# Advances in grid-based numerical modeling techniques for improving gas management in coal mines

C.Ö. Karacan
*NIOSH Pittsburgh Research Laboratory, Pittsburgh, Pennsylvania, USA*

TX. Ren & R. Balusu
*CSIRO Exploration and Mining, Australia*

ABSTRACT: Effective gas management in coal mines, as well as proper ventilation design, is very important for maintaining the safety of underground coal miners. Advances in numerical modeling techniques have enabled evaluations of the coal mining environment using advanced grid designs and computed gas distributions through detailed mathematical models. These models help engineers to “see” the “unseen” areas of the mine through visualization of the data and ultimately help improve worker safety. This paper summarizes the modeling efforts conducted by NIOSH in the U.S. and CSIRO in Australia to address various gas management issues encountered in longwall mines. The modeling studies involved two of the most widely used grid-based techniques, namely computational fluid dynamics (CFD) and numerical reservoir modeling. This paper discusses the application of these techniques for gob inertization and gas control for spontaneous combustion, pre-mining degasification of coalbeds, gob gas venthole design and performance evaluation in longwalls, and gas management during development mining.

## 1 Introduction

In underground coal mines, mine ventilation and methane control systems not only provide a workable environment but also reduce and eliminate explosive gas mixtures. In this regard, the use of simulation models is beneficial in the initial design of a particular ventilation and gas control system to test different scenarios. Simulation models also provide flexibility in making decisions where alternative designs need to be evaluated as ventilation or gas control problems arise in the mine.

“Classical” simulation programs, for instance MineVent* or Vnet* that rely on “network-type” modeling and solution algorithms are widely available for mine ventilation system design. They can be built easily, since they can interface directly with mine maps developed with AutoCAD. However, their capabilities to realistically model the mining environment are limited. They can be best used for the “network-like” regions in the mines, such as entries. However, these models are not capable of simulating what is happening in inaccessible regions, such as gobs, due to their 1-D and branched nature. Also, their information is usually limited to the pressures and flow rates at specific nodes or branches. Some programs, such as MFIRE*, can model the spread of fumes on a real time basis, in addition to calculating pressures, fan effects, and flow rates. However, these programs are becoming outdated due to the programming languages on which they were originally built (Hardy and Heasley, 2006). More advanced “network” programs, such as VUMA* and ENVIRON 2.5*, are capable of modeling additional parameters to assist designers in determining the aerodynamic and thermodynamic performance of the ventilation system (Biffi et al., 2006). These programs are also network based and are subject to similar limitations as their counterparts, in that they cannot model the gas control system as a whole. Also, it should be mentioned that all of these programs simulate steady state conditions and are only adequate for the purpose of defining performance parameters. They should not be used to model or analyze unsteady state conditions (Biffi et al., 2006).

Grid-based numerical modeling techniques are “non-classical” alternatives to the network-based models. They consider the mining environment as a volume rather than as one-dimensional ventilation “network” branches. Different mining-related geometries with varying transport properties can be created within the simulation volume. They also can model a wide range of processes, boundary conditions, and parameters, as well as unsteady state situations, which makes them advantageous compared to conventional approaches in ventilation design and gas management.

The aim of this paper is to introduce the recent advances in the application of the most widely used grid-based numerical techniques, computational fluid dynamics (CFD) and numerical reservoir modeling, to assess gas control capabilities in longwall mines. An overview is given of the modeling efforts conducted by the National Institute for Occupational Safety and Health (NIOSH) in the U.S. and the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia for various gas management issues encountered in longwall mines. The examples covered in this paper include the application of these techniques for gob inertization and gas management for spontaneous combustion control, pre-

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* Use of the names of commercial ventilation analysis packages does not imply NIOSH’s and CSIRO’s endorsement.

mining degasification of coalbeds, gob gas venthole design and performance evaluation in longwalls, and gas control during development mining of gateroad entries.

