



Surface Drilling Data Driven Completion Optimization – Impact on Frac Design, Production, and Economics of a Wolfcamp Formation Well

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Abstract

In a low commodity price environment, optimizing well performance is critical to producing at an economic rate. Since data collection for every horizontal well is expensive, most companies choose to apply a geometric completion design that doesn't account for the variation of stresses and rock properties along the wellbore. As shale reservoirs exhibit a high level of heterogeneity, a geometric completion will often result in sub-optimal well performance. Low cluster efficiency in unconventional reservoirs is remarkably common. Many studies have shown that a high percentage of frac stages contributed little to production, and in some cases, did not produce at all.

To overcome the challenge of the potentially high cost of completion optimization, a new solution that uses corrected mechanical specific energy (CMSE), calculated from commonly available surface drilling data, is provided. This drilling data is measured and collected during the standard drilling operation. The technique estimates the variability of stresses and reservoir properties along the lateral well and enables the placement of the perforation clusters of each stage in zones of similar rock property to improve cluster efficiency, which results in improved well production and economics.

The workflow is applied to a well in the Wolfcamp formation, Permian Basin. Two completion designs for the same well were evaluated for this study. A geometric completion is compared against an engineered completion designed using minimum horizontal stress as a reference log which was estimated using surface drilling data. A hydraulic fracturing simulation is run for each of the two scenarios using the same treatment. The first three years of production forecast is compared for the two cases using an asymmetric tri-linear model followed by an economic analysis. The simulation results shows 34% higher cumulative oil production for the engineered design after 3 years, that the NPV of the engineered design would be about 3 times more than geometric NPV after 3 years of production and the geometric designed well will be able to start to make profit after 675 days while the engineered design will reach profitability 6 months earlier.

This reliable and cost-effective technique offers an understanding of the reservoir along the lateral which allows E&P companies to engineer their completion designs at every well and achieve a significant increase in productivity.

Introduction

The oil and gas industry have been seeking ways of reducing the operational costs of drilling and completion that are reliable, repeatable and easy to deploy. As E&P companies are striving to spend as little capital as possible to make the biggest returns possible, these requests and hopes usually become challenges and goals to technical workers. Particularly for shale plays, it has been a tough ride to obtain the precise idea of geology along the wellbore due to the heterogeneity existing in shale reservoirs.

Although logging while drilling (LWD) and measurement while drilling (MWD) tools provide useful information, these tools are too expensive to deploy at each and every well. A major advantage that drilling mechanics-based approaches have over pressure estimation techniques using LWD is that they compute the essential mechanical properties at the bit instead of



further up the Bottom Hole Assembly (BHA) where these tools are located. Surface drilling data allows us to simulate subsurface geology as it provides vital information along the wellbore without any additional risk or expense.

This drilling data derived information includes estimation of geomechanical properties (such as Young's modulus, Poisson's Ratio), pore pressure, stresses, porosity, and natural fractures. Starting from the derived CMSE and geomechanical properties, the completion design and fracturing design are conducted. The most common completion design used in the shale industry is still a geometric design because typical reservoir evaluation tools are limited and companies are hesitant to use new technologies. According to Paryani et al, (2017) most Permian Basin operators use almost the same design for completion with a 20ft-30ft cluster spacing. However, is this geometric cluster spacing going to be the best for every case? With this question in mind, the unconventional oil and gas industry has been interested in a more efficient fracturing strategy that would enhance hydrocarbon production. An engineered completion design, which considers in-situ stress and pressure depletion, was introduced as another solution to achieve the goal and the result has been shown to enhance the overall cluster efficiency.

Starting from calculating CMSE, this paper will introduce a way to utilize available surface drilling data with any other valuable information to optimize cluster efficiency by adjusting the spacing, thus enhancing oil production.

Rock Properties and Stresses Estimation Using CMSE

Commonly available drilling data such as torque (T), rate of penetration (ROP), weight on bit (WOB), rotational speed (N) and bit size (D), are used to calculate the mechanical specific energy (MSE) defined as

$$MSE = 4 \frac{WOB}{\pi D^2} + 480 \frac{N T}{ROP \times D^2}$$

All the parameters needed to compute the MSE are commonly measured at the surface during any drilling operation. Due to friction losses, the MSE calculated at the surface differs from the downhole MSE (Majidi *et al.* 2016). Instead of using a risky and costly downhole tool to measure MSE, friction losses along the drill string and the wellbore are estimated and subtracted from the MSE to estimate the corrected mechanical specific energy (CMSE). Ouenes *et al.* (2017) have shown that the CMSE calculated from surface drilling data had very comparable values and trend as a downhole MSE measurement thus eliminates the need to use a costly and risky downhole tool. Figure 1 shows the key standard drilling data commonly recorded during the drilling operation and used to calculate CMSE. The reservoir property pseudo logs estimated from CMSE include Unconfined Compressive Strength, Confined Compressive Strength, Young's Modulus, Poisson's Ratio, pore pressure, stresses, porosity, stress brittleness, and natural fracture index.

