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A Parametric Study on the Benefits of Drilling Horizontal and Multilateral Wells in Coalbed Methane Reservoirs

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Abstract

Recent years have witnessed a renewed interest in development of coalbed methane (CBM) reservoirs. The success stories in San Juan basin and other CBM horizons have triggered this renewed interest. Many operators are asking questions regarding the most optimum way of producing CBM reservoirs. Drilling horizontal and multi-lateral wells are gaining popularity in many different coalbed reservoirs with varying results. This study concentrates on many variations of horizontal and multi-lateral wells and their potential benefits. It has been the rule of thumb that vertical wells are appropriate for thicker CBM reservoirs such as those found in San Juan basin and horizontal and multi-lateral wells should be used in thinner beds. Recently some operators are drilling horizontal and multi-laterals even in thicker beds and are claiming economic success.

In this study, we identify the most appropriate drilling patterns for coalbed methane reservoirs of different thickness and with different characteristics. The reservoir characteristics that have been studied include gas content, permeability, and desorption characteristics. The yard-stick for comparing different drilling configurations in this study is the net present value (NPV). This way cost of drilling has been taken into account when different horizontal and multi-lateral configurations are compared with one another. Furthermore, we have compared dual-, tri- and quad- laterals with fish-bone (also known as pinnate) configurations. In these configurations, the total length of horizontal wells as well as the spacing between laterals (SBL) has been studied.

CBM Background. Coal represents an unusual reservoir rock due to its highly complex reservoir characteristics. One of the characteristics that distinguish coal seams from conventional gas reservoirs is that coal represents both the source and the reservoir rock at the same time. Unlike conventional sandstone reservoirs, where the gas is found in free state within the pore structure of the rock, the methane gas is adsorbed onto the internal structure of the coal, which allows significant amount of gas to be stored in the coal rock[1].

Coal seam system is a naturally fractured heterogeneous reservoir characterized by macropores (fracture system, also known as cleat system) and micropores (coal matrix system). In general, the coal cleat system is orthogonal with one direction cross-cutting the other and varies from the case to the case, having significant impact on the coal deliverability[1]. The CBM production depends highly on the fracture system - fracture spacing and fracture interconnection. If the cleat system for any reason is not developed enough, the gas production could be very difficult. This occurs due to the low values of porosity and permeability in the matrix, making it almost inpossible for gas to move from matrix into the fractures. At the beginning, the coal system is in equilibrium and typically, water must be produced continuously from coal seams to reduce the reservoir pressure and release the gas. Gas from the coal can be produced only after initial dewatering of the system, and upon reaching low reservoir pressure. The dewatering process can take anywhere from few days to several months, which depends on CBM well configuration. Generally, the water production declines until the gas rate reaches the peak value. This 'time-to-peak-gas' is a critical parameter since the gas production starts declining after reaching the maximum[2]. Upon reaching the peak, gas production starts to decline and behavior of CBM production becomes similar to conventional reservoirs.

Horizontal Wells. Methane can be drained through small diameter horizontal holes. One of the main advantages of the horizontal wells is that the well direction, shape, and position can be controlled[3]. Using horizontal wells, an almost ideal position of the well can be determined and performed in respect to principal permeability directions of the coal. Proper positioning of the well as well as length of borehole drilled perpendicular to main fracture system of the coal, can significantly contribute to draining large areas.

Question is which shape of horizontal well to drill in order to produce larger amount of gas in the shortest possible time. Drilling horizontal wells in coal seams is highly important to the sweep efficiency. As the length and contact of well bore to the coal seam increase, the time for water production decreases. Usually, the gas production curve of vertical and horizontal wells will significantly differ from each other. In a very short time, the horizontal well will dewater the system, and significant water production will take place. The gas flow peak will occur soon after the well starts to produce. Probably, the most important part of the gas flow curve is the one after gas flow peaks. The slope of the curve is important, since the well will produce like conventional gas reservoir from that point. The flatter the curve, the better production will be for the rest of the well's life. The issue is that; horizontal wells are capable of draining the system very fast due to much longer well bore contact with the reservoir. Consequently, the adsorption process is triggered quickly and the well will elicit a very steep negative decline curve relatively fast. After reaching the peak, the gas production will start to decrease, again due to large contact area between horizontal well and the reservoir.

Parametric Study: Systematic Approach

In this study, a number of simulations have been performed in order to investigate the influence of different horizontal well shapes, their various length, spacing between laterals (SBL), and various reservoir properties on the deliverability of a certain type of coal. To better explain various steps performed in this study, a flowchart is created (Figure 1). Starting point of this research was determining the different horizontal well configurations that would be used and implemented in the study. As a result, five horizontal well shapes were examined:

1. Singlelateral
2. Duallateral
3. Trilateral
4. Quadlateral
5. Pinnate

No matter which horizontal shape has been applied to the reservoir simulator, the vertical length (depth from the surface to the point that well starts the horizontal – kick off point) is constant in all cases during this study. Definitions of a lateral well, SBL, and vertical depth are illustrated in Figure 2. Investigated well configurations are illustrated in Figure 3.