## 2 Applications of Grid-Based Numerical Modeling Techniques for Gas Control in Underground Coal Mines

In recent years, NIOSH and CSIRO have engaged in the investigation of gas flow dynamics within longwall gob areas and development entries for improving gas capture, minimizing the risk of spontaneous combustion, and developing gob inertization and coalbed degasification methods to supplement the mine's ventilation system. CFD models were developed by CSIRO and detailed reservoir models were developed by NIOSH for various mining and site-specific conditions. Both modeling efforts were integrated with field work to collect calibration and verification data. This section gives examples from these modeling studies to illustrate the capabilities of grid-based modeling approaches for ventilation and gas control research.

### 2.1 ANN Modeling of Ventilation Emissions from U.S. Longwall Mines

A fundamental insight into the mechanics of gob gas flow is essential for developing effective gas management and ventilation strategies. Such an understanding is also beneficial to the management of longwall gob gas to prevent spontaneous heatings (Yuan et al., 2006).

CSIRO developed CFD models to obtain a detailed understanding of the gas flow mechanics and distribution in the caved zone of longwall gobs using actual mine layouts. Longwall gob permeability distributions and gas emissions in the gob were incorporated into the model by a set of user-defined functions, or subroutines that were written separately and attached to the main CFD solver. In the model, the caved longwall gob was treated as porous media. A typical geometry and mesh used in the longwall gob gas flow models are shown in Figure 1.

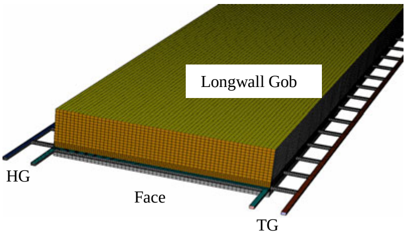


Figure 1. Typical model geometry and mesh used in the longwall CFD gas flow models.

Figure 2 shows the predicted gob gas migration pattern from the CFD model representing the common longwall geometry (1000 m in length (3280 ft) × 200 m in width (656 ft) × 60 m (196 ft) in height) in some mines in Australia. In the model:

- The HG side was 20 m (65.6 ft) lower in elevation than the TG side,
- A U-ventilation pattern with a total airflow of 50m$^3$/s (105,900 ft$^3$/s) was used, and
- Total gob methane emission was 600 l/s (21.2 ft$^3$/s).

The modeling results indicated that oxygen concentration in the gob on the headgate (HG) side was higher than on the tailgate (TG) side where oxygen concentration was up to 12% even at distances over 500 m (1640 ft) behind the face. Methane tends to migrate towards the high elevation side of the gob close to the tailgate. The layering of gob gas was also observed using similar models in which the ventilation air penetrated along the lower sections of the gob, particularly immediately behind the face and further along the HG side.

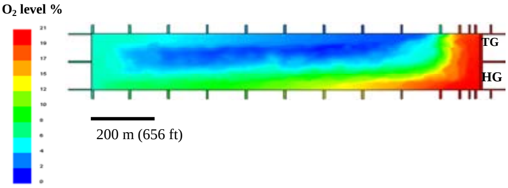


Figure 2. Plan view of oxygen concentrations in the gob (along a horizontal section in the middle depth).

A similar problem was investigated by NIOSH using a reservoir modeling approach. A typical reservoir grid representing the mining environment is shown in Figure 3. As in the case of the CSIRO/CFD modeling study, determining and inputting permeability changes in the gob as a result of mining were key elements of this model. This was achieved using FLAC (Fast Lagrangian Analysis of Continua) modeling of the area and converting stresses to permeabilities (Esterhuizen and Karacan, 2007). The reservoir model was different from the CFD model, in that permeability values could be directly entered into the model as an array without the need for writing separate user-defined functions.

The aim of this study was to model air leakage into the gob, to investigate the effect of gob gas ventholes drilled to different depths on gob gas flow, and to determine the movement of released tracer gas (Esterhuizen and Karacan, 2007). Figure 4 shows the effect of a gob gas venthole drilled too deeply (<9 m (35 ft) into the gob. This figure shows that the presence of a pressure sink due to the borehole changes flow circulation in the gob and thus allows the borehole to produce ventilation air from the gob.

