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An Evaluation of Engineered Completions Based On Mechanical Specific Energy

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Abstract

The concept of using Mechanical Specific Energy (MSE) to drive engineered completion designs was first introduced at the SPE ATCE in September 2015. Since its' introduction this approach has been deployed by more than 50 operators on over 300 horizontal laterals drilled in the North American shale basins. The scope of work presented in this paper is a collection of case studies that demonstrate the effectiveness of this MSE-based technique as a tool for engineered completion designs.

The evaluation of this technology is done through 6 case studies using 3 distinct approaches. The first set of case studies benchmarks MSE-based engineered completions to those produced by more traditional reservoir evaluation tools, such as full-waveform sonic logs and micro-seismic monitoring. This is important because many practitioners consider these high-technology measurements to be "ground truth" and require an understanding of the relationship between drilling-based answers and wireline or LWD-based answers. The second approach focuses on the analysis of well pairs that are drilled and completed in a similar fashion and would typically be expected to produce at comparable rates. These well pairs have been selected because one well is significantly out-producing its neighboring well(s) and this production variance can't be readily explained. This analysis demonstrates that an MSE-based analysis can accurately predict differences in well productivity, thus proving that variations in productivity can be directly attributed to lateral variability in reservoir properties evaluated using an MSE-based analysis. Finally, the third case study approach demonstrates the impact MSE-based completions can have on actual well productivity. Our test case wells are completed using engineered designs based on MSE and the resulting production profiles are compared to a significant volume of wells in close proximity that are completed using standard geometric designs.

These 6 case studies demonstrate that engineered designs based on common drilling data are consistent, accurate and reliable. They deliver all of the value and improved production of traditional log data-based engineered completion techniques in a more convenient and cost effective manner. This combination of low cost and high dependability makes this engineered completion technology ideally suited for an every well event in the North American shale business.

Introduction

The introduction of new technology to the oilfield is generally met with a healthy dose of skepticism. Before oil and gas operators deploy a new approach it is important that they have a complete understanding of the strengths and the limitations of the proposed new approach. This is particularly true in this case since we are asking completion engineers to adopt an approach that is based on drilling data, something that they are generally unfamiliar with. Drilling data was not originally intended to be used for reservoir characterization and thus is far from a "fit-for-purpose" solution. Despite the fact that drilling geomechanics and completions geomechanics are closely related it is still a stretch for most engineers to accept this approach without compelling evidence.

The following case studies are intended to help the industry get comfortable with the application of MSE-based analysis for the design of engineered completions. The 6 case studies presented are sub-divided into 3 categories: Ground Truth, Ranking Offset Wells and Production Validation.

Ground Truth Case Studies

Case Study 1

The first test any new technology must pass is how well it compares to incumbent technologies that are already accepted as "ground truth." In the case of engineered completions the technology that is universally accepted is the full-waveform sonic logging tool. The vast majority of the case studies that been published on engineered completions have sonic data as the input into the workflow. The sonic geomechanics workflow is mature and based on sound scientific principles that are well accepted by the industry. Naturally, many operators who have been introduced to MSE-based engineered completions want to know how well MSE answer products match the results from the sonic workflow.

On our subject well, a SonicScanner tool was run and subsequently analyzed using the sonic geomechanics workflow. Two of the answers products are Unconfined Compressive Strength (UCS) and Brittleness Index (BI) shown in tracks 3 and 4 (Fig 1). Track 2 shows the MSE curve color-coded as per the Hardness Index shown in Figure 2. At a macro-level there is an excellent correlation between these three parameters, along with gamma ray (GR) in track 1. The detailed stage-level analysis that follows reveals that MSE is a highly reliable input to the engineered completion workflow.

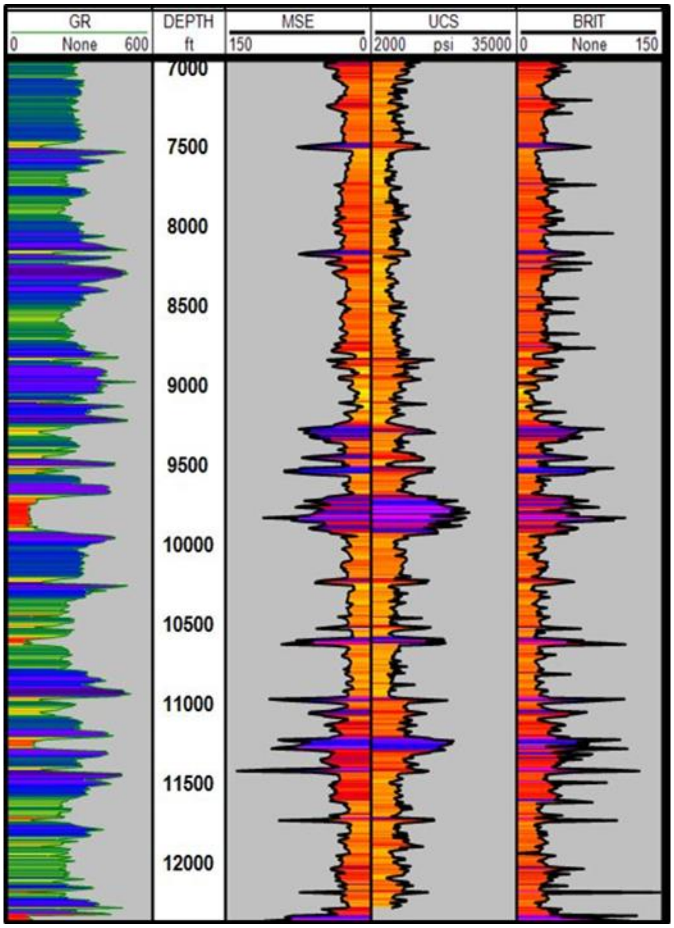
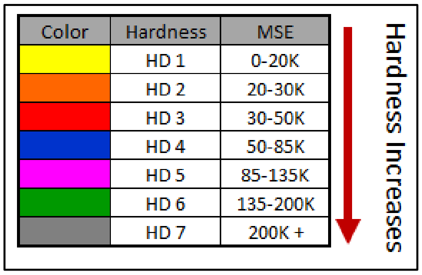


Figure 1: Comparison of MSE to Sonic UCS and BI



Color	Hardness	MSE
🟨	HD 1	0-20K
🟧	HD 2	20-30K
🟥	HD 3	30-50K
🟦	HD 4	50-85K
🟪	HD 5	85-135K
🟩	HD 6	135-200K
⬜	HD 7	200K +

Figure 2: MSE Hardness Index

Stage Level Analysis

Stage X: The sonic-based results indicate that intervals B and D are in a common facies with high UCS values and a high BI. The GR reads lower in both of these intervals and the MSE values agree that this facies is much tougher to drill (Facies HD4 and HD5).

