Numerical Analysis of the Impact of Longwall Panel Width on Methane Emissions and Performance of Gob Gas Ventholes

C.O. Karacan; W.P. Diamond; G.S. Esterhuizen and S.J. Schatzel

National Institute for Occupational Safety and Health (NIOSH),
Pittsburgh Research Laboratory

ABSTRACT

In coal mining, longwall mining is a preferred method to maximize production by extracting large blocks of coal that have been outlined with a set of development entries. In U.S. mines, longwall panels are typically 305 m (1,000ft) wide (with a continual trend towards even wider panels), and usually over 3,050 m (10,000ft) in length. The increasing size of longwall panels, while helping to increase coal production, may also increase methane emissions due to the exposure of the mining environment to a larger area of fractured, gas-bearing strata. Thus, understanding the impact of increased panel widths on methane emissions, and designing gob gas ventholes and bleeder systems accordingly, can enhance the safety of the underground workforce by reducing their exposure to potentially explosive accumulations of methane/air mixtures.

As part of its mine safety research program, NIOSH's Pittsburgh Research Laboratory has initiated a reservoir modeling effort to better understand the interaction of the various geotechnical factors influencing gas flow within and to the underground longwall mining environment. A focus of this modeling effort has been 1) the prediction of the incremental amount of methane emissions to be expected due to increasing longwall panel widths, and 2) optimizing gob gas venthole completion practices to capture more of the gas in the subsided strata above longwall panels before it can enter the ventilation system of the underground workplace. The history matching phase of the study has been carried out on a 381-m (1,250ft) wide panel in the Pittsburgh Coalbed. Simulations have also been completed for a 442 m (1,450ft) wide panel to estimate the incremental increase in methane emissions and the performance of current gob gas venthole placement configurations. Additional venthole placement configurations were simulated to investigate options for optimizing methane capture from the subsided strata above the wider longwall panel.

INTRODUCTION

Longwall mining is a high-volume coal extraction method where a rectangular "panel" in the coalbed has been outlined with a set of development entries. However, longwall mining creates large-scale disturbances around the longwall face and in the overlying strata. The immediate consequences of these disturbances are caving of the unsupported immediate roof strata into the void left by the progressive extraction of the coalbed. The height of caving is dependent on the mining height as well as the strength and stratigraphy of the roof strata, generally extending upwards 3 to 6 times the thickness of the mined coalbed [1-3]. Caving of the roof causes an area of relieved stress in the overlying strata where rocks are fractured vertically and horizontally along bedding planes. The thickness of the fractured zone can vary up to 100 times the height of the mined coalbed [2], depending on the rock layers, thickness of the overburden, and the size of the panel (Figure 1).

The occurrence of such an extensive area of stress relief and the resultant rock damage changes the gas transport characteristics, particularly permeability, in the overlying strata. Any gas that is contained in this area of relieved stress will be released (coalbed gas initially by desorption and diffusion flow mechanics), as the permeability of these zones is dramatically increased and new permeability pathways are created by the mining-induced fracturing. Relaxation of the roof and floor strata and the associated fracture connectivity allows gas to flow from all of the surrounding gas sources towards the lower-pressure sink of the underground workings. These gas sources include overlying (and in some cases underlying) coalbeds, carbonaceous shales, and to some extent other more traditional gas reservoirs such as sandstones [4]. In their study, Diamond et al. [4] found that as much as 91% of the longwall gob gas originated in the overlying coalbeds, with those as high as 61 m (200ft) above the mined coalbed contributing gas to the longwall gob. The magnitude of the gas flow depends on the degree of strata relaxation and on the type and strength of the rocks in the adjacent strata [5], as well as the volume of gas available in the affected strata. Gas-bearing strata can be directly exposed to the caved zone which is in contact with the mine ventilation system, or connected to it by fractures.

In mines where the released gas from subsided and relaxed strata places a burden on the mine ventilation system, gob gas ventholes are commonly drilled from the surface above the panel to capture the gas before it enters the underground working environment. As mining advances towards the venthole, the surrounding gas-bearing strata will fracture and establish preferential pathways for the released gas to flow towards the pressure sink of the venthole once it has been mined under (Figure 2). Gas production may vary over the life of the venthole, generally with high concentrations of methane (> 80%) at early stages, and becoming a mixture of methane and mine ventilation air later in mining, depending on the proximity of the venthole to the caved zone, the gas content of the overlying strata, and the interaction of the venthole with the ventilation system [6].

Methane control using gob gas ventholes in the longwall mining environment has become a standard practice in many U.S. longwall coal mines, and has proven to be useful in reducing the amount of methane that enters the working environment from relaxed and fractured strata. However, there are various factors to be considered in designing gob gas ventholes for specific mining conditions. For instance, the number of ventholes used and the well spacing on a particular longwall panel depends on the rate of mining and the gas content of the strata above and below the mined coalbed. The location of the ventholes on the panel is also important. Diamond et al. [7] showed that placing the gob gas ventholes on the margin of the panels instead of in the traditional centerline location could increase gas production substantially (almost 80% in the site-specific study).

In recognition of the importance of gob gas ventholes for methane control, Mills and Stevenson [8] reported that approximately 30 to 40 percent of the total gas liberated from several mines operating in the Mary Lee-Blue Creek coal interval, Alabama, was produced by gob gas ventholes. Dixon [9] stated that the mines could not operate at economic levels without gob gas drainage and also reported that the methane level in mine bleeder entries can be reduced as much as 80% using gob gas ventholes.

As a proven technology for today's longwall operations, gob gas ventholes offer an extra margin of safety. The competitive nature of the domestic and international coal industry is constantly pushing mining companies to increase the size of their longwall panels, especially the panel width. In addition to the larger volumes of gas released from the surrounding strata, increasing panel widths can result in increased methane emissions due to the greater coal surface area exposed on the longwall face, and the larger amounts of coal being transported on the pan line and conveyor belt systems.

Diamond and Garcia [10] conducted a study in mines operating in Pocahontas No. 3 Coalbed in Virginia to investigate the consequences of increasing panel width on face emissions in gassy coalbeds. Continuous longwall face emission monitoring studies were conducted at two adjacent mines where the face length was to be extended from 229 to 305 m (750 to 1,000ft). A regression analysis of the face emission data predicted that a 75-m (250-ft) longer face would produce 7%-13% more gas. In a more recent study to estimate the face emissions with increased longwall face lengths in the Pittsburgh Coalbed in Pennsylvania, Schatzel et al. [11] used both a graphical regression analysis and a more detailed linear optimization technique on the same set of measured face emission and ventilation data to differentiate methane increases and contributions from different sources. They concluded that methane emission rates would increase by 35% to 48% when comparing a longwall face length of 305 m (1,000ft) to 488 m (1,600ft).

The larger volume of surrounding gas-bearing strata being affected by mining-related disturbances due to increased longwall panel widths potentially results in higher gas emissions into the underground workplace, if the gas is not captured effectively by gob gas ventholes. Conventional venthole design strategies that are practiced with current panel widths may not be sufficient to remove the expected additional methane volumes from wider panels. Several approaches may be utilized to deal with the potential for these increased volumes of released methane. Rather then drilling additional gob gas ventholes based on trial and error, a theoretical reservoir modeling approach should be used to better understand the complexities of the interaction between the mine and the associated gas reservoirs. This approach would help to plan gob gas venthole strategies in advance of extending the panel width to more efficiently respond to changing gas emission conditions.

OBJECTIVES OF THE STUDY

Advanced numerical models can simulate the rock mass and associated reservoir and gas flow responses to longwall mining, thus allowing for the simulation of methane flow and emissions without costly trial and error field experiments. This paper presents the development and application of geomechanical and reservoir models to investigate the effect of increased longwall panel widths on rock response, permeability changes, methane emissions, and the design and performance of gob gas ventholes.

To meet the study objectives, a two-stage approach was taken. The first stage was the use of FLAC2D (Fast Lagrangian Analysis of Continua 2D, [12]) finite difference code to simulate the geomechanical response of rock layers to longwall mining in terms of stress, strain, and fracturing, and the use of this output to calculate permeability changes based on empirical relationships. The calculated permeability fields were then used to update the initial permeabilities in a dynamic reservoir model developed using Computer Modeling Group's GEM software [13] to simulate gas flows and emissions associated with longwall mining. Finally, the reservoir model was used to simulate the performance of various configurations of gob gas ventholes for a panel 61 m (200ft) wider than the 381-m (1,250-ft) base case for which actual gob gas venthole production data were measured over the life of the panel.

GEOLOGY AND MINE LAYOUT

The study mine operates in the Pittsburgh Coalbed in Greene County, Pennsylvania. Overburden depths range between 152 and 274 m (500 and 900ft). The study area is in a new longwall mining district for the mine, and is not surrounded by other mined-out panels. Longwall panels in this area are super-critical, i.e., the panel width is greater than the height of the overburden, which results in a more complete and immediate caving of the overburden strata into the mine void. The first two panels in this area are 381 m (1,250ft) wide and the widths are planned to be increased to 442 m (1,450ft) starting with the third panel in the district. The panel lengths are generally 3,350 to 3,960 m (11,000-13,000ft).

A generalized stratigraphic section of the strata above the Pittsburgh Coalbed in the study area was obtained from cores and is shown in Figure 3. The Sewickley Coalbed as well as rider coals directly above the Pittsburgh Coalbed are believed to be the primary source of strata gas in the area. Within this interval, the thickest coalbed is the Sewickley Coalbed. 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 any other gas-bearing horizons above the caved zone, will migrate to the operating gob gas ventholes placed in the fractured zone, as shown in Figure 2. The Waynesburg Coalbeds, approximately 95 m (310ft) above the Pittsburgh Coalbed, are generally characterized by low gas contents, and are not expected to contribute significant volumes of gas to the mining environment.

A sandstone paleochannel complex is present in parts of the study area. This sandstone channel is located immediately over the Pittsburgh Coalbed and replaces part, or in some areas all, of the overlying shale unit. The thicknesses of the sandstone and shale section vary considerably throughout the study area, but the combined thickness of this unit above the Pittsburgh Coalbed is about 12 m (40ft).

METHANE CONTROL PRACTICES

Longwall methane control at the study mine includes the bleeder ventilation system, horizontal methane drainage holes in the Pittsburgh Coalbed, and gob gas ventholes. The bleeder ventilation system includes the peripheral bleeder entries surrounding the panel and the associated bleeder fan shaft. The bleeder fan in the study area is at the top of a 1.8-m (6-ft) diameter air shaft.

Gob gas ventholes ideally are generally drilled to within 12 or 13 m (40 or 45ft) of the top of the Pittsburgh Coalbed (into the fractured zone, but not into the caved zone, Figure 2), and are completed with 17.8-cm (7-in) casing and 61 m (200ft) of slotted pipe on the bottom, as shown in Figure 4. Usually, a vacuum is also applied to these ventholes by installing pumps (commonly referred to as exhausters or blowers) on the surface well head. The purpose of this completion strategy is to create a pressure sink across several potential gas-bearing horizons and to capture the released gas before it can enter the underground workplace. For these gob gas ventholes to work effectively, they must be drilled close enough to the mine to capture methane from the fractured zone but far enough above the caved zone to minimize the amount of ventilation air that is drawn into the ventholes.

