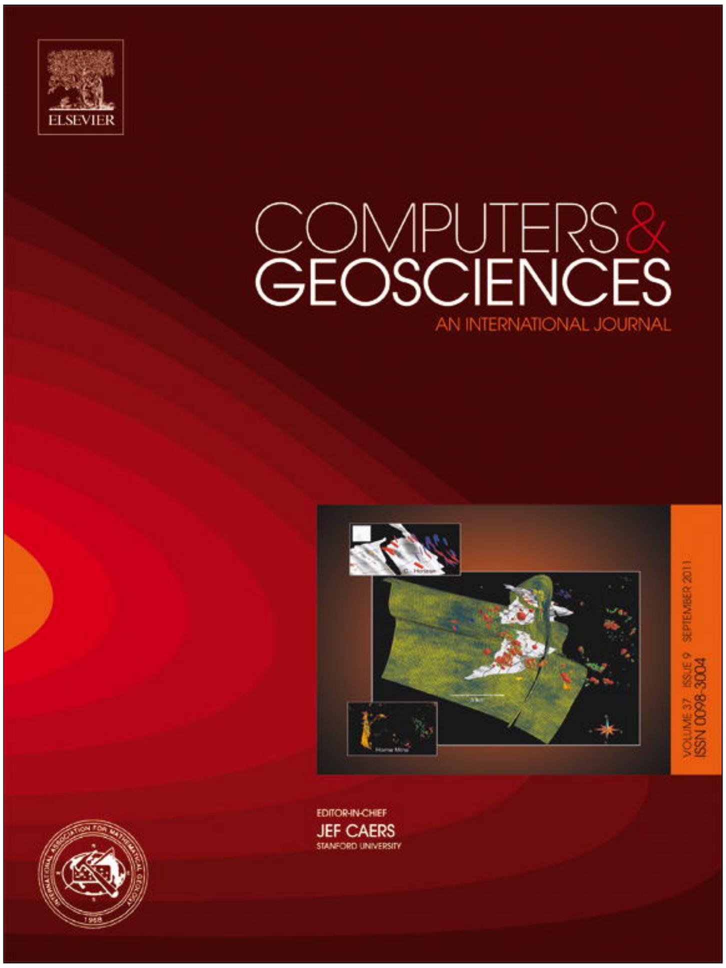

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A new methane control and prediction software suite for longwall mines ☆

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A R T I C L E I N F O

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A B S T R A C T

This paper presents technical and application aspects of a new software suite, MCP (Methane Control and Prediction), developed for addressing some of the methane and methane control issues in longwall coal mines. The software suite consists of dynamic link library (DLL) extensions to MS-Access^{TM,} written in C++. In order to create the DLLs, various statistical, mathematical approaches, prediction and classification artificial neural network (ANN) methods were used.

The current version of MCP suite (version 1.3) discussed in this paper has four separate modules that (a) predict the dynamic elastic properties of coal-measure rocks, (b) predict ventilation emissions from longwall mines, (c) determine the type of degasification system that needs to be utilized for given situations and (d) assess the production performance of gob gas ventholes that are used to extract methane from longwall gobs. These modules can be used with the data from basic logs, mining, longwall panel, productivity, and coal bed characteristics. The applications of these modules separately or in combination for methane capture and control related problems will help improve the safety of mines.

The software suite's version 1.3 is discussed in this paper. Currently, it's new version 2.0 is available and can be downloaded from http://www.cdc.gov/niosh/mining/products/product180.htm free of charge. The models discussed in this paper can be found under "ancillary models" and under "methane prediction models" for specific U.S. conditions in the new version.

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1. Introduction

Longwall mining is an underground mining method that maximizes coal production from coal beds that contain few geological discontinuities, such as faults, folds, and pinchouts. In longwall operations, a mechanical shearer progressively mines a large block of coal, called a panel, which is outlined with development entries or gate roads. The location of mining along the panel is known as the mining face. A schematic representation of a longwall panel is given in Fig. 1. Longwall mining is a continuous process in an extensive area, where the roof is supported temporarily with hydraulic supports, called shields, which protect the workers and the face equipment. As the coal is extracted, the supports automatically advance and the roof strata are allowed to cave behind the supports. The caving of immediate roof strata results in a stress relief in overlying formations, which fracture horizontally and vertically based on their mechanical strength (Karacan et al., 2007a). This caved or fractured zone is called the gob. Singh and Kendorski (1981) and Palchik (2003) analyzed the nature of strata disturbances due to longwall mining and predicted that the gob created by the collapse of immediate roof rocks can reach four to eleven times the thickness of the mining height depending on the strength and porosity of the overlying rocks (Fig. 1).

