Design of Methane Drainage Systems to Reduce Mine Ventilation Requirements

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ABSTRACT

There are numerous proven methods to drain methane from coal seams in coal mines. These systems include vertical wells drilled ahead of mining, horizontal boreholes, gob wells, and others. However, these drainage systems are not typically applied properly to optimize gas recovery and minimize the cost of ventilation to the mine. This lack of optimization generally occurs due to the large up-front costs associated with the drainage systems and the lack of knowledge regarding the drainage technology. This results in the mine having a "reactive" response to methane drainage issues as opposed to a "pro-active" plan for handling methane drainage. This paper demonstrates the use of a coalbed methane reservoir simulator to design vertical well methane drainage systems ahead of active longwall mining. Using the reservoir simulator and a hypothetical mine, the degasification system is optimized with respect to 1) the cost/benefit of the vertical well program, 2) the impact on the mining operation and mine ventilation, and 3) the reduction in coal seam gas content in the mined seams.

KEYWORDS

Coalbed Methane, Degasification, Methane Drainage, Reservoir Simulation, 3-D Model, Vertical, Degas, and Permeability.

INTRODUCTION

The application of techniques for the control of methane emissions in coal mines (along with the control of other gas emissions and general improvement of the mine environment) has been in existence for many centuries. Beginning with simple draft ventilation methods, the technology for methane[1] control has developed into sophisticated ventilation and methane degasification systems. The degasification systems include vertical wells draining methane in advance of mining, horizontal and cross-measure boreholes draining methane in conjunction with mining, and gob wells draining methane from mined-out gob areas. However, these drainage systems are not typically applied properly to optimize methane recovery and minimize the cost of the ventilation and degasification systems to the mine. This lack of optimization generally occurs due to the large up-front costs associated with the drainage systems and the lack of knowledge regarding drainage technology. This results in the mine having a "reactive" response to methane emissions as opposed to a "pro-active" plan for handling methane emissions.

Optimization of the drainage systems can be achieved through the use of reservoir simulation to describe the flow of methane through the coal seams and the impact of various degasification system designs on the flow of the gas. This study demonstrates one aspect the use of reservoir simulation in methane control – the design of a vertical well methane drainage system for optimum economic degasification ahead of an active longwall mine.

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[1] Throughout this technical paper the terms *methane, coalbed methane, mine gas, firedamp, natural gas,* and *gas* are used interchangeably. The authors recognize that the composition of the gas emitted and/or produced from coal seams usually contains not only methane but also other gas components in varying quantities. For simplicity, within this technical paper the terms highlighted above refer to a methane-rich gas that is contained in and produced from coal seams.

BACKGROUND

As well documented in the literature (Deul and Elder, 1973; Deul and Kim, 1986; Stefanko and Licastro, 1976), methane from coal seams in underground mining environments has been known and documented as a potential hazard ("unwholesome gas") since the late 16th century. Reports from early in the 18th century from Great Britain identify the occurrence of methane explosions in what then were termed deep British mines.

In the United States, methane related mining problems were first identified by a report of a mine explosion in the state of Virginia in 1839 (Deul and Kim, 1986). According to Deul (1986), methane explosions occurred at irregular intervals until 1875 when an increase in the frequency of explosions was reported. This corresponded to the rapid increase in the growth of the eastern U.S. coal mining industry (required to supply the rapidly expanding base metals and other industries) and the trend toward mining deeper coal horizons.

Similar situations were encountered in the coal mining industry throughout Europe and the far east such that beginning in the early 1900s efforts were put forth by various governments and governmental agencies to mitigate the presence of methane in coal mines. Within the U.S., the formation of the U.S. Bureau of Mines (USBM) in 1910 significantly impacted mine safety, primarily through the development and implementation of improved mine ventilation systems, rock dusting procedures, and the use of permissible (safety) explosives, electrical equipment, and cap lamps.

