Reservoir simulation-based modeling for characterizing longwall methane emissions and gob gas venthole production

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Abstract

Longwall mining alters the fluid-flow-related reservoir properties of the rocks overlying and underlying an extracted panel due to fracturing and relaxation of the strata. These mining-related disturbances create new pressure depletion zones and new flow paths for gas migration and may cause unexpected or uncontrolled migration of gas into the underground workplace. One common technique to control methane emissions in longwall mines is to drill vertical gob gas ventholes into each longwall panel to capture the methane within the overlying fractured strata before it enters the work environment. Thus, it is important to optimize the well parameters, e.g., the borehole diameter, and the length and position of the slotted casing interval relative to the fractured gas-bearing zones.

This paper presents the development and results of a comprehensive, "dynamic," three-dimensional reservoir model of a typical multi-panel Pittsburgh coalbed longwall mine. The alteration of permeability fields in and above the panels as a result of the mining-induced disturbances has been estimated from mechanical modeling of the overlying rock mass. Model calibration was performed through history matching the gas production from gob gas ventholes in the study area. Results presented in this paper include a simulation of gas flow patterns from the gas-bearing zones in the overlying strata to the mine environment, as well as the influence of completion practices on optimizing gas production from gob gas ventholes.

Keywords: Longwall mining; Reservoir modeling; Ventilation; Gob gas ventholes; Reservoir simulation

1. Introduction

Longwall mining is an underground mining method that can maximize coal production in coalbeds that are continuous with few geological discontinuities. In these operations, a mechanical shearer progressively mines a large block of coal, called a panel, which is outlined with development entries or gate roads. This is a continuous process in an extensive area, where the roof is supported only temporarily during mining with hydraulic supports that protect the workers and the equipment on the face. As the coal is extracted, the supports automatically advance with the rate of mining, and the roof strata are allowed to cave behind the supports.

It has been suggested (Singh and Kendorski, 1981; Palchik, 2003) that the caved zone (Fig. 1) created by longwall mining is highly fragmented, and generally extends upwards three to six times the thickness of the mined coalbed. In this zone, the overlying rock layers fall into the mine void and are broken into irregular shapes of various sizes. It has been found that the height of the caved zone could reach four to eleven times the thickness of the mining

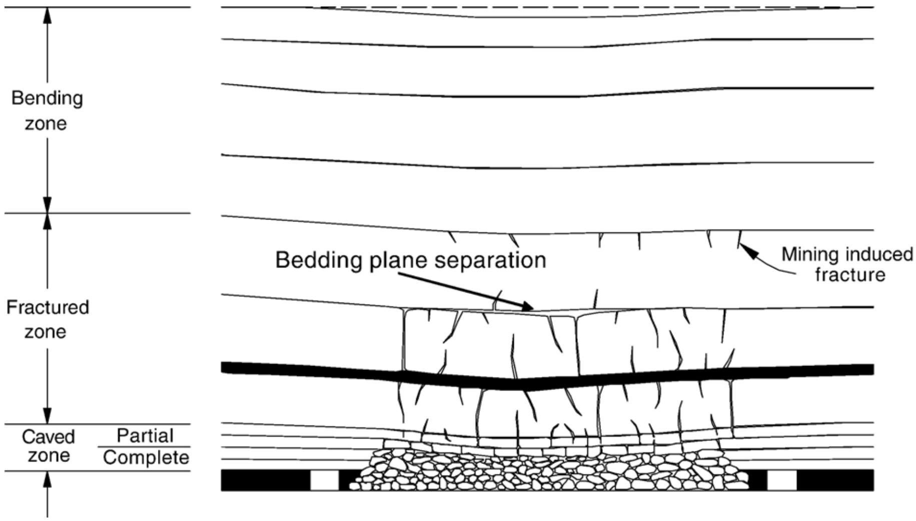

Fig. 1. Schematic of strata response to longwall mining (modified from Singh and Kendorski, 1981).

height where overburden rocks are weak and porous (Palchik, 2003).

Above the caved zone is a fractured zone (Fig. 1) characterized by mining-induced vertical fractures, and horizontal fractures caused by separations along bedding planes. The caving of the mine roof causes an area of relieved stress in this zone. The blocks in each of the broken rock layers are contacted either fully or partially across the vertical fractures, with the number and extent of the fractures diminishing with increasing height above the caved zone. The thickness of the fractured zone can vary up to 100 times the height of the mined coalbed, depending on the characteristics of the associated rock strata, thickness of the overburden, and the size of the longwall panel (Palchik, 2003).

The occurrence of such an extensive area of mining-induced stress relief and resultant rock damage changes the gas flow-related properties in the overlying (and in some cases the underlying) strata, particularly the permeability. Any gas that is contained within the coalbeds in this area of relieved stress will be released slowly over time, while free gas in other porous formations, such as sandstones, will be released more quickly, as the permeability of these zones is dramatically increased and new permeability pathways are created. Relaxation of the roof and floor rocks and the associated fracture connectivity allows gas to flow from all surrounding gas sources toward the low-pressure sink of the underground workings, including the caved zone. Fig. 2 shows a super-critical longwall panel, where the panel width is larger than overburden thickness, and flow paths for gas migration to the active mine workings and gob gas ventholes after subsidence. Gas-bearing strata, particularly overlying gas-bearing coalbeds and sandstones, can be directly exposed to the caved zone or connected to it by fractures. In the absence of methane drainage boreholes such as gob gas ventholes, this released gas, commonly

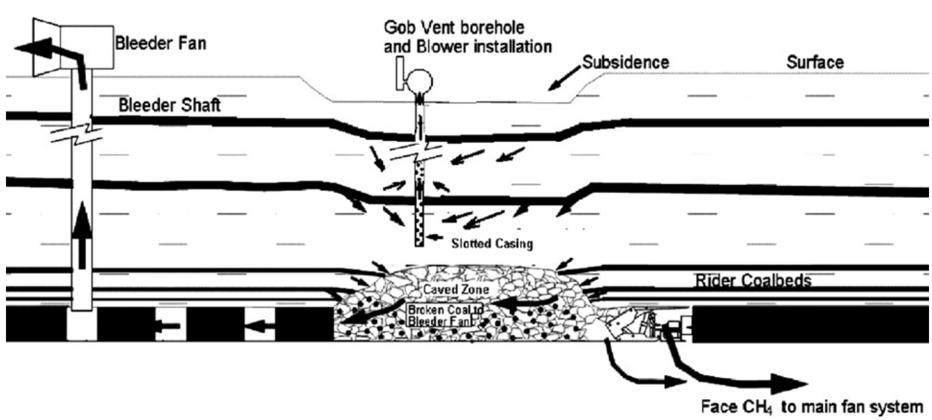

Fig. 2. Schematic of a supercritical panel situation and the gas migration paths.

referred to as "gob gas" may enter the mine atmosphere from above.

In general, experience suggests that it is difficult to make accurate gas production estimates for gob wells and that these predictions are underestimated relative to actual gob gas venthole production by a factor of two or more. The key factors to this underestimation of gas production capability are the difficulty in predicting the degree of stress relief in gas-bearing strata associated with longwall mining and, consequently, the drainage radius for each well (Zuber, 1998). To better understand the flow of gas in the longwall mining environment, a reservoir modeling study was initiated for a mining area in the Pittsburgh coalbed in southwestern Pennsylvania for which the National Institute for Occupational Safety and Health (NIOSH) had a substantial data set for gob gas production.

1.1. Longwall gob gas ventholes

Gob gas ventholes are drilled into the overburden above longwall panels to capture the gas released from the subsided and relaxed strata before it enters the mining environment, where it can be an explosion hazard. Most gob gas ventholes are drilled within a short distance, 10–30 m (30 ft–100 ft), of the coalbed being mined and cased with steel pipe. Commonly, the bottom section of the casing [generally about 60 m (200 ft)] is slotted and placed adjacent to the expected gas production zone in the overburden strata. The usual practice is to drill the gob gas ventholes from the surface prior to mining. As mining advances under the venthole, the gas-bearing strata that surround the well will fracture and establish preferential pathways for the released gas to flow towards the ventholes (Diamond et al., 1994).

Exhausters are placed on gob gas ventholes to maintain a vacuum on the wellbore, so that they operate at the minimum possible flowing pressure and create a pressure sink in the overburden strata to induce gas flow towards the venthole. Gas production may exhibit variable gas quality. In the early stages of production, the gas quality is generally high (>80%), and there is very little contamination by mine ventilation air. Maximum daily methane production generally occurs within the first several days after a hole is intercepted by the longwall. Relatively high production rates are usually sustained for only a few weeks or in some cases for a few months (Diamond et al., 1994). Later in time, gob gas production may exhibit decreased methane levels as ventilation air is drawn from the active mine workings.

The quality of the gas from gob wells can be controlled to some extent by varying the vacuum on the well to correspond with the profile of expected methane release. However, for mine safety, maintaining the methane concentration in the mine within statutory limits is always the overriding factor for controlling the vacuum on the gob gas ventholes, as it is for all other mine-related methane drainage systems (Zuber, 1998; Mucho et al., 2000). Commonly, when the methane concentration in the produced gas reaches 25%, the exhausters are de-energized as a safety measure, and the holes may be allowed to free flow.

The location of the ventholes on the panel is important, as Diamond et al. (1994) showed in a study of a Lower Kittanning coalbed longwall mine where the holes on the ends of the panels were generally the highest-quantity and longest-duration producers. This was attributed to enhanced mining-induced fractures on the ends of the panels where the overburden strata are in tension on three sides due to the support of the surrounding pillars. This observation led to the experimental placement of gob gas ventholes in the zone of tension along the margin of a panel, instead of in the traditional centerline location, which is in compression due to subsidence and recompaction of the longwall gob. Analysis of seven months of gas production data indicated that the experimental near-margin holes produced 77% more gas than did centerline holes on the same panel (Diamond et al., 1994).

Improvements in venthole gas drainage evaluation and prediction capabilities for site-specific mining conditions and circumstances can address longwall gas emission issues, resulting in ventholes designed for optimum production and mine safety. To improve gas capture at a reasonable cost, it is important to understand the behavior of the entire gob gas venthole system, including the venthole placement and completion strategies, the reservoir properties of the gob in the caved zone behind the face, the fractured rock mass around the workings, and, finally, the ventilation system. A theoretical reservoir modeling approach is the best, if not the only means to predict methane emissions in advance of mining (Noack, 1998) under varying conditions and to design drainage systems accordingly for either reducing the chance of unexpected methane emissions or for responding more quickly and effectively to unknown conditions encountered during longwall mining.

1.2. Modeling approach for optimizing gob gas venthole performance

A detailed model to realistically represent the multiple variables associated with underground coal mining operations and their interaction and influence on the performance of gob gas ventholes does not currently exist.

Previously, Ren and Edwards (2002) used a computational fluid dynamics (CFD) modeling approach to investigate gas capture from surface gob gas ventholes. That paper introduced how this approach could be used to improve the design of surface gob wells for methane recovery while minimizing the leakage of air into the gob. The results indicated that the position of the wells plays an important role in determining gas production rate. Wells drilled into the areas where fractures extend towards the methane source bed were likely to achieve higher capture efficiency. Lunarzewski (1998) used boundary element and sequential bed separation methods for floor and roof strata relaxation and immediate roof bending separation, as well as gas emission rate calculations to develop "Floorgas" and "Roofgas" simulation programs to characterize the strata relaxation zones, gas emission boundaries, and parameters for gas emission prediction. Tomita et al. (2003) developed a three-dimensional (3-D) finite element model (FEM) to predict the volume of methane gas emitted from surrounding coal and rock layers based on stress distribution and permeability change.

