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Impact of Stimulation Treatments on Production Performance of Horizontal Wells in the Marcellus Shale

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**Impact of Stimulation Treatments
on Production Performance
of Horizontal Wells in the Marcellus Shale**

Kimberly L. Larch

**Thesis 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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2012**

**Keywords: Marcellus Shale; Stimulation; Hydraulic Fracturing
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ABSTRACT

Impact of Stimulation Treatments on Production Performance of Horizontal Wells in the Marcellus Shale

Kimberly L. Larch

The interest in exploitation of ultra-low permeability formations, such as the Marcellus Shale, has increased in the recent years. Shale formations require massive stimulation treatments to achieve economic production. The recent advances in horizontal drilling and multistage hydraulic fracturing have proved successful in achieving commercial production. However, the parameters that directly affect lifetime production of the wells have not been well established.

The primary objective of this study is to examine the effects of basic stimulation parameters used in hydraulic fracturing of Marcellus Shale wells on production performance. Historical production data and stimulation treatment information have been collected and analyzed for a number of horizontal wells both in West Virginia and Pennsylvania. A commercial reservoir simulator which utilizes a dual porosity model and accounts for adsorbed gas was utilized for history matching and predicting the long term production performance. The impact of the stimulation parameters including the number of stages, stage spacing, the volume of water used, and the volume of sand used on production performance was investigated. Examination of the results revealed that stage length and stage spacing impacted the initial production of a horizontal well, but did not necessarily promote greater recovery. It was also identified that the volume of water per stage and the volume of sand per stage correlated to 10-year predicted cumulative production. Increased production resulted from both larger sand and larger water volumes.

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Table of Contents

Abstract.....	ii
Acknowledgements.....	iii
List of Tables.....	v
List of Figures.....	vi
Chapter 1: Introduction.....	7
Chapter 2: Literature Review.....	10
Chapter 3: Methodology.....	15
Chapter 4: Results and Discussion.....	17
Chapter 5: Summary and Conclusions.....	36
Chapter 6: Recommendations.....	38
Bibliography.....	39
Appendix A.....	40
Appendix B.....	46
Curriculum Vitae.....	53

List of Tables

Table 4.1: Initial data set.....	17
Table 4.2: Initial data set technical data averages.....	17
Table 4.3: Range of fracturing parameters in final study group.....	21
Table 4.4: ECLIPSE base model parameters.....	25
Table 4.5: Fracture characteristics of modeled wells.....	27
Table 4.6: Modeling cumulative results.....	30
Table 4.7: Modeling results based on number of stages.....	31

List of Figures

Figure 1.1: Extent of the Marcellus Shale.....	7
Figure 1.2: Marcellus tiers and producing wells.....	8
Figure 2.1: Extent of U.S. shale gas plays.....	10
Figure 2.2: Devonian stratigraphic column.....	11
Figure 2.3: Illustration of horizontal drilling and hydraulic fracturing.....	12
Figure 2.4: Detailed illustration of hydraulic fracturing.....	13
Figure 3.1: Methodology flowchart.....	16
Figure 4.1: Technical well data statistics versus date.....	19
Figure 4.2: Completed horizontal wells by county and state.....	20
Figure 4.3: Map of Greene and Wetzel County study wells.....	22
Figure 4.4: Fracturing parameters versus production.....	23
Figure 4.5: Model generated by ECLIPSE.....	24
Figure 4.6: Marcellus Shale thickness map.....	26
Figure 4.7. Model parameters varied during history matching.....	28
Figure 4.8: Study well S2 daily flow rate and cumulative production curves.....	29
Figure 4.9: Stage length versus cumulative predicted production.....	32
Figure 4.10: kh versus 10 year predicted production.....	32
Figure 4.11: Production per stage versus water volume per stage.....	33
Figure 4.12: Production per stage versus sand volume per stage.....	34
Figure 4.13: Production per stage versus water-sand ratio.....	35

Chapter 1

Introduction

The Marcellus Shale is a significant source of natural gas located in the Appalachian Basin. This black organic shale is prolific in size—underlying sections of Pennsylvania, West Virginia, Ohio, and New York. Figure 1.1 shows the extent of the Marcellus Shale in the Appalachian Basin. Current studies estimate that 487 trillion cubic feet of recoverable reserves with 50% probability are present in the Marcellus Shale (Engelder, 2009). This large quantity of natural gas is located very strategically in regards to geography, and will become an invaluable source of energy for industrial processes in the Northeastern areas, Eastern Seaboard, and Great Lakes region of the United States.

Figure 1.1: Extent of the Marcellus Shale. (“Marcellus Shale”, 2012).

Located 4,500 feet to 8,500 feet underground, the natural gas in the Marcellus Shale is accessed and produced most efficiently by using innovative horizontal drilling practices in combination with massive hydraulic fracturing stimulation treatments. These technologies allow enormous amounts of gas to be released from each individual well. Horizontal drilling makes it

possible to contact and produce large portions of the reservoir from one surface location. The total drainage area of horizontal wells is many times larger than the area drained by traditional vertical wells in the same target zone. The well stimulation practice known as hydraulic fracturing creates micro-fissures in the rock and permits fluid flow, thus allowing natural gas and other hydrocarbons to be produced. In the Marcellus Shale, this stimulation is crucial to the production of natural gas because of the ultra-low permeability of the rock.