However, even with the adoption of these improved methods and equipment, methane emissions continued to be a source of potential danger. Clearly, supplemental efforts to those described above were required in certain mines, especially the deeper, high gas emission-prone mines. The proposed solution to this problem was the removal of the methane from the coal prior to its mining or the venting of the methane contained within the mined-out coal areas. This process (degasification, firedamp drainage, demethanation) employed various combinations of in-mine and surface relief techniques to remove the methane. The methods employed were initially developed within the European coal mining industry, beginning in earnest during the 1920s and becoming systematic by the early 1950s with the formation by the Council of Organization for European Economic Cooperation of the technical assistance program on the *"drainage and use of methane from coal mines"* (von Schonfeldt, 1989). Similar programs were also developed in what was then the Soviet-influenced eastern European countries and the republics of the Soviet Union.

Efforts in the United States in methane control were initiated by the USBM in 1964, although industry had already begun a development program of it's own by the early 1950s (Spindler and Poundstone, 1960). However, the work of the USBM did not begin in earnest until the passage in 1969 of the Federal Coal Mine Health and Safety Act, which was quickly enacted following the massive Farmington, West Virginia coal mine disaster. Significant government and industry efforts during the 1970s firmly established the techniques for controlling methane, including the use of in-mine horizontal and cross-measure boreholes, gob wells, and vertical, fracced wells, along with other more conventional methane control methods (i.e., ventilation). As should be expected, much of the USBM work (and that of private industry) built upon the earlier work conducted in other parts of the world (especially Europe), with modifications to these techniques for the unique geologic and mining conditions and operations in the U.S.

While the techniques for controlling methane became widespread during the 1980s and 1990s, the design and application of any given methane degasification system was based on trial and error. This was because no rigorous analytical method or tool was available to the industry to model the degasification system within the three-dimensional mine environment. In general, degasification systems were installed and their impact on methane emissions was monitored. If methane emissions continued to be too high, expansion of the system was undertaken (drilling of additional horizontal boreholes, for example) and mining costs increased; if the emissions were significantly reduced, reduction in the size of the system (i.e., fewer horizontal boreholes) occurred, with the added benefit of lowering mine development costs.

However, in these situations optimum development was only achieved after significant expenditures of time and capital. Ideally, the design of a methane degasification system should be similar to that employed in the design of optimum mine ventilation networks – computer-aided and optimized before the mine development is initiated. With the advent of three-dimensional analytical models that describe the flow of fluids and gasses through coal seams, the engineer now has a design tool to eliminate the need for the trial and error of a degasification system.

STUDY APPROACH

The design of vertical well degasification programs must consider the reservoir properties of the coal seam to be mined as well as the coal seams underlying and overlying the mined seam that may contribute gas during mining. The design also must consider the parameters of the mining plan, including the timing of when specific areas will be mined and the required reduction in gas content and methane emissions of the coal seams prior to mining. The key coal seam reservoir parameters which impact the effectiveness of vertical degasification programs include reservoir pressure, adsorbed gas content, thickness, and permeability. Of these parameters, permeability is generally the largest contributor to vertical well productivity. Permeability is also a parameter which can be highly variable across a given mine area.

The design of vertical degasification systems include two major steps. The first is the simulation of vertical well production and recovery for a range of expected reservoir conditions. Permeability, the parameter that largely controls productivity, is generally unknown (with a high degree of accuracy) before drilling wells. Therefore, it is important to investigate a range in expected permeability in the forecasting of vertical well production in order to understand the expected range of well productivities which might be realized in the field. The second step in the process is the design of the degasification system in terms of well placement and the timing of well installation. These decisions will be made relative to the plan for future mining activities. Especially important is 1) the degree of degasification of the coal seams required for safe mining and 2) the expected or forecast lead-time between the installation of vertical degasification wells and the beginning of mining.

