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Maximizing Refrac Treatment Recovery Factors in Organic Shales Using Expandable Liners and the Extreme Limited Entry Process

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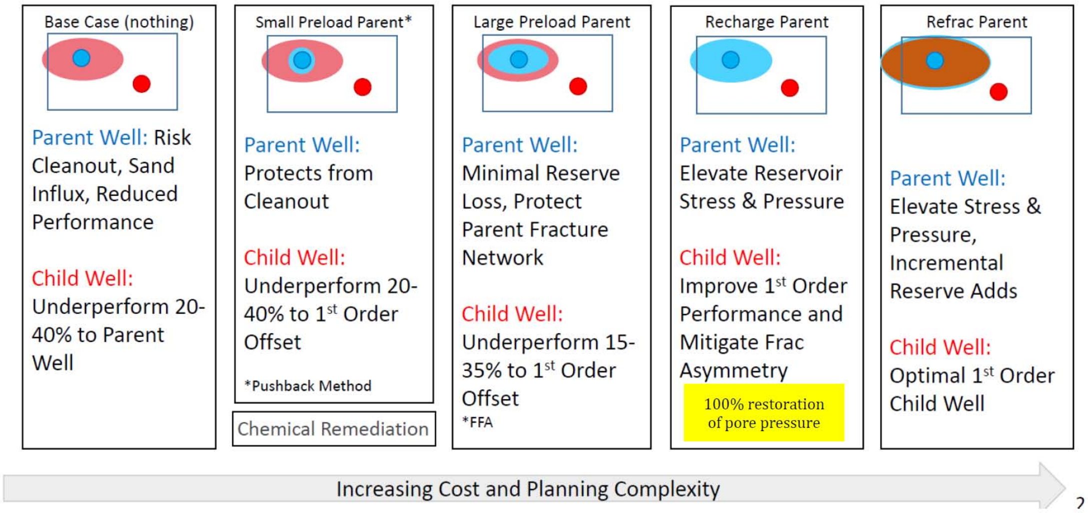
Abstract

With the industry shifting gears toward pad development there has been a significant increase in operator press releases to stockholders expressing concern about fracture driven interactions (formerly called "frac hits") within a drilling spacing unit (DSU) (Triepke 2018). Primary wells (formerly called "parents") (Daneshy 2019) are the initial wells on the pad and infill wells (formerly called "children") are all those that follow on the pad or an adjacent pad. Failure to protect the primary well from infill well fracture driven interactions can result in up to 40% EUR losses in infill wells from asymmetric fractures (Elliott 2019) (Ajisafe et al 2017). Adverse frac interactions between wells in a DSU can be largely eliminated with a combination of primary well refracs and infill well zipper fracs. In the primary well protection process there is a movement away from "preloads" as the overall results from the preloads to date suggest they are not effective in preventing infill well frac asymmetry unless the primary well can be restored to its original stress conditions. A number of operators have announced plans in press releases to increase well spacing in the DSUs to reduce well to well interference. A number of of organic shale operators have also announced performance related reserve write downs according to a March 13, 2019 Simmons Energy report (Harrison and Todd 2019). While in some cases the writedowns were due to changes in pricing expectations, the combination of a known reserve bashing situation and numerous operators still relying on preloads for parent protection raises a red flag. It is highly likely that there is a relationship between DSUs that use preloads instead of refracs for primary well protection and poor overall performance from the DSU. It was proposed in the keynote address at a recent primary-infll frac interaction conference that refraccing primary wells is significantly more effective than preloading them in preventing large infill EUR losses (Elliott 2019) (Figures 1 and 2). Figure (3) has a microseismic interpretation of an infill well assymetric frac offsetting a primary well with no refrac. The stranded hydrocarbons are clearly where there is no microseismic activity. For a DSU with 600,000 BO wells the combination of the 40% infill well EUR loss and the loss of up to two PUDs per DSU can be in the $29 million range so this is hardly an academic exercise.



Parent Well: Risk Cleanout, Sand Influx, Reduced Performance

Child Well: Underperform 20-40% to Parent Well

Parent Well: Protects from Cleanout

Child Well: Underperform 20-40% to 1st Order Offset

*Pushback Method

Chemical Remediation

Parent Well: Minimal Reserve Loss, Protect Parent Fracture Network

Child Well: Underperform 15-35% to 1st Order Offset

*FFA

Parent Well: Elevate Reservoir Stress & Pressure

Child Well: Improve 1st Order Performance and Mitigate Frac Asymmetry

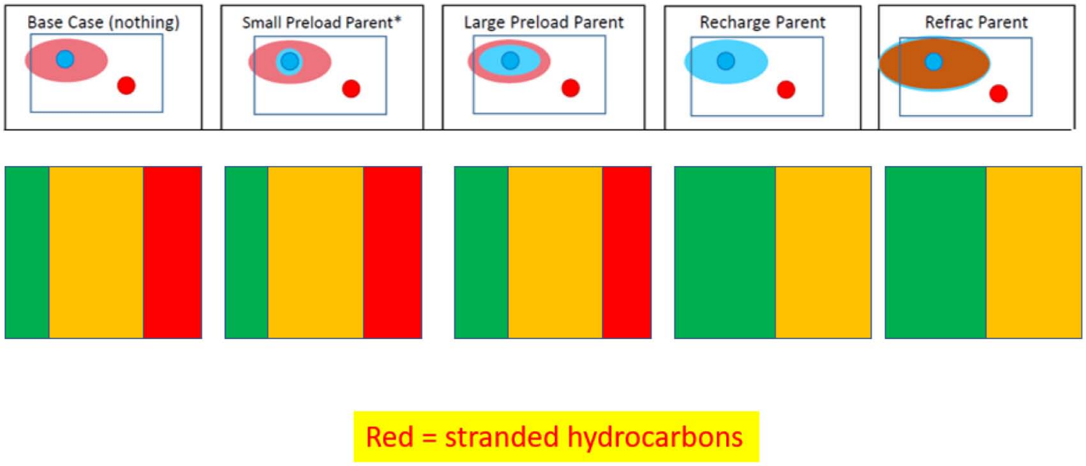
100% restoration of pore pressure

Parent Well: Elevate Stress & Pressure, Incremental Reserve Adds

Child Well: Optimal 1st Order Child Well

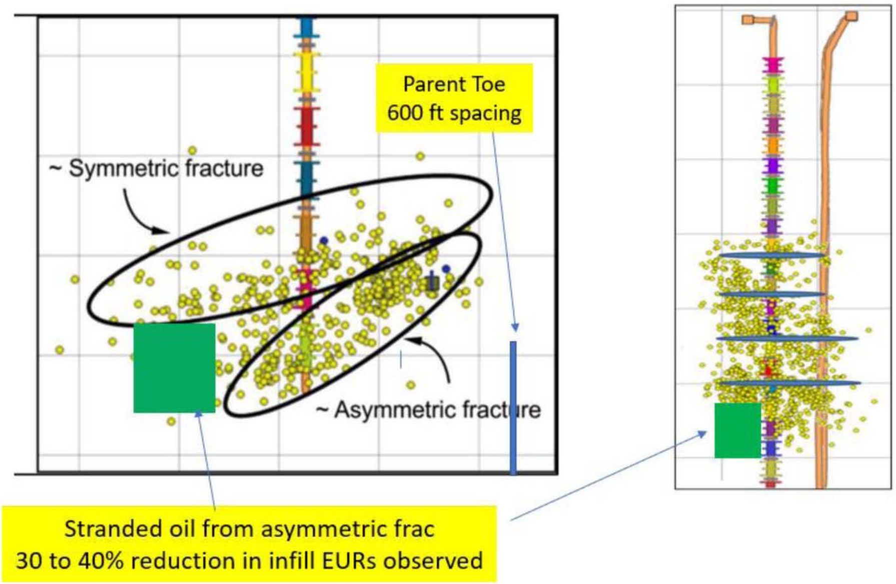
Increasing Cost and Planning Complexity

Figure 1—Depletion Mitigation Opportunities



Red = stranded hydrocarbons

Figure 2—Depletion Mitigation Results



Stranded oil from asymmetric frac
30 to 40% reduction in infill EURs observed

Figure 3—Infill Well Asymmetric Frac in Toe Stage with Depleted Primary Well Overlap

Historically, refrac operations in horizontal organic shale wells have had unpredictable production results, with the industry moving toward mechanical isolation following an often painful history that included single stage "pump and really pray" treatments with no diversion to "pump and pray" with chemical or ball sealer diversion. While results from mechanical isolation have been more consistent than these first two methods (Cadotte et al 2018), there is now a lot of discussion on the best mechanical isolation method to use. The two most common isolation techniques are cemented conventional casing and expandable liners. The main advantage of the cemented casing is lower up initial costs, with a $123,000 difference in cost before frac operations commence for a 5000 ft refrac liner. The main advantage of the expandable liner is a larger diameter that allows for 20% to 25% higher pump rates. With the combination of the Extreme Limited Entry (XLE) completion technique and expandable liners the higher treatment rates translate directly into longer stage lengths while still maintaining high cluster efficiency. The resulting lower stage count reduces the overall stimulation cost well below the incremental initial cost of the expandable liner, with a net savings of $446,000 per refrac over the cemented liner option for a 5000 ft lateral. The savings would be higher for longer laterals as the stage number difference will increase.