Sensitivity analysis (parametric study) represents a set of simulation runs in which all parameters are kept constant, but only one is changed systematically. This approach enables us to monitor changes of simulation outputs influenced by only one variable. The first step taken in this part of the approach was to develop a model representing CBM, and test it using different well configurations. Dual porosity model was used to create CBM reservoir including Gilman and Kazemi shape factor calculation. Cartezian grid model has been chosen for the modeling of CBM reservoir, which has the input parameters shown in Table 1. This homogeneous model using Cartesian grid has been formed having a constant drainage area of 320 acres, consisted of 30x30 squared blocks each size of 120 feet. As previously mentioned, regardless of the horizontal shape applied to the reservoir simulator, the vertical length is constant in all cases during this study. The production period has been determined as 15 years. The parametric study is divided into three. In the first part the influence of well configuration and spacing between laterals is investigated considering the five configurations mentioned above. In the second part, influences of several reservoir/coal properties such as permeability, time constant, gas content, and desorption characteristics are investigated. Third part includes a study on thickness. In each part, gas recovery, and net present value (NPV) results at the end of a 15-year production period is presented. Net present value is calculated for a discount rate of 8%, after considering the costs associated with drilling operations. The most important cost factor was the horizontal drilling cost, which was assumed as $100/ft after discussing it with industry professionals. It should be noted that; this is an average value for a drilling operation under perfect conditions, and it might increase with arising problems during drilling.

Well Configuration/Spacing between Laterals. Starting point in this part of the study is the vertical well placed in the middle of the reservoir having horizontals spreading out toward upper left corner of the model (Figure 4). Single lateral well configuration was the first one to be investigated. Normally, this was the only case in the study, where spacing between laterals (SBL) was not used. Well configurations with different horizontal lengths were simulated. Drainage area was kept constant and for the whole set of simulations, only horizontal length of the well and SBL were continuously changed step by step. Once SBL was determined (the narrowest one) it remains constant, changing only horizontal length from the shortest to the longest length while running the simulator for each different scenario that took place. The maximum length of a horizontal well is constricted by the shape and the size of the reservoir. Having dual-, tri-, and quad- laterals, spacing between laterals (SBL) was introduced as a variable. The process explained for singlelateral wells was applied to the rest of investigated well shapes taking into account the new variable (*i.e.* SBL). Upon creating all possible scenarios for a minimum value of SBL, a new SBL with the higher value than the previous one was introduced. Again the same procedure took place, keeping SBL constant while changing horizontal length from minimum to maximum. Following the completion of all possible cases for one configuration of horizontal wells, another configuration is introduced. The very same procedure was applied to trilateral and quadlateral horizontal well configurations.

The problem having pinnate shape required some modification of this approach. Obviously, there is no SBL existing with the single lateral horizontal configuration, but dual-, tri-, and quad- lateral configuration possesses SBL, which was investigated in these three cases. For the pinnate horizontal well shape, another scenario was needed because of the specific shape of this well configuration. Another variable was introduced, namely number of laterals.

Reservoir Properties. The second part of the sensitivity analysis required the definition of coalbed reservoir properties subject to change during the study. Knowing all the steps performed in the first part of this analysis, this time the minimum well length and SBL has been defined and kept constant, while changing reservoir data one by one. The goal of this approach was to introduce a new dimension to the model, which is changing one reservoir property at a time. The quadlateral well configuration with 680 feet of spacing between laterals has been used to conduct parametric studies to assess effects of parameters such as permeability, time constant, and gas content. That configuration has been chosen, since it was the one, which has come up with the best gas recovery results.

Thickness. In this part of the study, a relatively smaller model has been developed to investigate gas recovery in different cases based on pay thickness. A 15x15 grid block model was developed with the same grid block size of 120 ft. Vertical depth was kept constant. Cases with a single layer having a net pay thickness of 4 ft and 12 ft, and a case with three layers having thickness of 4 ft each were simulated with well configurations of single vertical, four-spot, and horizontal wells.

Results and Discussions

In this section the results of the study will be presented and discussed.

Well Configuration/Spacing Between Laterals. Having values of the actual gas production as the simulator output and calculating initial-gas-in-place as 820 MMSCF, and initial-water-in-place as 520,000 bbls, gas recovery for each well configuration has been calculated and plotted against total horizontal length of the well. Gas recovery/total horizontal length shape behavior is shown in Figure 5. Gas recovery results for dual-, tri-, quad- lateral and pinnate configurations are shown in Figures 6 through 9.

The best producers from five different well configurations have been compared to one another (Figure 10). Our investigation shows that the quadlateral well configuration with the spacing between laterals of 680 ft and total horizontal length of 8,000 ft is the one with the highest gas recovery (around 36%). The strongest competitor, pinnate well configuration have a little bit better recovery (38%), but for the total horizontal length of 18,000 ft. The question is investing in drilling of additional ten thousand feet of horizontal section for gas recovering of 2-3% more. If these two horizontal well configurations are compared for the same total horizontal length of 8,000 ft, it is obvious that quadlateral well configuration can recover 5-10% more gas.

