Numerical analysis of the influence of in-seam horizontal methane drainage boreholes on longwall face emission rates

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Abstract

High methane emissions originating from the active face areas and from the fractured formations overlying and underlying the mined coalbed can adversely affect both safety and productivity in underground coal mines. Since ventilation alone may not be sufficient to control the methane levels in the longwall mining environment, gob gas ventholes have become a standard supplementary methane control option in many mines. As mines progress into deeper and gassier coalbeds, or as longwall panel size increases, ventilation and gob gas ventholes together may not be sufficient to maintain methane levels within statutory limits. To decrease the risk associated with methane emissions under these circumstances, in-seam horizontal methane drainage is often used to reduce the gas content of the coalbed prior to mining. Horizontal methane drainage borehole completion designs, drilling strategies, and degasification lead times may need to be adjusted for site-specific conditions due to mine design, geology, and the gas content of the coalbed.

This study investigates different horizontal methane drainage borehole patterns, borehole lengths, and degasification times prior to and during panel extraction to evaluate their effectiveness in reducing methane emissions using a "dynamic" 3D reservoir modeling of a 381-m wide longwall panel operating in the Pittsburgh coalbed. Results of this study showed that dual and tri-lateral boreholes are more effective in decreasing emissions and in shielding the entries compared to fewer shorter, cross-panel, horizontal boreholes parallel to the longwall face. Modeling results showed that after 12 months of pre-mining methane drainage, the average longwall face emission rates can be reduced by as much as 10.3 m^3/min and 6.8 m^3/min using tri- and dual-lateral boreholes, respectively. It was also shown that if pre-mining methane drainage time is short, it is important to continue methane drainage during the panel extraction to maximize reductions in longwall face emissions since additional face emission reductions achieved during this period can be comparable to pre-mining degasification.

Keywords: Longwall mining; Methane drainage; In-seam horizontal boreholes; Reservoir simulation

1. Introduction

1.1. Methane emission sources during longwall mining

Methane emissions can adversely affect both the safety and the productivity of underground coal mines. During longwall mining, methane emissions can originate from three major sources. These sources can be summarized in the following manner: (1) gas emissions from the ribs surrounding the bleeder ventilation system, (2) gas emissions from the active longwall face and mined coal on the conveyor belts, and (3) gas emissions from subsided strata (Mucho et al., 2000).

The first gas source originates from the unmined coalbed adjacent to the development entries of the bleeder system and from the solid coal ribs. Although this emission tends to decrease over time, it may become a significant contributor of gas to the bleeder ventilation system (Mucho et al., 2000). The second source is the combination of the gas content from the mined coal itself and the methane being emitted from the fresh face on the longwall. The third source is the fractured and caved rock in the subsided strata (gob) overlying the extracted panel as the longwall face advances (Fig. 1). The caved zone is characterized as a fragmented rock mass, whose height is about 3 to 6 times the thickness of the mined coalbed (Singh and Kendorski, 1981; Palchik, 2003). The stress relief due to caving causes the overburden strata above the caved zone, including gas bearing coalbeds, to fracture vertically and horizontally. The thickness of the fractured zone (Fig. 1) can vary up to 100 times the height of the mined coalbed, depending on the size of the panel, the geology and geomechanical properties of the layers (Palchik, 2003). The source of the gas emissions determines the selection of an effective methane control system.

1.2. Typical longwall methane control measures

Ventilation has always been the primary means of controlling methane in the mining environment. Mucho et al. (2000) demonstrated that methane emissions within the caved zone are directly influenced by the ventilation system. Therefore, it is desirable to capture the methane released in the fractured zone before it can migrate to the pressure sink of the caved zone.

Gob gas ventholes are commonly used to control the methane emissions from the fractured zone and are drilled from the surface to a depth that places them above the caved zone so they do not directly interact with the ventilation system (Fig. 1). The bottom section of the pipe, generally about 60 m in length, is slotted and placed adjacent to the expected gas production zone. These ventholes generally become productive after the mining-induced fractures propagate under the well (Diamond, 1994) and the gas flow is mainly controlled by the permeability of the fractures. Exhausters are placed on gob gas ventholes to maintain a pressure sink around them to capture the gas from large distances and reduce the migration of methane from the fractured zone to the caved zone.

Methane emissions from the face, ribs, and conveyor belt are directly discharged into the mining environment; therefore, the ventilation system must have sufficient capacity to dilute and render harmless any unexpected increases in methane emission levels. As mines move into deeper coalbeds with potentially higher gas contents, and as longwall panel widths increase resulting in additional gas emissions in the face area, ventilation systems may not be sufficient to maintain methane levels within statutory limits (Diamond and Garcia, 1999; Schatzel et al., 2006). The most common supplemental gas management practice is to degasify the coalbed prior to mining to reduce the volume and rate of these emissions (Thakur, 1997). In addition to reducing the in-place gas content of the coalbed, it has been shown that methane drainage is also effective for reducing the risk of gas outbursts by decreasing the pressure of the coalbed in

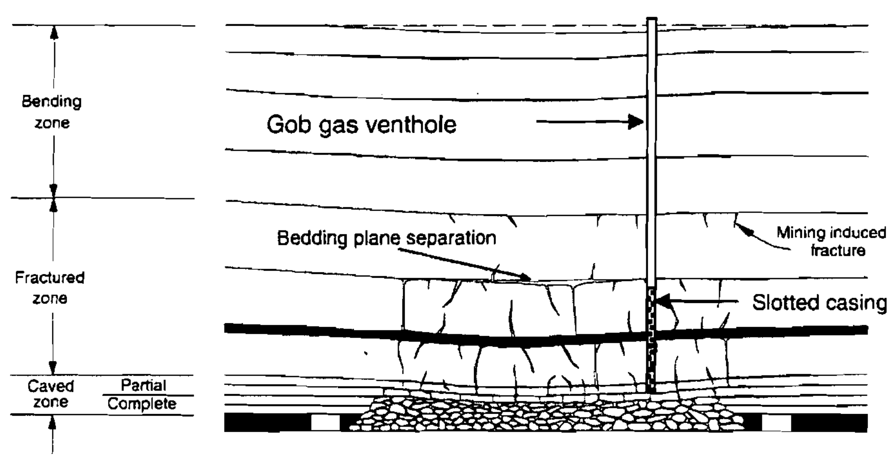

Fig. 1. Schematic of strata response to longwall mining (modified from Singh and Kendorski, 1981).

the vicinity of the mine workings (Hungerford, 1995; Noack, 1998).

1.2.1. Degasification of coalbeds using horizontal boreholes for reducing emissions

The most commonly applied methane control solution, especially in high in-place gas content coalbeds, is drilling methane drainage boreholes into the panel area prior to longwall mining to reduce the methane content of the coalbed (Diamond and Garcia, 1999). These boreholes can be vertical boreholes drilled from the surface or in-seam horizontal boreholes drilled from the underground entries (Diamond, 1994). Although in-mine drilling can be challenging because of the logistics of working in the restrictive underground environment, one advantage is that virtually the entire drilled lengths of the boreholes are in the gas producing horizon of the mined coalbed. In recent years, a new pinnate-drilling™ technique has been successfully applied in coalbeds in the Appalachian Basin and in the Western states of the U.S. using horizontal methane drainage boreholes directionally drilled from the surface (PTTC, 2004). This technique combines the logistically less complicated process of drilling from the surface with the high productivity of horizontal methane drainage boreholes.

The design considerations for horizontal degasification boreholes may change depending on the mining conditions and on the coalbed to be degasified. Generally, in-mine horizontal boreholes are used to perform two basic mine safety functions: reducing the in-place gas volume within the panel prior to mining and shielding active workings, especially development sections, from gas migration from the surrounding virgin gas reservoir. In-seam horizontal methane drainage boreholes are usually completed open hole, with a short segment (9–15 m) grouted to seal the end of the borehole near the mine workings (Zuber, 1998). Long (>305 m) horizontal boreholes drilled parallel to the gateroads in advance of entry development can be utilized to drain methane from the panel area (Fig. 2A) and they can be used to shield the advancing development entries from the flow of gas from the surrounding coal reserves (Fig. 2B). Shorter, cross-

