High Density Perforating & eXtreme Limited Entry

Paul Weddle – VP Drilling & Completions

Liberty Resources II

SPE Webinar

West Side Study Group

5/20/2020

Mining the Bakken – SPE 184828 & 189880

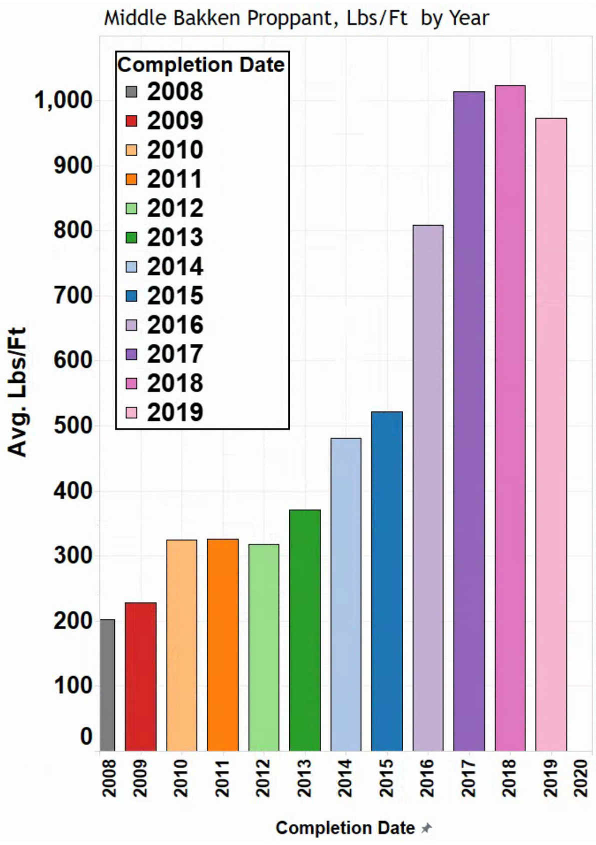
- Williston Basin Completion Evolution
- Summarizing HDP + XLE + 1 SPC
- Diagnostic Data Examples
- Key Variables & Sources of Variability
- Published Impacts of XLE
- Conclusions

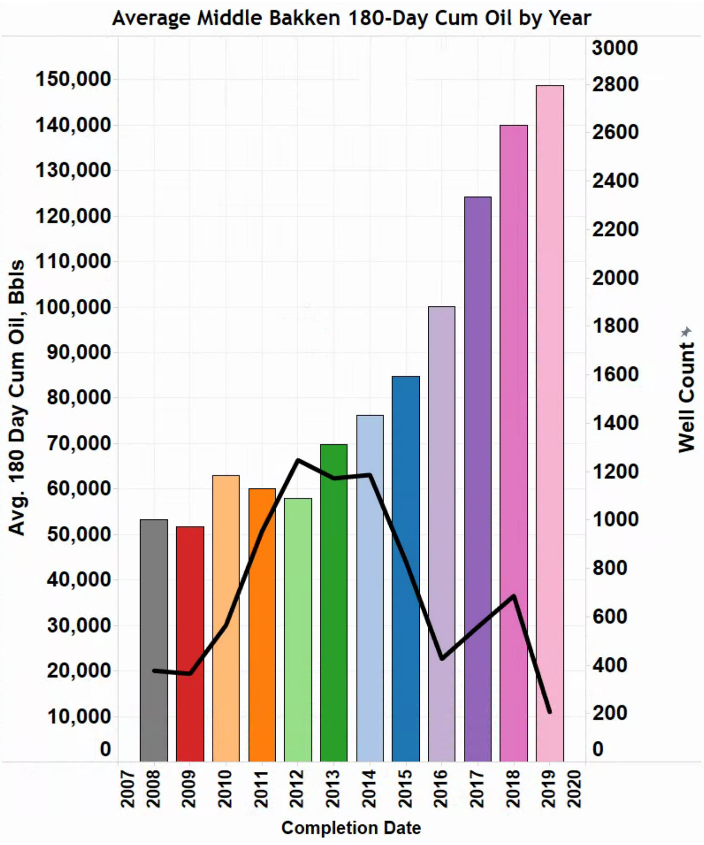
Williston Basin – Middle Bakken Completion Evolution

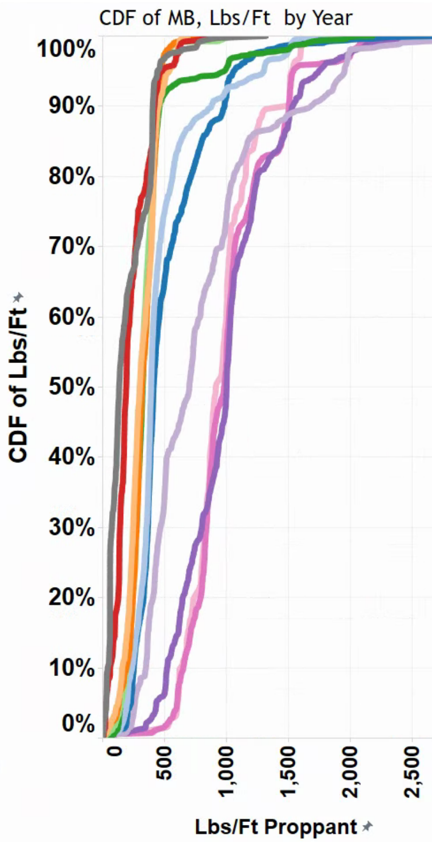
- Pre 1986 – Vertical wells
- 1986-1999 – Hz wells, OH, 1 frac
- 2007 – Start of multi-stage Hz's

Liberty Resources 2011-2019

- 2011- Q3 2014: OH, swell packers, PnP (4-7 clusters), 35 stages
- 2014 Q4: Cemented, PnP, 35-50 stages, started HDP, bio ball trials
- 2015 Q4: Trialed solid particle diverter, 100% sand fracs
- 2016 Q1: XLE trials
- 2016 Q2: XLE becomes standard, stage count reduction trials
- 2016 Q4: Reduced stage count standard (27stgs /10,000ft)
- 2018 Q1: Started 1 hole per cluster trials (1 SPC)
- 2019 Q2: 1SPC standard. Started angled perf trials







NDIC Middle Bakken data updated through October 2019

HDP + XLE + 1 SPC

What?

- High Density Perforating (HDP): A strategy to place a dense fracture network more contained within the producing formation to dramatically increase productive surface area.
- Extreme Limited Entry (XLE): A perforating design that incorporates known operational constraints to maximize the amount of perforation friction in each stage while still achieving the designed pump rate.

Why HDP?

- Economic benefit: Reduce stage count, maintain cluster count per well and pounds of sand per cluster.

Why XLE?

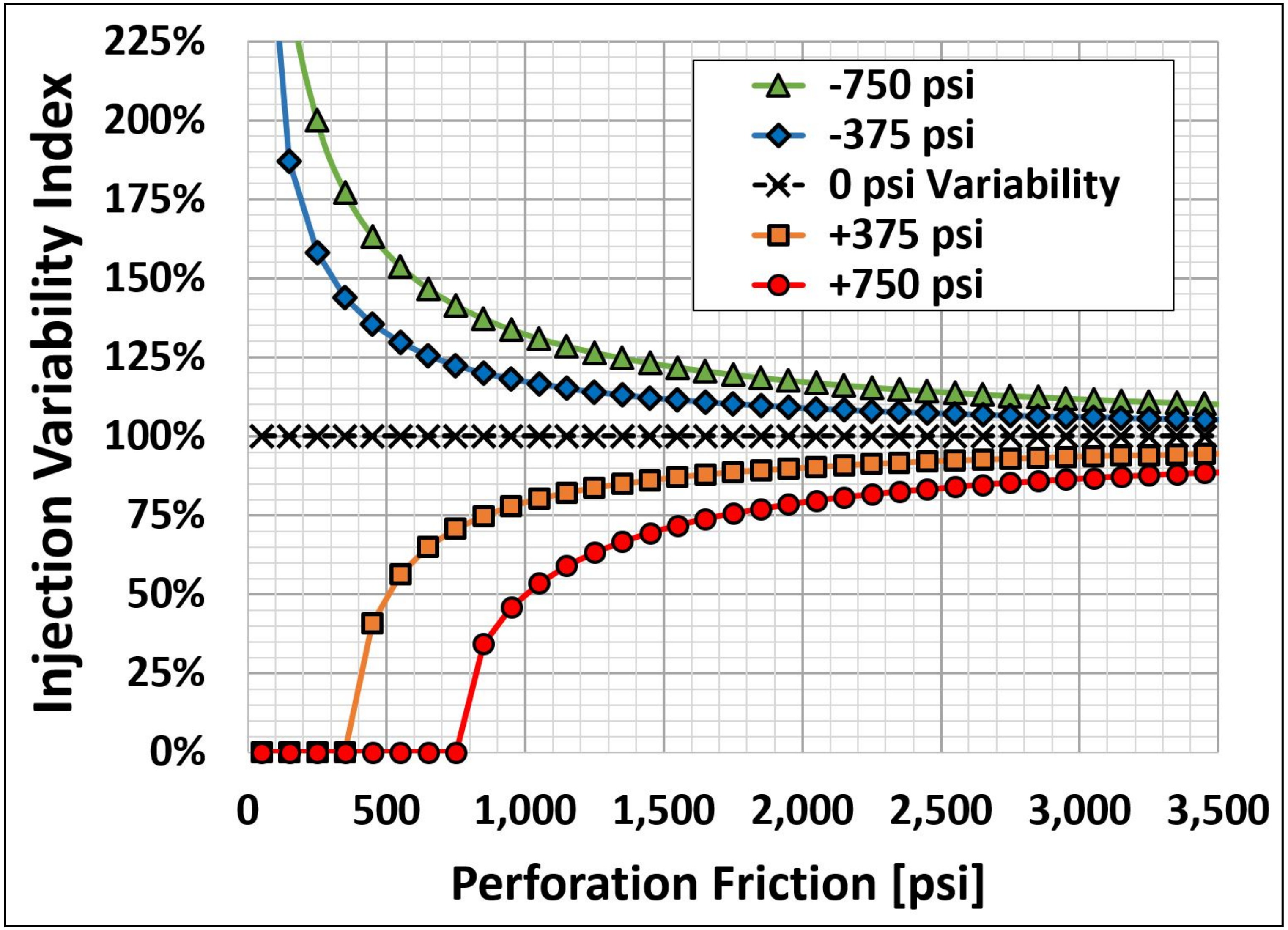
- Consistently treat a high number of perf clusters by overcoming intra-stage fracture-entry pressure differences and more evenly distribute frac fluid to each fracture initiation point.

Why 1 Hole Clusters?

- Rare to get 100% of clusters open…Thus, there is a fluid distribution imbalance with > 1 hole per cluster.
- Further reduces risk of “super clusters” by evening out fluid placed per cluster.
- Elevates the value of step down tests when “holes open” = “clusters open”.
- Zero Degree Phasing (Up): minimize near well tortuosity and prevent sanding off with prolonged shut down.

eXtreme Limited Entry – XLE

The Injection Variability Index



$$\Delta P_p = Ppf = \frac{0.2369\ \rho\ Q^2}{D_P^4\ N_P^2 C_D^2}$$

$$Q_2/Q_i = SqRt(P_{pf2}/P_{pfi})$$

- The injection rate through $\boxed{a}$ perforation is squared relative to the pressure change across it.

  $$(P_{pf} \propto Q^2)$$

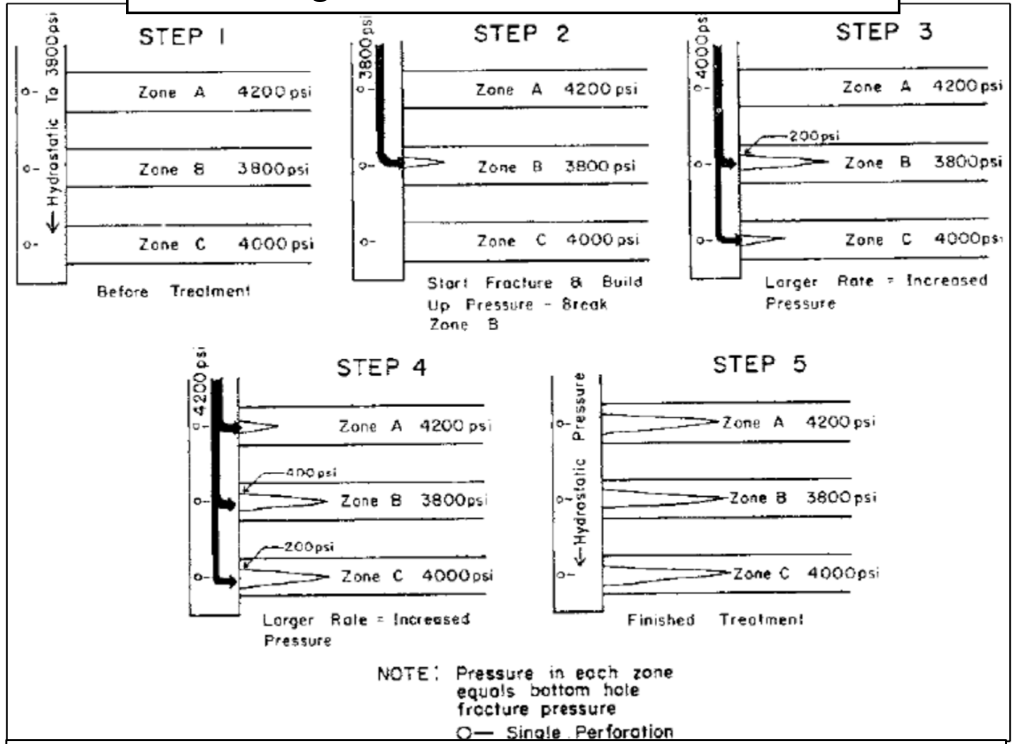
- Increasing the perforation friction counteracts variations in fracture-entry pressures; as the perforation friction increases the fluid distribution converges.

