RESERVOIR MODELING-BASED PREDICTION AND OPTIMIZATION OF VENTILATION REQUIREMENTS DURING DEVELOPMENT MINING IN UNDERGROUND COAL MINES

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Abstract

During development mining, ventilation capacity may decrease and the ventilation requirements may depart from initially planned values depending on the mining rate, increases in the methane emission rate, and changes in ventilation airway leakages. Insufficient ventilation air quantities and the occurrences of high methane liberation rates can overwhelm the existing quantity of ventilation air and result in elevated levels of methane gas during development mining. This condition can both limit the development of that section and increase the risk for an ignition that may lead to an explosion. Thus, the prediction of ventilation air requirements prior to mining can enhance worker safety by reducing the likelihood that explosive methane-air mixtures form.

This study presents an approach for prediction of methane inflow rates using coalbed methane reservoir modeling. For this purpose, a two-phase coalbed reservoir model of a three-entry type roadway is developed. In the model, grids are dynamically controlled to simulate development of entries. Examples are given for methane inflow and ventilation air requirements as a function of mining rate, development section length, mining height, and the existence of degasification boreholes. This technology can be used to limit the methane concentrations occurring as a result of the influences of various coalbed and operational parameters.

Introduction

Ventilation planning is one of the most important elements for coal mining because of its impacts on productivity and safety. It is important to improve predictive and optimization methods to provide adequate ventilation airflow based on the coalbed and mining parameters. Entry length and the number of crosscuts (leakage) increase as development mining progresses, requiring additional airflow to adequately ventilate the working areas. In order to improve the safety of underground coal mines, it is important to have the predictive capabilities to estimate methane emission rates based on coalbed and mining parameters at a particular stage in mining and to be able to optimize the mine ventilation requirements. Furthermore, as development lengths increase, it may become increasingly difficult to keep methane levels under statutory limits by ventilation alone. One of the most effective approaches in this situation is to drill horizontal boreholes in the coalbed to drain excessive methane from the coalbed before mining starts and to shield entries from migrating methane. Horizontal drilling and its application to degasify coal seams are well-documented in the literature [1-4].

Over the years reservoir-modeling methods and simulators have been developed that can realistically represent the complex physics of reservoir flow mechanisms in coalbeds and gas production operations using diverse well designs [5]. These simulators have been successfully applied in various coal basins for coalbed gas recovery using both vertical and horizontal boreholes [6-8]. These models offer advanced predictive capabilities to simulate the development mining process and the prediction of methane inflow rates [9] as well as the subsequent determination of airflow requirements based on coalbed and mining parameters. However, as the number of independent variables increases, model solution and analysis become increasingly difficult.

This paper applies coalbed reservoir simulation for improved prediction of methane inflow rates and optimization of ventilation requirements during development mining. The reservoir models were based on a typical three-entry Pittsburgh Coalbed mine operating in the Southwestern Pennsylvania section of the Northern Appalachian Basin. These models were developed using Computer Modeling Group's [10] compositional reservoir simulator (GEM). The work evaluated the presence and lack of coal seam degasification and shielding against methane. The models were run "dynamically" to simulate advance of entry development using a "restart" approach [11-13]. The reservoir model predictions were compared with the in-mine monitoring data of air quality and flow rate obtained during tailgate and headgate entry development around a longwall panel. Various mining and degasification-related parameters were considered for parametric runs using this reservoir simulator.

Reservoir Modeling of Development Mining

The base model for development mining was a coalbed methane reservoir model created in cartesian coordinates. It simulated both entry development and fluid flows in the unmined sections of the coalbed and in the entries. A three-entry tailgate and headgate development, typical of coal mines operating in the Southwestern Pennsylvania section of the Northern Appalachian Basin, was analyzed. Figure 1 shows the layout of such a mine.

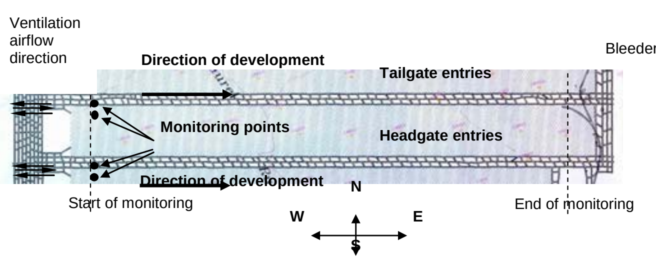

Figure 1. The modeled longwall panel showing entry sections where mining and ventilation data was gathered during development mining

The parameters and their average values in Table 1 were used. The pre-mining reservoir data for the particular mine site were gathered from previous NIOSH publications [14], external reports, personal communications with the operating mining company, and previous history matching studies [11-12].