This paper demonstrates the design of a vertical well degasification program using a hypothetical mine in the Black Warrior basin, Alabama. We chose this area because it is one in which a large amount of data are available regarding coal seam reservoir properties.

SIMULATION OF VERTICAL WELL DEGASSIFICATION

The first step in the design of a vertical degasification system is estimating the typical production that might be realized from vertical degasification wells. For this paper, we generated a series of reservoir simulations to forecast vertical well performance for a typical mining scenario in the Black Warrior basin, Alabama. We used publicly available information on the coal seams in this area to construct our simulation models.

For this study, we used COALGAS™, a coalbed methane reservoir simulation model developed by S. A. Holditch and Associates (HOLDITCH) specifically for analysis and forecasting of coalbed methane well production (Zuber, 1997). Figure 1 and Table 1 show the baseline reservoir properties used for our simulations. Figure 1 also provides a schematic showing the coal seams that are considered important to degasify prior to mining for this example. In this case, the Mary Lee coal seam is the seam to be mined, and the Pratt, and Black Creek coal seams are seams which are expected to contribute gas emissions to the mine during the mining process.

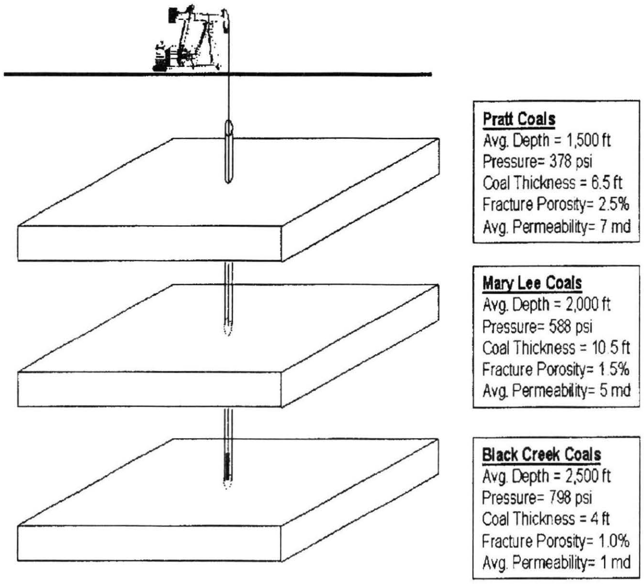

Figure 1. Schematic of the reservoir model and reservoir parameters used in the study.

Table 1. Summary of base properties used for vertical well simulation.

Property	Value
Coal density, gm/cc	1.32
Ash content, wt %	9
Moisture content, wt %	1.5
Characteristic sorption time, days	10
Hydraulic fracture half-length, ft	100
Hydraulic fracture conductivity, md-ft	1,500
Minimum flowing bottomhole pressure, psia	25

To generate the simulation cases required for the design of the mine degasification system, we set up a three layer single-well simulation model using the baseline parameters shown in Table 1 and the parameters for the individual coal layers shown in Figure 1. The sorption isotherm used for these simulations is shown in Figure 2. The gas-water relative permeability relationship used for these simulations is shown in Figure 3.

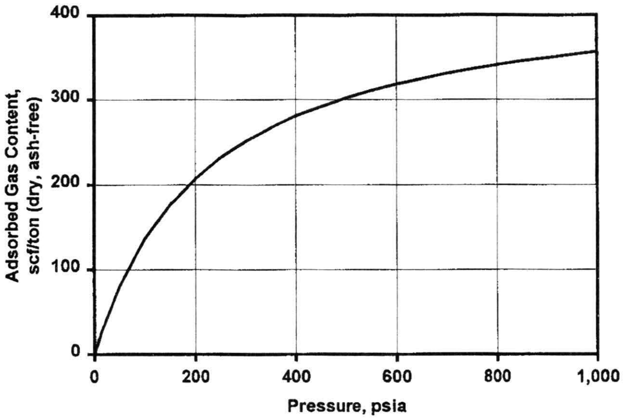

Figure 2. Coal sorption isotherm used for the simulation.