Intervals C and E are in a common facies according to the Sonic UCS and BI, in alignment with the GR. The MSE concurs as both intervals are in the Red facies (HD3). Interval A is shown to be the easiest to drill, Orange Facies (HD2), and this is corroborated by the UCS and BI results.

Stage Y: In this stage the GR clearly identifies two intervals (B and D) to be much cleaner than the rest of this stage. The MSE agrees, showing them to be much more difficult to drill (HD4/HD5 Facies). In interval B, both the UCS and BI are in excellent agreement. In interval D, the Sonic BI picks up the facies change while the UCS does not. This is a rarity and in this case it is the UCS that disagrees with the other three measurements.

Intervals A, C and E all have higher GR readings that suggest this is a common facies. The MSE and BI are in perfect agreement, with interval C looking slightly tougher than the other two but overall very similar. The UCS value is also quite consistent across all three sections, with interval E having a slightly lower UCS value than the other two. In general the match between MSE, UCS and BI is very good in this stage.

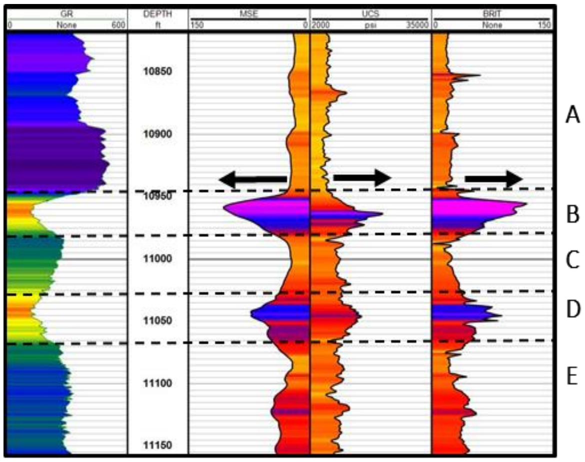


Figure 3: Comparison of MSE and Sonic, Stage X

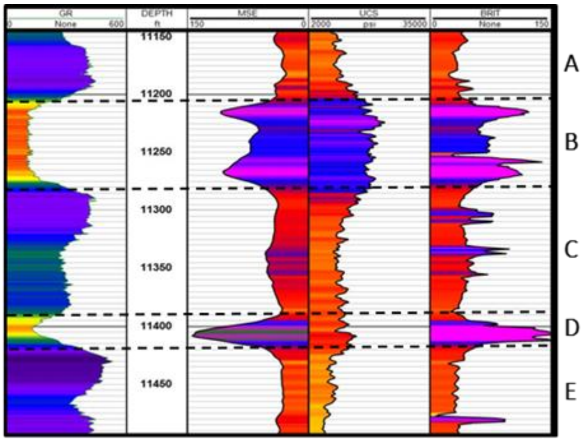


Figure 4: Comparison of MSE and Sonic, Stage Y

Stage Z: Intervals A, C, and E, all have GR values that are lower than the shaliest sections of stages A and B. This suggests these intervals would be tougher, more brittle rock than the shales in the other two stages. However, the UCS, MSE, and BI all agree that this facies is weaker (Facies HD2).

This demonstrates that while there is often a good correlation between MSE/UCS and GR, this relationship isn't always perfectly linear.

As with the other two stages, the GR, UCS, MSE and BI all agree that intervals B and D are in the same facies.

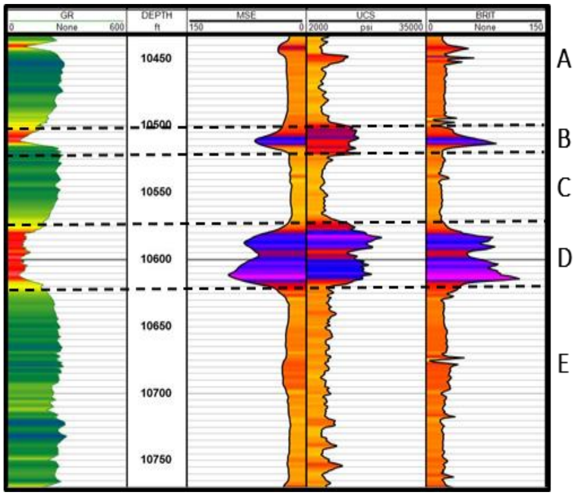


Figure 5: Comparison of MSE and Sonic, Stage Z

Case Study 2

Another important consideration when evaluating the utility of MSE is understanding its relationship to the operational aspects of hydraulic fracturing. In Case Study 2, the lateral we chose is a relatively simple example from the Wolfcamp formation in Reeves County, TX. The logplot (Fig. 6) demonstrates an obvious correlation between the GR and MSE. In the interval between 13,300 ft. – 15,700 ft., the GR reads approx. 80 API higher than the rest of the lateral and the MSE shows this interval to be much easier to drill (HD3 Red Facies). This is a facies change that we observe often in this basin.