Reservoir modeling methods and simulators have been developed over the years that can realistically represent the complex physics of reservoir flow mechanisms in unconventional reservoirs, such as coalbeds, and gas production operations with diverse well completions (King and Ertekin, 1991). These simulators have been successfully applied in various coal basins for gas recovery from coalbeds using both vertical and horizontal boreholes (Ertekin et al., 1988; Young et al., 1991; Young et al., 1993; Zuber, 1998). However, modeling of the reservoir behavior and prediction of gob gas venthole performances during active longwall mining requires that additional variables be considered that are not encountered in a static reservoir environment. These considerations are due to the moving boundary conditions and geomechanical response of rock units to the stresses and strains imposed by an advancing longwall face, and by the changing reservoir properties above a panel as a response to mining.

In one study, Zuber (1997) coupled the moving boundary condition due to mining and modeled the face and rib emissions during development mining. However, this study was mainly conducted on a single grid layer to analyze the gas emissions from ribs and newly exposed coal face during development mining, and thus did not consider the longwall mining environment and methane control issues associated with gobs. In a more recent study, Karacan et al. (2005) developed a 3-D model of a new longwall mining district to simulate the effects longwall panel width would have on methane emissions and the performance of gob gas ventholes. The focus of that effort was the prediction of the incremental amount of methane emissions to be expected due to increasing panel widths and optimizing gob gas venthole completion and placement practices to capture more of this gas to prevent it from entering the underground workplace.

2. Objective and description of this study

This paper presents the development and results of a comprehensive, "dynamic," 3-D reservoir model of a typical multi-panel Pittsburgh coalbed mine using Computer Modeling Group's (2003) compositional reservoir simulator (GEM). The alteration of permeability fields in and above the panels as a result of the mining-induced disturbances has been estimated from mechanical modeling of the overlying rock mass using FLAC-2D (Itasca Consulting Group Inc., 2000), a finite difference model for simulating the mechanical behavior of rocks in response to mining-induced stresses, as described in more detail in Esterhuizen and Karacan (2005). The moving boundary problem imposed by the advancing longwall face has been addressed with many "restart" models, where the output of the previous run is saved in a file to be used by the succeeding run as the input, within the approach. A pseudo-ventilation system has been incorporated into the model to investigate its interactions with the gob gas reservoir. Model calibration was performed through history matching of the gas production from the existing ventholes in previously mined longwall panels at the mine site. Results presented in this paper include a simulation of possible gas emission sources, as well as the influence of gob gas venthole completion practices on optimizing gas production.

3. General description of the study area and the mine

The study mine is located in the Appalachian Basin in southwestern Pennsylvania, which contains one of the largest mineable coal deposits in the world and is a promising region for coalbed methane production by either conventional coalbed methane (CBM) wells or from the gob gas ventholes associated with the extensive coal mining operations in the basin.

The multi-panel mining area covered by panels G through K (Fig. 3), was selected for this 3-D modeling study because of data availability and previous NIOSH tracer gas studies that were conducted to characterize gas flows in the longwall gob in this area. Overburden depths ranged between 150 and 270 m (500 and 900 ft). Longwall panels in the primary study area were initially 253 m (830 ft) wide and were increased to 305 m (1000 ft) starting with F Panel (just above G panel in Fig. 3). Thus, the

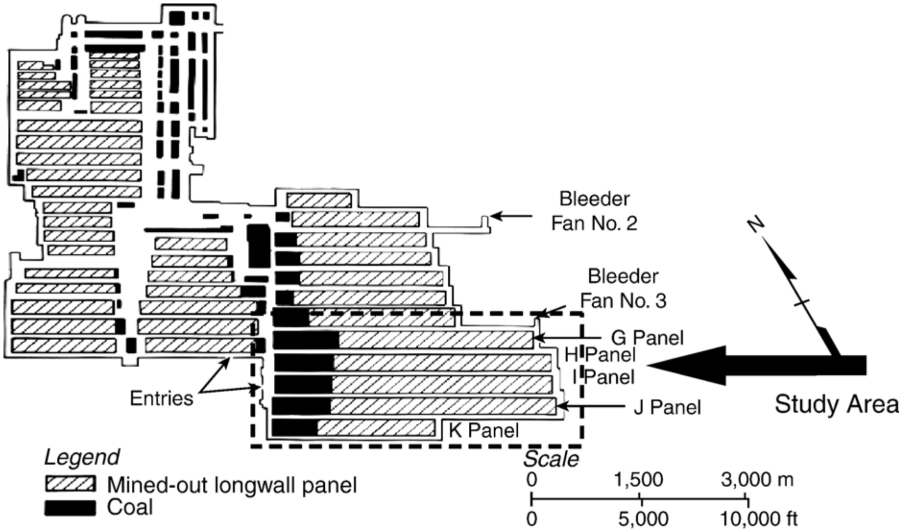

Fig. 3. Layout of the longwall mining area selected for modeling.

panels are super-critical, i.e., the panel width is greater than the height of the overburden, which results in a more complete caving of the overburden strata into the mine void. A generalized stratigraphic section of the strata above the Pittsburgh coalbed in the study area is shown in Fig. 4. Several coalbeds with a combined thickness of almost 3 m (10 ft) are present in the 26 m (85 ft) of strata immediately above the Pittsburgh coalbed, and they are believed to be the primary source of strata gas in the area. Within this interval, the thickest coalbed is the Sewickley coalbed, which is about 25 m (75 ft) above the Pittsburgh coalbed. Between these two major coalbeds, there are comparably thin Pittsburgh rider coals and the sometimes-present Redstone coalbed. The Upper and Lower Waynesburg coalbeds with a total thickness of about 2 m (7 ft) are located about 95 m (310 ft) above the Pittsburgh coalbed. Although the Pittsburgh coalbed is the primary coalbed gas reservoir in this section, the Sewickley and Waynesburg coalbeds have also been reported to be CBM producers in this area (Bruner et al., 1995).

Methane control in the study mine longwall district includes the bleeder ventilation system, gob gas

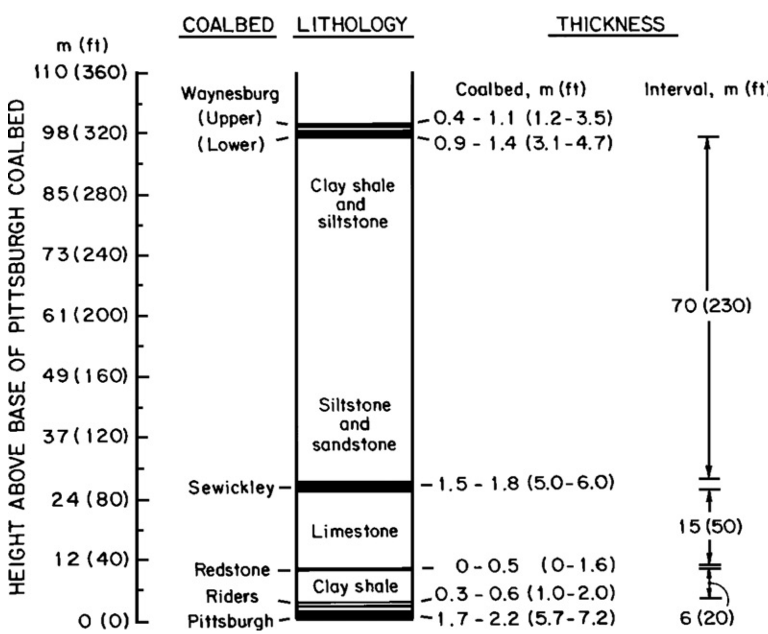

Fig. 4. A generalized stratigraphic section of the strata above the Pittsburgh coalbed in the study area.

ventholes, and underground horizontal methane drainage boreholes. The bleeder ventilation system includes the peripheral bleeder entries surrounding the panels, the former gateroads between the mined-out panels, and the associated bleeder fan shaft(s). The bleeder fans in the primary study area are at the top of 1.8 m (6 ft) diameter air shafts. Gob gas ventholes at this mine site are generally drilled to within 12 m (40 ft) of the top of the Pittsburgh coalbed, and 17.8 cm (7 in.) casing with 61 m (200 ft) of slotted pipe on the bottom is installed, as shown in Fig. 5 (Mucho et al., 2000).

4. Reservoir model development for longwall mining

The reservoir model was constructed using the GEM software, which is an efficient, multidimensional, equation-of-state (EOS) compositional simulator that can simulate the dual-porosity behavior of coal seams for coalbed/enhanced coalbed methane recovery. This section describes the approach followed to build a reservoir model to simulate the dynamic process of longwall mining.

4.1. Grid model of the study area

For the current study, a three-dimensional grid model of the mine area shown in Fig. 3 was created using

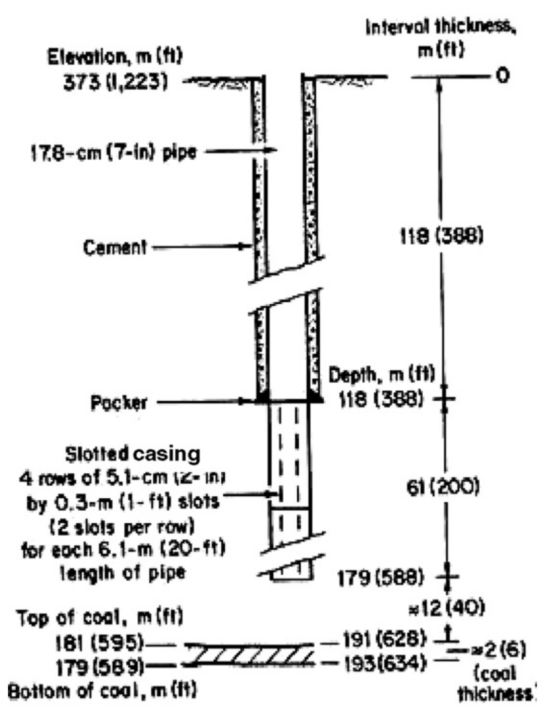

Fig. 5. Typical gob gas venthole completion scheme used in the study mine area.

Cartesian grids. The dimensions of the grid model were based on the area covered by the five longwall panels (G, H, I, J, K) in the selected study area, and the development and bleeder entries between them. At this mine site, each panel was 305 m (1000 ft) in width and 3500–4000 m (12,000–13,000 ft) in length, except the K panel which was 2130 m (7000 ft), and the total width of each set of three entries on either side of the panels, including the gate roads and the pillars, was determined from the mine maps to be about 61 m (200 ft).

The number of vertical layers and their thicknesses were based on the generalized stratigraphic log of the area shown in Fig. 4. In the grid model, the top-most layer of the model was assigned to the Waynesburg coalbed, and the bottom-most layer was the Pittsburgh coalbed, or mining layer. Floor strata have not been included into the model in this study. The other lithologies shown in the log were represented in the grid model based on their thicknesses and their sequence as a function of depth. Although this log presents only major generalized stratigraphic layers in the study area, it was sufficient to determine the number of vertical layers and their thicknesses for generating the grids in the vertical direction. Also, the layers shown in Fig. 4 were assumed to be uniformed in thickness and continuous throughout the field. Thus, the structure map for the top of the Pittsburgh coalbed (mining layer) was digitized as the reference elevation, and the depths of other layers were determined based on their thicknesses.

In the grid model, the Pittsburgh coalbed layer was constructed differently from the other layers to include the details of the longwall mining operation, the related mining environment, and the lower part of the caved zone. This layer was constructed in such a way that it would host both the mined and unmined Pittsburgh coalbed, and the entries that surrounded the panels. The entries were represented by a single grid rather than a detailed gridding for each gate road at the tailgate and headgate sides to simplify these underground transport and ventilation airflow pathways. Thus, single grid entries represent the combined effects of the three-entry system.