The gob gas ventholes in the study area are instrumented by NIOSH in cooperation with the coal company to continuously measure gas production rates and methane concentrations after the wells become operational, and monitoring continues as mining progresses over time. These gas flow data are an integral part of the database necessary to conduct the reservoir modeling studies presented in this paper.

DESCRIPTION OF GEOMECHANICAL MODEL FOR ANALYSIS OF STRATA RESPONSE AND PERMEABILITY CHANGES DURING LONGWALL MINING

Geomechanical models were used to evaluate the effects of longwall mining on the surrounding rock mass and to calculate mining-related permeability changes. The FLAC model simulated mining in increments, starting from the left side of the grid and advancing to the right (Figure 5). The rock mass was modeled with considerable detail, capturing the layered nature of the coal measure rocks. Each layer was provided with appropriate strength and elastic properties based on laboratory and field test results [14]. The model runs captured 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 was run to equilibrium at each step so that rock failure and stress redistribution would occur. The model runs included a sufficient lateral extent of mining so that full subsidence of the overburden strata would occur over the simulated mined area.

Calculation of permeability changes was carried out using the final stress and rock failure distributions. Initial permeabilities in the rock mass were based on field scale data from mines in the Eastern United States, as well as other published sources [15-17]. Table 1 summarizes the initial horizontal and vertical permeabilities used in the FLAC models.

The effect of both stress changes and rock fracturing on permeability was determined from the FLAC model runs. An exponential relationship was used to compute the effect of stress changes on rock mass permeability after the work of Ren and Edwards [18] and Lowndes et al. [19]. Permeabilities were calculated independently for the horizontal and vertical directions as follows:

$$k_h = k_{h0} e^{-0.25(\sigma_{yy} - \sigma_{yy0})} \tag{1}$$

$$k_v = k_{v0} e^{-0.25(\sigma_{xx} - \sigma_{xx0})} \tag{2}$$

The parameters for these equations are given in the nomenclature section.

In the model, the parameters were set so that a stress change of 10 MPa would result in a change in permeability of about one order of magnitude. In addition, fractured rock was assumed to experience an increase in permeability of 100 md above the current permeability in both the horizontal and vertical directions, regardless of rock type. Similarly, bedding shear failure was assumed to increase the permeability by 50 md in the bedding (horizontal) direction.

Figure 5 shows an example of the permeability distribution around an advancing longwall face calculated by the FLAC models. The figure shows a low permeability zone ahead of the face where stresses are high as well as a higher permeability zone behind the face where stress relief has taken place. The fractured zone, location of bedding shearing, and the typical location of a gob gas venthole within the fractured zone is also shown as indicated on the figure. The details of the permeability calculation and geomechanical analysis are given in Esterhuizen and Karacan [20].

DESCRIPTION OF RESERVOIR MODEL FOR ANALYSIS OF METHANE EMISSIONS DURING LONGWALL MINING AND GOB WELL PERFORMANCE

Grid Model of the Area

For this study, a three-dimensional grid model of the mine area was created from mine maps using Cartesian grids. The dimension of the grid model was based on actual panel dimensions and was constructed in such a way that the width of the grid model will be about 5 times the current panel width of 381 m (1,250ft) as shown in Figure 6. The total width of the development mining on either side of the panel, including the gate roads and the pillars, was determined from the mine maps to be about 61 m (200ft). Panel 1 was located in the middle of the grid system, which was fine grided to enable increasing panel widths for the modeling exercise.

The number of vertical layers and their thicknesses were based on the generalized stratigraphic log of the area shown in Figure 3. In the grid model, the bottom-most layer was dedicated to the Pittsburgh Coalbed, or mining layer. The other lithologies shown in the log were represented in the grid model based on their thicknesses. Although this log presents only major layers in the mine area, it was convenient for determining the number of vertical layers and their thicknesses for generating the modeling grids in the vertical direction.

For convenience in generating the grids, the layers shown in Figure 3 were 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. In generating the model elevations, the formation top map with respect to sea level for the mining layer (Pittsburgh Coalbed) was digitized as the reference elevation, and the depths of other layers were determined based on their thicknesses as determined from stratigraphic logs.

In the grid model, the Pittsburgh Coalbed layer was constructed differently from the other layers in the area 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 gateroads that surround the panel. To simplify the ventilation pathways, the mine entries were represented by a single grid rather than a detailed gridding for each gateroad on the tailgate and headgate sides of the panel (Figure 6).

Figure 7 shows the 3-D grid reservoir model that was constructed for this study. In this figure, only the primary layers representing the Waynesburg, Sewickley, and Pittsburgh Coalbeds and the sandstone paleochannel complex were retained, while the other intervening rock layers have been removed for visualization purposes. The figure also shows the actual gob gas ventholes from the first longwall panel in the district and the wellbores that are used to represent the basic elements of the ventilation system in the model.

Gob Gas Ventholes and Pseudo-Ventilation System

Four gob gas ventholes with 17.8-cm (7-inch) casing and 61 m (200ft) of slotted pipe at the bottom were drilled on the first panel in this new mining district. However, the ventholes were drilled to varying proximities [14, 11, 9 , and 12 m (47, 35, 30, and 40ft)] above the top of the Pittsburgh Coalbed as opposed to the preferred ~12 m (~40ft) distance, which places the bottom of the venthole above or close to the top of the caved zone. The ventholes are located about 100 m (300ft) from the tailgate side of the panel, and are 166, 830, 1,635, and 2,458 m (544, 2,720, 5,362, and 8,060ft), from the start-up end of the panel. The ventholes are modeled based on these actual completion parameters.

A simplified version of the ventilation system was also incorporated into the model to simulate ventilation airflows during longwall mining. Since the reservoir model does not have the inherent capability to simulate the geometries of a mine ventilation system, wells are used to simulate the injection (intake) and removal (return) of ventilation airflows, including the bleeder fan shaft (Figure 7). A single well injecting air into the entries with a rate constraint of 1,700 m^3/min (60,000 cfm) to simulate the typical ventilation airflow rates at the mine site was used to model the air intake part of the ventilation system. The bleeder fan was modeled with 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 constraint of 1.36 KPa (0.2 psia) suction pressure. Another vertical well was employed to model the return air side of the ventilation system. The vertical wells representing the ventilation intake and return were also used to control the ventilation pressures at the mining layer at the assigned bottom hole pressure constraint.

Reservoir Description and Reservoir Parameters

In the mining industry, it is not common practice to perform extensive data gathering for gas reservoir analysis. Thus, most of the data required by the reservoir simulator for this unique mining application was gathered from previous NIOSH publications that addressed general reservoir and gob gas venthole performance issues in this same general study area, from external reports, and from personal communications with the operating mining company to obtain reasonable assumptions for setting the initial, pre-mining reservoir properties to the coal and non-coal units.

In the current study, coal/sand sequences and coalbeds interspersed with conventional gas reservoirs and non-productive shales were handled by turning off the coalbed related special features by model layer and forcing the simulator to behave as a conventional dual-porosity model in those layers. In the aerial sense, lithology and flow-related parameter changes (especially in the mining layer and in the caved and subsided zones as the face was advancing) were modeled by assigning different rock regions in which the reservoir parameters, including the fracture properties, were varied.

Table 2 gives representative reservoir parameters used in the model for coal and non-coal lithologies that were calculated, obtained from the literature, and/or estimated from history matching techniques. These values, particularly permeabilities, represent the values prior to mining and thus prior to any disturbance on the strata. In order to make geomechanical calculations to determine the response of the overlying strata to mining-induced stresses and to calculate the permeability changes, the previously described FLAC software was used. The changes in competent rock properties in the strata overlying the panel during and after mining disturbance were coupled with the reservoir model during simulation of the longwall face advance.

The most important coal-related reservoir parameters are the nature of the cleats, their spacing, gas content, and adsorption data. Law [21] reported cleat spacing of 0.5 to 9.7 cm (0.016 to 0.32ft) in the Northern Appalachian Basin. In this study, cleat spacing was estimated at 3.0 cm (0.1ft), which was a value based on the reported mean cleat spacing values of 2.4 cm (0.08ft) and 3.2 cm (0.11ft) from outcrops of the Pittsburgh and Sewickley Coalbeds, respectively [21]. The gas content and adsorption related 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 [22] on various coal samples. 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 as estimated by history matching techniques. These values were taken to be uniform throughout the layers.

The permeability of the caved zone in the longwall gob (Figures 1 and 2) is not easily predictable since it mostly depends on the type of rock units, the extent of their fragmentation and packing in the void space, and caving height. Therefore, it is natural to assume that this permeability value may vary widely for different locations and for different roof rocks when they cave. Brunner [23] investigated the problem of the migration of ventilation air through longwall gobs using a mine ventilation model and a laminar resistance grid constructed over the caved zone. He assigned a resistance value to each resistance element in the grid based on idealized gob conditions. The gob permeability values he used and tested in his model ranged between 10^{-5} and 10^{-7} m^2 (10^{10} and 10^8 md). Based on a fractured porous medium vs. permeability classification, these values fall into the heavily fractured rock category. In this study, the permeability of the caved zone was estimated using history matching techniques. The detailed approach and analysis of this parameter for the study resulted in a permeability of about 10^{-8} m^2 (10^7 md) in the horizontal direction and 10^{-9} m^2 (10^6 md) in the vertical direction, due to compaction of the gob. These values fall into the open-jointed to heavily fractured rock classification in the horizontal direction and into jointed rock classification in the vertical direction.

In the model constructed for this study, the open entries surrounding the longwall panel serve 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 these areas were calculated from the mine maps as 40% and 30 m (100ft) respectively.

Simulation Strategy for Longwall Mining

During longwall mining, the strata disturbances described previously move along with the face, and gas production from the ventholes starts at the time each successive venthole location is intercepted by the mining-induced disturbances. This leads to a moving-boundary problem for modeling this type of process. In this study, the problem was addressed with “restart” models, each of which represents a time interval for the mining advance and related strata disturbance. Each model restart run was performed so that it would progress up to either the next venthole location or to a defined location on the panel for the distance and time characterizing the intervening face movement. In this process, the simulation outputs from the previous model run were written in a “restart” file, then used by the next model run, which updated the longwall face and reservoir changes for the next face position.

RESULTS AND DISCUSSION

Model Calibration and History Matching of Actual Production Data

History matching is a well-accepted method in reservoir engineering for calibrating models and estimating unknown parameters. There is always a valid concern as to the degree of correctness of calibrations and the range for unknown parameters determined as a result of history matching. However, it has been shown and widely accepted that with careful analysis of reservoir conditions and a good sense of the reasonable value ranges for the unknowns and their expected behaviors, history matching is a valid and valuable technique. This is especially true in a situation where every parameter cannot be determined by practical means and many unknowns are present, therefore, history matching is probably the only choice.

