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Application of Decline Curve Analysis to Unconventional Reservoir

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Application of Decline Curve Analysis to Unconventional Reservoir

Ahmed Wasel AlQattan

This problem report is submitted to the Benjamin M. Statler College of Engineering and Mineral Resources at West Virginia University in Partial fulfillment of the requirements for the degree of

Master of Science

In Petroleum and Natural Gas Engineering

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ABSTRACT

Application of Decline Curve Analysis to Unconventional Reservoir

Ahmed AlQattan

The oil and gas industry has been dealing with the unconventional reservoirs for about only two decades. Consequently, many challenges remain in evaluating the unconventional reservoirs. A few of these obstacles are the absence of the adequate production history, understanding the fluid flow regime after hydraulic fracturing, and estimating the drainage volume of the reservoir. One of the essential elements for evaluation of the oil and reservoir is to estimate the production rates over time in order to investigate the economic potential of the project.

Decline Curve Analysis (DCA) is most common the methodology for predicting the production rates over the time based on past production data. However, conventional DCA methods cannot be applied to unconventional reservoir due to lack of sufficient and consistent past production history. Accordingly, several DCA methods (Arps, PLE, SPED, and Duong) have been proposed to estimate the production over time for unconventional reservoirs. However, their reliability and accuracy remain uncertain.

In this problem report, field production data from hydraulically fractured horizontal wells completed in Marcellus Shale will be analyzed using different DCA methods for unconventional reservoirs. Accordingly, this will lead to a better understanding which DCA method can provide accurate predictions of the future production rates from the unconventional reservoirs.

ACKNOWLEDGEMENTS

I deeply appreciate all the support given by my research advisor Dr. Kashy Aminian, the chair of my advisory committee. In addition, I also would like to acknowledge my committee members. Furthermore, I am deeply very appreciative for my family for the mental and emotional support during this wonderful journey.

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q = Flow rate, volume/time

D = Initial decline rate, 1/ time

q_0 = Initial rate, volume/time

D_∞ = Loss ratio at (t=∞), 1/time

$D1$ = Loss ratio at (t=1), 1/time

Q = Cumulative production, volume

G_p = Cumulative gas production, volume

a = Vertical axis intercept of q/G_p vs. time plot, dimensionless

m = Slope of log-log plot of q/Gp vs. time plot, dimensionless

$t(a,m)$ = Duong time function, dimensionless

q_1 = Slope of q vs. t(a,m) plot, volume

q_∞ = Vertical axis intercept of q vs. t(a,m) plot, dimensionless

n = Constant loss ratio or time ratio, dimensionless

τ = Characteristic time constant

Γ = Gamma function, dimensionless

Introduction and Problem Statement

Oil and gas industry specially in the western world have been investing a lot of money in the unconventional resource within the last two decades. Accordingly, it has become very essential for the oil and gas industry to evaluate the future recoverable oil and gas for accurate economic evaluation. Since the past production for unconventional reservoir is not readily available, it has become essential for the - industry to employ the most advanced techniques to obtain the most reliable economical value.

One of the common approaches for estimating the future recoverable hydrocarbon is the Decline Curve Analysis (DCA) models. The DCA models are developed based on the past production data to predict the future production over time. The first models of the DCA was developed in 1945 by Arps. It is applicable to a reservoir under boundary dominated flow (BDF) conditions. However, it has been recognized that this method leads to overestimation when applied to a reservoir with long transient flow period such as gas shale reservoir. To avoid overestimating the future production, new DCA models have been developed. These new models include the Power law Exponential Decline (PLE), Stretched Exponential Decline (SPED), and Doung Method. However, the reliability and accuracy of these new models remain uncertain for ultra-low permeability shale reservoirs.

CHAPTER 2. LITERATURE REVIEW

2.1 Background

The oil and gas reservoir are either classified as conventional reservoir or unconventional reservoir. The conventional reservoir is defined as the reservoir which has high permeability and it can be produced with the conventional methods. On the other hand, the unconventional reservoir is defined as the reservoir with low permeability and requires application of the advanced technologies such as horizontal well and hydraulic fracturing to make it economically viable. The hydraulic fracturing method is consisted of injecting water with proppants under high pressure. The high pressure would allow the fracture to open and the proppants to enter the fracture to assure the fracture would remain open once the injection has ceased. Furthermore, horizontal drilling has been utilized in the recent years and it has shown tremendous result in term of increasing the production due to the increased contact with the reservoir.

There have been an intense focus on unconventional reservoir development in recent years since it has become profitable. Particularly in countries with significant unconventional resources such as United State of America (USA). The development of the unconventional reservoir has strengthened the national economy and providing significant natural gas supply which is a cleaner-burning energy.

2.2 Flow Regimes:

Oil or gas well encounter several flow regimes during their life. The flow regimes that are encountered in a horizontal well completed in an ultra-low permeability formation include linear flow, fracture interference flow, linear flow in un-stimulated matrix, and boundary dominated flow (Joshi, 2013). The flow regime can be determined by plotting flow rate against time on log-log scale. The first flow regime is usually which can be identified with a negative half-slope linear trend on the log-log plot. This linear flow regime will last until the fracture boundary is reached. The fracture interference flow regime usually occurs when fracture stages are spaced closely. The fracture interference flow regime is considered to

be a boundary dominated flow. The linear flow in un-stimulated matrix will generally occur later followed by pseudo-steady state which is also a boundary dominated flow.

2.3 Reserve Estimation:

The initial step of estimating the reserve is through computing the mount of the movable oil or gas based on saturation, which can be obtained by laboratory analysis, and based on the boundaries of the reservoir structure. This method provides a preliminary estimate of the reserve and usually is undertaken to make the decision for the operator whether the field is profitable or not. The Decline Curve models are developed to obtain more accurate estimate of the reserve when sufficient production history becomes available. The predictions by DCA usually becomes more accurate as more data is compiled through the time. However. Different DCA models have been proposed which can be applied to determine the production based on the characteristics of the field. The common DCA models used in the industry are discussed illustrated in the following sections.

2.3.1 Arps Decline Model

The first method to use past production rates to estimate the future production rates was introduced by developed by Arps in 1945. Arps method is based on the three different curves which are Exponential, Hyperbolic, and Harmonic.

The Arps general decline curve equation is as follow:

$$q = qo/(1 + \text{bDt})^{-1/b} \ldots\ldots..(1)$$

Where:

$$q_0 = intial \text{ stabilized } rate$$

$$D = initial\ decline\ rate$$

$$b = constant\ loss\ ratio$$

When the "*b*" is *0*, the decline curve becomes is exponential and when the "*b*" is *1*, the decline curve becomes harmonic. If the "b is *0* and *1*, the decline curve is hyperbolic. The application of the hyperbolic decline curve to production data from the shale reservoirs often leads to a value greater than *1* for "*b*". This can be attributed to the long transient period associated with the ultra-low shale permeability. The prediction using a value greater than *1* for "*b*" results in over-estimation of the future production rates and the reserves.

2.3.2 Power Law Exponential Decline Model (PLE)

The power law exponential (PLE) decline curve was introduced in 2008 by Ilk et al to overcome the over-estimation due to application of the Arps method in low permeability reservoirs. This model was developed to provide a better estimate for the future production rates when the past production includes data from both the transient and boundary dominated periods. Therefore, it is a good candidate for application in unconventional formations. The PLE Model is as follows:

$$q \ = \ q_0 \, exp\left(-D\infty \, t - \frac{D1}{n} t^n\right)........(2)$$

Where: $q_0 = intial \ rate$

$D = Arps' decline \ constant$

$D_\infty = loss \ rato \ at \ (t = \infty)$

$D_1 = loss \ rato \ at \ (t = 1)$

$n = time \ exponent$

It can be observed that PLE is a power law function in the early times since "$D_\infty \, t$" term is insignificant. On the other hand, at later times as "$D_\infty \, t$" term becomes significant, the model is approaches exponential decline. Furthermore, the cumulative production cannot be developed since "$D_\infty \, t$" term is an infinite.