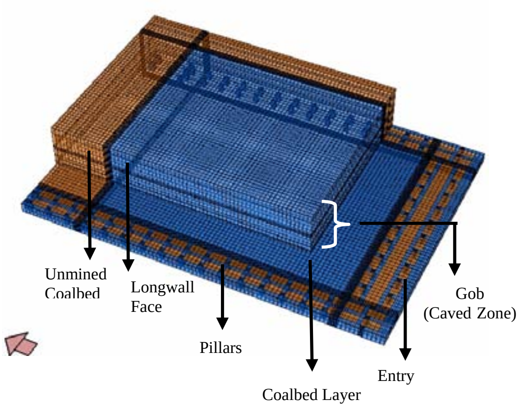


Figure 3. A three-dimensional grid model of the gob and the mining layer. The top layers were cropped for length and width to help visualize the modeled mining layer.

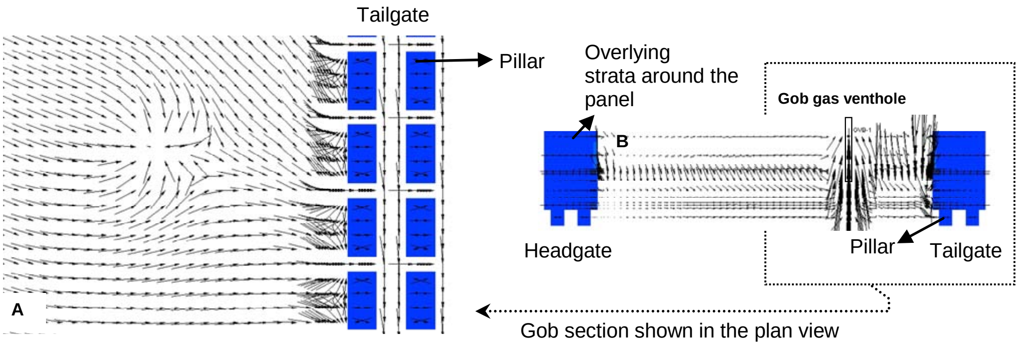


Figure 4. Influence of a gob gas venthole penetrating into the caved zone. A: A plan view of the lower part of the caved zone near tailgate entries. B: A vertical cross-section across the gob gas venthole location.

## 2.2 Modeling Gas Control in Longwall Gobs Using "Gob Gas Ventholes"

A particular application of grid-based modeling related to longwall mining is the optimization of surface gob gas venthole designs with the objective of maximizing gas production. This modeling can reduce the emissions into the mine workings as well as minimize the risk of spontaneous combustion.

CFD was used to model in combination with field monitoring and trials to optimize gob drainage design parameters. Figure 5 shows the predicted oxygen concentration patterns in the gob with the use of surface gob gas ventholes drilled on both headgate and tailgate sides. Results indicate that gas removal from gob gas ventholes would substantially improve the overall performance of the gas drainage system and reduce the size of methane-rich area on the tailgate side as well as the gas concentrations (in comparison to Figure 2).

This optimum gob gas drainage strategy helps in reducing gob gas migration towards the face and also helps in reducing the sharp gas emission fluctuations associated with changes in barometric pressure. These strategies, together with a set of guidelines for optimum gob drainage strategies, have been successfully implemented at several Australian coal mines (Balusu et al., 2002).

A similar problem was tackled by NIOSH using numerical reservoir simulation. In that study, the impacts on methane emissions and gob gas venthole performance were investigated when increasing panel width from 381 m (1250 ft) to 442 m (1450 ft). Also, an optimum gob gas venthole drilling strategy was sought to remove the excess gas due to this increase in panel dimensions. The modeled area is shown in Figure 6 (Karacan et al., 2005).

In Figure 6, the number of vertical layers and their thicknesses were based on generalized stratigraphic sections for the mine site. The positioning of gob gas ventholes in the model was based on their locations on the study panels, and these ventholes were configured based on their actual reported completion data. Most of the data required by the reservoir simulator for this application were gathered from previous NIOSH publications that addressed general reservoir and gob gas venthole performance issues in this same study area. Additional site-specific data were obtained from the cooperating mining company to develop reasonable assumptions for setting the initial (pre-mining) reservoir properties of the coal and non-coal units. The geomechanical FLAC model was used to evaluate the effects of longwall mining on the surrounding rock mass and to calculate mining-related permeability changes.