In this study, performing a dynamic simulation approach by restart models to simulate the advance of a longwall face (described previously) was an integral part of the calibration and history matching phase of the simulation, as well as for modeling venthole performance scenarios for different panel widths. The major matching parameters that were changed at each restart were disturbed/undisturbed permeability values for the different horizons, desorption time constants for coal, relative permeabilities, and permeability of the caved zone. During calibration and prediction runs, the fractured rock permeabilities predicted by FLAC computations, fracture spacing changes, coal desorption time changes, relative permeabilities for subsided and fractured rock, and transmissibilities in the vertical direction were incorporated into the zones above the mined out section of the panel as the face was advanced to various locations between restarts. Since modifying porosity between restarts for different regions causes material balance instabilities, this effect was addressed with fracture spacings. During dynamic runs, all known and fixed values and the initial estimates of the unknowns were used, and field measurements of gob gas venthole production values were compared with model predictions. Based on this comparison for the entire 268-day simulation, adjustments were made to the unknown parameters, and additional calibration runs were completed until an acceptable agreement was obtained.

Longwall gob gas ventholes are normally not water producers, except for occasional condensation of water vapor at the well head. Most of the strata water, especially within the caved zone, flows to the mine void unless this zone has been desaturated or drained previously by other means. Although there might be regional differences, Hunt and Steele [24] report that the Central and Northern Appalachian Basin is depressurized and desaturated due to its geological history, extensive coal mining, and the drilling of numerous oil and gas wells through the coalbeds to deeper horizons. No water production data were available for this panel; however, no major water influx into the caved zone was reported by the operating mining company. Therefore, although the model has been set up as a two-phase model for flow, water flow was turned off by setting the connate water saturation to initial water saturation values in the relative permeability curves assigned to each layer.

The study panel has four gob gas ventholes that were continuously monitored by NIOSH for gas production rates and volumes (corrected to STP conditions), and methane concentration in the produced gas stream. The measurement of flowing bottom-hole pressures is not commonly done in these types of wells due to the difficulty in instrumenting the ventholes for this purpose. These ventholes are produced using exhausters that create a negative pressure against the mine ventilation pressure to help extract the gob gas. The pressure sink created by the producing gob gas ventholes also helps to induce gas flow towards the ventholes, which helps to reduce the volume of methane that can enter the underground workplace.

Some of the produced methane is used to fuel the engines that operate the exhausters. While using produced methane to fuel the engines is an operational advantage for remote locations, operationally (and for modeling purposes) this sometimes presents a problem. If the methane concentration in the produced gas stream falls below the minimum requirement to run the engines, or when mechanical or other operational problems result in the wells going off-line or running at less than optimum conditions, changes occur in the flowing bottom-hole pressures of the ventholes. In fact, pressure measurements taken at the well head below the flame arrestors indicate that well pressures are not constant, but fluctuate depending on various factors. Thus, in the absence of reliable flowing bottom-hole pressure data, the alternative approach that was taken for this modeling study was to use gas flow rates as the constraints in the model at the expense of computational time and convenience, and to match the flow rates as well as concentration and pressure values to field data and expectations.

Figures 8 and 9 show the actual and simulated gas production rates and methane concentrations for the four gob gas ventholes monitored on the first longwall panel in the study area. The production rate and methane concentration data match quite well for most of the field measurements for the entire 268-day period when mining was active on this panel. The shifts on the time scale for each well to become productive are caused by, and depend on, when the well location was intercepted by the longwall face.

The calculated bottom-hole pressures for the four gob gas ventholes are given in Figure 10. This figure shows that when the venthole location is intercepted by the longwall face on the panel, the pressure sharply drops to atmospheric pressures or below due to their completion depths being in close proximity to the mine ventilation pressures (less than atmospheric pressure since exhausting ventilation system is used) by way of the mining induced fractures. This was the criterion for accepting the calculated bottom-hole pressures and was basically maintained by the mining-induced fracture permeabilities assigned to each layer. Even during the periods when the ventholes are shut-in, they stay close to or under atmospheric pressure conditions as expected. The bottom-hole pressures calculated during this step were used later as the operating constraints for the different gob gas venthole placement scenarios, presented in the following discussion.

Analysis of the Effect of Longwall Panel Width on Methane Emissions and Gob Gas Venthole Performance

The mine operating in the study area currently has a single completed longwall panel in the new mining district with a width of 381 m (1,250ft) and a length of approximately 3,350 m (11,000ft). The mine plan includes one additional longwall panel of the current dimension, then increasing the panel width by 61 m (200ft) to 442 m (1,450ft). Since the purpose of this study is to investigate the effect of increased panel widths on gas emissions, the primary question to be answered from a mine safety and methane control perspective is whether the current number and configurations of ventholes will adequately control the projected increase in gob gas on the larger longwall panels. To answer this question, the venthole production from the first panel in the district has been analyzed with the assumptions and limitations stated previously, and then compared to the simulated venthole production and the methane emissions for the increased panel width.

Different numerical model runs for well placement and operating scenarios were performed for the increased panel width to investigate the performance of different options to optimize the extraction of gob gas by the ventholes and to thus minimize the migration of gob gas to the ventilation system. In these scenarios, the four actual ventholes from the first panel were placed and produced based on their measured production histories as discussed in the previous sections, then operated according to the bottom-hole pressure history constraint calculated in the calibration/history matching phase of this study. Additional optimally completed and produced ventholes - i.e., ventholes completed in the fractured zone ~12 m (~40ft) above the top of the Pittsburgh Coalbed layer with 61-m (200-ft) of slotted casing and operated with -0.2 atm (-2.7 psi) suction pressure at all times after they become productive were then added as infill ventholes. Unless specified differently, these additional ventholes also used 17.8-cm (7-in) diameter casing. In two of the case scenarios, only optimal ventholes were used with different configurations in order to produce the same amount of methane as in the actual and optimal well combinations to minimize the number of ventholes. Scenarios were also simulated where the well casing diameter was increased to 20.3 cm (8 in) for the 442-m (1,450-ft) wide panel, and alternatively decreased to 12.7 (5 in). The various venthole placement scenarios and completions (cases) are presented schematically in Figure 11.

Analysis of Expanding Panel Width from 381 m (1,250ft) to 442 m (1,450ft) with only Four Actual Ventholes in Operation

For this analysis, the results of simulation runs for the 381-m (1,250-ft) wide panel using the four actual gob gas ventholes were compared with the results when the panel width was increased to 442 m (1,450ft) using the same venthole placement, completions, and production history. In order to expand the panel size, the grids representing entries and the panel on the headgate side were moved 61 m (200ft) outward within the fine-grid section in the model, and the reservoir properties in this and overlying layers were assigned according to the new geometry. The locations of the ventholes that were 91 m (300ft) from the tailgate side of the panel, the completion data, and their operating constraints were kept constant between two cases.

Figure 12 presents the simulated methane concentrations and methane production rates for the two panel sizes using the same venthole performance criteria. As can be seen from these figures, the gob gas venthole performance predicted for changing panel sizes are very similar with the same set of operating ventholes in place. This behavior is to be expected once the wellbore flow model (Eq. 3) is analyzed, and its parameters are used by the reservoir simulators. The wellbore model equation is basically a summation of flow, as defined by the product of productivity index (Eq. 4) by total mobility (Eq.

5) and difference between grid block and the well bottom hole pressures from individual layers for a multilayer completion.

$$Q_J = \sum_l PI_l \lambda_{T,l} (P_g - P_{wbh}) \tag{3}$$

$$PI = 2 f_{comp} kh \frac{w_{frac}}{\ln\left(\frac{r_e}{r_w}\right) + S} \tag{4}$$

$$\lambda_T = \sum_j \frac{k_{r\,j}}{\mu_j} \tag{5}$$

The parameters used in these equations are listed in the nomenclature section at the end of this paper.

It should be noted that there is no term directly related to panel size in Eqs. 3-5. The most likely parameter that may be influenced as a consequence of subsidence variations for the increased panel width is the permeability associated with the productivity index term (Eq. 4). However, for supercritical panels (as are both of these base cases), subsidence should be complete and thus stress conditions should be similar irrespective of the panel width. In fact, the FLAC computations confirmed this behavior. This behavior also suggests that differences in the wellbore conditions should not be expected between the two cases. Geomechanical calculations showed that there is not a major change in vertical and horizontal permeabilities in the subsided regions as a result of changing the panel width, as shown in Figure 13. This figure shows the permeabilities for 366-m (1,200-ft) and 488-m (1,600-ft) panel widths; we can expect similar permeability changes for the 381-m (1,250-ft) and 442-m (1,450-ft) cases.

The gob gas venthole performance in terms of methane production for the two base cases was also similar as shown in Figure 12. The cumulative methane production at the end of simulations of 268 days of mining is only about 0.95 MMSCF (~1%) less for the wider panel base case. This may be due to the increased distance methane released on the headgate side of the panel must travel to the ventholes that are located on the tailgate side of the panel. In the event that all of the gas released from the surrounding strata on the headgate side of the panel does not efficiently migrate to the ventholes on the tailgate side, additional methane must be handled by the mine ventilation system.

Although the performance of gob gas ventholes is not influenced significantly with an increased panel width of 61 m (200ft), the simulation results indicate that an additional 137 MMSCF (355 cfm) of methane will be released from the overlying strata as a result of mining on the larger panel over the 268 days of simulation. The additional methane liberated from the overlying strata must be handled by the mine ventilation system when only the four actual venthole are operated on the 442-m (1,450-ft) wide panel.

<u>Alternative Gob Gas Venthole Placement Scenarios and Performance Analysis for a 442 m (1,450ft) Wide Panel</u>

The following discussions present alternative gob gas venthole placement and completion scenarios to investigate potential options to maximize methane capture to minimize the methane loading of the ventilation system on the 442-m (1,450-ft) wide panel in the Pittsburgh Coalbed. It should be noted that these simulations are based on site-specific reservoir simulations and are not intended to be a general prediction of gob gas venthole performance for other coalbeds.

The alternative gob gas venthole placement and completion scenarios (cases), as shown schematically in Figure 11, are: (A) moving the existing four actual ventholes to locations 152 m (500ft) from tailgate side, i.e., 61 m (200ft) closer to the centerline of the panel than on the first panel; (B) adding four optimal infill ventholes located between each actual well; (C) adding four optimal ventholes located

90 m (300ft) from the gateroads on the headgate side of the panel, positioned diagonally to the actual ventholes; and (D) adding four optimal ventholes located 90 m (300ft) from the gateroads on the headgate side and positioned directly opposite the actual wells on the tailgate.