Although higher horizontal length increases the total gas recovery, increasing horizontal drilling costs must be considered to find out the optimum configuration. Figure 11 shows NPVs for the quadlateral well configuration, which is now the recommended well configuration. The graph shows the results with respect to the horizontal length, and SBL. This graph suggests that the optimum configuration would be the quadlateral well configuration with a SBL of 680 ft, and a total horizontal length of 3,100 ft.

Reservoir Properties. The quadlateral well configuration with 680 feet of spacing between laterals with a horizontal length of 8000 ft has been used to investigate the influence of parameters such as permeability, time constant, and gas content.

a) Permeability: The fracture permeability in *i*, and *j* directions have been changed together as to have values: 2, 5, 8, 10 and 15 md, while the permeability in the *k* direction is kept constant at 2 md. Gas recovery after 15 years of production has increased with increasing permeability as expected. Permeability values changing between 2 and 15 md had a corresponding range of 0.19 and 0.35 of overall gas recovery (Figure 12). Figure 13 reflects the NPV values for each case which also has a similar trend.

b) Time Constant: Values of 10, 50, 150, and 200 days have been assigned to the time constant, τ (*i.e.* coal desorption time), to see the changes in the reservoir behavior due to the time constant parameter. After 15 years of production, overall gas recovery did not differ too much with varying values of time constant. It has been observed that overall gas recovery would have a range between 0.26 and 0.29, for time constant values changing between 10 days and 200 days (Figure 14).

Since it is a known fact that; time constant mainly effects the earlier production from a CBM reservoir, it has been decided to consider the first year's production in each case. Figure 15 shows the cumulative gas that is produced during the 15 years of production for each case with different time constant values ranging from 10 to 200 days. As discussed; as far as the long-term production (*i.e.* 15 years in this case) is concerned, time constant does not have a significant effect on overall gas recovery. However, while the gas produced after the first year is around 120 million cubic feet for a time constant of 10 days; in case the time constant is as large as 200 days, the first year production is around 80 million cubic feet. Considering the expected difference of production of 40 million cubic feet of gas, it can be concluded that the time constant has a significant effect on the first year production of the reservoir. It is observed that the difference occurred in the cumulative production after the first year keeps being constant during 15 years of production.

Assuming a gas price of $5/MSCF, this difference would be equal to as much as $200,000. This amount of difference is clearly reflected in Figure 16, which shows NPV values for each case.

c) Gas Content: Gas content is one of the most important parameters that influence the gas recovery from coal beds. The same system has been simulated with different values of gas content as 350, 395, and 450 scf/ton. Considering these values, five different isotherms have been generated by changing Langmuir volume and pressure constants, which are controlled by maximal adsorbed mass, and Langmuir adsorption constant, respectively. Characteristics of these five isotherms are shown in Table 2. One of the isotherms is an average isotherm for Northern Appalachia and others are defined as modifications to that isotherm. Initial reservoir pressure is kept at 450 psi for all cases. The graph that shows the behavior of each isotherm is shown in Figure 17, which indicated the corresponding gas content with respect to pressure for the saturated case for each isotherm. The final gas recoveries after 15 years of production for each isotherm are shown in Figure 18. The isotherms are ranked based on the recovery as; Modification-3, Northern Appalachia, Modification-1, Modification-2 and Modification-4, respectively. Considering the isotherm curves shown in Figure 15, the decline behaviors of five isotherms support the gas recovery values. Figure 19 shows the net present value results for each case, which shows a similar trend with the one obtained for gas recovery.

Thickness. Figure 20 shows gas recovery results for each well configuration and for each case which are; case with a single layer of 4 ft, case with a single layer of 12 ft, and the case with three layers, each having a thickness of 4 ft.

This graph clearly shows that horizontal well configuration brings the best gas recovery. The large gap between the gas recovery results for the case with a single layer of 4 ft and others is simply caused by the difference in the initial-gas-in-place. In our analysis, the case with single layer could not recover its investment. The case with three layers had a net present value profile like the one shown in Figure 21. This graph also clearly shows that drilling horizontal wells is favorable, rather than drilling vertical wells.

Conclusions

A parametric study to determine the benefits of drilling horizontal and multilateral wells in coalbed methane reservoirs is presented. Various well configurations such as: single-, dual-, tri-, quad-lateral, and fish-bone (pinnate) were investigated, while considering parameters such as; spacing between laterals, and total horizontal length. Besides, sensitivity analyses were conducted to see effects of thickness, number of layers, and various reservoir/coal parameters such as: permeability, time constant, and gas content. Major conclusions of this study can be summarized as follows:

1) Production from coalbed methane reservoirs can significantly benefit from horizontal and multilateral wells. Recovery and economical results clearly shows that production from these unconventional well configurations is favorable.
2) The most optimum well configuration can be determined by considering the total horizontal length, spacing between laterals, and number of laterals. Higher horizontal length increases the contact with the coal seam, and yields for more gas recovery, but it also increases the associated drilling costs at the same time. After considering the economics, the optimum configuration, which is suggested by this study, is: quadlateral well configuration, with spacing between laterals of 680 ft, and total horizontal length of around 3,100 ft.
3) Time constant has no significant effect on the overall recovery. However, it is an important factor that influences the production in the first year, thus the economics of the first year.