Introduction

The reservoir data supporting primary well refracs as a valid strategy is strong. The industry has been refining organic shale completion techniques to concentrate more frac energy into smaller rock volumes, with the goal being to maximize the near wellbore stimulated rock volume (SRV). Rate-transient analysis in the Permian Wolfcamp formation has shown a clear relationship between SRV and production results (Xiong 2017 Figure 4). Additional work done with history matched numerical simulations also in the Permian Wolfcamp suggests that recovery factors can be maximized in that formation in the 14% range with cluster spacing in the 10 ft range (Xiong 2017 Figure 5). This is supported by a horizontal pressure monitoring well in the Eagle Ford with a long-term producing offset with 50 ft cluster spacing having virgin pressure in over 85% of the rock volume 70 ft away from the producing lateral or 7.5 ft of stimulated rock. This is logical considering the slow travel time for fluids through a virtually impermeable matrix and the rock must be hydraulically fractured to produce. It takes a gas molecule 100 days to travel one meter in 100 nd matrix permeability rock so it is unrealistic to assume that unfractured rock will yield any significant volumes of gas or oil. The width of the SRV from tracers near wellbore (Leonard et al 2018 Figure 6) in the Permian Wolfcamp was wider than the observed drainage width from the pressure gauges in the Eagle Ford, however the 19 ft average cluster tracer width is still not adequate to drain the 50 ft cluster spacing there in the more brittle formation. A comparison between core and DFIT permeability for an organic shale well reinforces the assertion that unfractured matrix rock does not contribute to productivity (Barba 2015) (Figure 7). A test done in the Cline formation had less than 100 nd of "as received" GRI permeability, however the DFIT (Diagnostic Fracture Injection Test) over the same interval had 27,000 nd (0.027 md). In short, the closer the cluster spacing the higher the SRV when the matrix cannot produce without being hydraulically fractured.

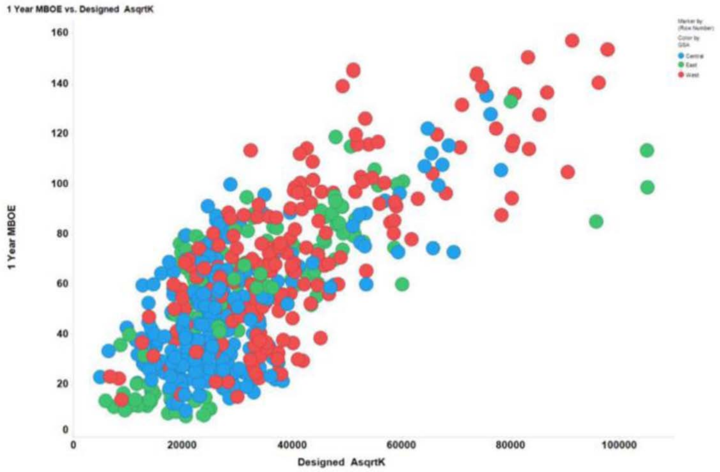


Figure 3—The Estimated $A\sqrt{k}$ Based upon Completion History vs One Year Cum Production

A root k from Rate Transient Analysis
A = SRV area

Figure 4—Permian Wolfcamp SRV From RTA vs Cum Production

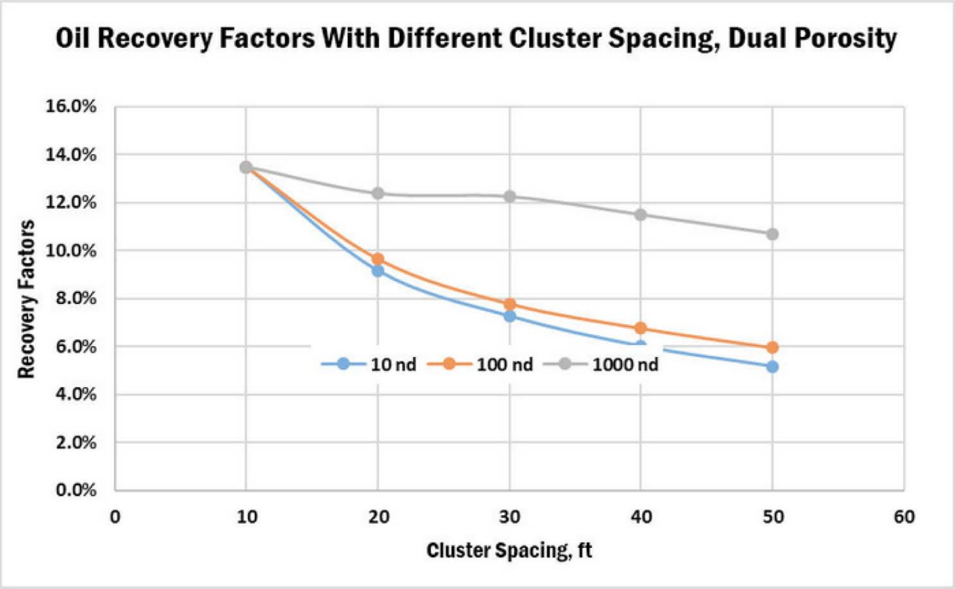


Fig. 10—Recovery efficiency based upon the dual-porosity model at the end of year 30.