As of June 2011, over 3,000 Marcellus Shale wells have reportedly been drilled, as recorded by the West Virginia and Pennsylvania Departments of Environmental Protection. Thousands more have been permitted to be drilled in the future. Figure 1.2, created by Northeast Natural Energy (NNE), illustrates the location of the majority of these wells, represented by the red dots. The wells shown in the Figure were reported to be horizontal, Marcellus Shale wells producing natural gas as of December 2011. As would be expected, drilling activity has mainly

Figure 1.2: Marcellus Tiers and Producing Wells. (Courtesy of NNE).

been concentrated around the most productive regions of the shale. As shown in Figure 1.2, these areas are located in Southwestern Pennsylvania (Greene County) and Northeastern Pennsylvania (Bradford and Susquehanna Counties). With the recent decline in natural gas prices, a significant portion of drilling activity has moved to the western portions of the shale, because wet gas has been determined to be produced by the formation there, and is a more lucrative venture. The color tiers shown in Figure 1.2 delineate areas that geologists have determined to be potentially the most productive based on electrical logs, petrophysical analysis, seismic interpretation, formation thickness, thermal maturity, and state reported production information. The light red areas designate the most productive zones, then decreasing to the pink zones, and finally the orange and yellow zones.

With this background understanding of horizontal drilling and hydraulic fracturing, this study will seek to more clearly understand the relationship of certain specific hydraulic fracturing parameters to the overall lifetime productivity of horizontal Marcellus Shale wells.

Chapter 2

Review of Literature

Section 2.1: Shale Deposits

Shale deposits have recently been identified as an extremely significant and widespread source of energy in the form of natural gas, and occasionally oil. Shale is more widely present across the world than conventional oil and natural gas formations. These “unconventional” gas plays have recently been identified as huge sources of domestic energy for the United States. Figure 2.1 below shows the extent of shale gas play in the lower forty-eight states, and it is easily observable how significant these shales will be for the United States energy future due to the sheer size and widespread distribution of these plays.

Figure 2.1: Extent of U.S. shale gas plays. (EIA, 2008)

As mentioned in the introduction, the Marcellus Shale is a huge part of the domestic energy future involving natural gas. The Marcellus is conveniently located near very industrially active cities and heavily populated areas of the northeastern part of the United States. This location itself makes the play extremely important. Secondly, the sheer size and available recoverable reserves from this formation are astounding. It has been predicted that drilling activities could be present in the shale for the next thirty years with production from these wells for the next sixty to ninety years!

Section 2.2: Horizontal Drilling in the Marcellus Shale

In terms of stratigraphy, the Marcellus Shale is located in the Middle Devonian geological group (NETL, 2010). Figure 2.2 shows the stratigraphic column in this region. Historically, operators in the Appalachian Basin have produced many of the gas sands located above and below the Marcellus Shale. The Marcellus has long been known as a very gaseous

Period		Group/Unit	
Penn		Pottsville	
Miss		Pocono	
Devonian	Upper	Conewango	
		Conneaut	
		Canadaway	
		West Falls	
		Sonyea	
		Genesee	
	Middle	Tully	
		Hamilton Group	Moscow
			Ludlowville
			Skaneateles
			Marcellus
		Onandaga	
	Lower	Tristates	
		Helderberg	

Figure 2.2: Devonian stratigraphic column. (NETL, 2010)

rock and has caused drillers problems for decades. However, not until recently with the improvements and combination of horizontal drilling and hydraulic fracturing has it been possible to produce the gas from this zone in an economic manner. Horizontal drilling, as implied by the name, allows drillers to steer the drill bit and bottom hole assembly in such a manner that the wellbore actually turns horizontally. Because of this, it is now possible to access the gas-filled rock through direct contact with the wellbore for thousands of feet, in comparison to conventional vertical drilling that only contacted the formation as a function of the zone's natural thickness. Figure 2.3 illustrates these concepts of horizontal drilling in combination with hydraulic fracturing.

Figure 2.3: Illustration of horizontal drilling and hydraulic fracturing.

("Virginia Department of Mines," 2006)

Section 2.3: Hydraulic Fracturing

Hydraulic fracturing has many different applications and purposes. Some of the most important and pertinent to the Marcellus Shale include the following: to increase the flowrate of oil and/or natural gas from low permeability reservoirs, to connect the natural fractures in the

formation to the wellbore, to increase the area of drainage or the amount of formation in contact with the wellbore, and to connect the full vertical extent of a reservoir to a horizontal wellbore (DOE, 2004). The stimulation practice known as hydraulic fracturing involves using intense pressures to create extremely small, but long cracks in a hydrocarbon containing rock. These fractures are achieved through pumping millions of pounds of sand, known as proppant, and thousands of gallons of water into the rock at high pressures. These pressures must overcome the in situ critical stresses that naturally occur in the rock in order to propagate the fracture out into the formation. These small cracks allow the hydrocarbons to naturally flow from the surrounding rock and into the wellbore, which is a lower pressure zone, and then successively to the surface for production and distribution. Figure 2.4 generally illustrates this process. This overall process is performed in sequential stages, as illustrated by Figure 2.3. These “stages” allow for smaller, focused areas of the rock to be fractured, and are separated by composite plugs, which isolate the previous stages from the subsequent stages.

Figure 2.4: Detailed illustration of hydraulic fracturing. ("What is Hydraulic Fracturing," 2012)

Section 2.4: Simulation Modeling

In this project, the majority of the work involving the commercial reservoir simulator, ECLIPSE, was based on a previous study performed at the West Virginia University Department of Petroleum and Natural Gas Engineering by Mr. Hossein Belyadi entitled “Production Analysis of Marcellus Shale”. In his research, Belyadi developed a base model for both vertical and horizontal wells in Upshur County, West Virginia (Belyadi, 2011). This study was a great foundation for understanding the fundamental settings and model design when using ECLIPSE. The current study modifies this base model to predict the long-term production of wells located in the Marcellus Shale in a more comprehensive manner. The model incorporates many of the complex reservoir properties that are present in the Marcellus Shale. These properties include horizontal wellbore, multiple fractures, dual porosity, adsorbed gas, hydraulic fracture geometry and characteristics, and in situ rock properties. ECLIPSE is based around a template style system. All pertinent information concerning the reservoir and the stimulation are initially built into this template. The template then generates a three-dimensional model of the well and subsequently performs flow and production analysis from this model.

