GEODynamics®

Perforating Design Impacts on Hydraulic Fracturing

SPE-GCS Northside Study Group

September 10, 2019

Outline

1. Design and Limited Entry
2. Diagnostics
3. Perforation Technology
4. Case Histories
5. Fluid and Proppant Transport

Perforating Design Requirements

"All I need is a hole in the pipe"

"What perforation hole size am I getting"

"Can I obtain a consistent perf diameter without centralizing the gun system"

"I don't need a deep penetrating perforation charge, the frac doesn't propagate out the end of (conventional) perf tunnels anyway"

"We routinely pump frac stages through toe sleeves"

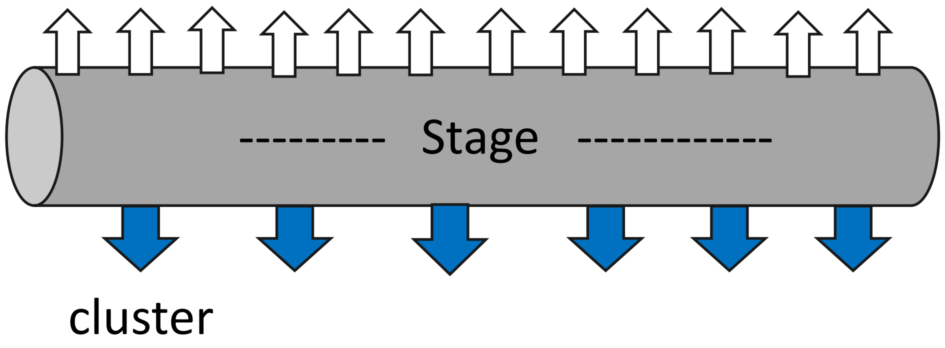
"I want fewer perforations per cluster"

"How can I increase my cluster efficiency"

"What perforation pressure drop do I need to achieve limited entry"

Limited Entry

Use Pump Rate to maintain Pressure Drop to simultaneously treat multiple clusters in a frac stage



Today
12 to 30 clusters
1 to 4 perfs per cluster
~2,400 psi differential pressure
100 BPM / 20 clusters = 5 BPM/cluster

18 to 24 months ago
6 to 8 clusters
4 to 6 perfs per cluster
~1,200 psi differential pressure
100 BPM / 8 clusters = 12.5 BPM/cluster

Same hydraulic fracture geometry?

Hole Size Matters

Pressure Drop is a function of Injection Rate per Perforation and the Perforation Hole Size raised to the 4th Power

$$\Delta P_{perf} = \frac{0.237\ \rho\ Q^2}{D^4\ C^2}$$

Where: ΔP_{perf} = Total perforation friction, psi
Q = Flow rate through each perforation, BPM/perf
D = Diameter of perforation, in.
C = Perforation discharge coefficient (0.9 for round perforation)
ρ = Fluid density, lbs./gal

Equal Entry Hole - Design 1

10 clusters, 3 perfs per cluster

	EEH 35 Initial Breakdown	EEH 35 Proppant Erosion
Hole Size	0.35 inch dia.	0.37 inch dia.
ESTIMATED Cv Factor	0.70	0.90
Injection Rate	80 BPM	80 BPM
Number of Perfs	30 perfs	30 perfs
Rate per Perf @ 100% Efficiency	2.67 BPM/Perf	2.67 BPM/Perf
Perf Friction @ 100% Efficiency	1,925 psi	933 psi
Perf Friction @ 95% Efficiency	2,133 psi	1,033 psi
Perf Friction @ 90% Efficiency	2,377 psi	1,151 psi
Perf Friction @ 85% Efficiency	2,665 psi	1,291 psi
Perf Friction @ 80% Efficiency	3,008 psi	1,457 psi
Perf Friction @ 75% Efficiency	3,423 psi	1,658 psi
Perf Friction @ 70% Efficiency	3,929 psi	1,903 psi