Fig. 6 shows the 3-D grid model that was constructed for this study. The figure shows only the Waynesburg coalbed (top layer) and Pittsburgh coalbed (bottom layer) layers. The other layers between the Waynesburg and Pittsburgh coalbeds have been removed for a better visualization of the wellbores used in the model. The stratigraphic log was inserted to the right of Fig. 6 for reference purposes. The bottom figure shows the grid construction for the mining layer, including the specific features discussed in the previous paragraphs. Fig. 6 also shows the gob gas ventholes and the elements of the pseudo-ventilation system described in the following section.

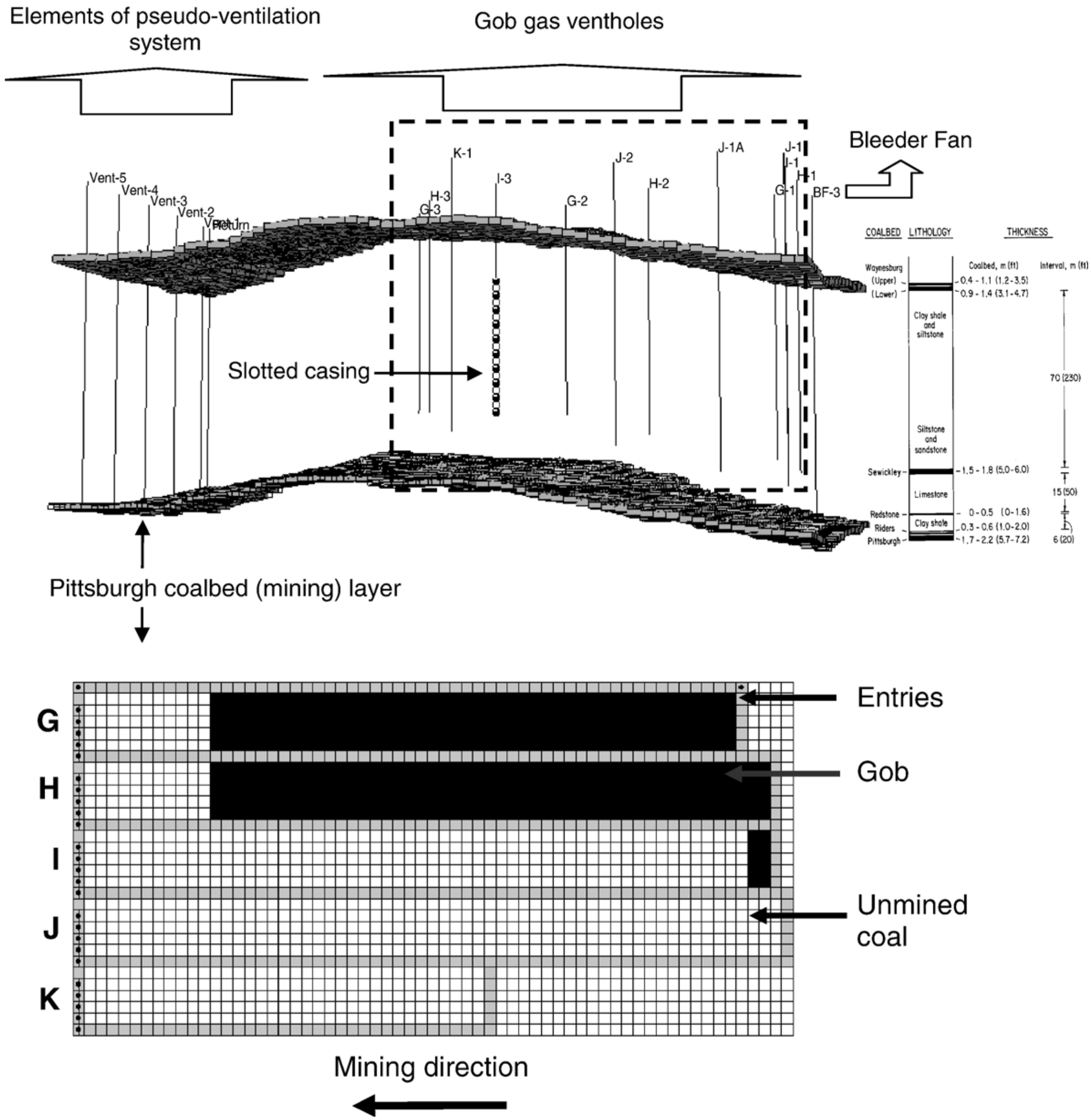

Fig. 6. 3-D representation of grid model of the study area that shows Waynesburg (top layer) and Pittsburgh (bottom layer) coalbeds. Figure also shows gob gas ventholes, their placements, completion representation, and elements of pseudo-ventilation system. Lower figure shows the panels in mining layer (Pittsburgh coalbed) and the grids of certain mining-area regions.

4.2. Gob gas ventholes and the pseudo-ventilation system

To include a simplified version of the ventilation system (called pseudo-ventilation system in this paper) in a longwall mining area, a set of horizontal wells representing the ventilation air input and a vertical well representing the bleeder fan were built into the grid model to represent the ventilation airflows to dilute methane in the entries and in the gob (caved zone). The horizontal wells were designed to inject nitrogen into the entries with a rate constraint to simulate the typical airflow rate at the mine site. One horizontal well was dedicated to each panel for ventilation purposes (Fig. 6). Each of the horizontal wells were operated sequentially for the time period required for mining of the associated panel as the changing longwall face location was simulated during model runs, as will be described in the following sections.

The bleeder fan was modeled with a vertical well in the grid model at the tailgate side of the G panel, with the completion interval being equal to the height of the entries (thickness of the Pittsburgh coalbed). To model the large diameter air shaft, the diameter of the well was assigned to the maximum wellbore diameter allowed in the model of 0.74 m (2.5 ft). During simulations, the bleeder fan was operated with bottom-hole pressure constraints to control the mine ventilation pressures. The bleeder fan and the elements of the pseudo-ventilation system are shown in Fig. 6. The locations and completions for the gob gas ventholes (Fig. 6) were determined based on their actual locations and their individual completion records.

4.3. Reservoir characterization and data sources

The construction of dual-porosity reservoir models in general requires detailed consideration of the geology and related reservoir-rock properties. The key concept in this study was the incorporation of parameters that realistically represent reservoir properties and their changes in response to longwall mining within the model. Most of the data required by the simulator for this study was gathered from previous NIOSH publications documenting research activities in the surrounding area, as well as external reports and personal communications with the operating mining company for setting the initial, pre-mining reservoir properties to the coal and non-coal units. However, since reservoir properties were not available for each individual layer in the model grid, particularly for non-coal layers, the same properties were assigned for all similar lithologies.

In the central and northern Appalachian Basin coalbeds, face and butt cleats are perpendicular and parallel, respectively, to the fold axis. In the northern Appalachian Basin, the face cleat of the Pittsburgh coalbed rotates from N 80° W in northwestern West Virginia to N 57° W in southwestern Pennsylvania (McCulloch et al., 1974), where the study mine was located. This rotation of the cleat direction in the field enabled close orientation of the cleats in the direction of grids.

Cleat spacing is an important reservoir property for modeling gas flows in coalbeds. Law (1993) reported cleat spacings of 0.5–9.7 cm in the northern Appalachian Basin. In this study, cleat spacings were taken as 3 cm (1.2 in.), which was a value based on the reported mean cleat spacing values of 2.4 cm (0.94 in.) and 3.20 cm (1.26 in.) from outcrops of the Pittsburgh and Sewickley coalbeds, respectively (Law, 1993). The gas content and adsorption-related data for the Pittsburgh coalbed and other major coalbeds in the area were obtained from direct method gas content determination tests (Diamond et al., 1986), and the adsorption data were obtained from available adsorption isotherms. For the coal layers for which no adsorption isotherms data were found (i.e., Pittsburgh riders and Redstone coalbed), their properties were assumed to be the same as for the Pittsburgh coalbed.

In this study, history matching techniques were used to estimate the undisturbed or initial permeabilities for major coalbeds and the permeability of the caved zone in the longwall gob. The fracture permeabilities for the Pittsburgh, Sewickley, and Waynesburg coalbeds were estimated to be 4 md in the face-cleat direction and 1 md in the butt-cleat direction. In the simulations, these initial values, like others, were assumed to be uniformed throughout the individual layers.

The permeability of the caved zone in the longwall gob is not easily predictable and little data are available in the literature. For this study, the permeability value was determined as a result of the overall model calibration procedure, using geomechanical calculations generated by the FLAC (Fast Lagrangian Analysis of Continua, Itasca, 2000) program (to be discussed in greater detail in the following sections), and by verifying the estimated values for methane concentrations (<1%) in the caved zone grids near the face location as calculated by the simulator. This approach resulted in an estimated permeability of about 10^{-9} m^2 (10^6 md) in the horizontal direction and 10^{-11} m^2 (10^4 md) in the vertical direction for the caved zone. These permeability values fall into the range of open-jointed to heavily fractured rock in the horizontal direction and into jointed rock classification in the vertical direction (Hoek and Bray, 1981).

Brunner (1985) investigated the migration of air through longwall gobs using a ventilation model, and constructed a laminar resistance grid over the caved zone. He assigned a resistance value to each resistance element in the grid. The permeability values he used and tested in his resistance model for the gob ranged between 10^{-5} and 10^{-7} m^2 (10^{10} and 10^8 md). However, he did not consider any distinction between vertical and horizontal permeability. Based on fractured porous medium vs. permeability classification, these values fall into the range of heavily fractured rock (Hoek and Bray, 1981).

In the model, the entries surrounding the longwall panels serve as main pathways for ventilation airflow. Thus, the permeabilities for this portion of the Pittsburgh coalbed grid layer (three entries plus the associated coal pillars combined) were assigned an average high value [10^{-7} m^2 (10^8 md)] within the allowed limits of the simulator for minimum resistance. The fracture porosity and fracture spacing required for the entry area were calculated from the mine maps. For these calculations, the pillars were conceptualized as solid structures and the roadways were conceptualized as fracture openings. Thus, from the area ratios of entries to the total area (pillars and entries) in a unit length of the section, an

Table 1
Representative prior to mining reservoir-rock properties used in the study

Parameter	Pitt. coal	Sandstone	Limestone	Shale	Entries
Permeability-*x* (md)	4	20	2	0.2	9×10^{7}
Permeability-*z* (md)	0.25	20	2	0.1	9×10^{7}
Effective porosity (fraction)	0.04	0.1	0.02	0.01	0.4
Eff. fracture spacing (m)/(ft)	0.03/0.01	15/50	60/200	60/200	30/100
Langmuir P. (MPa)/(psi)	2.25/326	–	–	–	–
Langmuir vol. (cc/g)/(scf/ton)	15.5/490	–	–	–	–
Desorption time (days)	20	–	–	–	–
Coal density (g/cc)	1.35	–	–	–	–

approximate area of 40% (or volume) occupied by fractures was calculated. The length of one side of a pillar, which was about 30 m (100 ft), was taken as the fracture spacing for the entries. Table 1 gives a few of the representative reservoir parameters that were calculated, obtained from the literature, or estimated from calibration runs and used in the model. These values, particularly permeabilities, represent the values prior to mining.

One of the important considerations in reservoir modeling of longwall mining process is the estimation of permeabilities or change of competent rock properties in the overlying strata of the panel during and after mining disturbance has occurred, and including these changes to the reservoir model at different face positions. These changes were predicted by geomechanical techniques and their effects on reservoir permeabilities were estimated as discussed in the following section.