Chapter 3

Methodology

The primary objective of this study was to examine the basic stimulation parameters used in hydraulic fracturing of Marcellus Shale wells and their relationship to lifetime production performance of these wells. With these recent advances in technology and the combination of horizontal drilling and hydraulic fracturing, multistage fracturing operations have proved extremely successful. However, the fracturing parameters that most directly affect the overall lifetime production of these unconventional shale wells are not well established. The optimization of these parameters could result in the increased ultimate recovery of hydrocarbons from the shale, thus increasing the net present value of each well. The parameters under evaluation in this study include the number of hydraulic fracturing stages in a horizontal well, the stage spacing or length, the volume of water used per stage, and the volume of sand injected per stage.

The objectives of this study were achieved through several different means. A flowchart for the methodology used in this research is shown in Figure 3.1.

. Historical production data was acquired from completed Marcellus Shale wells throughout the states of West Virginia and Pennsylvania. Additionally, well completion and stimulation data as reported to state agencies was gathered. Commercial reservoir modeling software was used for history matching and production forecasting. First, the necessary data was collected from the various state agencies. This data was then narrowed and a small, final set of study wells was chosen. The characteristics present in these wells were evaluated and examined. In parallel to this, a basic model was developed and refined for predictive production evaluation of horizontal shale wells. This model was then used to history match the historical production of selected study wells. This process developed a refined predictive model in four different areas of the Marcellus Shale. The results of the history matching were then analyzed and conclusions were drawn for each fracture parameter examined.

Figure 3.1: Methodology Flowchart.

Chapter 4

Results and Discussions

Section 4.1: Data Collection

All electronically available completion and production information was collected for horizontal Marcellus Shale wells in West Virginia and Pennsylvania. Table 4.1 below shows the statistics of the data set collected for all horizontal Marcellus Shale wells.

Table 4.1: Initial data set.

Data Statistic	West Virginia	Pennsylvania
Permitted Horizontal Wells	387	2,803
Completion Reported	103	683
Production Reported	71	1,016
Operators	13	28
Counties	10	27

In West Virginia, completions data was gather from the database website, West Virginia Copy, www.wvcopy.com. Every individual completion form for each well was compiled into a Microsoft Excel database manually. The data was current as of July 2011. Production information in West Virginia was gathered as published on the website of West Virginia Department of Environmental Protection Office of Oil and Gas, www.dep.wv.gov/oil-and-gas. The most recent production information in West Virginia was current as of December 2010.

Table 4.2: Initial data set technical data averages

Statistical Average	West Virginia	Pennsylvania
Vertical Depth	7,030 ft	7,247 ft
Measured Depth	11,311 ft	10,754 ft
Lateral Length	3,309 ft	3,385 ft
Number of Stages	10.4	10.2
Stage Length	357 ft	343
Total Water Volume	103,482 bbl	93,302 bbl
Total Sand Volume	4,064,032 lbs	4,226,242 lbs
Pumping Rate	87.6 bpm	73.4 bpm

Similarly in Pennsylvania, completions and production information was gathered on a well-by-well basis through the Pennsylvania Internet Record Imaging System (PA IRIS) ONBASE server at www.pairis.state.pa.us/dcnr/. Completion data was reported up to August 2011 and production data was reported up to December 2011.

Generalized trends were examined from this large initial data set in order to gain a better understanding of the type of completion styles that were being used by operators basin-wide. As shown in Table 4.2, technical data given in this large data set provides a baseline for understanding the broad range of fracturing parameters being used by operators. Slight variations seen between the data average for each state can be primarily attributed to the depth and rock property differences present in the different areas of the Marcellus Shale. Figure 4.1 represents on an individual basis the information averaged in Table 4.2 and arranged by date. It is easily observable that the completion trends have changed as a function of time. This can be related to an increased understanding of the reservoir and an improvement in drilling and stimulation technologies as more wells have been drilled into the shale. It is now possible to drill longer wells, some over 6,000 feet long, thus enabling more hydraulic fracturing stages to be completed. It is interesting to note that stage lengths have slightly decreased since the first wells were drilled in 2007. The effect of stage length on lifetime production will be addressed later in this study. Included in Appendix A are graphs showing the sand amount versus date (Figure A1), the volume of fluid versus date (Figure A2), and the average pumping rate versus date (Figure A3).

Also of interest is the location and density of the activity in both West Virginia and Pennsylvania. Figure 4.2 shows the number of horizontal Marcellus Shale wells completed by county and state. This shows that the northern panhandle of West Virginia is very active, which could be contributed to the fact that there is wet gas in this region. As expected, counties located in the “hot spot” regions of Pennsylvania as discussed above in Figure 1.2 are the major targets of drilling. Figure 4.2 also illustrates that the activity has been more widespread in Pennsylvania than it has been in West Virginia.

Figure 4.1: Technical well data statistics versus date. .

Figure 4.2: Completed horizontal wells by county and state.