Various factors impact ventilation requirements during development mining. Among these factors, coalbed parameters and mining parameters are probably the most important. Since ventilation requirements depend upon the quantity and rate of methane liberation into the entries, coalbed reservoir parameters such as pressure, methane content, adsorption parameters, and permeability have a direct impact on the methane emissions and thus on the ventilation design considerations. In this study, the average properties shown in Table 1 were used in the models. Thus, the variables originating from coalbed reservoir properties were mostly eliminated from parametric runs and subsequent analyses. The main areas of emphasis were mining parameters, the methane concentration level to be maintained, and the presence or absence of a degasification/shielding program to reduce methane inflow into the developed entries.

Table 1. Values of some of the reservoir parameters of the coalbed used in the models.

Parameter	Value
Permeability-Face Cleat (milli-darcies)	4
Permeability-Butt Cleat (milli-darcies)	1
Effective Porosity (%)	4
Effective Fracture (Cleat) Spacing (ft)/(m)	0.1/0.03
Langmuir P. (psi) / (MPa)	326/2.2
Langmuir Vol. (scf/ton) / (cc/g)	498/15.5
Desorption Time (days)	20
Initial Water Saturation (%)	60
Coal Density (lb/ft^3) / (g/cc)	84.7/1.4
Pressure (psi) / (MPa)	90/0.61

For modeling advance of tailgate and headgate entries, a three-entry development model around a longwall panel was studied. Figure 2 shows snapshots of mining advance, pillar layout, and ventilation scheme. The middle entry was modeled as the "track" or haulage entry, where intake air entered. In this entry, ventilation air injection and mine pressure assignments to the grids were performed using an injector well. The entry to the left of "track" was designated as the "belt" entry, where flow direction was out from the mine. The third entry was designated as the "return" entry carrying away majority (>90%) of the methane emissions and the methane-loaded ventilation air.

During development mining, the entries and the cross cuts to be ventilated are continuously extended. The amount and rate of methane emission into the developed entries depend upon the extent of the continually created surfaces. As the continuous miner advances, new volumes are created that must be ventilated while new surfaces are created that liberate gas into that volume. In this study, the development of a three-entry continuous mining model, shown in Figure 2, was handled using "restart" model runs. These models were run sequentially with each characterizing an entry advance with a specified development rate where the assigned properties of the entries replaced the coalbed properties and ventilation-related features were built. All three entries were developed simultaneously to a specific distance in a predefined amount of time, allowing calculation of the rate of mining advance. For different mining rates, the times in the recurrent data set were changed. Thus, the rates reported in this study are not linear mining rates, but instead represent the rates of the mine section advance. Based on this approach, a 150 ft (45.7 m) section advance corresponds to 570 ft (173.7 m) of linear mining distance shown in Figure 1, including entries and cross cuts.

As the entries were developed at the designated rates, the pillars and cross cuts were also developed at the same time. The pillars between the entries were 125 ft (38.1 m) in length and 75 ft (22.9 m) in width, and had the same properties as the coalbed. However, during the development of entries, the permeability was replaced with a high permeability in all three directions. Also, the coal-matrix pressures in the mined grids were assigned to atmospheric pressures to simulate the mining process. The development of cross cuts was modeled in the same way as the entries. However, during each simulation run only the last set of cross cuts was left fully open for ventilation airflow. During development of cross cuts, stoppings or block walls (between track-belt and track-return) were automatically created between the restart runs to force ventilation flow through the last open cross cuts at each section advance. A "curtain" resistance in the last section of the "track" diverted some of the intake air towards the "belt" entry to ventilate both belt and face. Figure 2 shows the progress of mining as well as the entries, cross cuts, pillars, ventilation airflow paths, and the locations of the curtains dynamically created during simulations. A permeability of 100 millidarcies was assigned to the stoppings to represent leakage, a common occurrence in underground mining.