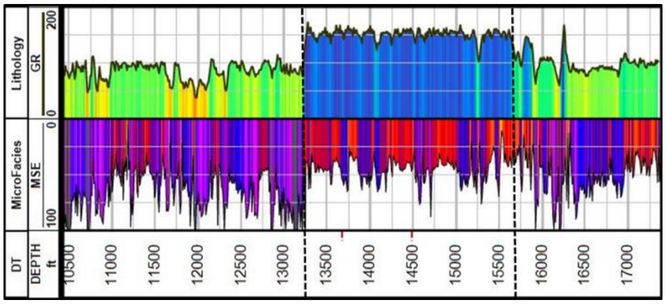


Figure 6: MSE/GR log, Wolfcamp, Reeves County, TX

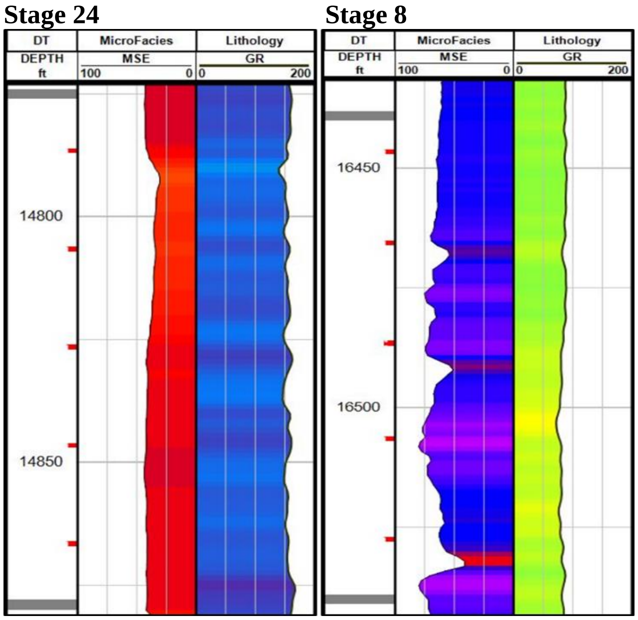


Figure 7: Homogeneous intervals from two different facies

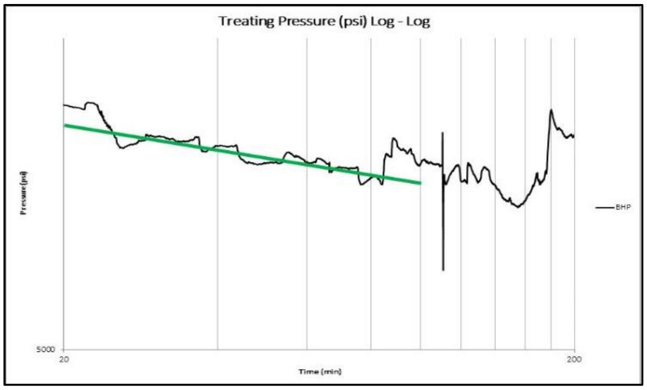


Figure 8: Treating pressure profile in Red facies (Stage 24)

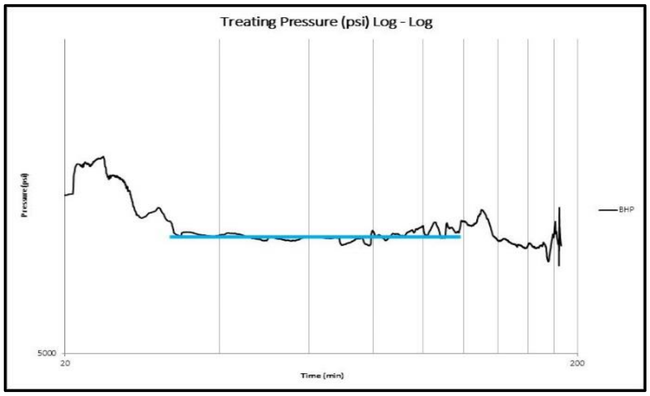


Figure 9: Treating pressure profile in Blue facies (Stage 8)

In Figure 7 we have zoomed in to look at two individual stages that are representative of the two predominate facies in this lateral. Stage 24 is of particular interest because it is placed in a very homogeneous section of the Red Facies. All six perf clusters are placed in rock with identical properties which is an ideal case when evaluating the pressure response observed during the hydraulic fracturing operation. Stage 8 is also very homogeneous in nature but it is placed in the tougher to drill Blue facies. Once again, all six clusters are predicted to have identical geomechanical properties and we expect them to break down simultaneously during the fracturing process. While we do expect all clusters to treat simultaneously in both stages this does not mean the two stages will behave the same during the fracture treatment.

The slopes in the treating pressure plots in Figures 8 and 9 demonstrate the difference in the operational performance between the Red facies and the Blue facies. Interpretation of these slopes has been documented by Nolte (ref 5).

In the Red facies (Fig 8) we see a negative slope (green line), indicating a fracture that is propagating unconfined through barriers. This behavior is typical of a planar fracture that is generating one simple fracture geometry.