The gob created by longwall mining allows methane that was once confined within the overlying strata (or reservoir) to release after fracturing and find a path through gob to flow into the mine environment. Emissions of methane into the mine atmosphere and accumulation in a working area in the mine may cause a dangerous mixture of methane and air, which could lead to an explosion. Therefore, it is critical to be able to predict the magnitude of methane emissions and act with accurate and appropriate methane control measures before the problems become severe.

Due to the large number of variables affecting potential emission sources, accurate prediction of the rate of methane flow into the working areas and eventually into the ventilation system is a complex problem. Current prediction models depend on accurate representation of the gob and the fractured strata that act as a gas reservoir in order to predict methane emissions, the amount of mine-air leakage into the gob, and effective control methods. The reservoir properties of the gob are extremely important, but difficult to compile and interpret (Lunarzewski, 1998; Karacan et al., 2007a). This behavior is a product of the challenges and unknowns related to the gob environment and its inaccessibility for direct measurements and inhomogeneity of the overburden. In this regard, knowledge of the dynamic elastic properties of roof rock and the overlying coal-measure formations is necessary to assess the size and thickness of the gob and fractured interval

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☆ Code available from: http://www.cdc.gov/niosh/mining/products/product180.htm.

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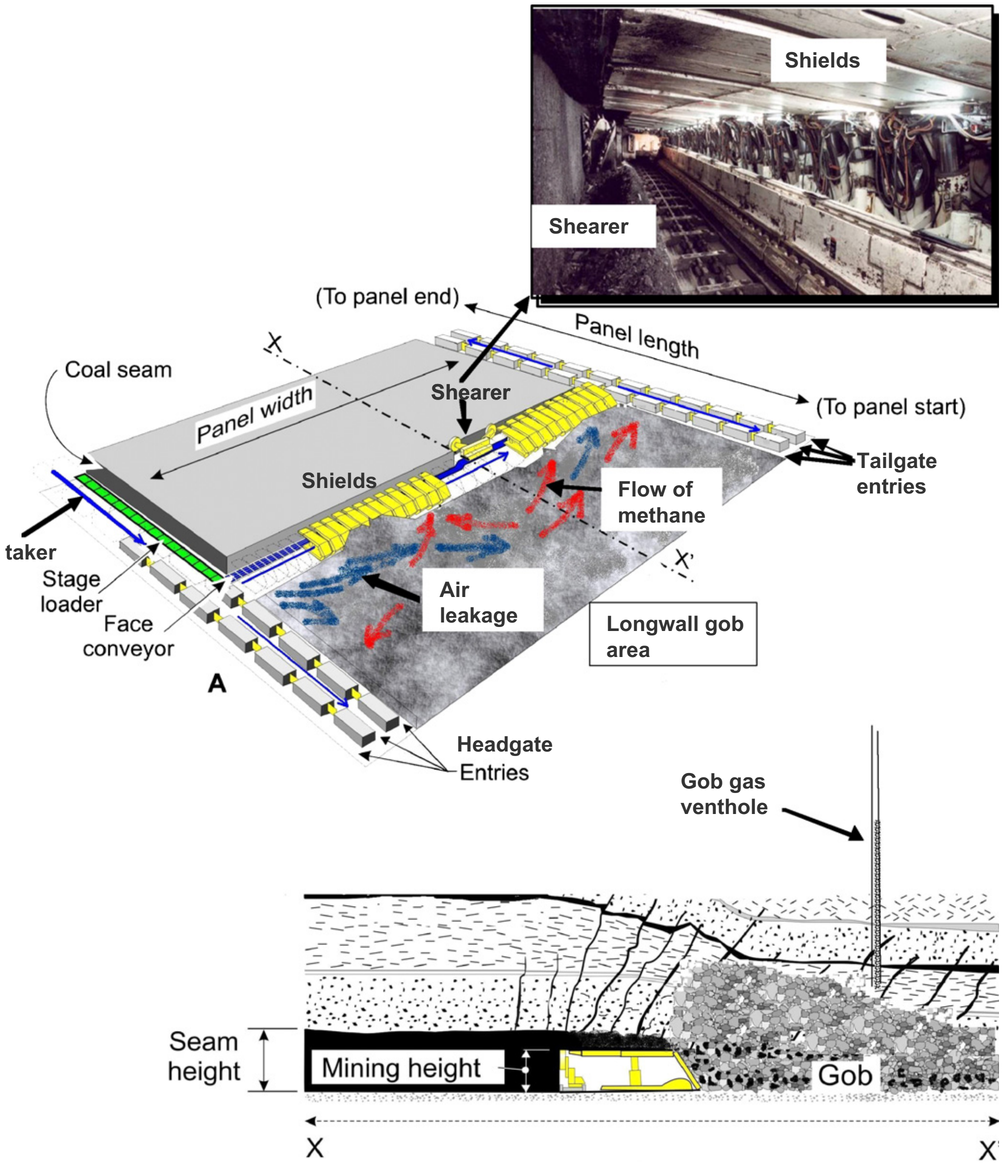