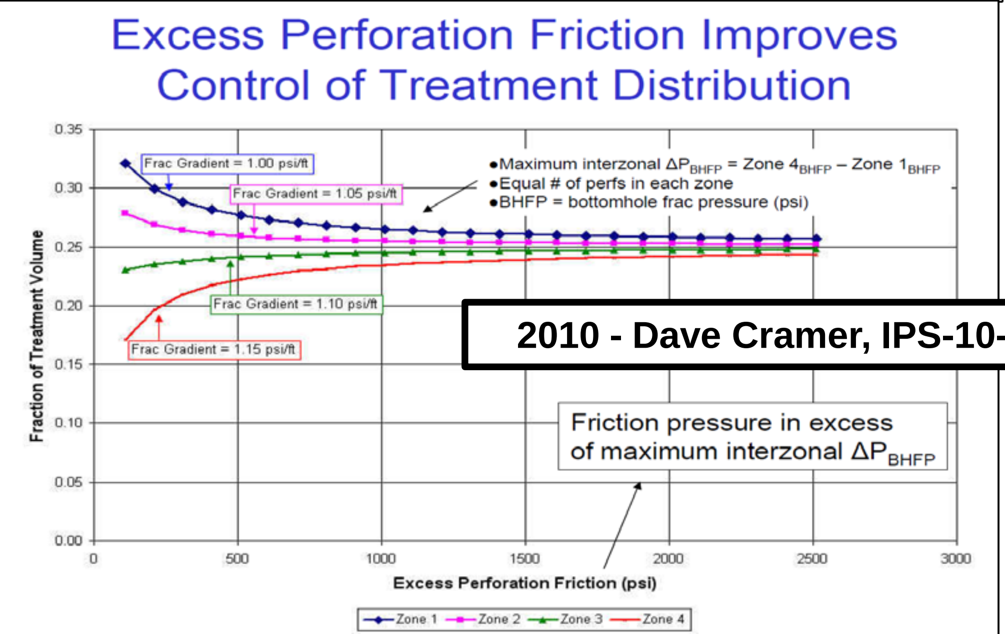
LIBERTY RESOURCES

Notable Industry Publications

- 1960 – “Pinpoint Sand Fracturing” case study. Murphy and Juch
- 1962 – “Limited Entry” term published. Lagrone & Rasmussen, SPE 530
- 1963 – Oilfield ΔPperf equation published based on Bernoulli Theorem. McClain
- 1987 – Limited Entry in Massive Hydraulic Fracturing Treatments – DJ Basin. Cramer, SPE 16189
- 1988 – Effects of Perf Friction on BHTP, Lab Work. Crump and Conway, SPE 15474
- 1995 - Net pressure increases shown to impact “real time” Pperf calculations. M.J. Eberhard & D.E. Schlosser, SPE 29553
- 1997 & 2000 – Step-Down Test Analysis Problems. Wright C., Weijers L., SPE 62549
- 1999 – New Perf Pressure Loss Correlations for LE. El Rabba, SPE 54533
- 2017 – High Density Perforating Published – Weddle et al., SPE184828
- 2017 – “eXtreme Limited Entry” improves distribution efficiency. Somanchi et al., SPE 184834
- 2018 – “Injection Variability Index” introduced for XLE & HDP perforating techniques – Weddle Et al., SPE 189880

1962 - Lagrone and Rasmussen, SPE 530





2010 - Dave Cramer, IPS-10-002

1 HOLE PER CLUSTER – Summary Discussion Points

Erosion:

- Twice the proppant per hole with 1spc vs 2spc for a given pounds per cluster design.
- Larger hole diameters theoretically minimize the erosion rate per pound pumped.

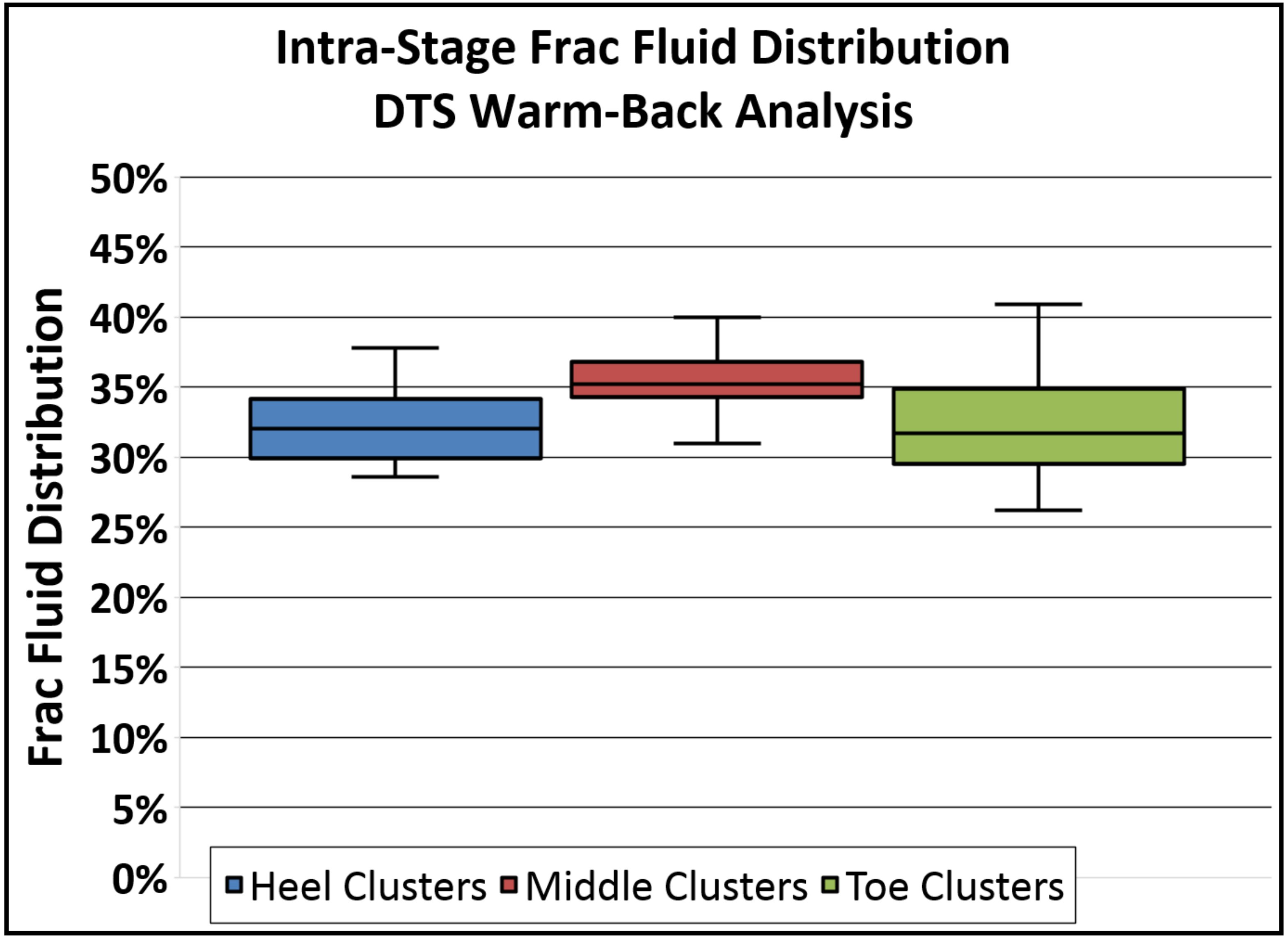
1 SPC:

- 0^o phasing consistency and casing offset still requires even-hole perforation charges to minimize EHD variations.

Diagnostics Limitations:

- Not yet able to confidently calibrate proppant actually transported through each perforation or cluster.
- While it is useful, camera and ultrasonic perf imaging are not yet complete diagnostics on their own.

Results – Post Frac Warmback Analysis



Summary:

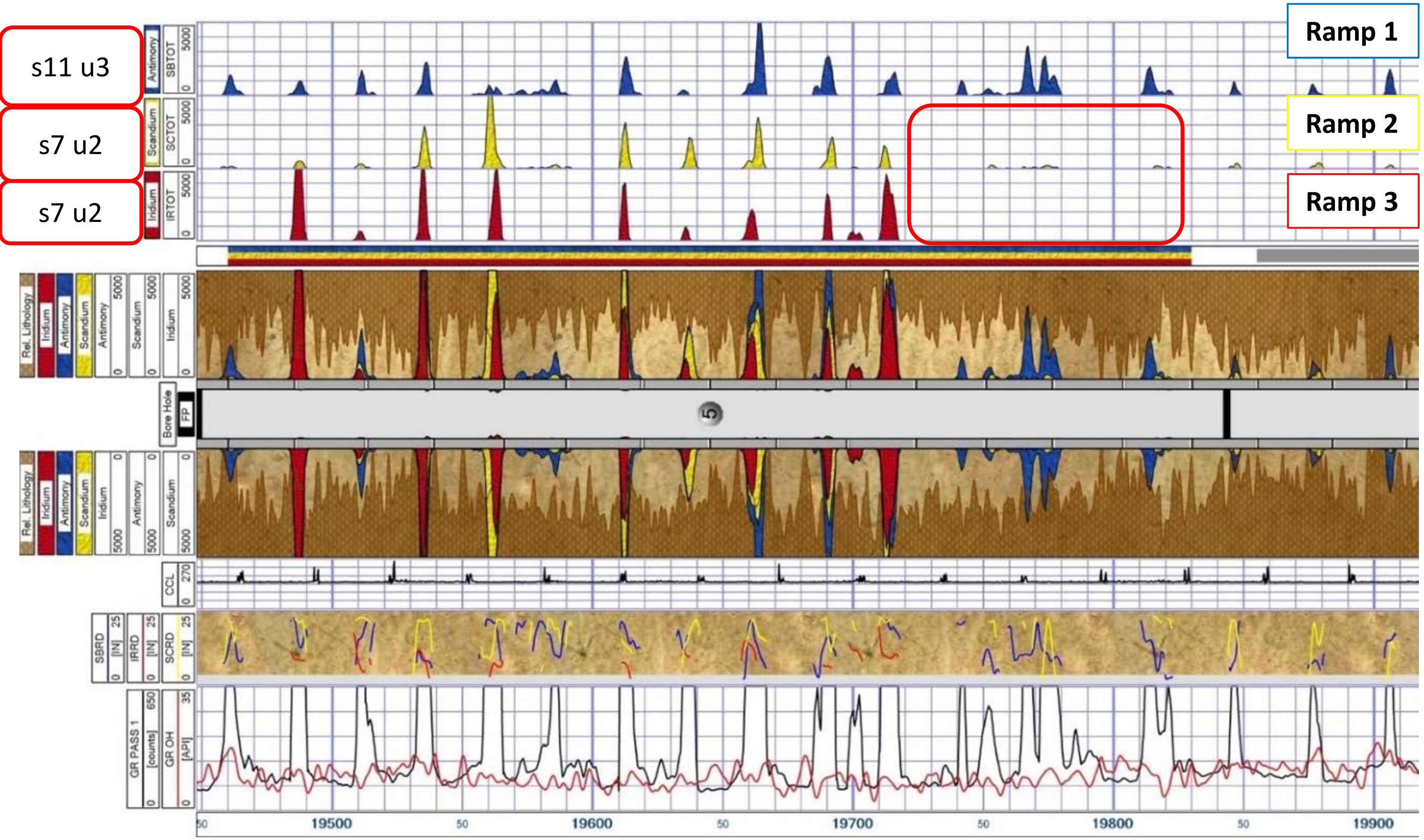
- Each stage broken into thirds for fluid distribution analysis.
- Confirmation that XLE aids in evenly distributing frac fluid.

Diagnostic Comments:

- DTS/DAS provides high confidence of fluid distribution, not proppant.
- Erosion measured from camera diagnostics does not confirm proppant distribution because the amount of erosion is relative kinetic energy changes w/in the stage from heel to toe.

SPE 189880

Results - Proppant Transport in The Casing Matters!



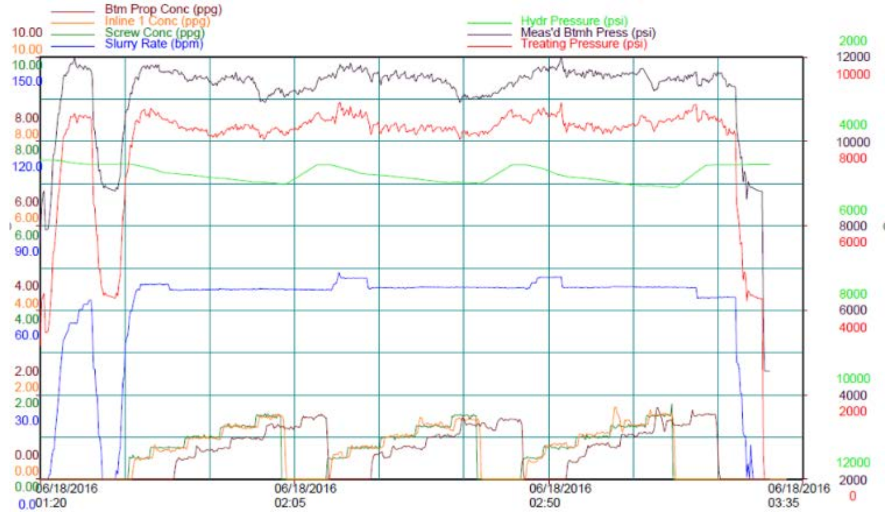
<u>Observations in a 4.5" 11.6# Hz Liner:</u>

Ramp 1: 67 bpm or <u>4.8 bpm/active cluster</u>

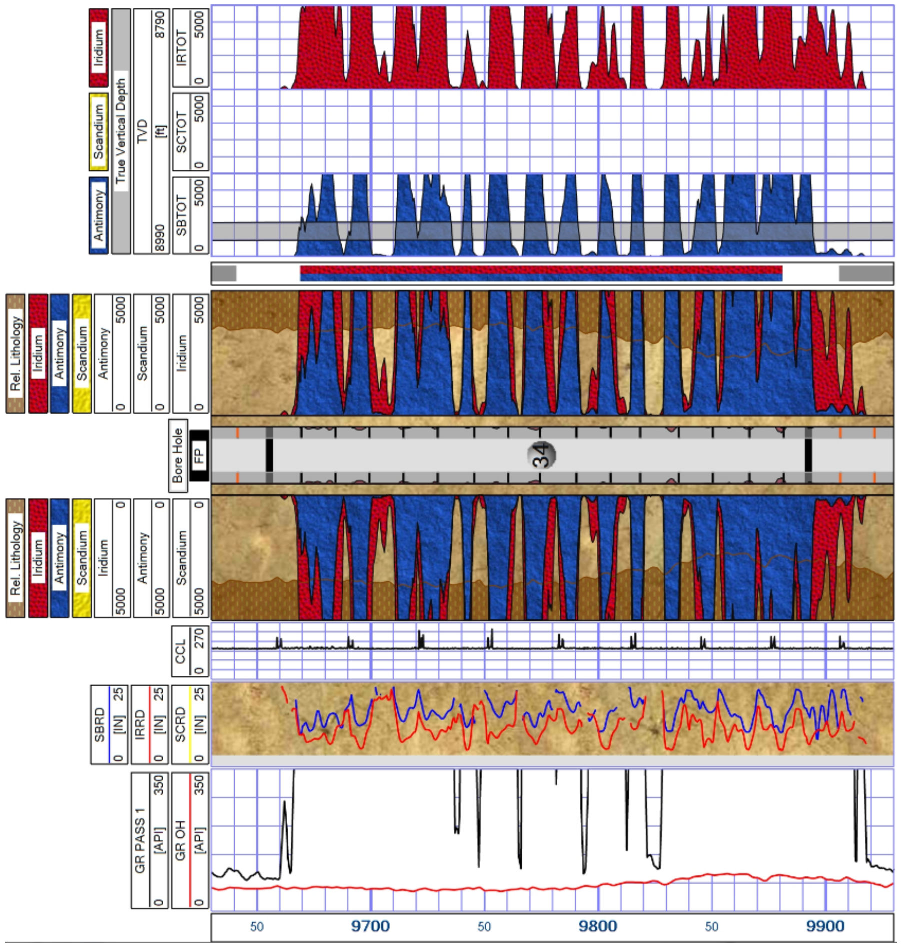
- Critical velocity needed of >6.0 bpm
  - Shah, 1990, SPE 18994 – 6.4 bpm
  - Orasker – 6.0 bpm for LRII HVFR design
- Significant loss of clusters in ramp 2 vs ramp 1