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2.3.3 Stretched Exponential Decline Model (SEPD):

This method was developed by Valko (2009). It was based on fitting the past production data dominated by the transient flow regimes. The SPED Model is as follows:

$$q = qo\ exp\left(-(\tfrac{t}{\tau})^n\right)........(3)$$

Where:

$$q_0 = intial\ production\ rate$$

$$\tau = characteristic\ time\ constant$$

$$n = exponent$$

The cumulative production can be determined as follows:

$$Gp = \tfrac{q0\tau}{n}\{r\left(\tfrac{1}{n}\right) - r\left(\tfrac{1}{n}, (\tfrac{\tau}{n})^n\right)\}........(4)$$

Where:

$$Gp = cumulative\ production$$

2.3.4 Duong Model

This model is developed based on the assumption that the ratio of production rate to cumulative production against time is straight line when plotted on a log-log scale. Two equations are used for this model as follows:

$$\tfrac{q}{G_P} = at-^m....................(5)$$

$$Where: q = flowrate$$

$$G_p = cumulative\ production$$

$$a = vertical\ axis\ intercept\ of\ log-log\ plot$$

$$m = slope\ of\ log-log\ plot$$

Accordingly, q_1 and q_∞ are correlated as follow:

$$q = q_1 t(a,m) + q_\infty \ldots\ldots\ldots(6)$$

Furthermore, the cumulative production can be determined as follows:

$$G_p = \frac{q_1 t(a,m)}{at - m} \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

This is when q_∞ is expected to be zero.

Chapter 3. Objective and Methodology

3.1 Objective

The objective of this study was to analyze the production data from a horizontal well producing from a shale gas reservoir to determine whether the DCA methods (Arps, PLE, SPED and Duong) will be able to provide reliable future production rates.

3.2 Methodology

To accomplish the objective, production data from two Marcellus shale horizontal wells (permit # 3527 and permit #1622) are selected and analyzed as describe in the following sections

3.2.1 Data collection and Filtration

The production data were obtained from the West Virginia Geologic and Economic Survey Database. Once the production data were obtained, the data were smoothed out by removing the outliers to establish a consistent decline trend.

3.2.3 Decline Curve Analysis (DCA)

The smoothed production history was divided into two sets for each well. The first sets (about one third on of the data) were selected for DCA to obtain the parameters for Arps, PLE, SPED and Doung decline curves. The parameter for Arps, PLE, SPED methods were obtained by iterative approach using the "solver" in Microsoft-Excel to determine the best value for each parameter with least normalized errors. Meanwhile, the parameters of Duong's methods were obtained by first by plotting q/G_p against time to determine a and m values and then by plotting q against $t(a,m)$.

Then, the decline curve models were utilized to predict the production rates for the same time period as the second sets. Finally, the predicted production rates by different models were compared against the actual production rates in the second sets.

Chapter4. Results and Discussion

4.1 Well (1)

Figure 1 illustrates the entire production history of well (1). As it can be seen from Figure 1, there is little anomaly in the decline trend. The first outliers occur at 22 and 33 months. These outliers could occur due to operational problems or errors in reporting. The other outliers occur during between 88 and 125 months. These anomalies can be attributed to the fluctuations as the well is approaching the end of its life.
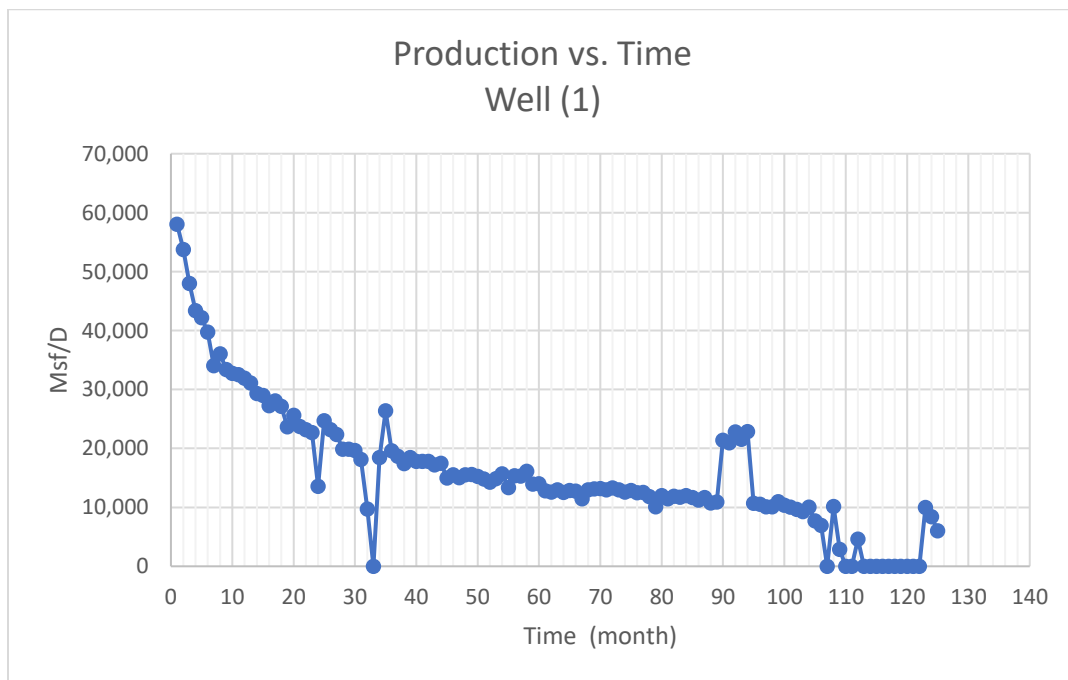

Figure 1. The Entire Actual Production Data for Well (1)

Figure 2 shows the three anomalies sections. The first and the second anomalies will be averaged out and the third anomaly will be removed.
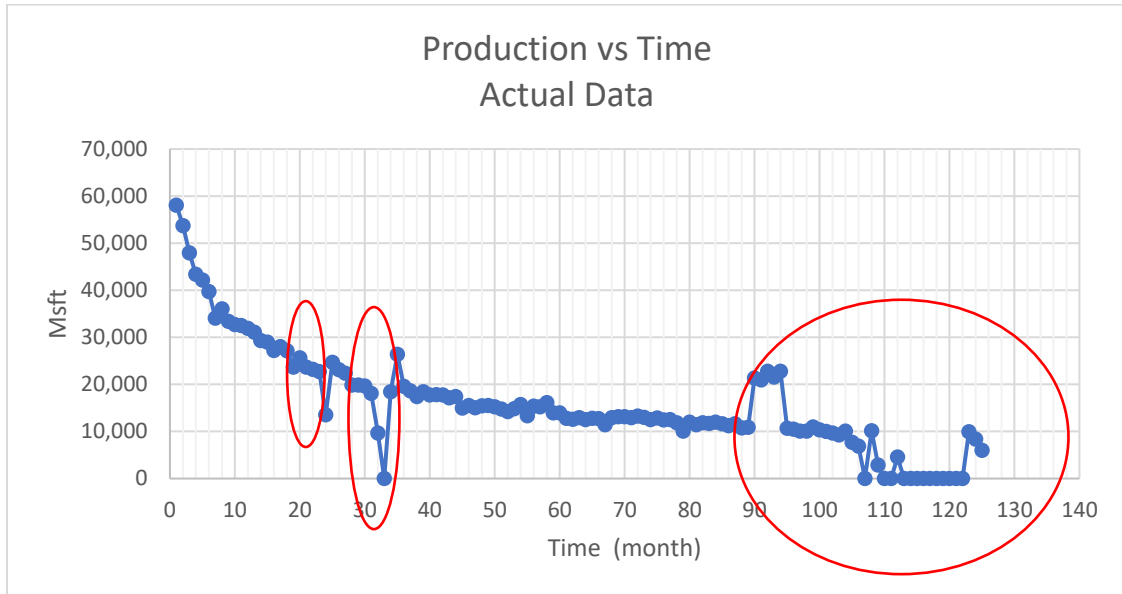

Figure 2. Identifying Anomalies for Well (1)

Figure 3 illustrates the clean production without the anomalies, so the production time frame is now 89 months
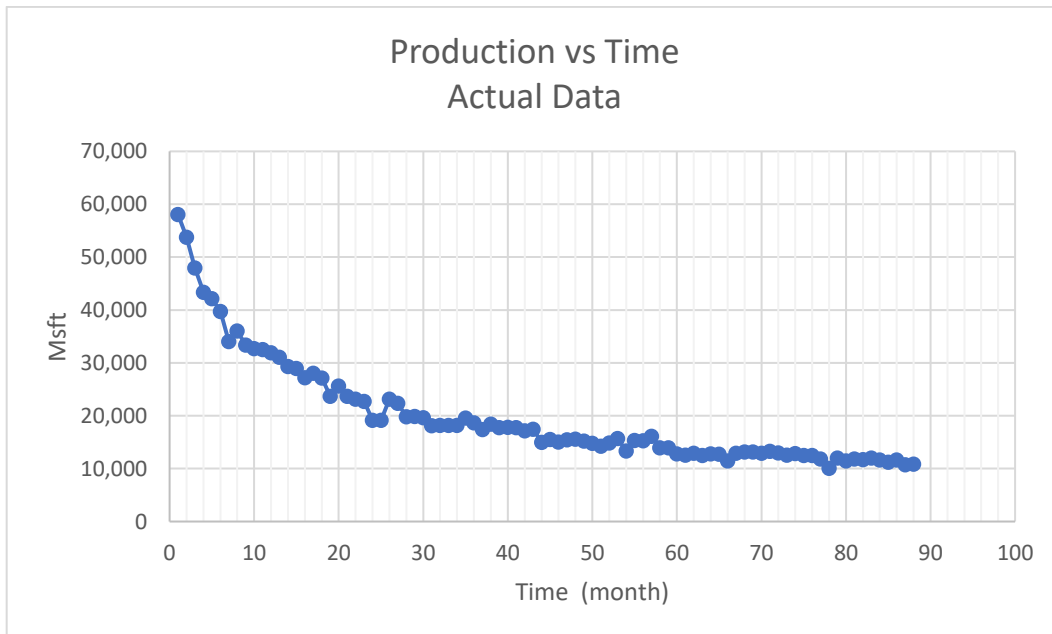