Equal Entry Hole - Design 2

12 clusters, 2 perfs per cluster

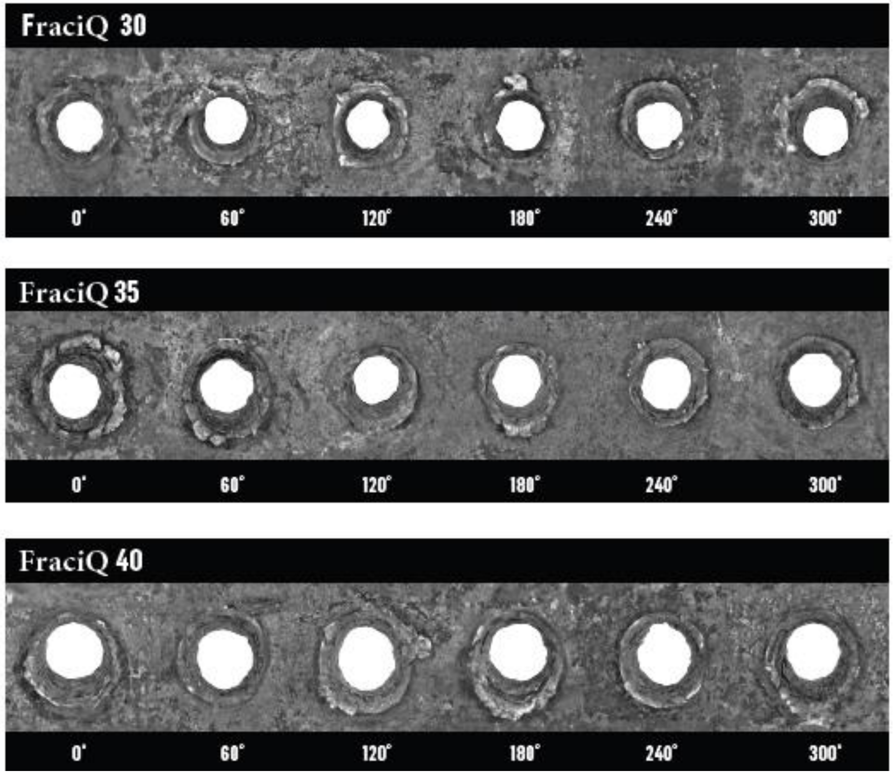
	EEH 40 Initial Breakdown	EEH 40 Proppant Erosion
Hole Size	0.4 inch dia.	0.42 inch dia.
ESTIMATED Cv Factor	0.70	0.90
Injection Rate	90 BPM	90 BPM
Number of Perfs	24 perfs	24 perfs
Rate per Perf @ 100% Efficiency	3.75 BPM/Perf	3.75 BPM/Perf
Perf Friction @ 100% Efficiency	2,232 psi	1,111 psi
Perf Friction @ 95% Efficiency	2,473 psi	1,231 psi
Perf Friction @ 90% Efficiency	2,755 psi	1,371 psi
Perf Friction @ 85% Efficiency	3,089 psi	1,537 psi
Perf Friction @ 80% Efficiency	3,487 psi	1,736 psi
Perf Friction @ 75% Efficiency	3,968 psi	1,975 psi
Perf Friction @ 70% Efficiency	4,555 psi	2,267 psi

Observations

From Over 2,500 Step Down Test Analyses

- Shallow penetration charges work well
- Geology and rock stress still matter
- Higher confidence level on analyses with Equal Entry Hole perforations
- Perforation phasing not a big a factor
- Less tortuosity with shallow penetration charges
- Conventional deep penetration charges of varying hole size are difficult to analyze (lower confidence level on analyses) and generally indicate higher tortuosity
- Performing a Step Down Test every 5 to 10 frac stages has value
- Many operators appear to shoot too many holes
- Higher perforation differential pressure diversion works
- We do not understand fluid and proppant transport; and perforation erosion as well as we would like

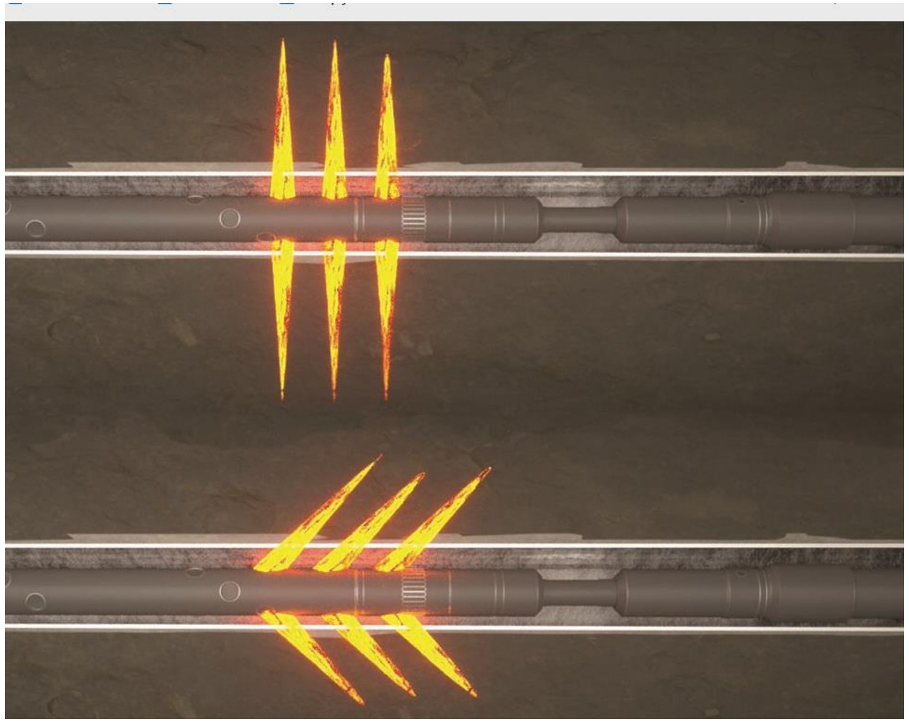
Equal Entry Hole (EEH) Shape Charges



1. Consistent hole size charge
2. Enables Limited Entry design for diversion
3. Shorter, equal penetration, regardless of water gap or casing
4. Engineered for maximum consistency
5. For use with diverter products
6. Improves perf cluster efficiency
7. Shape charge technology engineered for current unconventional casing, size, weight and grade
8. Customized entry hole selection

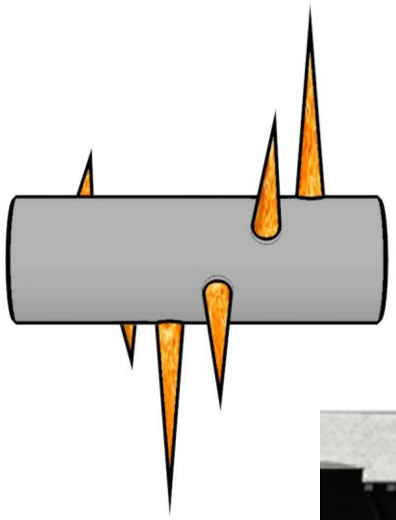
Angled Equal Entry Hole (AEEH) Shape Charges