In addition to the venthole placement scenarios (Cases A-D), the cased diameters of the ventholes were changed for two different cases as shown on Figure 11. For Case E, the diameters of four actual ventholes were increased to 20.3 cm (8 in) without any optimal ventholes in the model, and for Case F, the diameters of the ventholes in Case B were decreased to 12.7 cm (5 in). The results of each of these scenarios were compared to the actual production obtained from the four ventholes on the 381-m (1,250-ft) panel. To determine the minimum number of optimal ventholes that will produce the same maximum amount of methane as in the highest-producer configuration of actual and optimal ventholes, two final scenarios where simulated. In Case G, six optimal ventholes were used along the tailgate side of the panel, and in Case H, two of the optimal ventholes were placed on the headgate side opposite the first two ventholes on the tailgate side Figure 11.

In order to compare the production performance of optimal ventholes that are included in the scenarios with the performance history of the four actual ventholes on the first panel, and also to emphasize the importance of completing and operating the wells properly, simulation runs were conducted to replace the four simulated actual ventholes with four optimal ventholes on the 442-m (1,450-ft) wide panel. As shown on Figure 14, optimal ventholes produce gas that is 85-90% methane through the entire mining period, whereas the methane concentration of the gas produced by the actual wells in the study area decline significantly with time, with the methane concentration being in the 65-70% range for most of the mining period. The difference in methane concentrations between the two scenarios is due to the fact that some of the actual ventholes were drilled into or very close to the caved zone, and thus their produced methane was diluted with mine ventilation air.

The total cumulative methane production is about 98.6 MMSCF for the four actual ventholes over the 268 days simulated for the 442-m (1,450-ft) wide panel, whereas the four optimal ventholes produce about 141 MMSCF of methane, or about 50% more than the actual wells produced on the first panel in the study area. This basic analysis points out the importance of implementing proper completion practices and paying close attention to gob gas ventholes' operation, i.e., keeping them running, to optimize their methane control capability.

Figures 15 and 16 show methane concentrations and cumulative methane produced, respectively, from gob gas ventholes located with the different configurations (A-F) shown on Figure 11. Methane concentration data presented in Figure 15 show that the highest and lowest methane concentrations result when the diameters of the wells are reduced (Case F) and increased (Case E), respectively. The decrease in methane concentration in the produced gas from the four simulated larger diameter ventholes (Case E) may be due to the increased capture of mine air from the four actual ventholes, several of which were drilled into the caved zone.

The next configurations to produce gas of lower methane concentration are those only using the four actual ventholes [the 381-m (1,250-ft) base case and Case A with the four actual 17.8-cm (7-in) ventholes placed at 152 m (500ft) from the panel margin instead of at 90 m (300ft)]. Again, the reason for the lower methane concentration in the produced gas is attributed to the increased capture of mine air from the simulated actual ventholes, several of which were drilled into the caved zone. Gob gas venthole configurations, B, C, and D, on the other hand, produce similarly high methane concentrations. This is due to the infill optimal ventholes and their associated completion and performance parameters, as discussed previously.

Figure 16 and the accompanying data summarized in Table 3 compare the cumulative methane production volumes from each of the gob gas venthole configuration scenarios (Cases A-F) shown in Figure 11. The lowest cumulative methane production (Case A) is obtained when the four ventholes with the actual completions are located 152 m (500ft) from the tailgate entry of the 442-m (1,450-ft) panel. This configuration produces 13.2 MMSCF less methane compared to the base case production from the

381-m (1,250-ft panel), thus illustrating the importance of near-margin well placements where enhanced fracture permeabilities exists for a longer time [7].

The highest cumulative methane productions are achieved when additional optimal infill ventholes are used. Simulation results show that Case D, with the four actual ventholes on the tailgate side of the panel and 4 additional optimal ventholes located on the headgate side of the panel (directly opposite the tailgate ventholes), produces 138 MMSCF more methane compared to the four actual ventholes on the 381-m (1,250-ft) panel. Case C, with four actual ventholes on the tailgate side of the panel and 4 additional optimal ventholes located on the headgate side of the panel (but diagonal to the tailgate ventholes) is the next highest incremental producer of methane at 119 MMSCF. While Cases C and D are similar, Case D is probably the higher producer because the tailgate and headgate ventholes are intercepted at the same time, resulting in a quicker overlap of their drainage radius which enhances gas desorption from the overlying coalbeds. Also, when headgate and tailgate ventholes are intercepted at the same time, the headgate ventholes start producing earlier and stay on production longer compared to Case C. The third highest incremental methane producer is Case B (four actual and four optimal infill ventholes on the tailgate side of the panel) with 113 MMSCF more methane than the four actual ventholes on the 381-m (1,250-ft) panel.

This analysis shows that drilling additional gob gas ventholes increases gas production considerably, provided that they are drilled and operated properly. Also, placing optimal wells on the headgate side of the panel may improve production by a marginal amount by capturing additional gas that is released from the overlying strata on that side of the panel. This may become an important methane control issue as panel widths continue to increase, because at some critical panel width it is possible that gob gas originating in the headgate area may not be able to efficiently migrate to the pressure sink of the wells placed on the tailgate side of the panel. Under these conditions, the additional gob gas may require additional gob gas ventholes to be placed in this area.

The cases where the diameters of four actual gob gas ventholes were increased by one inch (Case E) and the diameters of all gob gas ventholes, including the infill ventholes, were decreased by two inches (Case F) produce 31 and 38 MMSCF more methane, respectively, compared to the 381-m (1,250-ft) base case. However, this incremental amount is much less compared to the cumulative methane captured by 7-in ventholes (Cases B, C, and D).

One of the main considerations in gob gas venthole design and operation should be to locate and drill the ventholes optimally and operate them continuously. This will minimize the number of ventholes that need to be drilled to produce the same amount of methane that can be achieved with a larger number of less than optimally drilled and operated ventholes. In scenarios G and H (Figure 11), the performance of two configurations using six optimal gob gas ventholes were simulated and compared with the performance of Case D, the highest methane producer (138 MMSCF).

Figure 17 and the accompanying data summarized in Table 3 compare the cumulative methane production from gob gas venthole configuration Cases G and H with that of Case D. The data shows that Case G, where six optimal ventholes were located along the tailgate side of the panel, produced about 86 MMSCF more methane than the 381-m (1,250-ft) base case, whereas Case H with two of the optimal wells on the headgate side produced 134 MMSCF more methane. Thus, the six optimal ventholes of Case H produced almost as much methane as the eight (four actual and four optimal) ventholes of Case D. The performance difference between Case G and H are due to the location of the ventholes and to the length of time they stay on production.

<u>Analysis of the Amount of Methane Released on the Longwall Face as a result of Expanding Panel Width from 381 m (1,250ft) to 442 m (1,450ft)</u>

The approximate amount of methane present in the coal at reservoir conditions which may report to the ventilation system as face emissions can be calculated using adsorption isotherm analysis performed on Pittsburgh coal samples. The Langmuir volume and pressure for Pittsburgh coal samples were 490 scf/ton and 350 psi, respectively, on a moisture equilibrated basis. Thus, the amount of methane that can theoretically be released when the in situ reservoir pressure (~ 90 psi) is reduced to atmospheric pressure is about 80 scf/ton. For the 581,500 tons of incremental coal that will be mined when the panel size is increased by 61 m (200ft), the cumulative methane volume will be about 47 MMSCF. This suggests that any additional amount of methane greater than 47 MMSCF in the simulations will come either from the immediate roof or from overlying strata, and may migrate to the ventilation system if not captured by the gob gas ventholes.

It should be noted that the actual mined panel at the study site was partially degasified with horizontal methane drainage boreholes. This volume of produced methane should be subtracted from the 47 MMSCF of predicted total methane given above for the additional 61 m (200ft) of mined panel width. However, no methane production data is available for those horizontal boreholes; therefore, this unknown volume of actual produced methane has not been subtracted from the predicted increase in longwall face emissions.

Impact of Gob Gas Venthole Configurations on Controlling Ventilation System Methane on a Wider Face

From a mine safety perspective, it is also important to evaluate the impact of gob gas venthole configurations on controlling the migration of methane to the ventilation system on wider longwall panels. As discussed previously, modeling an increase in panel width from 381 m (1,250ft) to 442 m (1,450ft) results in about 47 MMSCF of additional methane liberation from the coal mined on the longwall face and 137 MMSCF from the overlying disturbed strata, i.e., gob gas, for a total of 184 MMSCF of additional methane. The 47 MMSCF of additional methane liberation on the face will report to the ventilation system unless additional methane drainage provisions such as horizontal boreholes are used. Alternatively, ventilation airflow can potentially be increased to dilute the additional gas. The additional 137 MMSCF of methane released from the overlying strata may report to the ventilation system if no extra methane control measures (such as additional gob wells or different configurations) are implemented. This volume of cumulative methane represents the potential of an average of about 355 cfm of additional methane entering the ventilation system over the 268 days of the simulated mining for this study. The following discussion will address the additional 137 MMSCF of gob gas that may enter the ventilation system and the effectiveness of the various configurations of simulated ventholes to remove the additional gob gas resulting from the mining of the 442-m (1,450-ft) wide panel.

Table 4 presents the amount of uncaptured methane that will be available for flow to the ventilation system on a 442-m (1,450-ft) wide panel with the various gob gas venthole configurations that have been simulated relative to the gob gas volume for a 381-m (1,250ft) panel. The greatest amount of uncaptured methane for potential flow from the overlying disturbed strata to the ventilation system (148 MMSCF or 380 cfm) is Case A, where the gob gas ventholes are placed an additional 61 m (200ft) away from tailgate side towards the center of the panel. The minimum amounts of uncaptured methane reporting to the ventilation system on the wider panel occurs with Case B (25 MMSCF or 65 cfm), Case C (17 MMSCF or 44 cfm), and Case D (-1 MMSCF) when optimal ventholes are used. In particular, Case D (where the additional optimal ventholes are operated on the headgate side of the panel directly opposite the existing actual ventholes) is very effective in reducing the potential volume of methane reporting to the ventilation system. The minimal uncaptured methane flow into the ventilation system for Case D is comparable to the 3 MMSCF uncaptured methane for Case H where six optimal ventholes are used (Figure 11) instead of eigth ventholes (four actual and four optimal).

SUMMARY AND CONCLUSIONS

Increasing the size of longwall panels may also increase methane emissions due to the exposure of the mining environment to a larger area of fractured, gas-bearing strata. Thus, understanding the impact of increased panel width on methane emissions, and designing gob gas ventholes and bleeder systems accordingly, can enhance the safety of the underground workforce.

In this study, a 3-D dynamic reservoir model was developed to simulate longwall operations for a mine operating in Pittsburgh Coalbed. Permeability data for the mining-induced disturbed rock mass were computed by a geomechanical model as input to the reservoir model. The reservoir model was calibrated by matching historic gas production rates and methane concentration data from four actual gob gas ventholes while keeping the well pressures at expected levels for the 381-m (1,250-ft) wide panel in the study area to determine unknown parameters and constraints. This base case was then used as a comparison for the simulation predictions performed for the 442-m (1,450-ft) wide panel. Reservoir simulations for various gob gas venthole configurations were used to investigate the effect of mining a panel of 61 m (200ft) of additional face length on venthole performance. The effectiveness of these gob gas venthole configurations to drain gas from subsided strata on the wider panel, thus minimizing methane emissions to the ventilation system, was also addressed in the simulations.