Section 4.2- Narrowing Data and Selecting Study Wells:

After the initial data was collected, criteria were defined in order to narrow the data set and choose specific wells to history match. First, the well was required to have both reported production and completions data. Secondly, in order to be able to perform history matching later in the study, wells were required to have at least two years of reported production data. Third, the reported completions data had to contain the number and length of fracturing stages, the sand

volume and mesh sizes used, and the amount of water used during hydraulic fracturing. These three criteria eliminated a large number of wells in the initial data set. Next, this smaller group of wells was mapped. Wells that were not geographically located near other horizontal Marcellus Shale wells were eliminated. From this, a small group was defined for four different areas and will be discussed in further detail later. Finally, the production from this group was further examined in order to determine that a normal production trend was present, and that the production had not been noticeably impacted by outside, uncontrollable conditions, such as pipeline availability.

Following this detailed elimination process, twenty-six horizontal Marcellus Shale wells were chosen as the final study group. These wells represent the Marcellus Shale in four different areas—Greene County, Pennsylvania; Lycoming County, Pennsylvania; Susquehanna County, Pennsylvania; and Wetzel County, West Virginia. Table 4.3 provides a detailed summary of the range of the fracturing parameters that were present in the final study group. Figure 4.3 shows the geographic location of each of the Greene County, Pennsylvania and Wetzel County, West Virginia study wells. Additional maps of the Lycoming County (Figure A4) and Susquehanna County (Figure A5) wells are included in Appendix A.

Table 4.3: Range of fracturing parameters in final study group.

Parameter	Maximum	Minimum
Lateral Length (feet)	1,333	4,632
Stage Length (feet)	213	615
Volume of Water (barrels)	7,545	18,132
Volume of Sand (pounds)	250,355	979,820

Figure 4.3: Map of Greene and Wetzel County study wells. (Courtesy of NNE).

Section 4.3- Examining Characteristics Under Study:

General comparisons were still possible in this smaller study group. Figure 4.4 shows comparisons of the critical fracturing parameters under examination in comparison to the actual production of these wells. With two years of production, neither Figure 4.4A nor 4.4B show a distinct relationship between the number or length of stages and the actual production. However, these charts represent that the data set chosen for further examination has a large range of fracture characteristics and associated production, which proved helpful in defining a model for a diverse group of wells. Figure 4.4C and 4.4D also show that there is no apparent relationship between the volume of water or sand used per stage during the stimulations and the gas production of the well at two years. These relationships are further examined later in this paper in relation to predicted production.

Figure 4.4. Fracturing parameters versus production.

Section 4.4- Development of Basic Model:

As noted in the methodology section, the commercial reservoir simulator ECLIPSE, designed by Schlumberger, was used to evaluate these wells further. Reservoir simulation provides a method in which to predict the future performance of an individual well, in this case. Hossein Belyadi initially developed the base model originally used in this research (Belyadi, 2011). The model was constructed on the basis of a dual porosity system and adsorbed gas model. ECLIPSE has the ability to model horizontal wells with multi-stage hydraulic fractures, while also incorporating these shale specific properties. ECLIPSE is also very helpful in that it generates 3-D images of the well, reservoir, and hydraulic fractures, as shown in Figure 4.5.

Figure 4.5: Model generated by ECLIPSE.

Table 4.4 shows all of the critical parameters that are needed to generate a predictive model in ECLIPSE. Obviously, several of these parameters, such as depth, thickness, lateral length, reservoir pressure, number of stages, and stage length, were varied based on the individual physical attributes of the particular well being studied. The parameters that were adjusted during the history matching process are designated in light purple in Table 4.4. These parameters will be further discussed in detail later. Formation thicknesses were determined for each county. In Greene County, pilot wells were already a part of the selected group, so actual

Table 4.4: ECLIPSE base model parameters

Base Parameters	Starting Value	Unit
Depth	7,000	Feet
Thickness	75	Feet
N. Fracture Porosity	0.002	Fraction
Matrix Porosity	0.05	Fraction
N. Fracture Permeability	0.002, 0.002, 0.0002	md
Matrix Permeability	0.0002, 0.0002, 0.0002	md
Rock Compressibility	1×10^{-5}	1/psia
Density	100	Lb/ft ³
Reservoir Pressure	3000	psia
Water Saturation	0.15	Fraction
H. Fracture Half Length	500	Ft
H. Fracture Width	0.01	In
H. Fracture Porosity	0.2	fraction
P_{wf}	500	Psia
Gas Diffusion Coefficient	1	ft ² /day
H. Fracture Permeability	20,000	Md
Stage Length	250	Ft

thickness measurements were used during modeling. In the remaining three counties, formation thickness was determined from publically available maps. For example, Figure 4.6 shows the thickness map used to determine the average thickness in Wetzel County, West Virginia. Figure A6, included in the Appendix is the thickness map used for the Pennsylvania counties. The following values were chosen to represent the reservoir thicknesses of the wells in each county—Lycoming, 250 feet; Susquehanna, 175 feet; and Wetzel, 50 feet. Additionally, pressure gradients were gathered for each of the areas either directly from operators in the study area or from published maps and ranged from 0.49 psi/ft to 0.69 psi/ft.

Figure 4.6: Marcellus Shale thickness map. (NETL, 2010).

Section 4.5- Testing against Historical Production and Refining of Basic Model:

Fourteen of the twenty-six wells in the study were chosen to be modeled using ECLIPSE. These wells were chosen based on certain characteristics that set them apart from the other wells, such as, but not limited to, large or small production, many stages, short stage lengths, or a large water to sand ratio.

Table 4.5 shows the wells that were chosen to be modeled along with the specific fracture characteristics of each well that this study examined. These wells were re-named based on their county name in order to protect operator information associated with API numbers. For example, study well G1 is located in Greene County. The number value assigned is completely arbitrary.