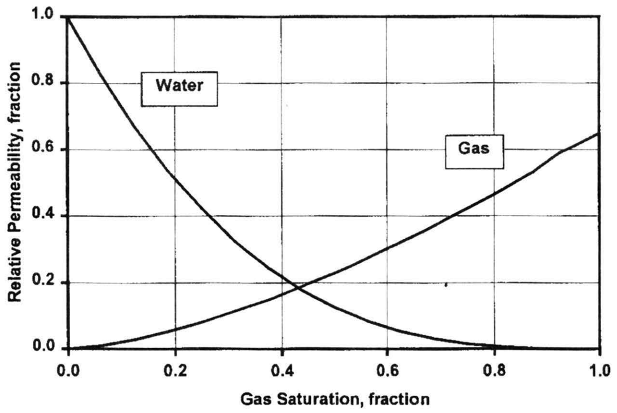

Figure 3. Gas-water relative permeability curves used for the simulation.

To generate these simulations, required for the design of the mine degasification program, we made a series of single-well simulation forecasts using the simulation model set up for this project using well drainage areas of 10, 20, 30, 40, 60, and 80 acres. Table 2 shows the cases simulated and the average distance between wells for each case.

Table 2. Well spacing cases simulated using single-well model.

Case	Drainage Area (acres/well)	Average Distance Between Wells (ft)	Gas in Place Per Well (MMscf)
1	10	660	97
2	20	933	194
3	30	1,143	291
4	40	1,320	388
5	60	1,617	582
6	80	1,867	776

For each case shown in Table 2, we simulated production for a single-well assuming a maximum water lifting rate of 100 barrels (4,200 gallons) per day on initial production. We simulated 20 years of production for each case. Figures 4 and 5 show the gas production rate and water production rate for the simulated cases, respectively. Figure 6 shows the forecast cumulative gas production for these cases. As expected, the per well recovery increases as the drainage area per well increases.

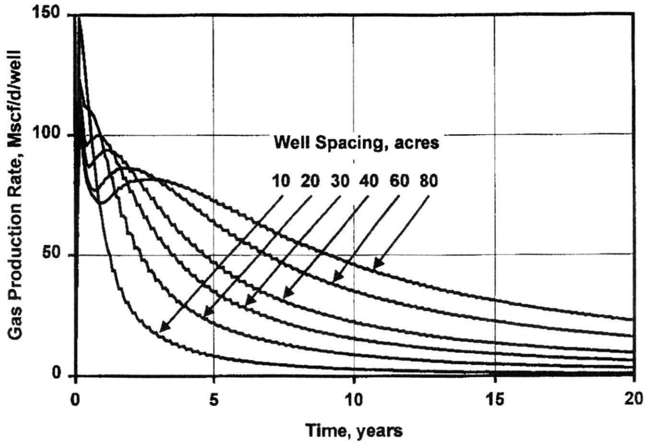

Figure 4. Simulated gas production rate for a single well at various well spacings.

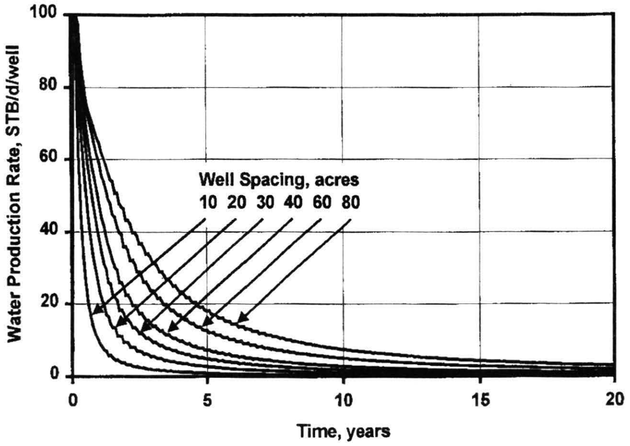

Figure 5. Simulated water production rate for a single well at various well spacings.