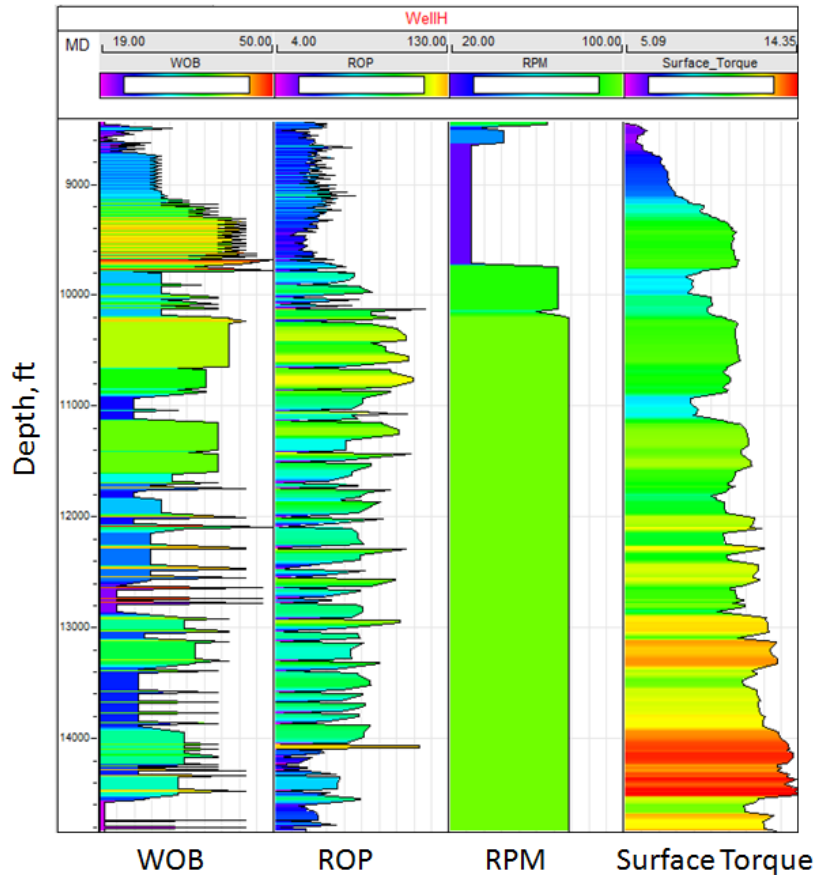


Figure 1. Commonly available surface data used to compute CMSE

The Unconfined Compressive Strength (UCS), which is a measure of rock strength, is derived from the corrected mechanical specific energy (CMSE). Pore Pressure is predicted during the process using drilling efficiency trend line approach where we capture the deviations of the trendline from the drilling efficiency dataset to compute the pore pressure, an approach similar to sonic and resistivity based pressure estimation methods. Pore pressure is a vital property needed during drilling in order to stay within a safe drilling window and maintain wellbore stability. Another application of pore pressure estimation is predicting depleted zones around existing producers which could lead to well interference or frac hits with new offset wells. From UCS and pore pressure, in-situ stresses can be estimated. Pore pressure and Shmin are validated using a diagnostic fracture injection test (DFIT). Figure 2 illustrates the pore pressure and stresses estimated from the drilling data.

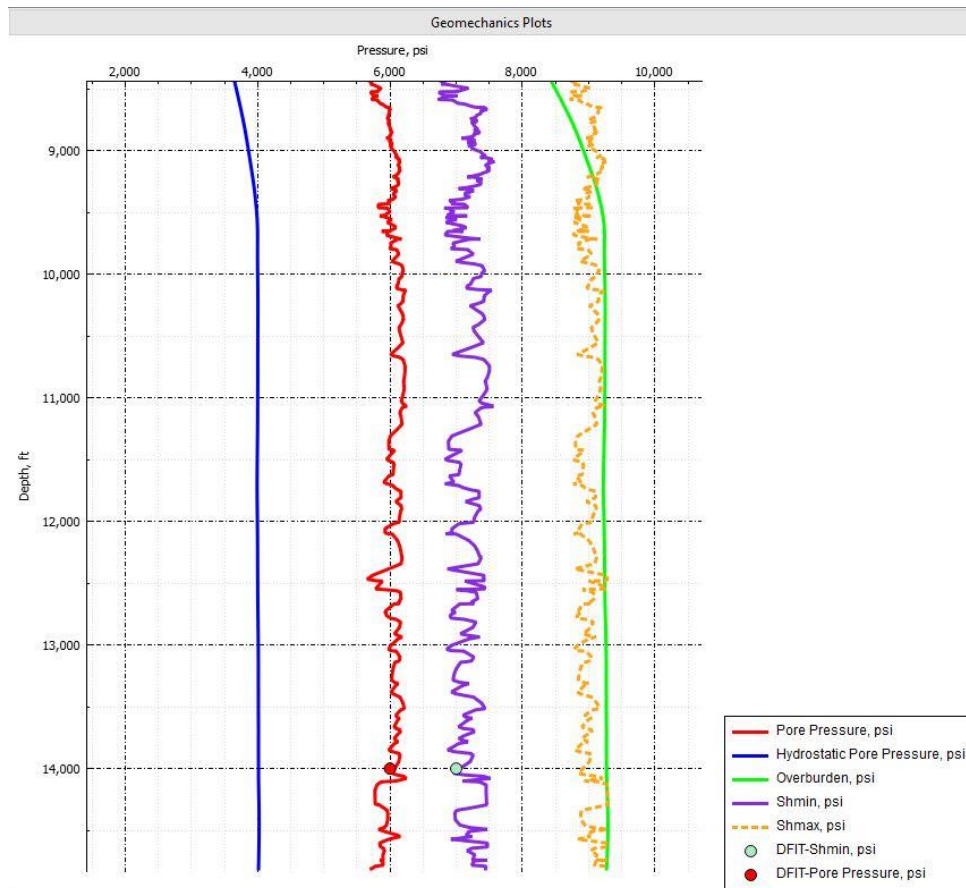


Figure 2. Surface Drilling Data is leveraged to estimate pore pressure and stresses along the wellbore

From UCS, lithology-based correlations are used to derive Young's Modulus (YM). Once YM is estimated, different correlations are used to estimate Poisson's Ratio (PR), Shear Modulus (G), porosity, a natural fracture index, and stress brittleness. Figure 3 illustrates the estimated key geomechanical properties along the lateral of Well H.