2^{nd} Generation Equal Entry – Angled Charge for Proppant Transport

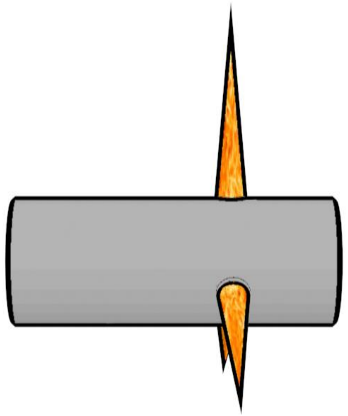


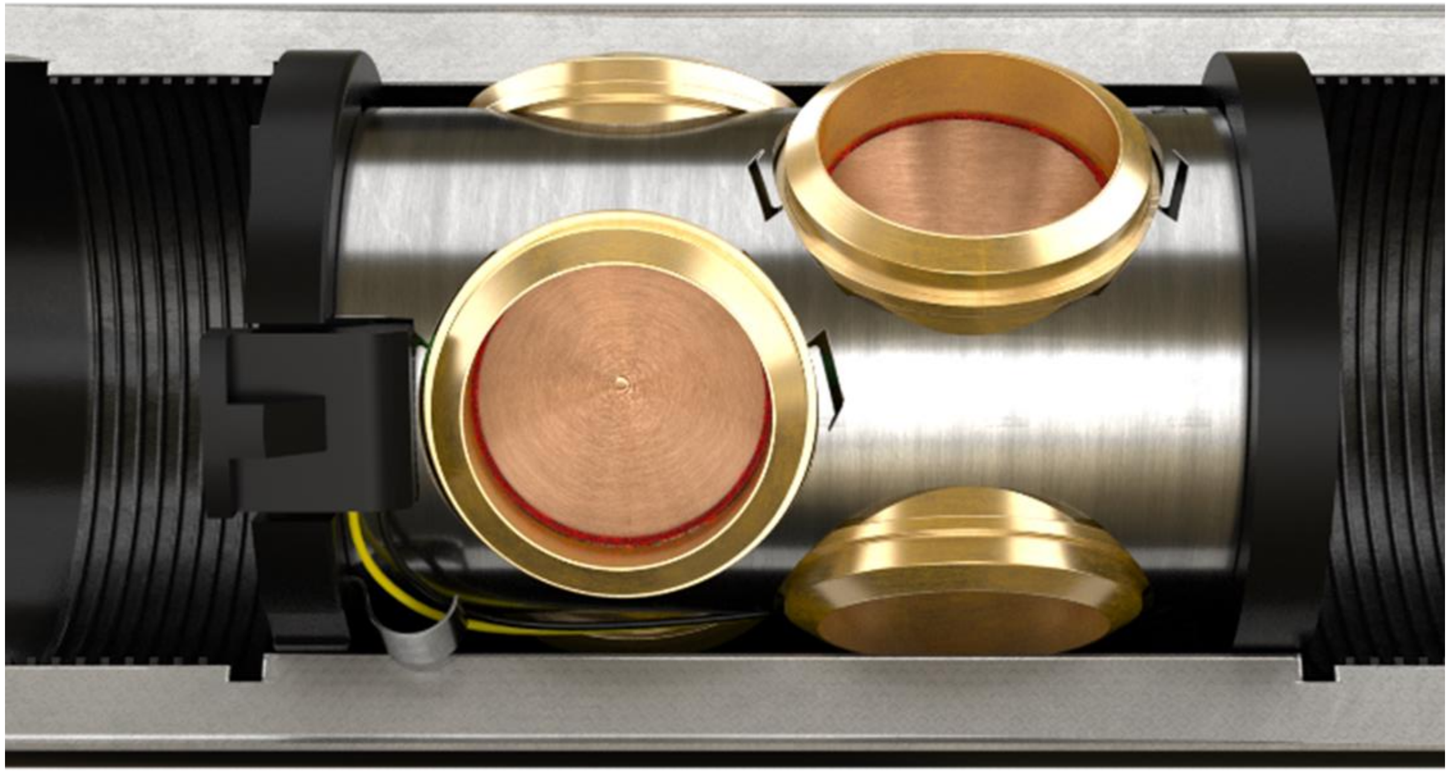
1. Consistent hole size charge
2. Provides an “off ramp” for more efficient proppant placement
3. Perforating tunnels are tilted in direction of fluid flow
4. Enables Limited Entry design for diversion

Spiral Pattern vs Single Plane



Which design would be better for fracture initiation and reducing tortuosity?