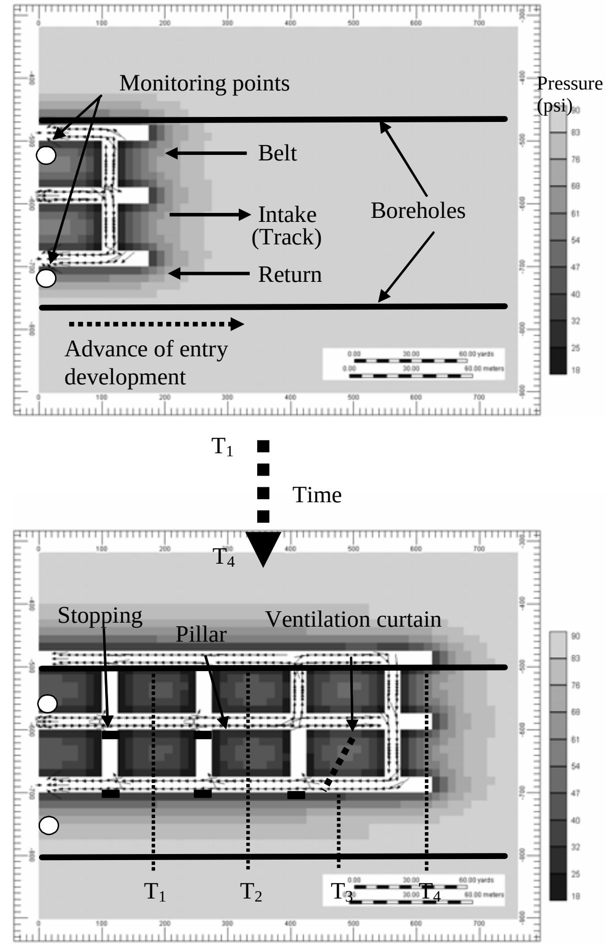

Figure 2. Snapshots of mining advance, pillar layout, and the ventilation scheme in the coalbed reservoir model. Locations where total methane inflow is monitored are also shown. The figures show the progress of mining in the coalbed at the end of first and fourth section advances.

In this study, two different modeling approaches were undertaken to predict methane inflows and to estimate ventilation requirements during development mining. In the first approach, the methane inflows and the ventilation air requirements were determined based on the absence of any degasification wellbores around the entries to shield them from migrating methane. The variables of this model were mining rate, mining height (coalbed thickness), methane percentage in the ventilation air, and length of developed entries. In the second modeling approach, the presence of horizontal wellbores along the entries, as shown in Figure 2, was considered for their effects on degasification and shielding against methane inflow. The wellbores were 3 inches (7.6 cm) in diameter, with no wellbore skin, and operated with -0.2 psia (-1260 Pa) bottom-hole pressure to extract the methane. The lengths of the boreholes were equal to the lengths of the entries.

Table 2. The parameters and their range of values changed in simulation runs.

Parameter	Range
Mining height (ft) / (m)	5-7 / 1.52-2.13
Entry length (ft) / (m)	1000-12000 / 305-3660
Mining rate (ft/day) / (m/day)	25-175 / 7.6-53.3
Methane concentration in mine air (%)	0.5-1.5
Distance of shielding wells to entries (ft) /(m)	19-87 / 5.8-26.5
Degas. duration before mining (days)	0-180

During simulations, the proximity of the horizontal wellbores to the entries was changed between 19-87 ft (5.8-26.5 m) and the pre-mining degasification period was varied between 0-6 months. In all cases, the wellbores were operated during mining regardless of the duration of the pre-mining degasification period. The parameters and their ranges used in reservoir models are summarized in Table 2.

Model Validation by Comparing Reservoir Model Prediction with In-Mine Monitoring Data

The predictive performance of the reservoir model was compared with in-mine measurements of methane inflow, reported as monthly averages, during development of the tailgate and headgate entries. The reservoir models utilized mining parameters that were close in value to those obtained from recent field studies, i.e., 7 ft (2.1 m) mining height, 70 ft-110 ft (21.3 m-30.5 m) per day advance rate, and 2000-12000 ft (610-3660 m) development length. Airflow rates were calculated to produce a constant 0.5% methane concentration based on methane inflow measurements.