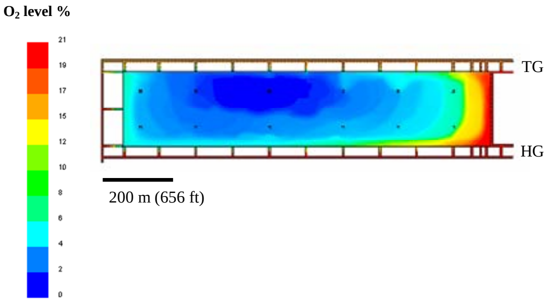
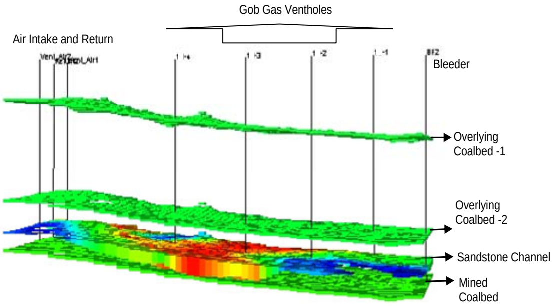


Figure 5. CFD applications in the development of optimum gob gas venthole drilling strategy. Figure shows oxygen distribution in the gob.

Figure 6. 3-D grid model of the study area (inner layers removed) showing the major coalbeds and the sandstone paleochannel (a depositional feature that changes the thickness of or sometimes completely washes out the coalbed). This figure shows the actual wells used in the model. Colors represent different strata thicknesses.

Results of this study showed that increasing the width of the panel did not change the productions of gob gas ventholes, although the emissions from the fractured strata did increase with width and could enter the mine's ventilation system if not captured. Thus, alternative gob gas venthole drilling patterns were modeled (Karacan et al., 2005) to optimize the capture of this gas. Figure 7 shows the cumulative methane productions that could be obtained with two different borehole patterns shown in the inset figure. Different colored curves in Figure 7 correspond to the cumulative productions that could be achieved with each of these borehole patterns. The results showed that the scenario with gob gas ventholes on either side of the panel, as in the CFD model, achieved the highest venthole production, which reduced emissions to the level seen before panel size was extended. This should result in a safer mining environment.



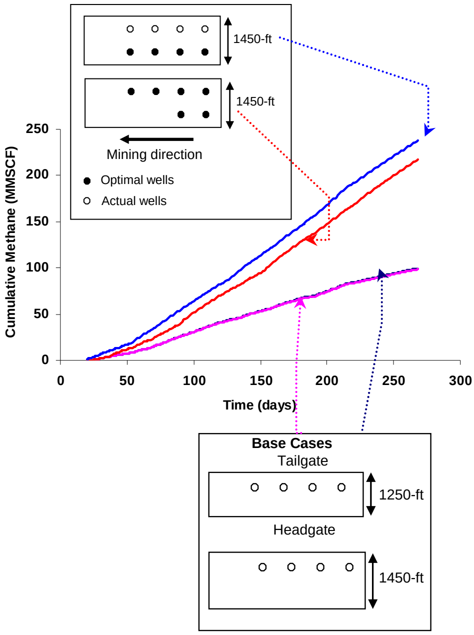


Figure 7. Comparison of cumulative gob gas venthole methane production from the 381-m (1250-ft) and 442-m (1450-ft) panels with various well configurations. An actual borehole is the one drilled and operated in the modeled area. An optimum borehole is the one drilled 90 m (300 ft) from the tailgate to 10-12 m (40-45 ft) to the tope of the coalbed and operated continuously.

## 2.3 Simulations for Spontaneous Heating Control and Gob Inertization

Control of spontaneous combustion in a longwall gob is critical safety and optimum production of in some of the mines in Australia and in the western US. CFD simulations have been used to investigate different ventilation layouts and practices with respect to the likelihood of spontaneous combustion for Australian longwall mines. Results from the CFD studies have helped improve ventilation designs and practices to minimize the onset of heating problems. These models investigated the spontaneous heating and combustion risks by evaluating gas distributions in the gobs and by recommending different ventilation schemes for various methane emission rates in the gobs.