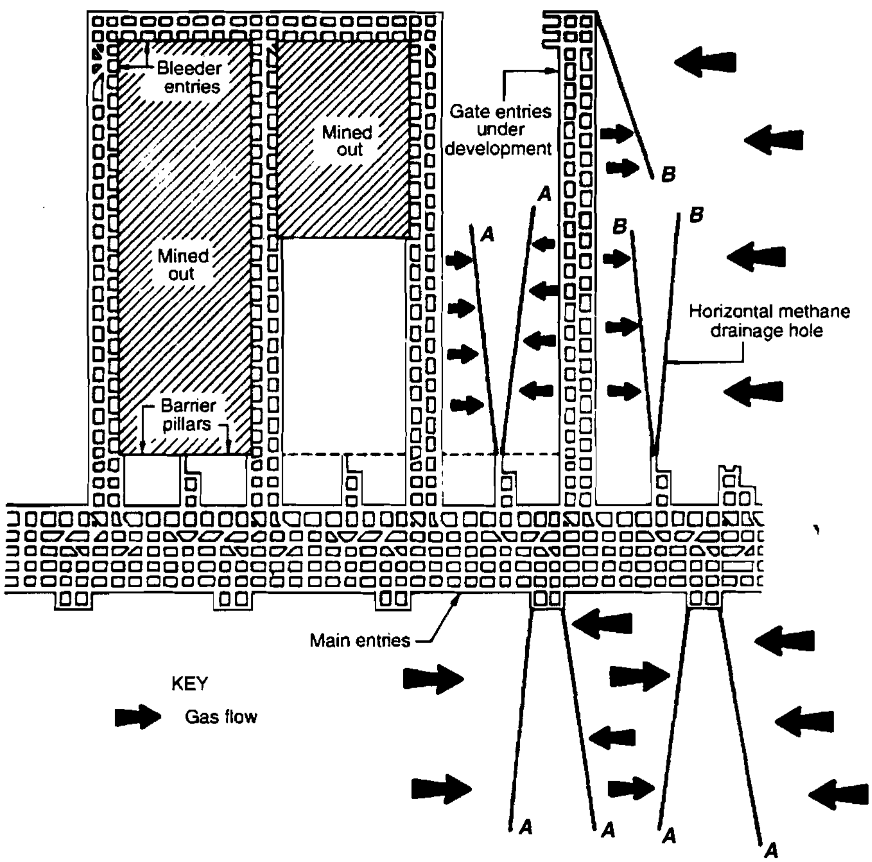

Fig. 2. Schematic plan view of long horizontal boreholes for methane drainage in longwall mining in advance of mining (A) and for shielding (B) (from Diamond, 1994).

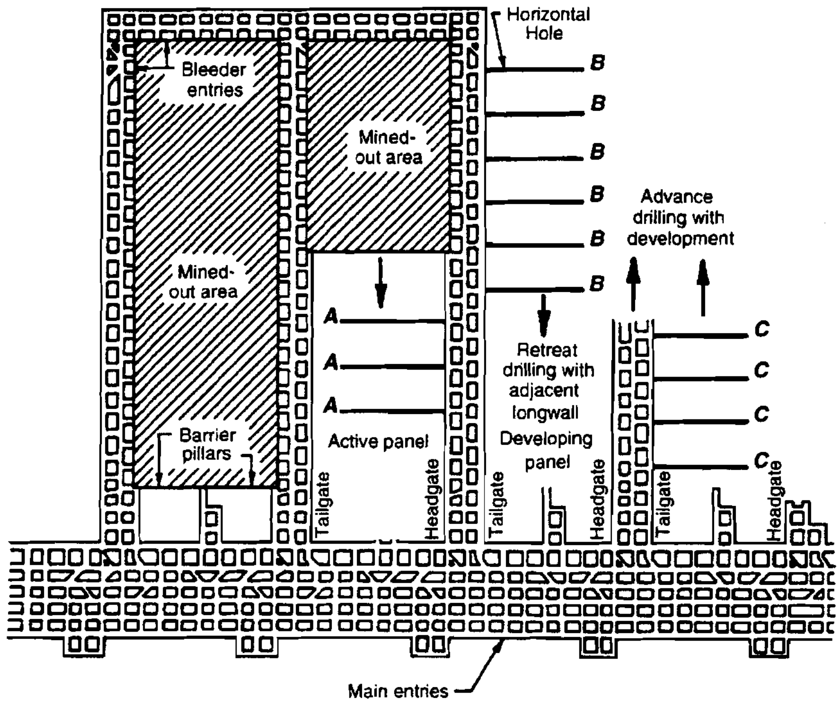

Fig. 3. Schematic plan view of short horizontal boreholes for methane drainage from longwall panels on active panel in advance of face (A), on developing panel adjacent to active panel (B), and from advancing development entries (C) (from Diamond, 1994).

panel, horizontal boreholes drilled from the advancing entries (Fig. 3A–C) can also be used to drain gas in advance of longwall mining from the panel.

One of the most important aspects of methane drainage using any pattern of boreholes is estimating the amount of lead time required to reduce the in-place gas volume sufficiently in order to reduce gas emissions effectively during longwall mining. The life of the horizontal boreholes is dependent on the mine plan. Typically, 6 to 12 months of gas production prior to mining is required to degasify an outlined longwall panel sufficiently (Zuber, 1998). Horizontal boreholes drilled near the recovery rooms are usually allowed to produce gas even after the mining starts. As the longwall face approaches these borehole locations, production is generally terminated as a safety measure by injecting water or gel into the borehole to block the flow of gas. Thus, there are two phases in the production history of a horizontal borehole: prior to mining and during mining, or panel extraction. The relative gas production contributions of these two phases will vary considerably depending on the well configuration and spacing, duration of pre-mining drainage, and rate of mining.

The importance of drainage time in reducing methane content of the coal was reported by Aul and Ray (1991). They noted that only 30% of the gas could be removed from longwall panels in the Pocahontas No.3 coalbed if the drainage time was about 2 months. However, horizontal boreholes that produced for about 10 months were able to drain 80% of the in situ gas. Based on these data, they concluded that at least 6 months is required to drain sufficient quantities of gas to have a positive impact on methane emissions during mining. As a result of the horizontal borehole methane drainage program, ventilation air volume at the longwall face was reduced from 3400 m^3/min (120,000 cfm) to 720 m^3/min (25,000 cfm).

Numerical models can evaluate methane drainage options for controlling underground emissions. Several papers discussing the theoretical basis and the use of coalbed methane simulators to analyze the performance of vertical or horizontal methane drainage boreholes have been published (King et al., 1986; Remner et al., 1986; Ertekin et al., 1988; King and Ertekin, 1994). Other papers have discussed the use of simulators for designing methane drainage systems for specific field studies (Brunner et al., 1997), estimating the extent of gas drainage with time (Diamond et al., 1989), and evaluating the production potential and strategies of various methane drainage systems (Kelafant et al., 1988). However, fewer numerical modeling studies have investigated the applications and interactions of gob gas ventholes, ventilation, alternative horizontal in-seam boreholes configurations, and drainage lead times on the effectiveness of gas drainage before and during mining. This is partly due to the unconventional modeling required to simulate a moving boundary type reservoir, as is the case with longwall mining, coupled with the complex geomechanical considerations associated with the extraction of the coalbed. Nevertheless, a few studies used a similar moving boundary type reservoir simulation approach (Zuber, 1997) to estimate methane emission rates during gateroad development. Karacan et al. (2005, 2006) and Esterhuizen and Karacan (2005) adapted the moving boundary problem to the longwall mining environment. Their reservoir models evaluated the impacts of various venthole completion factors on gob gas production and further optimized venthole performances for wider longwall panels.

2. Objectives of the study

The objective of this study is to determine the impact of in-seam horizontal methane drainage borehole configurations, borehole spacings, and gas drainage lead times in advance of mining for reducing the in-place methane content of a longwall panel operating in the Pittsburgh coalbed. Potential reductions in longwall face emissions are also estimated. Due to the complexity of the mining environment, a numerical modeling approach was required to achieve the study objective. Computer Modeling Group's GEM software (CMG, 2003) was used to develop the 3D reservoir models necessary to evaluate the multiple variables included in the study. The mechanical response of the overlying strata to mining was modeled using Itasca Consulting Group's (Itasca, 2000) FLAC2D (Fast Lagrangian Analysis of Continua 2D) and the calculated permeability changes were incorporated into the longwall mining reservoir model. The model was calibrated using history matching techniques to match the production histories of gob gas ventholes operating in the study area and the average methane production rates of horizontal degasification boreholes operating in the area. Various pre-mining lead times (3, 6, 9 and 12 months) were simulated using multiple in-seam horizontal borehole configurations. Additionally, the models with 3 and 12 months of pre-mining methane drainage were extended to include a 268-day longwall mining simulation (the actual mining duration of the study panel) to evaluate the additional effects of mining and continued degasification on face emissions.

3. Study area

The model was developed and calibrated for a longwall mining area in the Pittsburgh coalbed located in Greene County, Pennsylvania (Karacan et al., 2005). The study area at the mine was located in a new mining district where panels were initially 381-m wide and were increased to 442 m starting with the third panel. Panel lengths were generally 3350 to 3960 m. The annual production from the mine is approximately 5.9 million tones per year, of which 5.0 million tones are produced from the longwall mining system. Face emission rates are variable making peak towards the end of head-to-tail passes, but emissions exceeding 0.11–0.12 m^3/s (233–255 cfm) trigger gas delays for several minutes during which measured methane concentrations decrease. The methane production rates of gob gas ventholes vary depending on their location on the panel. Initial methane production rates of gob gas ventholes are usually between 8500 and 14,200 m^3/day (0.3–0.5 MMscf/day) in this area and they decline with time. The cumulative production from four gob gas ventholes located on the study panel was about 2.8×10^6 m^3 (100 MMscf) during 268 days of panel extraction.