Ramp 2 & 3: 67 bpm or <u>7.4 bpm/active cluster</u>

- <u>Constant PCE</u> between ramps 2 & 3



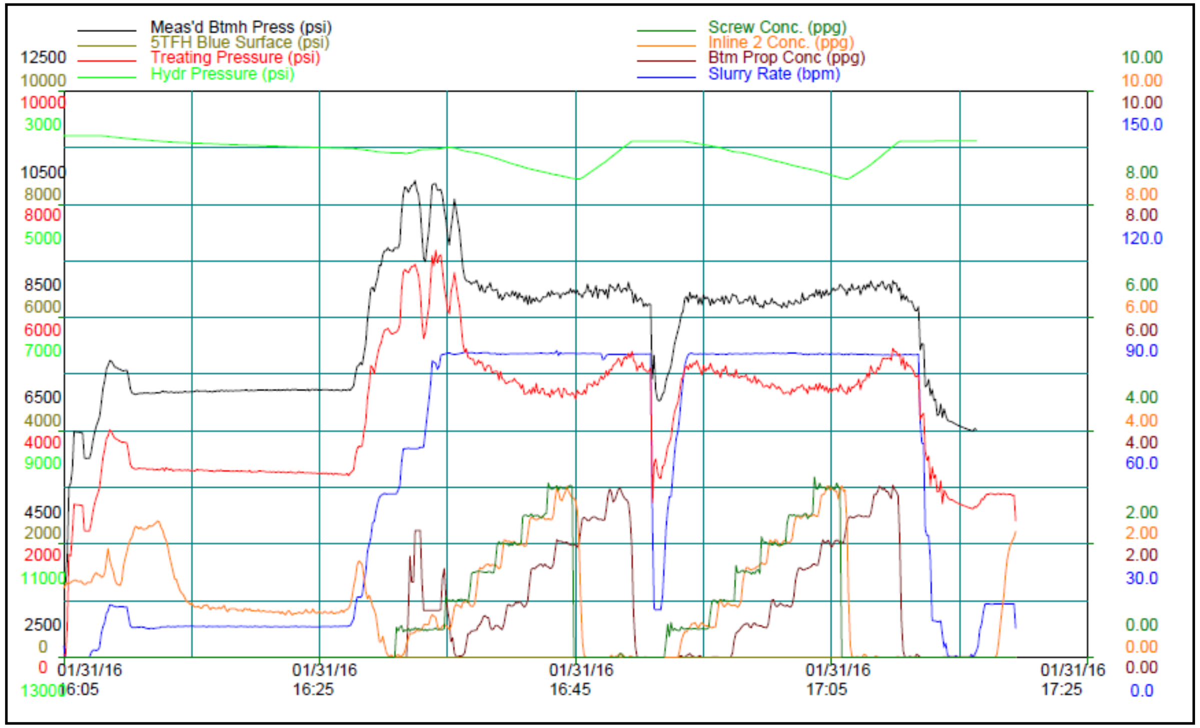
Results – Reducing Variability with Acid Breakdowns



Acid Soak: 100 bbls 15% HCL (4 x the standard)

- 3 lbs of Diverter: No response (cleaned up the NWB!)
- 100% Perforation Cluster Efficiency

Minimized the fracture-entry pressure from near wellbore friction/tortuosity, thus getting more efficiency for a given perf friction! -What else can we to do limit variability?



SPE 184828 • Mining The Bakken - Weddle

Before We Go Any Further…

Keep these classifications in mind as we cover the *variables* and *sources of variability* in the system.

Donald Rumsfeld said it well:

- There are **known knowns**; there are things we know we know.
- We also know there are **known unknowns**; that is to say we know there are some things we do not know.
- But there are also **unknown unknowns;** there are things we don't know we don't know.

	Knowns	Unknowns
Knowns	**Known Knowns** Things we are aware of and understand.	**Known Unknowns** Things we are aware of but don't understand.
Unknowns	**Unknown Knowns** Things we understand but are not aware of.	**Unknown Unknowns** Things we are neither aware of nor understand.

Variables and Sources of Variability in the System:

Known-Knowns or Known-Unknowns?

Static or Dynamic?

What can you and your team do about them?

Perforating:
- Phasing, Orientation, Casing vs barrel offset, Bobsledding w/shooting on the fly, angled perforations.

Perf Friction:
- Entry Hole Diameter, Holes shot & open, Perf erosion rate (heel vs toe erosion trends are not calibrated yet), Pumping rate, Pipe Friction, Coefficient of discharge, Max surface pressure allowed.

Proppant transport:
- In casing, In perf holes, In a frac network.
- Viscosity, Velocity, Density, Gravity, Turbulence, Toe up vs Toe down sections of lateral, Proppant concentration, Fluid distribution per cluster, Proppant distribution per cluster, Operational surface limits.

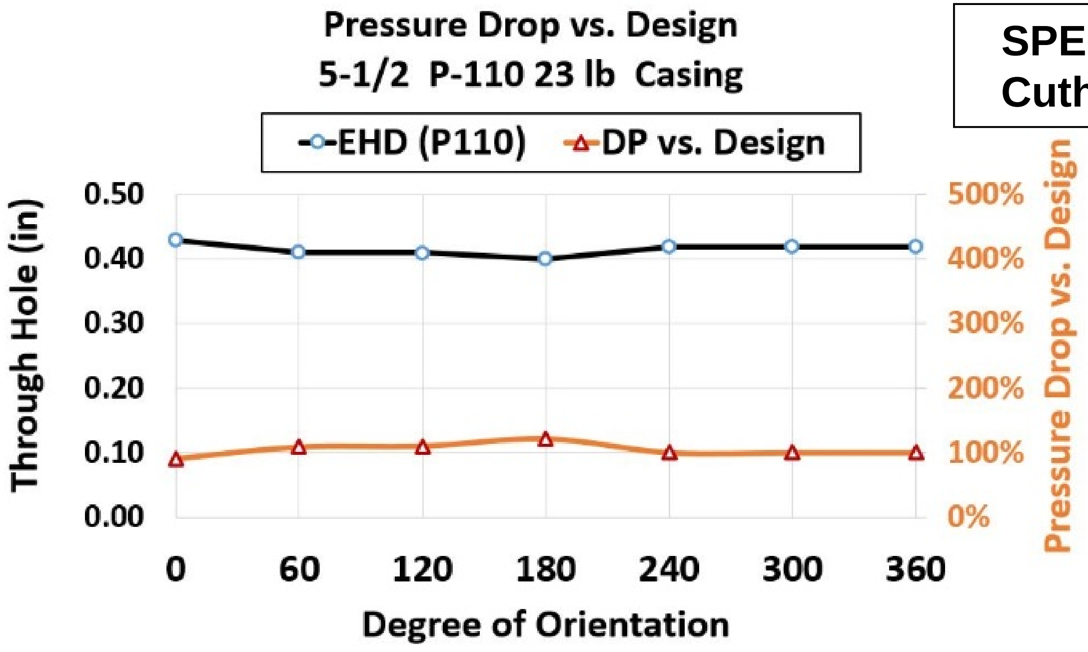
Near Wellbore Friction:
- Shots per cluster, Perf charge size, Penetration depth, Orientation, Phasing, Breakdown techniques: acid & sand slugs.

Stress Variability:
- *Minimum Stress* variations along the lateral and through the targeted formation.
- *Stress Shadowing* from other active clusters, prior stages, offset zippered stages, leak-off effects in zone and out of zone, depletion from offset wells.

Sources of Variability – Perf Performance & Phasing

Even-Hole Perforating Charges

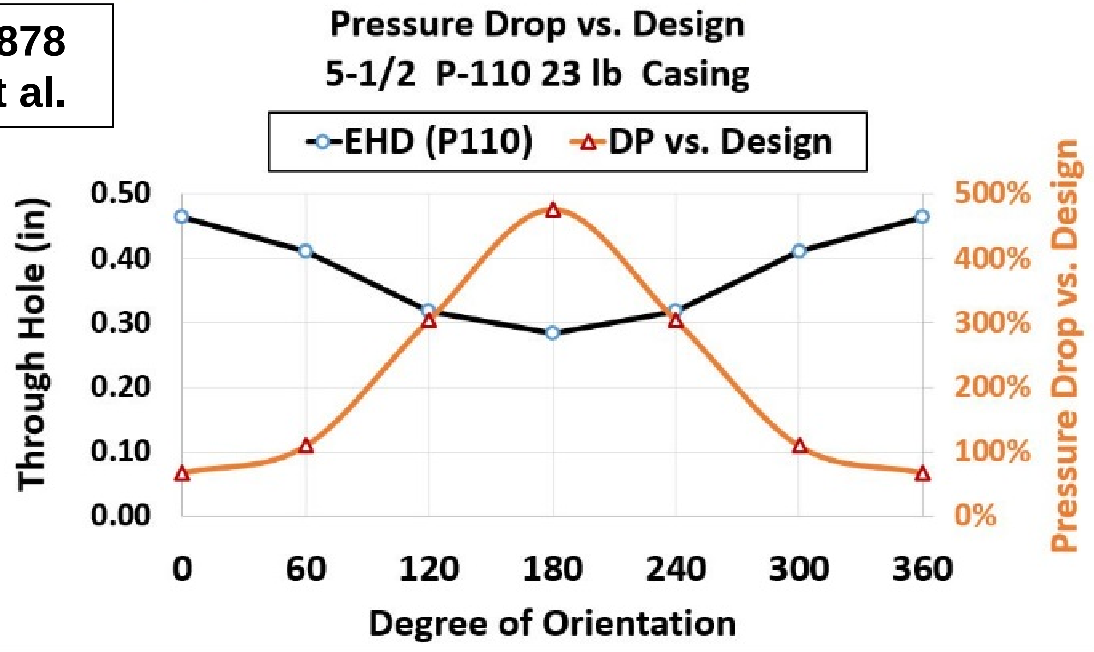
Shot No.	1	2	3	4	5	6	7
Phase	0	60	120	180	240	300	360
Clearance	0.00	0.26	0.90	1.30	0.90	0.26	0.00
API EHD	0.42	0.42	0.42	0.42	0.42	0.42	0.42
EHD (P110)	0.43	0.41	0.41	0.40	0.42	0.42	0.42
DP vs. Design	91%	109%	110%	122%	100%	100%	100%



SPE-184878
Cuthill et al.

Conventional Perforating Charges

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%



Even-Hole Charges Provide Consistency (more than we had before!):

What can we do to minimize this further?

- Shoot at a single phase, oriented.
- Utilize larger (but fishable) perf barrels.
- Other?

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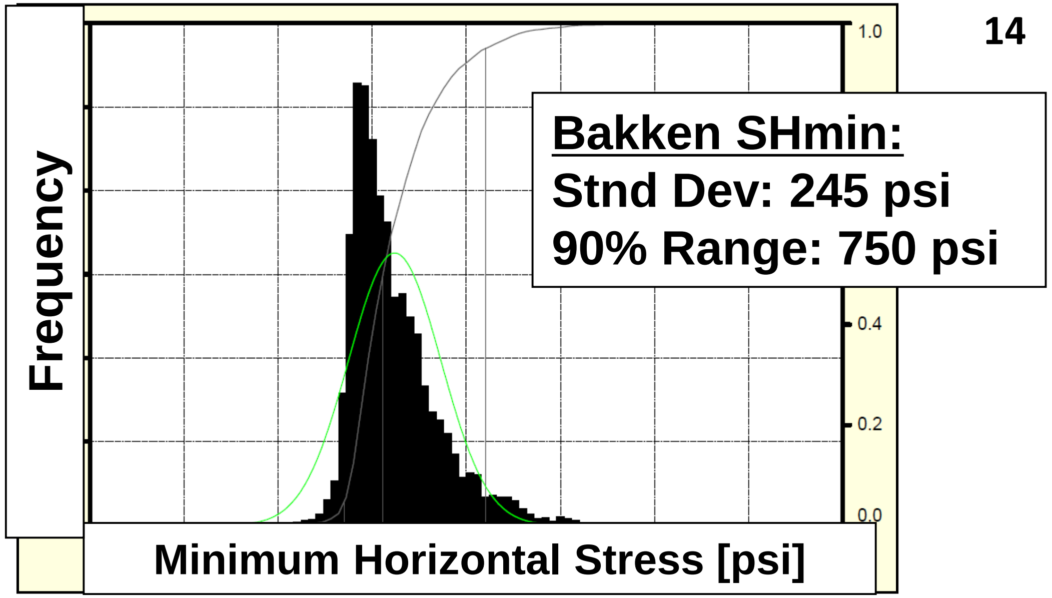
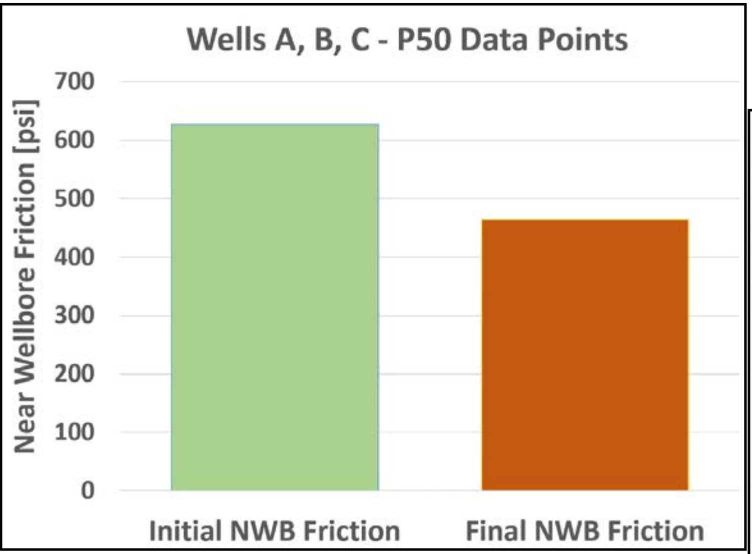
Sources of Variability – Rock

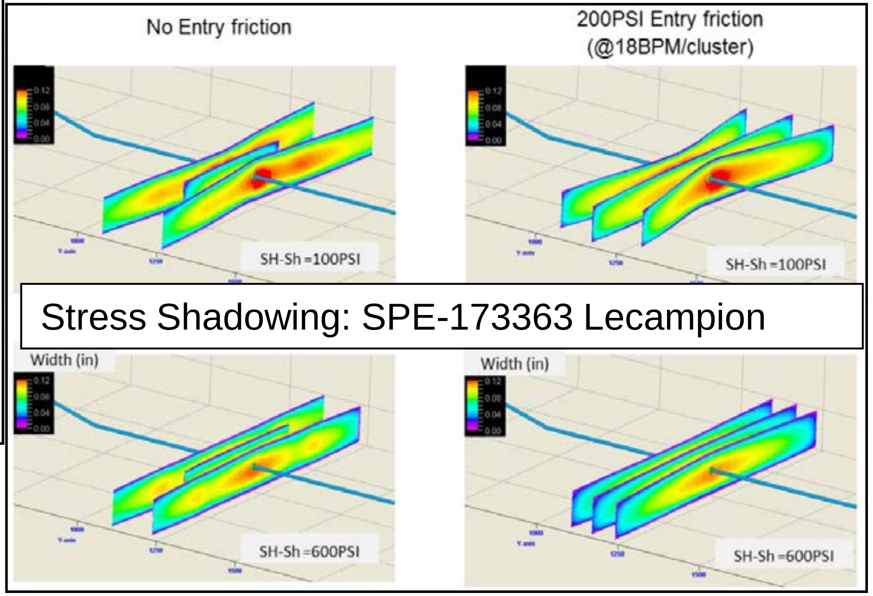
Known From Wellbore Logs, Reservoir Modeling and Step Down Data: ~1,500 psi