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Acknowledgement

Authors would like to thank Computer Modeling Group, Inc. for providing the software used in this study.

Table 1: Input parameters for the CBM model developed in the simulator.

Input Parameters	Value
Thickness, ft	4
Gas Content, scf/ton	350
Langmuir Volume Constant –V_L, scf/ton	480
Langmuir Pressure Constant –P_L, psi	167.5
Pressure, psi	450
Grid Top depth, ft	1000
Porosity Matrix, fr.	0.005
Porosity Fracture, fr.	0.08
Permeability – i, md	0.0001
Permeability – j, md	0.0001
Permeability – k, md	0.0001
Fracture spacing – i, ft	0.05
Fracture spacing – j, ft	0.05
Fracture spacing – k, ft	0.05
Sw (matrix), %	0.5
Sw (fracture), %	100
Permeability fracture – i, md	8
Permeability fracture – j, md	8
Permeability fracture – k, md	2
Temperature, F	75
Rock Density, gr/cc	1.442
Coal Desorption Time, days	231
Ash Content , fr.	0.05
Production Time, years	15
BHP, psi	30
Pressure Gradient psi/ft	0.43

Table 2: Characteristics of the isotherms that are generated with different Langmuir volume and pressure constants (V_L and P_L).

	V_L, scf/ton	P_L, psi	Gas content, scf/ton
Modification 1	480	167.5	350
Northern App.	542.03	167.5	395
Modification 2	480	96.84	395
Modification 3	617.5	167.5	450
Modification 4	480	30	450

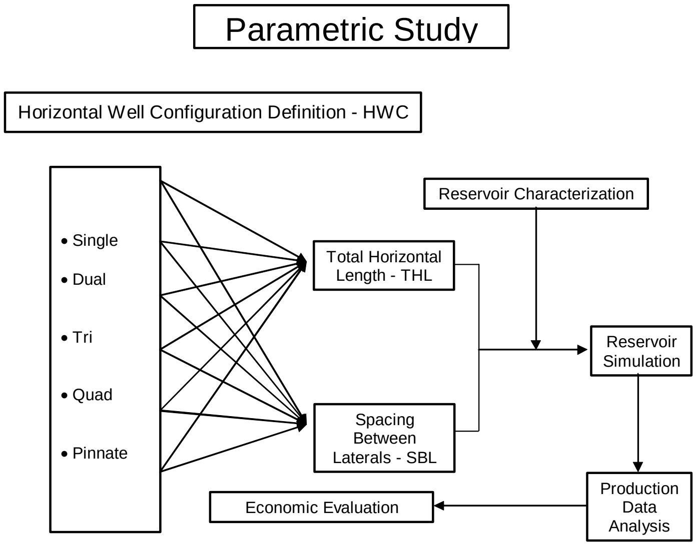

Figure 1: Flowchart of the study presented here.

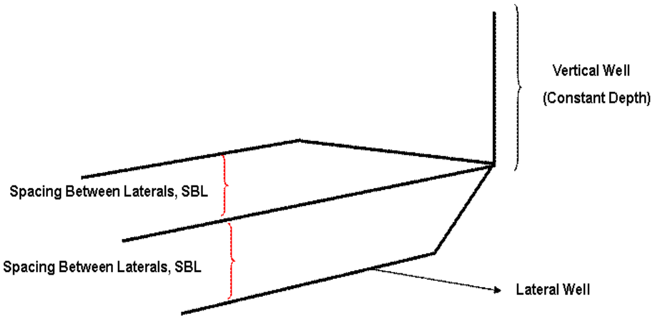

Figure 2: Definitions of terms related to a lateral well.

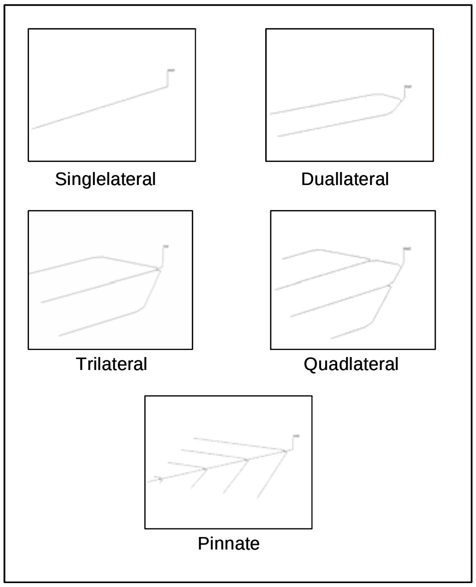

Figure 3: Investigated well configurations.