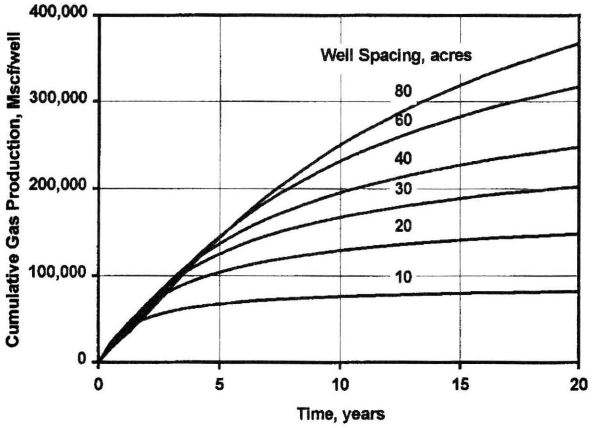

Figure 6. Simulated cumulative gas production for a single well at various well spacings

For the cases studied, the 20 year recovery on 10-acre well spacing is approximately 80 million standard cubic feet (80 MMscf) per well and the 20 year recovery on 80-acre spacing is approximately 370 MMscf/well. Note also in Figure 4 that the time to reach the peak gas production rate occurs sooner for smaller well spacings. The magnitude of the peak gas production rate is also larger for smaller well spacings. This is due to the fact that the dewatering of the fracture systems in the coal seams occurs much quicker in smaller spaced wells due to the more pronounced interference effects between closer spaced wells.

Another aspect of varying well spacing related to vertical well production is the length of time required to recover a certain amount of gas in place. Figure 7 shows the gas production forecasts generated for this study plotted as the percent recovery of the original gas in place for each case as a function of time.

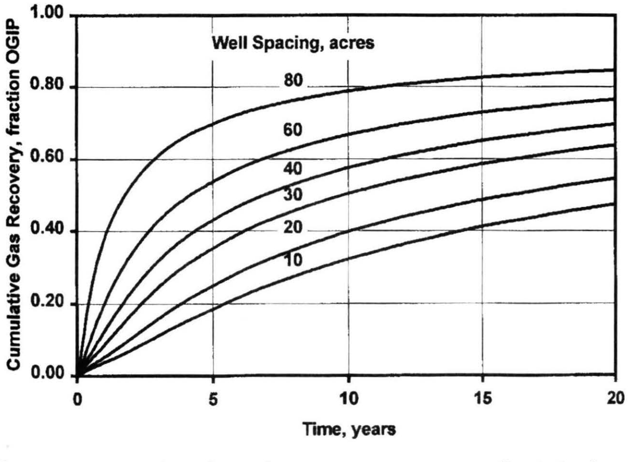

Figure 7. Simulated production as a percent of original gas in place at various well spacings.

This figure shows that the recovery of a given percentage of the in-place gas is achieved much faster for smaller well spacings. This is due to the positive influence of interference between wells which occurs more strongly for closer spaced wells. Figure 8 shows a different plot of the same gas recovery data. This figure shows the percentage of gas recovered as a function of well spacing for various production periods.

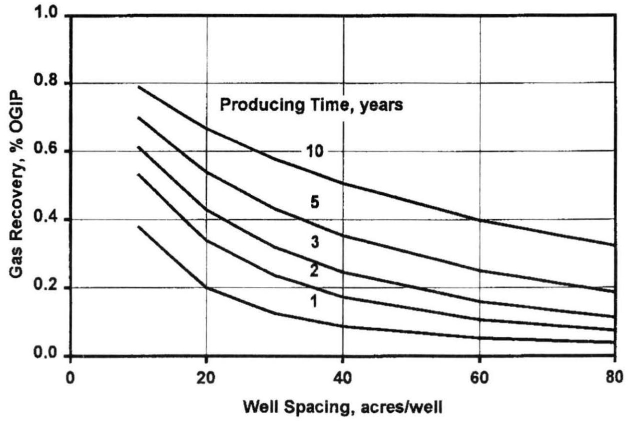

Figure 8. Percentage of gas recovered as a function of well spacing at various time periods.