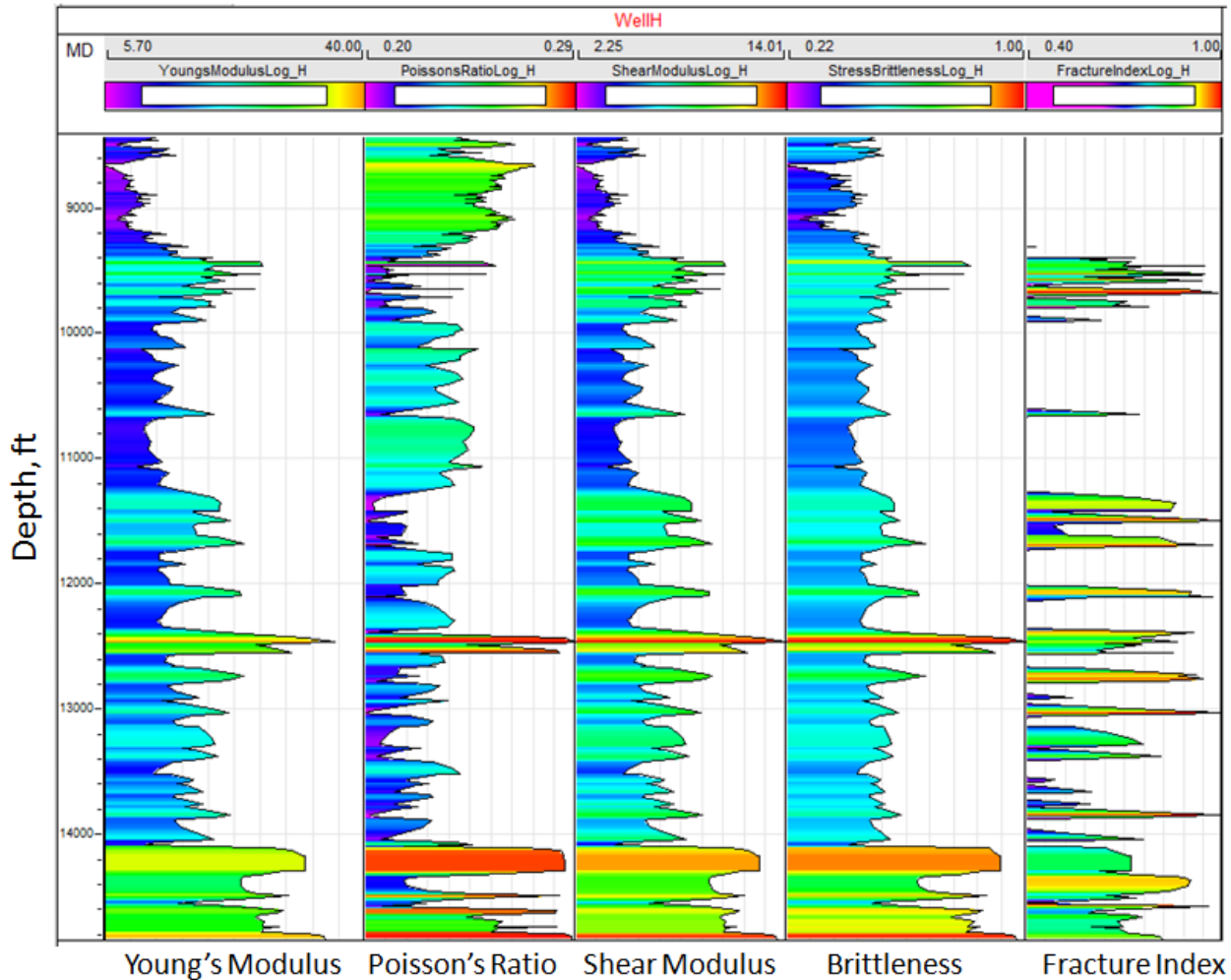


Figure 3. Key geomechanical logs, stress brittleness, and natural fractures index estimated along the wellbore

During drilling, the properties estimated using the drilling data can be used to guide the steering of horizontal wells in real-time to stay in the desired zone. As soon as the drilling is finished, the estimated properties along the well lateral provide reference logs to engineer a completion design for optimal hydraulic fracturing. Furthermore, the drilling-derived logs can be used to model 3D distributions of reservoir properties and use them as inputs in a geologically constrained 3D fracturing simulator. Leveraging the readily available drilling data helps overcome the challenge of collecting costly and hard to obtain data in horizontal wells.

Completion Design

As surface drilling data provides an estimation of the geological and geomechanical properties of subsurface near the wellbore, some of the critical geomechanical properties such as Sh_{min} , CMSE, and fracture gradient are used as reference logs for a completion design. The objective of completion design in DrillPredictor™ is to determine the most efficient number of hydraulic fracturing stages and locate clusters considering the minimal variation of reference rock mechanical property within the same stage. In this study, Sh_{min} , a proxy for fracture gradient, is used as a reference log. The number of intervals was decided to be 5 for the initial case. It means that estimated Sh_{min} values from CMSE calculation will be divided into 5 intervals that have a certain range of Sh_{min} values, represented by 5 different colors for visualization purpose. Completion design of DrillPredictor™ provides two main completion design options, Geometric Design and Engineered Design, which will be discussed in the following sections.

A. Geometric design

1) Initial Geometric design

The geometric design is evaluated stage by stage. The main goal of geometric design is to reduce the heterogeneity of reference log values (Sh_{min} in this case study) to allow treating pressure distribution at each cluster to be even as possible within the same stage. The cluster efficiency is defined as the percent of clusters which have higher likelihood of accepting the fluid in a given stage. In this study, stage 4, 10 and 13 show the greatest variability in Sh_{min} categories as shown in figure 4. Since there is high likelihood that there is going to be overtreating or undertreating at certain clusters, the cluster efficiency for this geometric design might be able to be enhanced with optimization function that is going to be introduced in the next section. Shown in figure 4, this initial completion design was based on geometric design. Length of each 17-stage was uniform as approximately 220 ft and 4 clusters have been used for each stage. Without optimization applied, the cluster efficiency of the initial design turned out to be 58.8%. In Figure 6, the cluster efficiency of initial geometric design is presented stage by stage. Note that there are only 5 stages (Stage 5, 9, 14, 16, 17) that have 100% of efficiency and 5 stages (Stage 1, 3, 4, 10, 13) have 25% of efficiency out of 17 stages in this case.

Completion Manager		2D Completion Optimization				
	Plug Depth	Cluster 1	Cluster 2	Cluster 3	Cluster 4	
Stage 1	14830.1	14794	14705.3	14616.7	14528	
Stage 2	14491.9	14456	14382.7	14309.3	14236	
Stage 3	14199.9	14164	14090.7	14017.3	13944	
Stage 4	13907.9	13872	13798.7	13725.3	13652	
Stage 5	13615.9	13579	13506	13433	13360	
Stage 6	13323.9	13288	13214.7	13141.3	13068	
Stage 7	13031.9	12996	12922.7	12849.3	12776	
Stage 8	12739.9	12703	12630	12557	12484	
Stage 9	12447.9	12411	12338	12265	12192	
Stage 10	12155.9	12120	12046.7	11973.3	11900	
Stage 11	11863.9	11827	11754	11681	11608	
Stage 12	11571.9	11535	11462	11389	11316	
Stage 13	11279.9	11243	11170	11097	11024	
Stage 14	10987.9	10952	10878.7	10805.3	10732	
Stage 15	10695.9	10660.5	10587	10513.5	10440	
Stage 16	10403.9	10369	10295.3	10221.7	10148	
Stage 17	10111.9	10077	10003.3	9929.67	9856	
shminLoq_WellHResult		6843.093 -6973.911	6973.911 -7104.729	7104.729 -7235.547	7235.547 -7366.365	7366.365 -7497.182

Figure 4. Initial Geometric Completion Design Colored in 5 Intervals of Sh_{min} .