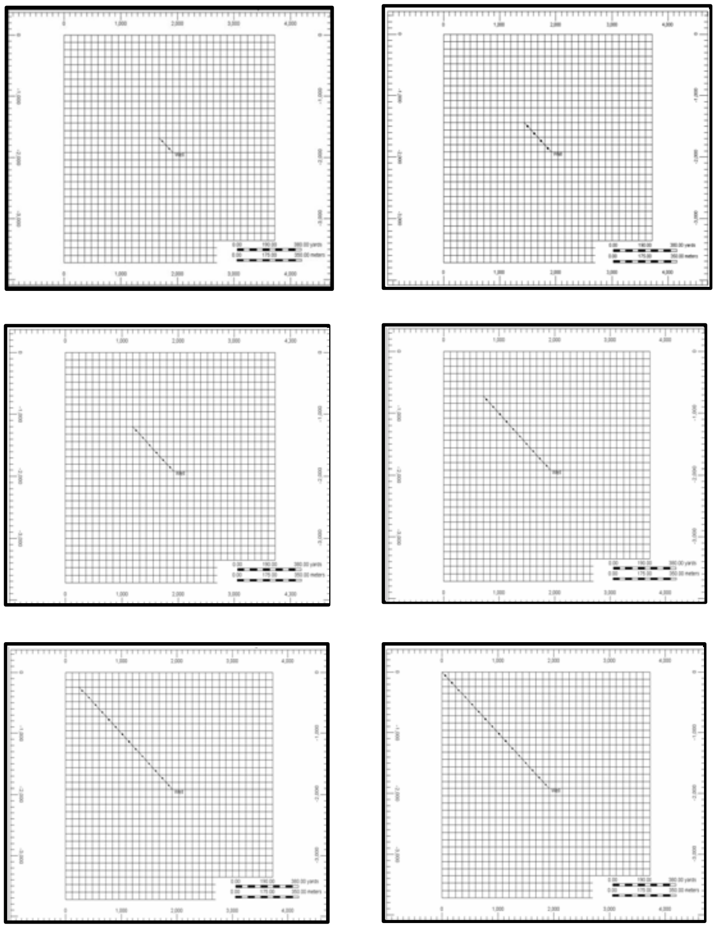

Figure 4: Single horizontal wells with different horizontal lengths.

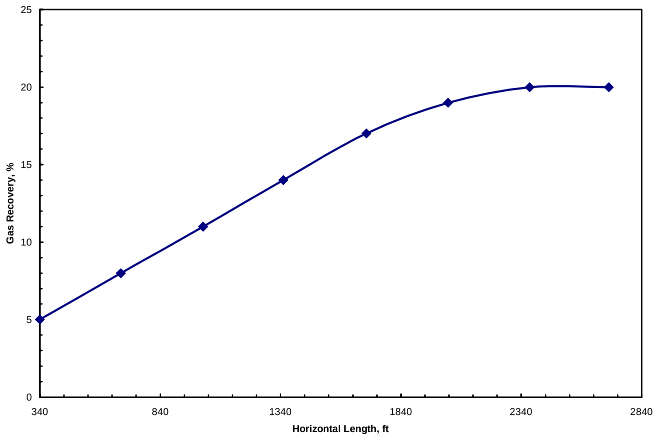

Figure 5: Gas recovery - singlelateral horizontal well configurations.

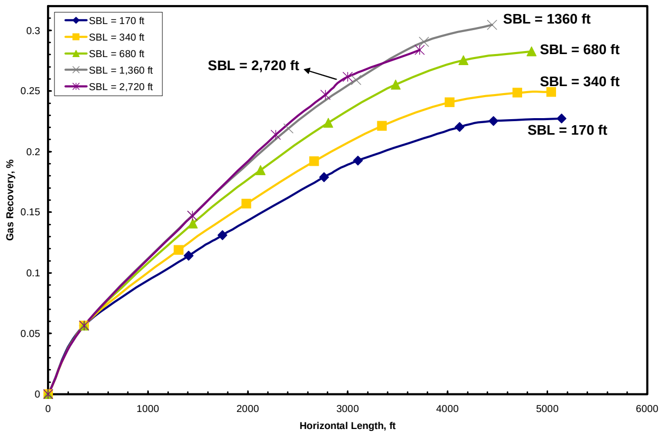

Figure 6: Gas recovery - duallateral horizontal well configurations.

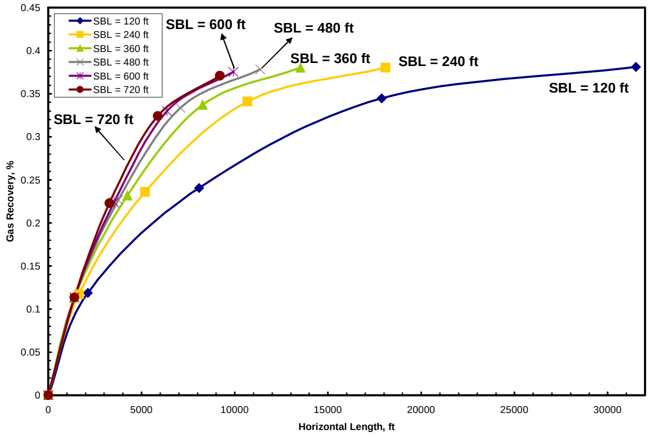

Figure 9: Gas recovery - pinnate horizontal well configurations.