The results shown in the previous figures are the basis for the designing a vertical degas program for a mining area. For the examples shown here, we have used one permeability value for the simulations made for a variety of well spacings. It would probably be necessary in most actual cases to run the simulations at various well spacings for two or three different values of permeability which cover the range of expected permeability for the coals in the mine area. This would provide a range of results that would be useful for understanding the impact of permeability on the degasification design.

DESIGN OF A DEGASIFICATION SYSTEM

To evaluate the effects of a vertical well degasification system on a coal mining operation, a hypothetical longwall mine was developed. This mine design was modified from work previously presented by Wang (1997) and Wang and Mutmansky (1998). The mine plan consisted of a 5,000-acre, flat-lying, geologically simple coal seam. Within this area, a longwall mine was designed that consisted of 24 longwall panels (900 ft x 7,000 ft), 5-entry mains (20-foot entries and 70-foot square pillars), 3-entry sub-mains and headgate/tailgate roads (20-foot entries and 70-foot square pillars), and 2 entry bleeders (20-foot entries and 70-foot square pillar), Figure 9.

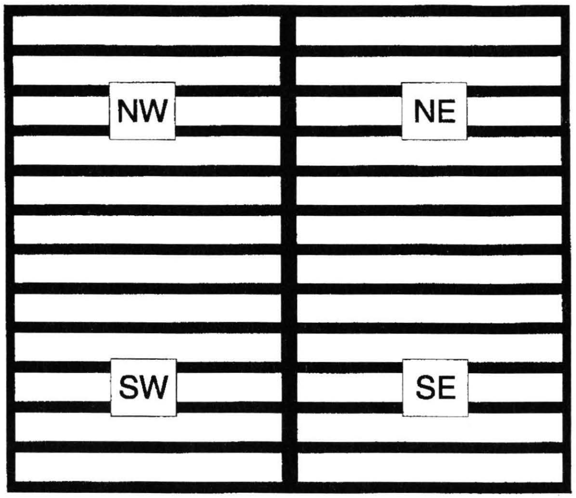

Figure 9. Schematic layout of the hypothetical mine used in the study.

For this study, mining was assumed to begin near the center of the block, developing the northwest mine quadrant first, followed respectively by the southwest, southeast, and northeast quadrants. Mining was projected to occur such that one to three continuous mining units would be required for the development entries and one longwall unit would be used for panel extraction. Panel extraction rate was estimated at 9 months per panel, with the development entries mined 1 to 2 years ahead of panel extraction.

The design of a degasification system for the hypothetical mine (or for any mine) must incorporate and balance numerous, often competing, interests. These interests include the 1) desired level of methane reduction in the coal before mining enters a specific area, 2) available length of time before mine development begins, 3) available financial capital for investment in the degasification system, and 4) desired return on investment for the degasification system. As shown earlier, the optimum system for maximum methane reduction could be drilling many wells at a 10-acre spacing (probably cost-prohibitive) or drilling wells on an 80-acre spacing but having 20 years to pre-drain the mine (financially attractive but conflicts with desire for near-term mining operations).

Two approaches to degasification design were used in this study. The first case assumed a constant well spacing whereas the second case assumed a variable well spacing. For ease in this demonstration, it was assumed that all wells were installed at the same time; however, this is another variable that can be modeled to optimize results.

The constant spacing case provides results similar to that presented earlier for the single well model runs. Figure 10 shows the gas content of the coal that the mining operations encounter at different years in the life of the mine when an 80-acre vertical well degasification system is installed. This degasification system required 95 wells to be installed over the mine area. Although significant reductions in the gas content of the coal is achieved during later years in the mine development, early-time mining operations benefit little from this system.