4.4. Geomechanical modeling of permeability changes

The effect of longwall mining on the permeability of the surrounding rock was evaluated using the FLAC finite difference program. The program has the capability to model the mechanical behavior of rocks in both the pre- and post-failure modes, can model the caved rock as a strain hardening material, and simulates the mining process as a sequence of interrelated modeling steps. Rock failure is allowed to take place in response to the stress redistribution around the longwall panel. Failure may occur in the overburden strata either by shearing along bedding planes or by fracturing through intact rock material.

Rock strength values used in the FLAC model were selected from the results of extensive mechanical property testing of coal measure strata, as reported by

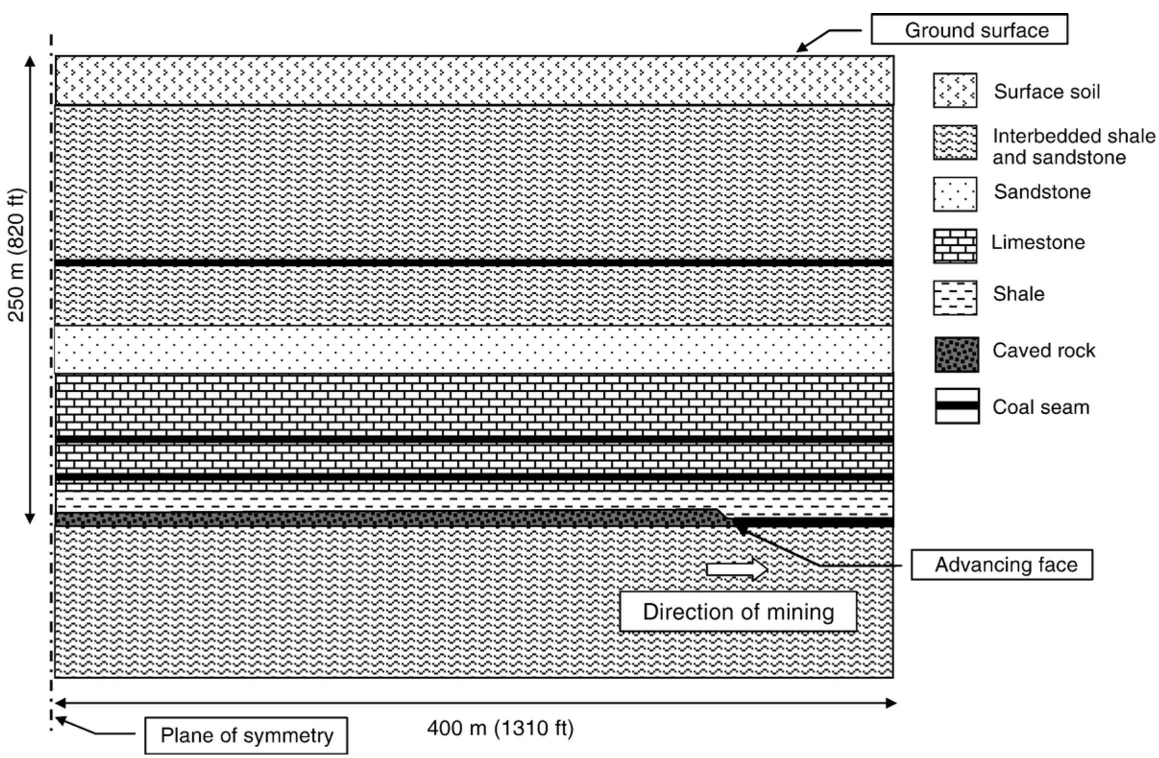

Fig. 7. Vertical section of the stratigraphy at the mine site, the caved rock, and the direction of mining as modeled using FLAC.

Rusnak and Mark (1999) and Molinda and Mark (1996). The model calculated the strength of the intact material as well as the strength of the bedding planes by using a ubiquitous joint approach in which bedding planes are assumed to be uniformly distributed throughout the rock mass. Rock failure was based on the Coulomb failure criterion, with strain softening and dilation occurring once the rock has failed. The model runs were taken to equilibrium at each step of the simulated mining process, so that rock failure and stress re-distribution would occur. The modeling steps included a sufficient lateral extent of mining, so that full subsidence of the overburden strata would occur over the mined area.

Two-dimensional FLAC models were created to simulate both longitudinal and cross-sectional profiles through an active longwall panel. The models included the rock mass from 100 m (328 ft) below the Pittsburgh coalbed up to the ground surface. The initial vertical stress in the model increased with depth according to the overburden load, while relatively high horizontal stresses were imposed as described by Dolinar (2003). Rock mass parameters were included in the model, with each layer having a specific strength, stiffness, and initial stress state. The caved rock was simulated to a height of four times the longwall extraction height, 7.3 m (24 ft) in this case. Rock failure was permitted to take place in the model in response to longwall mining using failure criteria and strength properties appropriate for the individual strata layers. Fig. 7 shows an example of a longitudinal model.

The fracture permeability of rock strata is highly dependent on the in situ stress, and most importantly in a mining environment, mining-induced changes in stress with time (Hoek and Bray, 1981; Lowndes et al., 2002). An exponential relationship was used to compute the effect of stress changes on the rock mass permeability after the work of Ren and Edwards (2002) and Lowndes et al. (2002). Permeabilities were calculated independently for the horizontal and vertical directions:

$$k_h = k_{ho} e^{-0.25(\sigma_{yy} - \sigma_{yyo})} \tag{1}$$

and

$$k_v = k_{vo} e^{-0.25(\sigma_{xx} - \sigma_{xxo})} \tag{2}$$

where k_{ho} and k_{vo} are initial permeabilities, σ_{xx} and σ_{yy} are the prevailing stresses and σ_{xxo} and σ_{yyo} are the initial stresses in horizontal and vertical directions, respectively. Figs. 8 and 9 show the results of a FLAC model for the horizontal and the vertical permeabilities,

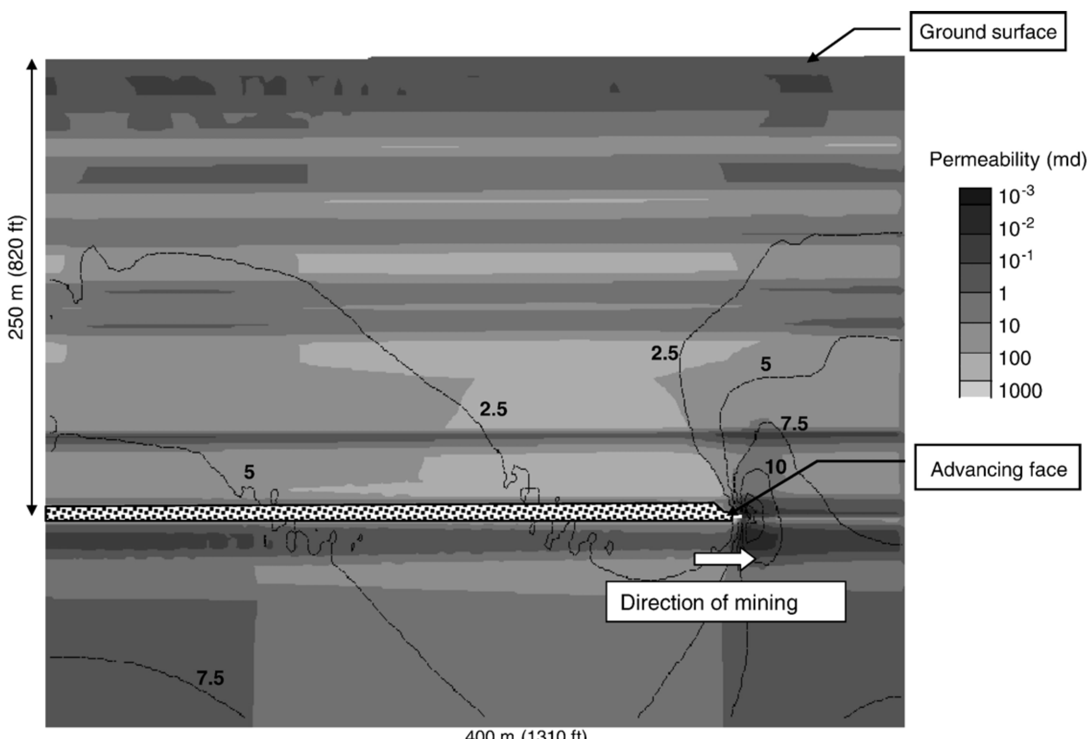

Fig. 8. Vertical section showing vertical stress contours (in MPa) and the horizontal permeability distribution as a result of longwall mining determined by FLAC modeling.

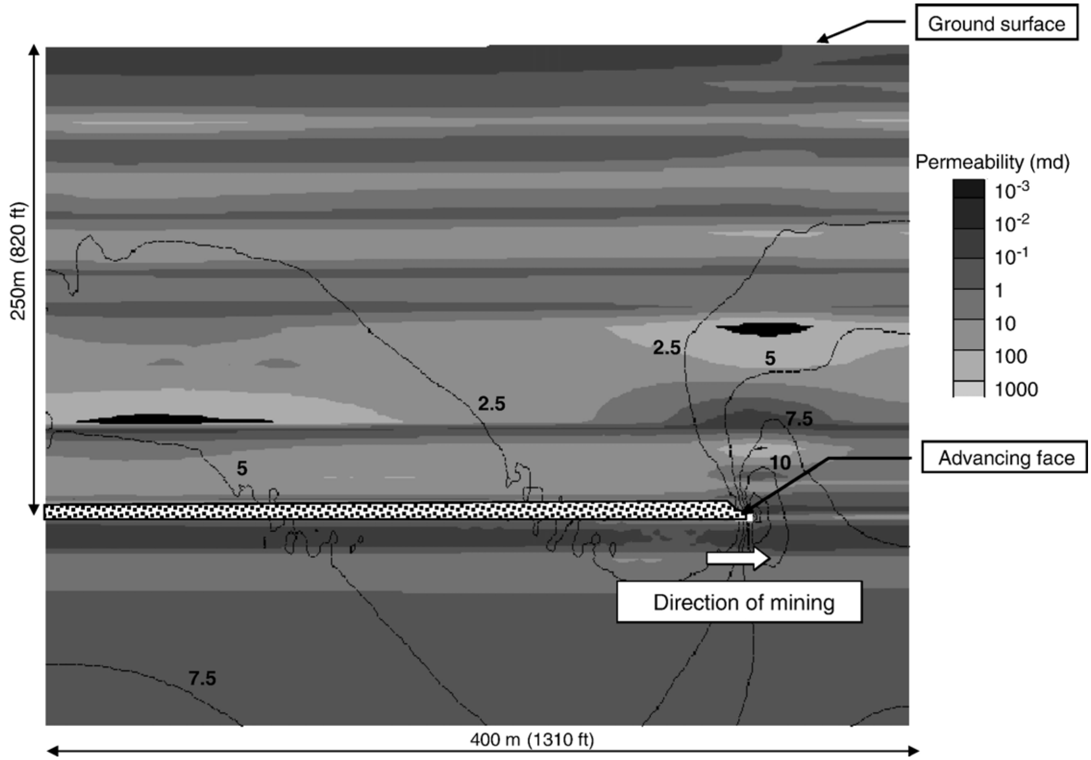

Fig. 9. Vertical section showing vertical stress contours (in MPa) and the vertical permeability distribution as a result of longwall mining determined by FLAC modeling.

respectively. In these figures, the vertical stress contours are also shown. A low permeability zone is indicated ahead of the advancing longwall face in the unmined coalbed, and higher permeability is present in the caved zone behind the face in the gob, and decreasing further away from the face as the subsided strata is re-compacted over time. Further details of FLAC model development for permeability calculations are given in Esterhuizen and Karacan (2005).