Fig. 1. Schematic representations of a longwall mine and the gob created behind the face (modified from Karacan, 2008). Arrows show the direction of air leakage and the methane paths in the gob. Side view shows the location of a gob gas venthole above the mined coal seam.

and to estimate methane flow in these zones (Whittles et al., 2006, 2007).

Gob gas ventholes (GGVs) are commonly used to control methane emissions from the fractured strata (Fig. 1). They are a form of supplemental control that removes some methane from the gob, preventing it from entering the mine and increasing the load on the mine ventilation system. These ventholes are drilled from the surface to a depth that places them above the caved zone, so that they usually do not directly interact with the ventilation system. They are cased, and the bottom section of the casing is slotted and placed adjacent to the expected gas production zone (Palchik, 2005). GGVs can be equipped with exhausters, which provide suction to capture sufficient gas from the fractured zone before it migrates into the mine. They are drilled prior to undermining, from as little as a week or two to many months beforehand, and generally become productive after the mining-induced fractures propagate under the well (Diamond, 1994; Karacan et al., 2007b). To adequately design and locate GGVs, it is important to be able to predict the performance of potential GGVs with a variety of borehole and operational parameters. Despite improvements in analytical and numerical modeling approaches, it is still difficult to accurately predict methane production for GGVs. Predictions may underestimate actual gob gas venthole production by at least a factor of two. The key factor in this underestimation is the difficulty in incorporating a predictive approach with the many factors that affect venthole performance (Zuber, 1998).

The main mine ventilation system must handle methane from a variety of sources, including methane that cannot be captured by supplemental methane controls like GGVs, and emissions due to the gassiness of the coal bed. The specific methane emissions from the coal bed vary based on operating parameters. Ventilation air that is provided to the mine must be increased for situations of high methane emissions to dilute them to safe levels before dangerous situations arise. Generally, it is economically feasible to handle specific emissions (total gas emission per unit amount of coal mined) up to 1000 ft^3/ton with a well-designed ventilation system. At higher specific emission rates, however, it is difficult to stay within statutory methane limits using ventilation alone (Thakur, 2006). This condition can adversely affect the safety of the underground workforce.

In case of high specific emissions, other supplemental methane control measures, such as degasification of the coal bed using surface vertical or horizontal wells, in-seam boreholes, or combinations of methods, are needed to mine the coal safely. It is advantageous, and economically more feasible, to determine the need for and the most effective type of degasification well ahead of mining by considering the various geological, coal bed, and mining parameters. The preferred methane recovery method depends on the mining parameters and the gassiness of the coal seam. In most cases, a combination of different drainage methods leads to the highest recovery of methane from the coal bed and its overlying strata before mining. Since drilling an array of vertical and horizontal boreholes is costly, a technical assessment prior to mine development is generally needed. Such an assessment requires both empirical and theoretical approaches. Since a comprehensive mine simulator that combines mining operation, coal bed reservoir, and methane production parameters does not currently exist, a technique that can identify the optimal degasification system for a given set of mining and geological parameters could be useful as a pre-planning tool prior to mining.

This paper presents technical methodologies that provide proxy solutions to the above-mentioned challenges and demonstrates applications of a new software suite that can help mining operations control and capture methane from longwall mines.