The overburden depths ranged between 152 and 274 m. A generalized stratigraphic section of the strata above the Pittsburgh coalbed in the study area is shown in Fig. 5. The Sewickley coalbed as well as the rider coals (not shown in this figure) directly above the Pittsburgh coalbed are believed to be the primary source of gob gas during longwall mining. Gas released from the Pittsburgh rider coals located in the caved zone is expected to migrate to the mine ventilation system, while gas in the Sewickley coalbed, as well as gas from any other gas-bearing horizons above the caved zone, migrates to the pressure sink of the operating gob gas ventholes in the fractured zone.

Gob gas ventholes are generally drilled to within 12 or 13 m of the top of the Pittsburgh coalbed and are completed with a 17.8-cm casing and 61 m of slotted pipe at the bottom (Mucho et al., 2000). NIOSH has instrumented the gob gas ventholes (four ventholes on the study panel) in the study area to continuously measure gas production rates and methane concentrations as they become operational, and these holes were monitored as mining progressed over time. These data became an integral part of the model calibration (Karacan et al., 2005).

A methane drainage program, including in-seam horizontal boreholes in the Pittsburgh coalbed, is also used at the study site to shield the gateroads during development mining and to reduce the in-place methane content of the outlined longwall panel. As the development sections advance, two to three sets of two horizontal boreholes (configuration A, Fig. 4) are generally drilled from what will eventually be the tailgate entries

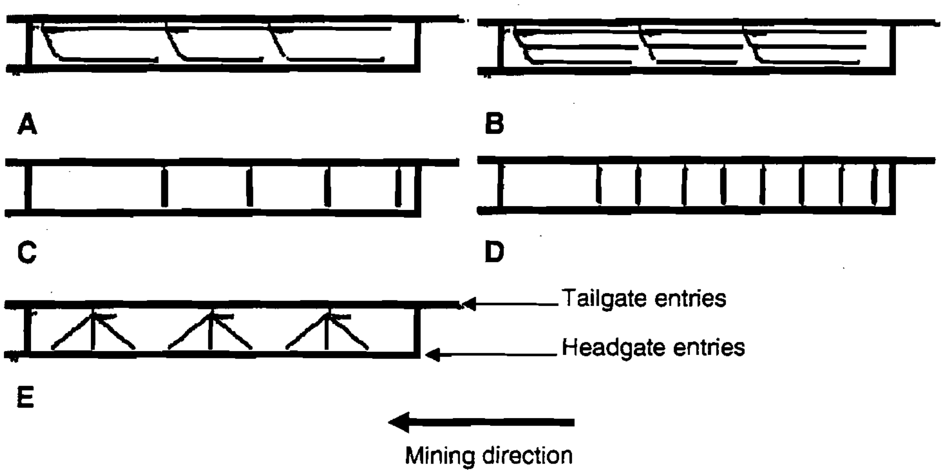

Fig. 4. Horizontal methane drainage borehole patterns modeled for degasification of the longwall panel. The entries represent a three-entry system with intervening coal pillars.

of each panel. The number of sets depends generally on the length of the panels and the length of the individual boreholes. The holes are drilled towards what will be the start-up end of each panel, with one hole paralleling the tailgate side of the panel about 35 m from the margin of the panel. The second hole of each set arcs across the panel parallel to the headgate side of the panel and provides both shielding of the development entries on that side of the panel and general drainage of gas from the interior of the panel. In most mining operations, the individual horizontal boreholes are connected to a common underground pipeline for gas flow metering and transmission to the surface. This approach is logistically easier than monitoring each hole individually underground. However, this does not provide the detailed production histories from individual boreholes and panels for evaluation and model calibration purposes.

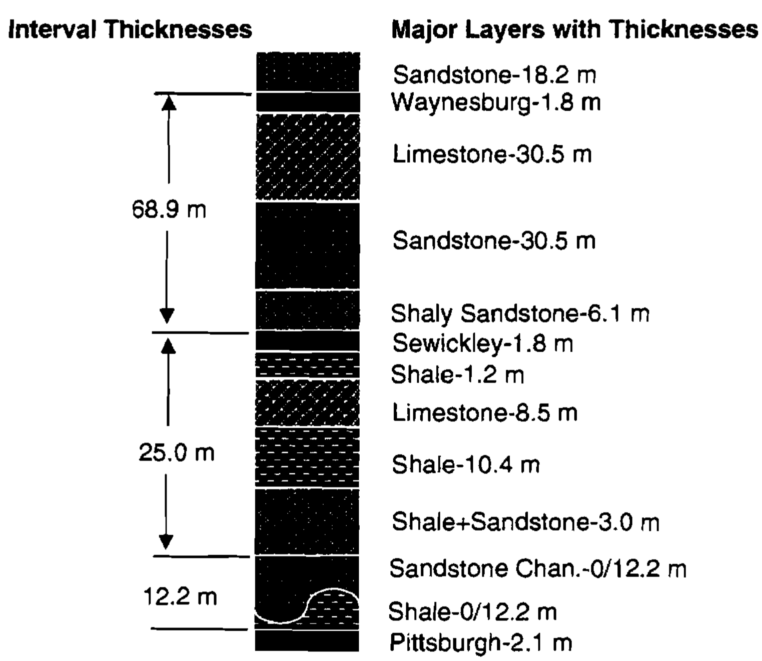

Fig. 5. Generalized stratigraphic section of the study area (not to scale) showing major rock units and their thicknesses used in the reservoir model.

4. Development and application of a reservoir model for evaluating longwall mining methane drainage

4.1. Grid model of the area

The 3D grid model of the area was created using Cartesian grids. Mine maps and existing panel dimensions in the study area were used to structure the grids for associated mine-related features. The number of vertical layers and their thicknesses were based on the generalized stratigraphic section representing the major layers in the mine area (Fig. 5). In generating the grids, each of the individual layers shown in Fig. 5 was assumed to be uniform in thickness and continuous throughout the simulated mine area, except for the sandstone paleochannel complex and associated shale unit overlying the Pittsburgh coalbed. For these two layers, non-uniform grids were used based on the spatial thicknesses determined from isopach contour maps.

Fig. 6 shows a cut-away of the 3D reservoir model that was constructed for this study. In this figure, some of the intervening rock layers have been removed for visualization purposes. The figure also shows the gob gas ventholes on the panel, wellbores that represent the basic elements of the ventilation system in the model, and the type of horizontal methane drainage wellbores typically used in this study area (configuration A, Fig. 4).

The grids of the Pittsburgh coalbed layer were structured differently from the other layers in the area to include the details of the longwall mining environment, the lower part of the caved zone, and the horizontal methane drainage boreholes. This layer was constructed in such a way that it would host both the mined and unmined Pittsburgh coalbed and the gateroads that surround the panel (Fig. 7).

4.2. Representation of elements of the methane control system

4.2.1. Gob gas ventholes

Gob gas ventholes are used as an aid to the ventilation system by capturing released strata (gob) gas as the rock layers are fractured during longwall mining. At this site, four gob gas ventholes were present on the study panel, each having a 17.8-cm (7-in.) casing and 61 m of slotted pipe at the bottom. However, the ventholes were drilled

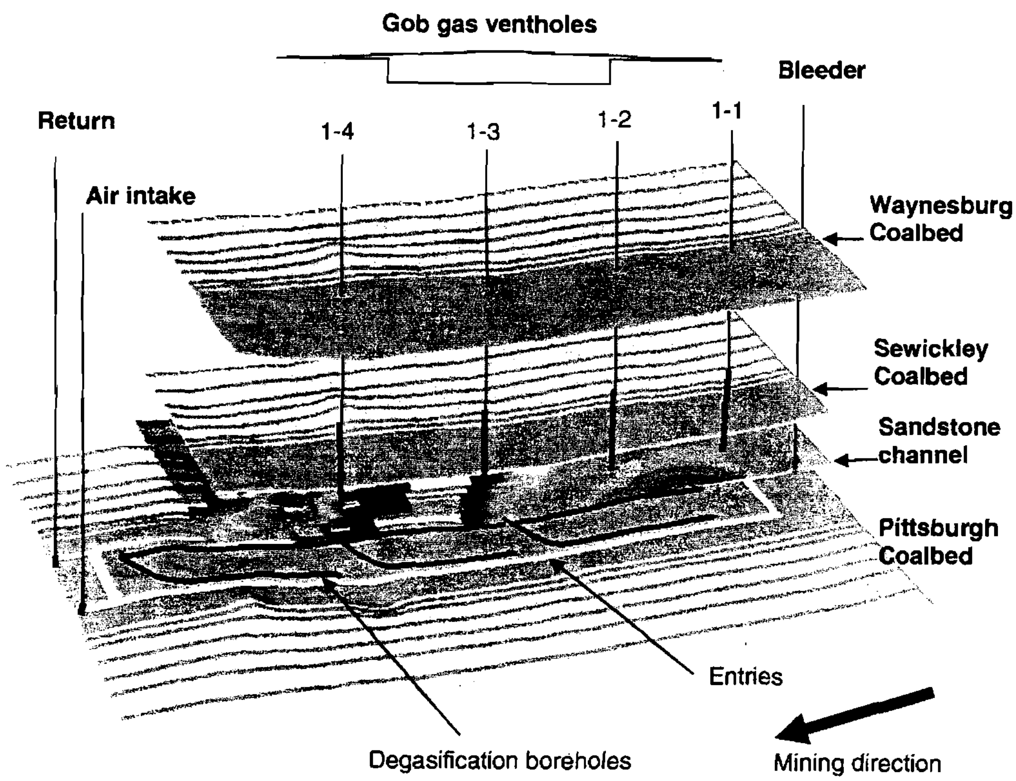

Fig. 6. Transparent, 3D, cut-away grid model of the study area (inner layers removed) showing the major coalbeds and the sandstone paleochannel. This figure also shows elements of the methane control system used in the model. The entries represent a three-entry system with intervening coal pillars. The heavy lines in the well trajectories represent the open-to-flow sections of the wells and lighter traces represent the cased sections of the wells.