Yuan and Smith (2007) improved the CFD approach to investigate spontaneous heating problems by including chemical reaction and oxidation of coal in combination with gas distributions. They calculated the temperature rise due to spontaneous heating and evaluated the risk of combustion in the gob for various ventilation parameters and coal activation values.

CFD models have also been used by CSIRO to develop optimum and effective strategies for inerting gobs during longwall sealing operations. Figure 8 shows oxygen distributions in the gob at different locations after 24 hours of inert gas injection. Inert gas at a rate of 0.5 m3/s (17.7 ft3/s) was injected through the HG seal and at 200 m (656 ft) behind the face on the headgate side respectively. The results indicate that the strategy of inert gas injection at about 200m behind the face significantly improves the gob inertisation process, compared with the traditional practice of injecting inert gas through headgate. Simulation results also show that other factors such as gas emission rates and ventilation during panel sealing would also have a significant influence on gob gas distribution and inertization.

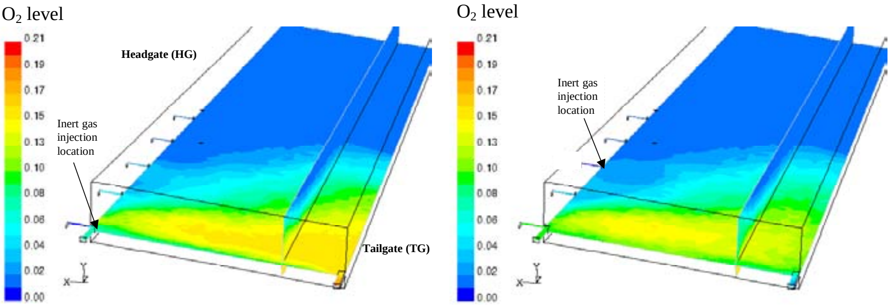


Figure 8. CFD simulations of gob inertization with different inertization strategies - Colors represent oxygen concentration.

In combination with field trials, optimum inertization strategies have been developed and implemented at an Australian coal mine. The gob environment became inert with oxygen level below 5% within a few hours of panel sealing (Balusu, Wendt and Xue, 2001). Further simulations with CFD and the knowledge obtained from these simulations have been used in conjunction with field conditions to develop the optimum proactive gob inertization schemes for two Australian coal mines. Excellent inertization results have been achieved (Balusu et al., 2005)

## 2.4 Modeling of Development Mining and Methane Control Strategies for Entry Development

In longwall development mining of coal seams, planning, optimizing, and providing adequate ventilation are very important steps to eliminate the accumulation of explosive methane-air mixtures in the working environment. Numerical reservoir simulation was used by NIOSH for prediction and optimization of methane inflows and ventilation air requirements to maintain methane concentrations below statutory limits. A coalbed reservoir model of a three-entry development section was developed, assuming either the presence or absence of shielding boreholes around the entries against methane inflow. In the model, grids were dynamically controlled to simulate the advance of mining for parametric simulations of different advance rates and coalbed parameters. An artificial neural network approach was integrated with this model for prediction efficiency (Karacan, 2007b). Also, multilinear equations were generated for different coalbed reservoir parameters to predict emissions (Karacan, 2007c)

For modeling the advance of tailgate and headgate entries, a three-entry development model around a longwall panel was studied. Figure 9 shows a snapshot of mining advance, pillar layout, and ventilation scheme. The middle entry was modeled as the “track” or haulage entry, where intake air was entering. The entry to the left of “track” was designated as the “belt” entry. The third entry was designated as the “return” entry, carrying away the majority (>90%) of the methane emissions. During development mining, the entries and the cross cuts constituting the volume to be ventilated were continuously extended.