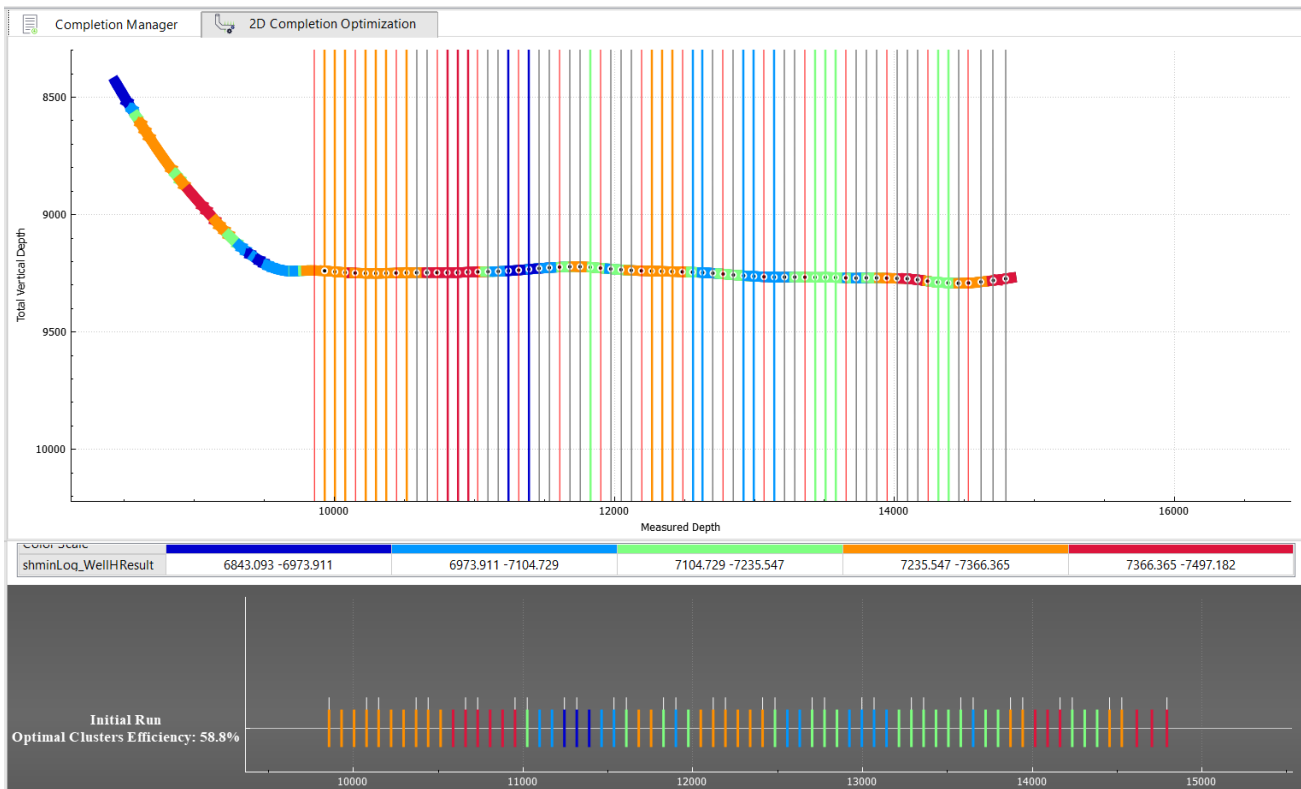


Figure 5. Initial Geometric Completion Design with 17 stages with 5 Interval of Shmin.

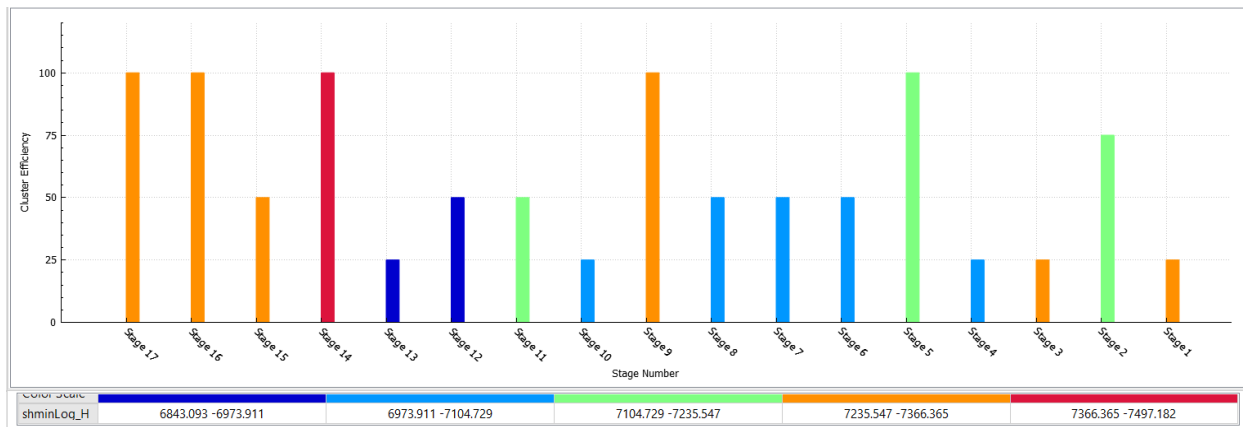


Figure 6. Initial Geometric Completion Design Cluster Efficiency

2) Initial Geometric Design Optimization

Starting with the cluster efficiency of 58.8% for the geometric design, auto-optimization has been applied. FracGeo's DrillPredictor™ presents the auto-optimization feature in completion design module which adjusts cluster locations according to the estimated reference geomechanical properties. The theory behind the auto-optimization is to locate clusters to the area where the reference rock mechanical properties are as close as possible within the same stage so that treating pressure to break the rock is similar within a stage. It ultimately enhances cluster efficiency by preventing overtreating or undertreating at certain clusters.

This case study showed the best cluster efficiency enhancement after three optimizations were applied. After the first auto optimization, the cluster efficiency increased to 61.8%. After the second auto optimization, the cluster efficiency increased to 63.2% and the third auto optimization resulted in a cluster efficiency of 72.1%. The original geometric design and three cluster repositioning/optimization runs are presented as shown in the boxes in Figure 7. For the cluster efficiency after three runs of auto-optimization, the number of clusters that have 100% of efficiency has been increased to 7 from 5 (initial geometric completion), and none of the clusters has 25% efficiency anymore (see Fig. 8).

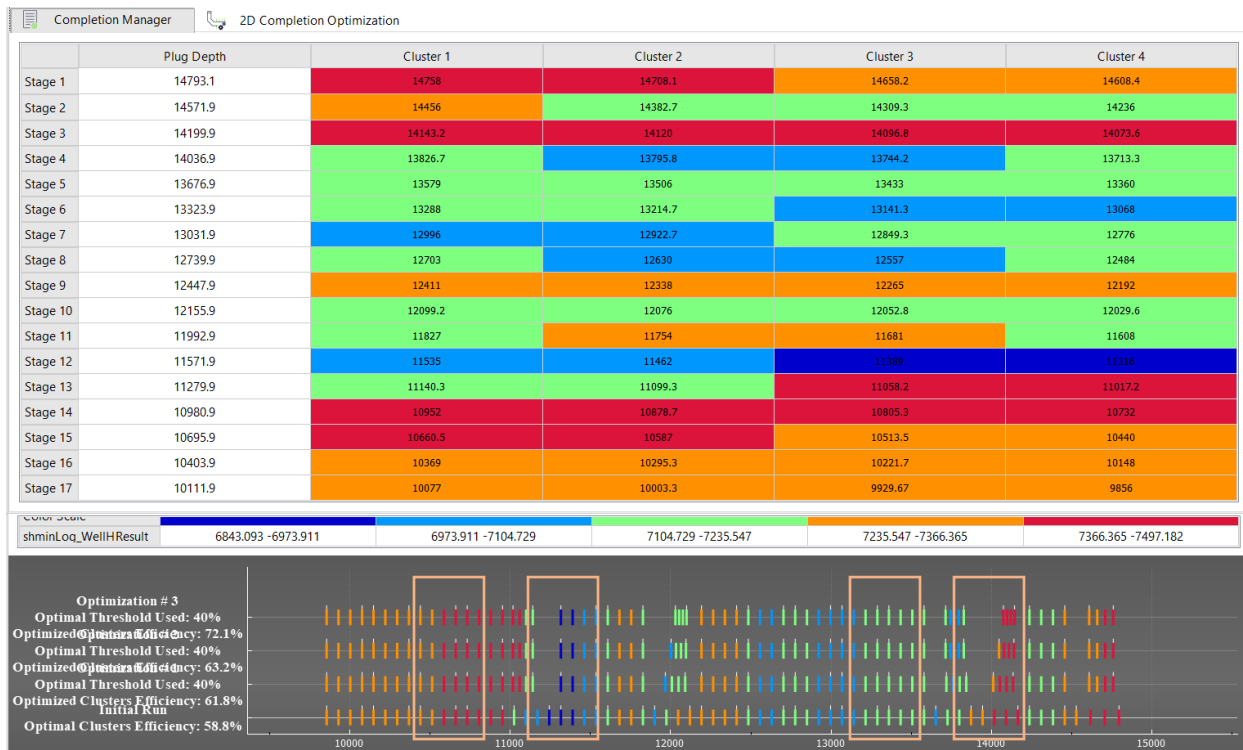


Figure 7. Optimized geometric completion design grouped in 5 colored intervals of Shmin. The boxes show the cluster relocating to enhance cluster efficiency based on Shmin.