The number of fracture stages per well ranged from 6 to 15 stages. Fracturing stage lengths varied from 213 feet in study well S1 to 586 feet in study well W3. In terms of water per stage, some operators used as little as 7,500 barrels during stimulation while other wells were fractured with almost 15,500 barrels per stage. Similarly, the sand per stage varied from 343,000 pounds to 960,000 pounds per stage. This wide range of parameters not only shows that the industry is generally undecided on what individual parameters need to be, but that research is needed and necessary in this particular area in order to optimize the process.

Table 4.5: Fracture characteristics of modeled wells.

ID	# Frac Stages	Stage Length (ft)	Water (bbl)/ Stage	Sand (lbs)/ Stage	Prod to Date (MCF)
G1	11	295	10,164	402,431	2,657,992
G2	8	296	8,949	355,068	1,380,134
G3	7	258	8,844	343,637	1,162,212
L1	10	309	15,278	772,280	1,771,329
L2	8	325	15,428	959,878	1,480,622
L3	8	292	12,695	592,138	1,033,018
S1	15	213	8,556	385,500	3,771,317
S2	6	222	8,859	397,809	2,101,892
S3	8	294	7,545	385,750	1,373,854
S4	10	326	9,221	378,435	1,601,791
S5	7	351	11,532	585,657	3,168,380
W1	9	391	9,648	367,566	1,504,675
W2	8	579	10,936	538,566	971,924
W3	7	586	10,613	560,846	742,707

Section 4.6- Development of Final Model:

All fourteen of these wells were modeled using ECLIPSE. Multiple runs were required for each well to ensure that the predicted production of the well matched the reported production. The drainage area of each well was modeled so that the reservoir had a four to one length to width ratio. However, one thousand feet was set as the minimum width of a reservoir, no matter

what the length. In addition to this, in the case of Greene and Wetzel counties, where the Marcellus is less than 100 feet thick, the well bore was placed in the center of the formation, and the fracture height was defined to be that same thickness. In Lycoming and Susquehanna counties, the Marcellus Shale is considerably thicker. It is well known that the majority of operators place the well bores in these counties in the lower, more organic rich section of the shale. For this reason, all wells in Lycoming and Susquehanna counties were modeled with the wellbore being placed in the center of the bottom 100 feet of the Marcellus. The fracture height was limited to that lower section of 100 feet as well. In order to match the predicted production to the actual recorded production of each individual well, three parameters were varied. A detailed list is shown in Figure 4.7. First, the fracture half-length was determined to be most representative when modeled between 275 feet and 500 feet. This parameter alone drastically impacted the predicted production curve. Variation of fracture half length caused the predicted production curve to shift along the y-axis. Secondly, the natural fracture permeability (also known as Bulk X-direction Permeability) ranged between 0.002 millidarcy to 0.02 millidarcy (md). This parameter greatly affected the production of the well after it had been active for several years. It is important to note that the majority of study wells had what would be considered “normal” natural fracture permeability between 0.002 md and 0.004 md. Lastly, varying the hydraulic

Well ID	Fracture Half Length (ft)	Bulk X-direction Perm (md)	Fracture Porosity	Initial Back Pressure (psi)	Back Pressure after 3 months (psi)
G1	500	0.010	0.20	250	250
G2	350	0.002	0.10	1000	500
G3	300	0.004	0.20	850	350
L1	400	0.003	0.20	750	400
L2	500	0.010	0.10	300	250
L3	300	0.002	0.10	800	500
S1	500	0.004	0.20	700	550
S2	500	0.015	0.20	250	250
S3	275	0.002	0.10	1000	1000
S4	275	0.002	0.10	1000	850
S5	500	0.020	0.20	250	250
W1	500	0.004	0.20	500	500*
W2	500	0.002	0.10	1000	400*
W3	400	0.002	0.10	1000	800*

Figure 4.7. Model parameters varied during history matching.

fracture porosity from 10% to 20% affected the initial production of the well. In general, the model over predicted the initial production of the well because it assumed that the entire space occupied by proppant was completely filled by free gas that would be produced essentially instantaneously. In actuality, this space is occupied by water remaining from the stimulation process that has not yet been removed from the wellbore. Additionally, back pressure was incorporated into the model to account for any pipeline or flow restrictions and to adjust for the pressure created by flowback water being produced during the initial production period. Typically, for the first three months of a wells production, the back pressure was kept relatively high, in order match the actual first production data. After three months, the model relaxed pressure to allow for more normal flow conditions. For the cases in Wetzel County, the back pressure was reduced after the shut-in period.

For example, daily flow rate and cumulative production curves for study well S2 are shown in Figure 4.8. Actual production values are shown in red while model generated predicted

Figure 4.8: Study well S2 daily flow rate and cumulative production curves.

production is shown in blue. It is important to note that production data submitted to Pennsylvania was in the form of a six-month cumulative value. For this reason, only four actual production data points appear in the graph. Simple, mathematical adjustments were made in order to compare these values on an million cubic feet per day (MCF/D) level. However, in West Virginia, production was reported on a monthly basis. It is easily recognizable that the model does an almost perfect job of matching the actual production data points. All models were designed to generate predicted production values out to ten years from the initial production. Figure A7 and A8 included in Appendix A are the daily flow rate and cumulative production charts for well W3. This particular curve is interesting because the study wells in Wetzel County experienced a two to three month shut in period after initial production. The model was able to easily account for this shut in period, thus showing the versatility of predictive reservoir modeling and this model in particular. Appendix B contains the daily flow rate and cumulative production curves for every well that was modeled in this study.