This software suite contains four main modules:

- Coal measure rock properties—predicts dynamic elastic properties of coal-measure rock for better roof support and methane control.
- Mine ventilation emission prediction—predicts ventilation air methane (VAM) emissions from longwall mines.
- Degasification system selection—recommends the best degasification choice.
- Gob gas venthole production performance prediction—predicts performance of gob gas ventholes, both methane percent and production.

2. Methane control and prediction (MCP) tool kit for longwall mines

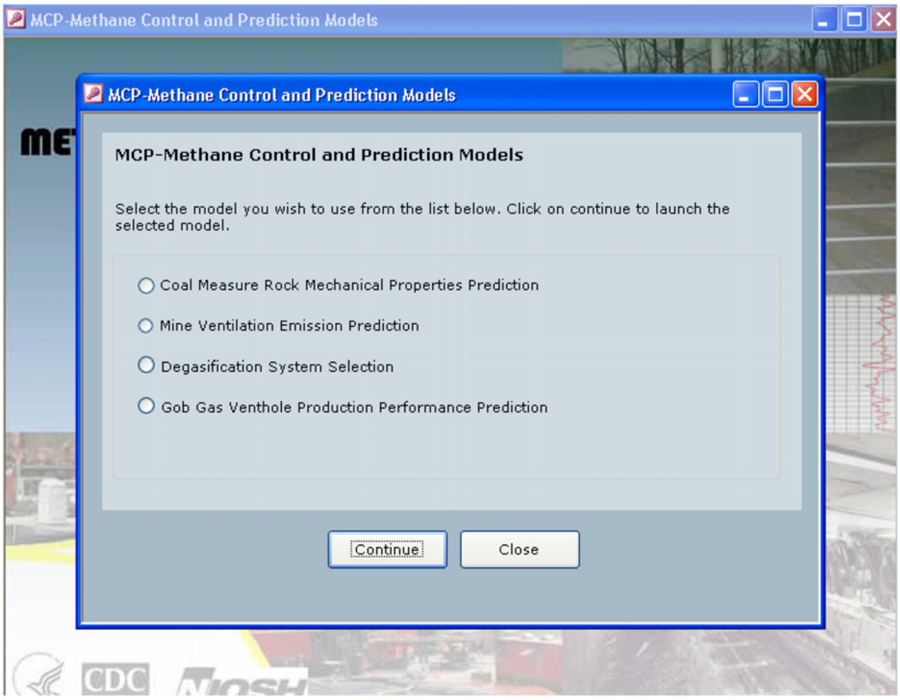
The current version (version 1.3, which is soon to be updated with version 2.0) of the methane control and prediction (MCP) software was developed with four modules under the MS Access^{TM} shell environment. Dynamic link libraries (DLLs) written in C++ are used to extend the analysis capabilities of MS Access^{TM}.

The models were developed using a database of information about mines, including basic well log, mining, longwall panel, productivity, and coal bed characteristics. The resulting models take the same types of information as input parameters. In order to obtain good predictions, MCP users need to enter the input parameters as realistically as possible for their situation. The modules are most accurate within the given min–max range, but there is some extrapolation flexibility in the calculation methods, allowing the modules to perform predictions beyond the minimum and maximum limits. When the entered data is beyond the limits, the program provides a warning and asks the user whether he/she would like to continue with the calculations. If the user approves, the program continues with its calculations.

A mean value is also provided for input parameters. The mean values are not the arithmetic averages of minimum and maximum values, but are the statistically determined mean values from the database employed in developing the models. If the user does not have a particular input parameter available to them, the mean value can be inputted as an approximate representative condition for that parameter.

One of the advantages of these software modules is the ability to perform sensitivity studies by varying the values of input parameters. Sensitivity studies were prepared in this paper and shown in Figs. 5, 8, 10, 11, and 13. These study figures were not created in MCP but with a separate program to better visually analyze the data.

MCP runs with any version of MS Access^{TM}. Fig. 2 shows the modules that are available to the user in the MCP model selection window. The following sections of the paper will be dedicated to describe each model individually and their applications for the



MCP-Methane Control and Prediction Models

Select the model you wish to use from the list below. Click on continue to launch the selected model.