Figure 3. Entire Clean Actual Data for Well (1)

Figure 4 illustrates the first one third of the clean data (30 months) to be used for DCA to come up with
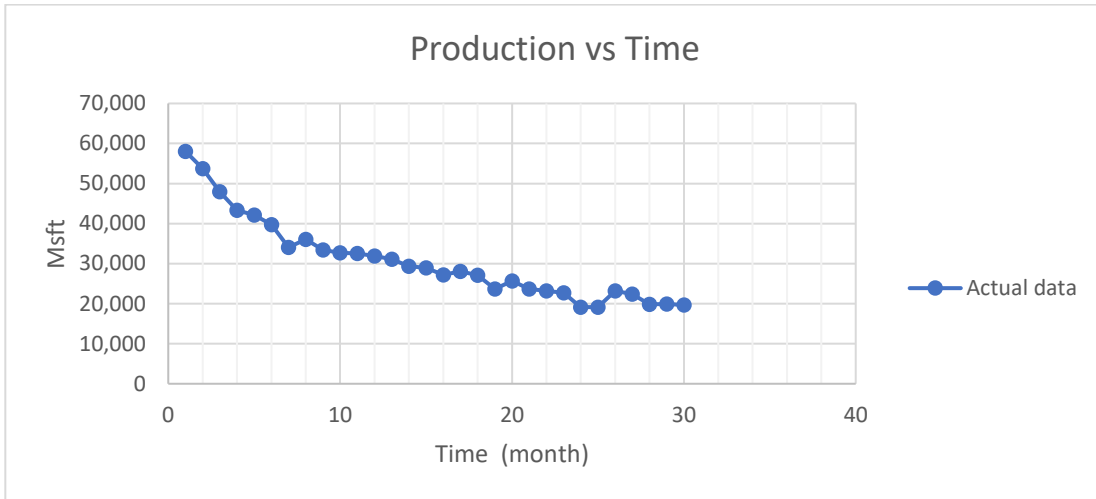
parameters for different decline curves.

Figure 4. Set 1 of Well (1) Clean Actual Data

Figure 5 illustrates the rest of the clean data to be used for comparison   to validate the predicted rates

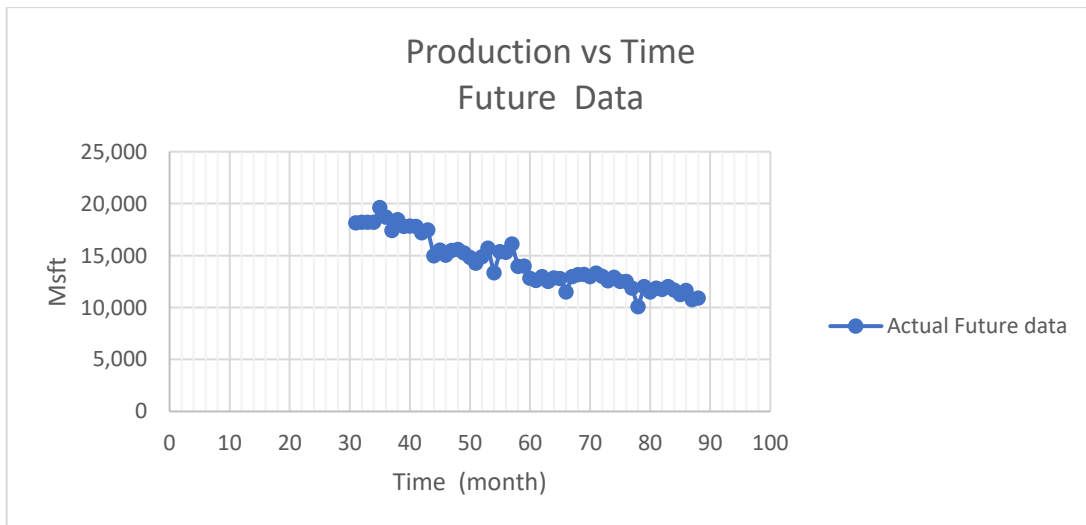by different DCA methods.

Figure 5. Set 2 of Well (1) Clean Actual Data for Future Testing

Figure 6 represents the DCA for different decline curves to obtain the parameters. As is it seen from

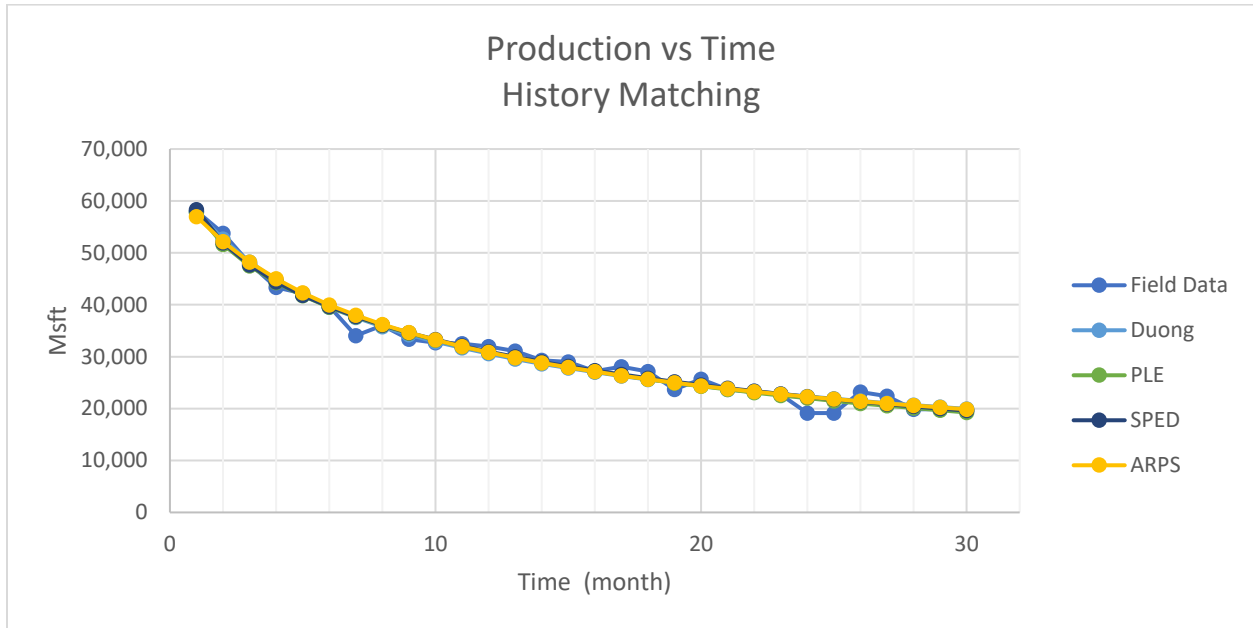Figure 6, All decline curves can be matched well with the data.

Figure 6. Decline Curve Matching - for Well (1)

Table 1 represent the DCA parameters obtained during the history match section.