Figure 3 shows the simulator predictions and measured methane inflows into the headgate and tailgate entries. The solid markers and the trendlines show the simulator predictions for methane emissions at the two different mining rates as a function of entry length. Since the simulations use constant mining and coalbed parameters, the methane inflow results show a continuous increase with the length of mined entries, as opposed to the scattered increase in measured data. Nevertheless, the developed model closely predicts the range of measured data.

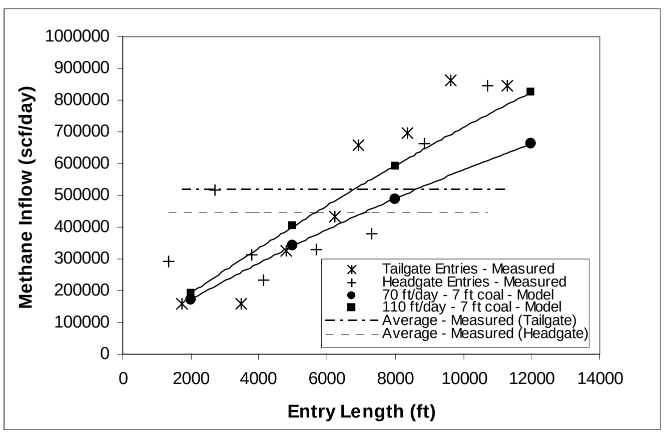

Figure 3. Comparison of methane in-flows based on measurements of airflow rate and air quality and the simulator predictions at two different mining rates.

The predicted airflow rates needed to maintain a constant 0.5% methane level in the ventilation air and the measured airflows that resulted in an average methane concentration of 0.5% are shown in Figure 4. This figure shows that, because of methane inflow increases, simulator predictions of airflows increase with entry length to keep the methane levels at 0.5%. Although the average predicted airflow is close to the average of the measured values, the measured values at the start and end of the mining are higher and lower than the predicted values, respectively. The model calculates the required amount of air based on simulated methane inflow. During gateroad development, the ventilation air rate was kept in a narrow range regardless of the length of the developed section or the mining rate. In fact, methane levels increased from 0.20% at the beginning of development to 0.85% at the end of development, indicating an abundance of ventilation air at the beginning and a lack of airflow at the end. This comparison suggests that adjusting airflow quantity based upon mining progress using a predictive method may be safer and more economical than supplying a fixed volume of air based on projected maximum demand.

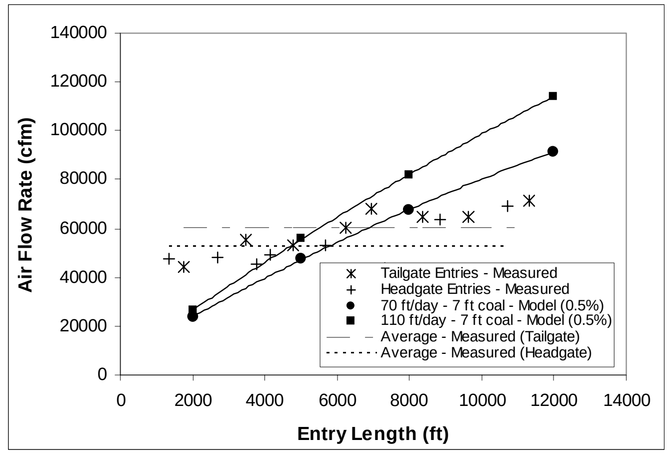

Figure 4. Comparison of airflow rate measured in the mine and the simulator calculations based on two different mining rates to maintain a constant methane level of 0.5%.

Parametric Analysis of Reservoir Modeling Results

The reservoir model generated parametric simulations to cover a range of values for the mining-related parameters shown in Table 2. Some of those results are presented in this section to show the relationships and the effects of different parameters on methane inflow into the entries. Once the methane inflow rate is known, the airflow requirements can be calculated to keep methane concentrations at a required level.