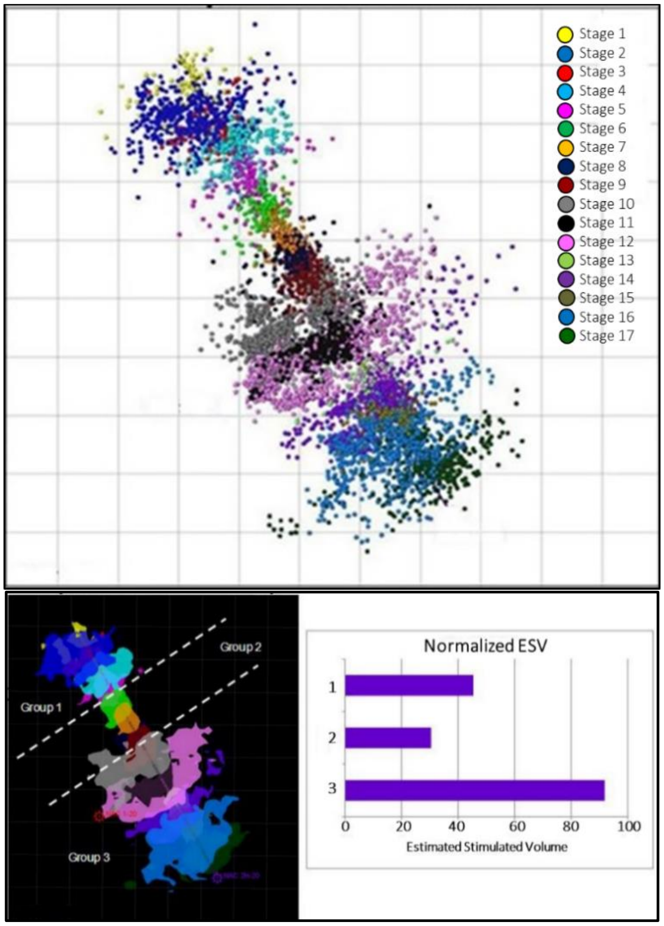


Figure 10: Microseismic signatures for a 17-stage completion

The zero slope shown in the Blue facies (Fig 9) is referred to as Type II fracturing behavior by Nolte. It indicates a situation where we are experiencing extended fluid leak-off while we are energizing an existing fracture network, continuously opening up existing natural fissures. The difference in treating pressure response between these two facies is analogous to the changes in micro-seismicity often observed between stages by other authors. The example in Figure 10 (ref. 3) is an example of how micro-seismic signatures vary from stage to stage within a wellbore. In this case study the stages were segregated into 3 Groups. The stages closest to the toe of the lateral (Group 1) behave much like our Blue facies. The stages closest to the heel of the lateral (Group 3) propagate planar fractures, much like our Red facies.

Ranking Offset Wells

One of the major advantages of the MSE technique is that the input data is available on every well, even wells that were drilled years ago. This allows us to evaluate historical wells to understand the relationship between our lateral heterogeneity predictions and actual well productivity. To make this approach credible we choose sets of wells where conditions correlate closely – the geology, the drilling program and the completion procedures need to be very similar on the subject wells and they should be as close together geographically as possible. When all of these conditions are satisfied we can safely assume that the primary factor driving variability in productivity between these “sister” wells is lateral heterogeneity.

Case Study 3

The two subject wells for this evaluation are dry gas Marcellus wells. These wells were drilled within 2.5 miles of each other and completed in an almost identical manner (see Table 1). Given the proximity of these 2 wells and the similarity in treatment designs the operator expected similar production results.

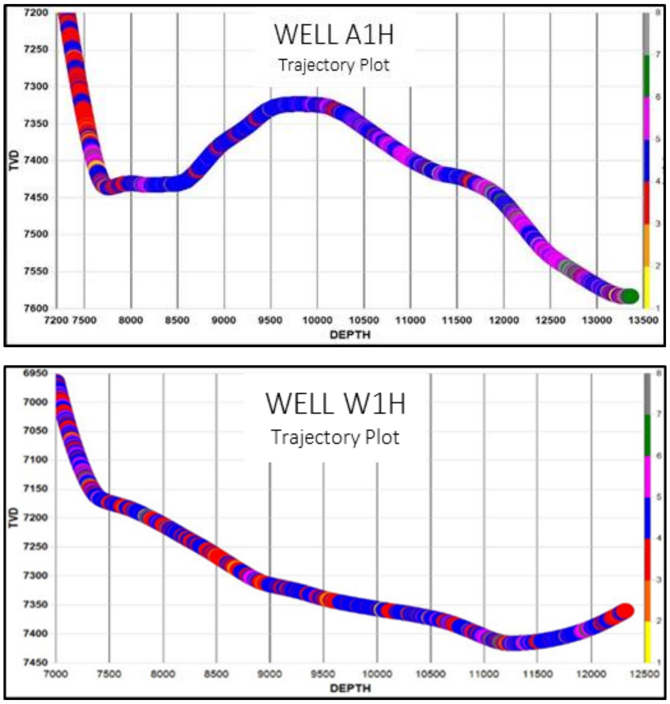
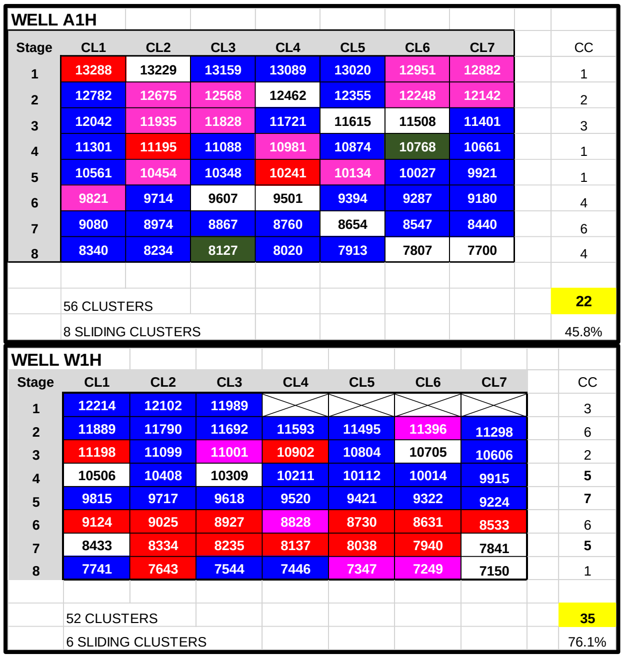


Figure 11: Trajectory plots for 2 Marcellus wells

The Trajectory Plots for the 2 wells are shown in Figure 11. Well A1H is a mixture of Facies H4 (Blue) and H5 (Magenta). Well W1H has more Facies H4 towards the toe and Facies H3 (Red) towards the heel. The impact of the lateral heterogeneity is more obvious in Figure 12, which shows the facies type for each cluster within the completion design.