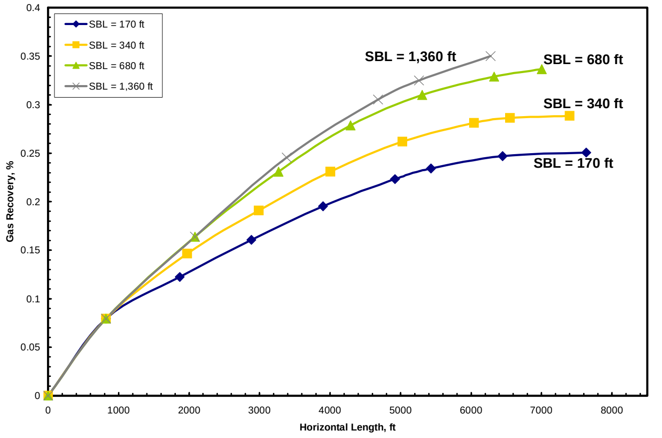

Figure 7: Gas recovery - trilateral horizontal well configurations.

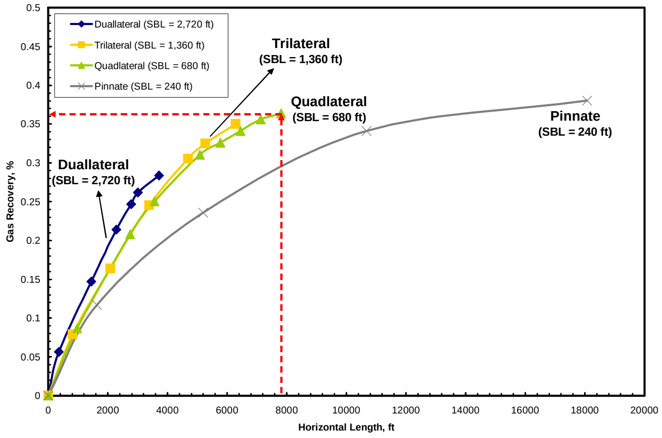

Figure 10: Gas recovery – best producers comparison.

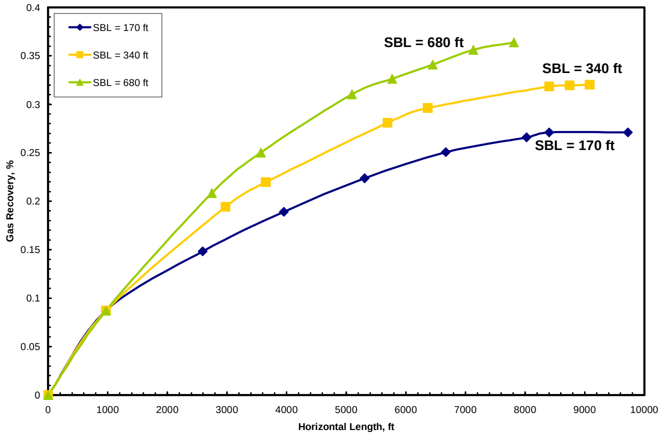

Figure 8: Gas recovery - quadlateral horizontal well configurations.

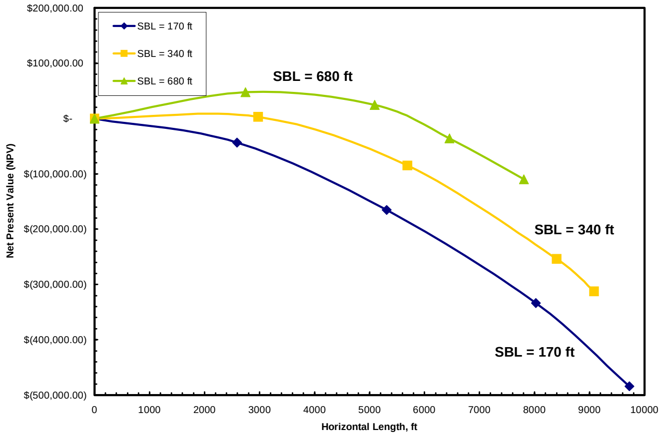

Figure 11: Net present value - quadlateral horizontal well configurations.