The general conclusions from the simulations conducted for this study can be summarized as follows:

1. Increasing the longwall panel width by 61 m (200ft) resulted in an additional 184 MMSCF of cumulative methane emissions (47 MMSCF from the longwall face, and 137 MMSCF from the overlying disturbed strata) to the ventilation system if not captured by an optimized methane control system.

2. Production from individual gob gas ventholes does not change appreciably when the longwall panel width is increased, provided that permeability and saturation fields are not affected. Therefore, given the increased volume of gas available for flow to the ventilation system on the wider panel, an optimized methane control system is probably required to keep methane concentrations in the ventilation system within safe, statutory limits.

3. The performance of optimally completed and operated gob gas ventholes are far superior to the actual wells that were drilled and operated on the first panel at the study mine site. Optimal gob wells produce about 50% more methane for the same period of time with very high methane concentrations (85%-90%). This shows the importance of operating the gob gas ventholes continuously and monitoring them constantly to minimize the amout of time they are off-line.

4. Moving the gob gas ventholes 61 m (200ft) away from their actual location on the tailgate side of the panel towards the centerline resulted in a 12 MMSCF decrease in their simulated gas drainage capability.

5. Simulating an increase in the diameters of the four actual wells by one inch on a wider panel increases their methane production by about 38 MMSCF compared to the same wells with 7-in diameter casings on the 381-m (1,250-ft) panel. However, this is not enough of an increase in gas drainage to eliminate the increase in methane emissions resulting from mining the larger panel. The same is true in the case of employing four optimal infill ventholes along with the four actual ventholes, while decreasing their diameters to 5 inches in an attempt to reduce drilling costs.

6. The optimum configuration simulated to increase gob gas venthole methane recovery on the wider panel was six optimally completed and produced ventholes (four on the tailgate and two on the headgate) and four actual ventholes on the tailgate and four additional optimal ventholes located on the headgate side of the panel. Placing eight ventholes on the tailgate side of the panel (four actual and four optimal infill ventholes) was a slightly less productive configuration.

7. Increasing the face length from 381 to 442 m (1,250 to 1,450ft) on longwall panels in the Pittsburgh Coalbed will require that additional methane control measures be implemented, including increasing the number of gob gas ventholes completed in an optimal configuration with the ventholes operated in a manner to reduce downtime, thus effectively draining a larger volume of the additional gas expected to be encountered on the wider panels.

NOMENCLATURE

f_{comp} Fraction of grid block penetrated by the well

h	Thickness
k	Permeability
k_h	Horizontal permeability
k_v	Vertical permeability
k_{h0}	Horizontal permeability (initial)
k_{v0}	Vertical permeability (initial)
$k_{r,j}$	Relative permeability to the phase
w_{frac}	Fraction of well
r_e	Effective radius of the well
r_w	Wellbore radius
Q_J	Total flow rate of the phase
PI_l	Productivity index from layer l
P_g	Grid block pressure
P_{wbh}	Well bottom-hole pressure
S	Wellbore skin
$\lambda_{T,l}$	Total mobility of the phase
μ_j	Viscosity of the phase
σ_{yy}	Vertical stress
σ_{xx}	Horizontal stress

SI METRIC CONVERSION FACTORS

ft x 0.3048	m
md x 10^{-15}	m^2
ft^3 x 28316.85	cm^3
psi x 6894.757	Pa
inch x 2.54	cm
cfm x 0.00047195	m^3/s

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Table 1. Initial horizontal and vertical permeabilities used in the FLAC models.

Rock Class	Rock types	Horizontal Permeability, md	Vertical Permeability, md
Soil	Clay bands	0.1	0.1
Very low permeability	Black Shale	0.2	0.1
Low permeability	Gray shale	1.0	0.5
Coal-face cleat direction	Coal	4.0	0.1
Coal-butt cleat direction	Coal	1.0	0.1
Moderate permeability	Limestone	2.0	2.0
High permeability	Sandstone	10.0	10.0

Table 2. Representative examples of prior-to-mining basic reservoir-rock properties (for fractures) used in the study.

Parameter	Pittsburgh Coalbed	Sandstone	Limestone	Shale	Entries
Permeability-x, md	4.0	10	2.0	0.2	$9x10^7$
Permeability-z, md	0.1	10	2.0	0.1	$9x10^7$
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)	2.38/(350)	-	-	-	-
Langmuir Volume, cc/g (scf/ton)	15.4/(490)	-	-	-	-
Desorption Time, days	20	-	-	-	-
Coal Density, g/cc	1.35	-	-	-	-

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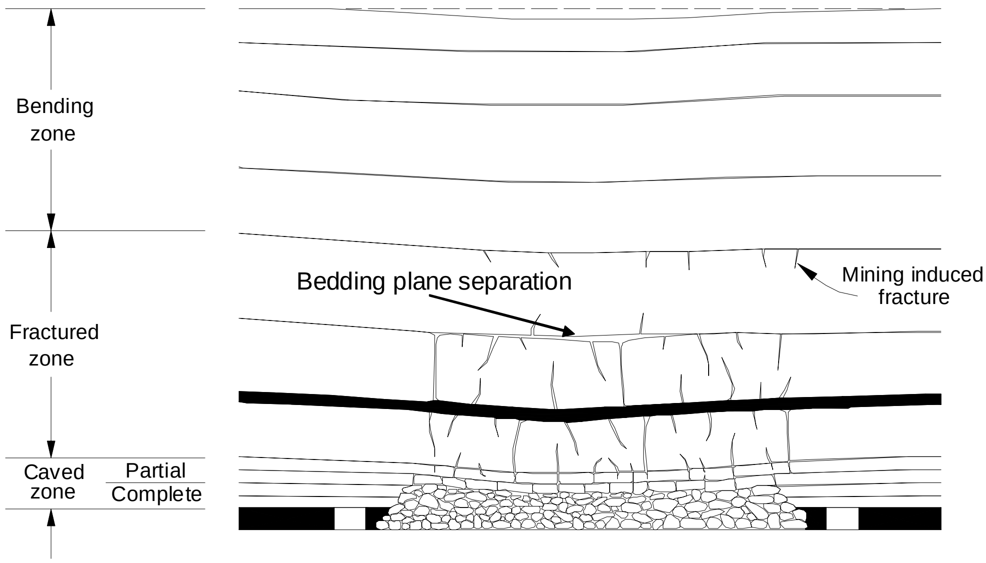

Figure 1. Schematic of strata response to longwall mining (modified from [1])

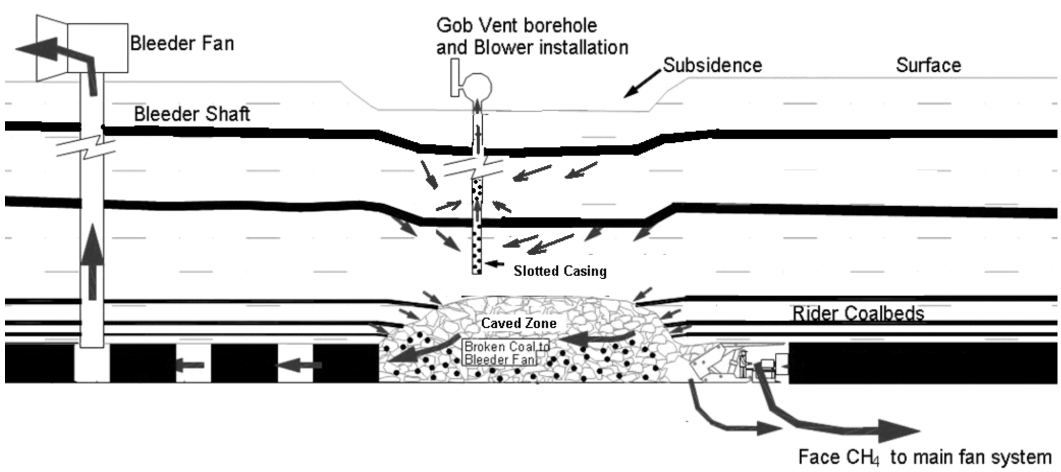

Figure 2. Schematic of a supercritical panel and associated gas migration paths.

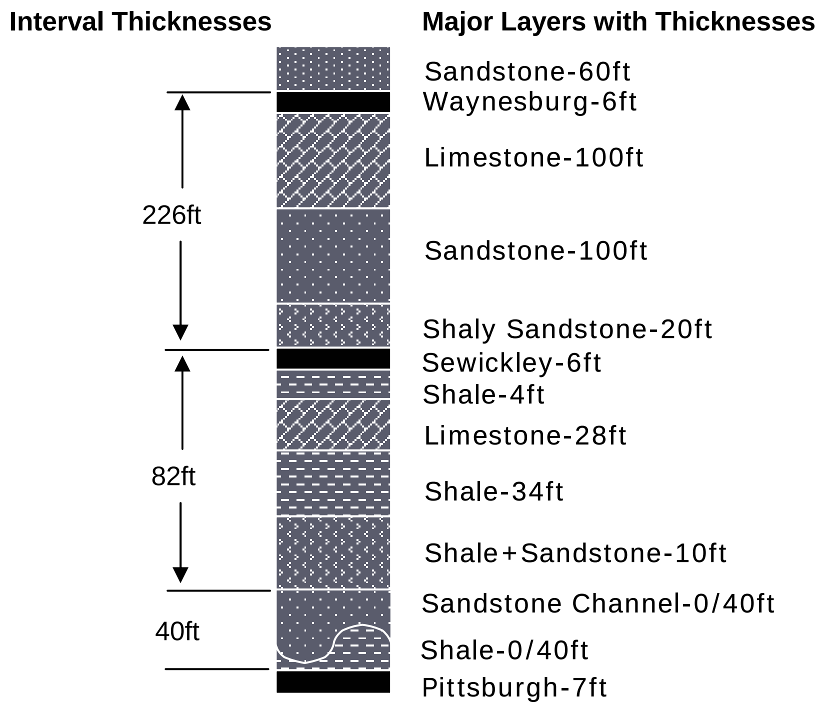

Figure 3. Generalized stratigraphic section of the study area (not to scale) showing major rock units and their thicknesses used in the model.