Table 1: Completion parameters for 2 Marcellus wells

	Well A1H	Well W1H
Proppant (k-lbs)	6088	5947
Stages	8	8
Prop/Stage (k-lbs)	761	743
Ttl Clusters	56	52
Clusters/Stg	7	6.5
Prop/Cluster (k-lbs)	109	114



WELL A1H

Stage	CL1	CL2	CL3	CL4	CL5	CL6	CL7	CC
1	13288	13229	13159	13089	13020	12951	12882	1
2	12782	12675	12568	12462	12355	12248	12142	2
3	12042	11935	11828	11721	11615	11508	11401	3
4	11301	11195	11088	10981	10874	10768	10661	1
5	10561	10454	10348	10241	10134	10027	9921	1
6	9821	9714	9607	9501	9394	9287	9180	4
7	9080	8974	8867	8760	8654	8547	8440	6
8	8340	8234	8127	8020	7913	7807	7700	4
	56 CLUSTERS							22
	8 SLIDING CLUSTERS							45.8%

WELL W1H

Stage	CL1	CL2	CL3	CL4	CL5	CL6	CL7	CC
1	12214	12102	11989	☒	☒	☒	☒	3
2	11889	11790	11692	11593	11495	11396	11298	6
3	11198	11099	11001	10902	10804	10705	10606	2
4	10506	10408	10309	10211	10112	10014	9915	5
5	9815	9717	9618	9520	9421	9322	9224	7
6	9124	9025	8927	8828	8730	8631	8533	6
7	8433	8334	8235	8137	8038	7940	7841	5
8	7741	7643	7544	7446	7347	7249	7150	1
	52 CLUSTERS							35
	6 SLIDING CLUSTERS							76.1%

Figure 12: Impact of lateral heterogeneity on completion efficiency (by stage) for Wells A1H and W1H

In Well A1H there are 3 stages (1, 4 and 5) where a single cluster is significantly weaker than the other 6 clusters, leading to highly inefficient fracturing. That only happens once in the W1H well, in stage 8. As a result our analysis predicts that only 46% of the clusters (22) were adequately treated in the A1H well as opposed to 76% (35) in the W1H well. If all other things are equal (which is our assumption) we would expect the impact of lateral heterogeneity to cause the A1H to under-perform the W1H by a factor of 59%.

During the first 24 months production the W1H well outperformed the A1H by a factor of 60%, very much aligned with our prediction. For this pair of wells the MSE responds well to lateral heterogeneity and the excellent correlation confirms that the variations we see in MSE are directly related to completion efficiency and ultimately, well productivity.

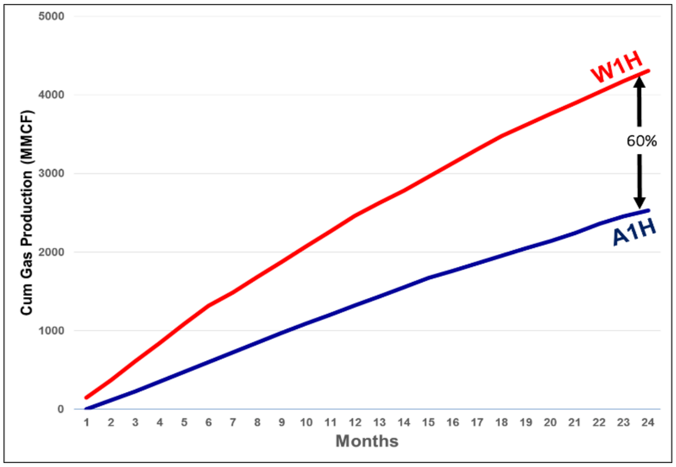


Figure 13: Cumulative gas production on 2 Marcellus wells

Case Study 4

The 3 subject wells in this case study were all drilled in 2013-2014, targeting the Bone Spring formation. The true vertical depth (TVD) of the three laterals is 10640 ft. +/- 20 ft. The completions were all executed in a similar fashion; 5 clusters/stage, 50 ft. cluster spacing, and 150,000 lbs. of proppant per stage. The lateral lengths varied between wells (4400-6150 ft.) as did the number of stages (17-25). Well productivity can be easily normalized to account for variations in lateral length. The similarity of these parameters make this set of wells appropriate for an evaluation of the relationship between lateral heterogeneity and well productivity.

Well A produces from a 6,150 ft. lateral with a 25-stage completion (Figure 14). MSE-based analysis predicts that 96 of the 125 clusters (77% efficiency) will contribute to flow. Well B produces from a 5,550 ft. lateral with a 23-stage completion. The prediction for this well is that 79 of the 115 clusters (63% efficiency) will contribute to flow. Finally, Well C produces from a 4,400 ft. lateral with a 17-stage completion where we predict that 40/85 clusters (47% efficiency) will contribute to flow. Well C is particularly interesting because it drilled very much like Well A until the midpoint of the lateral, where it appears to stray out of the target zone. The operator attempted to steer back into zone, but ultimately finished the well early because they were unsuccessful in their attempts to get back into the target formation.

The cumulative oil production curves from each well's first year of production (Fig 15) demonstrate an excellent correlation between well productivity and our prediction of contributing clusters. The analysis was able to differentiate the good well (Well A, with 161,355 BOE in Year 1) from the bad well (Well C, with 68,801 BOE in Year 1), both qualitatively and quantitatively. This case study supports the hypothesis that (1) well productivity was influenced by lateral heterogeneity and the resulting completion efficiency and (2) our process can quantify the completion efficiency and predict well performance accurately.