Table 1. Obtained Parameters of DCA Methods for well (1)

Obtianed Parameters for DCA Methods			
ARPS parameters			
q_o	D	n	
63235.1955	0.112982088	1.612214063	
Doung Parameters			
a		m	
1.0557		1.14	
SPED Parameters			
q_o	τ	n	
82599.4429	12.56935006	0.417321737	
PLE Parameters			
q_o	D∞	D1	n
79999.9989	0.001059329	0.32358	0.42915

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Figure 7 illustrates the predicted production rates based on all the decline curve methods using the obtained parameters and comparing them with the actual data. As it can be seen from figure 7, all the decline curves perform well in predicting the future production rates. Furthermore, Arps and Duong predictions are closer to the actual rates.
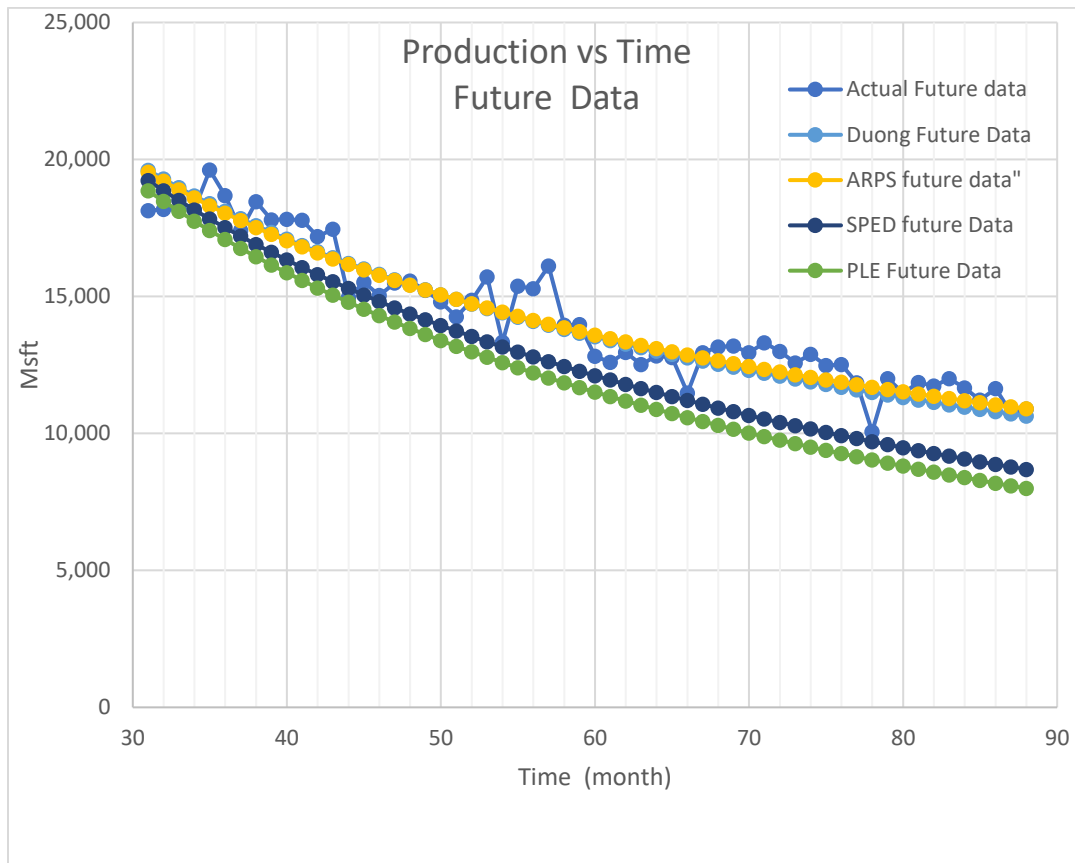

Figure 7. Decline Curve Predictions Compared to Well (1) Production Rates

Table 2 represents the R-square values of DCA methods for the predictions. It can be observed that Arps, Doung, and SPED have R-square values of more than 90%. However, R-square for PLE is less than 90% and it could be due to the fact the PLE requires four parameters where the other DCA methods require only three parameters.

Table 2. DCA Methods R-square Values for the Predicted Production Rates from Well (1)

DCA Method	ARPS	Doung	PLE	SPED
R Sequare	0.98382	0.98249	0.85202	0.91129

Figure 8 illustrates the entire production for all the DCA methods and compares them with the entire actual data. As it can be seen from figure 8, all the decline curve methods perform well. Furthermore, Arps and Duong are declining similarly over the time. On the other hand, PLE and SPED declining similarly over the time.
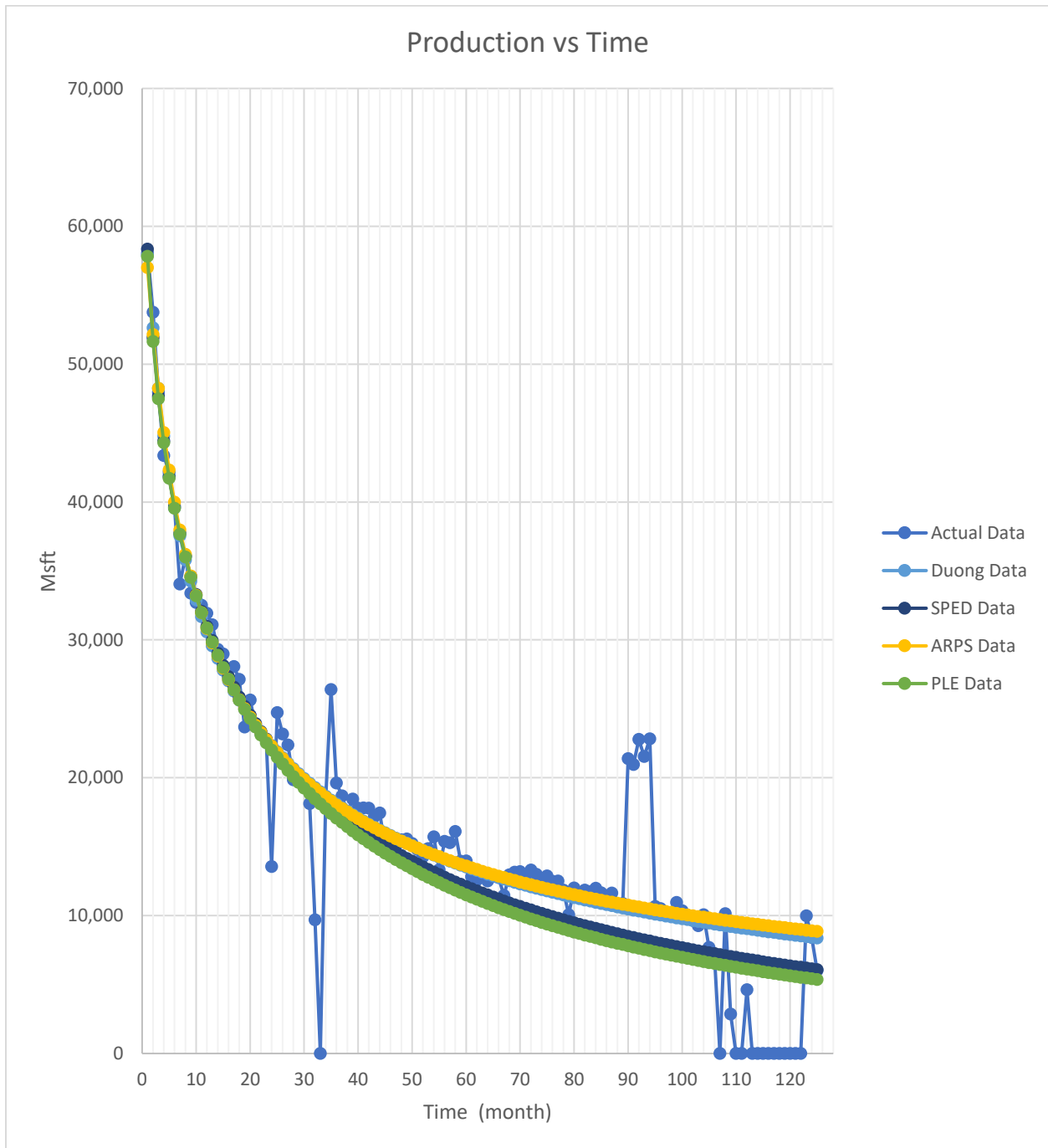

Figure 8. Decline Curve Methods vs. the Entire Data for Well (1)

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4.2 Well (2)

Figure 9 illustrates the entire production history of well (2). As it can be seen from Figure 9, there is little

anomaly in the decline trend. The first outliers occur at the first month. This outlier could occur because

the well is cleaning after fracture treatment. The other outliers occur during between 49 and 85 months.