1. Minimum Stress Variability: 750 psi
2. Near Wellbore Friction: 625 psi
3. Stress Shadowing: ~200+ psi

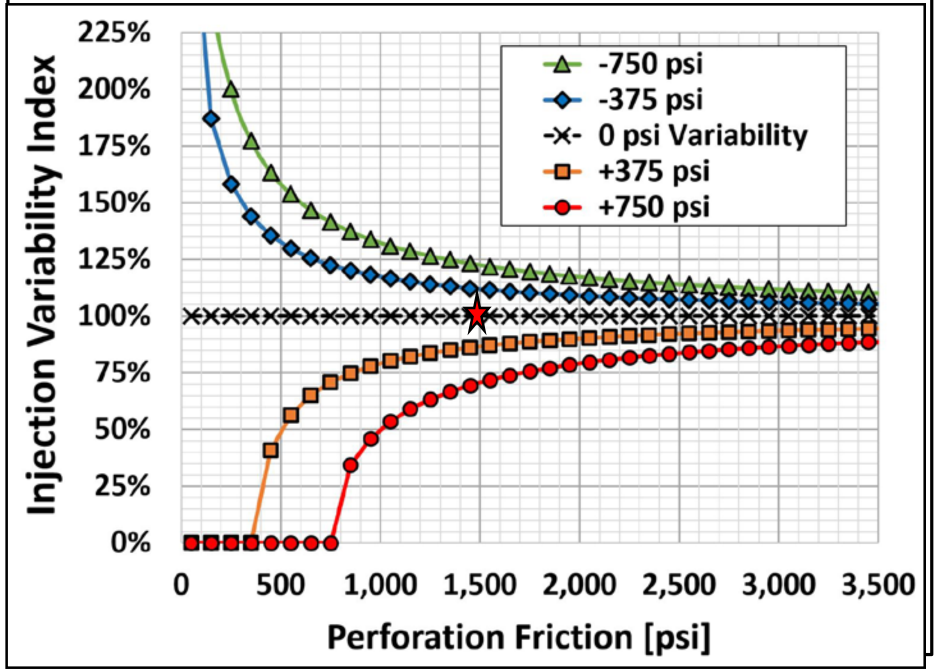




NWB = ~600 psi/stage, 40-60psi per open effective cluster



Design XLE for what you need… diminishing returns applies!



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Sources of Variability – Perf Design & Erosion Effects

Design Variables for Perf Friction:

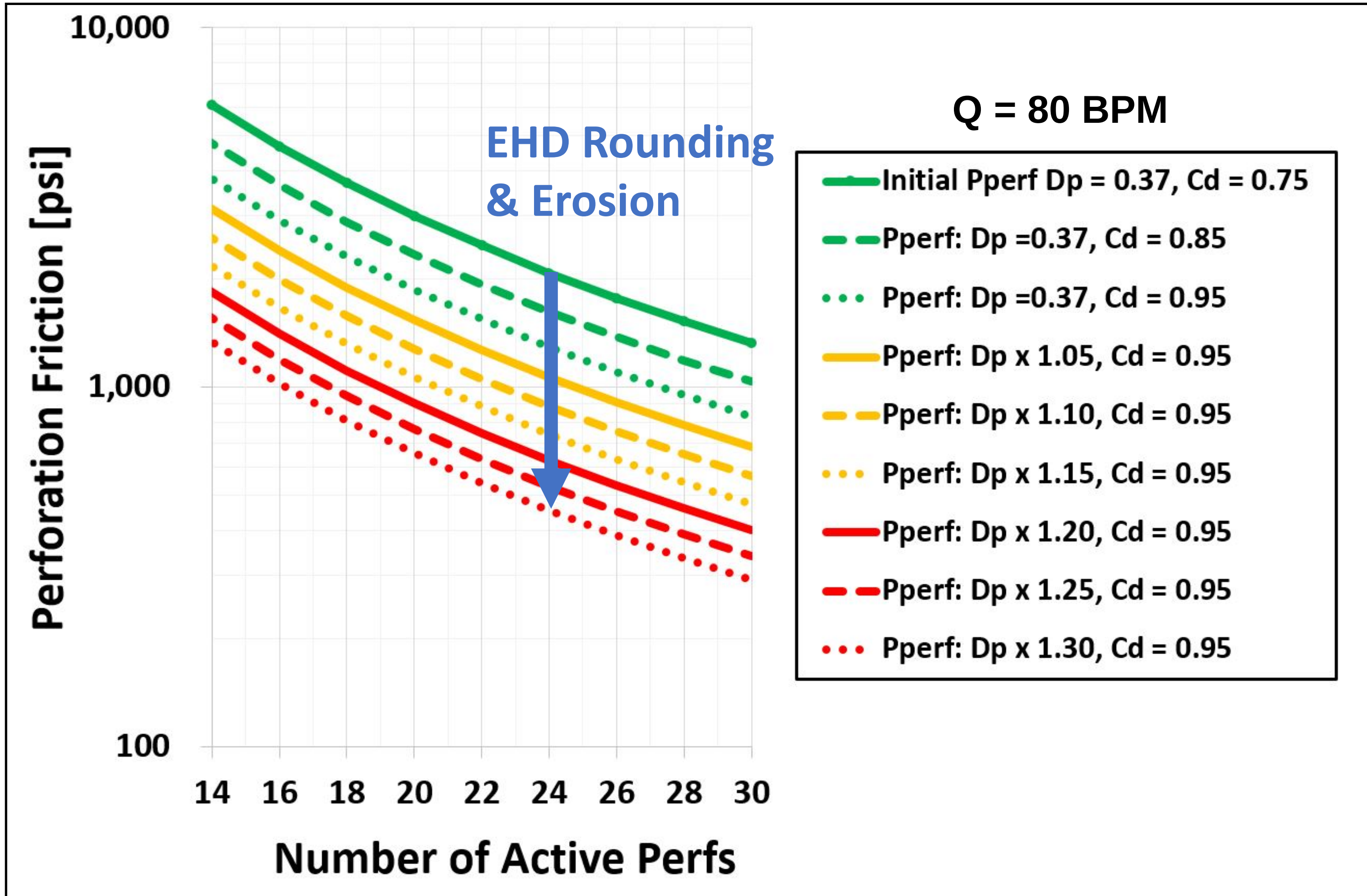
1. **D_P =** Diameter of Perforation Holes
   a. *Initial* diameter variability from phase
   b. *Final* diameter after proppant erosion
2. **N_P =** Number of *Open* Perforations
3. **C_D =** Coefficient of Discharge
4. **Q =** Pump Rate

$$\Delta P_p = Ppf = \frac{0.2369\ \rho\ Q^2}{D_P^4\ N_P^2 C_D^2}$$

Where:
ΔPperf = Total perforation friction, psi
Q = Total Flow Rate, BPM/perf
D_P = Diameter of perforation, in.
N_P = Number of *open* perforations
C_D = Perforation coefficient
ρ = Fluid density, lbs/gal

What can we do to limit the erosion rate?

- Lower ppa?
- Angled perforations or slots?
- Larger single hole clusters?



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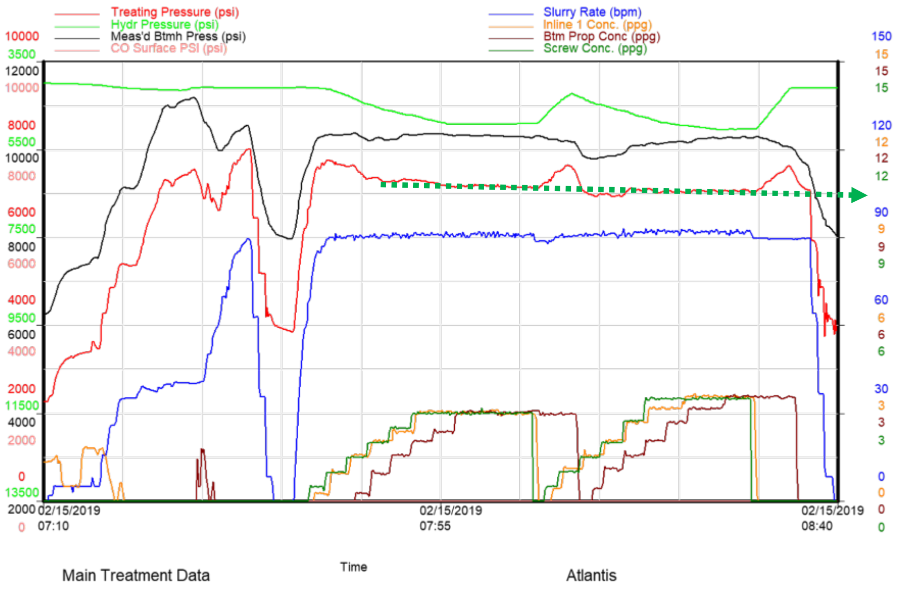
1 SPC vs. 2 SPC – Examples and Observations

Observations:

Comparison of 1 spc stage with a 2spc stage, 15 clusters each:

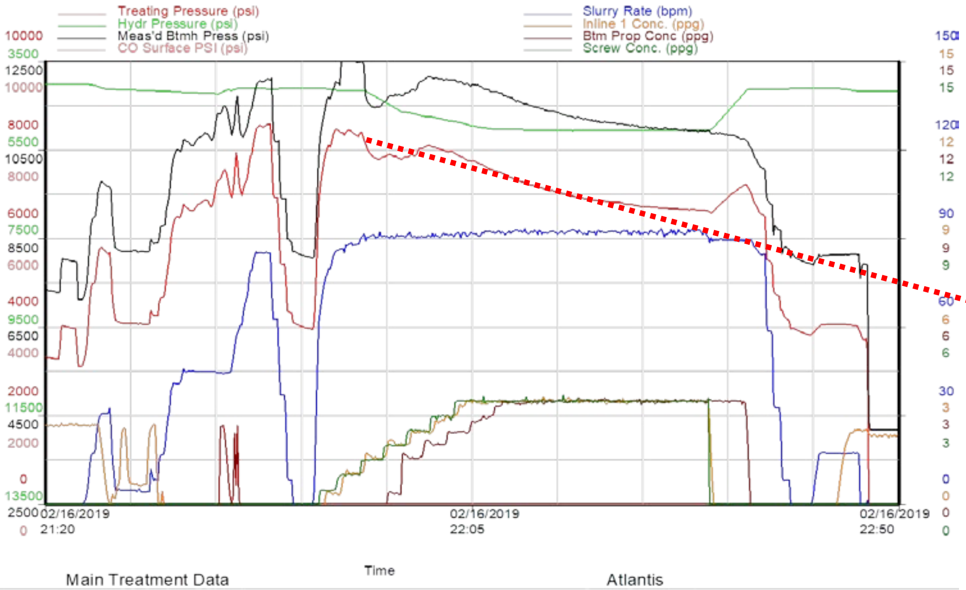
- Significant difference in bpm/hole and perf friction
- 64% more proppant per open hole in the 1 spc stage.
- 1 vs 2 proppant ramps. (higher % of job hitting perfs at higher PPA). But arguably, the erosion rate is noticeably higher from the start, even in the steps to ramp up PPA.

Middle Bakken Example – Stage 16



2 shots per cluster, 15 clusters, 30 total shots example:
Max Rate = 90BPM
Max Rate / OH = 3.9 bpm
Initial Holes Open = 23, **0.40" EH**
Initial Pperf = 1,797 psi @ 90bpm
Final Pperf = 846psi @ 90bpm
Rounding & Erosion = ~951 psi.

Middle Bakken Example – Stage 26



1 spc, 15 total holes example:
Max Rate = 90BPM
Max Rate / OH = 6.42 bpm
Initial Holes Open = 14, **0.44" EH**
Initial Pperf = 3,156 psi @ 85bpm
(note we pumped at 90, tested 85)
Final Pperf = 1,269psi @ 85bpm
Rounding & Erosion = ~1,887 psi.

- **A handful of stages consistently indicated a step change in the erosion rate occurs when above 3,000 psi in our 1 SPC design.**
- **Erosion of EHD does not appear to be a 1 or 2 variable relationship with #/perf.**