Figure 5—Permian Wolfcamp Recovery Factor vs Cluster Spacing

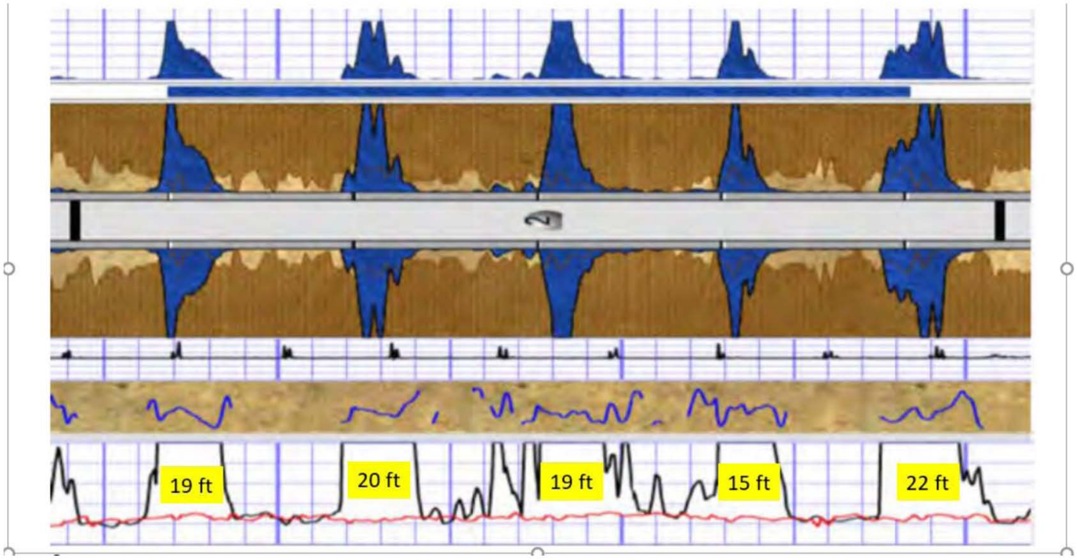


Figure 6—Midland Basin Wolfcamp RA Tracer Width at Wellbore

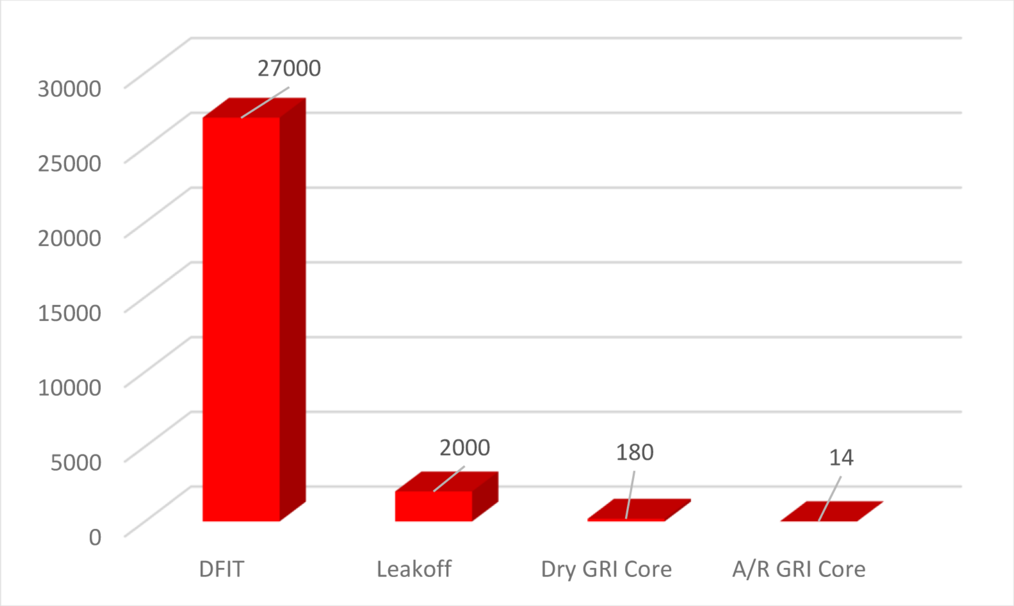


Figure 7—Organic Shale Permeability Comparison

A key element in the SRV maximization process is cluster efficiency or the number of clusters with radioactive tracer present compared to the total number of clusters. Recent work done by Weddle et al (2018) has shown that 85% cluster efficiencies can be achieved using the Extreme Limited Entry (XLE) process with a 1500 psi pressure drop across the perforations post erosion. With expandable tubulars, close (13.3 ft) cluster spacing (three per 40 ft casing joint), and uniform hole size perforations the number of frac stages required for a refrac operation can be substantially reduced with the larger diameter expandable liner over a cemented liner. For a 7500 ft lateral the number of refrac stages required for a 1500 psi pressure drop with the proposed perf and cluster configuration is 42 for the expandable liner (using 13.3 ft clusters in 173 ft stages) with a critical rate of 6 BPM per cluster at 80 BPM. If a 3.5-inch cemented liner is run the number of refrac stages required with the same perf and cluster configuration and a lower 60 BPM rate is 56 or 14 additional frac stages using the same cluster spacing. The subsequent cost savings can thus be significant while maximizing the recovery factor from the reservoir with the largest near wellbore stimulated reservoir volume and highest EUR possible. A secondary benefit of the closer cluster spacing is shorter frac heights and lengths with relatively uniform fluid distribution (Jaripatke et al 2018 Figure 8). This should reduce the occurrence of fracture driven interactions hits in offset wells. With the proposed close cluster spacing the primary well refracs should connect with and adequately recharge the existing depleted clusters and restrict asymmetric fracs in the infill wells. With the large disconnect between historic cluster spacings that are often 4 times or more the recommended cluster spacing there should be significant increases in the primary well production as well from contacting "new rock."

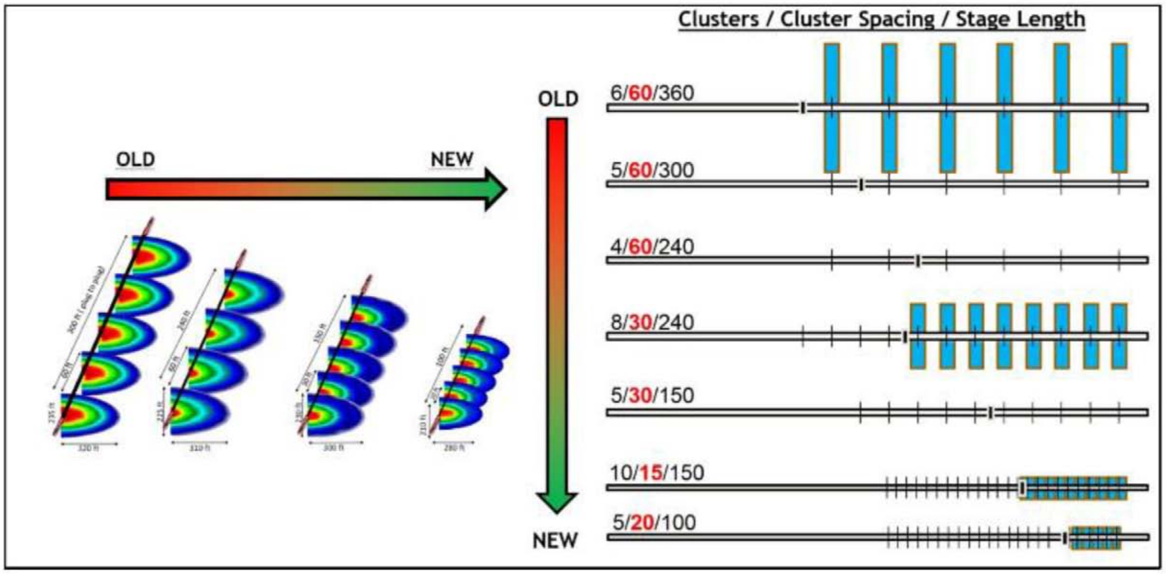


Figure 8—Frac Height and Length vs Cluster Spacing Trends

Well Spacing Issues

Without primary well refracs some organic shale operators are moving toward 6 wells/DSU (880 ft spacing) vs 8 dictated by reservoir diagnostics (660 ft spacing or a 330 ft wide rectangle). In SPE 187485 Xiong et all (2017) studied the Lower Spraberry Shale (LSS) on University Lands in Texas with rate transient analysis (RTA) to estimate the most likely drainage radius of each lateral. The RTA analysis indicated a 220 ft producing length. This 220 ft is 2/3 the distance that is geometrically available or 330 ft for an eight well pattern. At least one operator working in the same area as the LSS study has announced plans to reduce the number of wells per DSU from 8 to 6. Extensive recovery factor and EUR analysis of the study area indicates a typical well should produce 600,000 BO (liquids), and with a 1081 GOR the NPV10 of this well should be $11.15 million. With no parent refrac and a reduction from 8 wells down to 6 wells/pad this operator would lose $6.8MM NPV10 on the first child offset and $22.3MM NPV10 from loss of two producers or $29.2 MM total. These numbers far exceed any incremental production benefit from the parent well "new rock" refracturing process. Barba (2017) evaluated the refrac potential for the Midland and Delaware basin Wolfcamp and the average NPV10 for the economic cases was $3,167,865. This brings the total economic benefit to the DSU to $32,267,865. The direct economic benefit from the stranded hydrocarbons in the refracced primary well is only 10% of the total benefit (Figure 9). With the comfort factor among operators concerning preloads as a viable interference reduction strategy vs the recommended parent well refracs it is questionable whether the economics of the DSU are being considered by these operators vs the myopic focus on the economics of the parent well alone. With historic cluster spacings sometimes of 50 ft or more the 13.3 ft cluster spacing refracs should be economic in most cases as a stand alone entity provided economic reservoir volumes are present.