○ Coal Measure Rock Mechanical Properties Prediction
○ Mine Ventilation Emission Prediction
○ Degasification System Selection
○ Gob Gas Venthole Production Performance Prediction

Fig. 2. Model selection window of the methane control tool kit software.

interest of the geosciences and methane control/production community. The technical information related specifically to the development of each model will be kept at minimum and will be presented in the next section. Interested readers are referred to Karacan (2008, 2009a, 2009b, 2009c) for more detailed information on the development of these techniques, which utilize various statistical, mathematical approaches, prediction and classification artificial neural network (ANN) methods (Davis, 1986; Grima, 2000; Grima et al., 2000; Hardy and Beier, 1994; Krishnamoorty, 2006; Maier and Dandy, 2000).

3. Brief technical information and applications of the prediction modules

3.1. Module: coal measure rock mechanical properties prediction

This module predicts the dynamic elastic properties of coal-measure rock, which can help mining operations understand properties of the gob and make decisions about both roof support and methane control.

The module calculates shear and elastic (Young's) moduli of a formation using the information from basic gamma ray (GR) and density (DL) well logs. The shear modulus is the material's response to shearing stresses, such as friction, while Young's modulus is a material's response to linear stresses and strains. Young's modulus can also be used as an indicator of the stiffness of the material and of its yield strength. Higher values for Young's modulus typically represent stiffer materials.

Dynamic elastic properties can be directly measured by employing full wave sonic logs in the boreholes and by determining the transit times for primary and secondary waves in a full wave train. However, obtaining sonic logs from boreholes requires that the borehole be uncased and filled with water (Takahashi et al., 2006). Sonic logs may not be available in all situations, or may be too costly to obtain. Gamma ray and density logs are commonly run on exploration holes and are simple to conduct with few special conditions; therefore, this information is usually readily available. The presented approach and the associated software evaluates the "in-situ" rock elastic properties of coal-measure rocks for prediction purposes with reasonable accuracy (Table 1). These outputs are used for strata and fracturing and gob caving assessments for gas control and roof support. A statistical analysis was preformed including mean square error (MSE), Absolute error (Abs error) and R.

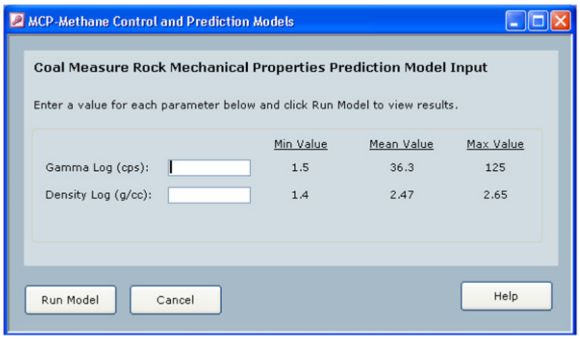
The prediction method developed for the dynamic elastic properties of rocks is based on processing the GR and DL logs by Fourier transforms, fractal statistics (fGn-fractional Gaussian noise and fBm-fractional Brownian motion), and then modeling using radial basis functions (RBF). The development detail of this model is given in Karacan (2009a).

3.1.1. Use and application of coal measure rock mechanical properties prediction module

Fig. 3 shows the input screen for the coal measure rock mechanical property calculation model. The model uses the data from gamma ray and density logs as inputs and calculates shear modulus and Young's modulus for the depth or strata of interest. The gamma ray and density log values from exploration boreholes are used to determine coal quality but are also used to assess the strength and possible geological abnormalities of the ore and the surrounding strata. Fig. 4 shows the output table obtained after using this model.

Table 1
Accuracy of performance measure for dynamic elastic properties.

Performance measure	Shear-modulus	Young-modulus
MSE	0.0894	0.2906
Nominal MSE	0.3089	0.1592
Mean Abs error (GPa)	0.2209	0.4213
Min Abs error (GPa)	0.0001	0.0100
Max Abs error (GPa)	1.0228	2.0058
R	0.8337	0.9183

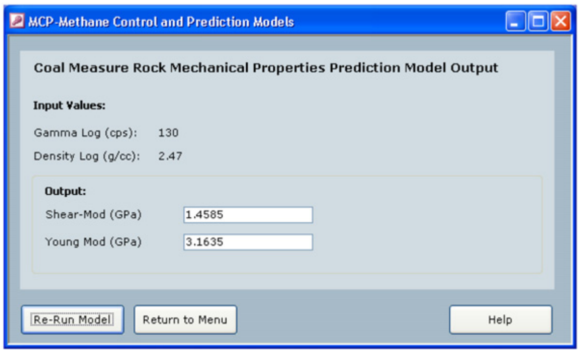


Coal Measure Rock Mechanical Properties Prediction Model Input

Enter a value for each parameter below and click Run Model to view results.