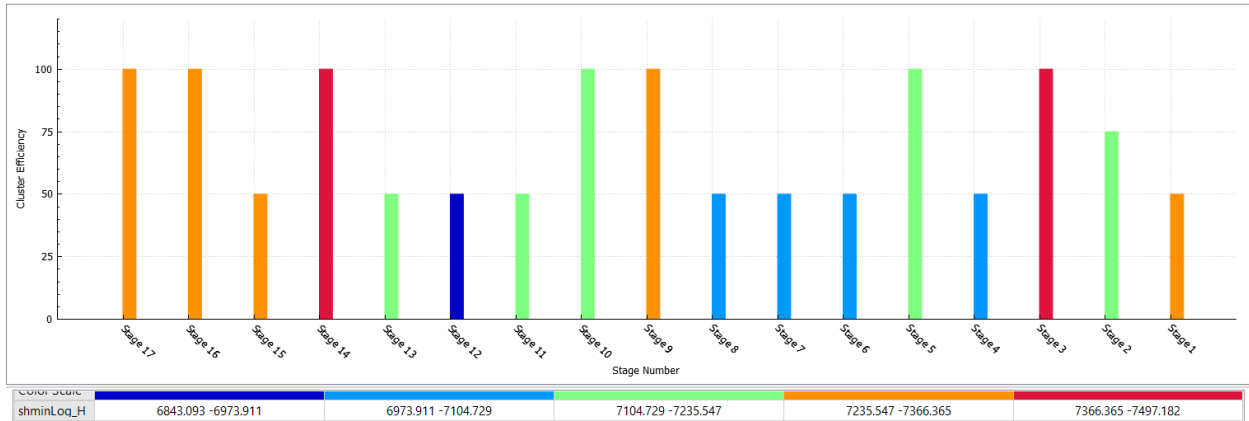


Figure 8. Optimized Geometric Completion Design Cluster Efficiency

B. Engineered design

Unlike geometric design that has uniform stage and cluster length, an engineered completion design has variable stage lengths that are adjusted according to the reference logs. In this case study, the reference log is chosen to be Shmin. With the engineered completion design that takes account into the heterogenous Shmin along the wellbore, the number of stages was increased by 2 (to 19 stages) from the initial geometric completion design. Figure 10 shows that cluster efficiency of 71.5% in the engineered completion design. The efficiency of the engineered design is about 12.7% higher than that of initial geometric design. Considering the initial geometric stage length in this case as 220ft, depending on the standard deviation in Shmin from the average values, the range of stage length shows as low as 140ft and as high as 380ft. As Figure 11 shows, the engineered completion design presented the most clusters that have an efficiency of 100%. 10 out of 19 stages show 100% cluster efficiency.

Stage	Plug Depth	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Stage 1	14804	14794	14704	14614	14524	14434
Stage 2	14424	14414	14294			
Stage 3	14284	14274	14184	14094	14004	13914
Stage 4	13904	13894	13794	13694	13594	
Stage 5	13584	13574	13484	13394		
Stage 6	13384	13374	13254			
Stage 7	13244	13234	13114			
Stage 8	13104	13094	12994	12894	12794	
Stage 9	12784	12774	12654			
Stage 10	12644	12634	12534	12434	12334	
Stage 11	12324	12314	12214	12114	12014	
Stage 12	12004	11994	11894	11794	11694	
Stage 13	11684	11674	11554			
Stage 14	11544	11534	11444	11354		
Stage 15	11344	11334	11214			
Stage 16	11204	11194	11094	10994	10894	
Stage 17	10884	10874	10784	10694	10604	10514
Stage 18	10504	10494	10394	10294	10194	
Stage 19	10184	10174	10084	9994	9904	9814

Figure 9. Engineered Completion Design Colored in 5 Intervals of Shmin.

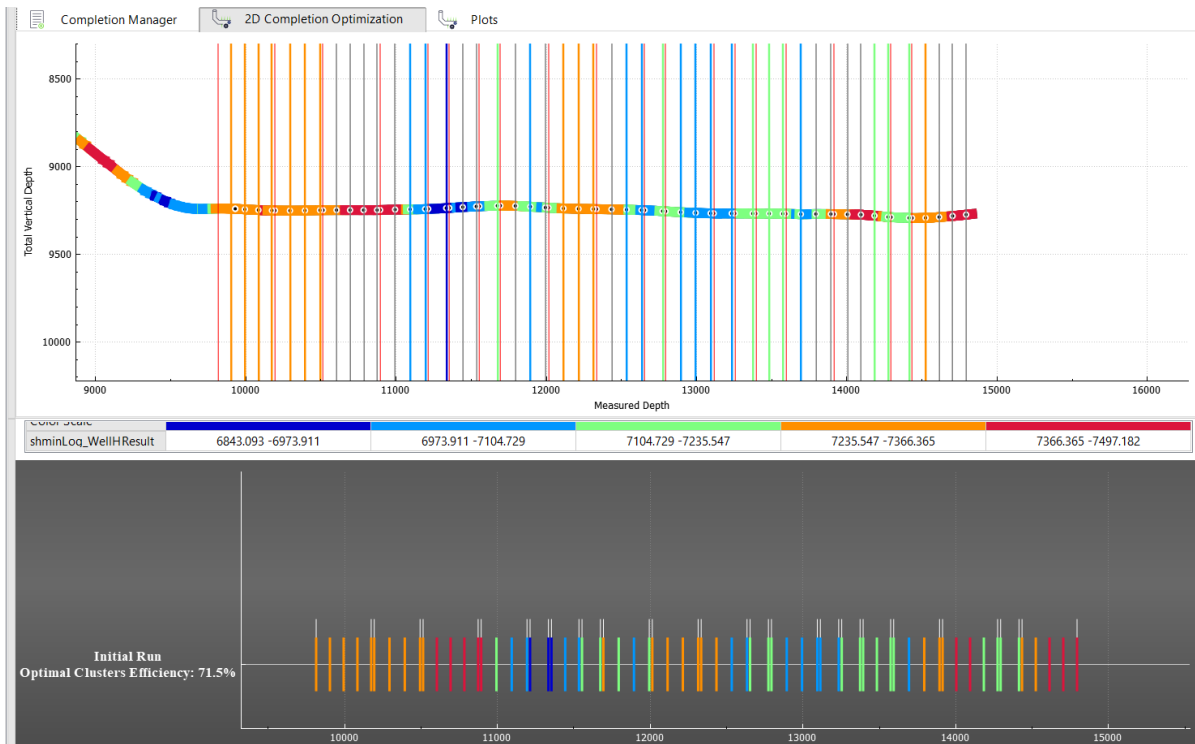


Figure 10. Engineered Completion Design with 5 Interval of Shmin.