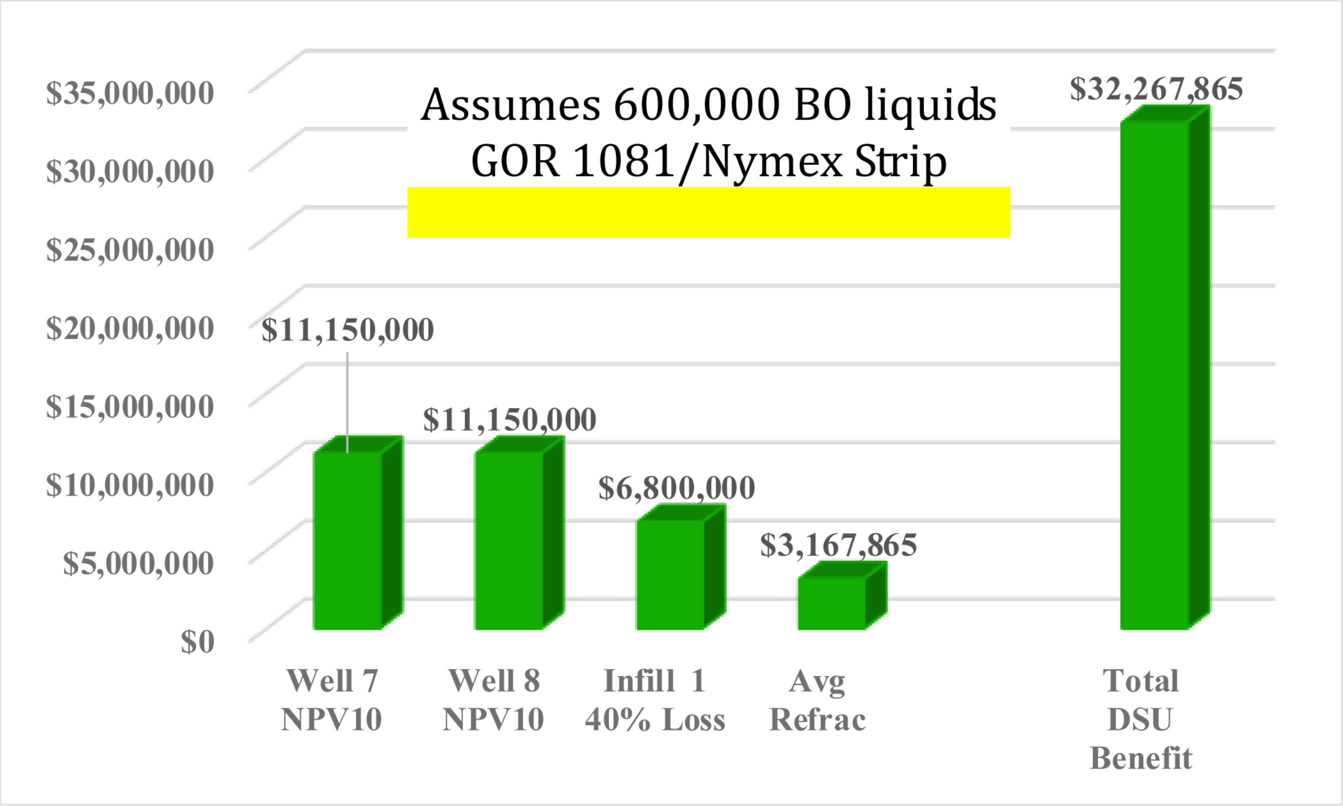


Figure 9—Refrac Economic Benefits-DSU Level

Limited Entry Process

Limited entry involves limiting the number of perforations in a completion interval to promote the development of perforation friction pressure during a stimulation treatment. The resulting "choking" effect creates excess pressure in the casing allowing for the simultaneous entry of fracturing fluid into multiple zones with varying in-situ stresses (Cramer 1987). The process was first discussed in the literature by Murphy and Juch (1960), followed by Lagrone and Rasmussen in 1962. Subsequent early work was done by Cramer (1987), Barba (1987), Crump and Conway (1991), Eberhard (1995), and El Rabaa (1999). The initial work by Lagrone and Rasmussen suggested a 400-psi pressure drop was appropriate, and this has been adjusted over time as field experience develops. Barba (1987) used the shear sonic based mechanical properties profile to determine the difference in closure stress among the zones to complete and added the 400 psi to that stress contrast in the delta pressure calculation. The wells where the process was implemented performed significantly better (2x cumulative production) than offset wells that were perforated with conventional phased perforations (typically 4 spf 90 degree phased with all permeable intervals perforated). The process has evolved over the years to its current state summarized in Weddle et al (2018) where 85% cluster efficiencies were consistently achieved with a minimum delta pressure of 1500 psi post erosion. Similar logic to the design criteria proposed by Barba (1987) was applied in that study, with the delta pressure target designed to overcome closure stress differences within a horizontal well frac stage, near wellbore friction, stress shadowing, and net pressure variations. Operators have typically used limited entry in the past for horizontal multistage treatments but with lower delta pressure thresholds. Wutherich and Walker (2012) proposed a 500 to 700 psi pressure drop criteria based on previous published studies. With the expansion of fiber optic sensor technology, a real time measurement of fluid flow through each perforation was available and the concept of extreme limited entry was advanced from these results (Somanchi, et al 2016). A side benefit of the fiber optic studies was the realization that horizontal shale wells could be completed using zero-degree phased perforations without seeing any discernable difference in productivity. Figure 10 is a graphical comparison of the expected drainage with XLE vs the expected drainage without XLE or other diversion.

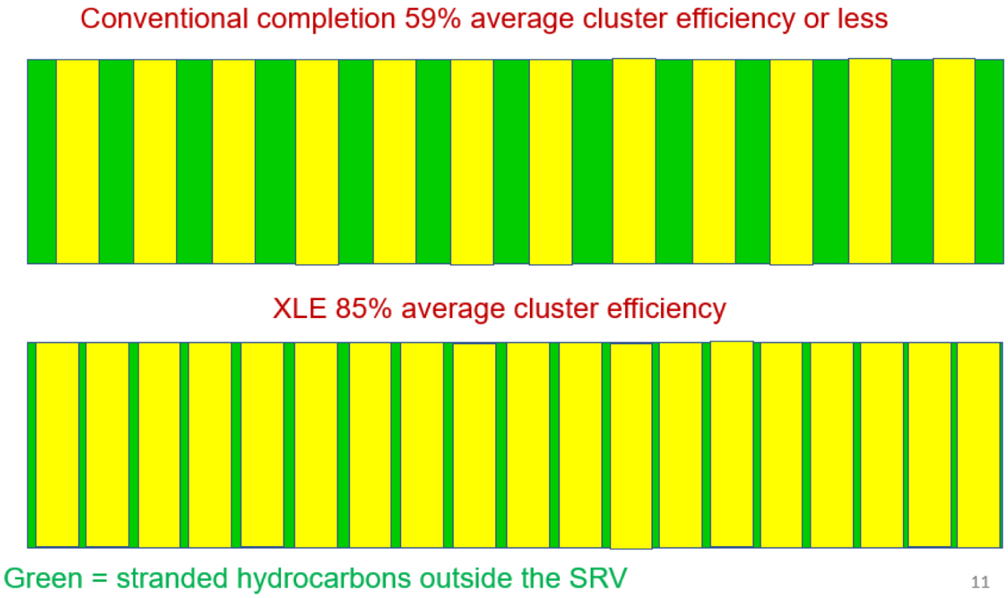


Figure 10—Cluster Efficiency vs Drainage

Proposed XLE Strategy

The trend in recent years in horizontal multistage fracturing operations has been larger volume treatments with shorter stages, with numerous operators using 15 to 30 ft cluster spacing in stages that are from 100 ft to 200 ft in length. The overall objective is to increase the stimulated reservoir volume which is directly tied to increases in EUR (Xiong 2017). Between the large "gaps" in SRV observed in the pressure monitoring well mentioned above and the 10 ft cluster spacing proposed from the Wolfcamp numerical simulation it suggests the clusters should be placed as close as possible to avoid the gaps. There is a practical limit to the cluster spacing driven by the gun movement during the pump down and perforating process where the perforating engineer can only fire the guns so fast. It is proposed that three clusters are perforated in each pipe joint (13.33 ft spacing) to improve the probability of eliminating significant gaps in the SRV. In some cases in higher modulus or more isotropic rock the spacing can be increased if the SRV can still be maximized. If the perforations per cluster are limited to one the cluster efficiency can be directly estimated from step down tests at the beginning or the end of a stage.