Table 4.6 shows the results of the modeling in terms of actual production, predicted five-year cumulative production (“cum prod”), and ten year predicted cumulative production. In this Table, the green shading represents the highest values, yellow the intermediate values, and red the lowest values. This table is color coded by county to emphasize the best and worst producers in each county and observe the trends associated with each. More importantly and representative,

Table 4.6: Modeling cumulative results

Well ID	Prod to Date	1 yr ACTUAL Production	Pred (5 yr) Cum Prod	Pred (10 yr) Cum Prod
G1	2,657,992	2,024,032	3,343,115	3,734,306
G2	1,380,134	808,981	1,975,353	2,340,294
G3	1,162,212	643,412	1,662,640	1,940,938
L1	1,771,329	1,102,404	2,890,189	4,000,269
L2	1,480,622	1,139,395	2,908,553	3,919,399
L3	1,033,018	645,693	1,965,755	2,803,629
S1	3,771,317	2,494,387	5,451,907	6,526,425
S2	2,101,892	1,569,796	2,803,669	3,286,880
S3	1,373,854	796,348	2,570,427	3,428,411
S4	1,601,791	851,743	3,425,960	4,649,053
S5	3,168,380	1,693,612	4,550,500	5,568,024
W1	1,504,675	901,219	1,871,641	2,208,538
W2	971,924	667,845	2,030,529	2,745,825
W3	742,707	484,072	1,566,860	2,123,513

Table 4.7 shows the data for each of the wells on a per stage basis. It is much easier to draw comparisons and examine the data from each well when based on the number of stages. Many observations can be drawn from this information, and will be discussed further in the form of charts and graphs related to the individual fracture parameters under study. Table 4.7 shows that the number of stages does not necessarily correlate to increased production over the lifetime of the well. Study well S1, for example, has the most fracture stages in the study, but it does not have the best production. Table 4.6 shows that this well experienced a huge influx of gas at the beginning of its life (most likely due to a high concentration of natural fractures already present in the formation), but in terms of effectiveness of the stimulation, this wells predicted production at ten years per stage is very low in comparison.

Table 4.7: Modeling results based on number of stages.

Well ID	# Frac Stages	Actual Prod/ # Frac Stages	ACTUAL Prod/ # Stages	Pred Prod (5 yr)/ # Frac Stages	Pred Prod (10 yr)/ # Frac Stages
G1	11	241,636	184,003	303,920	339,482
G2	8	172,517	101,123	246,919	292,537
G3	7	166,030	91,916	237,520	277,277
L1	10	177,133	110,240	289,019	400,027
L2	8	185,078	142,424	363,569	489,925
L3	8	129,127	80,712	245,719	350,454
S1	15	251,421	166,292	363,460	435,095
S2	6	350,315	261,633	467,278	547,813
S3	8	171,732	99,544	321,303	428,551
S4	10	160,179	85,174	342,596	464,905
S5	7	452,626	241,945	650,071	795,432
W1	9	167,186	100,135	207,960	245,393
W2	8	121,491	83,481	253,816	343,228
W3	7	106,101	69,153	223,837	303,359

Section 4.7- Predictive Performance Analysis Based on Completion Characteristics:

The first fracture parameter under review is the effect of the number of stages on the production of a horizontal Marcellus Shale well. Figure 4.9 shows the results from the fourteen simulated wells. Ten year production was designated in the figure by the blue diamonds while the five year production is designated by the red squares.

Figure 4.10 below shows the plot of kh versus the ten year predicted production of the modeled wells. The permeability (k) graphed is the natural fracture permeability (x-direction) and the height (h) is the total formation height. This graph shows that there is a loose relationship between this derived value of permeability and height. This could be due to the fact that two of the four areas studied had very thick sections of Marcellus Shale.

Figure 4.9: Stage length versus cumulative predicted production.

Figure 4.10: kh versus 10 year predicted production.

The next fracture parameter under investigation was the amount of water used to stimulate a well per stage. Figure 4.11 demonstrates this parameter in relation to the production per stage at three different time periods, including the one year actual production. There is no observable correlation after the first year of actual production. However, a trend become observable after five years and is even more definitive after ten years of production. To further examine this relationship, a similar graph showing just Greene and Lycoming counties is included in Appendix A. In that case, the linear correlation is even higher at eighty three percent. Furthermore, it is important to note that Figure 4.11 only shows the data for wells in Greene County, Pennsylvania, Lycoming County, Pennsylvania, and Wetzel County, West Virginia. This is due to the fact that the pressures observed in Susquehanna County, Pennsylvania were so significantly higher than the three other areas that the predictions in that area were scaled differently, even though there is an identifiable relationship between the wells in this county collectively. Figure A9 showing the relationship in Susquehanna County may be found in Appendix A.

Figure 4.11: Production per stage versus water volume per stage.

Similar to the examination of water usage, Figure 4.12 shows the relationship between the natural gas production per stage and the sand volume used to stimulate the well per stage. Similar correlation trends are observed with the amount of sand used as with the amount of water

used. For the same reasons as with the water volumes, Figure 4.12 only includes the data from study wells in Greene, Lycoming, and Wetzel counties. In Appendix A, Figure A10 showing this same relationship for just Greene and Lycoming counties is accessible. The correlation is much stronger when just these counties are compared-- 93.6% linear.

Figure 4.12: Production per stage versus sand volume per stage.

One final relationship of interest is the sand versus water ratio. Figure 4.13 shows this relationship plotted against incremental time period production, as before. As would be expected, the same trend appears as in the cases with just the water and just the sand. As time increases, the correlation between the ratio and the production strengthens.

Figure 4.13: Production per stage versus water-sand ratio.