These anomalies can be attributed to the operational issues as the well is approaching the end of its life.
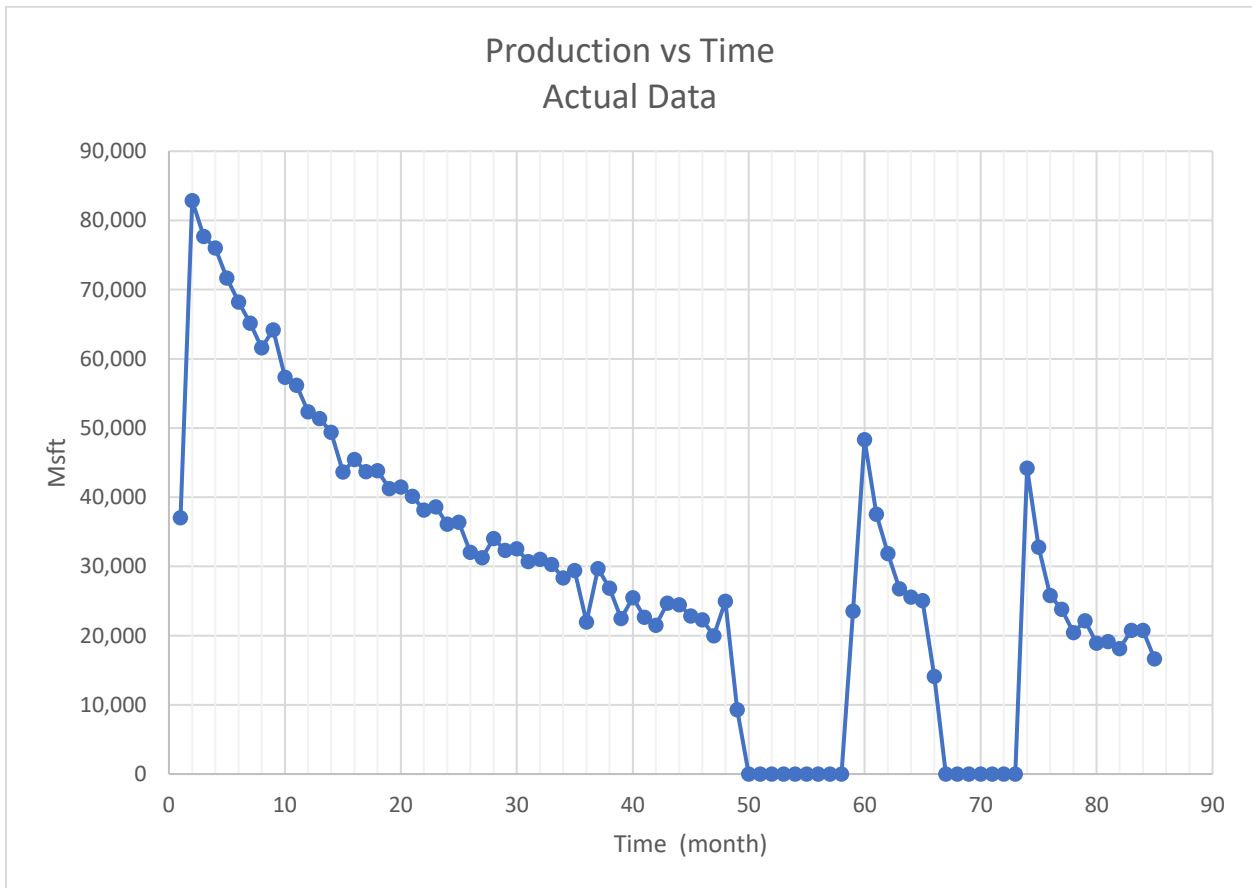

Figure 9. The Entire Actual Production Data for Well (2)

Figure 10 shows the two anomalous sections. The first and the second anomalies will be removed
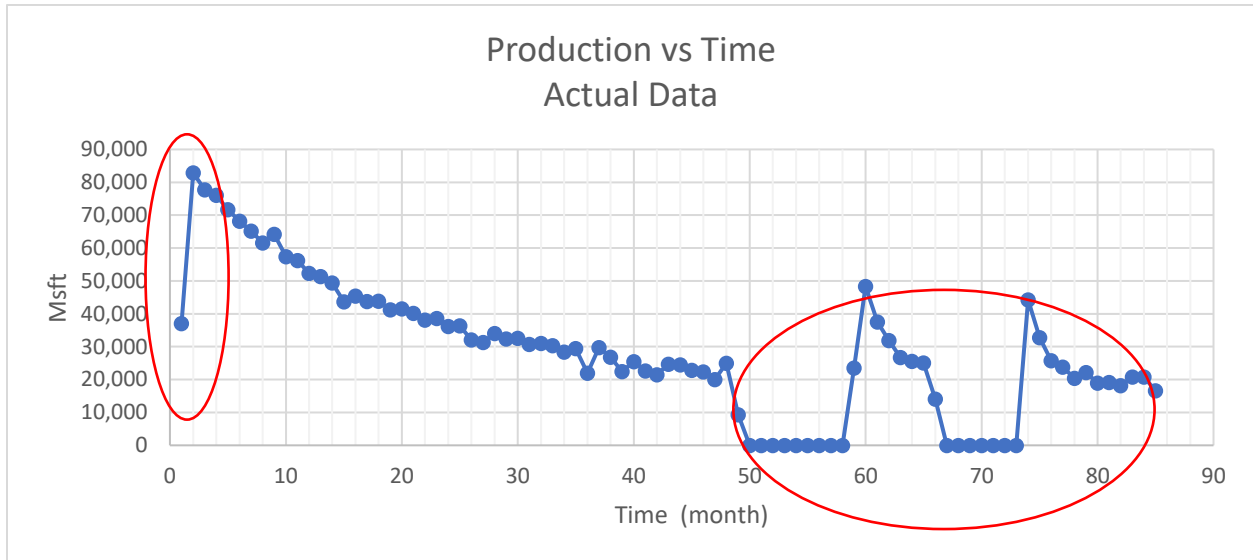

Figure 10. Identifying Anomalies for Well (2)

Figure 11 illustrates the clean production without the anomalies, so the production time frame is now
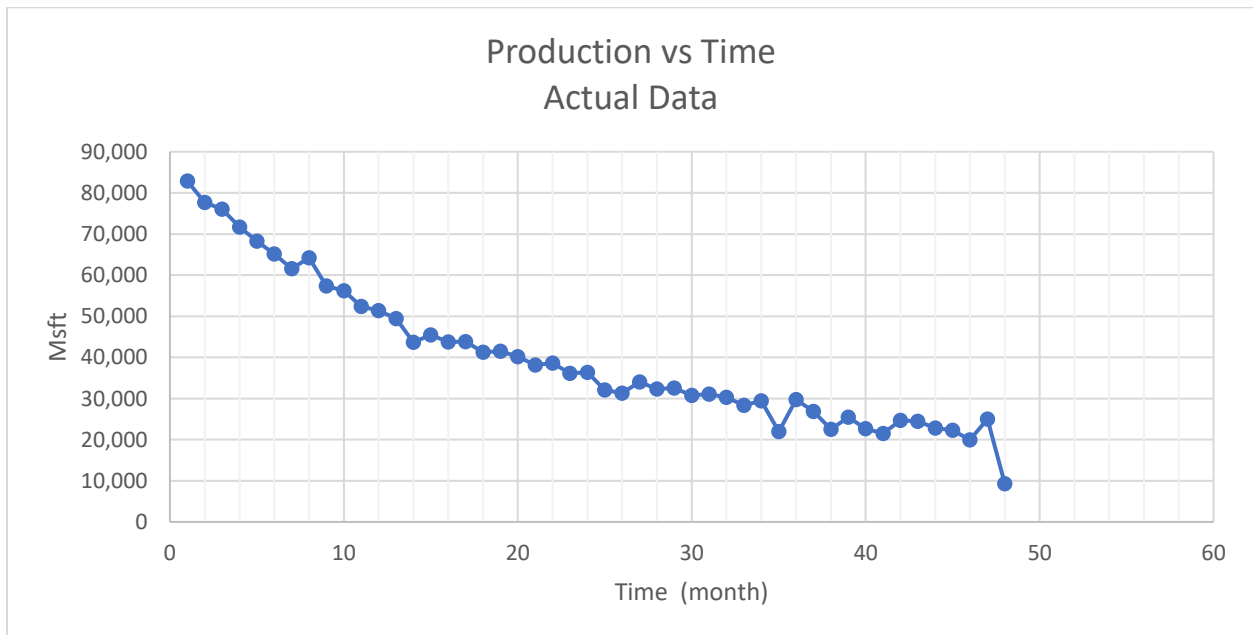
49 months

Figure 11. Entire Clean Actual Data for Well (2)