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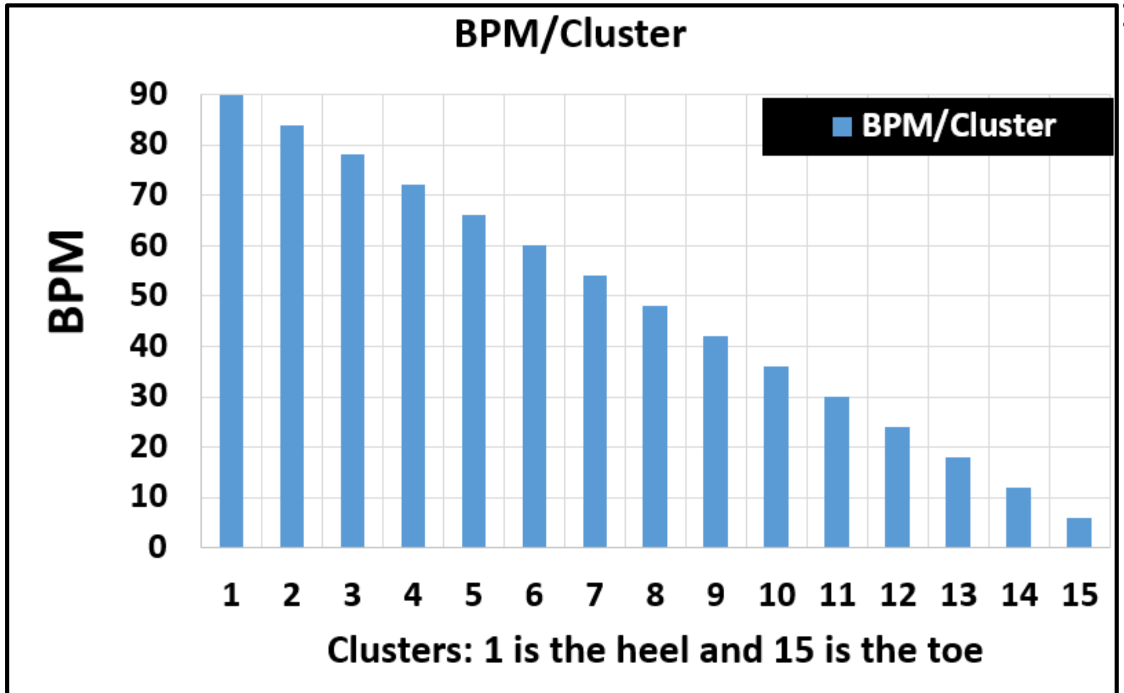
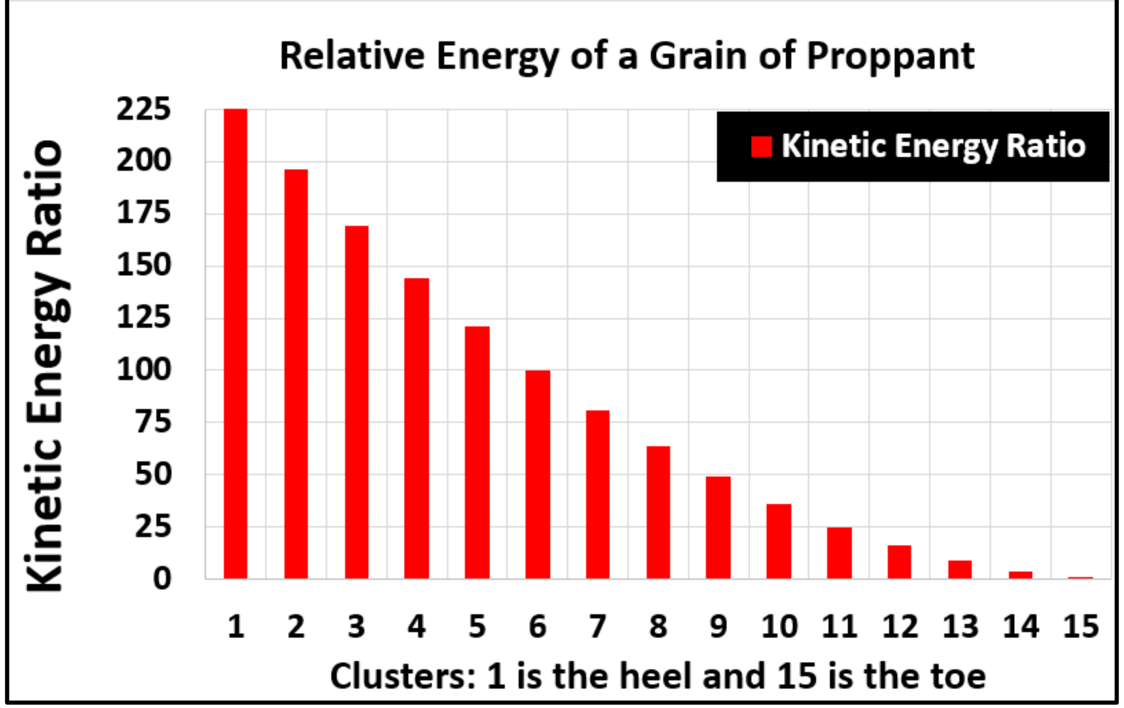
Kinetic Energy of Proppant from Heel to Toe Cluster:

- Camera data shows erosion of holes, but it cannot confirm the amount of proppant that caused that erosion. More specifically, it cannot tell you how much proppant went through each perforation.
- Kinetic energy of an object is proportional to the amount of erosional effects it has when it hits another object.
  - Kinetic Energy = ½ Mass x $Velocity^2$
- Industry needs more diagnostic tools to measure proppant placed per cluster!

If you don't believe me, experiment for yourself:

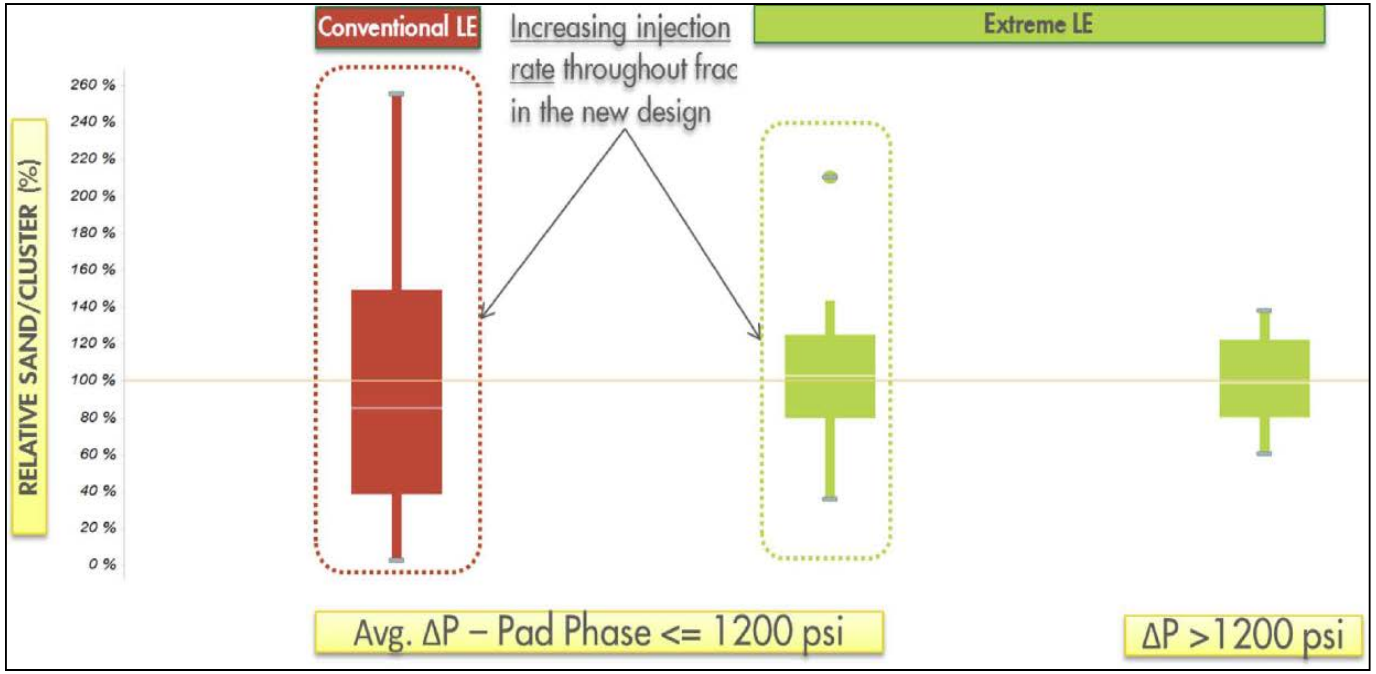




Published Impact of XLE – Shell (SPE-184834)

Conclusions:

- Increased perforation friction demonstrated a more even fluid distribution than prior designs.
- Increasing injection rate throughout the job aided in maintaining even fluid distribution.

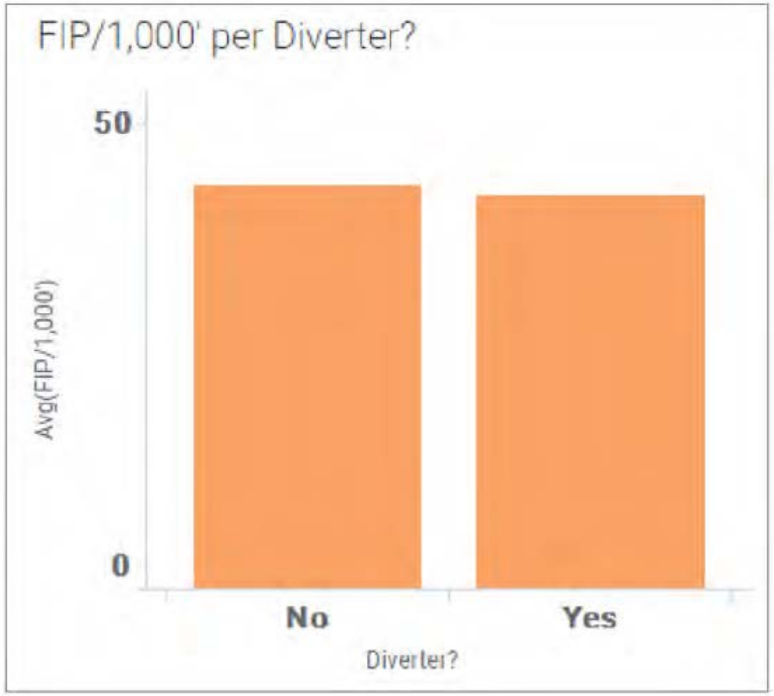


SPE 184834 - Somanchi et al.,

Published Impact of XLE – SM Energy (SPE-199712)

Conclusions:

- Diverter did not open incremental fracture initiation points.
- Wellbore orientation impacts heel or toe bias within a stage…gravity works!
- Increased stage length did not lead to performance degradation.
- Perf erosion (camera) not always linked to fracture initiation (DTS).



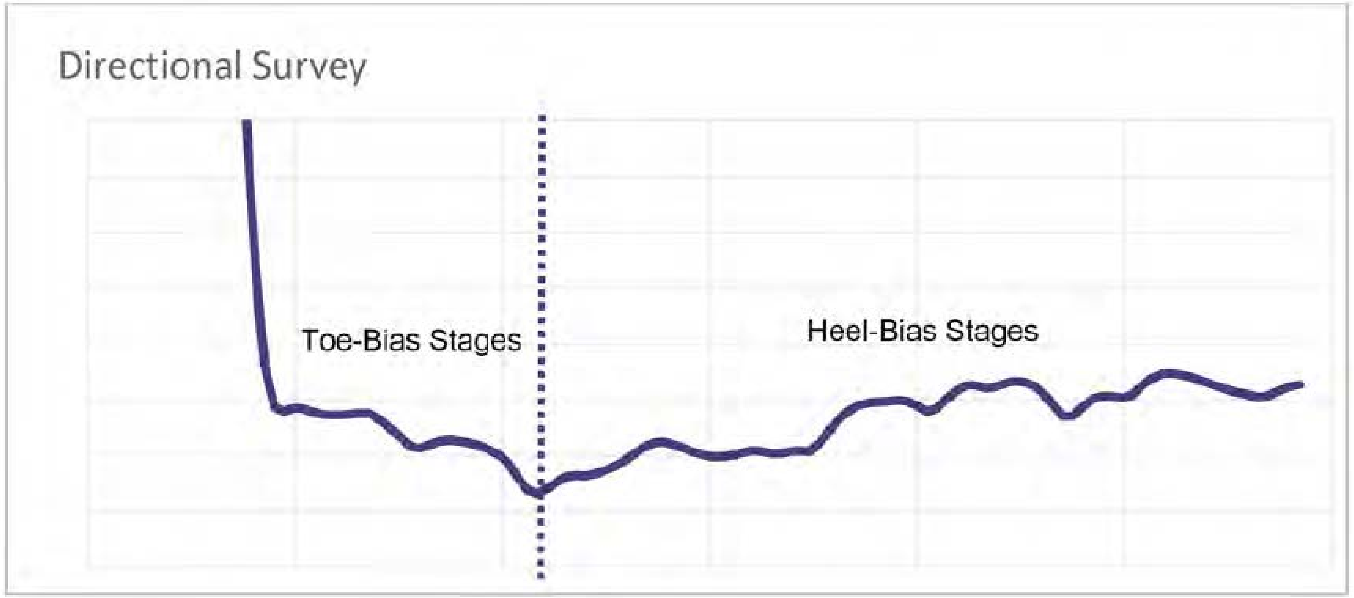
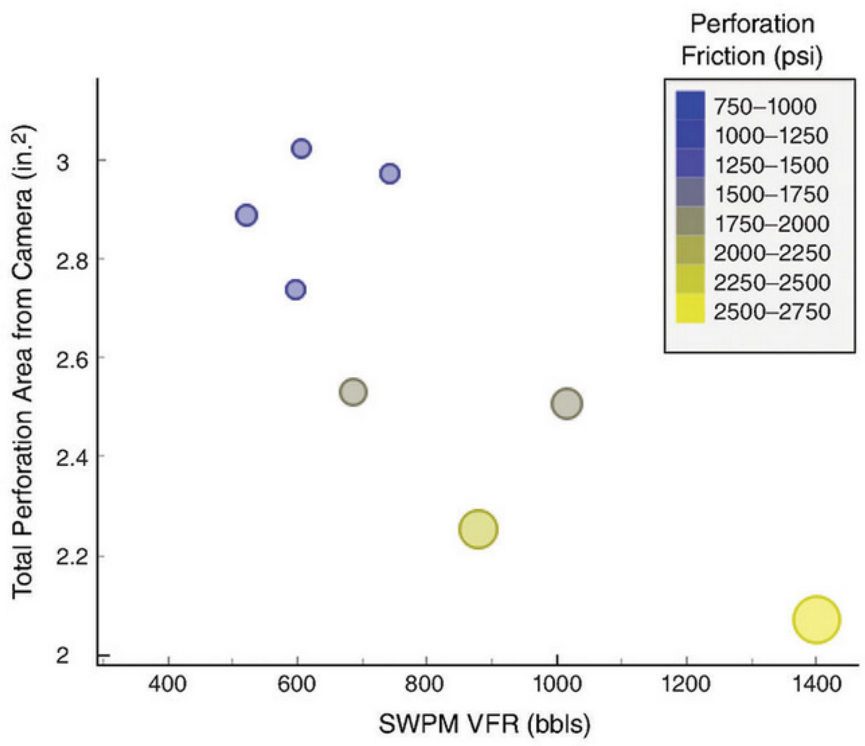


Figure 33—2D visualization of the lateral plotted with the directional survey coordinates. The transition point from toe-biased erosion stages to heel-biased erosion stages is noted.

Figure 7—Average fracture initiation points per 1,000' of lateral for stages pumped with and without PLA diverting agents.

Published Impact of XLE – Devon Energy

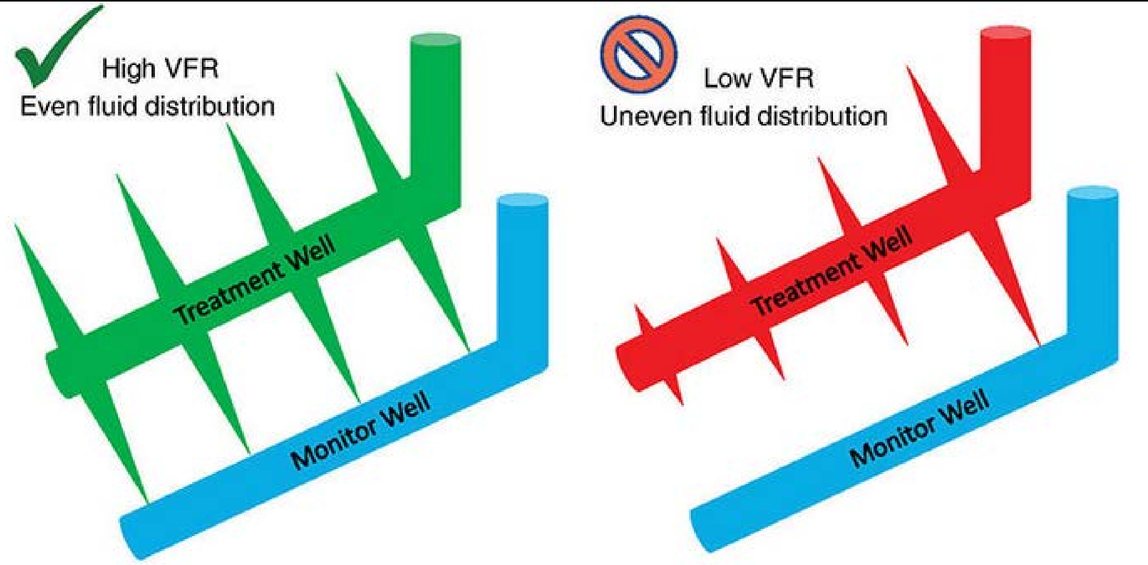
Sealed Wellbores and the Unlikely "Breakthrough" Behind Cheap, Accurate Fracture Diagnostics - JPT April 1, 2020.