Figure 5 shows the predicted methane inflow rates at 2000, 8000, and 12000 ft (610 m, 2440 m, and 3660 m) of roadway development in the 7-ft-high coalbed with different development rates. Results show that the methane inflow rate increases with the length of the development section because of the increase in surface area of the exposed coalbed. This increase is a strong function of the mining rate. However, the effect of the mining rate on methane inflow is less pronounced for shorter development distances than longer distances. For 2000 ft of roadway development, increasing the mining rate from 25 ft/day (7.6 m/day) to 175 ft/day (53 m/day) increases the methane inflow rate from 109100 scf/day (3090 m3/day) to 214000 scf/day (6060 m3/day), which is approximately a two-fold increase. With an 8000-ft entry development, increasing the mining rate from 25 ft/day to 175 ft/day increases the methane inflow from 244300 scf/day (6920 m3/day) to 700500 scf/day (19850 m3/day), a nearly three-fold increase. Similarly, increasing the mining rate from 25 ft/day to 175 ft/day in developing 12000 ft of entries increases methane inflow rate from 309000 scf/day (8760 m3/day) to 991150 scf/day (28080 m3/day), over a three-fold increase.

The methane inflow simulations performed for development mining can be used for evaluating and designing ventilation requirements. Figure 6 shows the calculated airflow requirements as a function of the mining rate to keep methane concentrations at predetermined concentrations during development of 2000- and 12000-ft (610-m and 3660-m) entry sections. For these calculations, the methane inflow rates shown in Figure 5 were used. With shorter development distances, only minimal adjustments to ventilation airflow are needed to keep methane levels below 1%. Such adjustments appear to be independent of the mining rate. With longer development distances, more ventilation airflow is needed to keep methane levels constant, and the amount is more strongly affected by the mining rate. If the ventilation rate cannot control methane levels, decreasing the mining rate can be considered as a desired control.

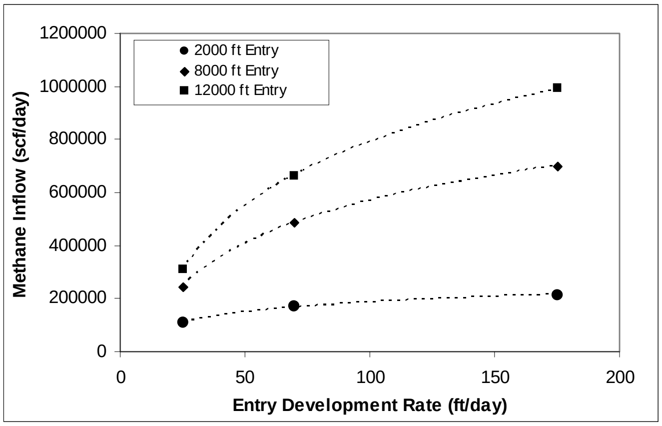

Figure 5. The change of methane inflow rates predicted by the reservoir simulation as a function of the mining rate for different entry lengths.

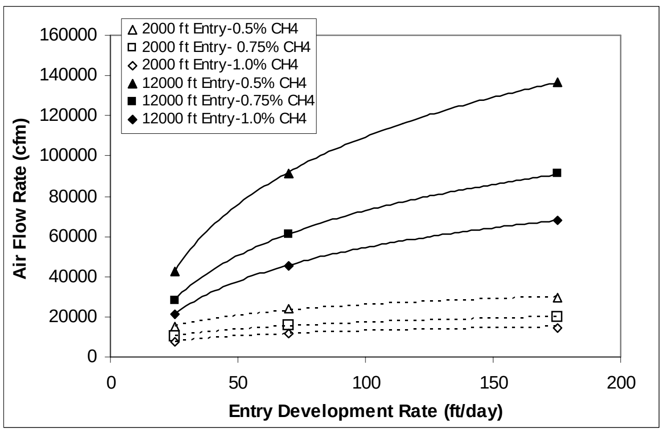

Figure 6. Calculated airflow rates required to maintain various methane concentrations for different mining rates and entry lengths.

Methane inflow during mining is also affected by the mining height of the developed entries. Figure 7 shows the simulated methane inflow rates for development lengths of 2000 and 12000 ft with advance rates of 25, 70, and 175 ft/day. This figure shows that the methane inflow rate is almost a linear function of the coalbed height for a given development length and mining rate. However, the effect of increasing coalbed height on methane inflow rate is less pronounced with shorter development distances than with longer distances, especially with high mining rates. Figure 7 suggests that if there are regional increases in the coalbed thickness in long development sections, decreasing mining rate may be a viable approach to avoid overloading the ventilation system with increased methane emissions.