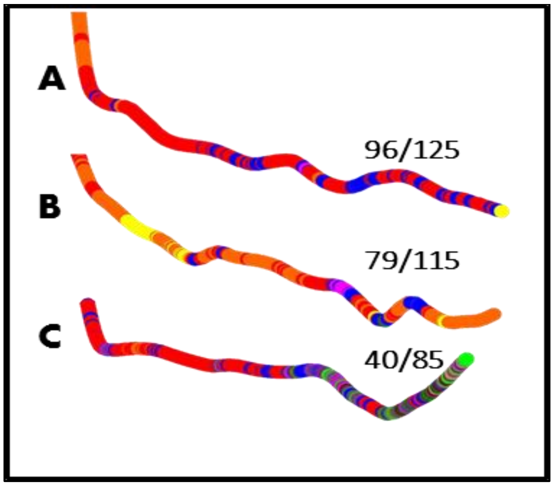


Figure 14: Trajectory plots for 3 Bone Spring wells

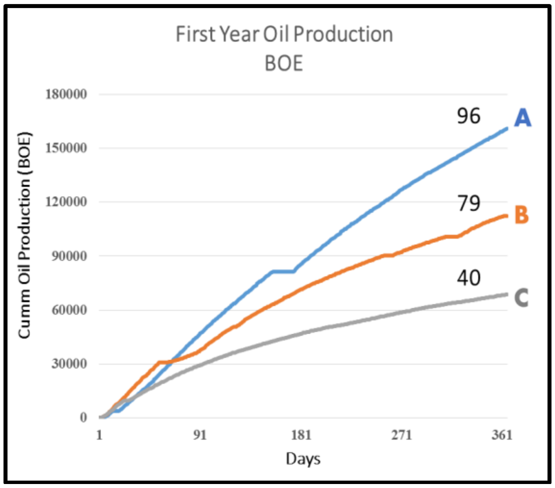


Figure 15: Cumulative oil production by well

Production Validation Case Studies

Case studies have been published that demonstrate the success of engineered completions in increasing well productivity (ref. 4). The following two case studies demonstrate a direct relationship between actual production and MSE-based engineered completions, both at the stage-level and the well-level.

Case Study 5

The earliest work on engineered completions originated using production logs results in the horizontal shales of North America (ref. 2). These production logs pointed out that many of the perforation clusters were under-performing while many other clusters appeared to be over-performing. In order to evaluate the effectiveness of MSE to design engineered completions production logs are ideally suited to the task.

The subject well for Case Study 5 was first put on production in Q2 2016 and a production log was run within the first month. Four months later, a second production log was run. Having two separate production log runs is both a blessing and a curse. On the one hand, where the two PL passes agree, it firms up our confidence in the analysis. Conversely, having two production log passes complicates the picture when the two passes don't agree with each other.

The subject well was completed using a 26-stage completion with a total of 86 perforation clusters. When comparing the two production log passes, 60 of the 86 clusters have the same interpretation on both PL passes. Of the remaining 26 clusters, 12 of them showed significant flow on pass 1 but no contribution to production on pass 2. These clusters might have been depleted during the first 4 months, or perhaps they became plugged up and stopped producing. The other 14 clusters showed no flow contribution during the first month but significant contribution 4 months later. This suggests that perhaps these clusters were slower to clean up but the second production log pass identified them as contributors.

For the 60 clusters where the two passes agree, it is a simple process to compare MSE-based predictions to actual results. For the other 26 clusters the decision was made to add the two passes together to determine the productivity for a given cluster. For this evaluation 6 categories were created. For each Category the example includes an MSE-GR log across the stage, along with a plot depicting the PL results for that stage. Along the x-axis are the 3 clusters while the y-axis shows the percentage of the total flow for the well coming from that perf cluster. The blue portion comes from the first PL pass (June) while the red portion comes from the second PL pass (October).

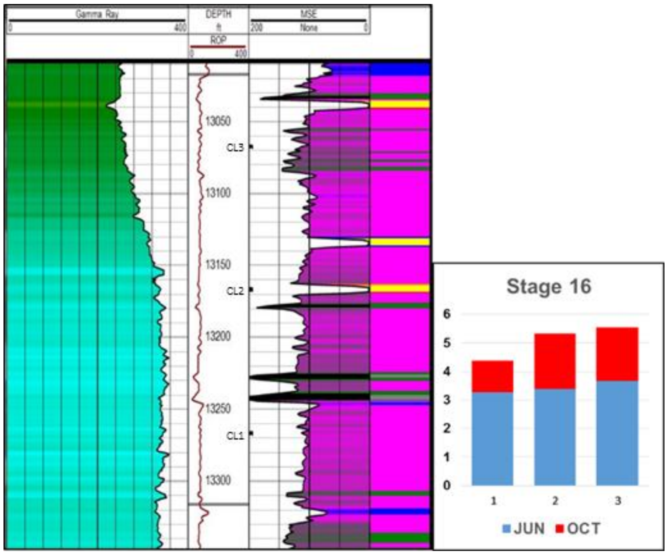


Figure 16: Category A, Stage 16

<u>Category A</u>

Of the 29 stages, there are 7 stages where all 3 clusters show significant flow on both passes of the production log. For these 7 stages we can also observe that the MSE facies is homogeneous within the stage. An example of this is Stage 16 (Fig 16), where all 3 clusters are placed in Facies HD5 (Magenta). For these stages, everything went exactly as predicted by MSE with all clusters contributing on both PL passes. Of interest in Stage 16 is that the GR suggests a facies change at the top of this stage, which is not in line with the production logs or the MSE facies.

Category B

There are also 6 stages where all 3 clusters show significant flow on at least one of the two production logs. On these stages we also observe that the MSE facies is consistent within the stage. An example of this is Stage 20, where all 3 clusters are placed in the HD4 (Blue) facies. Notice in this example, the GR is relatively constant, in good agreement with the production logs and the MSE analysis.

Category C

There are 3 stages where flow is dominated by one of the 3 clusters, and it is evident on both passes of the production logs. For these stages we also observe an obvious MSE facies change that explains why this cluster is dominant. An example of this is Stage 2, where Cluster 3 is in Facies HD3 (Red), while the other two clusters are in Facies HD4 (Blue). This suggests that the lower stress rock (CL3) was over-treated while CL1/CL2 were under-treated. The agreement between the 2 PL passes and the MSE facies is excellent in Category C. Of interest is the inability of the GR to pick up this change in rock strength.