Lengthening the frac stages may appear to be counter to the industry trend toward shorter stages, however the primary reason the stage lengths have been decreasing is to increase the near wellbore stimulated reservoir volume without changing the perforation strategy. If the number of perforations is not limited cluster efficiency can be low if shorter stages are not used. A large number of the organic shale completions carried the vertical well "best practice" of phased perforating to the horizontal world with 6 SPF 60-degree phased perforations. Even as recent as 2014 major operators were still using 8 to 12 spf 60-degree phased perforations with 60 to 80 ft cluster spacing (Pandya et al 2014). With that large number of perforations per cluster the only means to obtain limited entry is to shorten the length of the stages to limit the total number of clusters. The XLE process with 13.3 ft cluster spacing and high cluster efficiency accomplishes the same objective without reducing the stage length. An additional benefit of the closer cluster spacing is to improve the probability of entering the existing fractured intervals along with the more productive "new rock." If the refrac has the additional responsibility of protecting the primary well from infill well fracture driven interactions this is an important issue. Wider cluster spacing opens up the possibility that the depleted areas of the SRV may not be contacted and recharged and there could be pressure "sinks" that result in asymmetric fracs in the infill well SRV. This is definitely an area that bears further study, as lengthening the cluster spacing while still maximizing SRV is a function of the stress anisotropy, rock modulus, and fluid type. In the Eagle Ford the same operator that conducted the pressure monitor well test tried spacing in the 7.5 ft range. Based on the results they are moving back toward the 15 ft range. One additional item that enters here is that the offset well was originally fracced with a borate so the 7.5 ft width of the fractured interval may not be the same if slickwater was used. Borates tend to create more planar fractures while thinner fluids tend to be more of the off-balance type with more complexity. Another operator in a high modulus reservoir (Mancos) tried bringing the clusters down to the 10 to 15 ft range but had excess stress shadowing between the perfs. They have subsequently moved the clusters farther apart to the 25 ft range.

Perforation Hole Size Issues

Another key component of the XLE process is the use of constant or uniform hole size charges (Cuthill et al 2017). If conventional phased charges are used the hole diameter on the bottom of the casing can be significantly increased due to the close proximity of the carrier (Figure 11). The corresponding hole diameter in the top of the casing is reduced in the process. Several vendors have uniform hole size charges available to use for XLE, with the current minimum size being the 0.25-inch version and up to 0.55 inch diameters are available with the 3 1/8 inch diameter perforating guns. For refrac operations the vendors need to test their systems through two strings of pipe, and this has been done only down to the 0.3-inch diameter at this time by one of the major vendors. The single hole 0.4-inch perforations should provide more than enough friction to meet the 1500 psi post erosion goal. If the 0.4 inch perforation results in a larger number of clusters than the critical rate allows the hole size should be increased to 0.45 or 0.5 inches to bring the two numbers closer. For example, if the critical rate analysis suggests 15 clusters max (90 BPM) and the 0.4 inch perforations allow you to frac 20 clusters there is no reason to buy the extra horsepower with the 0.4 inch hole. The 0.45 or 0.5 inch perforations should provide adequate diversion at the minimum horsepower possible in that specific case. With critical rates in the 6 BPM range larger holes will typically be recommended due to the rate limitations on the total number of clusters. With one hole per cluster the only option to bring the excess pressure drop into the 1500 psi post erosion range is larger hole size.

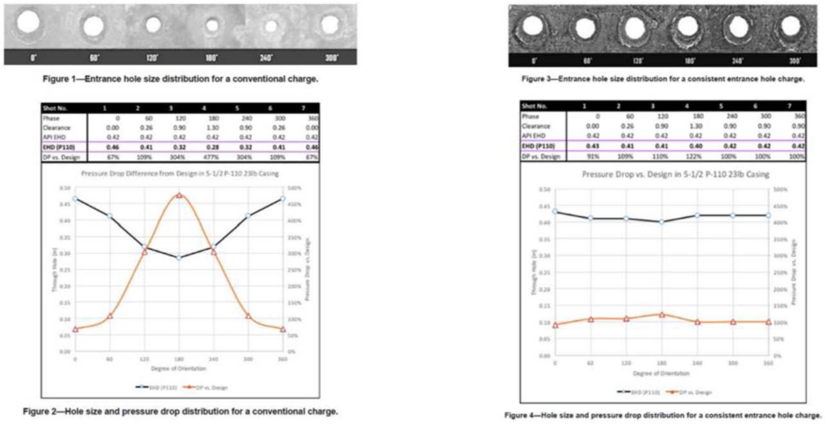


Figure 1—Entrance hole size distribution for a conventional charge.

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%

Figure 2—Hole size and pressure drop distribution for a conventional charge.

Figure 3—Entrance hole size distribution for a consistent entrance hole charge.

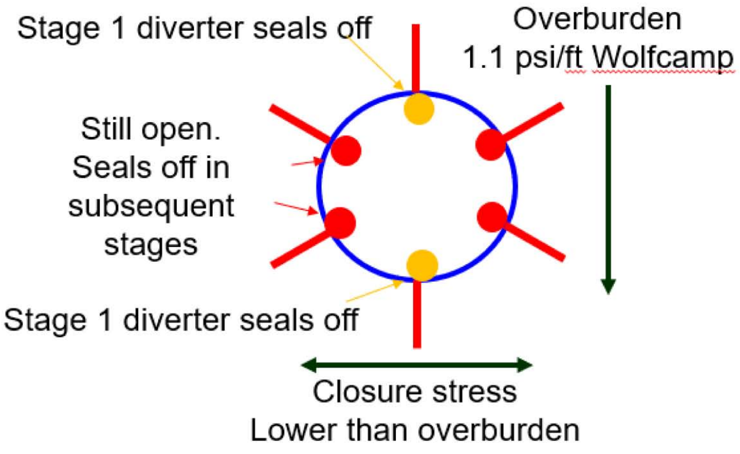
Shot No.	1	2	3	4	5	6	7
Phase	0	60	120	180	240	300	360
Clearance	0.00	0.26	0.90	1.30	0.90	0.90	0.90
API EHD	0.42	0.42	0.42	0.42	0.42	0.42	0.42
EHD (P110)	**0.43**	**0.41**	**0.41**	**0.40**	**0.42**	**0.42**	**0.42**
DP vs. Design	91%	109%	110%	122%	100%	100%	100%

Figure 4—Hole size and pressure drop distribution for a consistent entrance hole charge.

Figure 11—Conventional Perforation Hole Size vs Uniform Hole Size

XLE vs Intrastage Diversion

Weddle et al (2017) presented an earlier version of Liberty's cluster efficiency improvement program a year prior to their latest XLE paper. They improved the perforation cluster efficiency by dropping particulate diverter during each stage, and the results were similar to the XLE process (85% vs 59% for non-diverter non-XLE stages). While this may appear to be a viable option to emulate the results from the XLE process in the larger expandable liner it is not recommended. Reason one is the XLE process should result in a relatively uniform fluid distribution in all clusters which is an issue in the avoidance of frac hits. Diverter treatments force fluid from the lower stress clusters into the higher stress clusters, however the probability of runaway clusters increases significantly (extending the frac well past the target near wellbore SRV toward offset laterals). Second, if the clusters were not perforated 0 degree phased at the top of the casing and used phased perforations the stresses may not be homogeneous around the wellbore (Wutherich et al 2012) (Figure 12). Tracers often show proppant from more than one diverted stage in the same cluster which is most likely from the stress heterogeneity around the wellbore depicted in Figure 12. This suggests that the same clusters are being fracced more than once and this is counter to the goal of maximizing the SRV in the near wellbore. Third, it is an unnecessary operation and added expense if the same results can be obtained with XLE that also avoids the first two problems associated with diverter. As with most oilfield operations limiting the number of moving parts in a process reduces the complexity of the operation and with fewer moving parts typically fewer surprises occur.



