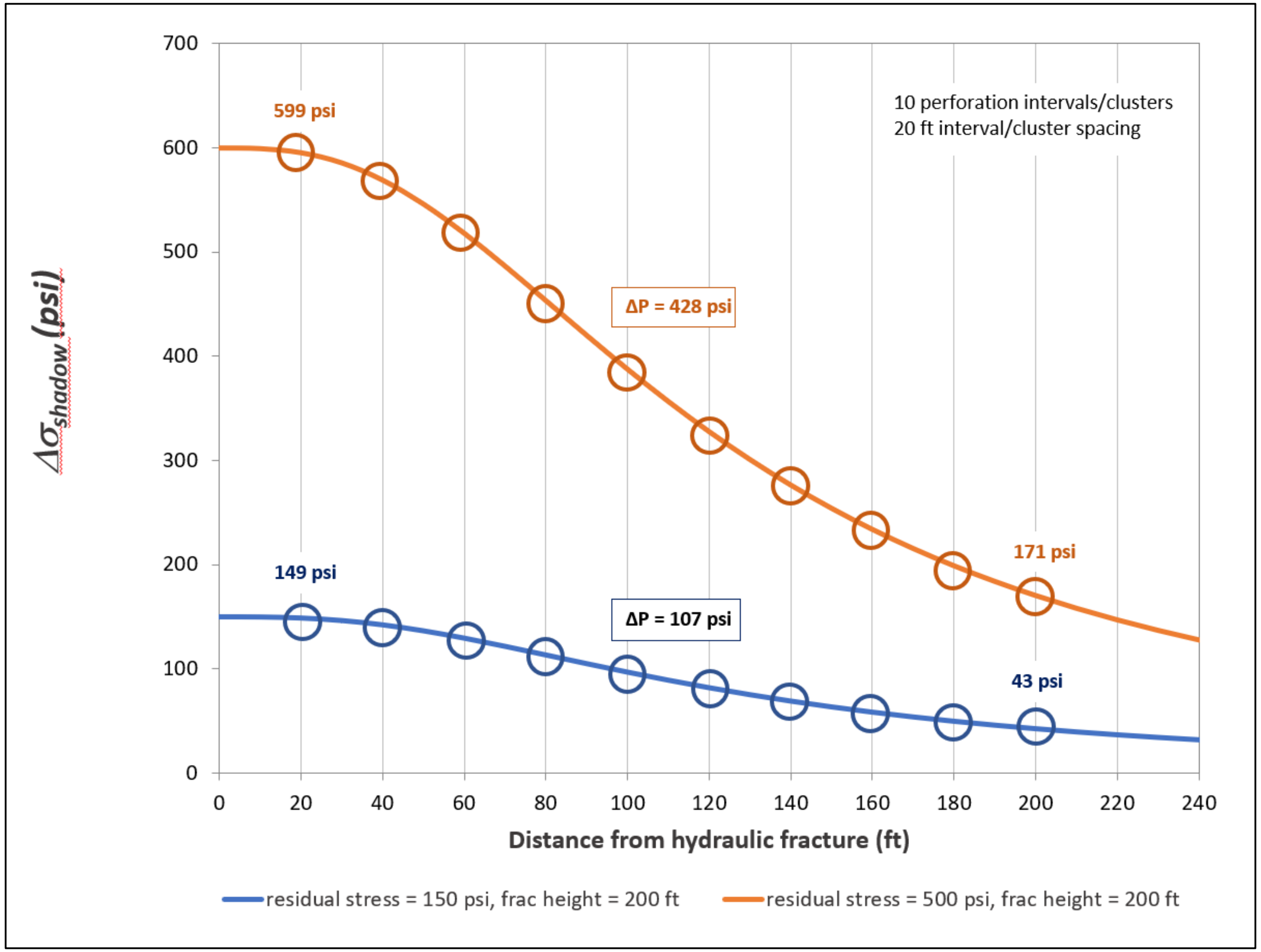


Sneddon (1946)