Each point on this chart represents one stage. Total perforation area was measured using a downhole camera for each stage, then sized and colored according to perforation friction. The results show a strong relationship between perforation area and volume to first response (VFR). *Source: Devon Energy.*

Key Takeaway:

- A strong relationship exists between the amount of perf friction and the amount of fluid it requires to hit an offset well…e.g. better fluid distribution per cluster is achieved with increased perf friction. Devon calls this the Volume to First Response (VFR).



Volume to first response (VFR). With the same cluster count and well spacing, higher VFRs correlate to better fluid and proppant placement between offsetting wells. *Source: Devon Energy.*

Published Impact of XLE: Liberty Resources (SPE 189880)

<u>Leveraging HDP + XLE to reduce stage count increases capital efficiency:</u>

- **50 to 21 stages** per 10,000 ft lateral.

<u>Reference for GOR Behavior: SPE 184397- Steve Jones</u>

- Depletion (withdrawals) drives GOR increase
- Effective cluster spacing drives rate acceleration

SPE 184397 – (STACK Play)

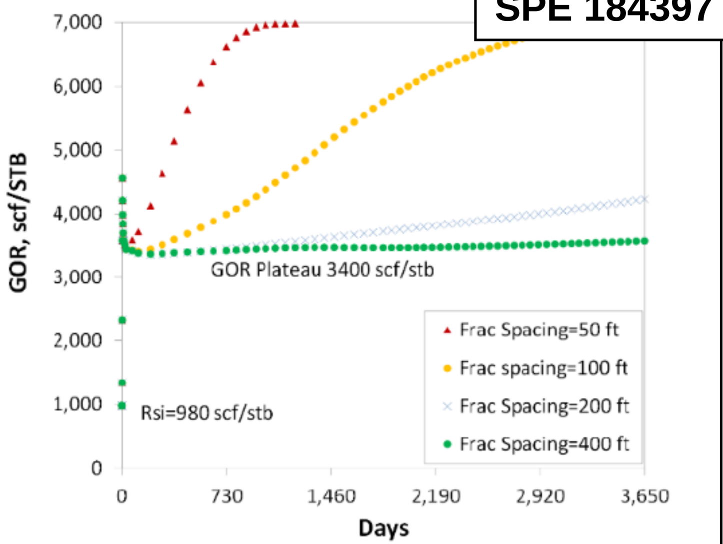
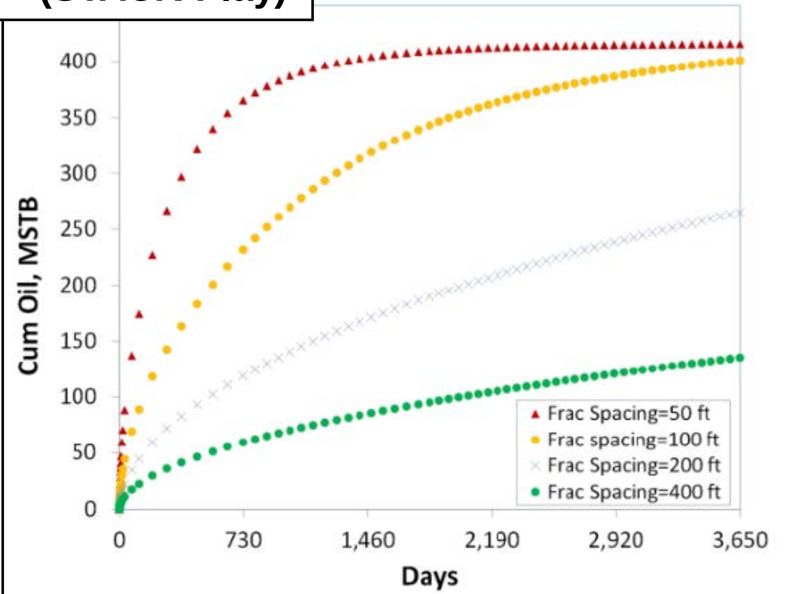
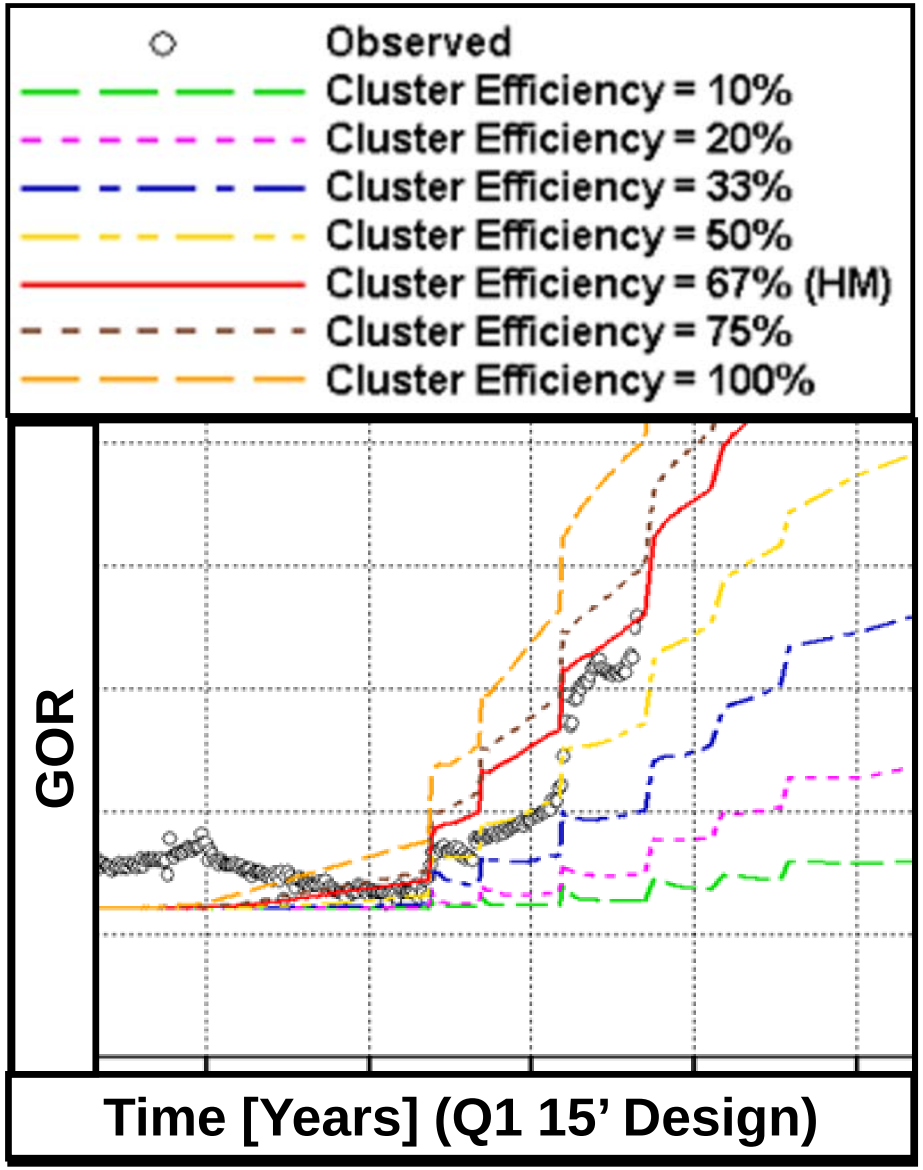


Figure 21: Simulated GOR vs. time for various fracture spacings. k=300 nd.





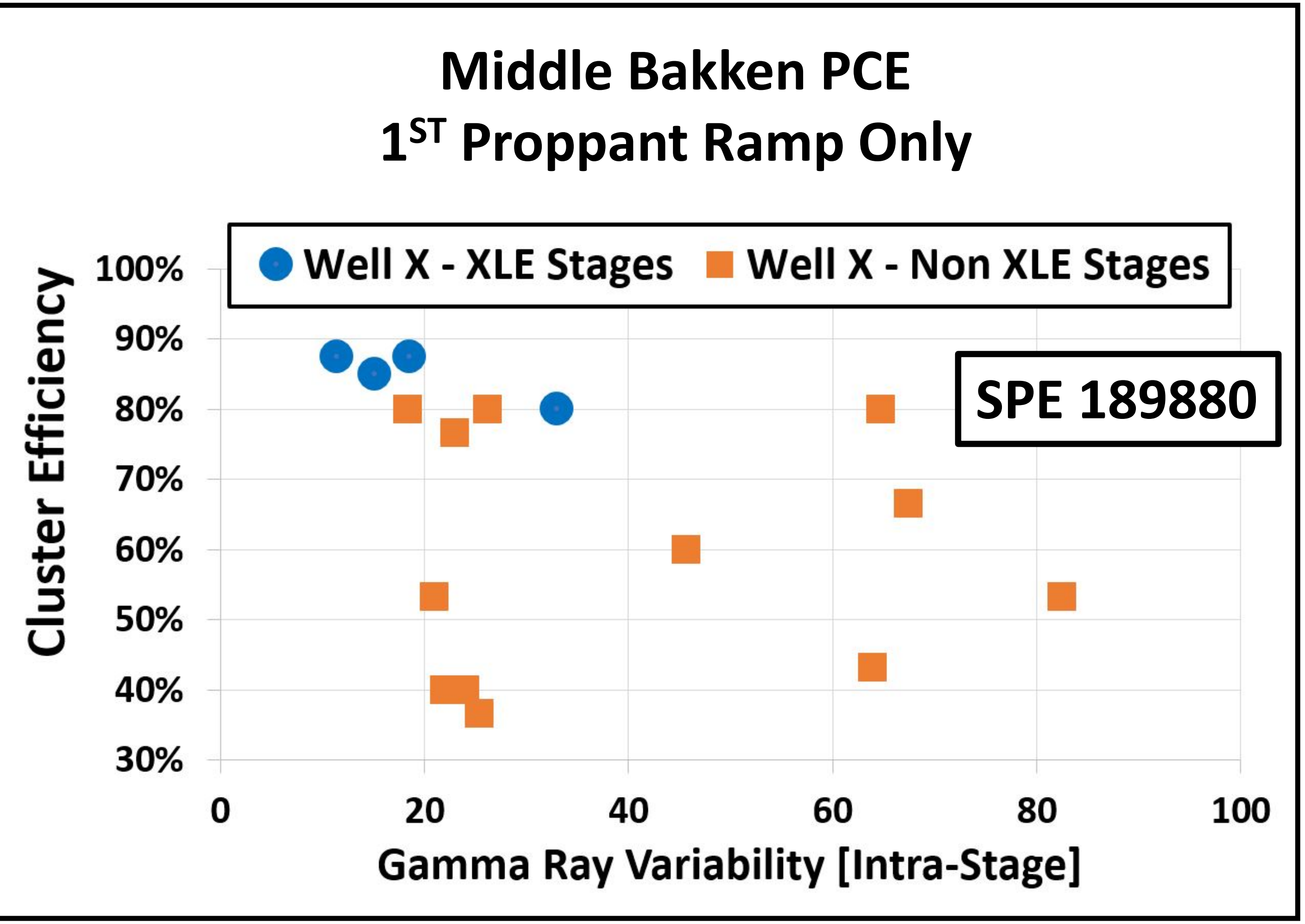
SPE-189880 • Weddle

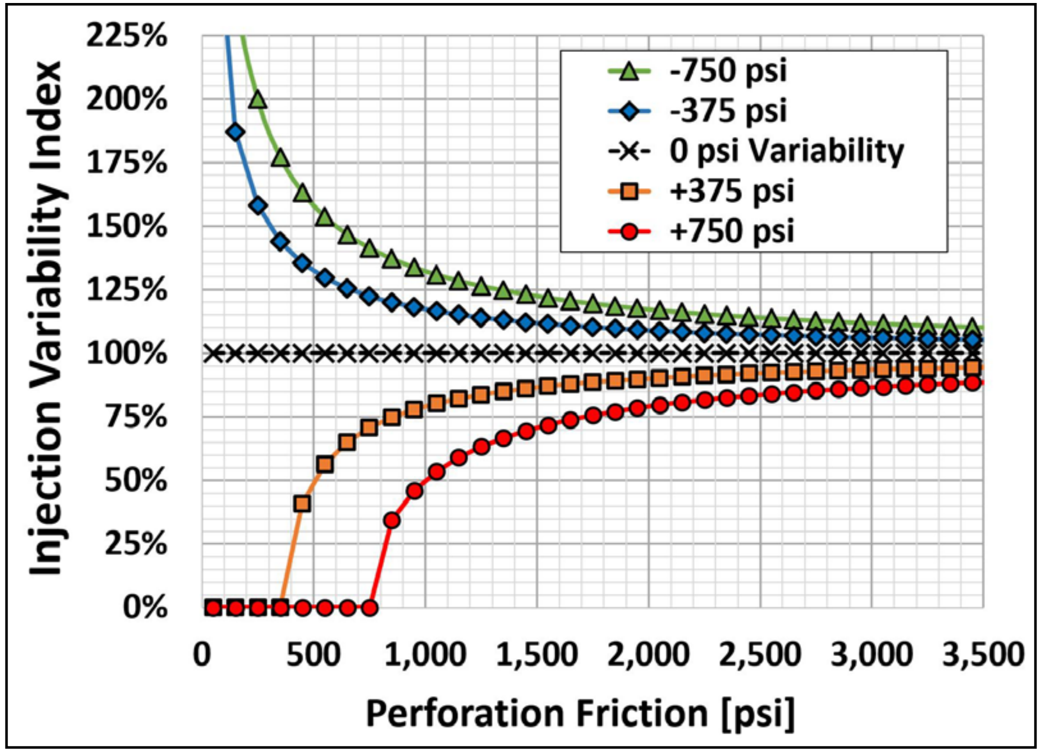
CONCLUSIONS

- **Increasing perforation friction (XLE) counteracts variations in fracture-entry pressures; as the perforation friction increases the fluid distribution to the perforations converge as shown with *The Injection Variability Index*.**
- **An HDP strategy can efficiently create conductive and productive surface area. Fracture geometry and conductivity are important considerations when applying an HDP strategy.**
- **Multiple diagnostic data sets demonstrate the success of XLE in driving cluster efficiency > 80% and more evenly distributing the frac fluid to each active fracture initiation point.**
- **Consistent diameter entry holes provide more operational consistency when using XLE and Step Down Tests. Utilizing 1-SPC increases consistency even further.**
- **Well planned and executed drilling, geo-steering, perforating and stimulation can minimize the impacts of the variability of the system, resulting in more consistent well results.**
- **Finding and development costs [$/bbl] can be optimized for a targeted cluster spacing and cluster count per well by utilizing an HDP + XLE strategy.**
- **The industry continues to leverage each others learnings into further progress!**

LIBERTY RESOURCES

Results – Initial 2016 XLE Field Trial with RA tracer





Middle Bakken stages *without* XLE:
- 85% Overall RA PCE, but low PCE in 1st proppant ramp of **59%**.