Explains why different stage tracers are often seen in the same perf clusters
Severe overflushing occurs after pressure increase and diversion of subsequent stage

Figure 12—Diverter Mechanics with 6 SPF 60 Degree Perforations

XLE vs Engineered Completions

A lot of work has been done to increase perforation efficiency by obtaining log and/or drilling data in the lateral that enables the perforation of "like rock." The concept is that placing perforations in rock with similar closure stress and avoiding higher stress rock in the same frac stage will result in improved results (Wigger et al 2014). In this study done in the Eagle Ford Shale production was improved over offset wells that used geometric cluster spacing. The improved results are credited to an increase in perforation efficiency from 64% to 82% rather than from accessing more productive rock. A drawback to this procedure is the potential creation of large "gaps" in the SRV if the clusters are more than 10 ft apart (based on Permian Wolfcamp simulations). The XLE process accomplishes both objectives of increasing perforation efficiency and minimization of gaps in the SRV vs only an increase in perforation efficiency with the engineered completion and lower SRVs. If an engineered completion is desired the spacing should be carefully evaluated to make sure SRV is still being maximized.

Stage Length Optimization Process

The limited entry process is characterized by the following equation:

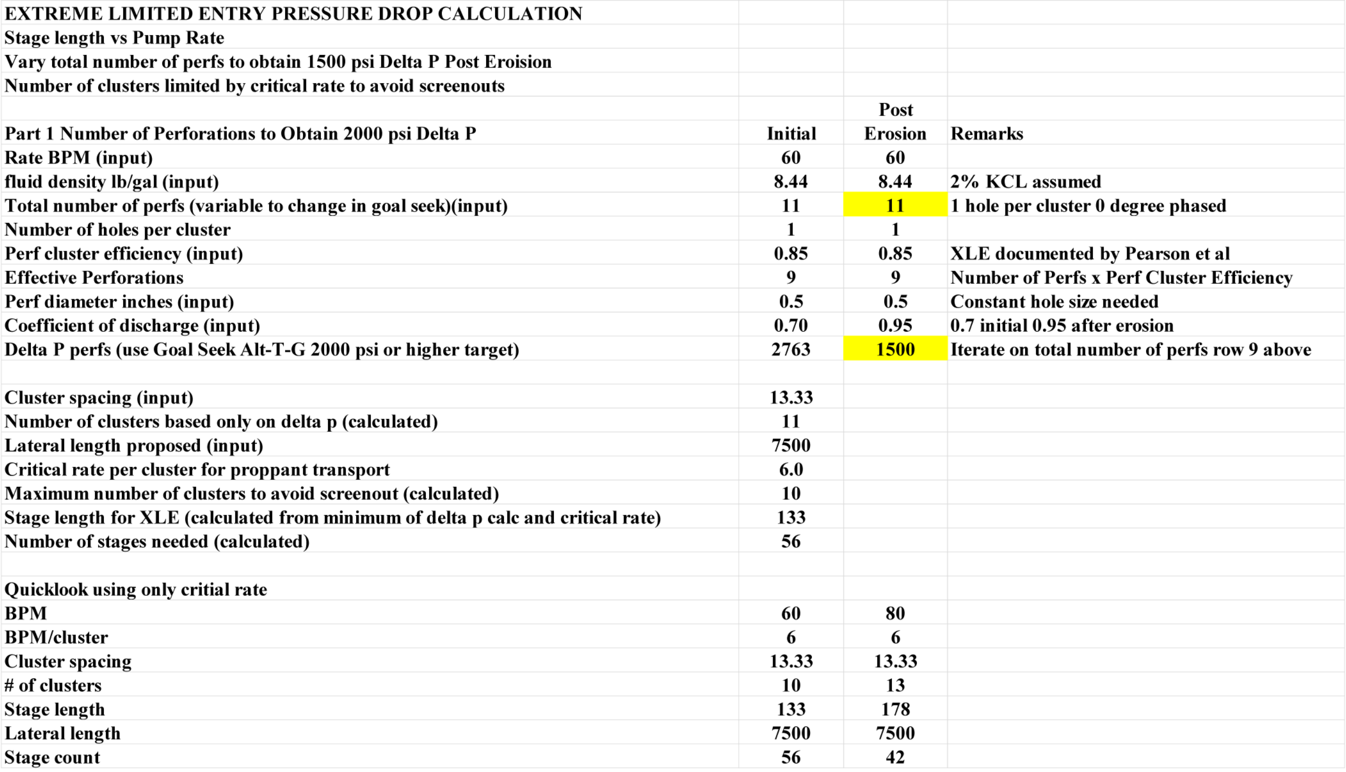
$$Ppf = 0.2369 * Q2*(\rho/N2*D4*Cd2) \qquad (1)$$

Where:

Ppf = Perforation friction pressure drop (1500 psi post erosion recommended)
Q = pump rate BPM
ρ = fluid density lb/gal
N = number of perforations open (total number*perforation efficiency)
D = perforation diameter inches
Cd = Discharge coefficient (0.70 initial and 0.95 after proppant erosion)

A simple Excel spreadsheet was constructed to estimate the total number of perforations required to generate a 1500 psi pressure drop (Figure 13). In the example presented the following assumptions were made:

85 BPM pump rate
8.44 lb/gal fluid density
15 total holes
1 perforation per cluster
85% perforation efficiency
13 effective perforations (from product of the total number of perfs and perforation efficiency)
0.5-inch constant diameter hole size
0.75 initial coefficient of discharge
0.95 final coefficient of discharge



EXTREME LIMITED ENTRY PRESSURE DROP CALCULATION			
Stage length vs Pump Rate			
Vary total number of perfs to obtain 1500 psi Delta P Post Eroision			
Number of clusters limited by critical rate to avoid screenouts			
Part 1 Number of Perforations to Obtain 2000 psi Delta P	**Initial**	**Post Erosion**	**Remarks**
Rate BPM (input)	**60**	**60**	
fluid density lb/gal (input)	**8.44**	**8.44**	**2% KCL assumed**
Total number of perfs (variable to change in goal seek)(input)	**11**	**11**	**1 hole per cluster 0 degree phased**
Number of holes per cluster	**1**	**1**	
Perf cluster efficiency (input)	**0.85**	**0.85**	**XLE documented by Pearson et al**
Effective Perforations	**9**	**9**	**Number of Perfs x Perf Cluster Efficiency**
Perf diameter inches (input)	**0.5**	**0.5**	**Constant hole size needed**
Coefficient of discharge (input)	**0.70**	**0.95**	**0.7 initial 0.95 after erosion**
Delta P perfs (use Goal Seek Alt-T-G 2000 psi or higher target)	**2763**	**1500**	**Iterate on total number of perfs row 9 above**
Cluster spacing (input)	**13.33**		
Number of clusters based only on delta p (calculated)	**11**		
Lateral length proposed (input)	**7500**		
Critical rate per cluster for proppant transport	**6.0**		
Maximum number of clusters to avoid screenout (calculated)	**10**		
Stage length for XLE (calculated from minimum of delta p calc and critical rate)	**133**		
Number of stages needed (calculated)	**56**		
Quicklook using only critial rate			
BPM	**60**	**80**	
BPM/cluster	**6**	**6**	
Cluster spacing	**13.33**	**13.33**	
# of clusters	**10**	**13**	
Stage length	**133**	**178**	
Lateral length	**7500**	**7500**	
Stage count	**56**	**42**	

Figure 13—XLE Optimization Spreadsheet

The calculated pressure drop with the above inputs is the desired 1500 psi post erosion target. The Excel function that is useful is the "Goal Seek" utility (Alt-T-G shortcut). The target is input at 1500 psi and the iteration needs to be done by varying the total number of perfs in the goal seek routine. With the cluster spacing fixed at 13.33 ft the total number of clusters (15) can be calculated from the total number of perfs and the stage length can be calculated as well. When the critical rate of 6 BPM per cluster is applied to the 85 BPM rate the number of clusters is reduced to 14. The effect of changing any of the variables can be calculated fairly quickly to compare to other wellbore conditions. A comparison of rate vs stage count is shown as Figure 14 for the 5000 ft case.