Using in-seam horizontal boreholes is an effective approach to shielding entries against methane inflow during development mining. To simulate the shielding effects of degasification wells and assess their impacts on the subsequent ventilation air requirements, 3-inch diameter (7.6-cm) horizontal boreholes with no wellbore skin were modeled and operated with -0.2 psi (-1360 Pa) bottom-hole pressure for pre-mining degasification periods of 0 months (i.e., no pre-mining degasification), 3 months, and 6 months. The boreholes were placed 19-87 ft (5.8-26.5 m) away from the entries. In all cases, the wellbores were operated during mining regardless of the duration of pre-mining degasification.

Figure 8 shows the variability of methane inflow rate with development length for horizontal boreholes located 19 ft (5.8 m) away from the intake and return entries and operated for various pre-mining durations. The data represent a 70 ft/day (21.4 m/day) development rate in a 7-ft (2.1-m) thick coalbed. Simulations show that the methane emissions are highest when shielding is not used against methane inflow before or during mining. Emission rates progressively decrease as a result of shielding and degasification duration. For instance, if the boreholes begin to operate when mining starts, the inflow rate decreases about 25% compared to the completely unshielded case. The methane inflow rates after longer pre-mining degasification times are less.

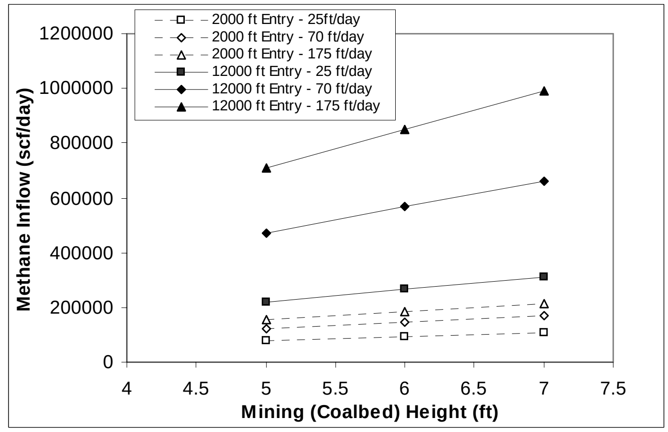

Figure 7. The predicted methane inflow rates into the entries for different seam heights during mining of different entry lengths with various mining rates.

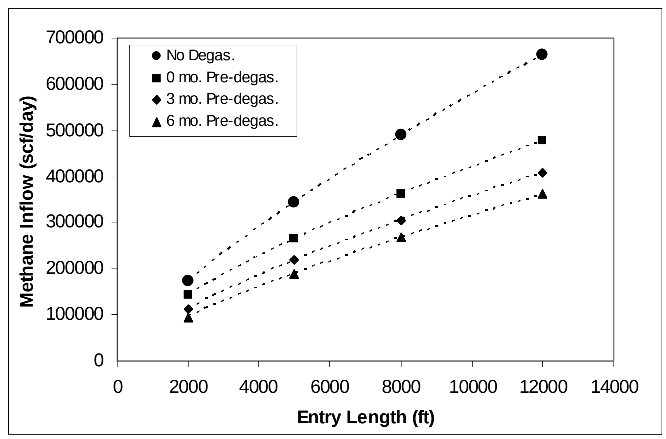

Figure 8. Methane inflow rate predictions for different development lengths and various pre-mining degasification durations. “No degas.” in the legend corresponds to a lack of degasification boreholes.

Figure 9 shows the effects of mining rate and pre-mining degasification duration when developing entries with lengths of 2000 and 12000 ft (610 m and 3660 m). The presence of methane shielding and the duration of pre-mining degasification are more important when development distances are long and mining rates are high.

Figure 10 shows the effects of shielding well proximity and development length on methane inflow rates. The simulated data shown are for a 70-ft/day (21.4-m/day) development rate in a 7-ft (2.1-m) thick coalbed after 6 months of pre-mining degasification. The no-degasification case does not include any shielding. This figure shows that those wellbores closest to the entries are most effective in reducing methane inflow rates during development mining about 50% at 12000 ft (3660 m) compared to no-shielding. Thus, positioning wells as close to the entries as practically possible is better for shielding purposes. However, local geology often dictates that shielding wells be positioned at least one hundred feet from the entries to avoid drawing excess gas toward these gateroads.