4.5. Scheduling of runs for "dynamic" reservoir modeling for longwall mining

Longwall mining and the response of overlying strata to mining disturbances are dynamic processes. As the mining face advances, the reservoir properties, especially the fracture permeabilities of individual layers, change based on their strength and based on how much stress they are exposed to. Production from each gob gas venthole usually starts soon after the location is undermined by the longwall and can continue for a significant length of time, even after the panel is completed (Diamond, 1994) because of the protracted influence of the mining-induced strata disturbances. This situation leads to a moving-boundary-value problem. Two methods can be used to handle this problem: one is at the differential equation level, and the other is at the coefficient matrix level in which transmissibilities are treated in such a way that fully mined cells are assigned the mine pressure and partially mined cells are treated as constant-pressure boundaries (King and Ertekin, 1991). However, this situation seems more applicable to simulation of single layers, where only the production from completions in unmined coalbeds is considered.

In this study, the moving boundary problem in 3-D was handled with 15 different "restart" model runs in the simulation. These restarts were run sequentially, each characterizing a stage in the mining/face advance and associated strata disturbances. Each restart run (mining step) was performed in such a way that mining would progress up to the next venthole location for the distance and time characterizing the face movement between successive ventholes. In this process, the simulation outputs from the previous model run are written to a "restart" file, then used by the next model run as updated longwall face and reservoir parameters for the next face position. Fig. 10 schematically presents the scheduling

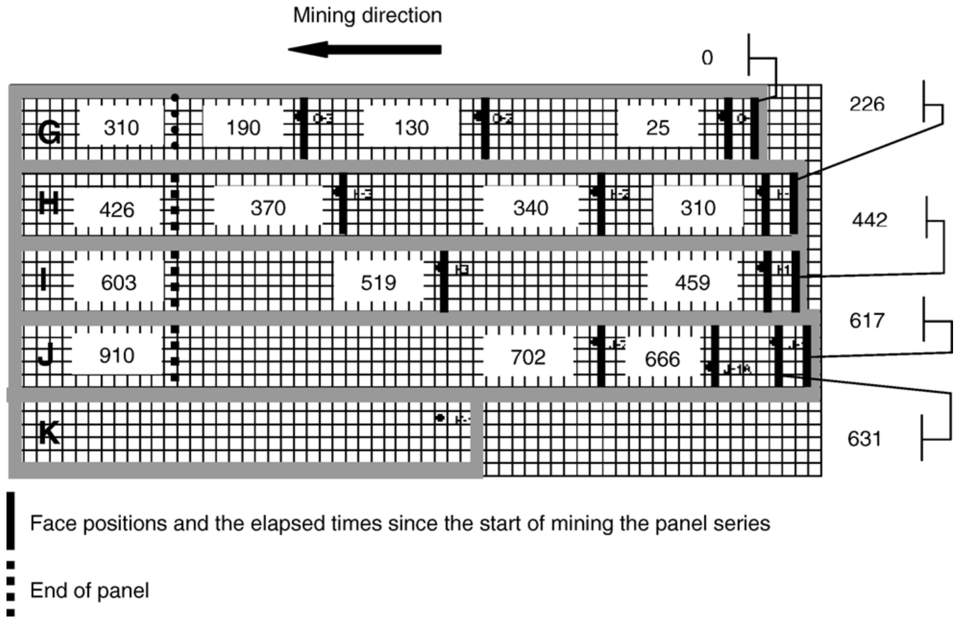

Fig. 10. Representation of panels in Pittsburgh coalbed layer and face position and time scheduling for "dynamic" modeling of longwall mining in the panels. The numbers show the time (in days) that passed since mining start in G panel. The distance and time interval between each solid bar represent the face advance and the duration it takes for each "restart" model run. The scheduling was made based on mine reports and the start of gas production from each gob gas venthole.

of face positions and the actual time (in days) when each gob gas venthole started production.

5. Model calibration through history matching

Model calibration through history matching can be used with accurate field and laboratory data for determining the remaining unknown reservoir properties and for predicting future well performance (Zuber et al., 1987). In this study, the known gas flow rates and gas composition from existing gob gas ventholes were history matched, while constricting the predicted bottom-hole pressures of gob gas ventholes around or below atmospheric pressures, as observed in the field, to estimate the disturbed and undisturbed permeabilities of fractured strata as a result of mining, a coal desorption time constant, and the permeability of the caved zone.

The fractured rock permeabilities, or permeability changes, calculated by FLAC computations, were incorporated into the model to update the properties of the regions affected by mining as the longwall face was advancing. Advancement of the longwall face was simulated during history match runs and became an integral part of the matching procedure. This was basically a trial-and-error approach, where a "dynamic" longwall mining simulation run was made using all known and fixed values and the "initial estimates" for the unknown values. Then, the simulated gas production rate and concentrations from each gob gas venthole were compared with the actual data.

Based on the comparison between simulated and actual productions for the entire period of simulation, adjustments were made to the unknown parameters, and additional runs were completed until an acceptable agreement was achieved. While adjustments were being made to the unknown parameters during the history match runs, the gob gas ventholes were operated with the targeted gas rates (the observed daily rates given on a weekly basis) as the well control constraint, and wellbore bottom-hole pressures and produced gas compositions were computed by the simulator. The acceptance criteria for the calculated pressures were that they should be lower than, but close to atmospheric pressures, as they normally should be in the longwall gob producing reservoir. This alternative approach was taken due to the lack of reported well bottom-hole pressure data for the gob gas ventholes, since these parameters are not commonly measured as part of the collected production data at most mine sites.

Although the model had been set up for two-phase flow, the water phase was mostly treated as immobile, except in the caved section, where the available water in the fractured strata was allowed to drain into gob during caving, increasing the water saturation in the caved zone by 5%. This was an estimated value, but the cooperating mining company verified that there was not any water production from any of the ventholes, and confirmed a general lack of water influx into the entries from the roof and the gob. Although there might be regional variations, these observations in the underground mining environment suggest that this region has been desaturated and depressurized during its geological past, as well as from the extensive coal mining and oil and gas production activities, as further inferred by Hunt and Steele (1991).

Figs. 11 and 12 show the actual and simulated gas production rates and methane concentrations for one venthole on each longwall panel in the study area. As can be seen from these figures, the gas production rate data match well for most of the data points, and the methane concentrations can be matched for average values and general trends. The shifts in time scale for each venthole to become productive are caused by, and depend on, when the venthole location was intercepted by the longwall face. The calculated bottom-hole pressures for the same ventholes are given in Fig. 13. This figure shows that before the ventholes are intercepted by the mining disturbances, the bottom-hole pressures (equal to the reservoir pressure when the well is shut-in) are slowly declining, basically because of the effect of the approaching longwall face and the gobs of nearby longwall panels. However, when the venthole location is intercepted by the longwall face, the bottom-hole pressure sharply drops to below-atmospheric pressures because of the venthole connection with mine pressures through the mining-induced fractures. Thus, depending on the completion depth and amount of applied vacuum, the venthole competes to varying degrees with the ventilation pressures to produce gas from the subsided strata. Even during the periods when the ventholes are not actively being produced (i.e., no vacuum pressure is being applied), they stay close to or under atmospheric pressure conditions. The bottom-hole pressures calculated in this step were used as the operating constraint for gob gas venthole completion scenarios that are presented in the following sections.

6. Results and discussion

6.1. Characterization of methane emission sources in relation to longwall mining

A better understanding of how the reservoir characteristics and subsided strata mechanics associated with longwall mining influence the release and migration of methane in the underground environment will help operators increase the efficiency of their methane control systems. Investigations of the source of longwall gob gas by Diamond et al. (1992) showed that overlying coalbeds were the primary contributors of gas to the gob. Previous studies by NIOSH at this current site suggested that the overlying Pittsburgh Rider coals, the Redstone coalbed (when present), and the Sewickley coalbed were most likely the primary sources of gob gas associated with the Pittsburgh coalbed (Mucho et al., 2000).

The longwall subsided strata reservoir model described previously was used to further characterize the methane sources that contribute to the gob gas at the study mine site. Fig. 14 shows a vertical cross section of the subsided strata reservoir over the headgate side of H panel and the

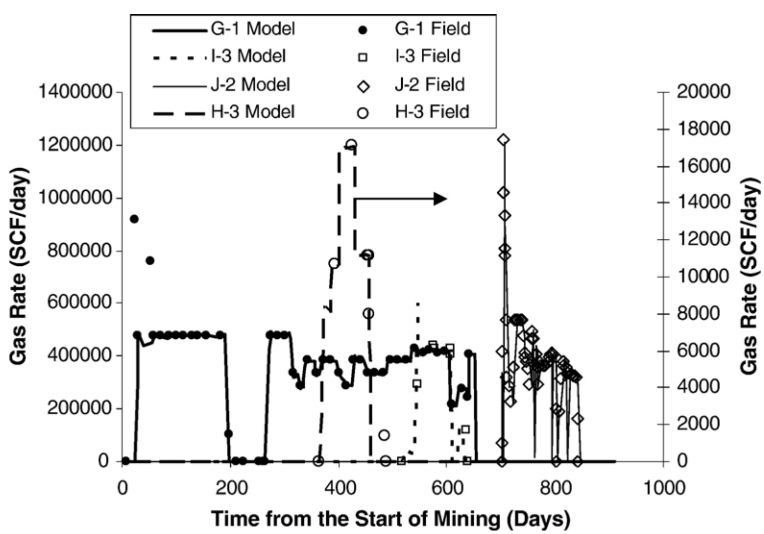

Fig. 11. Comparison of observed and simulated gas productions from one gob gas venthole at each panel mined. Values were obtained using the "dynamic" modeling approach described in this study (arrow showing the axis for H-3 data points).

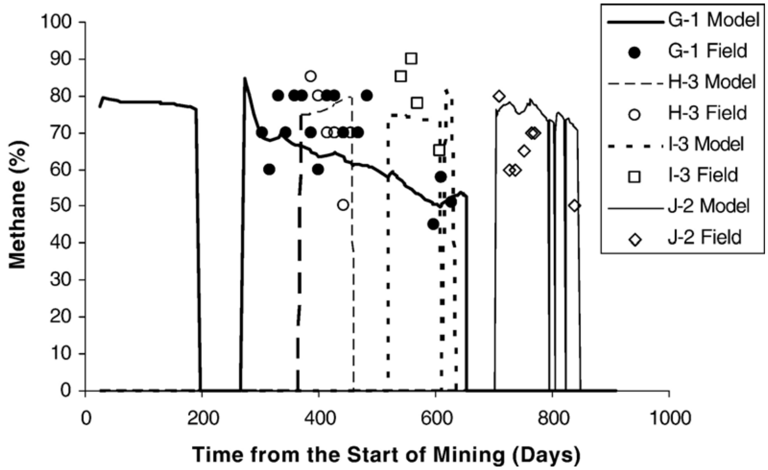

Fig. 12. Comparison of observed and simulated methane concentrations from one gob gas venthole at each panel mined based on current longwall mining modeling approach.