Figure 12 illustrates the first one third of the clean data (15 months) to be used for DCA to come up with parameters for different decline curves.
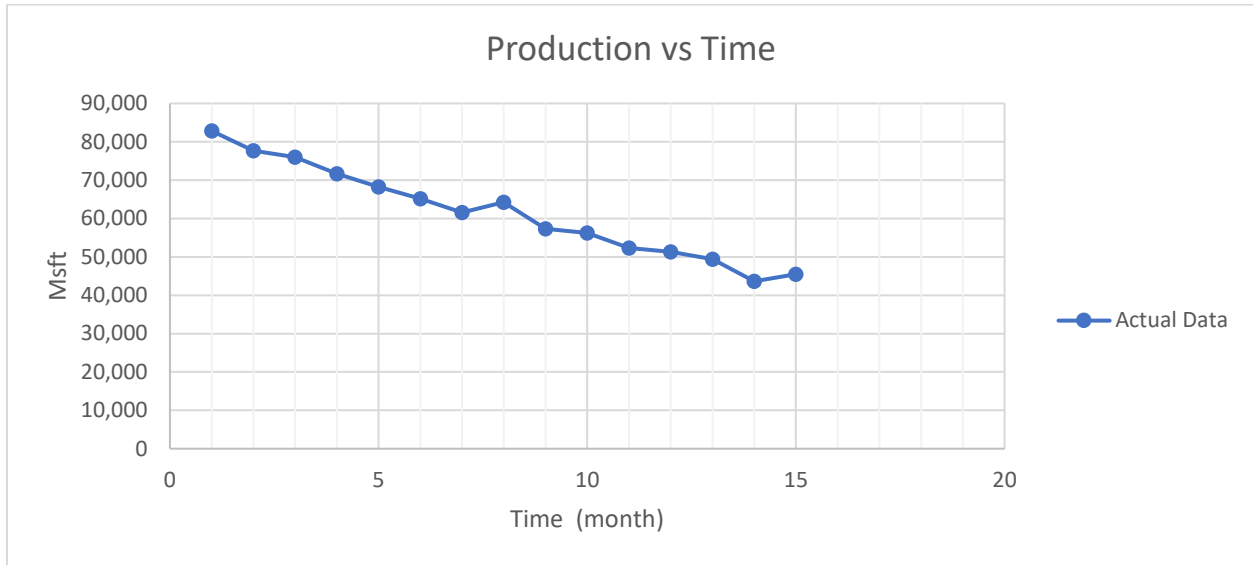

Figure 12. Set 1 of Well (2) Clean Actual Data

Figure 13 illustrates the rest of clean data to be used as comparison to validate the predicted rates by different DCA methods.
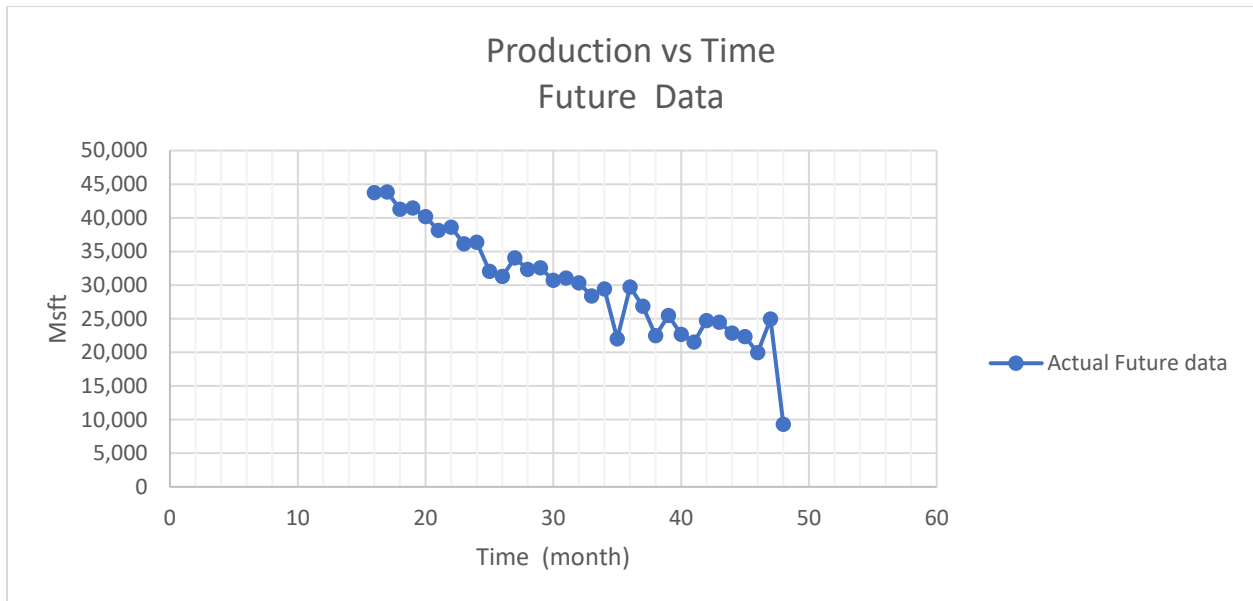

Figure 13. Set 2 of Well (2) Clean Actual Data for Future Testing

Figure 14 represents the DCA for different decline curves to obtain the parameters. As is it seen from Figure 14, All decline curves can be matched well with the data.

Figure 14. Decline Curve Matching - forWell (2)

Table 3 represents the DCA parameters obtained during the history match section.

Table 3. Obtianed Parameters of DCA Methods for well (2)

Obtianed Parameters for DCA Methods			
ARPS parameters			
q_o	D		n
85921.216	0.0575482		1.1
a		m	
1.0713		1.123	
SPED Parameters			
q_o	τ		n
85338.654	22.6988479		1.027646713
PLE Parameters			
q_o	D∞	D1	n
94516.515	0.04413521	0.0951064	0

Figure 15 illustrates the predicted production rates based on all the decline curve methods using the obtained parameters and comparing them with the actual clean data. As it can be seen from Figure 15, all the decline curves did not perform well in predicting the future production rate. This is probably due to the fact the data for history matching is not big enough since it is only fifteen months. Therefore, the history matching period will be increased to 30 months for further investigation.
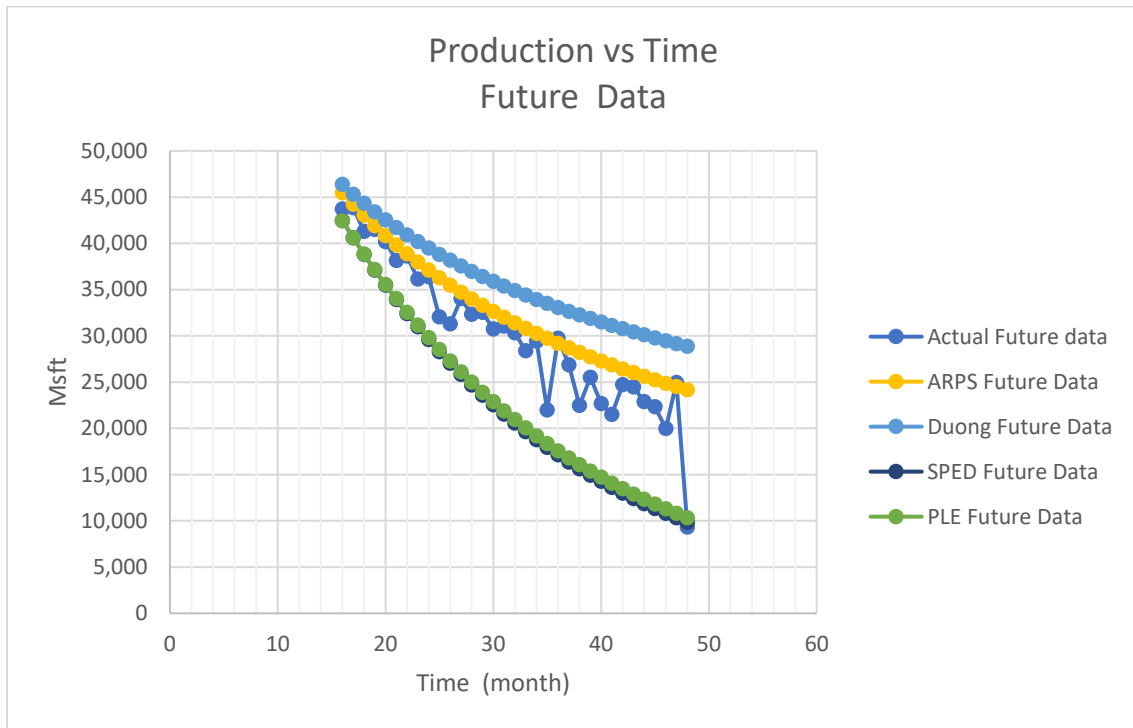

Figure 15. Decline Curve Predictions Compared to Well (2) Production rate

Table 4 represents the R-squares values of DCA methods for the predictions. It can be observed all the R-squares values are low. This is probably due to the fact the history match was only for 15 months.