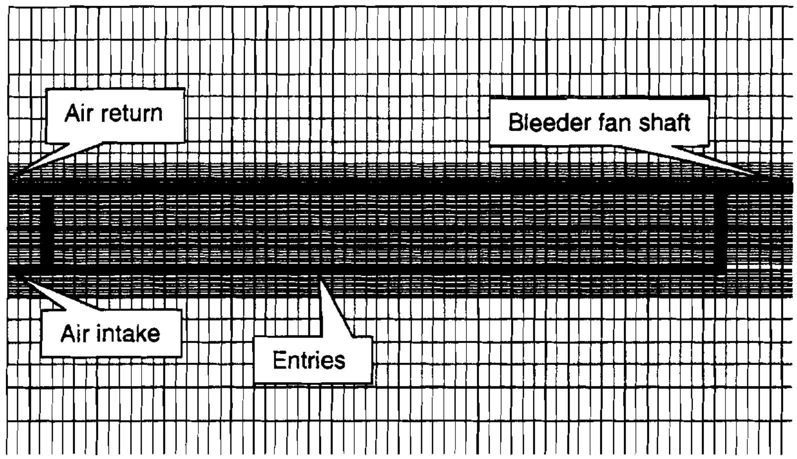

Fig. 7. Pittsburgh coalbed model layer grid showing simulated longwall panel, development entries, and ventilation system elements. The entries represent a three-entry system with intervening coal pillars.

to varying proximities, 14, 11, 9, and 12 m above the top of the Pittsburgh coalbed, as opposed to the preferred 12 m (40 ft) distance for all holes. This placed the bottoms of the ventholes above or close to the top of the caved zone. The ventholes were located about 100 m from the tailgate side of the panel and were 166, 830, 1635, and 2458 m from the start-up end of the panel.

Gob gas ventholes instrumented by NIOSH yielded continuous readings of gas production rates and methane concentrations. The production data measured in the field during panel extraction were used to calibrate the model using a history matching process. Venthole configurations were based on actual completion parameters of the study panel, while operations were based on the actual production histories during 268 days of mining. The history matching results for gob gas venthole productions in this panel area and details of model calibration are given in Karacan et al. (2005).

4.2.2. Simplified ventilation system

A simplified version of the ventilation system was incorporated into the model to simulate ventilation airflows in the gateroads during pre-mining degasification and during longwall panel extraction. For this component of the model, wells were used to simulate the injection (intake) and removal (return) of ventilation airflows, including the bleeder fan shaft (Fig. 7). The air intake part of the ventilation system was modeled by a single well injecting air at constant flow rate conditions.

The bleeder fan was modeled by a large-diameter vertical well on the tailgate side of the panel with the completion interval being equal to the height of the entries (thickness of the Pittsburgh coalbed). During simulations, the bleeder fan was operated with a bottom-hole pressure of −13.6 kPa (−2.0 psia). Another vertical well modeled the return air side of the ventilation system. The vertical wells representing the ventilation intake, return, and bleeder airflow also were used to control the ventilation pressures at the mining layer.

4.2.3. In-seam methane drainage boreholes

Five different horizontal, in-seam, methane drainage borehole patterns were evaluated in this study (Fig. 4, patterns A–E). The boreholes in patterns C and D were spaced equally. In all of the patterns, each borehole was modeled as a 3-in. (7.5-cm) diameter, unstimulated well drilled from the tailgate entries into the Pittsburgh coalbed. The total lengths of the simulated boreholes were 5606 m, 8476 m, 1158 m, 2316 m, and 1845 m (18,388 ft, 27,810 ft, 3800 ft, 7600 ft, and 6052 ft) for patterns A, B, C, D, and E, respectively. The boreholes operated at bottom-hole pressures equal to atmospheric pressure to represent the absence of any exhausters used to aid gas flow. Gas production was simulated for 3, 6, 9, and 12 months in advance of longwall mining. To evaluate gas production potential during mining, the 3- and 12-month pre-mining methane drainage models for each borehole pattern were extended by 268 days to include the production of gas during the longwall mining phase. To simulate methane drainage during mining, boreholes were shut-in as the face reached their locations, a practice employed at the study mine site.

Pattern A (dual-lateral borehole) horizontal methane drainage boreholes, commonly used at the study mine, were also used in calibrating the model by matching the average reported methane productivity (methane volume/production time/length of borehole) of the actual boreholes. The gas average gas production rate from the simulated boreholes in the model was matched to the reported average methane production rates of three horizontal degasification boreholes in the mining area [0.782 m^3/day/m (8.42 scf/day/ft) vs. 0.807 m^3/day/m (8.70 scf/day/ft)]. A similar field-data-based adjustment could not be made for water production because no data were available. Thus, the boreholes were assumed to produce minimal amounts of water.

4.3. Reservoir description

4.3.1. Basic reservoir description of the mining area

Table 1 gives the representative reservoir parameters for both coal and non-coal lithologies that were obtained by calculations, the reports about other districts in the area, personal communications with the operating mining company, and estimates from history matching techniques. These values, particularly the permeabilities, represent the reservoir values prior to mining and thus prior to any disturbance of the strata.

Some of the most important coal-related reservoir parameters are the cleat characteristics (spacing, direction, etc.), gas content, and adsorption data. In this study, cleat spacing was estimated at 3.0 cm, a value based on the reported mean cleat spacing values of 2.4 cm and 3.2 cm from outcrops of the Pittsburgh and Sewickley coalbeds, respectively (Law, 1993). The gas content and adsorption data for the Pittsburgh coalbed and for the other major coalbeds in the area were obtained from the results of laboratory methane adsorption isotherm tests and direct method gas content determination tests on various coal samples (Diamond et al., 1986). The fracture permeabilities for the coalbeds were estimated using history matching to be 4 md in the face cleat direction (approximately an East–West direction at the study site), and 1 md in the butt cleat direction (North–South direction).

Table 1
Examples of pre-mining basic reservoir-rock properties (for fractures) used in the study (x and z are horizontal, face-cleat, and vertical permeabilities, respectively)

Parameter	Pittsburgh coalbed	Sandstone	Limestone	Shale	Entries
Permeability-x, md	4.0	10	2.0	0.2	9×10^7
Permeability-z, md	0.1	10	2.0	0.1	9×10^7
Effective porosity, %	4.0	10	2.0	1.0	40
Effective fracture spacing, m/(ft)	0.03/(0.01)	15/(50)	60/(200)	60/(200)	30/(100)
Langmuir pressure, MPa/(psi)	2.25/(326)	–	–	–	–
Langmuir volume, cm^3/g (scf/ton)	15.4/(490)	–	–	–	–
Desorption time, days	20	–	–	–	–
Coal density, g/cm^3	1.35	–	–	–	–

In the model constructed for this study, the open entries surrounding the longwall panel served as main paths for ventilation airflow. The permeabilities for the area including the three entries and intervening coal pillars were assigned high values [9×10^{-7} m^2 (10^8 md)] within the allowed limits of the simulator for minimum resistance. The associated fracture porosity and fracture spacing for the entries were calculated from mine maps as 40% and 30 m, respectively.

Horizontal methane drainage boreholes drilled either into virgin coalbeds or into areas far from active mining may contain significant amounts of water that must be drained to initiate gas production. In this case, these boreholes show the characteristic production behavior of vertical coalbed methane wells (Ertekin et al., 1988). However, the Central and Northern Appalachian Basins have generally been depressurized, leaving the coalbeds undersaturated because of their geologic histories, extensive coal mining, and the presence of numerous oil and gas wells (Hunt and Steele, 1991). Also, horizontal methane drainage boreholes in this region are generally drilled from active mining operations that have themselves partially dewatered the coalbeds. Thus, these drainage boreholes generally do not experience significant amounts of water production and generally exhibit a declining methane production profile (Zuber, 1998). Although, water production data were not available for matching the model predictions for the study panel, the operating mining company reported no major water influx into the caved zone and no significant water production from either horizontal boreholes or gob gas ventholes. Therefore, it was assumed that there was minimal mobile water in the area.

4.4. Simulation of longwall mining methane drainage

Simulation of longwall panel methane drainage was conducted in two phases. In the first or pre-mining phase, methane drainage was simulated for periods of 3, 6, 9, and 12 months using the horizontal borehole configurations shown in Fig. 4. In the second simulation phase, the models with minimum and maximum pre-mining methane drainage intervals (3 and 12 months) were extended to include gas drainage during longwall mining. This defined the effects of the additional gas drainage time on total gas recovery and subsequent face emissions. However, incorporating longwall panel extraction required additional reservoir modeling considerations since longwall face advance and related strata disturbances had to be represented in the simulations.