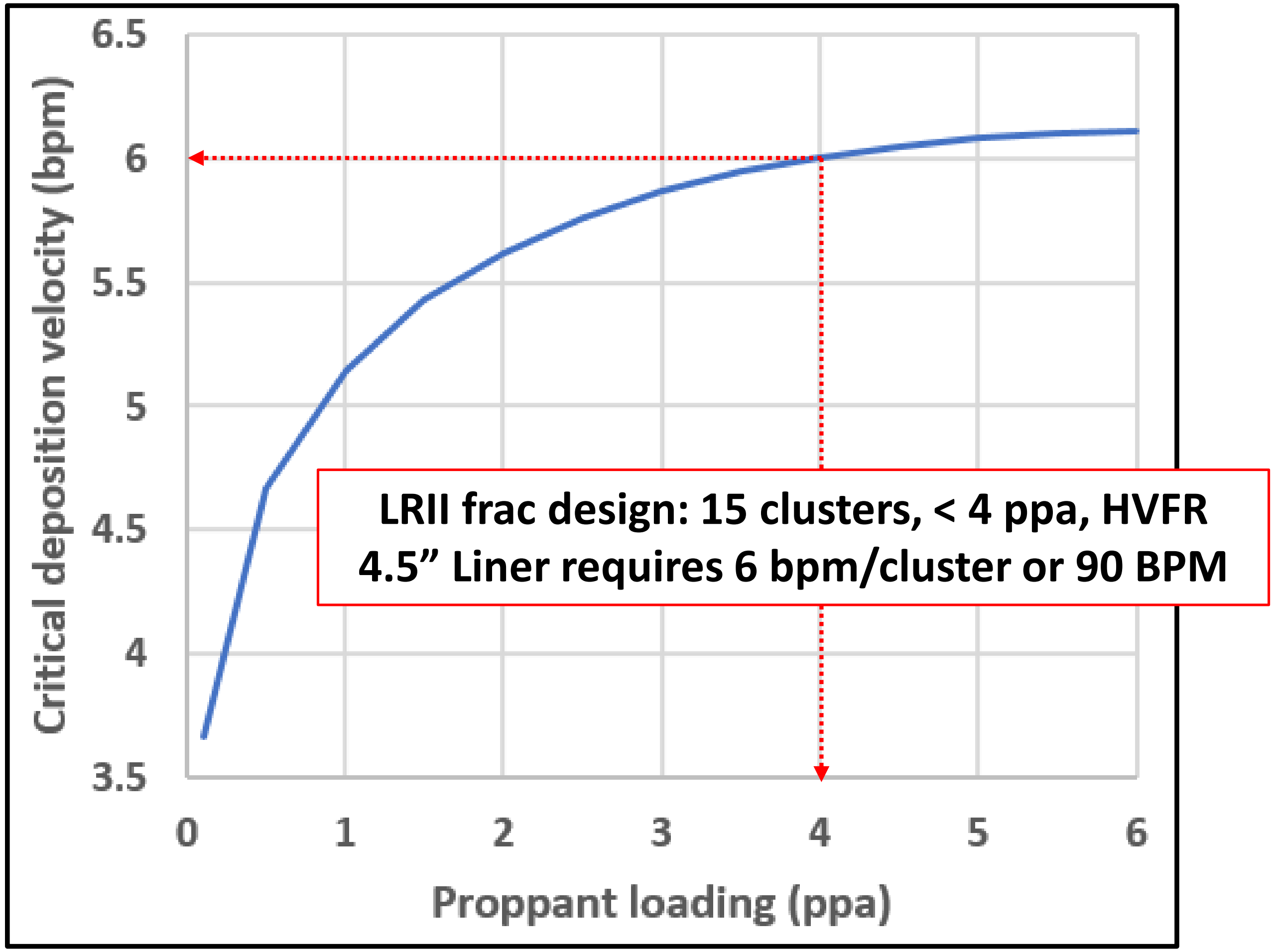
Middle Bakken stages *with* XLE:
- 93% Overall RA PCE and also high PCE in 1st proppant ramp of **85%**.

Sources of Variability – Proppant Transport in the Lateral

- **Oroskar Correlation**
  - Image Courtesy of Mark McClure w/ResFrac

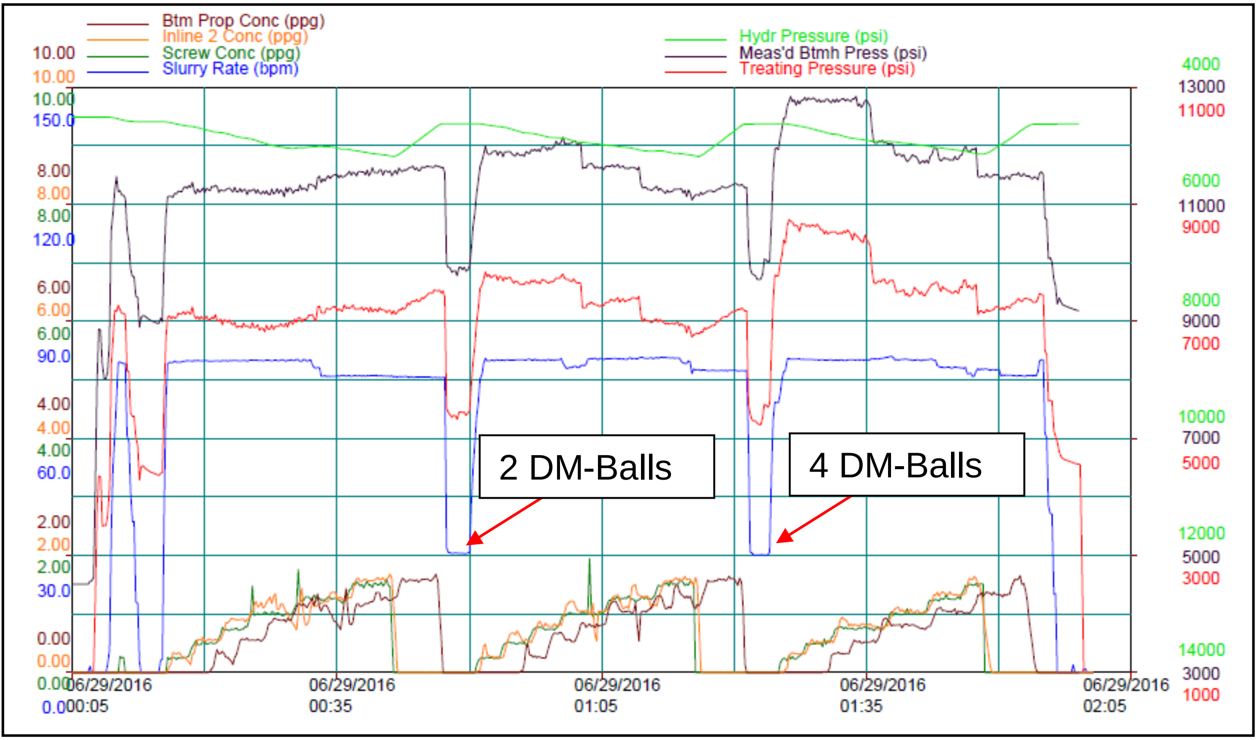
  <u>Variable list of what impacts it…</u>
  - Pipe Diameter
  - Proppant Density
  - Proppant Loading
  - Effective Viscosity
  - Water Density
  - Particle Diameter

- **Shah 1990, SPE 18994**
  - Critical velocity needed of >6.4bpm



VERIFYING STEP DOWN TESTS WITH DM BALL SEALERS

7/8” DM Ball Sealers - Middle Bakken

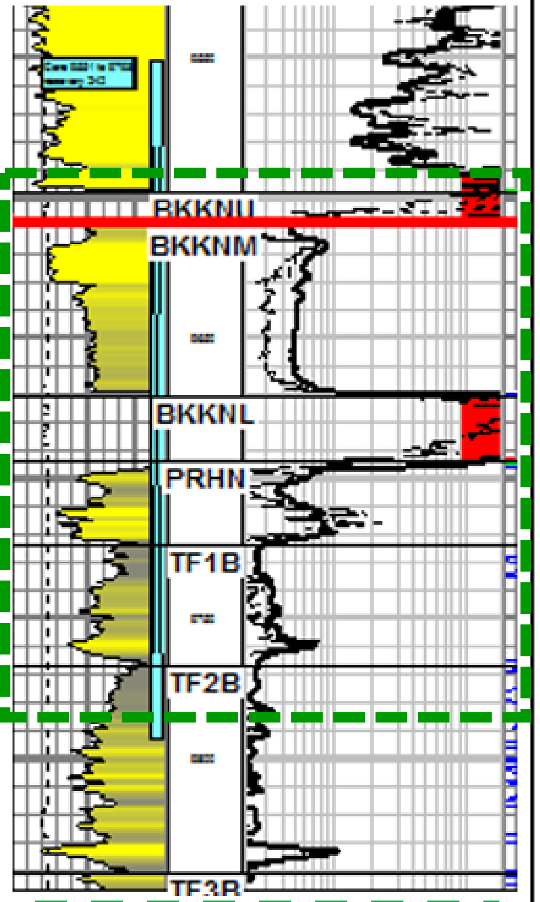


- Excellent calibration to calculated number of holes open from initial and final step down analysis in a cemented PnP well design

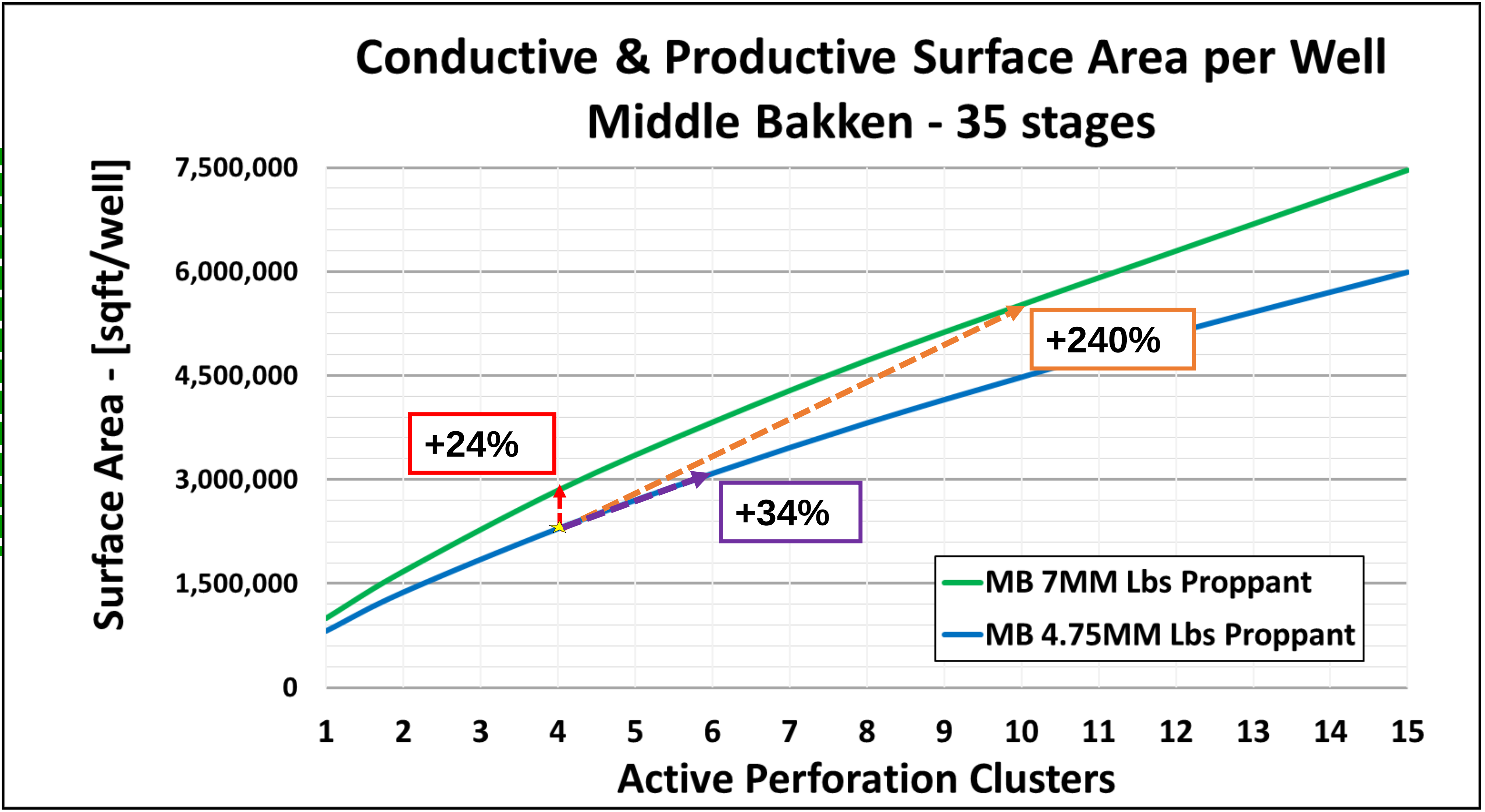
Initial step down analysis showed 12 holes open at 79.4 bpm. 1 hole per cluster, 0.56”:

1. <u>Pperf = 1,700 psi going into first sweep</u>
   2 DM Ball sealers deployed
2. Just 10 holes open at 79.4 bpm in 2nd ramp
   Calculated increase in Pperf = **<u>~750psi</u>**
   Actual increase in STP = **<u>~800psi</u>**
   STP drops twice in ramp, back to original STP
3. <u>Pperf = ~1,330 psi going into 2nd sweep</u>
   Cd=~0.85 with prior proppant placed
   4 x DM Ball sealers deployed
4. Just 8 holes open at 79.4 bpm in 2nd ramp
   Calculated increase in Pperf = **<u>~1,650 psi</u>**
   Actual increase in STP = **<u>~1,700 psi</u>**
5. STP drops in 3rd ramp
   Final step down indicated 11 holes open