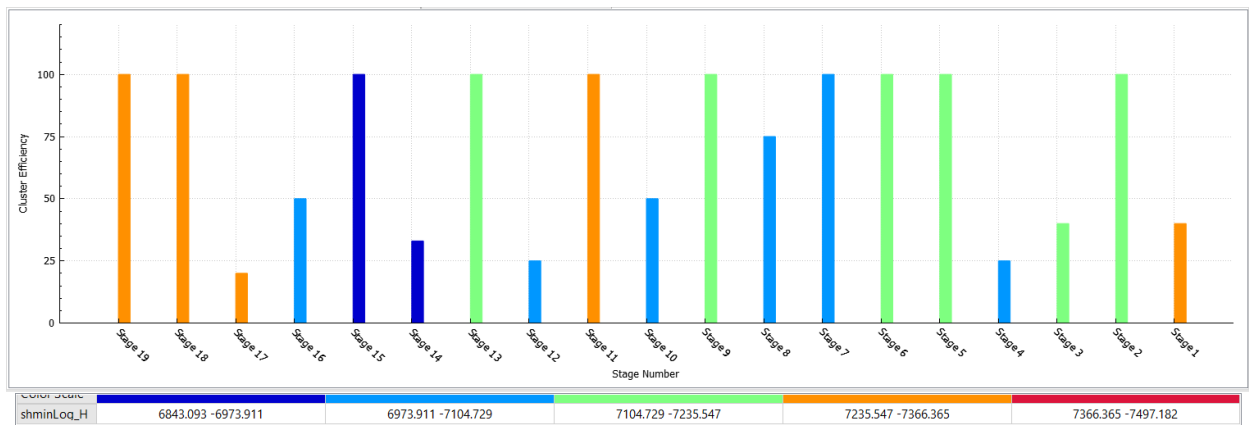


Figure 11. Engineered Completion Design Cluster Efficiency

Figure 12 shows the variation of stage length presenting as blue dots versus Shmin values in red curve. The trend shows that, in engineered design, stage length is designed to be longer where Shmin values are comparably lower and vice versa. This is based on the concept that complex fractures can be generated relatively easily in areas of low stress so we can pump bigger stage length. However, in areas of higher stresses, planar fractures will develop and hence we have to pump shorter stage lengths. After the engineered designed frac stage is determined, the proppant mass should be adjusted as figure 13. In this figure, the proppant mass requirement is proportional to the stage length. In other words, when the stage is longer, the more proppant mass is required, whereas, at shorter stage length, the less proppant mass is required.

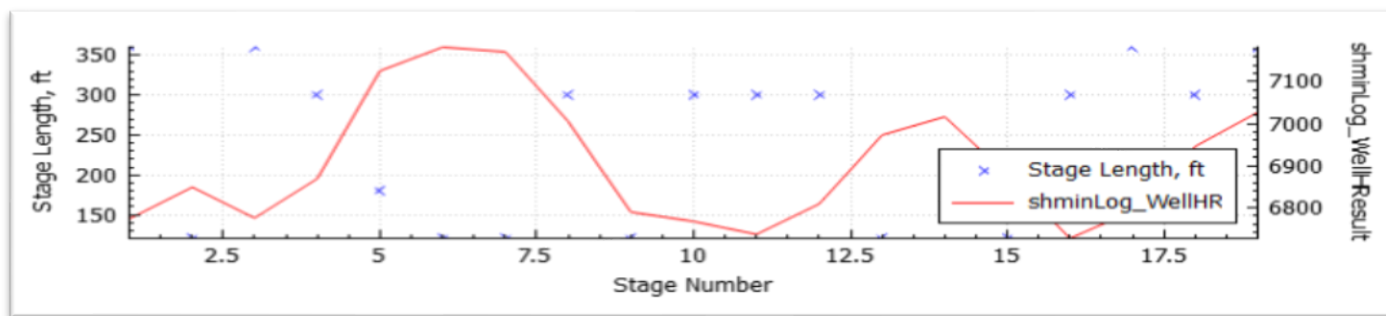


Figure 12. Variation of stage length and Shmin for the engineered completion

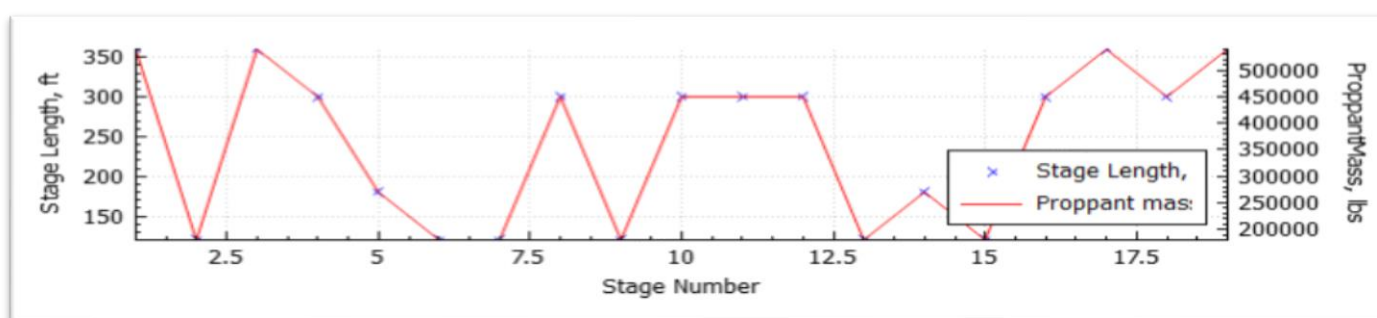


Figure 13. Variation of the amount of proppant required for each engineered stage

The workflow shown until this section and plots presented by DrillPredictor™ will assist frac engineers in continuing their work to the next step of the workflow.

Hydraulic fracturing simulation

Properties estimated using the drilling data such as UCS, pore pressure and Shmin, are used to build their corresponding 3D reservoir models either using Neural Networks or using geostatistical methods. Neural networks, or other artificial intelligence methods, are recommended when modeling pore pressure, stresses and natural fractures due to the high complexity of parameters that control the variability of these properties. These 3D models are then used as inputs to an asymmetric hydraulic fracturing simulator. Similar treatment parameters are used in both cases. 2500 lbm of 40/70-mesh proppant and 40 bbls of water per foot of lateral were used in the hydraulic fracturing simulator. The fluid was pumped at a maximum pump rate of 80 bpm.