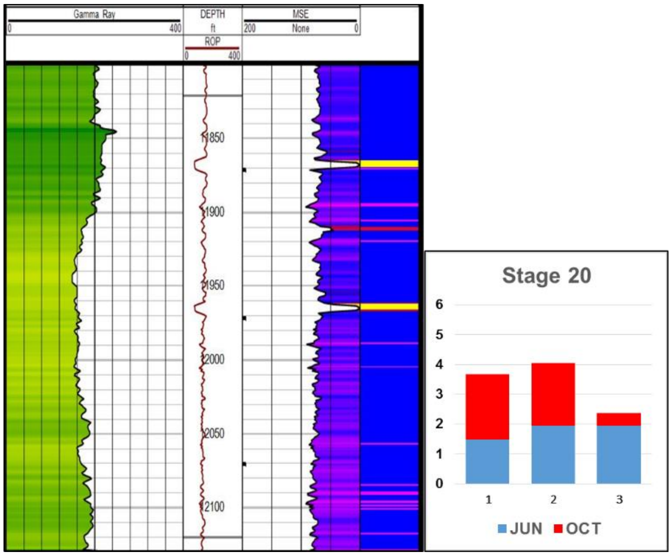


Figure 17: Category B, Stage 20

Category D

There are 3 stages where both PL passes agree with each other and disagree with the MSE analysis. Stage 9 is an example of this. The MSE facies analysis suggest that CL2 should produce better than the other two (Blue). The other 2 clusters are in the Magenta facies, with CL1 having a higher MSE value than CL3. While it makes sense that the cluster with the highest MSE (CL1) has the worst production, the MSE analysis did not manage to predict that CL2 and CL3 would perform equally.

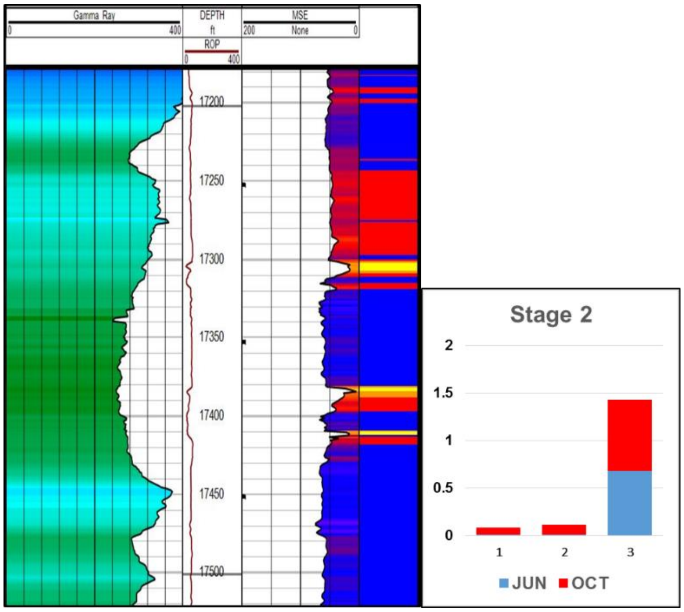


Figure 18: Category C, Stage 2

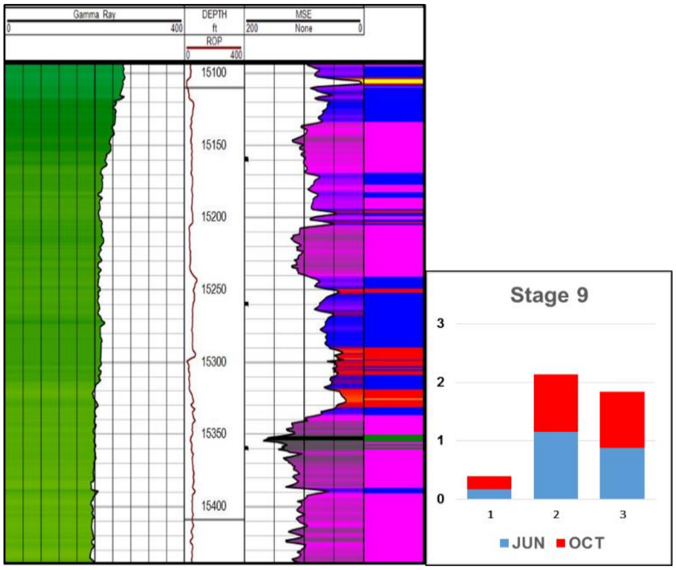


Figure 19: Category D, Stage 9

Category E

There is another group of 7 stages where our ability to do this analysis is impacted by the quality of the drilling data. A good example of this is Stage 14. In this case Clusters 1 and 2 are in similar MSE rock, while CL3 appears to be in very high MSE rock. A review of the drilling reports shows that drilling efficiency was negatively impacted by a bit failure in this interval. In fact, a BHA change at 13,680 ft. led to a huge change in MSE. The result is that we have 1 cluster where no opinion can be formed, but for the other 2 clusters the agreement between the production logs and the MSE data is excellent.

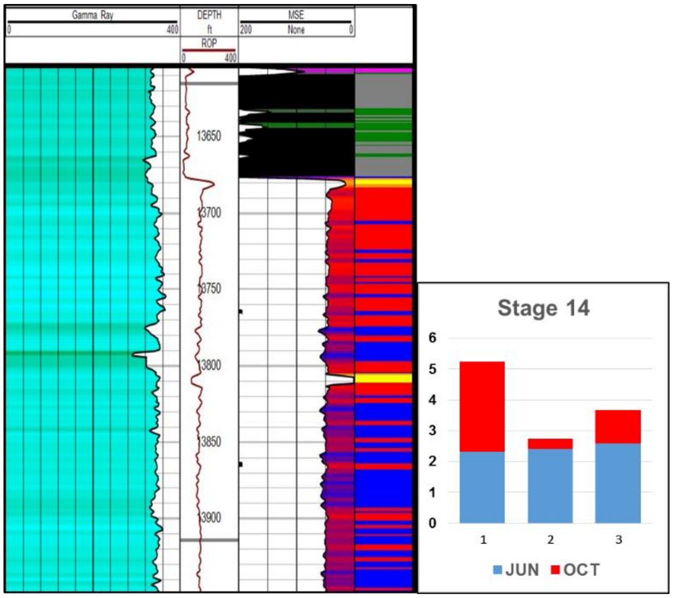


Figure 20: Category E, Stage 14

Category F

Finally, there are 3 stages where 2 or more clusters are impacted by drilling data issues. For these 3 stages no opinion on the match between the production logs and MSE can be formed.