Table 4. DCA Methods R-squares Values for the Predicted Production Rates from well (2)

DCA Method	ARPS	Doung	PLE	SPED
R Sequare	0.90732	0.71364	0.59714	0.56303

Figure 16 illustrates the entire production for all the DCA methods and compares them with the entire actual data. As it can be seen from Figure 16, all the decline curve methods did not perform well. So, a new case with longer history match time (30 moths) will be investigated. Furthermore, Arps and Duong are declining similarly over the time. On the other hand, PLE and SPED declining similarly over the time.
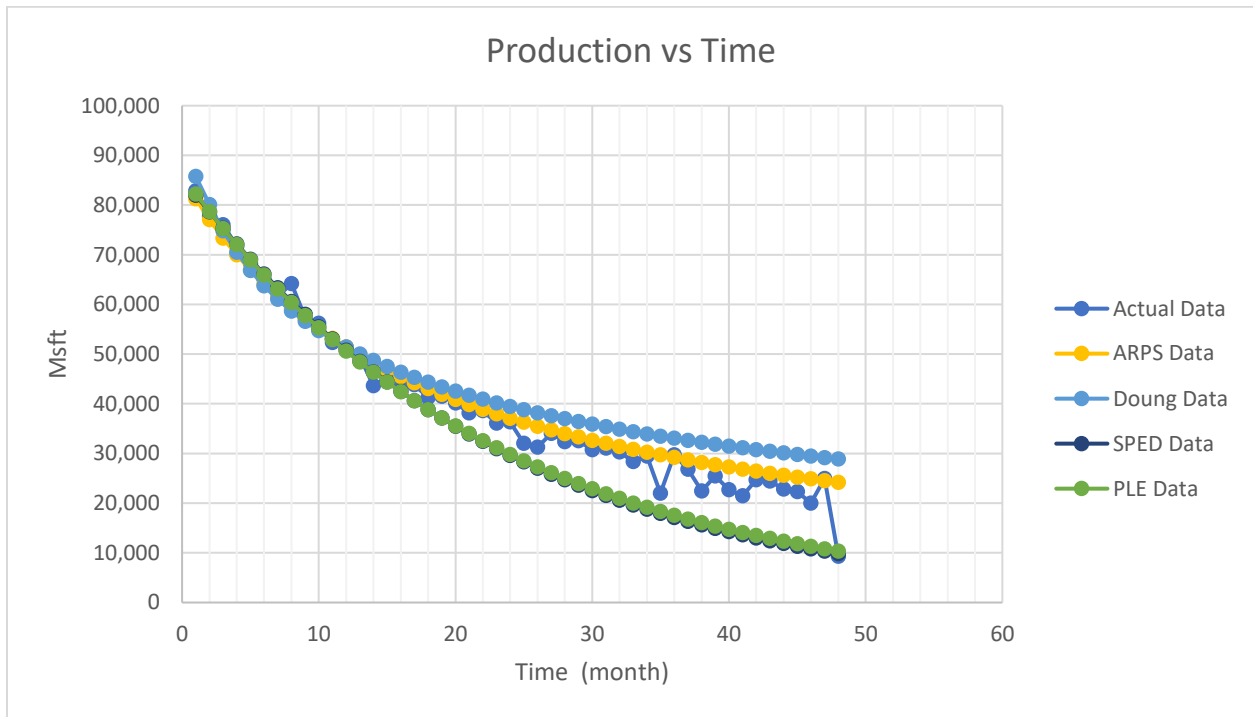

Figure 16. Decline Curve Methods vs. the Entire Data for Well (2)

4.3 New Case for Well (2)

Figure 17 illustrates a new case of well 2 which represents the first two third of the clean data (30 months) to be used for DCA to determine the parameters for different decline curves.
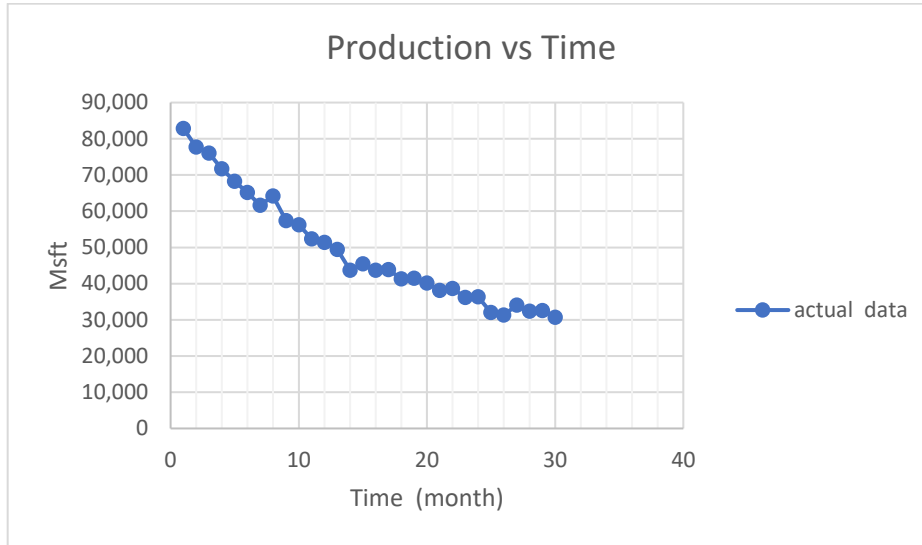

Figure 17. New Set 1 Of Well(2) Clean Actual Data

Figure 18 illustrates the rest of clean data to be used for comparison to validate the predicted rates by different DCA methods.
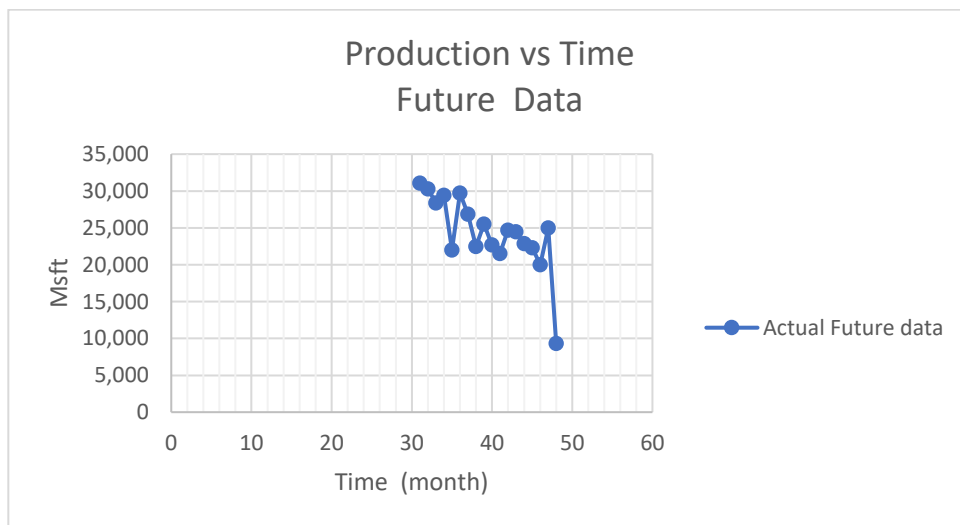

Figure 18. New Set 2 Of Well (2) Clean Actual Data for Future Testing

Figure 19 represents the DCA for different decline curves to obtain the parameters. As is it seen from Figure 19, the data can be matched well with all decline curves.

Figure 19. Decline Curve Matching - for New Case of Well (2)

Table 7 represent the DCA parameters obtained during the history match section.