High Density Perforating – Steepening the Curve…



Bakken Pool
115 ft thick



HDP – Impacts on Frac Geometry & Conductivity

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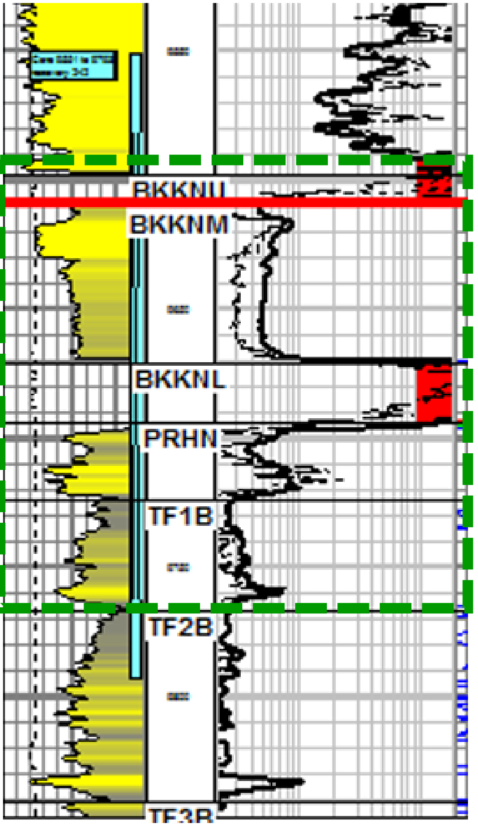
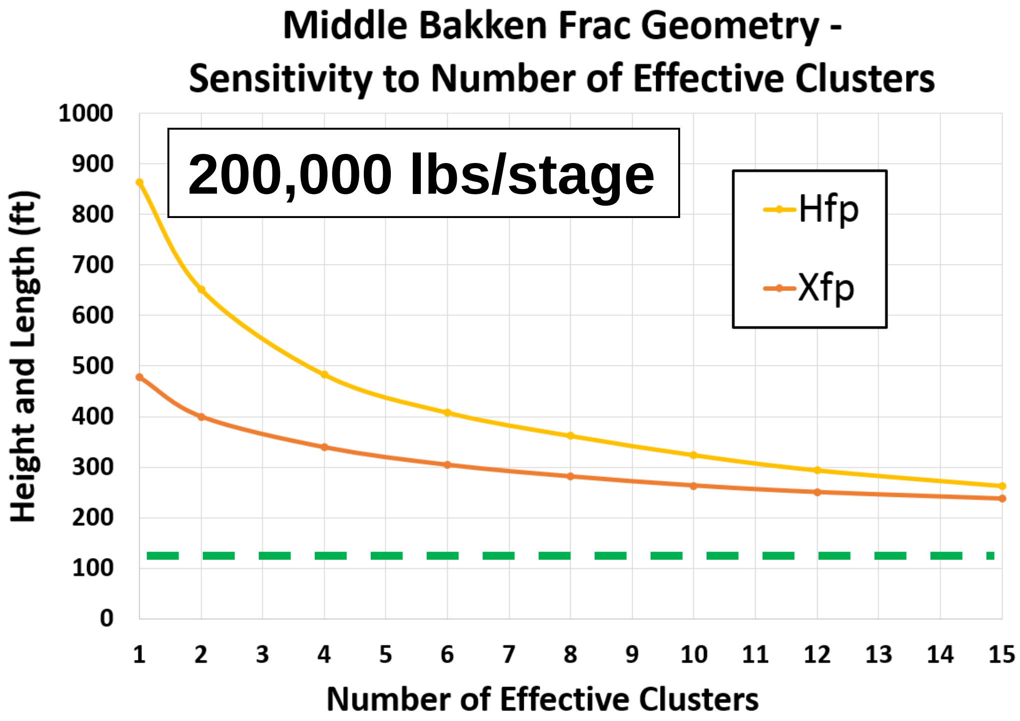
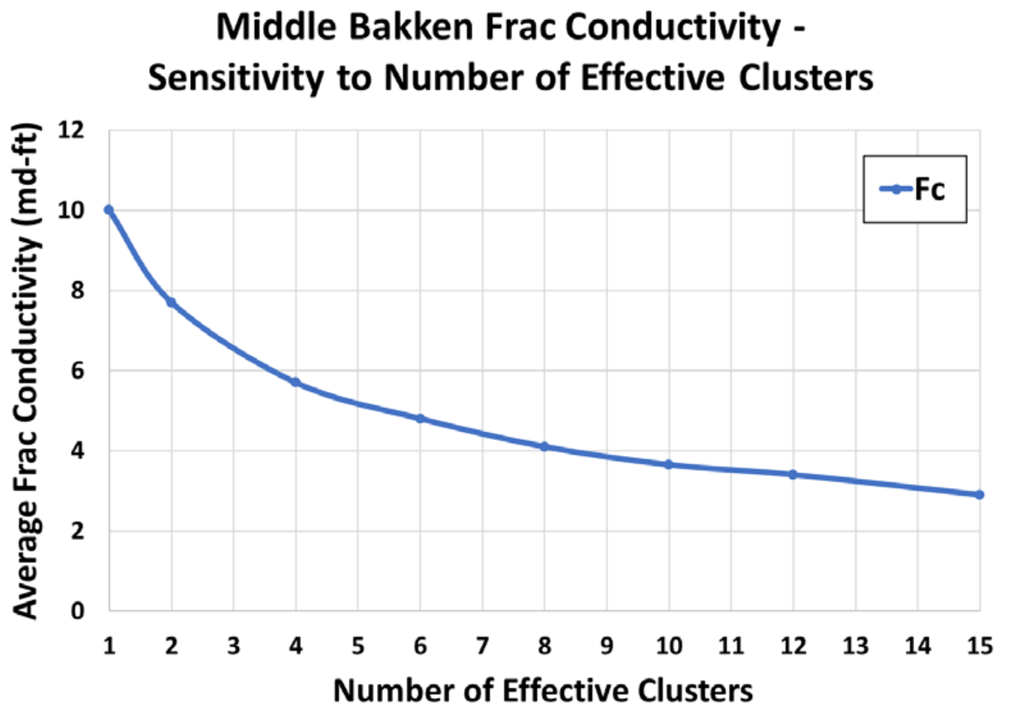






Bakken Pool Thickness ~115ft

SPE 184828 • Mining The Bakken – Weddle

- **All scenarios, 13,333 - 200,000 lbs/cluster place proppant through entire Bakken Pool.**
- **Conductivity is reduced…but sufficient for <10 BFPD per cluster that is expected.**
- **How much proppant is lost to above or below zone propped height?**

For more on this topic: SPE-199751

Wild Cards - Frac Plug Ball Testing Recommended!

Basic Testing Outline:

- 1.5” Seat based on current frac plug.
  - 1.875” Ball (+/-0.005”) – Material A
  - 2.375” Ball (+/-0.005”) – Material B
- 100F and 200F fresh water tests
- 5,000 psi for 30 seconds then 9,000 psi up to 8 hours or failure.
- Does this help explain “plug failure” signatures during frac even when we “tag” the plug on drill out?

1.875” Ball
200F Fail @ ~8.5K psi
100F Test Pass @ 9K psi

2.375” Ball
200F Fail @ 4.5K psi
100F Pass @ 9K psi

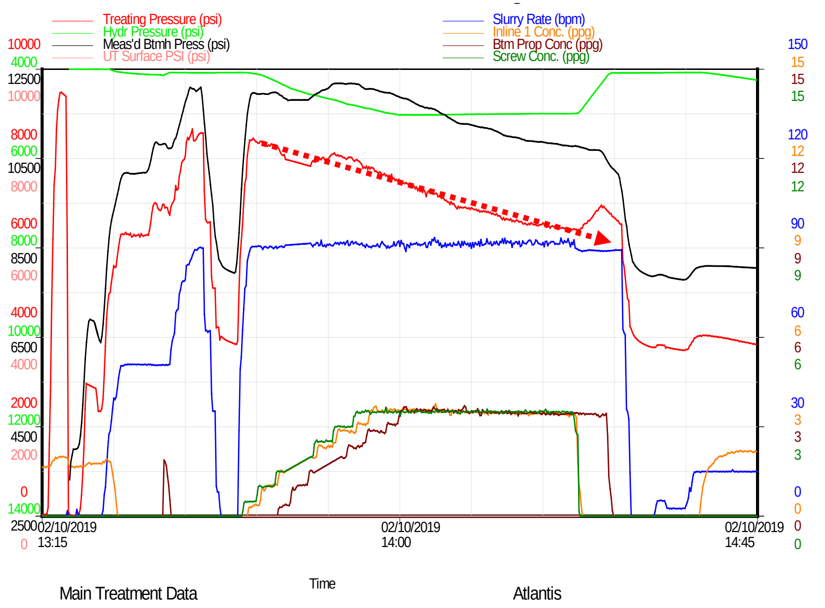
1 Hole Per Cluster – Examples and Observations

Observations:

Increased Erosion and "steeper" STP trend observed on some stages and interpreted as a higher erosion rate per pound pumped…**Why??**

- Difference in EH but the same bpm/hole, so a velocity difference and a perf friction difference.
- 1 vs 2 proppant ramps. (higher % of job hitting perfs at higher PPA). But arguably, the erosion rate is noticeably higher from the start, even in the steps to ramp up PPA.

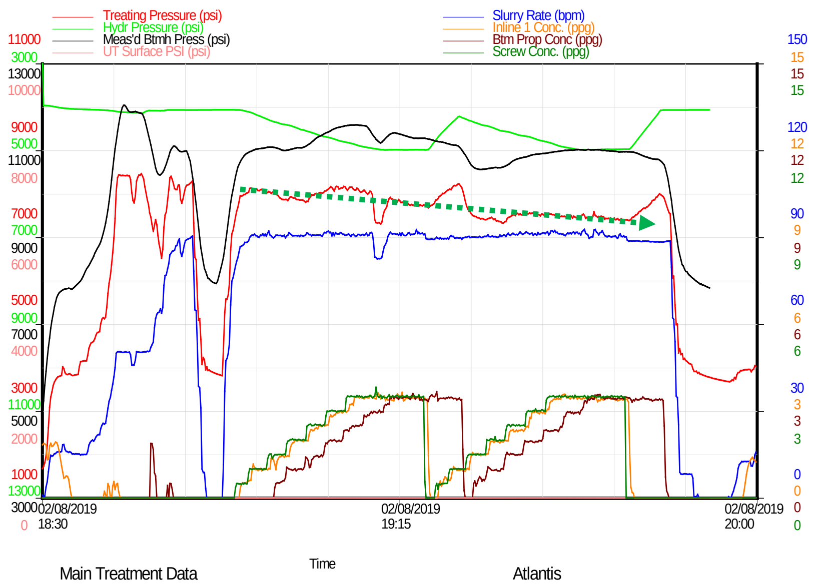
Middle Bakken Example – Stage 27



Max Rate = 90BPM
Max Rate / OH = 6.0 bpm
Initial Holes Open = 15, 0.44" EH
Initial Pperf = 3,396psi @ 90bpm
Final Pperf = 1,136psi @ 90bpm
Rounding & Erosion = ~2,200 psi.

Excessive rate of erosion?

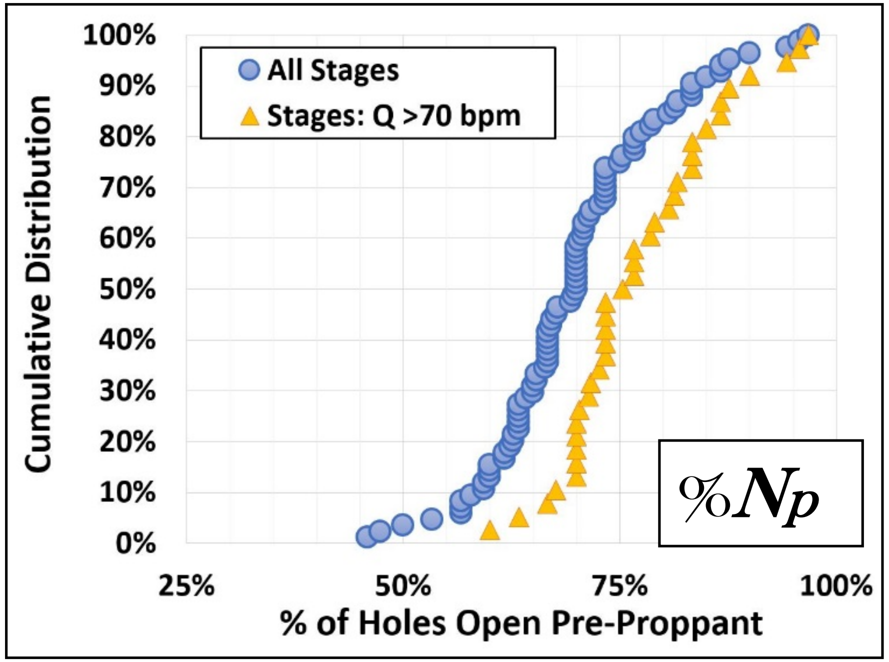
Middle Bakken Example – Stage 18

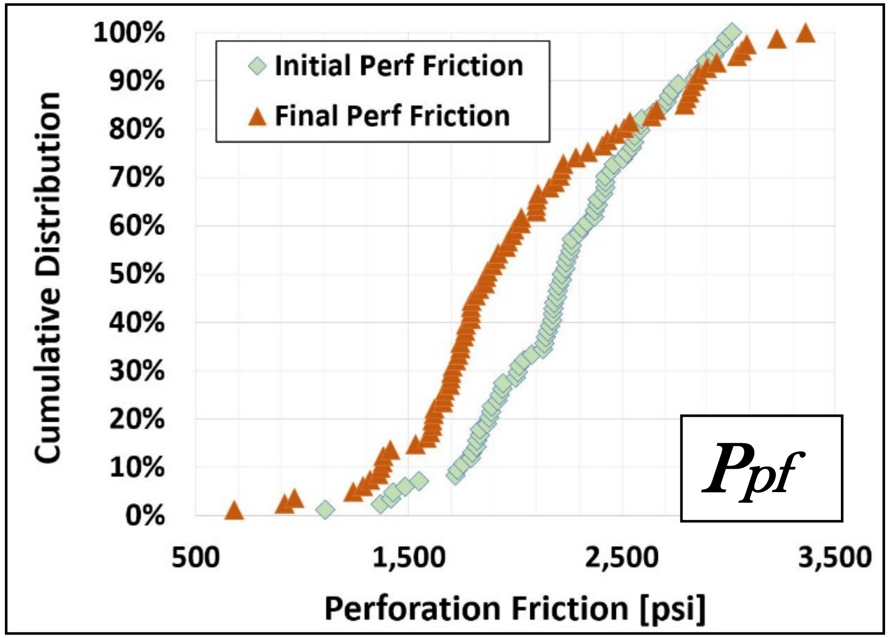


Max Rate = 90BPM
Max Rate / OH = 6.0 bpm
Initial Holes Open = 15, 0.49" EH
Initial Pperf = 2,593psi @ 90bpm
Final Pperf = 1,573psi @ 90bpm
Rounding & Erosion = ~1,000 psi.

Acceptable rate of erosion?

XLE CALIBRATION: HOLES OPEN (N_p) AND INITIAL vs FINAL P_{pf}





Holes Open: Multi-well calibration of N_p has resulted in a 75% holes open design assumption.

- Max rate before initial SDT effects Np
- Intra-stage **SHmin** variability effects % of holes open.

Perforation Friction Changes (Erosion): Initial and Final P_{pf} demonstrate magnitude of erosion.

- Pipe hardness: P-110 pipe vs L-80
- Proppant loading (ppa)
- Proppant per perforation
- Even hole charges vs standard API charges
- Work hardening of casing from perfs vs drilled holes in lab