The moving boundary problem imposed by panel extraction was addressed with "restart" models, in which the simulation outputs from the previous model run were written in a "restart" file. This file was then used by the next model run as the initial conditions for that run. The mechanical response of the overlying strata to mining was modeled using Itasca Consulting Group's (Itasca, 2000) FLAC2D (Fast Lagrangian Analysis of Continua 2D) and the calculated permeability changes were incorporated into the reservoir model between "restart" runs to simulate reservoir changes during panel extraction (Karacan et al., 2005). To extend the pre-mining methane drainage into the panel extraction phase, the restart files saved at the end of the 3- and 12-month pre-mining intervals were used as the initial conditions for the start of longwall mining. While the longwall face was advancing, the horizontal boreholes were allowed to produce methane from the unmined portions of the panel until they were intercepted by the longwall face at predefined dates/times in the data set.

For simulations during panel extraction with concurrent methane drainage, the gob gas ventholes became operational when their locations were intercepted by the advancing face. Methane drainage through the horizontal boreholes continued with the same constraints as during the pre-mining phase, although gas production terminated as the longwall face intercepted each borehole.

5. Results and discussion

5.1. *Effects of pre-mining degasification time and horizontal borehole pattern configuration on methane drainage performance*

The effects of pre-mining methane drainage lead time and configuration of the horizontal borehole pattern on reductions of gas-in-place within the longwall panel were assessed for 3, 6, 9, and 12 months of production periods prior to mining (Table 2). The original gas-in-place within the outlined longwall panel was calculated to be 10.3×10^6 m^3 (364 MMscf) based on an average methane content of 2.26 m^3/ton (80 scf/ton) for the Pittsburgh coalbed (Karacan et al., 2005). Table 2 gives a summary of the general performance of each borehole pattern. Within the study area, the dual-lateral pattern (A) was the most commonly used borehole configuration. The data show that the cumulative methane production from the panel increases, as expected, with increasing time interval. Cumulative methane production using pattern A is 1.1×10^6, 1.8×10^6, 2.3×10^6 and

Table 2
General performance comparison of different horizontal methane drainage borehole patterns shown in Fig. 4 after various pre-mining degasification time intervals

Time (months)	Parameter	Wellbore patterns (Fig. 4)				
	OGIP[a]: 10.3×10^6 m^3	A	B	C	D	E
3	Cumulative methane production ($\times 10^6$ m^3)	1.1	1.7	0.5	1.0	0.8
6		1.8	2.8	0.8	1.6	1.3
9		2.3	3.5	1.1	2.0	1.6
12		2.6	4.0	1.2	2.4	1.9
3	Percent of initial gas in panel area (%)	11.0	16.6	5.1	9.6	7.5
6		17.6	26.7	8.2	15.5	12.4
9		22.1	33.5	10.4	19.8	15.9
12		25.4	38.6	12.0	23.0	18.5
3	Average production rate ($\times 10^3$ m^3/day)	12.3	18.7	5.7	10.7	8.4
6		10.1	15.3	4.7	8.9	7.1
9		8.4	12.8	4.0	7.5	6.1
12		7.2	10.9	3.4	6.5	5.2
3	Average production per unit borehole length (m^3/m)	202.5	202.5	451.5	426.4	419.9
6		323.3	325.2	727.4	692.1	693.1
9		406.0	407.8	920.7	879.8	887.2
12		468.2	469.2	1068.4	1021.9	1031.2
3	Average specific production rate (m^3/day/m)	2.20	2.20	4.92	4.63	4.56
6		1.79	1.81	4.03	3.84	3.85
9		1.51	1.51	3.42	3.25	3.28
12		1.28	1.28	2.93	2.80	2.84

[a] Original gas in place within the panel area calculated based on an average methane content of 2.26 m^3/ton (80 scf/ton).

2.6×10^6 m^3 for 3, 6, 9, and 12 months of drainage from the panel, respectively. This corresponds to reductions of 11.0%, 17.6%, 22.1%, and 25.4% of the original 10.3×10^6 m^3 gas-in-place, respectively for the same drainage times. Fig. 8 shows the cumulative methane production for each simulated horizontal borehole pattern at the end of each degasification time interval.

Among all horizontal borehole patterns simulated, pattern B (tri-lateral pattern), with the longest total borehole length, provided the maximum reduction of gas-in-place within the longwall panel. Its total methane productions were 1.7×10^6 m^3 and 4.0×10^6 m^3 of methane after 3 and 12 months of methane drainage, respectively. Gas reductions in the panel area after these periods were 16.6% and 38.6% (Table 2). The difference in cumulative methane production from patterns A and B was due to the enhanced methane drainage in the middle part of the panel from the additional horizontal borehole placed in that area with pattern B.

The other patterns (C–E) drilled shorter, cross-panel, horizontal holes parallel to the longwall face. These produced lesser amounts of methane for the simulated periods than patterns A and B, mainly because of the shorter borehole lengths. After 12 months of methane drainage, patterns C, D, and E produced 1.2, 2.4, and 1.9×10^6 m^3 of methane, respectively, corresponding to 12.0%, 23.0%, and 18.5% reductions in the calculated methane content of the panel area. However, as the number of short cross-panel boreholes increases, their total production can match or exceed the performances of A and B. For instance, drilling short cross-panel boreholes that will give the same total borehole length as pattern B will require thirty of these boreholes along the panel. Although it is not simulated, present data with only eight of them (pattern D) suggest that the total production from 30 short boreholes will exceed the productions of both A and B. However, it should be noted that drilling costs may be more than that of A and B and they may not be as effective in shielding the entries, as will be discussed later.

The simulation results presented in Table 2 show that the average gas production rates for all patterns are highest for the initial 3 months of methane drainage. The average production rates for the first three months are 12.3, 18.7, 5.7, 10.7, and 8.4×10^3 m^3/day for patterns A, B, C, D, and E, respectively. As methane drainage time increases, average production rates decrease. This is an expected consequence of reducing the gas-in-place over time within the boundaries of the outlined longwall panel and producing lesser amounts of gas during the late stages of degasification. For 12 months of methane drainage, average methane production rates from patterns A, B, C, D, and E are calculated to decline to 7.2, 10.9, 3.4, 6.5, and 5.2×10^3 m^3/day, respectively.

Normalizing cumulative methane production and average flow rates to borehole length gives a better productivity comparison between drilling patterns (Table 2). This comparison highlights the importance of borehole orientation relative to face cleat and butt cleat direction, which are in the East–West and North–South directions, respectively, and associated permeability anisotropy, which is 4:1. Total methane production per unit borehole length and average flow rate per unit borehole length are higher for patterns C, D, and E,

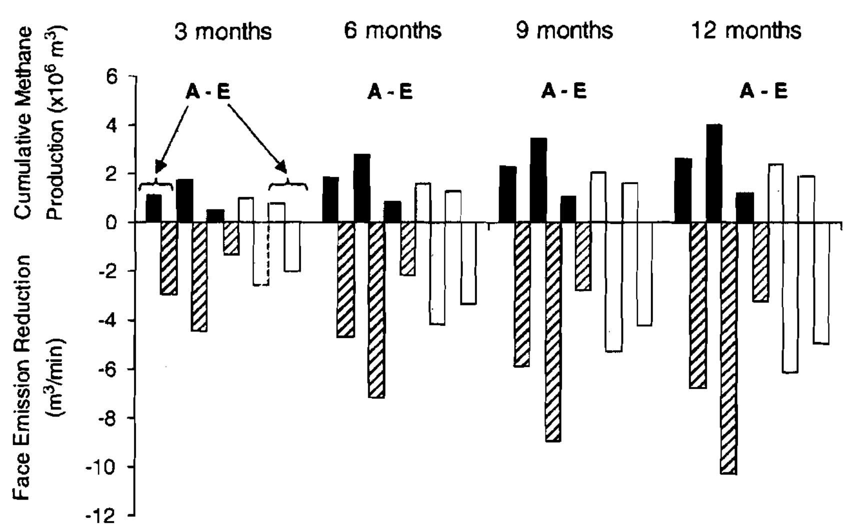

Fig. 8. Cumulative methane production and possible reductions in longwall face emission rates (100% emission degree basis) for different methane drainage time intervals and different horizontal borehole patterns (A–E) shown in Fig. 4.

compared to patterns A and B for the first 3 months of degasification. For instance, the total production and average flow rate per unit borehole length for 3 months of simulated methane drainage from pattern C, where the boreholes are drilled perpendicular to higher permeability face cleats, are 451.5 m^3/m and 4.92 m^3/day/m, respectively. However, the total production and average flow rate per unit borehole length for pattern A, where the boreholes are drilled perpendicular to the lower permeability butt cleats, are only 202.5 m^3/m and 2.20 m^3/day/m, or less than half that of pattern C.