Single Plane Equal Entry Hole (SPEEH) Shape Charges

70% Shorter Gun

Field Trials at 100 BPM

64 holes, 4 perfs per cluster, Spiral
vs.
48 holes, 3 perfs per cluster, SPEEH

~ 1,000 psi lower surface treating pressure with SPEEH

Case History 1

Well A Wolfcamp, 6 perfs/cluster, 5 clusters

Well B Wolfcamp, 6 perfs/cluster, 5 clusters

Note - All Step Down Test analyses were performed by the Operator and the results were shared with GEODynamics by the Operator

Well A

- Conventional (Conv)
  Stages 1-4 and 15-19 (9 stages)

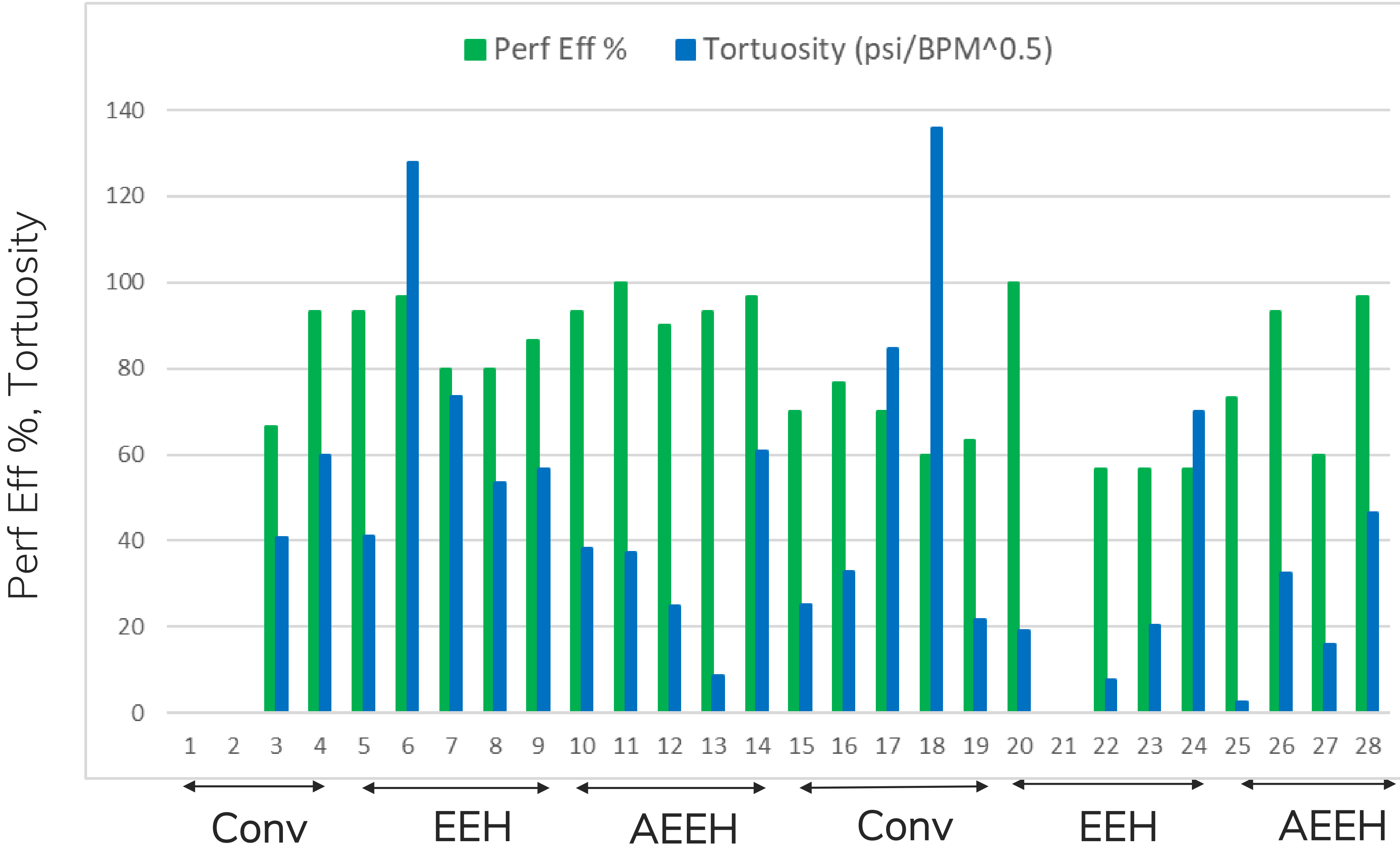
- Equal Entry Hole (EEH)
  Stages 5-9 and 20-24 (10 stages)

- Angled Equal Entry Hole (AEEH)
  Stages 10-14 and 25-28 (9 stages)

Average	Conv	EEH	AEEH
Open Perfs	21	24	27
Perf Efficiency %	70	80	90
Tortuosity (psi/BPM^0.5)	57	53	30

* No valid Step Down Tests for Stages 1, 2 and 21

Well A



Perf Eff %
Tortuosity (psi/BPM^0.5)
Perf Eff %, Tortuosity
140
120
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
Conv
EEH
AEEH
Conv
EEH
AEEH

Well B

- Conventional (Conv)
  Stages 1-5 and 16-19 (9 stages)