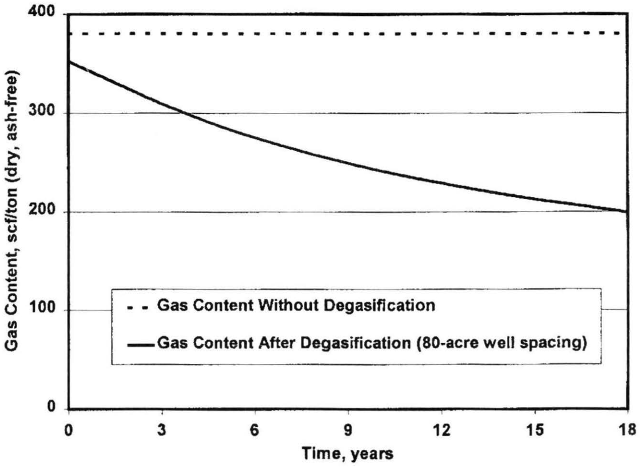

Figure 10. Effect of the 80-acre spaced degasification system on the gas content of the coal during mining.

The second (and alternative) system would be to install groups of wells with varying well spacing. Figure 11 shows the mine plan with areas identified as to the spacing of the vertical wells. As shown, the area of the mine to be developed during the first 3 years would utilize wells drilled on a spacing of 20 acres; the intermediate mine development period (years 3 through 9) would utilize 40-acre spacing for the wells; the final development area (years 10 through 18) would incorporate wells with a spacing of 80 acres. Table 3 presents the number of wells that would be required within each of the variable spacing areas.

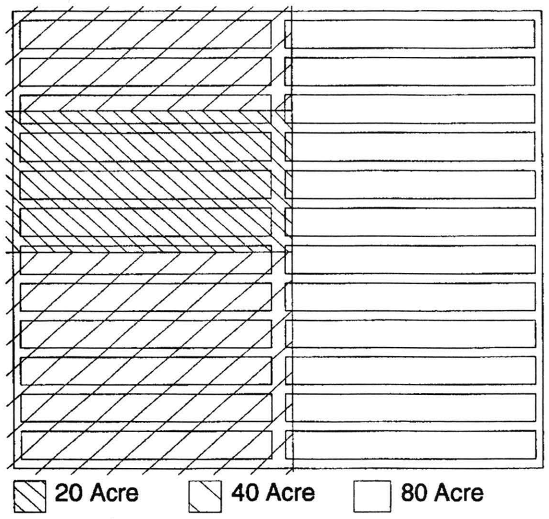

Figure 11. Schematic of the hypothetical mine with variable-spaced degasification areas.

Table 3. Number of wells required for the variable-spaced degasification system.

Well Spacing, acres	Number of Wells in Hypothetical Mine
20	55
40	72
80	80
	172 total wells

This variable-spaced vertical well degasification system would result in a significant reduction in the gas content of the mined coal beginning with the inception of mining, Figure 12. As shown, a 40 to 50 percent reduction in gas content of the coal is achieved with this system throughout the life of the hypothetical mine. Clearly this hypothetical mine would have a reduced ventilation requirement, thus improving overall mine operational costs, and potentially reduced down-time due to high emission levels, thus improving coal production rates and lowering per-ton mining costs.

FINANCIAL ANALYSIS OF THE DEGASIFICATION SYSTEMS

Although reduced capital and operating costs, increased productivity, and lower mining costs may be realized by a mine using an optimally design degasification system, any benefit must be offset by the potential financial burden of the degasification system. Using the hypothetical mine and the two degasification systems described above, discounted cash-flow analysis was performed to determine the financial burden (or reward) of a properly-designed vertical well degasification system.