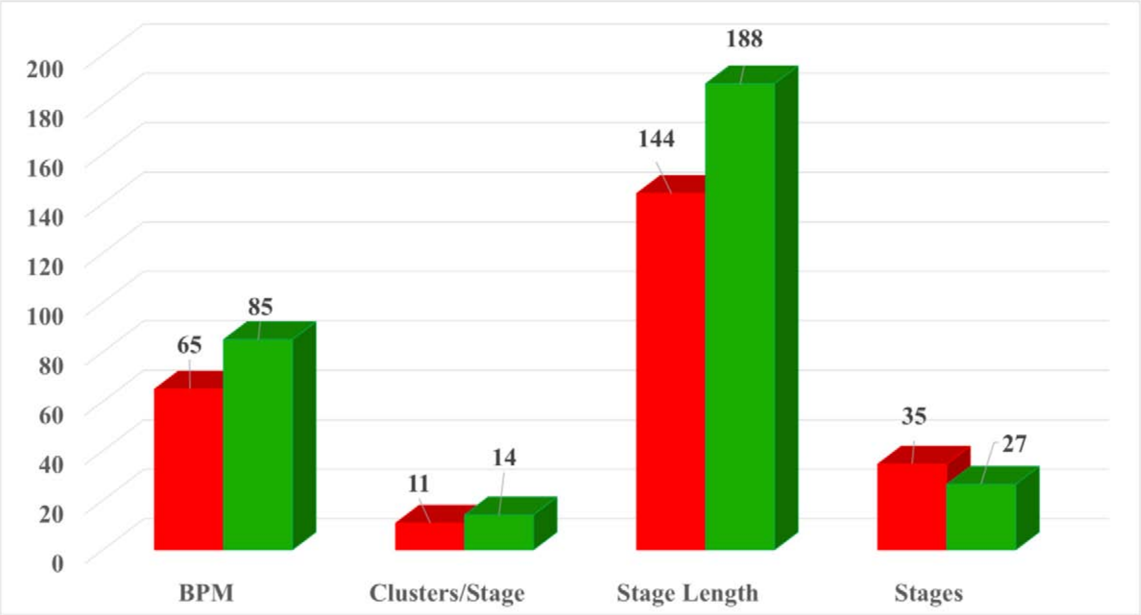


Figure 14—Stage Length vs Rate for 1500 psi Delta P

For the post erosion discharge coefficient Weddle, et al (2018) recommended changing the discharge coefficient from the pre-erosion value of 0.65 to 0.9 in equation (1). Cramer et al (2019) presented an integrated study using fiber optic acoustic data and post frac downhole video pictures of the perforations and they proposed an initial discharge coefficient of 0.75 and a post-erosion coefficient of 0.9. Willingham et al (1993) evaluated 4 lb/gal and 8 lb/gal of proppant concentration with the 4 lb/gal run increasing the discharge coefficient from 0.65 to 0.7. The 8 lb/gal test saw an increase to 0.9 value which was more in line with the Weddle et a (2018) numbers.

Critical Pump Rate Per Cluster Issues

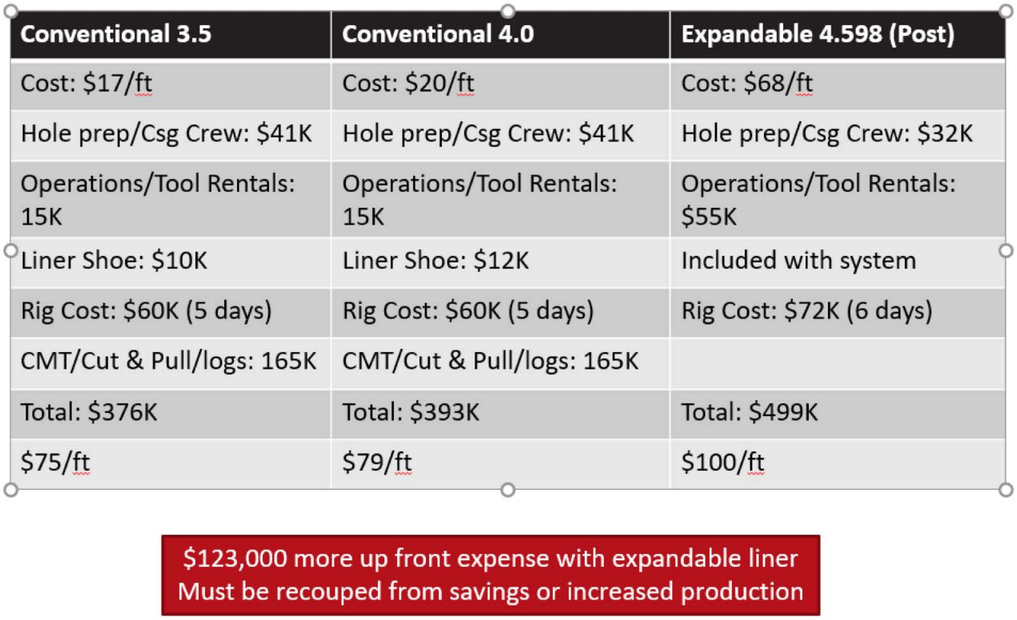
Shah and Lord (1990) discussed the critical rate per cluster to avoid screenouts, they suggested a 6.4 BPM critical rate. While there was some limited data for ungelled fluids the primary focus was on the currently popular fluids and proppants at the time and not slick water with 100 mesh and 40/70, though. Edward Wasp (1977) was a pioneer in critical rate work with slick water and 40/70 sized particles. At the time the Bechtel project engineer did not realize that slurry transport for coal mines in Utah would be relevant over 40 years later! The work by Wasp discussed equations developed by Durand (1952) and several others, the Durand equation assumes water and 40/70 at the max concentration (highest Froude number). The results from Durand were similar to the other methods Wasp discussed and we can thus focus on that model. For the most commonly use expandable liner (4.11-inch ID) the Durand equation suggests a critical rate of 4.14 BPM. Subsequent work by Ngameni et al (2017) presented data for 100 mesh and 40/70 in fresh water, where the critical rate for the largest diameter refrac liner (4.115-inch ID) configuration was just under 3 BPM (interpolating the numbers from Wasp, et al 1977). Biot and Medlin (1985) presented work that indicated the critical suspension rate for 40/70 proppant in 1 cp fluid was 3.23 BPM for the 4.115-inch ID liner. Their observations were that the static suspension rate was 10x the settling rate, with the other dynamic settling scenarios (rolling and saltation) having lower settling rates. Recent work done by McClure (2018) presented by Weddle (2019) suggests 6 BPM for the critical rate for Liberty's Bakken operations. More work is needed to narrow the range of uncertainty here, as the number of clusters for a 60 BPM refrac can be increased from 10 to 15 with a change from a 6 BPM critical rate to 4BPM. With 13.3 ft cluster spacing that would allow the stage length to be increased by 66 ft and the resulting stage count reduced from 56 stages to 38 stages. If a 90 BPM rate can be established the maximum number of clusters is 15 to still obtain limited entry without dropping below the critical rate (assuming the 6 BPM per cluster holds up to scrutiny). With 13.3 ft cluster spacing this places a practical limit on the stage length of 200 ft assuming the 90 BPM rate. It is recommended to use the more conservative 6 bpm value for designs until more field data is available to validate the theory derived lower critical rates. The literature suggests that the rate could be lower, though, and this specific issue has the potential to significantly reduce stage counts if lower rates can be used. On the other end of the critical rate range Cramer (2019) suggested that the frac geometry at each cluster should be considered in addition to the minimum rate to avoid screenouts. The work they have done suggests that 8 BPM may be more appropriate in certain situations. Additional work is underway to try and get this value refined as the savings to the industry when applied across the board can be significant with lower numbers provided the frac geometry is not adversely affected.