The simulation results showed that the engineered completion design required lower surface pressure than the geometric design even though the same pumping rate is used. The higher cluster efficiency of the engineered design resulted in similar fluid flow through each perforation leading to lower perforation friction pressure and thus lower surface treating pressure. The geometry of the fracture is affected by in-situ stresses and rock properties. The resulting frac geometry along the wellbore (Figures 14 and 15) shows the variation of fracture half-lengths and conductivity following the variability of stress and rock properties estimated by the surface drilling data.

The fracturing simulation of the engineered design shows some increase in propped fracture half-lengths compared to the geometric design. Additionally, the engineered design delivered bigger fracture widths due to having lower closure stress,

or minimum horizontal stress, at the re-positioned perforation clusters. Since the fracture conductivity is given by the product of the fracture permeability and the fracture width, the fracture conductivities obtained with the engineered design were higher than those obtained with the geometric design. Higher fracture conductivity is expected to result in improved production performance.

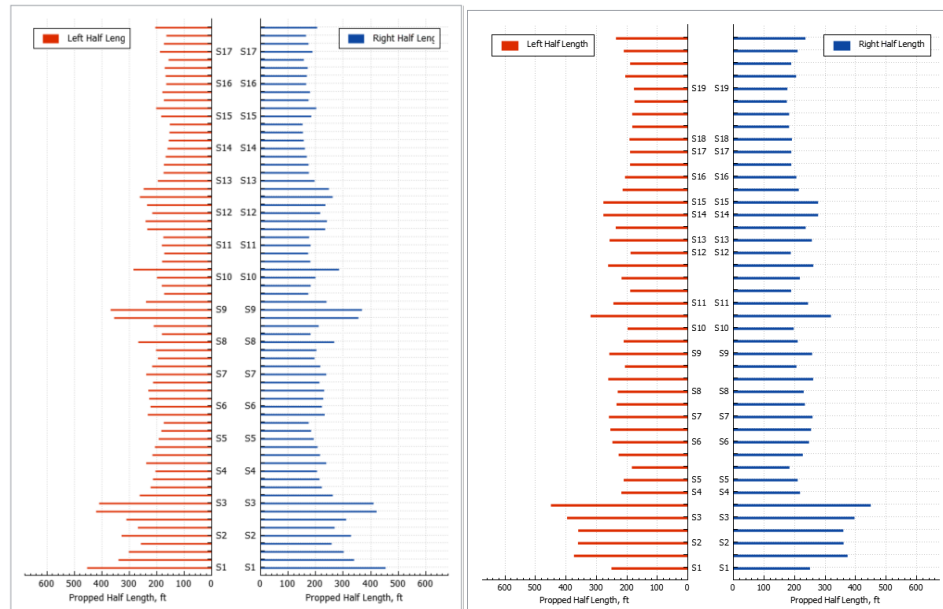


Figure 14. Fractures half lengths variations due to the variability of rock properties for the geometric design (left) and the engineered design (right)

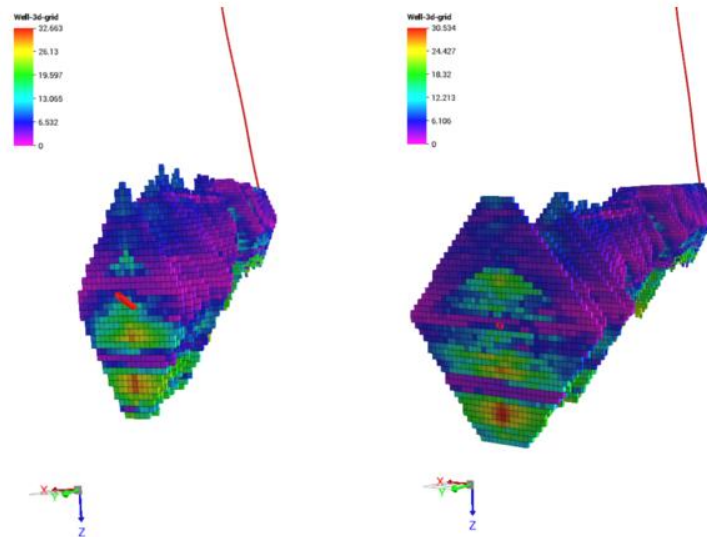


Figure 15. 3D view of the improved fracture conductivity generated by the hydraulic fracturing simulator for the engineered design case (right) compared with the geometric design case (left)

Production Forecast Using a Tri-linear Model

The next step is to forecast and compare the production for each completion design scenario. Production forecast is essential information for planning the development of an unconventional reservoir. The outputs of the hydraulic fracturing simulator are exported into an asymmetric tri-linear model constrained by the results derived from the hydraulic fracturing simulator to predict the well performance. The initial pressure set inside the tri-linear model was obtained from DFIT data. The production forecast for the two scenarios showed that, compared with the geometric case, the engineered completion resulted in 34% higher cumulative oil production during the first three years (figure 16). The engineered design also led to superior initial production rate results. The average initial 30-day rate (IP30) for the engineered design is estimated to be 629 bopd while for geometric design the IP30 was only 423 bopd. The oil rate vs. time for both cases is plotted in Figure 17.

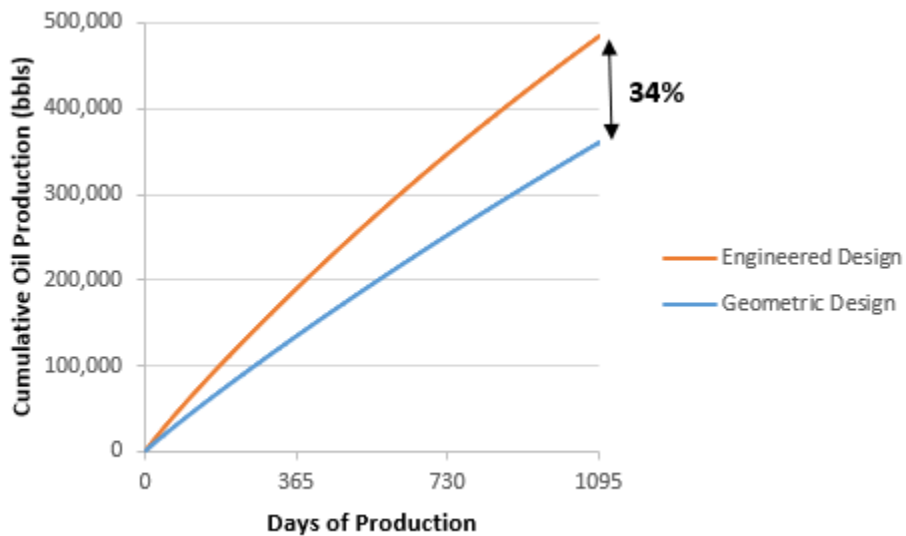


Figure 16. In the first 3 years of production the engineered design production forecast showed a 34% higher cumulative production than the geometric design