A similar evaluation for pattern D, where eight shorter, cross-panel methane drainage boreholes are drilled parallel to the longwall face (perpendicular to the face cleats) with a total length of only 2316 m, shows that this pattern drains methane quantities comparable to that of pattern A, which has a total borehole length of 5606 m. The cumulative methane production of pattern D is 2.4×10^6 m^3, as compared to 2.6×10^6 m^3 for pattern A after 12 months of degasification. The productivities of pattern D, based on total methane production (1021.9 m^3/m) and average flow rate per unit borehole length (2.80 m^3/day/m) are higher than both A and B and are similar to those of pattern C (1068.4 m^3/m and 2.93 m^3/day/m, respectively) based on 12 months of methane production. These data show that, although the cumulative production and thus reduction in initial gas content of the panel area is higher with an increased number of wells in pattern D compared to C, the production and production rate per unit borehole length are similar because of equal operating and completion conditions of the boreholes and uniform reservoir behavior.

The performance of pattern E for pre-mining degasification is between C and D in terms of productivity per unit borehole length. It produces 419.9, 693.1, 887.2, and 1031.2 m^3 methane per meter of drilled boreholes after 3, 6, 9, and 12 months, respectively.

5.2. *Effect of pre-mining degasification time and horizontal borehole pattern configuration on reducing potential face emissions*

Methane drainage prior to panel extraction reduces the potential for face emissions during mining as it reduces the in-place gas content of the coalbed to be mined. The horizontal borehole production data were evaluated to estimate the potential average reductions in face emission rates as a result of pre-mining methane drainage. The calculated average face emission reductions are presented in Table 3. For this calculation, cumulative methane production given in Table 2 was divided by the duration (268 days) of mining for the study panel. The assumption in this approach was that either the majority (75%) or the total (100%) of the produced methane would be released as face emissions during mining, if it was not removed prior to mining. This assumption is based on the work of Noack (1998), who proposed that, in the absence of empirical data, the degree of gas emission (percent of gas-in-place) could be assumed to be 100% in stratigraphic zones within 20 m to −11 m of the top and bottom of the mined coalbed, respectively, and 75% in the mined coalbed.

The calculated average face emission rates that can be expected if methane drainage is not utilized are

Table 3
Potential reductions in average longwall face emission rates after degasifying the coalbed for different horizontal methane drainage borehole patterns and pre-mining degasification time intervals

Time (months)	Parameter	Borehole patterns (Fig. 4)				
		A	B	C	D	E
3	Average face emission	2.9	4.4	1.4	2.6	2.0
6	reduction (m^3/min)	4.7	7.1	2.2	4.2	3.3
9	(degree of emission: 100%)	5.9	8.9	2.8	5.3	4.2
12		6.8	10.3	3.2	6.1	5.0
Average face emission (100% basis) without degasification (m^3/min)					26.7	
3	Average face emission	2.2	3.3	1.0	1.9	1.5
6	reduction (m^3/min)	3.5	5.4	1.6	3.1	2.5
9	(degree of emission: 75%)	4.4	6.7	2.1	4.0	3.2
12		5.1	7.7	2.4	4.6	3.7
Average face emission (75% basis) without degasification (m^3/min)					20.0	

26.7 m^3/min (943 cfm) for the 100% gas emission basis and 20.0 m^3/min (707 cfm) for the 75% emission basis (Table 3). These predictions are based on the calculated total in-place methane content of 10.3×10^6 m^3 (364 MMscf) in the outlined panel and 268 days of longwall mining. The importance of methane drainage using in-seam horizontal boreholes for reducing average face emission rates is demonstrated by converting the production volumes in Table 2 to face emission rates. The potential average face emission reductions calculated for the 100% and 75% degree of gas emission are given in Table 3. These data show that using horizontal borehole pattern B in the Pittsburgh coalbed reduces the average face emission rates by as much as 10.3 m^3/min (364 cfm) for the 100% emission basis and by 7.7 m^3/min (273 cfm) for the 75% basis after 12 months of pre-mining degasification. The methane emission reduction values for pattern A are as much as 6.8 m^3/min (240 cfm) for the 100% basis and 5.1 m^3/min (180 cfm) for the 75% basis. The possible face emission reduction values calculated for D are 6.1 and 4.6 m^3/min (215 and 162 cfm) for the 100% and 75% basis respectively for 12 months degasification period. Lesser amounts of face emission reductions are calculated for patterns C and E. Fig. 8 compares cumulative methane productions, different horizontal borehole patterns, and the reductions in face emission rates on the 100% degree of gas emission basis.

5.3. Contribution of continued degasification during mining and individual horizontal borehole pattern to overall degasification performance

The effects of continued methane drainage on face emissions during active mining were evaluated by switching on the panel extraction phase of the model and extending the modeling of the degasification process beyond the previously simulated 3 and 12 months of pre-mining methane drainage. During simulation of longwall degasification, gob gas ventholes were put into production as the longwall face advanced to their location. Gas production from the horizontal methane drainage boreholes continued until the longwall face reached the location of each borehole. This section analyzes the impact of continued degasification on gas production and the resultant additional reductions in face emissions. Fig. 9 shows, as an example, a snapshot of the pressure distributions in the primary coalbed gas reservoir layers associated with longwall mining of the Pittsburgh coalbed utilizing both gob gas ventholes and horizontal borehole methane drainage pattern A. This figure shows the position of the face at the second gob gas venthole

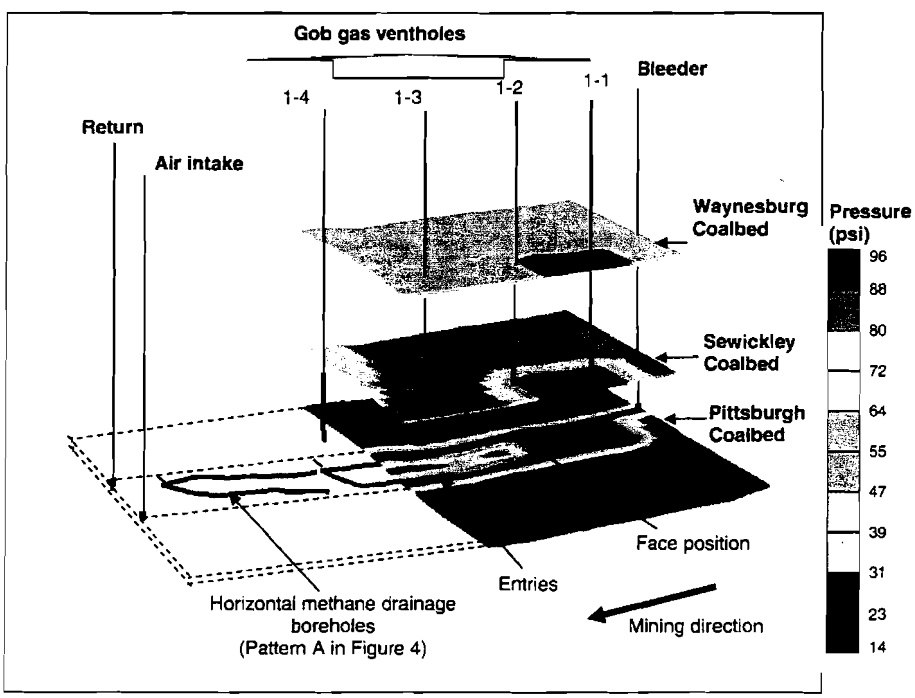

Fig. 9. A snapshot of coalbed pressure distribution at a defined longwall face position in mining layer and two other coalbed horizons during longwall mining and continued degasification using pattern A in Fig. 4. The boundaries of the model and the panel area are represented by dashed lines. The open-to-flow sections of the gob gas ventholes are depicted as heavy lines and the cased sections are shown as lighter lines.

location during panel extraction phase of the model. It should be noted that the pressures in the entries and around the degasification boreholes are close to atmospheric pressure levels. Also, reservoir pressures in and above the mined-out sections, including overlying fractured zones, have decreased from initial reservoir pressure to atmospheric pressure ranges due to the pressure sink created by the ventilation boundary conditions and the effect of imposed permeability fields during panel extraction calculated by FLAC modeling.

Fig. 10 shows methane production from the simulated horizontal methane drainage borehole patterns shown in Fig. 4 before and during panel extraction. The results show that methane production during panel extraction is substantially less than that of the pre-mining phase. Additionally, as the pre-mining degasification time increases from 3 to 12 months, the amount of methane produced by the horizontal boreholes during panel extraction decreases even more. The reduced methane production is probably due to a combination of two factors. First, the methane content of the coalbed is reduced during the pre-mining methane drainage phase, leaving less methane available for production at a slower rate during mining, especially after a longer pre-mining degasification. Second, the methane production from each horizontal borehole is progressively terminated as the longwall face reaches its location. Therefore, their production lives are significantly shortened during the panel extraction phase of the simulations. However, it should be noted that after only a short period of pre-mining methane drainage (3 months in these simulations), continued degasification during panel extraction becomes more important since more gas remains in place to be produced during this phase. The simulation results shown in Fig. 10 indicate that the highest cumulative methane production is achieved with long horizontal borehole patterns A and B. However, as the number of shorter, cross-panel, horizontal boreholes perpendicular to the higher permeability face cleats increases, as in pattern D, their cumulative production approaches that of pattern A.