Table 5. Obtained Parameters of DCA Methods for New Case of Well (2)

Obtianed Parameters for DCA Methods			
ARPS parameters			
q_o	D	n	
88842.2364	0.05987075	0.909064244	
Doung Parameters			
a		m	
1.1356		1.163	
SPED Parameters			
q_o	τ	n	
95716.2663	24.3000418	0.666831754	
PLE Parameters			
q_o	D_∞	D1	n
94516.5155	0.00885443	0.110609	0.611974587

Figure 20 illustrates the predicted production rates based on all the decline curve methods using the obtained parameters and comparing them with the actual data. As it can be seen from Figure 20, all the decline curves perform well in predicting the future production rate. This is probably due to the fact the data for history matching have been increased to 30 months.
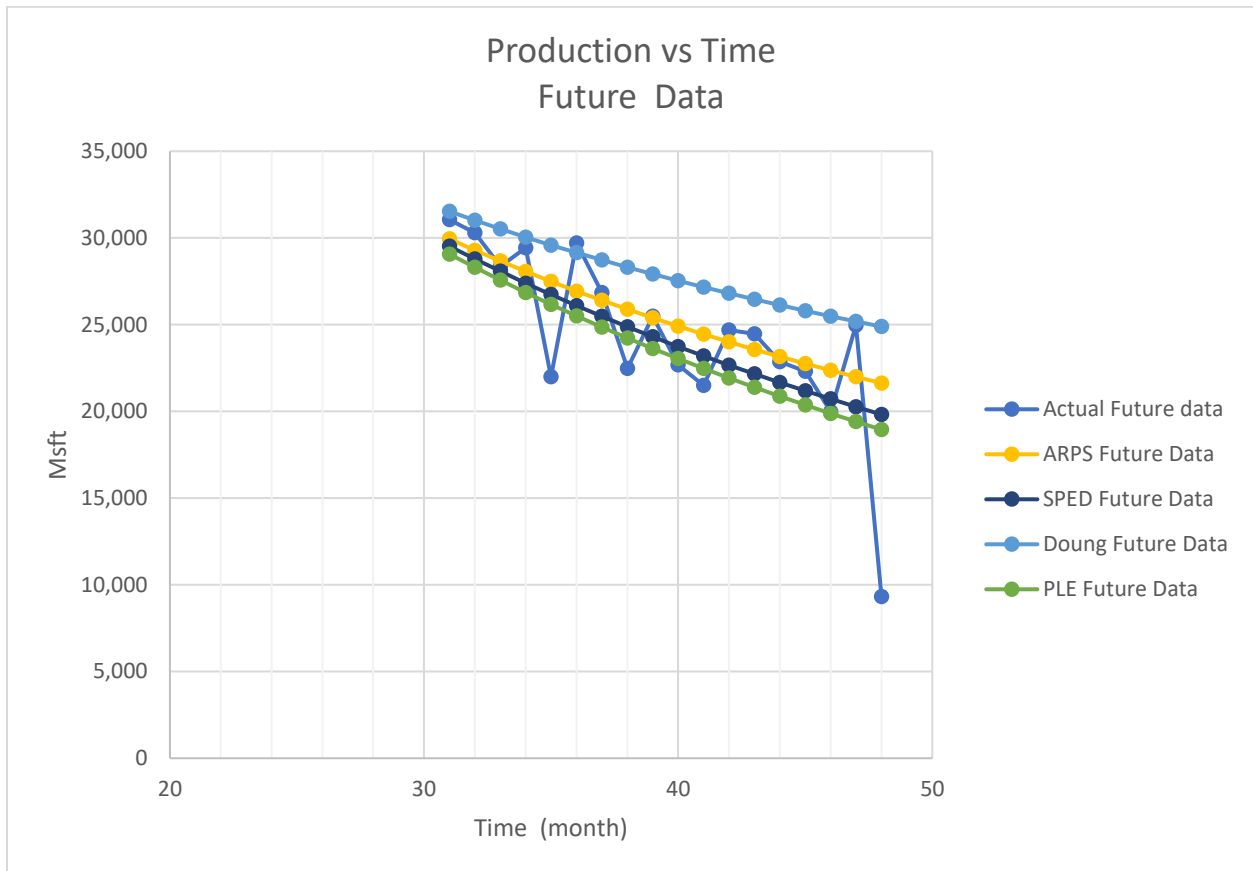

Figure 20. Decline Curve Predictions of the New Case Compared to Well (2) Production Rates

Table 8 represents the R-square values of DCA methods for the predictions. It can be observed that Arps, Doung, and SPED have R-square values higher than 90%.

Table 6. DCA Methods R-square Values for the Predicted Production Rates from New Case of Well (2)

DCA Method	ARPS	Doung	PLE	SPED
R Sequare	0.95067	0.90205	0.95584	0.95748

Figure 21 illustrates the entire production for all the DCA methods and compares them with the entire actual data. As it can be seen from Figure 21, all the decline curve methods perform well since the history match period is increased to 30 months. Furthermore, Arps and Duong are declining similarly over the time. On the other hand, PLE and SPED declining similarly over the time.
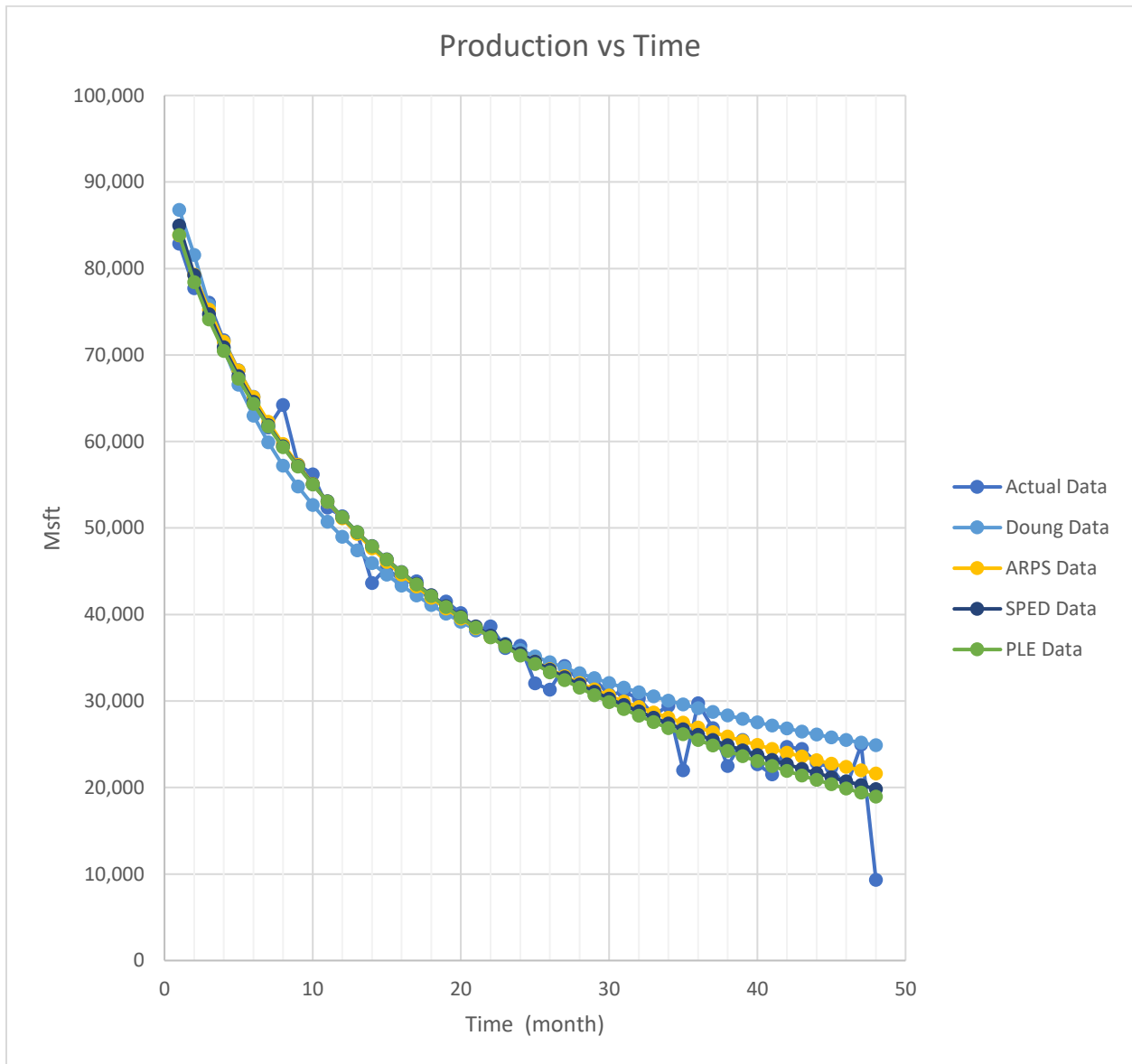

Figure 21. Decline Curve Methods of the New Case vs. the Entire Data for Well (2)

Chapter 5: Conclusions and Recommendations

The below are the conclusions that were observed in this report:

➢ Duong, Arps, SPED, and PLE decline curves can provide reasonable estimates of the future production rates provided sufficient production history is available to reliably determine the parameters of the different decline curves.

➢ The predicted production rates by Duong and Arps methods are similar as their decline trends with the time appear to be similar.

➢ The predicted production rates by SPED and PLE methods are similar but they appear to have steeper declines compared to Arps and Duong methods.

It is recommended that the investigations in this report be applied to additional horizontal Marcellus Shale well with different number of hydraulic fracture stages to further evaluate the applicability and reliability of different decline curve methods.

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