In summary, of the 29 stages in this case study, the agreement between the Production Log passes and MSE facies analysis was excellent for 23 of the stages. For the other 6 stages, no analysis was possible for 3 due to poor drilling data, and the MSE analysis disagreed with the production log results for the 3 other stages.

Case Study 6

The first 5 case studies make a very strong case for MSE as a reliable tool for engineering completions. The only question left unanswered is whether wells completed with MSE-based engineered designs actually perform better than wells done with geometric completions. This is not an easy question to answer since for any given well you only get to complete it once, so you can't compare a geometric versus an engineered completion on a given well. The only option is to compare wells done with engineered completions to a significant number of geometric wells in close proximity to see how they compare.

For this case study the 3 subject wells were drilled and completed in the Wolfcamp A formation during 2015. Two of the wells were direct offsets and were compared to 21 other wells (Group A) that were all within a 4 mile radius of each other. The third well was analyzed separately because it was located 17 miles southeast of the first two wells. Well 3 was compared to a group of 9 wells that were all within 4 miles of it.

The two Groups were chosen to ensure that the comparison wells had minimal differences in both geology and hydraulic fracture treatment technique. By controlling these factors we are able to effectively evaluate productivity differences between geometric completion designs and MSE-based engineered designs. Productivity is determined by using the first 6 months cumulative well production. The analysis is normalized for both proppant volumes and lateral length.

Results - Group A

In the first 6 months this group of 23 wells produced an average of 3.4 BOE/lateral foot per month. The two subject wells produced 5.7 and 5.2 BOE/ft per month, which is 61% better than the average. According to this metric only 2 of the other 21 wells in Group A wells out-performed the subject wells, putting these wells clearly in the top quartile for this Group. We also evaluated the technique by looking at BOE as a function of proppant volume. By this metric the 2 wells were 50% better than the average with only 3 of the other 21 wells ranking higher.

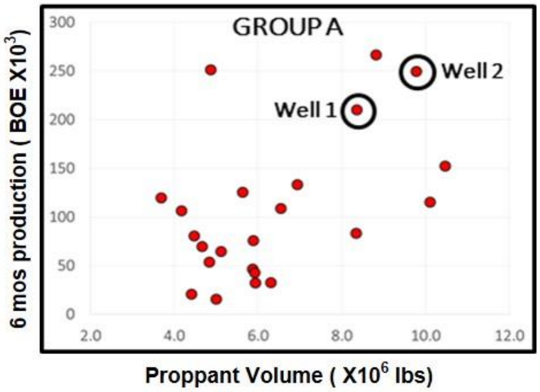


Figure 21: Wolfcamp wells, Group A

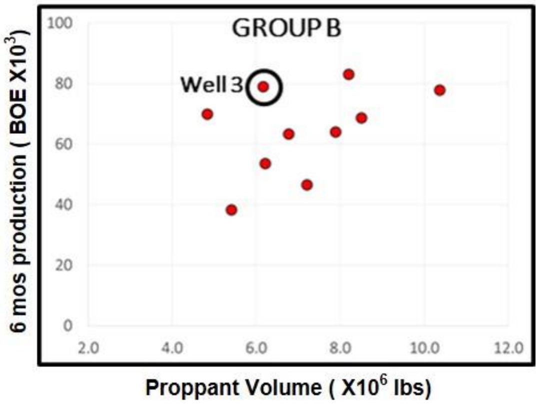


Figure 22: Wolfcamp wells, Group B

Results - Group B

The nine Group B wells are significantly less productive than the Group A wells. Group B wells averaged 2.3 BOE/lateral ft. per month. Well 3 produced 2.94 BOE/lateral ft. per month, 28% better than the group average and it is the best well in the group by this metric. As a function of proppant volume, the subject well was 38% better than the average and only 1 of the other 9 wells outperformed the subject well.

Conclusions

This set of case studies demonstrates that MSE is much more than just a cost-effective alternative; it is a technology that can deliver answers that rival the best in the business. The Ground Truth case studies showcased the excellent correlation between MSE-based answer products and answer products derived from the industry-leading sonic technology. There was also a strong correlation identified between the MSE facies and the Treating Pressure Plots acquired during the fracturing operation. Operators should be able to leverage this understanding to help improve operational efficiency during the fracturing operation.

The Ranking Well Pairs case studies confirm that variability in well productivity can be directly attributable to lateral heterogeneity and that MSE-based answers are effective in quantifying this heterogeneity and differentiating between strong producing wells and under-achieving wells. This type of analysis has been used successfully across various shale basins, including the Marcellus and Permian Basin examples presented in this paper.

Our Production Validation case studies looked at productivity at both the field level and the stage level. Wells completed using MSE-based engineered designs ranked well within the top 10% of their peers for both cases that we studied. The production results delivered by the 3 subject well are everything an operator could hope for in an engineered completion design.

At the stage level the match between the production log runs and our MSE predictions was excellent on 23 of the 26 stages we evaluated. Achieving this level of agreement between a production log and answers derived from drilling data is a significant achievement and helps explain the excellent results observed in the other 5 case studies.

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Nomenclature

Define symbols used in the text here unless they are explained in the body of the text. Use units where appropriate.

TVD =*True Vertical Depth (ft)*
MSE =*Mechanical Specific Energy (Kpsi)*
UCS =*Unconfined Compressive Strength (lbs/in^2)*
BI =*Brittleness Index*
ESV =*Estimated Stimulation Volume*
GR =*Gamma Ray Log (API)*
BOE =*Barrel of Oil Equivalent*
PL =*Production Log*
LWD =*Logging While Drilling*

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