		Min Value	Mean Value	Max Value
Gamma Log (cps):		1.5	36.3	125
Density Log (g/cc):		1.4	2.47	2.65

Fig. 3. Input screen for coal measure rock mechanical properties prediction model.



Coal Measure Rock Mechanical Properties Prediction Model Output

Input Values:
Gamma Log (cps): 130
Density Log (g/cc): 2.47

Output:
Shear-Mod (GPa) 1.4585
Young Mod (GPa) 3.1635

Fig. 4. Output screen for coal measure rock mechanical properties prediction model.

Although not explicitly programmed in this software, the shear and elastic (Young's) moduli can then be used to determine the bulk modulus and Poisson's ratio using the following relations:

$$E = 2G(1+\sigma)$$

$$K = \frac{E}{3(1-2\sigma)}$$

where E is the Young's modulus (GPa), G is the shear modulus (GPa), K is the bulk modulus (GPa) and σ is the Poisson's ratio (psi/psi).

Fig. 5 shows the results of a sensitivity study in which gamma ray and density log values were used to obtain different values of Young's and shear moduli. The figure shows that as the gamma ray reading increases, both Young's modulus and shear modulus decrease, indicating the presence of clays and higher natural radioactivity. This data is consistent with weaker rocks, such as shales. Stronger rocks, on the other hand, exhibit higher values of Young's modulus, density, and shear modulus and a lower gamma ray value, which is consistent with sandstones and limestones (Karacan, 2009d). These different kinds of overlying rock will impart different characteristics to the gob and have implications for methane control measures. Also, knowing the types of rocks and their elastic properties will improve the understanding of caving behavior of overlying formations and the basic requirements for better roof-support design.

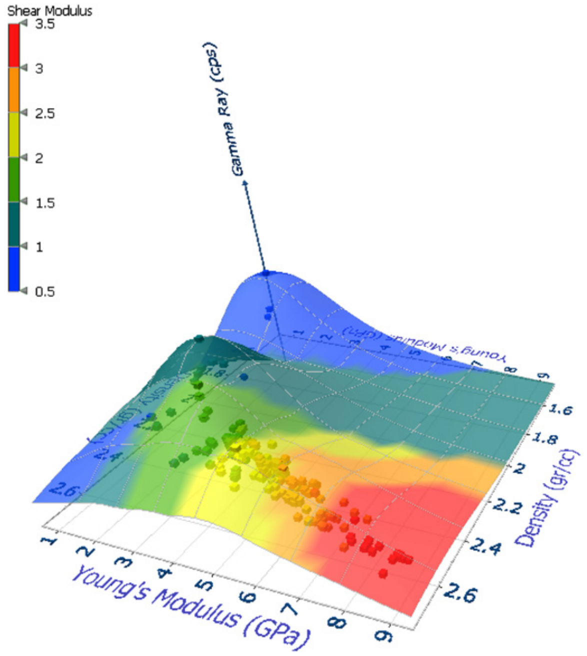


Fig. 5. Surface plot created from a graphics program showing shear modulus (GPa) and Young's modulus (GPa) outputs obtained using different density (g/cc) and gamma ray (cps) input values. The data points are shown under the surface as dots.

Table 2
Factor loadings of the variables after rotating the principle component (PC_R) matrix using Kaiser's varimax rotation. Bold entries show the most influential variables in each PC_R.

Variables	PC_R 1	PC_R 2	PC_R 3	PC_R 4	PC_R 5
Degasification	0.472	0.221	0.163	0.245	**0.538**
Basin	−0.287	−0.007	**0.917**	−0.136	−0.145
State	0.002	0.049	**0.951**	−0.196	0.002
Seam height	0.064	0.113	−0.093	**0.925**	−0.063
Cut height	0.048	−0.027	−0.225	**0.911**	−0.043
Panel width	0.036	**0.798**	−0.006	0.004	−0.029
Panel length	−0.248	**0.701**	0.093	−0.202	0.052
Overburden	**0.808**	−0.075	−0.129	0.108	0.121
Number of entries	0.271	−0.178	−0.045	−0.224	**0.805**
Cut depth	0.125	**0.745**	0.056	0.142	−0.076
Face conveyor speed	0.145	**0.834**	0.116	0.056	−0.167
Stage loader speed	0.147	**0.811**	−0.048	0.070	0.105
Lost+desorbed gas	**0.954**	0.024	−0.187	0.065	−0.011
Residual gas	−0.244	0.237	0.748	0.032	0.372
Total gas	**0.960**	0.077	−0.036	0.076	0.068
Rank	**0.907**	0.031	−0.174	−0.091	0.186
Coal production	−0.221	**0.688**	0.251	0.114	0.036