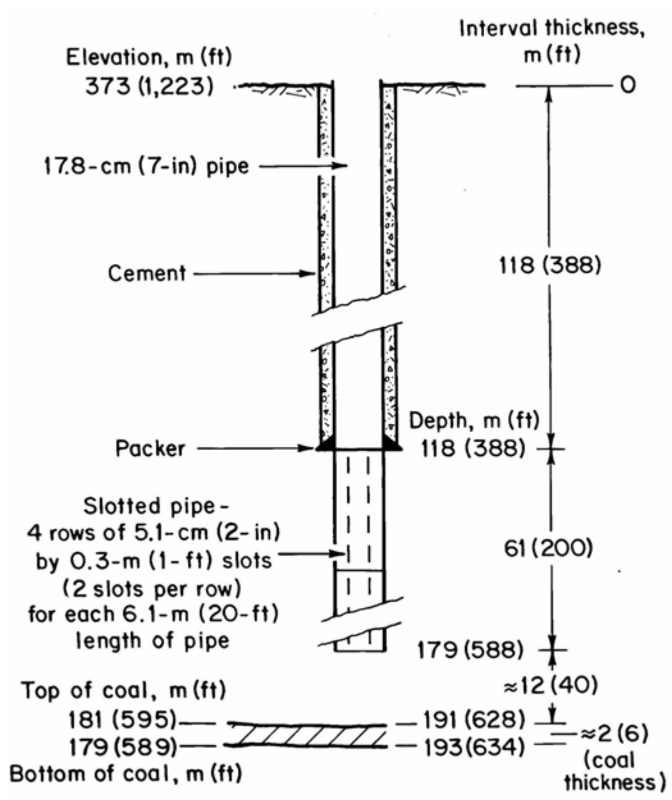

Figure 4. Typical gob gas venthole completion used in the study mine.

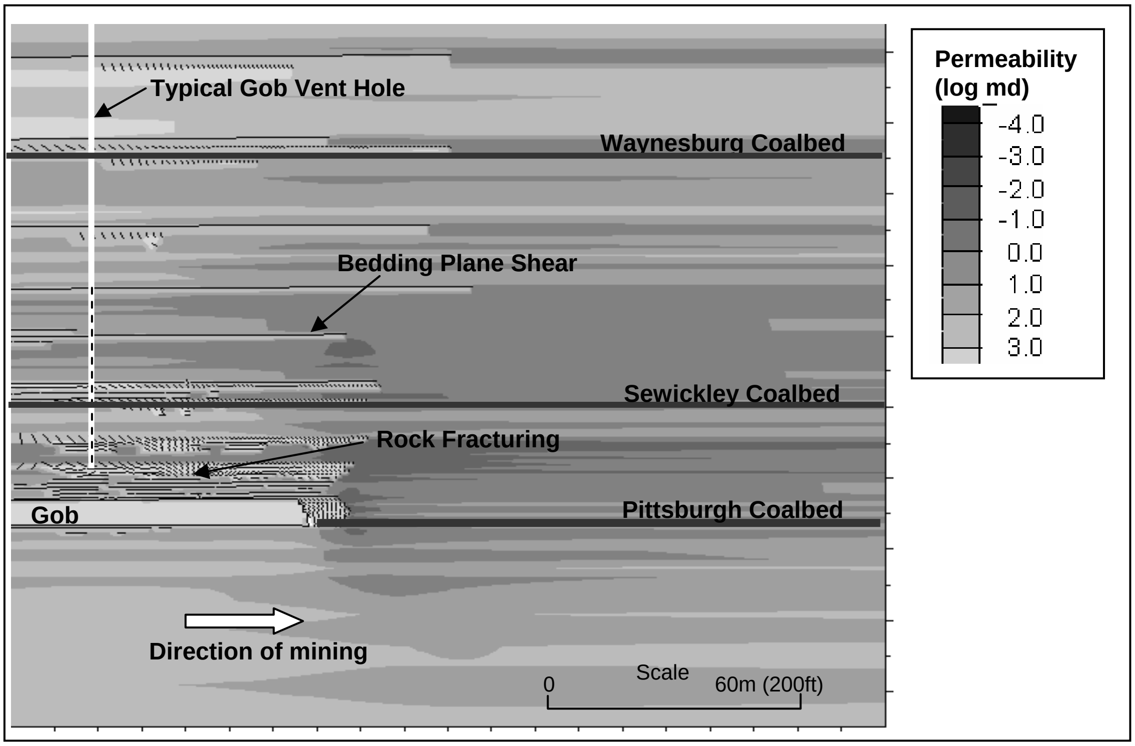

Figure 5. FLAC model results of a vertical longitudinal section through an advancing longwall face showing horizontal permeability contours, rock fracturing and bedding plane shear.

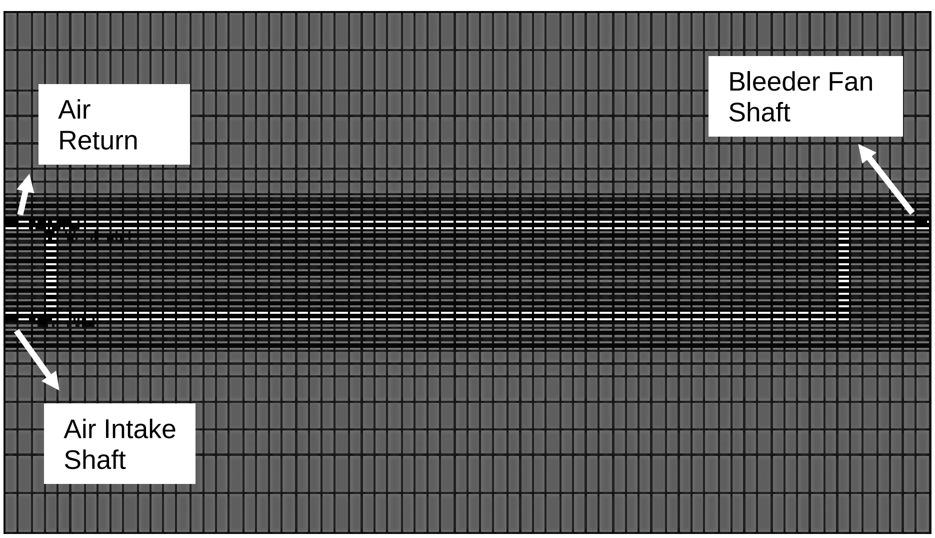

Figure 6. Pittsburgh Coalbed model layer grid showing simulated longwall panel, development entries, and “wells” used to model the ventilation system.

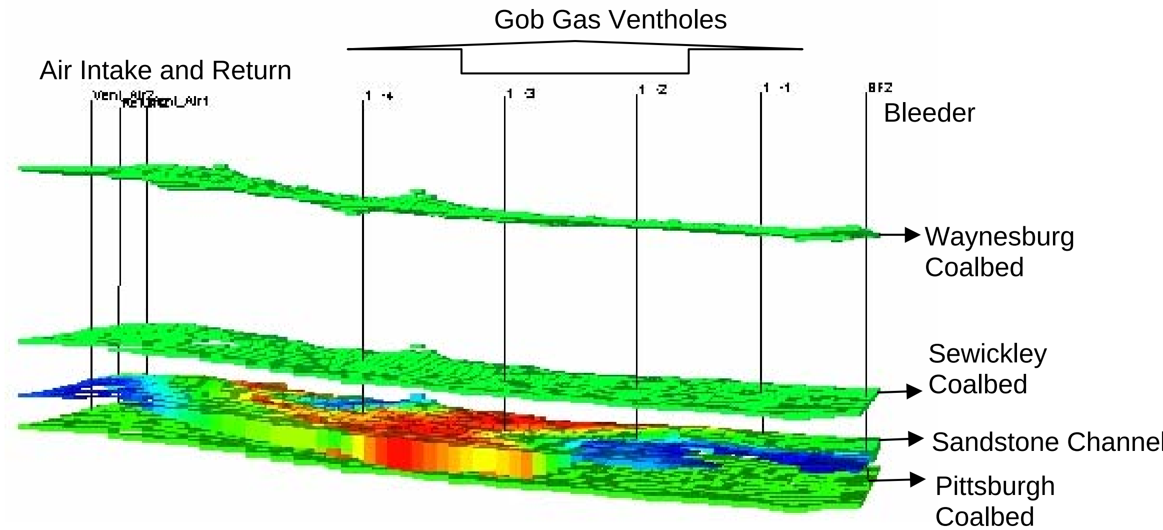

Figure 7. 3-D grid model of the study area (inner layers removed) showing the major coalbeds and the sandstone paleochannel. Figure also shows actual wells used in the model. Colors represent different thicknesses (red= 35-40ft, green= 5-15ft, blue < 5ft).

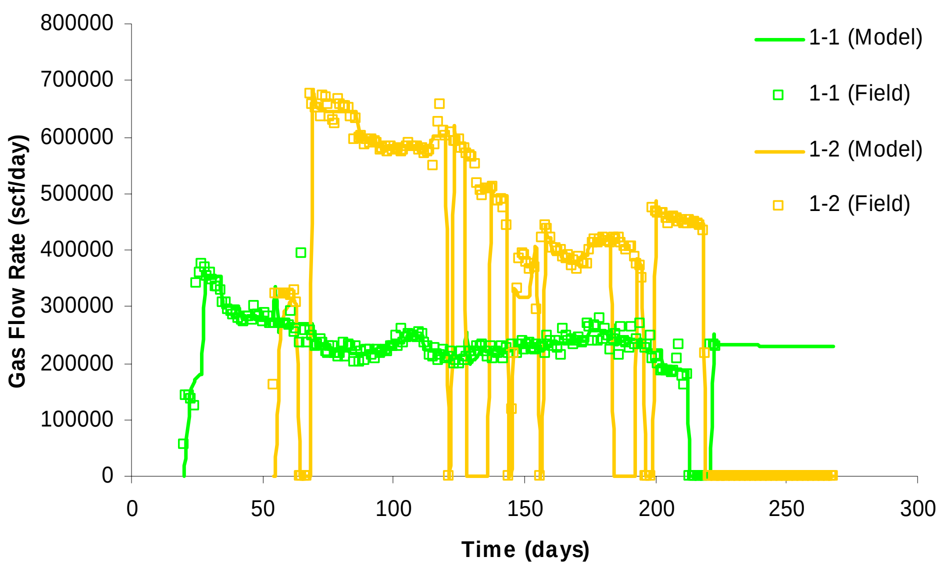

Figure 8-a. Graphs showing the history matches for gas flow rate from actual field measurements versus the model simulations for gob gas ventholes 1-1 and 1-2.

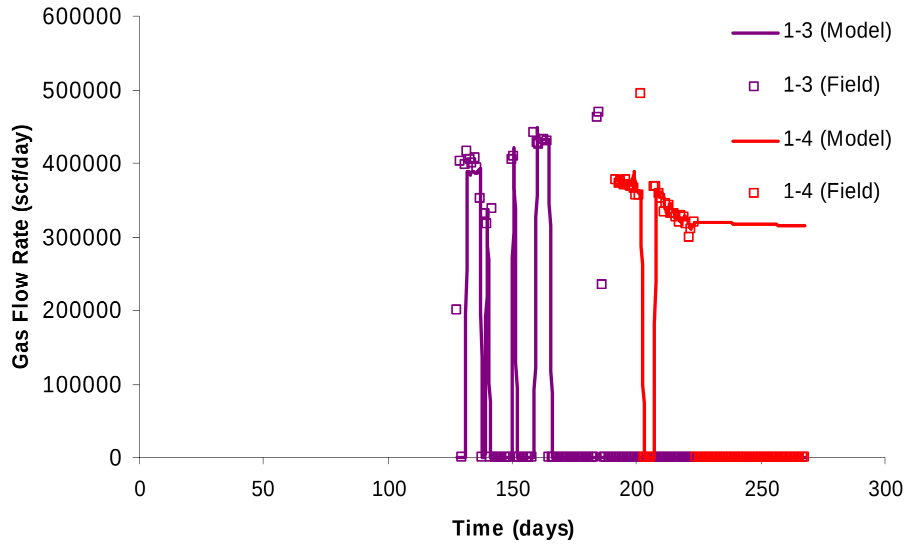

Figure 8-b. Graphs showing the history matches for gas flow rate from actual field measurements versus the model simulations for gob gas ventholes 1-3 and 1-4.