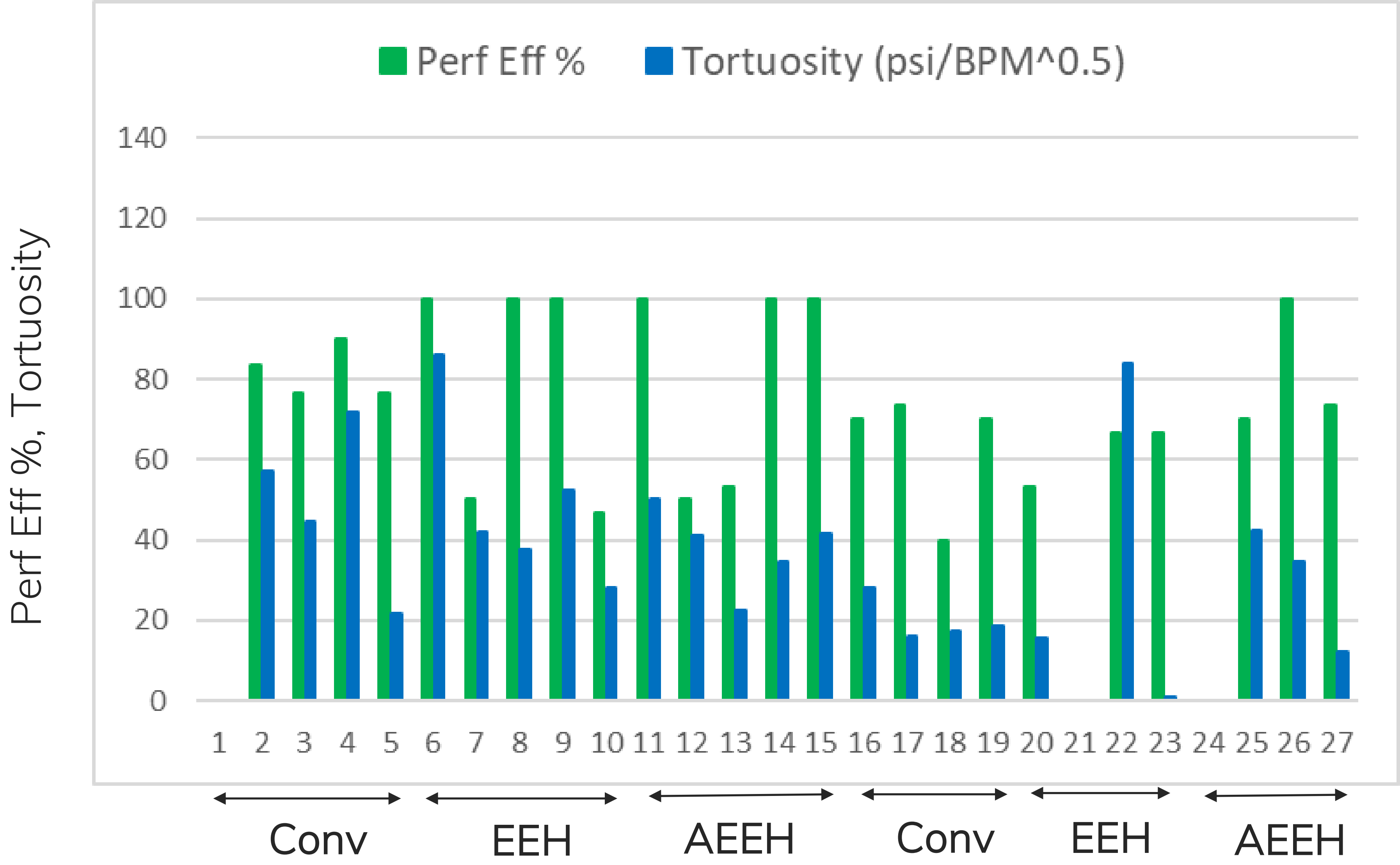
- Equal Entry Hole (EEH)
  Stages 6-10 and 20-23 (9 stages)

- Angled Equal Entry Hole (AEEH)
  Stages 11-15 and 24-27 (9 stages)

Average	Conv	EEH	AEEH
Open Perfs	22	22	24
Perf Efficiency %	73	73	80
Tortuosity (psi/BPM^0.5)	35	42	35

* No valid Step Down Tests for Stages 1, 21 and 24

Well B



Perf Eff %
Tortuosity (psi/BPM^0.5)
Perf Eff %, Tortuosity
140
120
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Conv
EEH
AEEH
Conv
EEH
AEEH