5.4. Effect of continued horizontal borehole methane drainage during mining on reducing face emissions

The overall reduction in average face emission rates due to methane drainage can be evaluated by analyzing the panel extraction phase and combining it with pre-mining methane drainage performance. The average reductions in longwall face emission rates due to methane drainage before and during mining were calculated based on the 75% and 100% degrees of emission bases (Fig. 10 and Table 4). The data show that longwall face emissions were reduced by 10.3 m^3/min (364 cfm) for the 100% basis and by 7.7 m^3/min (273 cfm) for the 75% basis with 12 months of pre-mining methane drainage using borehole pattern B. Reductions of 6.8 m^3/min (240 cfm) for the 100% basis and 5.1 m^3/min (180 cfm) for the 75% basis were obtained using pattern A prior to mining. The face emission reductions achieved with borehole patterns B and A after 3 months of pre-mining degasification were 4.4 m^3/min (157 cfm) and 2.9 m^3/min (104 cfm), respectively, for the 100% emission basis. As would be expected, the simulations show that 3 months of

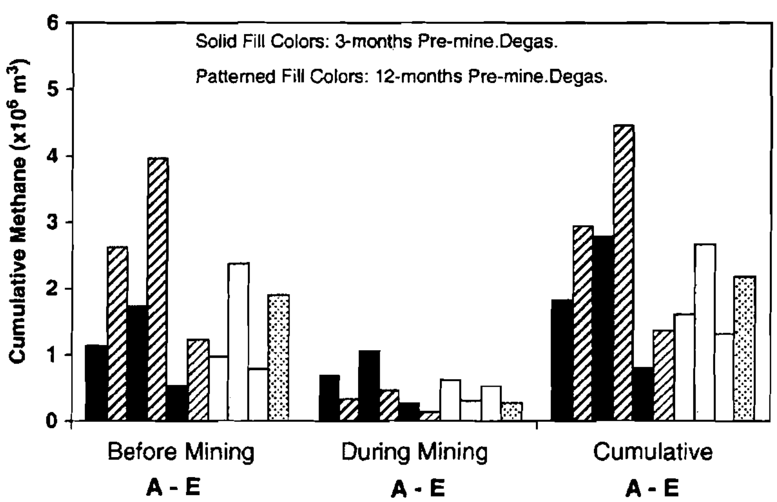

Fig. 10. Performances of different horizontal methane drainage borehole patterns shown in Fig. 4 during different phases of degasification, after 3 and 12 months of pre-mining degasification.

Table 4
Simulated reductions in face emission rates after different phases of methane drainage using horizontal boreholes from the longwall panel

Pre-mining degasification (months)	Quantity	Wellbore patterns (Fig. 4)									
		A		B		C		D		E	
	Degree of emission (%)	100	75	100	75	100	75	100	75	100	75
3	Pre-mining degasification (m^3/min)	2.9	2.2	4.4	3.3	1.4	1.0	2.6	1.9	2.0	1.5
12		6.8	5.1	10.3	7.7	3.2	2.4	6.1	4.6	5.0	3.7
3	During-mining degasification (m^3/min)	1.8	1.4	2.7	2.1	0.7	0.5	1.6	1.2	1.4	1.0
12		0.9	0.6	1.2	0.9	0.4	0.3	0.8	0.6	0.7	0.5
3	Total reduction (m^3/min)	4.7	3.6	7.2	5.4	2.1	1.5	4.2	3.1	3.4	2.6
12		7.6	5.7	11.5	8.7	3.6	2.7	6.9	5.2	5.7	4.2

pre-mining methane drainage is less effective in reducing face emission rates compared to 12 months.

After 12 months of pre-mining degasification, the additional reductions in face emissions with continued degasification during mining are 0.9 m^3/min and 1.2 m^3/min (30.1 and 43.7 cfm) for the 100% basis with patterns A and B, respectively. The additional face emission reduction that can be achieved with patterns D and E due to continued degasification is similar to that of A (0.8 and 0.7 m^3/min, respectively), and it is less with C after 12 months of pre-mining degasification. The data in Table 4 show that after only 3 months of pre-mining degasification, continued degasification during panel extraction becomes more important.

The data presented in Table 4 show that after 3 months of pre-mining degasification, continued methane drainage during mining using borehole pattern A reduces face emission rates by 1.8 m^3/min (63.6 cfm) for the 100% degrees of emission basis and 1.4 m^3/min (47.7 cfm) for the 75% basis. These reductions are more than 50% of what can be achieved in addition to 3 months of pre-mining degasification. Similar impacts are achieved with other borehole patterns as well, as a result of continued degasification during panel extraction after a short (3-month) pre-mining degasification period. On the other hand, the incremental reduction obtained with continued degasification during panel extraction in average face emission rates after 12 months of pre-mining degasification using the same borehole pattern is about 15% of what can be achieved by 12 months pre-mining degasification. Again, similar reductions in average face emissions were observed for the other borehole patterns after continued degasification. This analysis shows that continuation of degasification during panel extraction becomes more important if the pre-mining degasification duration is short.

After 3 months of pre-mining degasification, additional drainage during mining using borehole pattern B reduces face emission rates by 2.7 m^3/min (95.3 cfm) for the 100% emission basis and 2.1 m^3/min (74.2 cfm) for the 75% basis. These numbers show (Table 4) that additional degasification after a 3-month pre-mining production period with B is almost as effective as using pattern A (2.9 m^3/min) for pre-mining degasification for 3 months. This comparison emphasizes the importance of wellbore pattern design, continued degasification during panel extraction, and the duration of degasification before and during mining.

The total (including degasification before and during panel extraction) reductions in average face emissions after 12 months of methane drainage before and during mining are significant, particularly with horizontal borehole patters A, B, and D. The total reduction that can be achieved with pattern B is between 8.7 and 11.5 m^3/min (307–408 cfm). This reduction can decrease the average maximum emission rate that may be expected from the Pittsburgh coalbed from 20.0–26.7 m^3/min (707–943 cfm) to less than 11.3–15.2 m^3/min (400–500 cfm).

5.5. Effect of pre-mining degasification and in-seam horizontal boreholes on shielding the development entries from methane migration from the panel area and surrounding coalbed

In-seam methane drainage boreholes not only degas the longwall panel itself, but can also shield the advancing development entries from methane emissions from the surrounding virgin coalbed gas reservoir (Diamond, 1994). The impacts of borehole pattern on the effectiveness of shielding gateroads from methane migration were evaluated by simulating the cumulative methane emissions into the modeled ventilation system. In this analysis, two approaches were used. In the first approach, methane emissions were predicted in conjunction with operating in-seam horizontal methane drainage boreholes, configured as shown in Fig. 4. In the second approach, three horizontal boreholes were placed in the virgin coalbed along the gateroads on both sides of the outlined panel, as

Fig. 11. An example layout showing additional horizontal, in-seam boreholes on either side of the gateroads in addition to pattern A. The entries represent a three-entry system with intervening coal pillars.

shown in Fig. 11 for pattern A. It should be noted that this configuration of additional boreholes is only completely applicable to the first longwall panel developed in a new mining district, since the tailgate entries of each subsequent panel will be shielded by the holes drilled on the headgate side of the previous panel. These additional boreholes were modeled with the same completion and operating parameters as discussed previously for the in-seam horizontal boreholes of Fig. 4. The first approach is intended to analyze the amount of methane migrating into the gateroads from the panel area and the surrounding coalbed only in the presence of in-panel horizontal methane drainage boreholes. The second approach analyzes the effects of additional boreholes on shielding the entries from methane emissions from the surrounding coalbed during pre-mining degasification.

Table 5 gives the predicted methane inflow into the ventilation system from the surrounding virgin coalbed at the end of various methane drainage time intervals based on the presence of in-panel horizontal methane drainage boreholes (A to E in Fig. 4) along with methane inflow into the ventilation in the absence of any degasification borehole. These comparative results show that borehole patterns A and B, where near-margin horizontal boreholes are drilled from the tailgate, are more effective against methane inflow into the gateroads during pre-mining degasification than the other patterns because of their extended length along the entries. The simulation indicates that by using either pattern A or B, the potential methane inflow into the entries can be reduced by as much as 62×10^4 m^3 over 12 months, which corresponds to a decrease in methane inflow by ~ 1.2 m^3/min (~ 40 cfm), just by shielding against methane inflow originating from the coalbed within the panel area. It should also be noted that methane emissions into the mine ventilation system can be reduced by similar amounts using both patterns A and B. As would be expected, this suggests that the middle horizontal borehole segments in pattern B do not contribute much to gateroad shielding. The emissions into the gateroad entries originate mostly from the gas desorbing from the margins of the panel where the near-margin borehole segments are located and these boreholes are more effective in capturing this gas. Patterns C, D, and E, which use short, cross-panel methane drainage horizontal boreholes parallel to longwall face, are not as effective in shielding the entries as patterns A and B since they cannot effectively block all of the methane migration pathways.