Chapter 5

Summary and Conclusions

In summary, this study has successfully achieved the goals defined. In regards to the refinement and design of the reservoir model, the following outcomes are true:

- New model can successfully replicate past production behavior
- Fracture half-length, hydraulic fracture permeability, and natural fracture permeability have been identified as key, curve-adjusting parameters
- Accurate history matching was performed for wells in four different regions of the Marcellus Shale
- Various well events, such as shut in periods, can be incorporated into the model

Additionally, it also became very apparent that the initial reservoir pressure was a huge factor in the prediction of production and thus affected the conclusions that could be drawn as well as the comparisons among different regions.

While studying and analyzing the fracture parameters chosen to be examined during this study, the following conclusions were drawn involving the number and spacing of stages.

- Number of stages significantly impacted initial production
- As the number of stages increased, initial production increased
- As the stage length decreased, initial production increased
- Short stage lengths do not promote greater recovery

The relationship between stage length and initial production could be explained in part by the fact that more fractures are being created close to the wellbore, thus increasing the initial flow of hydrocarbons. The predicted production provided by the modeling suggested that the stage length may affect the production up to five years. Shorter spacing may also allow for overlapping, condensed fractures, thus affecting the initial production, but not accessing the full extent of the reservoir, and thereby not impacting the recovery. It may be concluded that average size stage lengths, around 300 feet, provide an acceptable recovery as well as economic efficiency in developing a reserve.

Both the volume of water per stage and the amount of sand per stage used during hydraulic fracturing had similar trends when related to lifetime production, as follows:

- Initial production was not affected by the volume of sand or water
- Increased water/sand resulted in increased long term (ten-year) production
- The correlation strengthened with time

In the case of the volume of water per stage, the trend could possibly be explained by the fact that increased water volumes may be able to dissolve more minerals that have previously closed up natural fractures, thus producing more permeability in the areas in which the water contacts. More water would allow for more flushing of the minerals, and increased contact with new natural fractures, thus explaining the higher natural fracture permeability obtained from the history matching which leads to long-term production increase.

Chapter 6

Recommendations

For further work, it is recommend to expand the study to more areas in the Marcellus Shale. Now that a seemingly comprehensive model has been developed and the specific parameters that need to be adjusted to model a well are better understood, it would be much easier to study more areas. Expansion of the study group would also confirm the results of this research and expand the understanding of the relationships of the fracture parameters.

Secondly, it is recommend to investigate and identify an optimized stage length. This question alone is one of the most important factors in the design of a well stimulation operation. An optimized stage length could greatly affect not only the way company designs their well completions, but could also provide for more lifetime recovery for a well. Further, it would be ~~very~~ beneficial to further study the relationship between water and sand volumes and the productivity of a well. This research shows a definite correlation, but an optimized value or function was not defined.

Finally, it is recommend to study several other fracture parameters and their relationship to the lifetime production of a well. These would include the sand mesh sizes and combinations, perforation cluster spacing, and the fluid-pumping rate.

Bibliography

- Belyadi, H. (2011). *Production analysis of marcellus shale*. (Master's thesis, West Virginia University).
- DOE. (2004, June). Hydraulic Fracturing White Paper.
- EIA. (2008, November). *Map of shale gas basins in the united states*. Retrieved from http://energyindustryphotos.com/shale_gas_map_shale_basins.htm
- Engelder, T. (2009). Marcellus. *Basin Oil & Gas Magazine*, Aug(2009), 18-22. Retrieved from <http://marcellus.psu.edu/resources/PDFs/marcellusengelder.pdf>
- Marcellus shale - appalachian basin natural gas play*. (2012). Retrieved from <http://geology.com/articles/marcellus-shale.shtml>
- Net feet of organic-rich shale in marcellus shale formation*. (2010, February). Retrieved from http://www.dcnr.state.pa.us/topogeo/oilandgas/images/Marcellus_Isopleth.pdf
- NETL. (2010). Projecting the economic impact of marcellus shale gas development in west virginia: A preliminary analysis using publicly available data. *National Energy Technology Laboratory*, Retrieved from www.netl.doe.gov/energy-analyses/.../WVMarcellusEconomics3.pdf
- Virginia department of mines minerals and energy division of oil and gas*. (2006). Retrieved from <http://www.dmme.virginia.gov/DGO/documents/HydraulicFracturing.shtml>
- What is hydraulic fracturing?*. (2012). Retrieved from <http://www.propublica.org/special/hydraulic-fracturing-national>

Appendix A

All figures contained in this appendix are discussed in detail throughout the body of the paper. However, a brief explanation will be offered here.

Figure 1A below represents the amount of sand injected per well versus data for the entire data set collected. Figure A2 represents this same trend but in respect to the volume of fluid used per well. Both of these data sets basically illustrate that the size of stimulations being performed in the Marcellus Shale has gotten larger with time. This is most likely due to the fact that in general, the horizontal wells are getting longer, thus allowing for more fracturing stages, and therefore resulting in a larger overall amount of sand used.

Figure A1

Figure A2

Figure A3 is a representation of this same data set in regards to the average pumping rate during hydraulic fracturing and date. This figure is included in order to give a general idea of the pump ranges that operators are currently using.

Figure A3

Figure A4 and A5 below show the locations of the 26 six study wells chosen that are located in Lycoming County and Susquehanna County, Pennsylvania. These wells are all located geographically close to one another. This was in an effort to eliminate any additional variations in well performance that could be due to geological differences.

Figure A4. (Courtesy of NNE)

Figure A5. (Courtesy of NNE).

Similar to Figure 4.6 above, Figure A6 illustrates the thickness of the Marcellus Shale in Pennsylvania. This particular map was used to determine the formation thickness in Lycoming and Susquehanna counties.