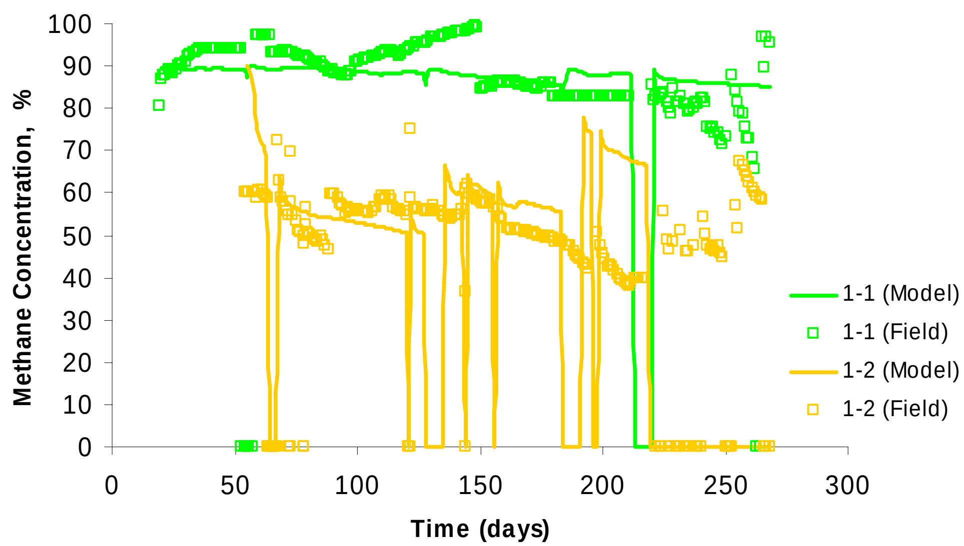

Figure 9-a. Graphs showing the matches for methane concentration in produced gas between field measurements and model runs for gob gas ventholes 1-1 and 1-2.

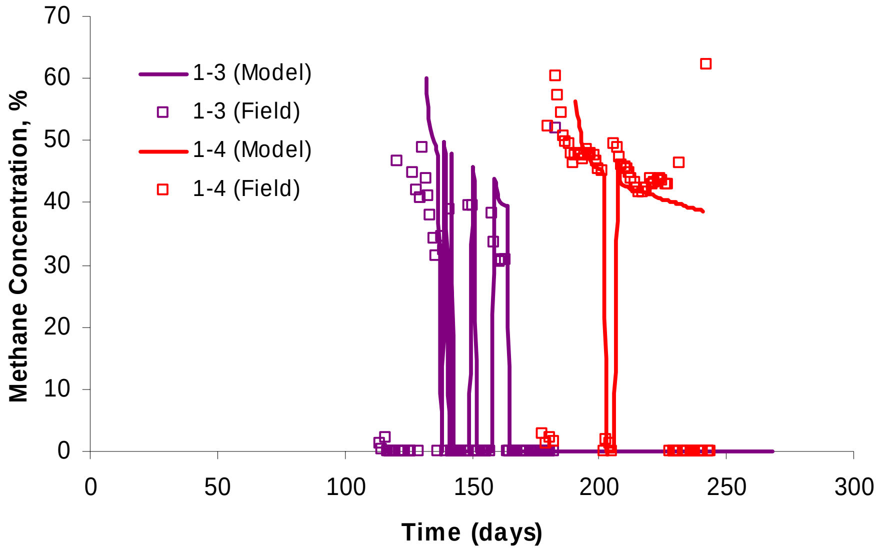

Figure 9-b. Graphs showing the matches for methane concentration in produced gas between field measurements and model runs for gob gas ventholes 1-3 and 1-4.

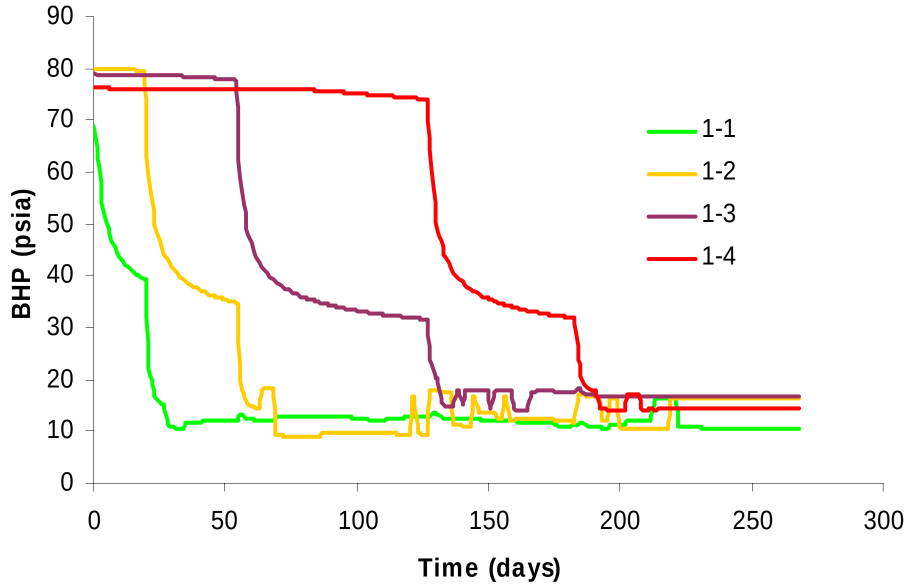

Figure 10. Predictions for bottom-hole pressures for the actual gob gas ventholes.

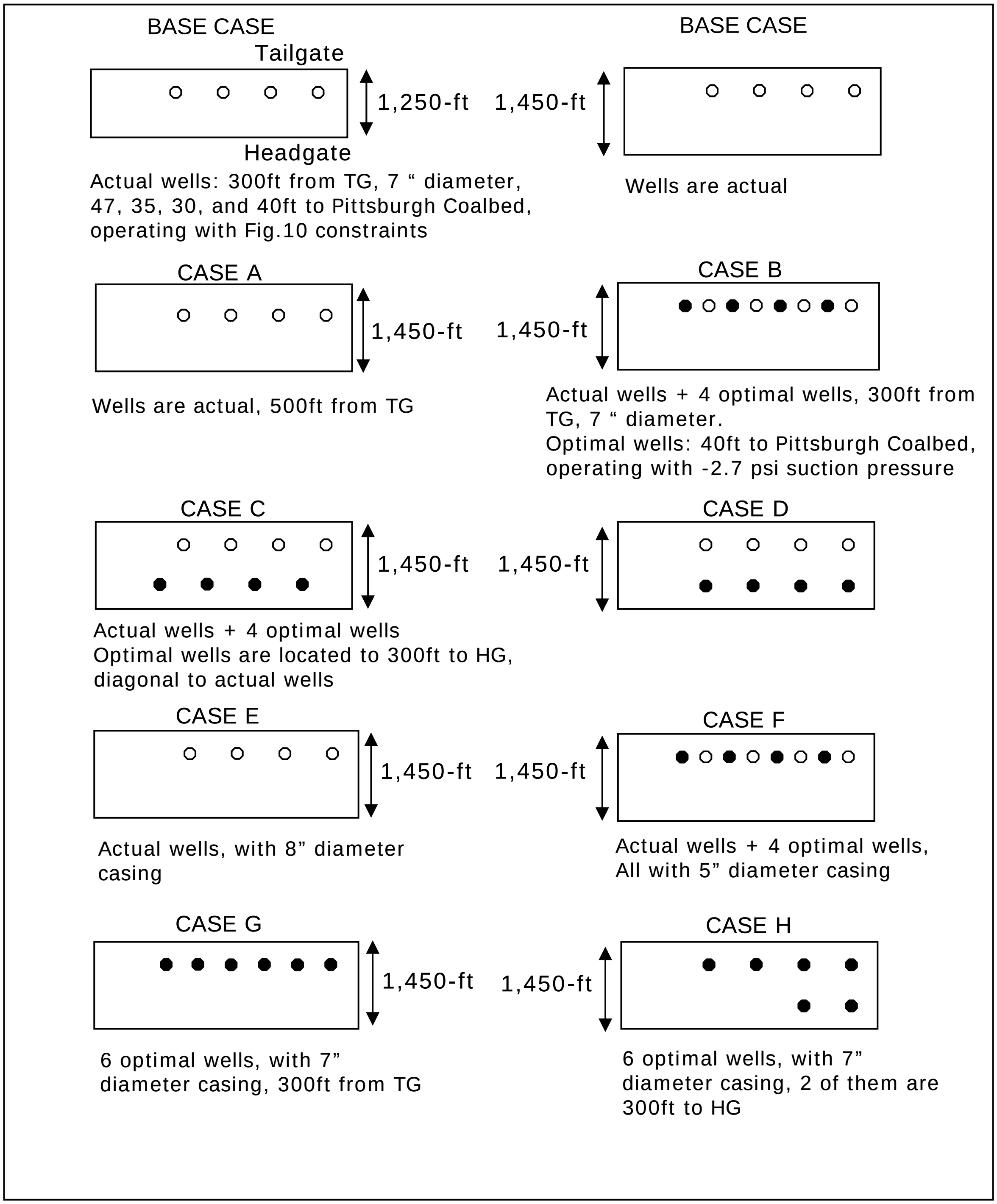

Figure 11. A schematic representation of well configurations and locations for the cases tested.