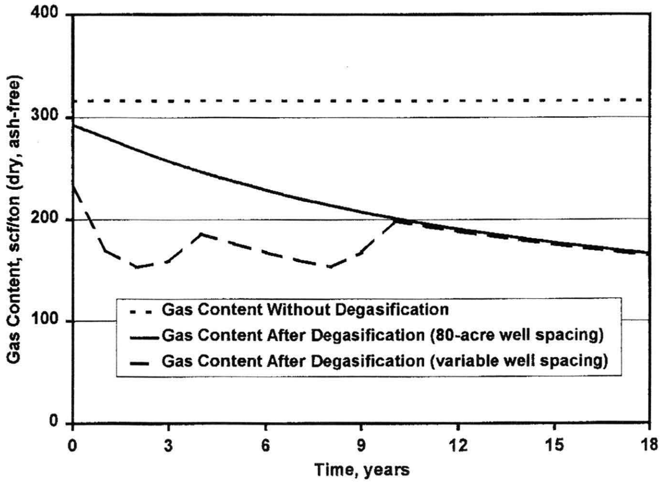

Figure 12. Effect of the two degasification systems on the gas content of the coal during mining.

Basic assumed financial parameters for this analysis are shown in Table 4. Detailed descriptions of the costs associated with a vertical well degasification program can be found in Kuuskraa and Boyer (1991) and Hobbs, *et al.*, (1997). The gas produced from the vertical well degasification system would be of natural gas pipeline-quality, similar to the on-going degasification efforts in the Warrior basin (Boyer, *et al.*, 1995). Therefore, for this analysis it was assume that the gas would be conditioned (dehydrated and compressed) and injected/sold directly into one of the numerous gas pipelines that cross the Warrior basin.

Table 4. Financial assumptions used in the economic analysis of the two degasification systems.

Financial Element	Value
Total well cost	$225,000
Operating costs	$500 per month
Gas selling price	$2.25 per Mscf
Royalty	12.5%
Severance tax	6%
Project life	19 years
Discount factor	10%

Results of the financial analysis, as shown in Table 5, indicate that both degasification systems generate a positive return on investment. The fixed 80-acre spaced system generated an attractive return on investment; the variable spaced system returned the investment with a very minor profit.

Table 5. Financial analysis results of the two degasification systems.

Element	80-acre Spaced Degasification System	Variable-Spaced Degasification System
No. of wells	95	172
Total investment, $	19.00 million	34.40 million
Gross gas reserves, Bcf	34.10	30.54
Net gas reserves, Bcf	29.83	26.72
Net revenue, $	67.13 million	60.13 million
Cumulative cashflow, $	33.27 million	13.92 million
Present worth*, $	10.66 million	0.05 million
Rate of return	22.30%	10.06%

*Present worth at 10% discount factor

SUMMARY

This paper demonstrates how reservoir simulation can be used to design a vertical well degasification system for a coal mine. The design of the optimum system begins with the forecasting of production for vertical wells in the mine area. The simulated forecasts should be made for a range of well spacings and reservoir permeability. The results of these forecasts then provide the basis for the design of the optimum degas program based on the mine plan.

The optimum degas system (using vertical wells) must give consideration to (1) the desired level of methane reduction in the coal prior to mining, (2) available lead time prior to mining, (3) available capital for the degas system, and (4) the desired return on investment for the degas system.

Based on the example vertical well degas program design discussed in this paper, we have drawn the following conclusions.

1. The maximum reduction in gas content of the coals prior to mining occurs when the smallest well spacing is used, regardless of lead-time before mining.
2. The minimum required investment in the vertical well degas system to achieve a given level of reduction in the gas content of the coals occurs when large lead times are available, permitting large well spacing to be used.
3. The optimum vertical well degas system utilizes variable well spacings related to the lead-time associated with different areas of the mine. Smaller well spacing is used in areas that are scheduled to be mined in 1 to 2 years and larger spacing is used in areas to be mined in later years.

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