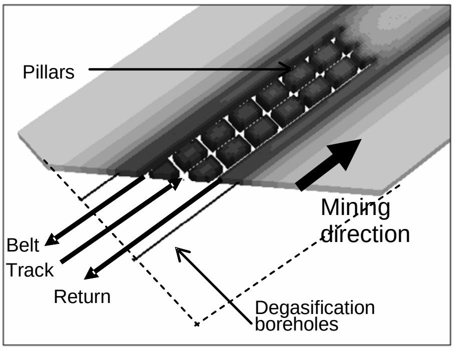


Figure 9. A three-dimensional snapshot of the model during development mining. Pillars, ventilation scheme, and the modeled shielding wells are also shown.

The amount and rate of methane inflow into the developed entries depended upon the extent of the continually created surfaces. This effect was simulated with models that ran sequentially, each characterizing an advance in entry development with a specified development rate.

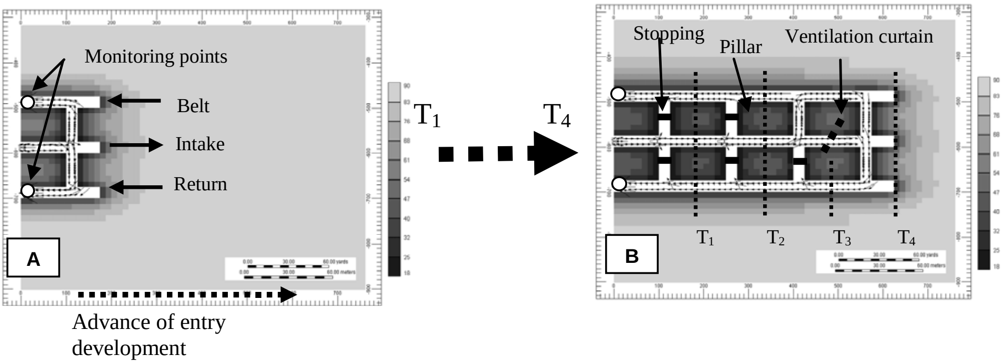


Figure 10. Snapshots of mining advance, pillar layout, and the ventilation scheme in the coalbed reservoir model. Locations where total methane inflow is monitored are also shown. The figures show the progress of mining in the coalbed at the end of first and fourth section advances.

Coalbed properties were replaced with the assigned properties of the entries and the ventilation-related features were built. The models were calibrated with the field measurements of methane concentrations during entry development. The development of cross cuts was modeled the same way as the entries in a dynamic fashion by assigning corresponding reservoir properties. However, during each simulation run, only the last set of cross cuts was left fully open for ventilation airflow. During development of cross cuts, stoppings or block walls (between track-belt and track-return) were automatically created between the restart runs to force ventilation flow through the last open cross cut at each section advance. A “curtain” resistance in the last section of the “track” diverted some of the intake air towards the “belt” entry to ventilate both belt and face (Figures 10a and 10b). These figures show the entries, cross cuts, and pillars created during simulations plus the paths of the ventilation airflow.

Two different modeling approaches were used to predict methane inflows and to estimate ventilation requirements during development mining. In the first approach, these values were determined based on the absence of any degasification wellbores around the entries to shield them from migrating methane.

The estimates of ventilation airflows that must be supplied to maintain specific methane concentrations are given in Figure 11 for varying mining rates and entry lengths. For these calculations, the methane inflow rates predicted by the simulator were used. With shorter development distances, only minimal adjustments to ventilation airflow were needed to keep methane levels below 1%.

Such adjustments appeared to be independent of mining rate. With longer development distances, more ventilation airflow is needed for constant methane levels and the amount of airflow was more strongly affected by the mining rate. If the ventilation alone cannot limit methane levels, decreasing the mining rate may be an effective, but not necessarily, a desired control (Karacan, 2007b).

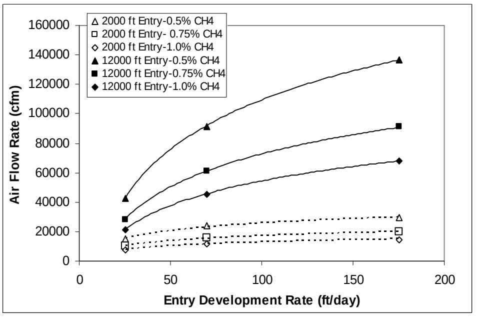


Figure 11. Calculated airflow rates required to maintain various methane concentrations for different mining rates and entry lengths.