Pittsburgh coalbed layer 630 days after the start of mining on the adjacent G panel. The methane mole percent data show that the methane concentration is high in gas emissions from Sewickley coalbed, and this coalbed seems the primary source of longwall gob gas in this region. Modeling results show that there is some methane emission from Waynesburg coalbed also due to a general pressure decline in the rock layers because of mining. These two coalbeds have been reported as producing horizons in coalbed gas wells in the Northern Appalachian Basin (Bruner et al., 1995). However, the Waynesburg coalbed is not thought to be a major contributor to the Pittsburgh gob gas, since its gas storage capacity is low (0.1–0.3 cm^3/g) according to Diamond et al. (1992), geomechanical modeling of the area showed that vertical fracturing does not normally extend up to the Waynesburg coalbed's elevation, and the slotted casings of the gob gas ventholes are set about 100 ft below the Waynesburg coalbed elevation). The Redstone coalbed (if present) and the Pittsburgh Rider coals are within the caved zone, and thus, gas from these coalbeds may report to the ventilation system because it is the closest pressure sink to this gas source.

Fig. 15 illustrates the model predictions across another vertical section of the subsided strata reservoir over the I panel tailgate. This figure shows two I panel gob gas ventholes and their effect in reducing methane concentrations within their effective radius and in the sheared zone below the Sewickley coalbed at the 630th day of mining of these panel series. From the modeling results shown in this figure, gas released from the Sewickley coalbed is

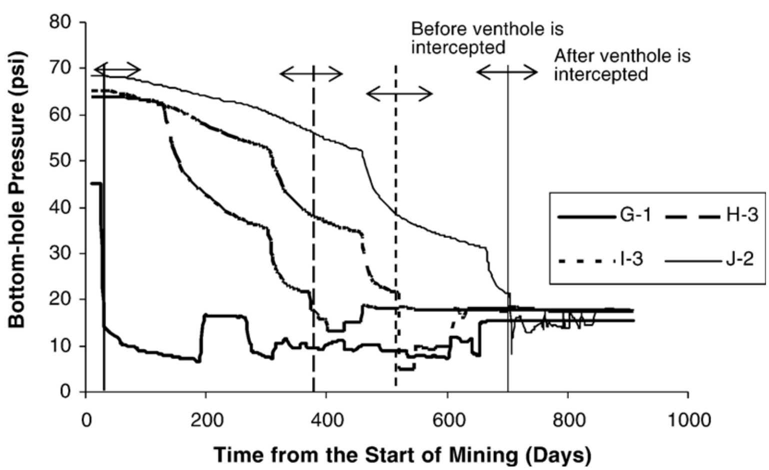

Fig. 13. Bottom-hole pressures calculated by the model for the shown gob gas ventholes of each panel (the opposing arrows show the times before and after the interception of each of the gob gas ventholes).

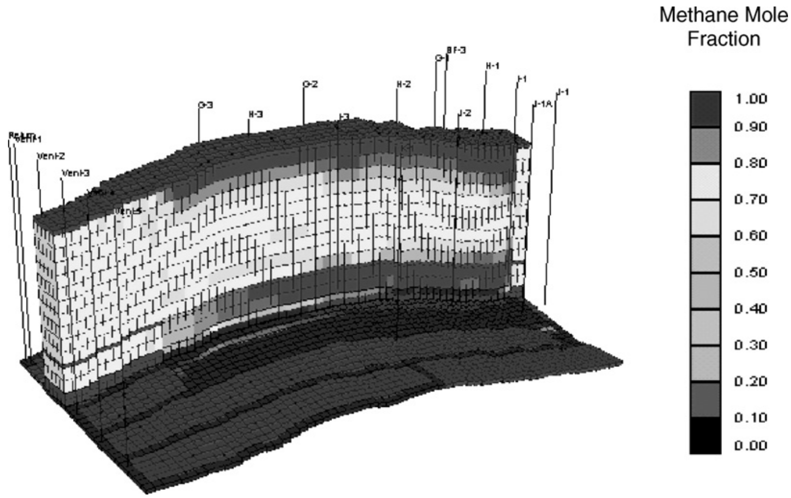

Fig. 14. A vertical cross section of the subsided strata reservoir over the headgate side of H panel and the Pittsburgh coalbed layer 630 days after the start of mining on the adjacent G panel. The methane mole percent data show that the methane concentration is high in gas emission from Sewickley coalbed and this coalbed seems the primary source of longwall gob gas in this region.

expected to be the primary source of gas captured by the gob gas ventholes, since they are the closest pressure sink acting upon this gas source. This also suggests that the methane emissions from Sewickley coalbed may enter the ventilation system if these wells do not operate continuously and effectively.

6.2. Effects of gob gas venthole completion practices on production

At the study mine site, the general completion practice for the gob gas ventholes was to drill to within 12 m (40 ft) of the top of the Pittsburgh coalbed, then install 17.8 cm

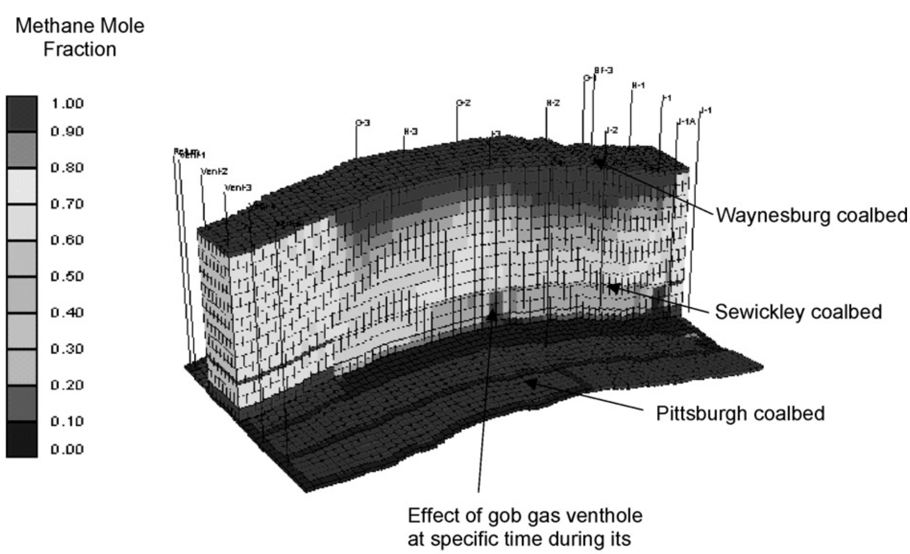

Fig. 15. A vertical section of the subsided strata reservoir over the I panel tailgate after 630th day since the start of mining. This figure shows two I panel gob gas ventholes and their effect in reducing methane concentrations within their effective radius and the sheared zone below the Sewickley coalbed at that specific time. It is also shown that gas released from the Sewickley coalbed is the primary source of gas captured by the gob gas ventholes, since they are the closest pressure sink acting upon this gas source. This observation also suggests that the methane emissions from Sewickley coalbed may enter directly to the ventilation system if these wells do not operate continuously, and effectively.

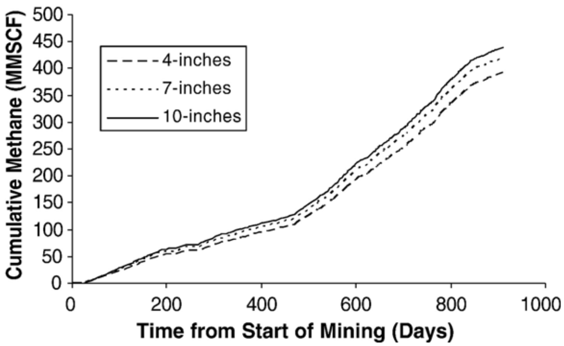

Fig. 16. Simulated cumulative methane production from all ventholes in four panels for different casing diameters.

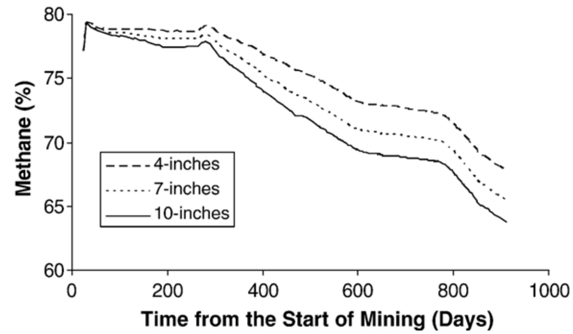

Fig. 17. Average methane concentration based on cumulative productions from all ventholes in four panels for different casing diameters.

(7 in.) casing with a 61 m (200 ft) slotted section at the bottom, as shown in Figs. 5 and 6. This completion strategy places the slotted casing adjacent to the gas-bearing strata in the fractured zone, and high enough above the caved zone so that the venthole does not extract excessive amounts of mine air. Thus, this completion strategy maximizes the capture of methane originating in the fractured zone, in particular gas from the Sewickley coalbed at the study mine site, before it can migrate to the caved zone and into the mine environment.

In this modeling study, a series of gob gas venthole completion scenarios were run using well pressures calculated in previous steps as the operating constraints to investigate how methane capture characteristics would be affected if the venthole diameter, slotted casing length, and slotted casing setting depth were changed. However, it should be kept in mind that, in such a complex environment, the permeability changes in the subsided strata are directly related to the strength of the associated rock units and to their response to a given stress level. Thus, the lengths of slotted casing located in different rock layers may make a difference in methane capture efficiency. Therefore, some of the results from this study may be specific only to the study mine site, other mines operating in Pittsburgh coalbed, and perhaps to other mining areas with similar mining and geologic conditions. However, it is reasonable to assume that the results may offer some degree of generalization in understanding and predicting the influence of various changes in completion design on gas production.

6.2.1. *Effect of slotted casing diameter*

The casing diameter of the gob gas ventholes at the study mine site was 17.8 cm (7 in.). To investigate the possible effects of different slotted casing diameters on methane production and concentration in the produced gas, alternative diameters were tested with the model. For this study, the casing diameter was increased to 25.4 cm (10 in.) and decreased to 10.2 cm (4 in.). The other completion parameters, such as length of slotted casing and setting depth, were held constant at their original design values, 61 m (200 ft) and 12 m (40 ft), respectively.

Fig. 16 shows cumulative methane production from all gob gas ventholes on the four mined panels in the study area as a function of mining time. The modeling results predict that methane production will increase with the use of the larger diameter casing. The cumulative methane production was 4.9% more with the 25.4 cm (10 in.) casing, as compared to the 17.8 cm (7 in.) diameter casing. Conversely, the amount of methane produced with the smaller, 10.2 cm (4 in.) diameter casing was about 7% less than that produced from the 17.8 cm (7 in.) diameter casing in the base case.

However, compared to the 17.8 cm (7 in.) casing base case, the amount of air produced from the 25.4 cm (10 in.)