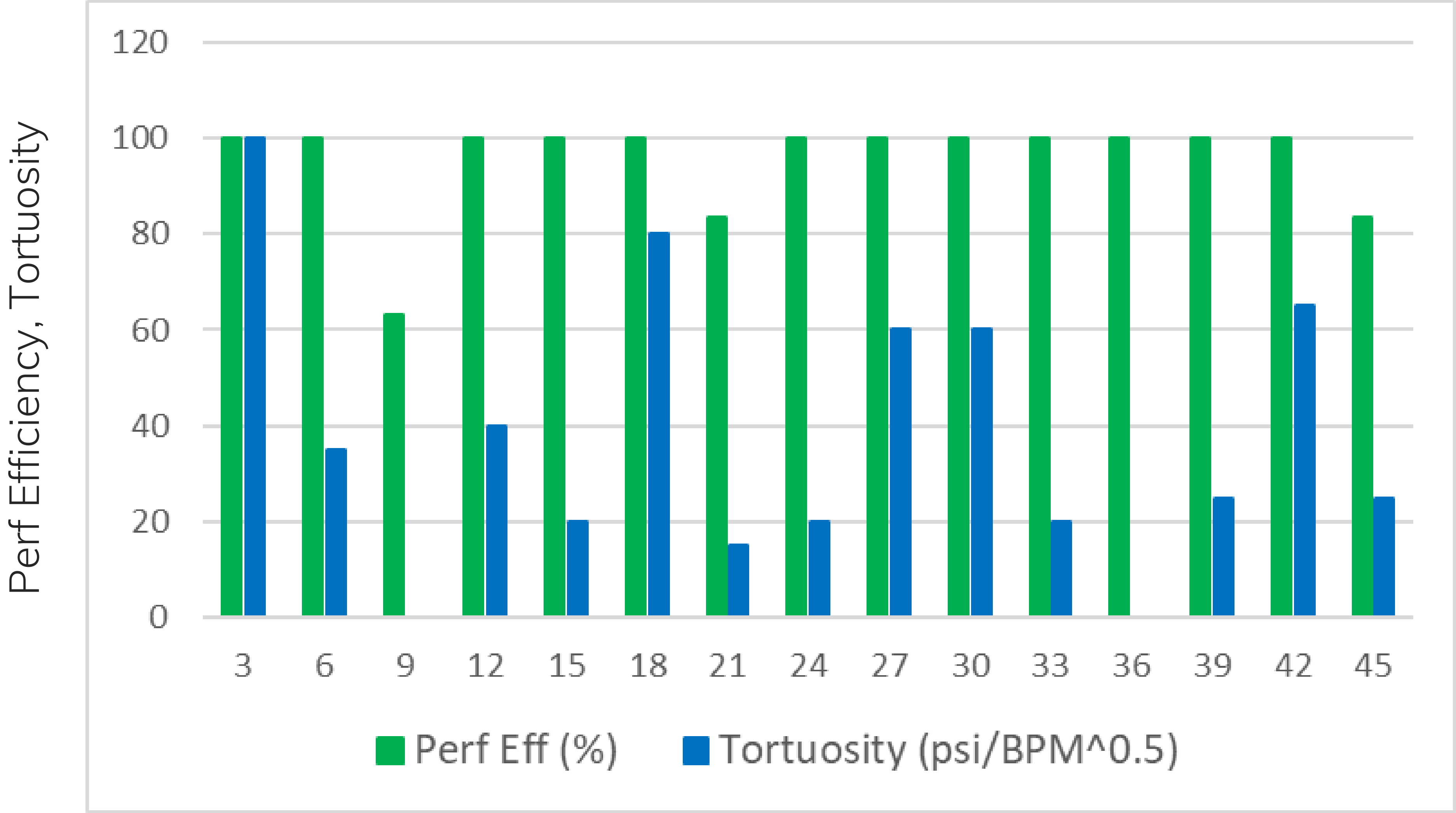
Case History 2

Equal Entry Hole (EEH) = 0.42 inch EHD

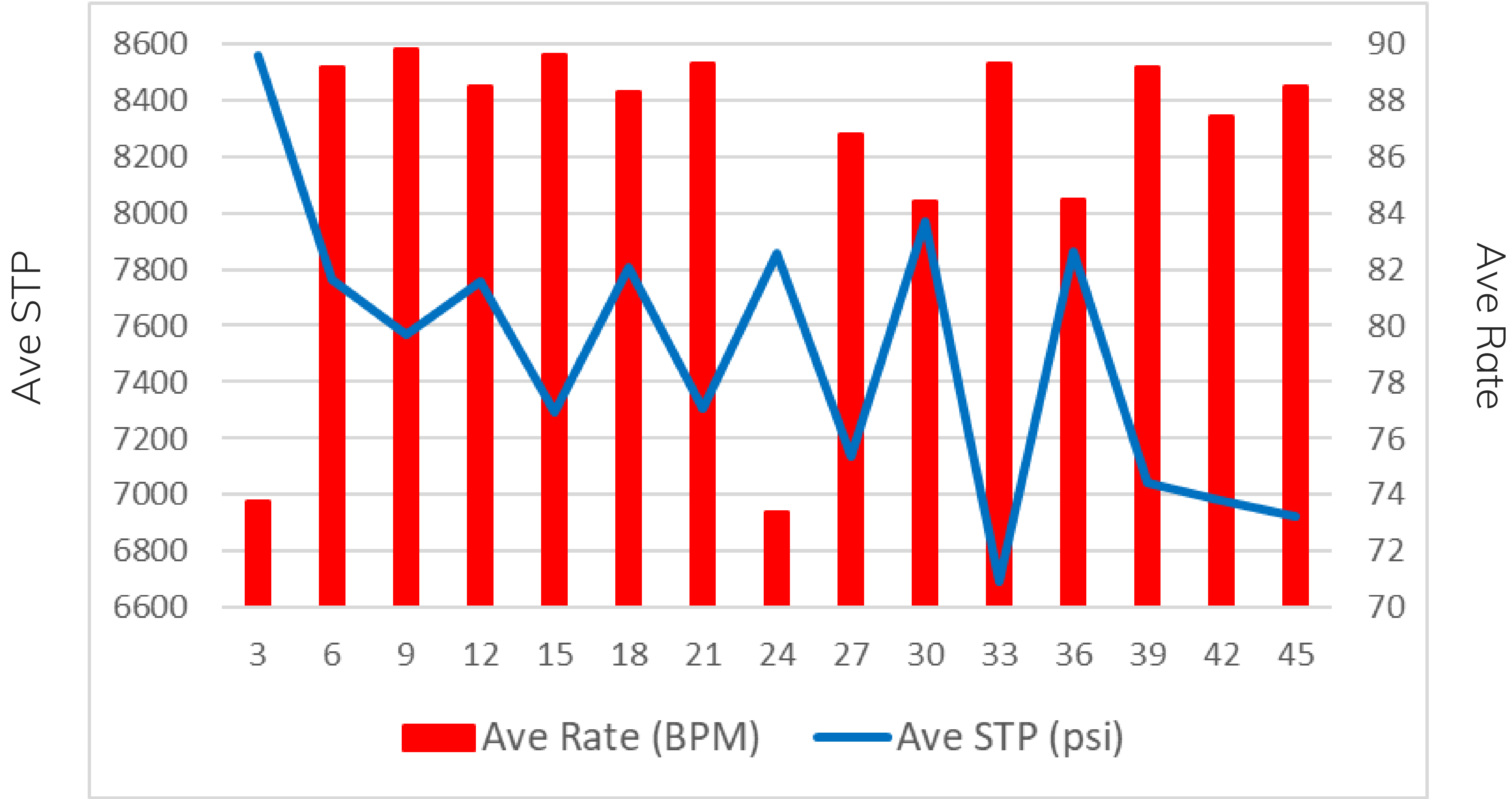
10 clusters, 3 perfs per cluster
Average number of perfs open (30 perfs shot) = 29 perfs
Average perf efficiency = 95%
Average Tortuosity = 38 (psi/sqrt(BPM))
Average Tortuosity at 90 BPM = 361 psi
Average Rate = 86.1 BPM
Average STP = 7,501 psi