A similar modeling approach was used to evaluate the effect of various coalbed reservoir parameters on methane emissions in development mining (Karacan, 2007c). The results of the simulations were used to generate simple predictive equations using multilinear regression analysis for a 15.3 m/day (50 ft/day) section advance rate. Table 1 shows the equations obtained using this approach.

Table 1. Linear models for predicting methane inflow rates into development entries of various lengths using key coalbed reservoir parameters (Thick: Thickness (in ft), Pres: Pressure (in psi), S. Time: Sorption time constant (in days), Ky: Butt cleat permeability in this study, but can be interpreted as the cleat permeability perpendicular to

entries (in milli Darcies), L. Vol: Langmuir volume (scf/ton), L. Pres: Langmuir pressure (in psi), W. Sat: Water saturation (in percent)). Reservoir parameters were determined using ANOVA and backward-elimination methods.

| Dev length (ft) | Methane inflow rate (scf/day) = |
|---|---|
| 2000 | -9025 0349 + (18676 8392 × Thick) + (1367 1790 × Pres) + (-581 1950 × S Time) + (13100 6770 × Ky) + (121 6918 × L Vol ) + (-197 1251 × L Pres ) + (-1280 3404 × W Sat ) |
| 6000 | -193021 3700 + (49697 1335 × Thick) + (2734 4987 × Pres) + (-997 3667 × S Time)+ (19103 2963 × Ky) + (298 3296 × L Vol ) + (-544 3628 × L Pres ) |
| 10000 | -256242 0600 + (73838 2649 × Thick) + (3764 7566 × Pres) + (-1256 0067 × S Time)+ (21052 8924 × Ky) + (457 1441 × L Vol ) + (-867 7456 × L Pres ) |
| 12000 | -283185 5900 + (85055 0763 × Thick) + (4219 7519 × Pres) + (-1357 3077 × S Time)+ (21403 8583 × Ky) + (532 4142 × L Vol ) + (-1023 3603 × L Pres ) |

The models presented in Table 1 do not contain all of the initially selected coalbed parameters. For instance, the model for the 610-m (2000-ft) case does not contain porosity, irreducible water saturation, end point relative permeability to gas, and face cleat permeability. Due to their low significance, they were eliminated from the set of independents during the backward-elimination process. It may be surprising to see that face cleat permeability is also not included in the equations for predicting methane inflow during development mining simulated in this study. This is because for this study the entries advance parallel to the face cleats, which makes butt-cleat permeability more significant for controlling methane inflows. For longer development distances, water saturation is also eliminated from the independent variables, since its significance on methane flow decreases for long entries.

Table 1. Linear models for predicting methane inflow rates into development entries of various lengths using key coalbed reservoir parameters (Thick: Thickness (in ft), Pres: Pressure (in psi), S. Time: Sorption time constant (in days), Ky: Butt cleat permeability in this study, but can be interpreted as the cleat permeability perpendicular to entries (in milli Darcies), L. Vol: Langmuir volume (scf/ton), L. Pres: Langmuir pressure (in psi), W. Sat: Water saturation (in percent)). Reservoir parameters were determined using ANOVA and backward-elimination methods.

## 3 Conclusions

This paper is a brief summary of advances in grid-based modeling that were developed by NIOSH and CSIRO to address gas management problems in underground coal mines. The results show that CFD and reservoir simulations can complement each other and, in most cases, be suitable, although more complicated alternatives to classical network ventilation models. This is especially true in situations where network models are neither suitable nor capable of solving the problem and where grid-based models are highly effective in modeling the mining environments and different mining processes. The visualization interfaces allow engineers to "see" the "unseen" areas of the mine, such as gobs.

The models presented in this paper have greatly improved the fundamental knowledge of gob gas flow patterns and gas distribution under the influence of various geological and mining parameters. The significant insights gained from these studies have helped to improve in the development of control measures and practices through the effective use of gob gas ventholes, spontaneous heating management, gob inertization strategies, and methane control in development mining.

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