Slide is based on the work of Nico Roussel

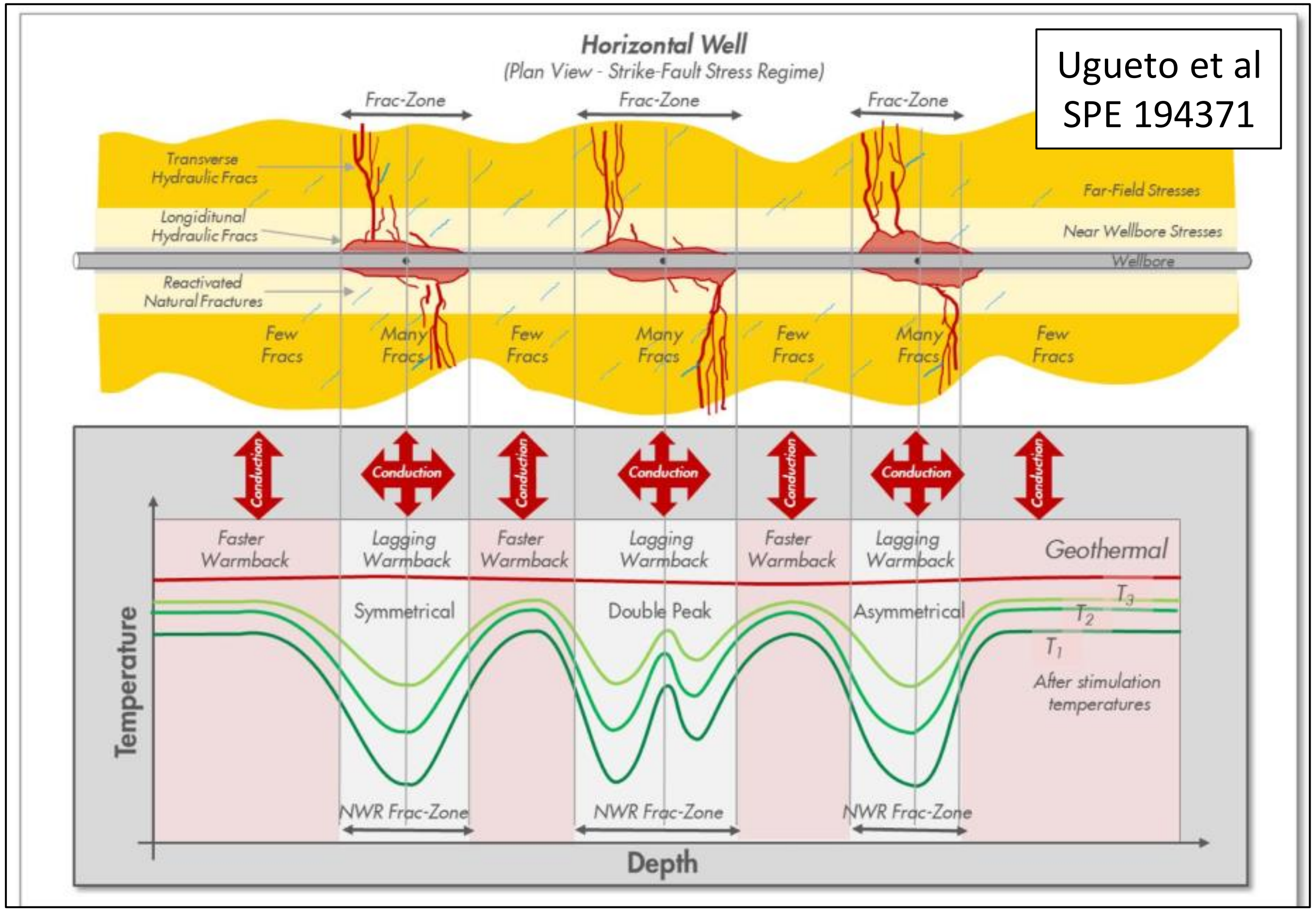
Mechanical stress interference, also called stress shadowing, is the change in reservoir stresses induced by mechanical deformation of hydraulic fractures. It impacts the magnitude and direction of principal stresses.

Worked Example of Stress Shadowing



Stress variation along the lateral imparted by stress shadowing from previous frac stage is a function of fracture height and residual (net) pressure of the previous frac stage. As fracture pressure decays following injection, stress variation diminishes.