- 12 out of 15 stages with SDT had 100% perforation efficiency
- 13 out of 15 stages with SDT had tortuosity
- Ave Rate was flat (Stages 3 and 24 were less than 74 BPM)
- Ave STP decreased from Stage 3 to 45

Equal Entry Hole Well



Equal Entry Hole Well



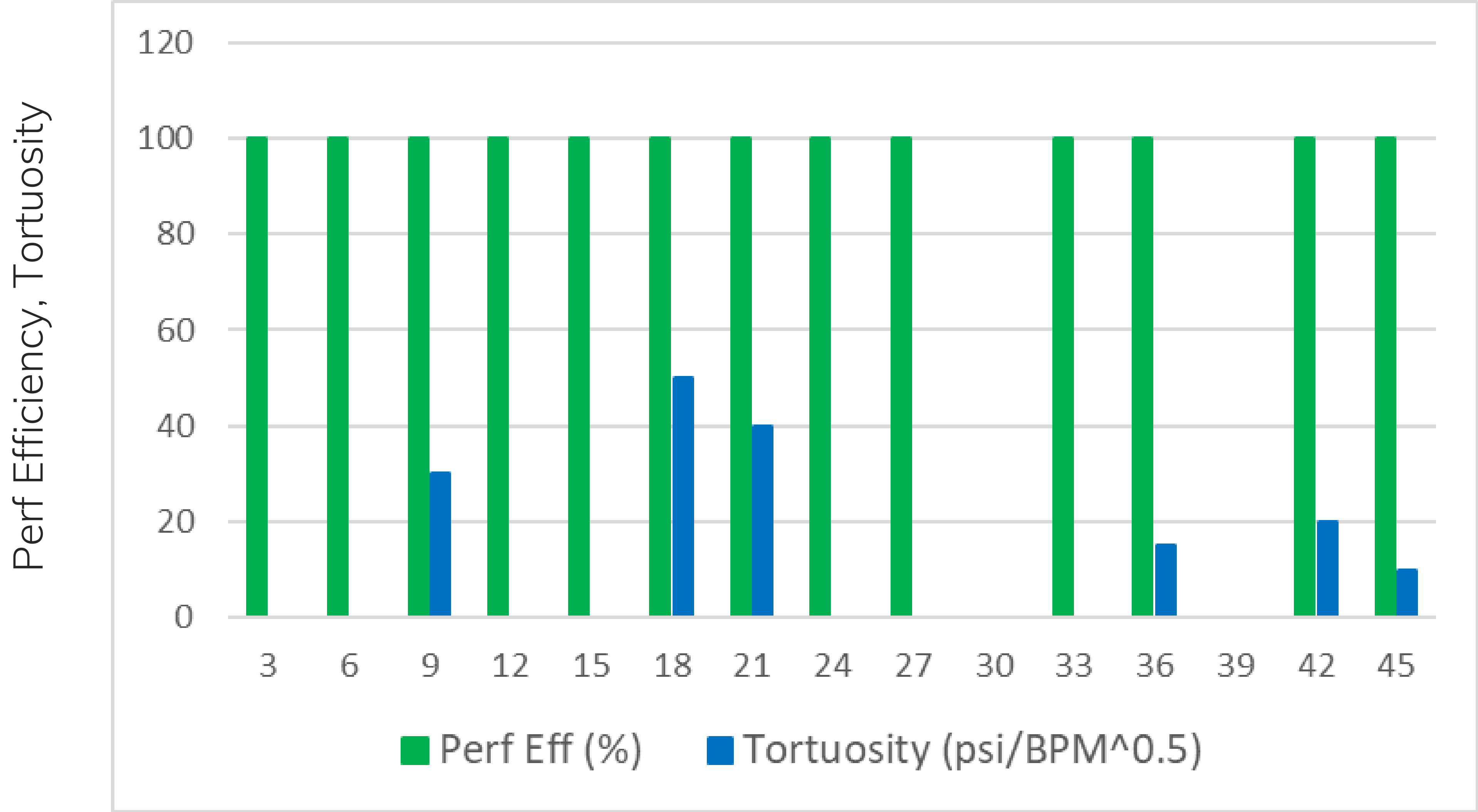
Case History 2

Single Plane Equal Entry Hole (SPEEH) = 0.32 inch EHD

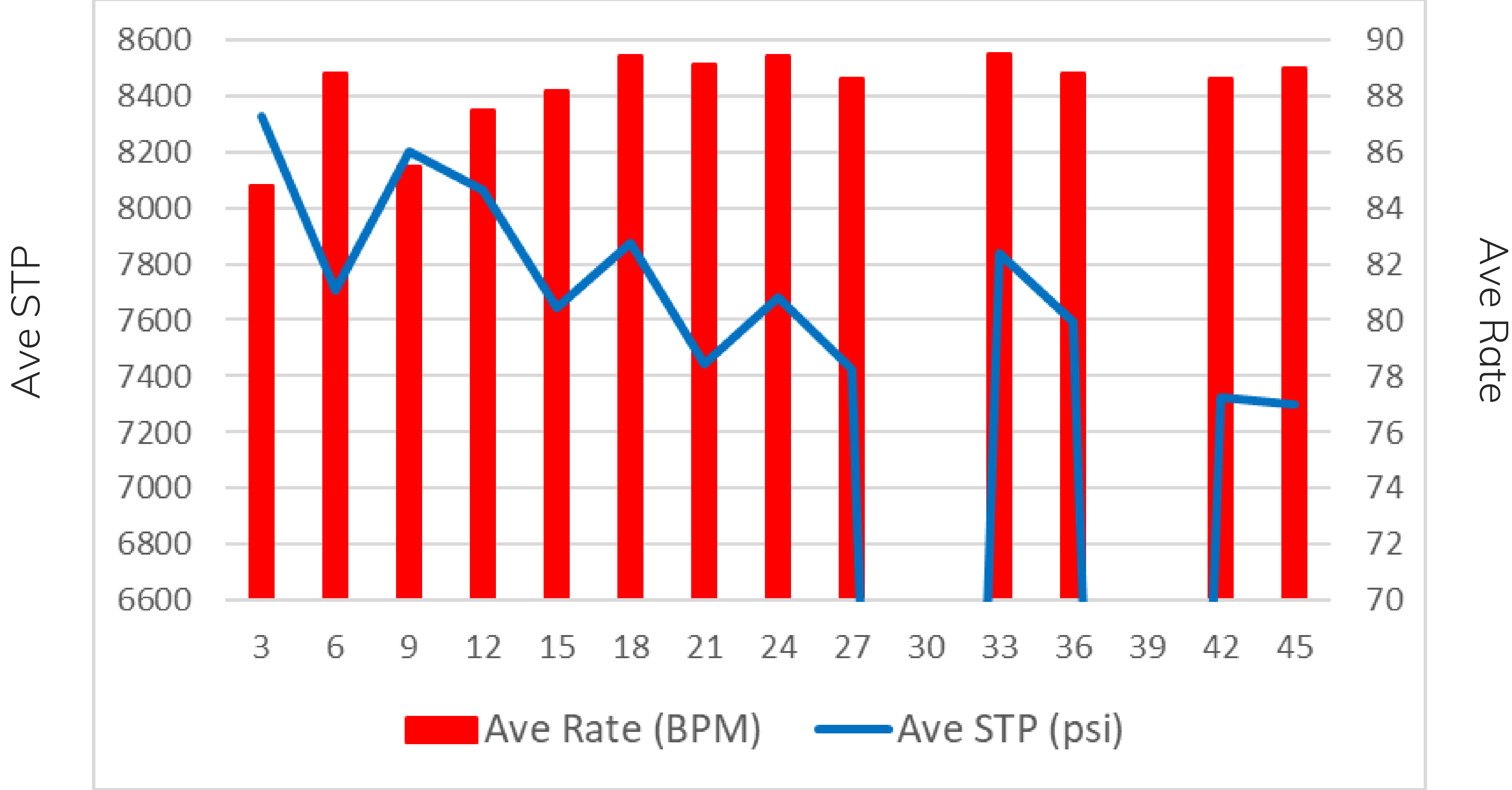
10 clusters, 3 perfs per cluster
Average number of perfs open (30 perfs shot) = 30 perfs
Average perf efficiency = 100%
Average Tortuosity = 13 (psi/sqrt(BPM))
Average Tortuosity at 90 BPM = 123 psi
Average Rate = 88.2 BPM
Average STP = 7,725 psi

- 13 out of 13 stages with SDT had 100% perforation efficiency
- 6 out of 13 stages with SDT had tortuosity
- Ave Rate was flat (all Stages were greater than 84 BPM)
- Ave STP decreased from Stage 3 to 45

Single Plane Equal Entry Hole Well



Single Plane Equal Entry Hole Well



Perforating and Hydraulic Fracturing

Well Design

Perforation System,
Number of Perforations,
Clusters and Frac Stages

Step Down Tests

Quick, Easy and
Economically Justified every
4 to 6 Frac Stages

Data Analysis

Perforation Efficiency,
Tortuosity, Fracture
Diagnostics, Ops/Geology
Review, Production Analysis

Design Changes

Maximize Well
Performance and
Economics

Final Thoughts

- Calculate limited entry perforation pressure drop for the initial injection with slickwater and after pumping a few thousand pounds of proppant (discharge coefficient increase and perforation erosion)

- Specify the perforating system that you ran your design calculations with and ensure that the system is delivered to the wellsite and run without improper substitution

- Perform fracture diagnostics – Step Down Tests, downhole camera, downhole imaging, etc. to evaluate perforation designs

- What effect does changing the pump rate per cluster have on the created fracture geometry?

What makes you think proppant moves uniformly with the fluid?

Does proppant placement vary as a function of <u>proppant size</u>?

- This could have many implications:
  - Erosion
  - Screen-outs
  - Well Productivity
  - Fracture Conductivity
  - Frac Hits
  - Proppant Flowback

THANK YOU
Q&A AND DISCUSSION

Steve Baumgartner and Phil Snider