Table 5
Predicted methane emissions into the ventilation system from the surrounding coalbed (within the panel and virgin coal) during different pre-mining degasification time intervals using different borehole patterns

Well pattern	Methane inflow into mine ventilation system ($\times 10^6$ m^3)			
	3 months	6 months	9 months	12 months
No degasification	2.23	3.56	4.51	5.26
A	2.11	3.28	4.07	4.64
B	2.11	3.28	4.06	4.64
C	2.21	3.51	4.43	5.13
D	2.19	3.48	4.38	5.06
E	2.21	3.51	4.41	5.04
A+	1.89	2.82	3.38	3.75
B+	1.89	2.82	3.38	3.75
C+	2.04	3.05	3.75	4.24
D+	1.97	3.02	3.70	4.17
E+	1.99	3.04	3.72	4.15

Table 5 also shows the predicted methane emissions into the mine ventilation system from the surrounding coalbed using six additional horizontal boreholes (A+ configuration shown as an example in Fig. 11) with a total length of 6340 m (20,800 ft) added to the base set of boreholes drilled in the panel (Fig. 4). These six additional boreholes were estimated to produce 1.10, 1.72, 2.13, and 2.44×10^6 m^3 of additional methane during 3, 6, 9, and 12 months of pre-mining methane drainage, respectively. The model simulations predict that these six additional methane drainage boreholes would reduce methane inflow to the gateroad entries from the surrounding virgin coalbed by 0.22, 0.46, 0.69, and 0.89×10^6 m^3 of methane between A and A+ (Table 5) for the same drainage times. Again, horizontal methane drainage borehole patterns A and B with six additional boreholes (designated as A+ and B+ in Table 5) were the most effective in reducing methane inflow into the gateroads. Compared to a case where no boreholes were present to shield the entries, operating A+ and B+ for 12 months resulted in 29% decrease in methane emissions into the ventilation entries (Table 5).

The results of a borehole drilling study for shielding the entries from methane inflow were reported by DuBois et al. (2006). The study was conducted in Pittsburgh coalbed at the same mining district modeled in this study. The horizontal boreholes of pattern A were drilled to maximize the shielding for both belt and return entries during headgate and tailgate development. This approach resulted in a pattern similar to the one designated as A+ in this study. The drilling strategy described in their paper permitted horizontal boreholes to be active for 6–24 months prior to any mining. They reported that as a result of employing horizontal boreholes, methane concentration decreased by 41% and methane emission into the entries decreased between 30 and 35%, close to the predicted values in this study for patterns A+ and B+.

6. Summary and conclusions

A 3D reservoir model was constructed for a 381-m wide longwall panel operating in the Pittsburgh coalbed. Multiple horizontal borehole patterns and degasification durations prior to and during panel extraction were simulated to evaluate their relative effectiveness in reducing in-place gas volumes and longwall face emission rates. The basic conclusions of this numerical modeling effort can be summarized as follows:

1. Cumulative methane drainage from the Pittsburgh coalbed increases with increasing in-seam methane drainage time. Among the horizontal well patterns modeled, pattern B produces the highest amount of methane: 1.7×10^6 m^3 after 3 months and 4.0×10^6 m^3 after 12 months of methane drainage. Patterns A and D produce similar amounts ($\sim 2.5 \times 10^6$ m^3 after 12 months). The other simulated horizontal borehole patterns (C and E), use fewer shorter, cross-panel, horizontal boreholes parallel to the longwall face and produce lesser amounts.
2. Normalization of horizontal borehole gas production by their productive length in the coalbed gas reservoir shows the importance of cleat direction and associated permeability anisotropy on borehole performance. Average methane production rates per unit length of borehole for patterns C, D, and E, drilled perpendicular or at angles to the higher permeability face cleat, are greater when compared to patterns A and B, which are drilled perpendicular to the lower permeability butt cleat. The average methane production and rate (3-month production basis) for the horizontal boreholes represented by pattern C are 451.5 m^3/m and 4.92 m^3/day/m of hole length, respectively. For pattern A, these values are 202.5 m^3/m and 2.20 m^3/day/m of hole length.
3. For the Pittsburgh coalbed with 12 months of pre-mining methane drainage, the average longwall face emission rates can be reduced by as much as 10.3 m^3/min (364 cfm) for the 100% emission basis and 7.7 m^3/min (273 cfm) for the 75% basis, using horizontal borehole pattern B. Using pattern A, reductions were 6.8 m^3/min (240 cfm) for the 100% basis and 5.1 m^3/s (180 cfm) for the 75% basis. Similar emission reductions can be achieved using pattern D, and lesser amounts with patterns C and E.
4. Methane production from horizontal methane drainage boreholes is less during the mining phase of degasification than during the pre-mining phase. Pre-mining degasification reduces in-place gas volume so that there is less gas to produce later. Also, production from each horizontal borehole is progressively terminated as the longwall face reaches its location on the panel. The impact of pre-mining degasification is particularly evident as the degasification time interval increases from 3 to 12 months. If the pre-mining methane drainage time is short, it is important to continue methane drainage during the mining phase to maximize reductions in longwall face methane emissions. In fact, it has been shown that if the panel gas volume is drained for shorter time periods, the contribution of methane produced during panel extraction may be a significant portion of the total gas production (more than 50%). This suggests that an additional average face emission reduction comparable to pre-mining degasification can be achieved during this period. Conversely, if the pre-mining degasification time is longer, then the additional methane production during panel extraction may be only 10–20% of the pre-mining degasification.
5. Methane migration into the mine ventilation airflow in the gateroad entries surrounding the outlined longwall panel can be reduced effectively by using horizontal methane drainage holes paralleling those gateroads (patterns A and B). Patterns C, D, and E that use short horizontal cross-panel boreholes drilled parallel to the longwall face are not as effective in shielding the development entries. They are not oriented to drain large volumes of gas along the margins of the panel, and they cannot block methane

migrating towards the entries beyond their effective radius. This suggests that emissions into the gateroad entries are originating primarily from the margins of the panel. Additional reductions in methane ernissions into the gateroads can be achieved by employing horizontal methane drainage boreholes in the surrounding virgin coalbed gas reservoir on either side of the gateroads.

Appendix A. Supplementary data

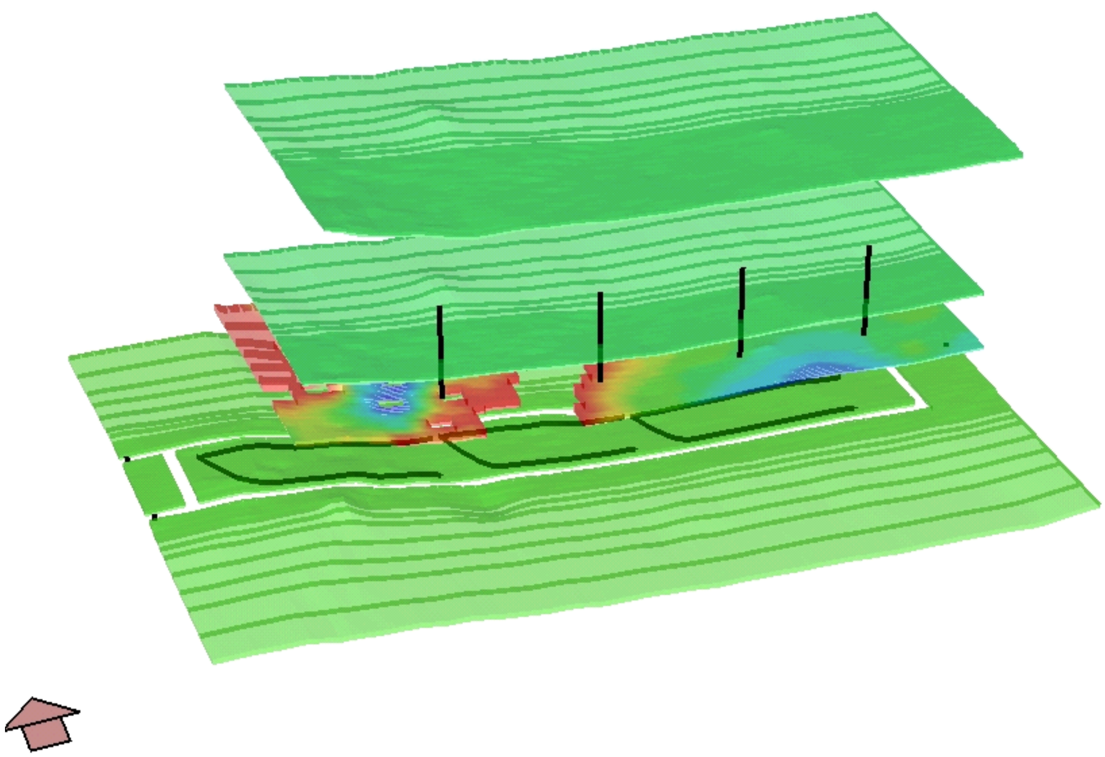

Figure 6. Transparent, 3-D, cut-away grid model of the study area (inner layers removed) showing the major coalbeds and the sandstone paleochannel. This figure also shows elements of the methane control system used in the model. The entries represent a three-entry system with intervening coal pillars. The heavy lines in the well trajectories represent the open-to-flow sections of the wells and lighter traces represent t he cased sections of the wells

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