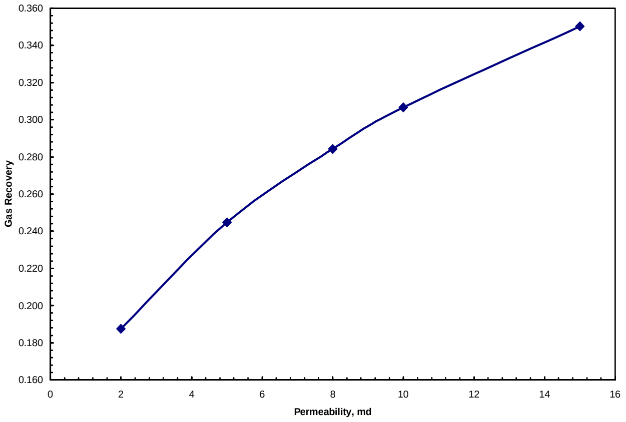

Figure 12: Effect of permeability on gas recovery.

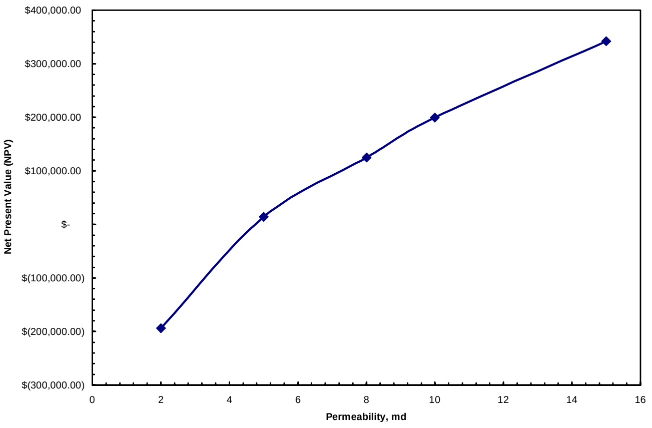

Figure 13: Effect of permeability on net present value (NPV).

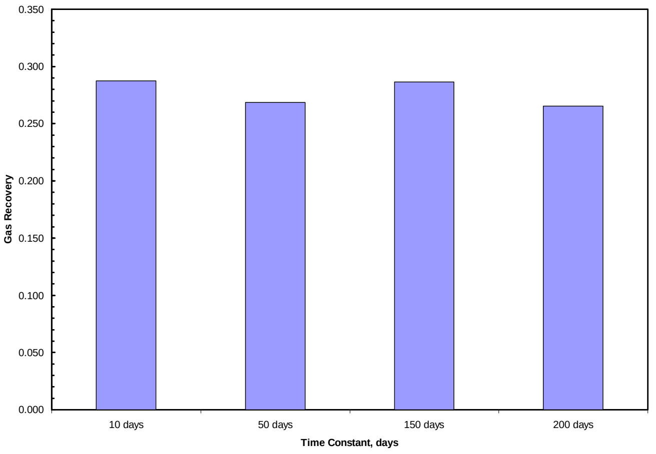

Figure 14: Effect of time constant on gas recovery.

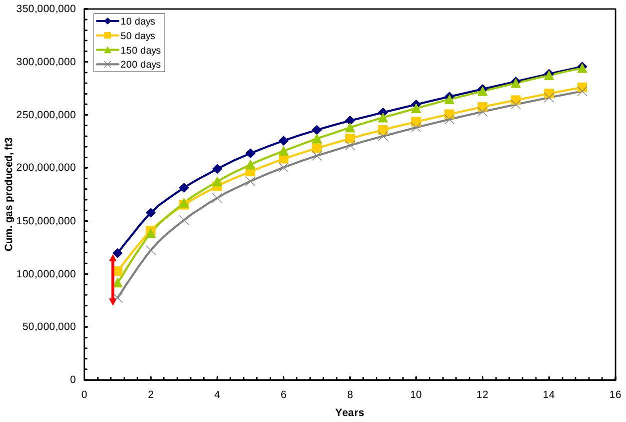

Figure 15: Effect of time constant on cumulative gas produced.

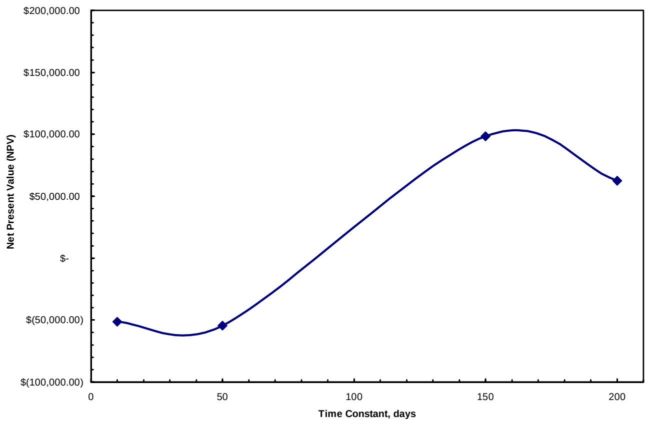

Figure 16: Effect of time constant on net present value (NPV).