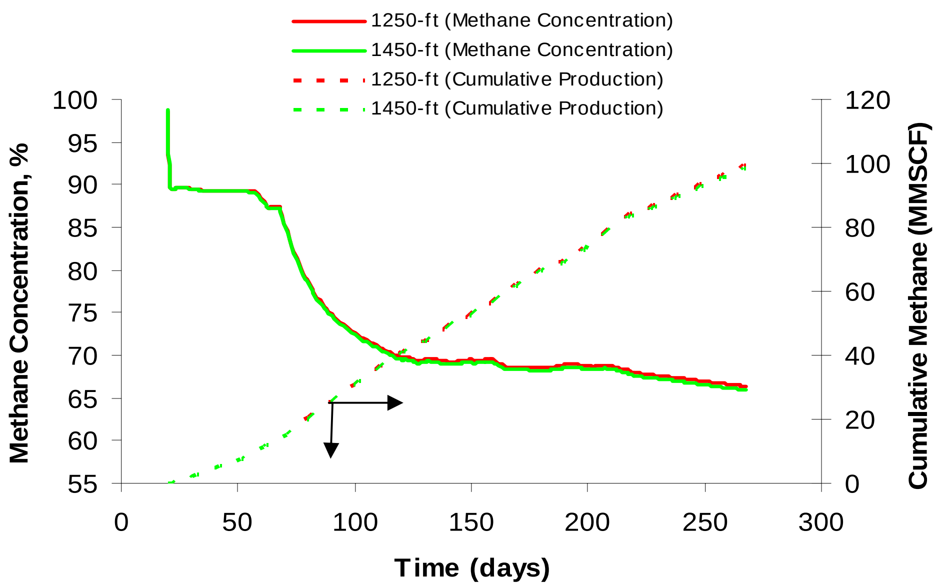

Figure 12. Comparison of cumulative methane production and methane concentration for gob gas venthole productions for different panel sizes.

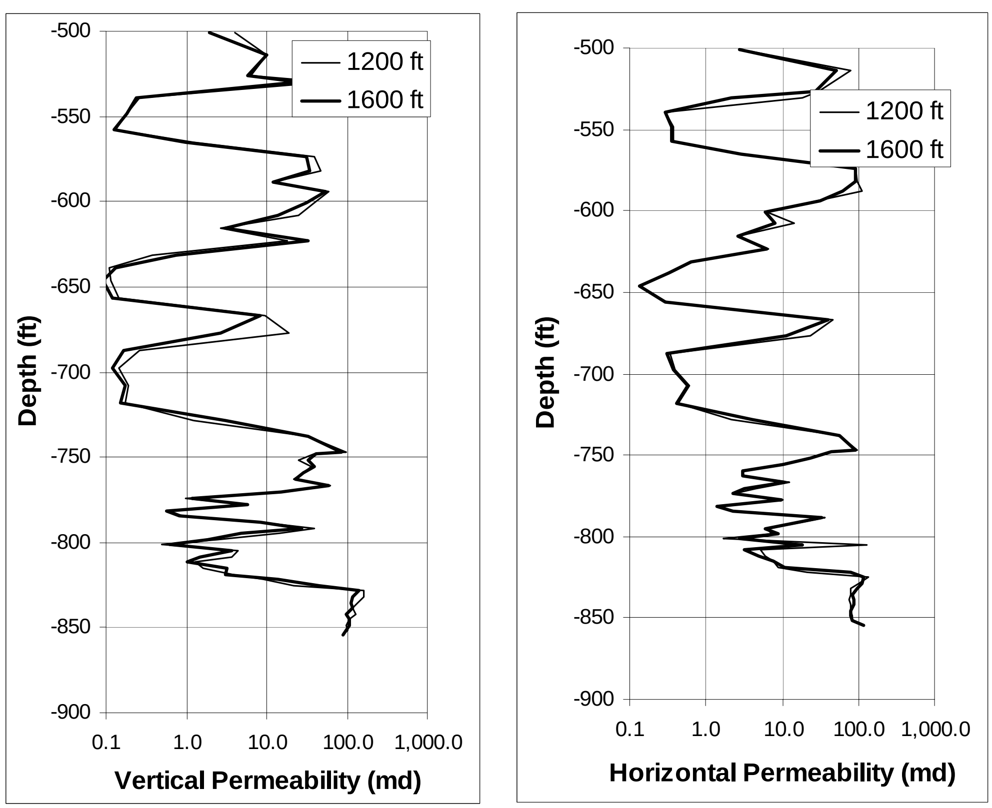

Figure 13. Comparison of horizontal and vertical permeability changes for 1,200-ft and 1,600-ft panel widths.

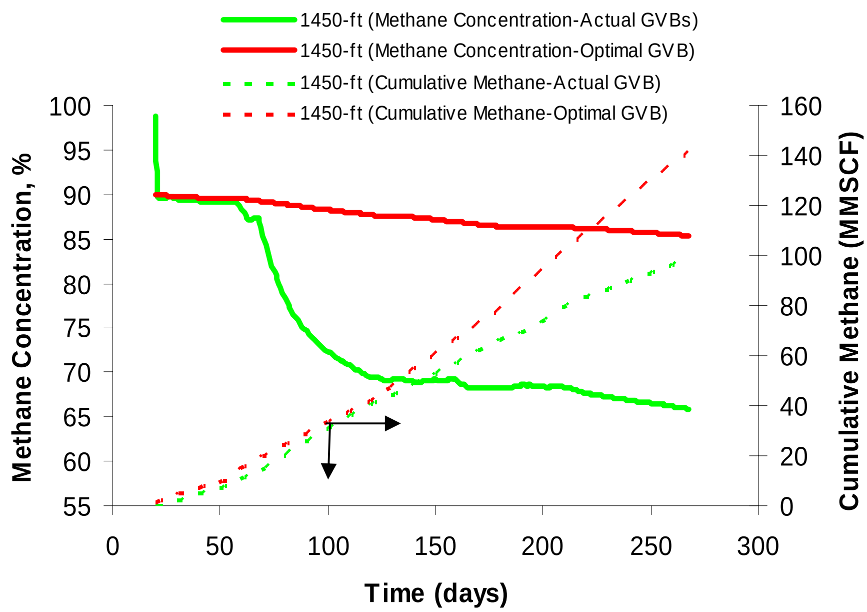

Figure 14. Comparison of the performance of actual GVBs (gob gas ventholes) at the study site with the optimal GVBs for the 1,450-ft wide panel.

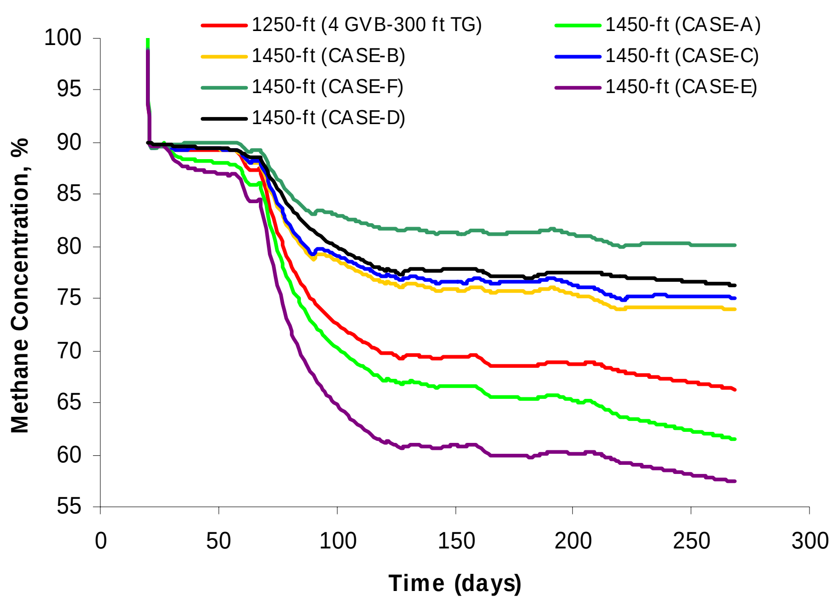

Figure 15. Comparison of methane concentrations in the produced gas from gob gas ventholes on the 1,250-ft and 1,450-ft panels with various well configurations as presented in Figure 11.

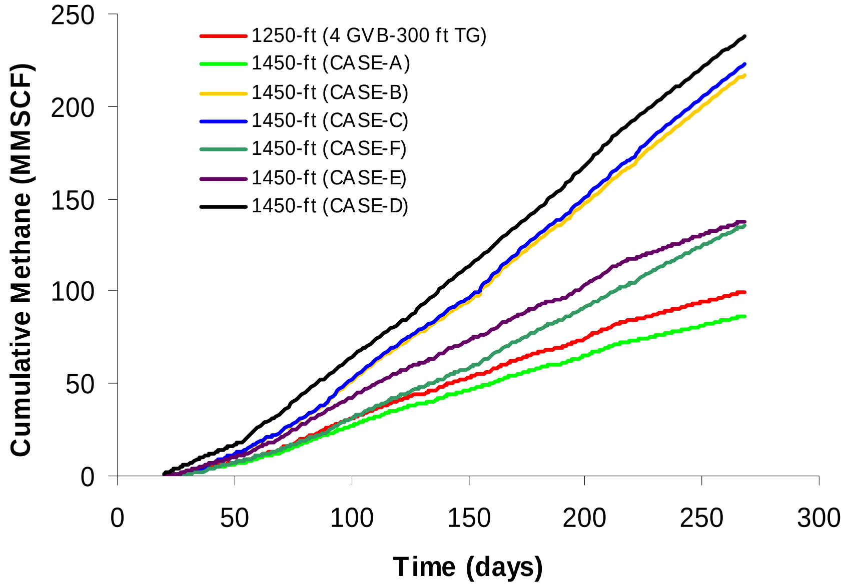

Figure 16. Comparison of cumulative gob gas venthole methane production from the 1,250-ft and 1,450-ft panels with various well configurations (A-F) presented in Figure 11.

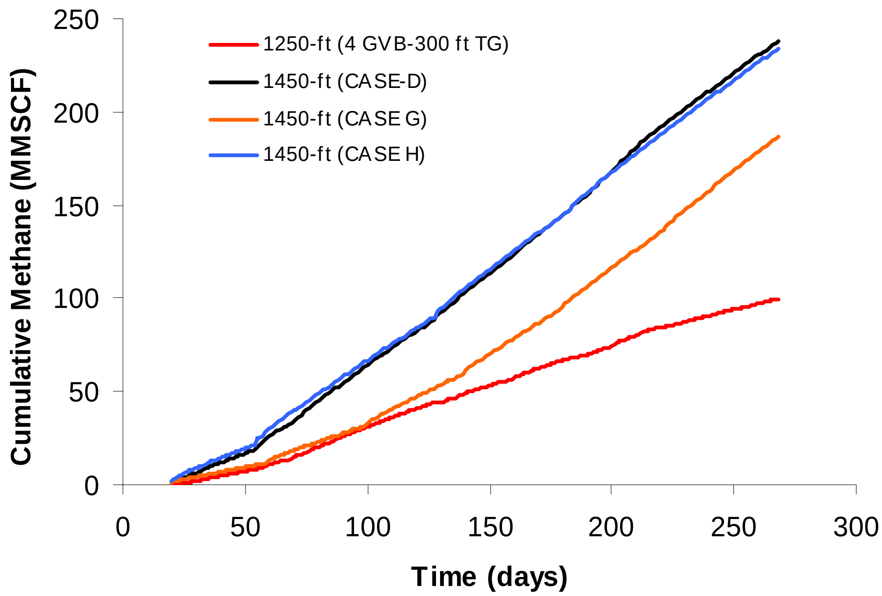

Figure 17. Comparison of cumulative gob gas venthole methane production from the 1,250-ft and 1,450-ft panel using CASE-D with configurations (G-H) that use only optimal wells presented in Figure 11.