Table 2
Effect of casing diameter on cumulative methane and total gas production and average methane composition of the produced gas

Casing diameter (inch)	Cum. CH_4 (MMscf)	CH_4 diff. rel. to 7 in. casing (%)	Cum. gas (CH_4+Air) (MMscf)	Diff. (CH_4+Air) rel. to 7 in. casing (%)	Cum. air (MMscf)	Air diff. rel. to 7 in. casing (%)	Ave. CH_4 conc. (%)
4	391.8	−6.7	609.4	−9.9	217.6	−15.2	64.3
7	419.8	–	676.5	–	256.7	–	62.1
10	440.1	+4.9	728.4	+7.6	288.3	+12.3	60.4

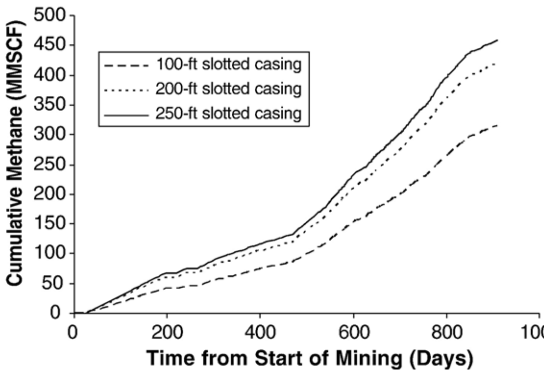

Fig. 18. Simulated cumulative methane production from all ventholes in four panels for different casing lengths.

diameter casing was 12.3% higher, and it was 15.2% lower with the 10.2 cm (4 in.) diameter casing. Thus, the methane concentrations were higher in the produced gas from the 10.2 cm (4 in.) diameter casing, and lower from the 25.4 cm (10 in.) diameter casing. In the case of the 25.4 cm (10 in.) diameter casing, the reduced methane concentration was most likely caused by more mine air being captured because of an increased depletion radius created by the larger diameter pressure sink. Since the total (CH_4+air) gas production (Table 2) increased with an increase in casing diameter, the marginal decrease in methane concentration still resulted in a higher cumulative methane production volume with a larger diameter venthole. The change of methane concentration in the cumulative gas production is shown in Fig. 17. The average predicted methane concentrations in the produced gas stream from the simulated gob gas ventholes with 25.4 cm (10 in.) and 10.2 cm (4 in.) casing was 60.4% and 64.3%, respectively, as compared to 62.1% for the 17.8 cm (7 in.) casing base case.

6.2.2. Effect of slotted casing length

Another gob gas venthole completion parameter investigated was the influence of the length of the slotted casing on gas production. For this set of simulations, the length of the slotted casing section was changed to 30.5 m (100 ft) and 76.2 m (250 ft), and the results compared to the original 61 m (200 ft) slotted casing base case. The casing diameter and setting depth were kept the same, 17.8 cm (7 in.) and 12 m (40 ft), respectively, for these simulations. Fig. 18 shows the cumulative methane production from the simulated gob gas ventholes as a function of mining time. The modeling results predict that the cumulative methane production will increase with an increase in casing length. The methane production from the simulated gob gas ventholes with 76.2 m (250 ft) of slotted casing was 459.4 MMscf (13.0×10^6 m^3), as compared to the 391.8 MMscf (11.1×10^6 m^3) in the original 61 m (200 ft) slotted casing base case (Table 3). This represents a 9.5% increase in methane capture from the ventholes in the four-panel study area. However, when the slotted casing length was shortened to 30.5 m (100 ft), the methane production decreased to 314.7 MMscf (8.9×10^6 m^3), an approximate 25% reduction from the 61 m (200 ft) slotted casing base case.

When the length of the slotted casing completion interval was increased to 76.2 m (250 ft) for the simulated gob gas ventholes, the cumulative volume of produced air was 302.8 MMscf (8.6×10^6 m^3), or 17.9% more than that for the 61 m (200 ft) slotted casing base case. This results in a lower average methane concentration in the produced gas stream from the ventholes with an increased completion interval. The cumulative volume of air produced by the gob gas ventholes simulated with 30.5 m (100 ft) of slotted casing was about 154 MMscf (4.4×10^6 m^3), or 43.5% less than that from the base case ventholes, resulting in a higher methane concentration in the produced gas stream from these holes.

The decrease in simulated methane concentrations resulting from the increase in slotted casing length for gob gas ventholes at the study site may be due to setting the extra slotted casing length adjacent to less fractured (lower permeability) strata, the increased flow resistance in that zone, which likely to increase the production and gas flow from the lower section of the hole closer to the caved zone. Although the flow rate is lower in the less fractured strata, compared to the deeper, more permeable sections of the strata, extending the slotted casing length to 76.2 m (250 ft) still resulted in the production of 12.7% more gas, as compared to the 61 m (200 ft)

Table 3
Effect of casing length on cumulative methane and total gas production and average methane concentration of the produced gas

Casing length (ft)	Cum. CH_4 (MMscf)	CH_4 diff. rel. to 200 ft casing (%)	Cum. gas (CH_4+Air) (MMscf)	Diff. (CH_4+Air) rel. to 200 ft casing (%)	Cum. air (MMscf)	Air diff. rel. to 200 ft casing (%)	Ave. CH_4 conc. (%)
100	314.7	−25.1	468.7	−30.7	154.0	−43.5	67.1
200	419.8	–	676.5	–	256.7	–	62.1
250	459.4	+9.5	762.2	+12.7	302.8	+17.9	60.3

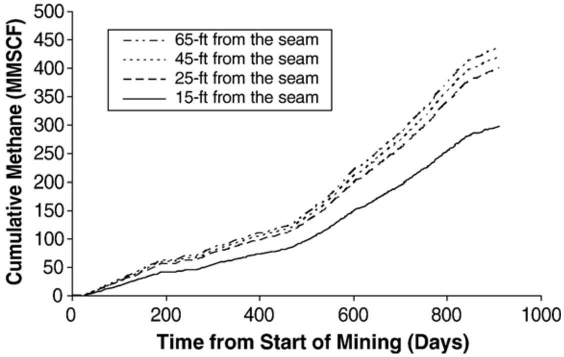

Fig. 19. Simulated cumulative methane production from all ventholes in four panels for different casing setting depths.

base case. This eventually resulted in the production of 9.5% more methane that otherwise might have migrated into the mining environment.

Decreasing the casing length to 30.5 m (100 ft) resulted in the production of gas with a higher average methane concentration, mostly from the Sewickley coalbed, where the strata disturbance was more severe because of its proximity to the mining. However, the modeling results indicate that the shorter casing length was not efficient in capturing and producing methane from the upper strata. Although the average methane concentration in the produced gas stream at the end of the simulated mining period was 5–7% higher with the shorter simulated slotted casing interval, as compared to that from the ventholes with longer casing intervals, the total gas and methane production for the venthole with 30.5 m (100 ft) of slotted casing was 30.7% and 25% less, respectively, as compared to the 61 m (200 ft) base case length. Table 3 summarizes the production data to show the effect of casing length on methane capture.

For design purposes, it should be emphasized that site-specific distribution of gas-bearing strata associated with the various lengths of slotted casing will have a profound effect on the methane production, e.g., coalbeds and gas-bearing sandstones and shales in the upper strata being in or out of the slotted casing completion zone. Therefore, it is important to make an assessment of the geological layers in the overlying strata and their gas emission potentials. For this purpose, gas content testing is critical (Diamond and Schatzel, 1998), along with the simulations, in determining the optimum length of slotted casing.

6.2.3. Effect of slotted casing setting depth

This scenario was simulated to investigate the effect of casing setting depth (distance above the top of the mining layer) on gas production. In the original venthole completion design, the casing setting depth was 12 m (40 ft) based on the caving height value estimated by Mucho et al. (2000) as 10.7 m (35 ft) above the Pittsburgh Coalbed. As alternative approaches, 19.8 m (65 ft), 7.6 m (25 ft) and 4.6 m (15 ft) setting depths were simulated. In these alternative cases, the 7.6 m (25 ft) depth corresponded to the upper section of the caved zone, which was simulated in this study as 7.3 m (24 ft) above the Pittsburgh Coalbed, and the 4.6 m (15 ft) depth corresponded to circumstances where the venthole was drilled well into the caved zone. For these scenarios, the casing diameter and slotted casing lengths were kept at their original design values, 17.8 cm (7 in) and 61 m (200 ft), respectively.

Fig. 19 shows the cumulative methane production for the simulated alternative casing setting depths. Raising the casing setting depth to 19.8 m (65 ft) above the Pittsburgh coalbed as compared to 12 m (40 ft) resulted in 4% more cumulative methane production. The predicted cumulative methane production declined by about 5% and 29% when the casing was set to within 7.3 m (25 ft) and 4.6 m (15 ft) of the top of the mining layer, respectively. The total gas production increased by 4.9% with the 19.8 m (65 ft) slotted casing setting depth scenario (mostly due to the increase in methane production), and decreased by 5% for the 7.3 m (25 ft) setting depth (mostly because of the decrease in methane production). The total gas production increased by about 10.3% with the 4.6 m (15 ft) slotted casing setting depth. In the 4.6 m (15 ft) setting depth scenario, the lower slots of the casing were in the caved zone influenced by the mine ventilation system where flow resistance was small. Therefore, the ventholes pulled 74% more mine air, as compared to the operator's standard 12 m (40 ft) setting depth (Table 4). Since most of the produced gas

Table 4
Effect of slotted casing setting depth on cumulative methane capture, total gas production, and average methane composition at the end of mining

Setting depth (ft)	Cum. CH_4 (MMscf)	CH_4 diff. rel. to 40 ft depth (%)	Cum. gas (CH_4+Air) (MMscf)	Diff. (CH_4+Air) rel. to 40 ft depth (%)	Cum. air (MMscf)	Air diff. rel. to 40 ft depth (%)	Ave. CH_4 conc. (%)
65	436.1	+3.9	709.3	+4.9	273.2	+6.4	61.5
40	419.8	–	676.5	–	256.7	–	62.1
25	399.8	−4.8	642.9	−5.0	243.1	−5.3	62.2
15	298.7	−28.8	746.1	+10.3	447.3	+74.0	40.3

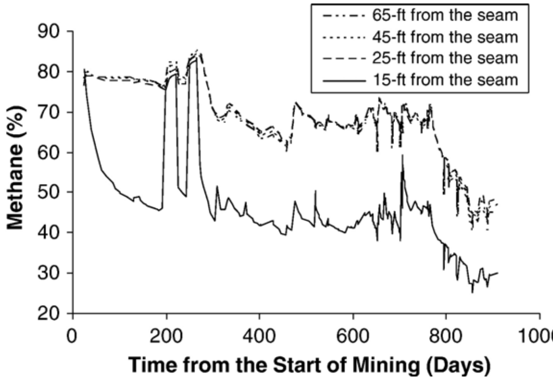

Fig. 20. Simulated methane concentration in the instantaneous productions evaluated based on production from all ventholes in four panels for different casing setting depths.

was mine air at the 4.6 m (15 ft) setting depth (Figs. 20 and 21), the average methane concentration in the cumulative produced gas at the end of mining on the panel was only 40%, as opposed to the 60–70% average methane concentration calculated for other slotted casing setting depths.

A real-world example of the gas quality consequences of completing gob gas ventholes into the caved zone is illustrated with measured gas concentration data from two ventholes continuously monitored at another site, very close to the study area simulated in this paper. For this new site, the height of the caved zone was estimated to be ~12 m (~40 ft), higher than at the primary site investigated for this study, because of the presence of the sandstone paleochannel with varying thickness above the Pittsburgh coalbed layer. The first gob gas venthole on one of the new monitored panels was completed to a depth of 14.3 m (47 ft) above the top of the Pittsburgh coalbed, generally within the standard depth range for the mine site. However, the second venthole on the same panel was

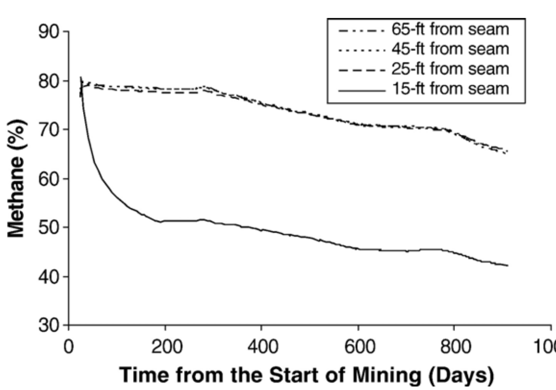

Fig. 21. Average methane concentration based on cumulative productions from all ventholes in four panels for different casing setting depths.

inadvertently drilled deeper to a depth of 10.6 m (35 ft) above the top of the Pittsburgh Coalbed, which is in the caved zone. As shown in Fig. 22, the methane concentration in the produced gas from the venthole completed into the caved zone averaged about 30% less than that of the standard completion depth above the caved zone because of the increased production of mine ventilation air. It should be noted that, even though the estimated caved zone height for which the predictions for the study site described in this paper is slightly different than the new site where the data shown in Fig. 22 was measured, a similar methane concentration decrease (25–30%) was predicted for the ventholes penetrating into caved zone.