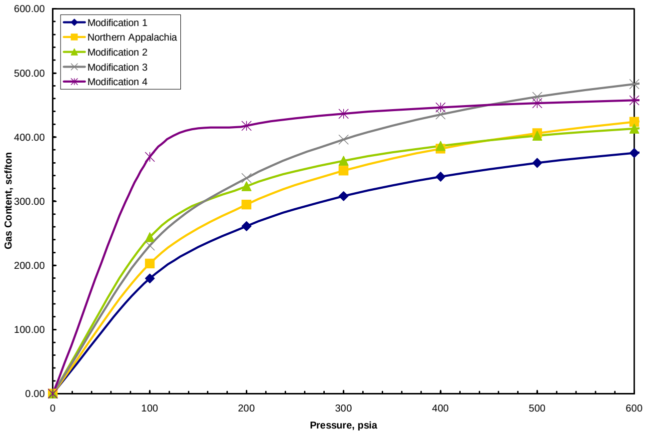

Figure 17: Five isotherms defined with different pressure and volume constants (V_L and P_L).

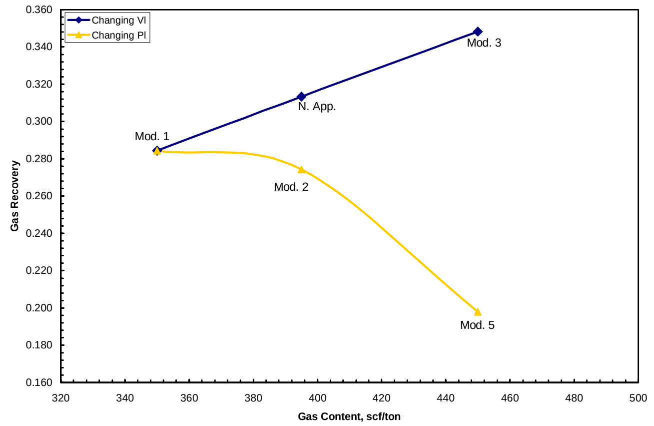

Figure 18: Final gas recoveries for five isotherms, after 15 years of production.

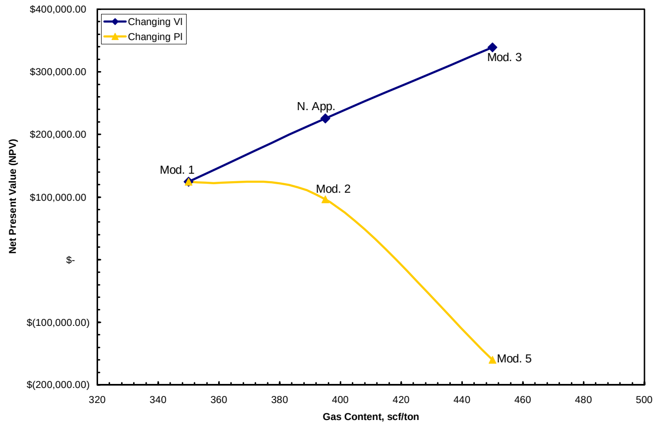

Figure 19: Net present values (NPV) for five isotherms, after 15 years of production.

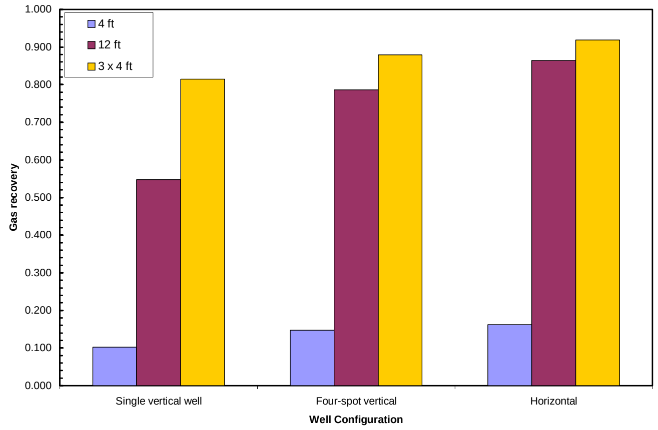

Figure 20: Gas recovery results for different well configurations and for different cases of thickness.

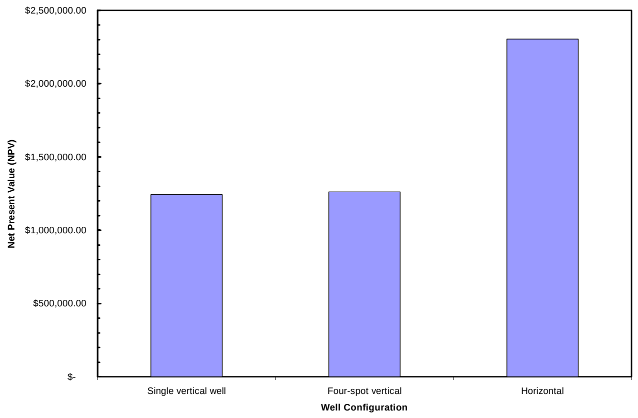

Figure 21: Net present value (NPV) results for the case with three layers, each having a thickness of 4 ft, for different well configurations.