More Evidence of Axial (Longitudinal) Starter Fracture

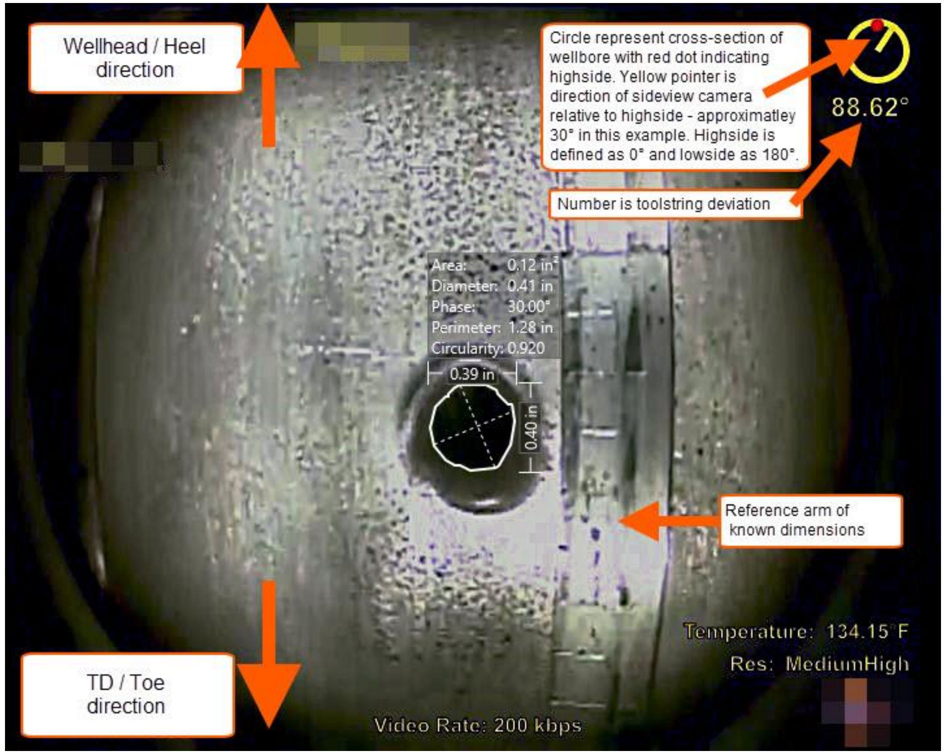


Ugueto et al
SPE 194371

Near-wellbore frac geometry, based on DTS interpretation. Inferred longitudinal component is up to 25 feet.

Determining In-Situ Perforation Dimensions Using Video-based Perforation Imaging (SPE-194334-PA)

Tool string and side view camera



Wellhead / Heel direction

Circle represent cross-section of wellbore with red dot indicating highside. Yellow pointer is direction of sideview camera relative to highside - approximatley 30° in this example. Highside is defined as 0° and lowside as 180°.

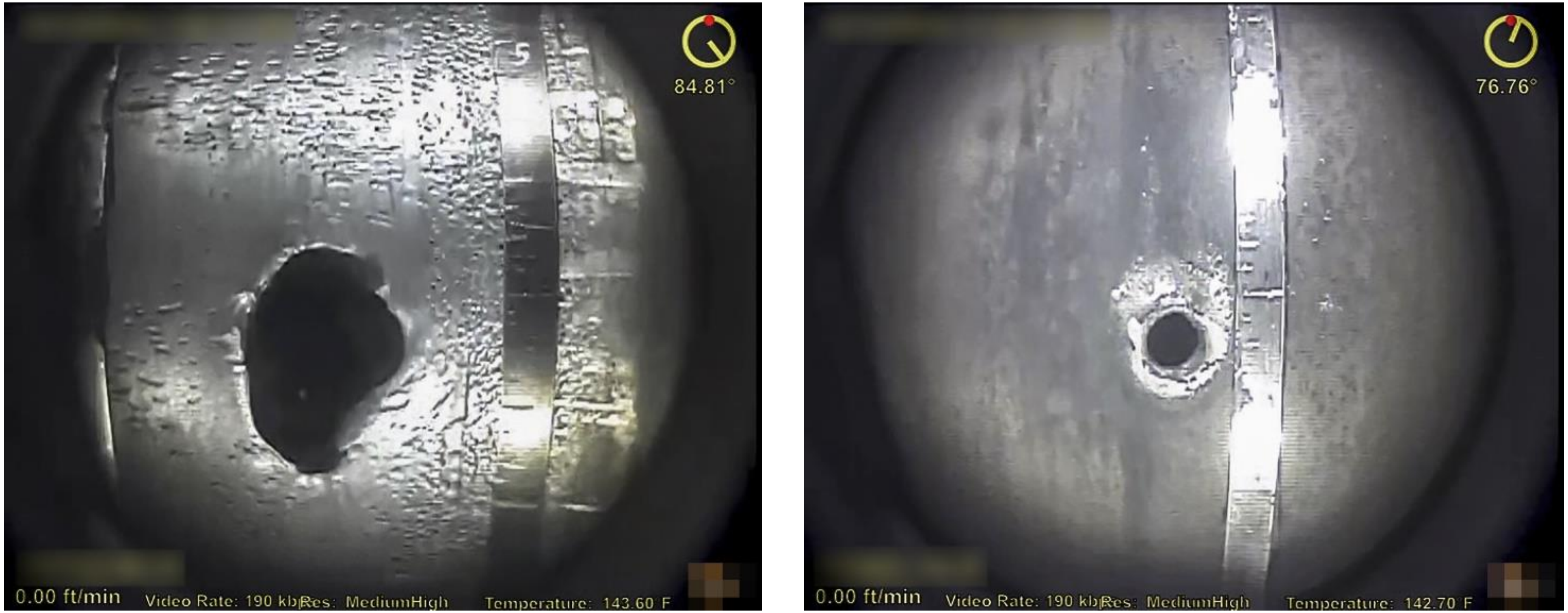
Number is toolstring deviation

Reference arm of known dimensions

TD / Toe direction

Direction and orientation of the perforation image relative to heel/toe and high-side of hole

Post-treatment Images of Contiguous Perforation Entry Holes



Contiguous entry holes were heavily eroded on the low side and minimally eroded on the high side of the well. Perforating at 0 degree and 180 deg phasing is the worst possible combination.

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.