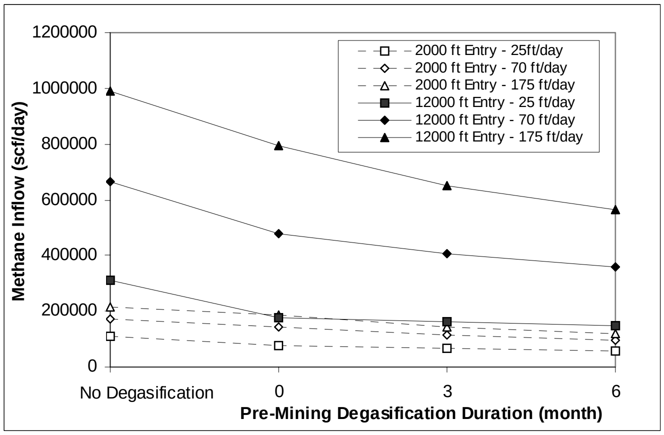

Figure 9. Effect of degasification duration on methane inflow rate for various development lengths and rates.

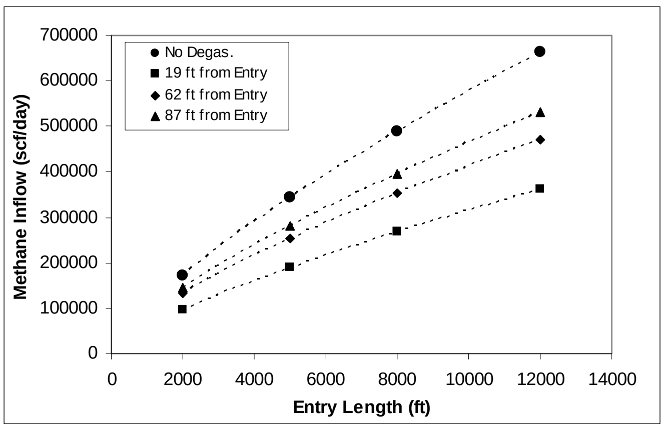

Figure 10. Effect of proximity of shielding wells to the entries and the length of entries on methane inflow rate.

Summary and Conclusions

This study presented the development and application of "dynamic" reservoir models to predict and optimize ventilation airflow requirements to control methane inflows during gateroad development. The reservoir models were developed for a typical three-entry system and considered the presence or absence of shielding boreholes to limit methane inflow. Model simulations were performed by changing various mining and degasification parameters to predict methane inflows and airflow requirements. The reservoir model predictions were compared with the in-mine measurements available from the mining of tailgate and headgate entries around a longwall panel.

This study made the following conclusions:

1. Reservoir simulation can be used effectively for modeling development mining in underground coal mines. It can predict methane inflows into the entries based on various coalbed and operating parameters, from which the ventilation airflow requirements can be predicted to maintain a desired methane level.

2. Methane inflow rate increases with entry length due to increases in the surface area of the coalbed exposed to the mine environment. However, the effect of the mining rate is less pronounced on methane inflow for shorter development distances compared to longer development distances.

3. For shorter development distances, marginal adjustments in ventilation airflow may be adequate to keep methane levels under 1%. The model showed that this adjustment was generally independent of the mining rate. However, longer developments require significantly more ventilation air capacity to keep methane levels constant. This amount is a function of the mining rate.

4. Methane inflow rate is a linear function of the coalbed height for a given development length and mining rate. However, the effect of increasing coalbed height on methane inflow rate is less when mining short, compared to long, entry developments, especially with high mining rates.

5. Employing shielding boreholes to protect entries from methane migration during mining is an effective approach. Even if the boreholes cannot be operated for a long time prior to the start of mining, their presence during mining can reduce methane inflow rates (about 25%), especially during mining of longer sections.

6. Positioning of the boreholes relative to the gateroad entries is important. These results show that positioning wellbores as close to the entries as practically possible is more effective, especially when mining long developments at higher mining rates. Although this is true in theory, practical considerations often limit the proximity of these boreholes to the entries to avoid drawing gas toward the gateroad developments.

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