Validation of Results

In several studies the limited entry process was supplemented with fiber optic sensor arrays that measured the cluster efficiency in real time. When fiber optic sensors are not available a commonly used technique is the step-down test (Pandya, et al 2014). To accomplish the test the pumps are all brought on line, a stabilized frac rate is established, then the pumps are pulled off line one at a time with the rate held at each step until the pressure is stable. These can be done either at the beginning or the end of a stage, with the advantage of getting the test at the beginning being a higher confidence factor in perforation diameter pre-erosion. Another technique for determining cluster efficiency is radioactive tracers where the cluster efficiency is the number of clusters with tracer divided by the total number of perforations. While several studies have suggested XLE can achieve 85% cluster efficiency it would be prudent to try and validate this in the local area of operations if possible.

Economic Comparison Expandable Liners vs Cemented

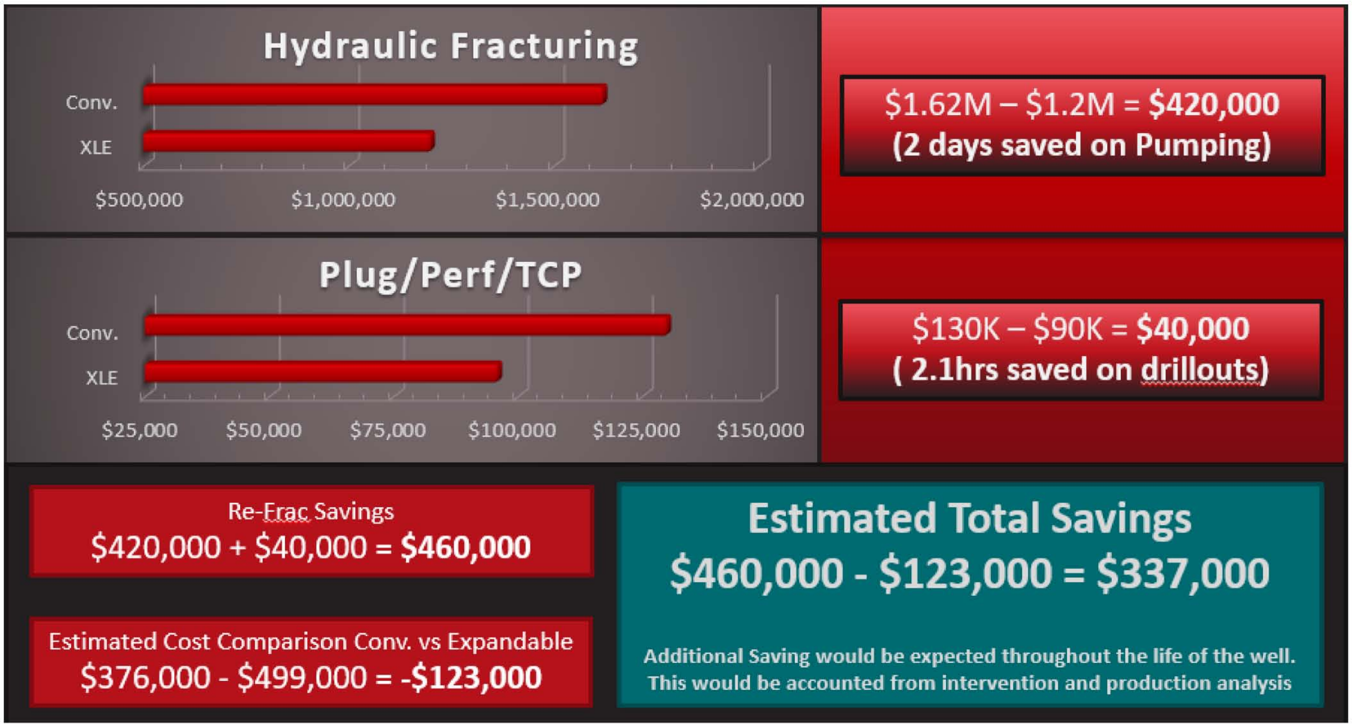
The main advantage of the cemented casing is lower up initial costs, with a $123,000 difference in cost before frac operations commence. The main advantage of the expandable liner is a larger diameter that allows for 20% to 25% higher pump rates. With the combination of the Extreme Limited Entry (XLE) completion technique and expandable liners the higher treatment rates translate directly into longer stage lengths while still maintaining high cluster efficiencies. The resulting lower stage count reduces the overall stimulation cost well below the incremental initial cost of the expandable liner, with a net savings of $446,000 per refrac over the cemented liner option for a 5000 ft lateral. The savings would be higher for longer laterals as the stage number difference will increase. Figures (15) and (16) show the details of the economic comparison.



Conventional 3.5	Conventional 4.0	Expandable 4.598 (Post)
Cost: $17/ft	Cost: $20/ft	Cost: $68/ft
Hole prep/Csg Crew: $41K	Hole prep/Csg Crew: $41K	Hole prep/Csg Crew: $32K
Operations/Tool Rentals: 15K	Operations/Tool Rentals: 15K	Operations/Tool Rentals: $55K
Liner Shoe: $10K	Liner Shoe: $12K	Included with system
Rig Cost: $60K (5 days)	Rig Cost: $60K (5 days)	Rig Cost: $72K (6 days)
CMT/Cut & Pull/logs: 165K	CMT/Cut & Pull/logs: 165K	
Total: $376K	Total: $393K	Total: $499K
$75/ft	$79/ft	$100/ft

$123,000 more up front expense with expandable liner
Must be recouped from savings or increased production

Figure 15—Cost Comparison Conventional Cemented Liner vs Expandable



$1.62M – $1.2M = **$420,000**
(2 days saved on Pumping)

$130K – $90K = **$40,000**
(2.1hrs saved on drillouts)

Re-Frac Savings
$420,000 + $40,000 = **$460,000**

Estimated Cost Comparison Conv. vs Expandable
$376,000 - $499,000 = **-$123,000**

Estimated Total Savings
$460,000 - $123,000 = $337,000

Additional Saving would be expected throughout the life of the well.
This would be accounted from intervention and production analysis

Figure 16—Savings from Expandable (Increased ID Conventional 3.5" vs Expandable 4.25"

Conclusions

The XLE process provides a means to maximize perforation cluster efficiency and minimize the number of frac stages needed to maximize the near wellbore SRV and corresponding higher EURs. It provides a mechanism to stimulate short spaced clusters (13.3 ft cluster spacing proposed) with high cluster efficiencies (85% expected). If the number of perforations per cluster are limited (one is proposed) and the hole size is uniform stage lengths can be increased without decreasing the overall stimulated rock volume. If the critical rate is 6 BPM at 90 BPM the XLE process allows for the stimulation of a 7500 ft lateral with 38 stages compared to 47 stages required if the rate is limited to 70 BPM. The decreased stage count results in significantly lower pumping, rig time, perforation, supervision, and plug expenses. In a comparison of the two main mechanical isolation methods (cemented liner vs expandable tubulars) the savings from the increased pump rate with the expandables more than offsets the increased cost of the larger diameter tubulars. Finally, with the proposed close cluster spacing primary well refrac clusters should be close enough to the depleted cluster areas to recharge them and reduce the probability of an asymmetric infill well fracture driven interaction. Studies have shown that asymmetric infill well fracs can have up to a 40% reduction in EUR from the large volume of rock that is left unstimulated. This damage has been observed consistently when the primary well is not refracced, attempts to reduce the damage with fluid preloads have only been effective in minimizing primary well damage but not the infill well frac asymmetry. There is most likely a strong correlation between the widespread use of preloads for parent protection and the move toward increased well spacing even though the commonly used 8 wells per DSU should not result in significant production interference. If the number of slots in a DSU are reduced the economic effect of the loss of PUDs can be significant. For a DSU with 600,000 BO wells the total loss per DSU from the infill well asymmetry damage and the loss of up to two PUDs can be in the $29 million range. These numbers far exceed any incremental production benefit from the primary well "new rock" refracturing process, with the average NPV10 from the stranded hydrocarbons in the refracced primary well 10% of the total economic benefit to the DSU. With the comfort factor among operators concerning preloads as a viable interference reduction strategy vs the recommended primary well refracs it is questionable whether the overall economics of the DSU are being considered by these operators vs the myopic focus on the primary well alone.

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