The increased production of mine ventilation air from the gob gas ventholes is a problem for several reasons. The first concern is that if the venthole is producing at its maximum capacity, then all of the available methane in the subsided strata may not be captured, and thus can migrate to the underground workplace where it is a potential explosion hazard. In addition, when coalbeds and associated caved zone strata are prone to spontaneous combustion, the flow of additional mine air into this zone may pose an increased risk of a mine fire of spontaneous combustion origin. There are also economic issues associated with producing higher levels of mine ventilation air from the gob gas ventholes. Obviously, there are costs associated with providing ventilation air to the underground workings, as there are with the drilling and operation of the ventholes. Economically, it is counter-productive to incur cost to first introduce the ventilation air to the mine, and then incur additional cost to remove it from the mine via the gob gas ventholes. Finally, for those mining operations capturing gob gas for commercial sale, it is very important to maintain as high a methane

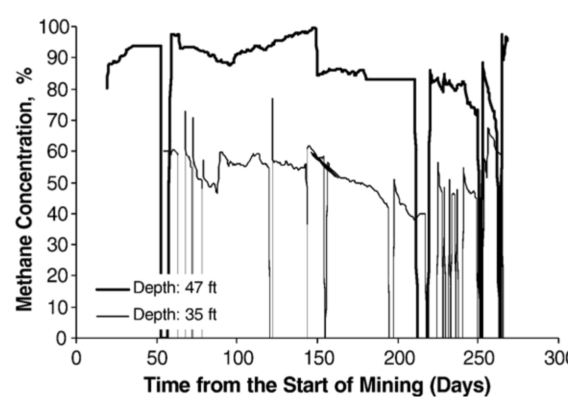

Fig. 22. Methane concentrations measured in the gas production stream from two gob gas ventholes completed to different depths above the Pittsburgh coalbed on the same longwall panel at a mine site close to the study site.

concentration as possible in the produced gas stream, or additional expenses will be incurred to remove the non-hydrocarbon gases prior to selling it to the pipeline.

7. Summary and conclusions

A comprehensive "dynamic" reservoir model of a multi-panel longwall mine site operating in Pittsburgh coalbed was constructed. In the model construction, various mining and reservoir conditions were taken into account. A retreating longwall face was modeled using 15 different "restart" models. Models were run based on a schedule built from the actual longwall face advance and gob gas venthole production histories. The reservoir response to the stresses induced by longwall mining and the resultant permeability changes were computed by geomechanical models and were coupled with the reservoir model to simulate the reservoir property changes during mining.

The "dynamic" model was calibrated with a history matching procedure that compared model predictions with field observations of gas production rate and methane concentrations from each gob gas venthole on the panels. Using the developed model, gas emission sources, gas flow paths, and various gob gas venthole completion designs were investigated. Some of the results may be site-specific and may be applicable mainly to the study mine site and perhaps to other mines operating in the Pittsburgh coalbed. However, the results offer some generalization in understanding and predicting the effect of various completion changes on gas production from gob gas ventholes.

The following summarizes the general conclusions of this study:

(1) The model demonstrated that gob gas production characteristics from the coalbeds and other gas-bearing formations are affected by subsidence. For the study site, the Sewickley coalbed was a major contributor to the gob gas venthole production and for gob gas flow to the mine.
(2) Keeping the other completion parameters constant, increasing the gob gas venthole diameter increased cumulative methane production from the subsided strata. Although a marginal decrease in the methane concentration was evident from this completion change, possibly due to increased mine-air extraction with a larger sink, the increased gas flow rate increased the overall volume of methane produced, when a larger diameter was used.
(3) Longer sections of slotted casing produce more gas, and thus more methane. In this study, it was predicted that methane production with 76.2 m (250 ft) of slotted casing was 9.5% greater than it was for the standard 61 m (200 ft) of slotted casing. However, when the slotted casing length was shortened to 30.5 m (100 ft), the methane production decreased by about 25% compared to the production with the original length.
(4) Casing setting depth plays an important role on the amount and concentration of methane captured. Modeling results showed that when the setting depth was close to or within the caved zone, the methane concentration in the produced and total amount of methane capture decreased. In this study, computations showed that increased casing setting heights above the mined coalbed resulted in more cumulative methane production. When the casing setting depth was increased to 19.8 m (65 ft) above the Pittsburgh coalbed, the cumulative methane production increased by about 4% compared to the original base case scenario. Similarly, cumulative methane production decreases of about 5% and 29% were calculated when the casing was lowered to depths of 7.3 m (25 ft) and 4.6 m (15 ft) above the top of the Pittsburgh coalbed.

One additional consideration for changing the setting depth for the slotted casing may be the competency and productivity of the formations surrounding the slotted casing. For example, if the mechanical properties of immediate strata above the coalbed at one site are different from those at another site (for example caused by the presence of a sand channel), a different caving height and fracturing height may be expected as a result of longwall mining. Thus, the slotted casing setting depth may need to be adjusted accordingly. Similarly, if there are layers with appreciable gas emission potential (such as thin rider coalbeds) into the mine, this may also be a consideration to capture the optimum amount of gas by changing the setting depth of slotted casing.

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Appendix A. Supplementary data

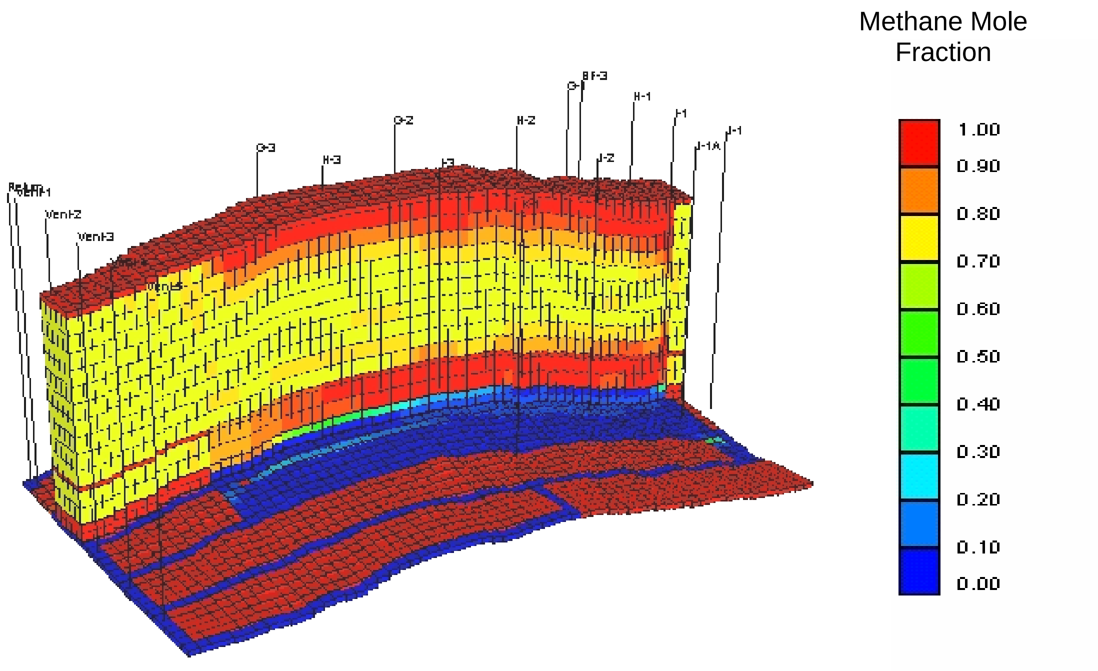

Figure 14. A vertical cross section of the subsided strata reservoir over the headgate side of H panel and the Pittsburgh coalbed layer 630 days after the start of mining on the adjacent G panel. The methane mole percent data show that the methane concentration is high in gas emission from Sewickley coalbed and this coalbed seems the primary source of longwall gob gas in this region.

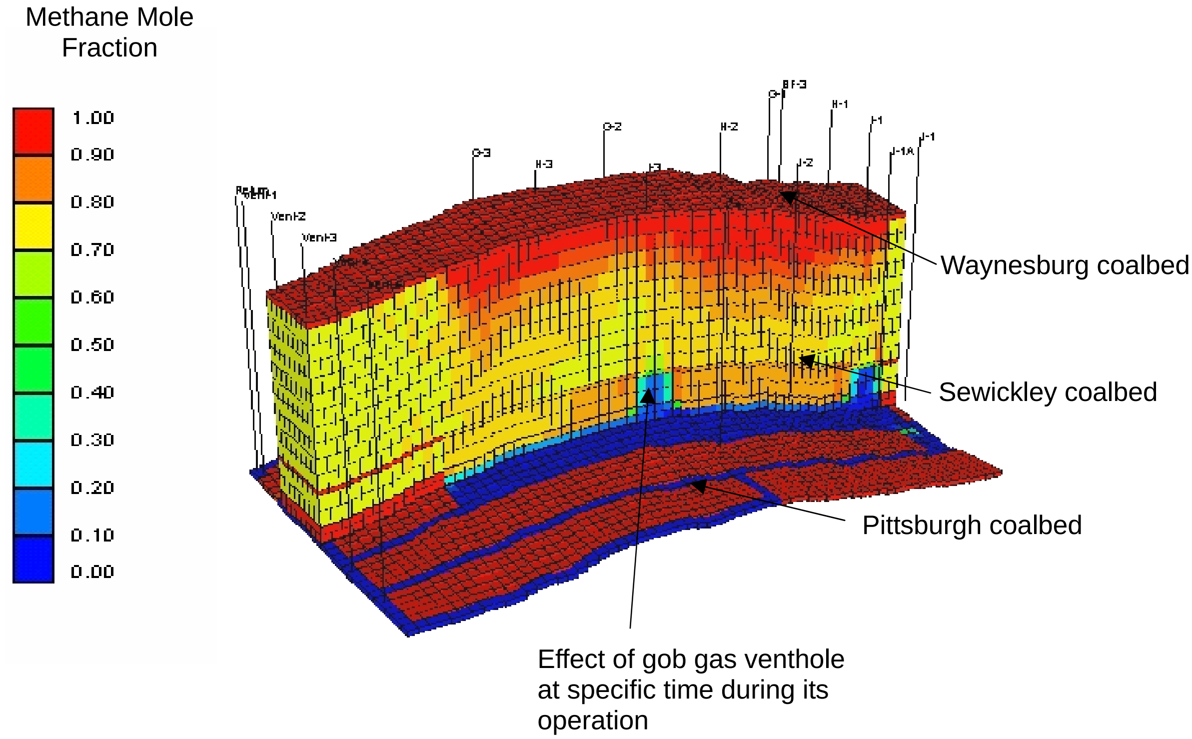

Figure 15. A vertical section of the subsided strata reservoir over the I panel tailgate after 630[th] day since the start of mining. This figure shows two I panel gob gas ventholes and their effect in reducing methane concentrations within their effective radius and the sheared zone below the Sewickley coalbed at that specific time. It is also shown that gas released from the Sewickley coalbed is the primary source of gas captured by the gob gas ventholes, since they are the closest pressure sink acting upon this gas source. This observation also suggests that the methane emissions from Sewickley coalbed may enter directly to the ventilation system if these wells do not operate continuously, and effectively.)

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