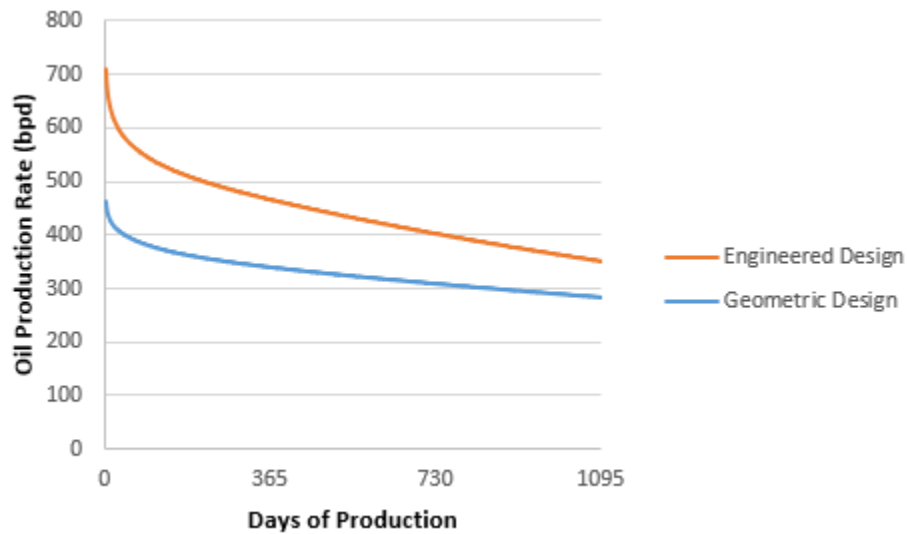


Figure 16. Production forecast for the engineered and the geometric cases shows a significant production improvement due to optimized cluster efficiency

Economic Analysis

Horizontal well operations are known to be more complicated than that of vertical wells due to the many variables involved, requiring longer operational time and advanced technology. This complication directly leads to the higher cost of drilling, completion and maintenance. Therefore, a comprehensive economic analysis accounting for all the cost and expenses would be critical.

Based on the three-year production forecast of the two completion scenarios, geometric design and engineered design, an economic analysis is conducted in this section.

For this case study of a Wolfcamp well in the Midland Basin, a few input values were assumed according to the most reasonable findings in the current market. Table 1 shows the inputs that have been used for the economic analysis calculation. The initial investment includes drilling and completion cost as well as other expenditures that are required at the initial stage. This amount was set based on the length of the lateral section of the well and the well location. Note that engineered design has 2 more stages compared to the geometric design, therefore completion cost has been increased.

Item	Cost
Oil Price	\$50/bbl.
Operational Cost	\$7/bbl.
Federal Tax	35%
Initial Investment, Geometric	\$8,000,000.00
Initial Investment, Engineered	\$8,470,000.00
Discount Rate	10%

Table 1. Used Input for Economic Analysis

Figure 16 show the trend of 3 years of the cumulative oil production forecast of engineered design and geometric design. It shows that the engineered design production is higher than the geometric design throughout the years of observation, which supports that NPV (Net Present Value) of engineered design is higher than that of geometric design as shown in table 2. The

result shows that NPV of engineered design would be about 3 times more than geometric NPV after 3years or production. Both ROI (Return of Investment), how much Net Present Value per Investment, are greater than 1, which explains that both of geometric and engineered designs are evaluated as successful designs. When it comes to comparison of each design, the engineered design has bigger returns within the same time. With the production rates, the geometric designed well will be able to start to make profit after 675 days and the engineered design will bring the profit even faster, 478 days (Figure 18).

Well	NPV	ROI	Breakeven (days)
Geometric	\$4,228,101.89	1.53	675
Engineered	\$12,941,343.39	2.53	478

Table 2. The result of Economic Analysis after 3 years of production

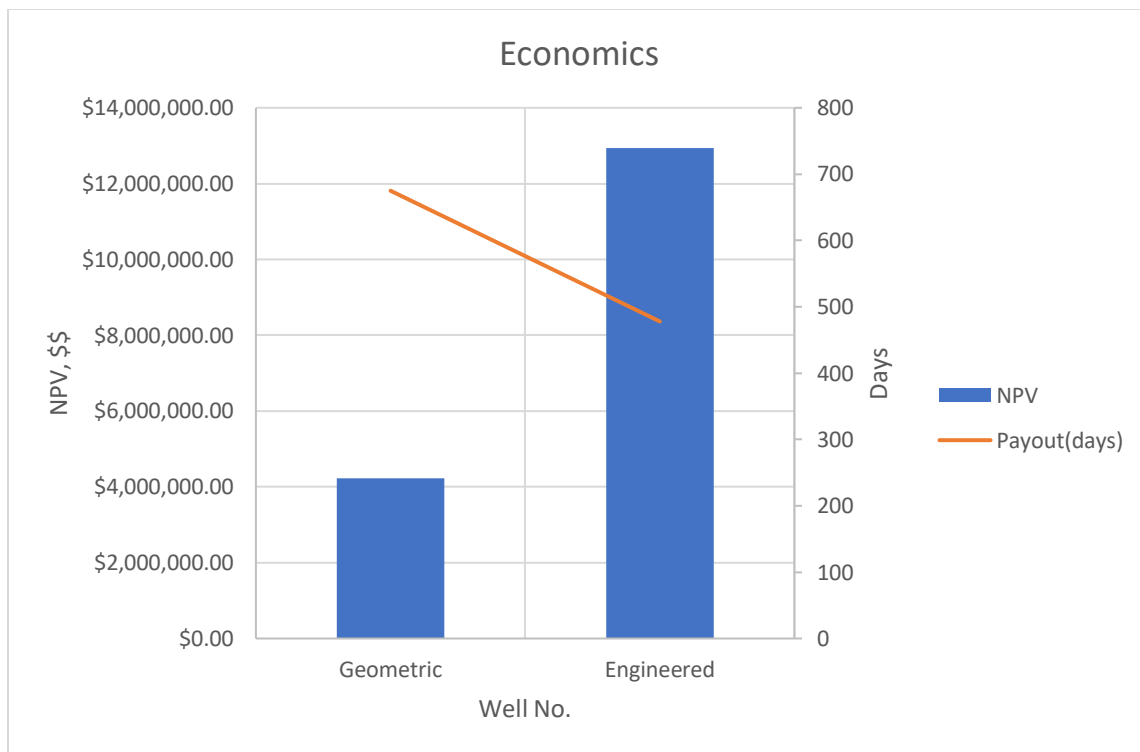


Figure 18. The result of Economics Analysis in Graphs. The blue column shows NPV of Geometric and Engineered design and the red linear graph shows payout days.

Conclusion

The innovative, cost-effective technology presented in this paper provides to the completion engineers an optimized completion design directly upon the conclusion of the drilling operation. This surpasses conventional completion optimization methods which take many days to perform. This methodology provides a reliable solution to the scarcity of well data in unconventional reservoirs. Reservoir variability is captured and incorporated into engineering designs to improve the



economics of every well. A fast and improved unconventional wells management can be achieved by integrating the completion optimization, hydraulic fracturing design, production forecasting, and economics into a single software platform.

The case study emphasized the ability of the surface drilling data to provide a simple solution that is based on drilling data available at every well, resulting in a significant productivity optimization without any significant additional cost.

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