Figure A6. ("Net feet of," 2010).

Figure A7 and A8 represent the daily flowrate and cumulative production history matching curves generated for Study Well W3. These are significant because this particular well experienced a shut in period. These figures illustrate that the model can easily adjust for different situations in the lifetime of a well.

Figure A7

Figure A8

Figure A9 illustrates the trend discussed earlier that is observable between the 10 year predicted production performance and the volume of water per stage used during stimulation. This trend appears to become stronger with time. Figure A9 shows just the data from Susquehanna County, Pennsylvania.

Figure A9

Both Figure A10 and A11 represent data combined from the 10 year predicted production analysis from Greene and Lycoming counties, Pennsylvania. These are included to show that the 10 year predicted production curve has a very good correlation value for both the water volume per stage and the sand volume per stage.

Figure A10

Figure A11

Appendix B

Study Well G1

Study Well G2

Study Well G3

Study Well L1

Study Well L2

Study Well L3

Study Well S1

Study Well S2

Study Well S3

Study Well S4

Study Well S5

Study Well W1

Study Well W2

Study Well W3

Curriculum Vitae

■ ■ ■ ■ **KIMBERLY LARCH AYERS**

	102 EAGLE DRIVE MAIDSVILLE, WV 26541 CELL: 304.839.4089 LARCHKL@GMAIL.COM		
EDUCATION	MASTERS OF SCIENCE DEGREE	WEST VIRGINIA UNIVERSITY	GPA: 3.89/4.0 Petroleum & Natural Gas Engineering EXPECTED GRADUATION MAY 2012
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WORK EXPERIENCE	NORTHEAST NATURAL ENERGY, LLC	CHARLESTON & MORGANTOWN, WV	Engineering Intern Summer 2011-Spring 2012
	<ul style="list-style-type: none"> ▪ Worked closely with drilling and completion operations of Marcellus Shale wells ▪ Helped in developing AFEs and bidding work for Marcellus Shale drilling program ▪ Completed ARIES evaluations of shallow field operations ▪ Assisted in production operations of shallow Pennsylvania wells ▪ Regularly updated and tracked invoicing, costs, and well production 		
	LARCH OIL & GAS CORPORATION	CHARLESTON, WV	Development, Royal Distribution, & Permitting 2006-2011
	<ul style="list-style-type: none"> ▪ Assisted in developing historical production in the Kanawha County area ▪ Small, family owned and operated company allowed for multi-faceted experience ▪ Managed all land, permitting, and royalty distribution activities ▪ Tracked all well production and suggested improvements and new projects ▪ Developed small, investor-based drilling program 		
	TIMBERLINE JUNIOR SKI RACE TEAM	DAVIS, WV	Coach and Official 2006-2011
	<ul style="list-style-type: none"> ▪ Officiated and organized regional and local events ▪ Instructed children from ages five to eighteen in the technical aspects of ski racing ▪ Improved personal communication skills with both athletes and parents ▪ Developed leadership abilities and learned to work as a team with other coaches 		
	WVWC DEPARTMENT OF CHEMISTRY	BUCKHANNON, WV	Chemical Hygiene & Administrative Assistant 2007-2008
	<ul style="list-style-type: none"> ▪ Developed knowledge of administrative management practices and problem solving techniques ▪ Assisted in the development of a Chemical Hygiene Plan ▪ Learned the importance of chemical safety in both the laboratory and environment 		

RESEARCH	<u>SPRING 2012:</u>	"Simulation of Generalized Production Trends in the Marcellus Shale Based on Fracturing Characteristics" PENDING PUBLICATION BY THE SOCIETY OF PETROLEUM ENGINEERS		
	<u>SPRING 2010:</u>	"Generalizations of Newton's Method"		
	<u>FALL 2009:</u>	"Fractal Behavior of the Riemann Zeta Function"		
	<u>SPRING 2009:</u>	"Analysis of Hydrocarbons Found in Natural Gas Using Gas Chromatography"		
	<u>FALL 2008:</u>	"An Analysis of Chloride, Nitrate, and Sulfate in Water Samples from Peck's Run Sub-watershed Using Ion Chromatography"		
HONORS	<i>Academic</i>	EngineeringWV Magazine Featured Cover Story		2012
		PNGE Outstanding Graduate Student		2011 & 2012
		Wild Well Control Training "Best in Class"		2011
		National Omicron Delta Kappa Foundation Scholar		2010-2011
		Greater Kanawha Valley Foundation R. Ray Singleton Scholar		2010-2011
		WVWC Senior Academic & Leadership Achievement Award		2010
	<i>Athletic</i>	Academic All-American, U.S. Collegiate Snowsports Association		2008
LEADERSHIP	<i>Institutional</i>	STUDENT REPRESENTATIVE:	WVWC Board of Trustees	2009
		VICE PRESIDENT:	WVWC Student Senate	2009
	<i>Academic</i>	PRESIDENT:	WVU Student Section of AADE	2011-2012
		MEMBER:	WVU Society of Petroleum Engineers	2010-2012
		VICE PRESIDENT:	WVWC Benzene Ring	2008-2010
		SECRETARY:	ODK Academic Honorary	2008-2009
	<i>Athletic</i>	MEMBER:	WVU Ski Team	2010-2011
		MEMBER:	WVU Cycling Team	2010-2011
		CAPTAIN:	WVWC Ski Team	2006-2010
SKILLS	<i>Technical</i>	Microsoft Office	ARIES	SCADA Lynx
		SherWare Distribution Manger	ECLIPSE	Pason
	<i>Training</i>	Wild Well Control Certification		