3.2. Module: mine ventilation emissions prediction

This module uses an artificial neural network (ANN)-based methodology to predict ventilation emissions from longwall mines. Ventilation emissions data obtained from different U.S. mining regions were combined with corresponding coalbed properties, geographical information, longwall operation parameters, and productivities to create a database. The database was analyzed using principle component analysis (PCA) to reduce complexity and to determine the most influencing variables for ANN modeling (Grima, 2000). Table 2 shows the results of PCA after Kaiser's varimax rotation and the most influencing parameters for ANN modeling.

Table 2 gives not only the loadings of each variable in rotated components (PC_R), but also shows how the variables are separated between columns according to their characteristics or to the properties that they represent. The table shows that the first PC_R is mostly related to gas content of the mined coalbed with both overburden and rank positively correlated with total and lost plus desorbed gas contents. The highest loading is from total gas content (0.960), followed by lost plus desorbed gas (0.954), rank (0.907), and overburden thickness (0.808). The second PC_R represents longwall panel dimensions, coal productivity, and underground coal transportation. In this group, face and stage loader conveyer speeds have the highest loadings (0.834 and 0.811, respectively), followed by longwall panel width, cut depth, and panel length. The loading of coal production is less. Based on the results of PCA and comparative evaluation of various input parameters for their influence on the results, total gas content, panel width, face conveyor speed, coal production, state, seam height, cut height, stage loader speed, and number of entries were selected as the input variables for the ventilation emission model.

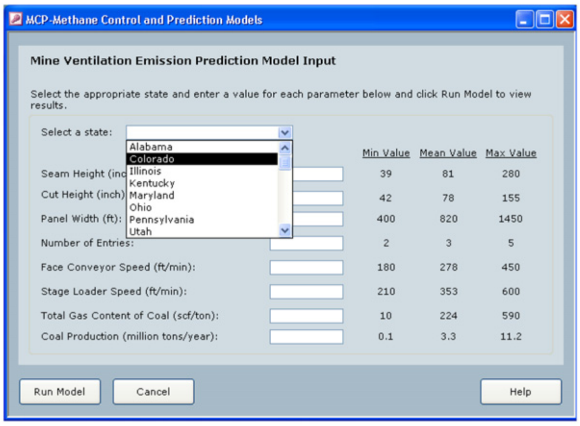
The ANN model was built using a multilayer perceptron (MLP) approach and was trained and tested using the database to achieve minimum mean square error (MSE) and high correlations (R) between measurements and predictions. Table 3 shows the performance parameters obtained from the testing stage of the developed network. For detailed information, readers are requested to refer to Karacan (2008).

3.2.1. The use and application of mine ventilation emissions prediction model

This module calculates the predicted ventilation methane emissions from a longwall mine located in one of a pre-determined list of coal producing states (or in basins that are characteristically similar in geology to one of the states). The prediction of methane emissions is based on the location of the mine and a set of mining and geological conditions that most affect the ventilation emissions as determined by PCA. The pre-determined list of states is available in a pull-down menu on the input screen (Fig. 6), along with other required inputs.

Table 3
Testing performance of the final ANN model used in the software after optimizing its network parameters.

Performance parameter	
MSE	1.613
NMSE	0.086
Min. error (MMscf/day)	0.003
Max. error (MMscf/day)	3.087
R	0.956



Mine Ventilation Emission Prediction Model Input

Select the appropriate state and enter a value for each parameter below and click Run Model to view results.

Select a state:

	Min Value	Mean Value	Max Value
Seam Height (inch):	39	81	280
Cut Height (inch):	42	78	155
Panel Width (ft):	400	820	1450
Number of Entries:	2	3	5
Face Conveyor Speed (ft/min):	180	278	450
Stage Loader Speed (ft/min):	210	353	600
Total Gas Content of Coal (scf/ton):	10	224	590
Coal Production (million tons/year):	0.1	3.3	11.2

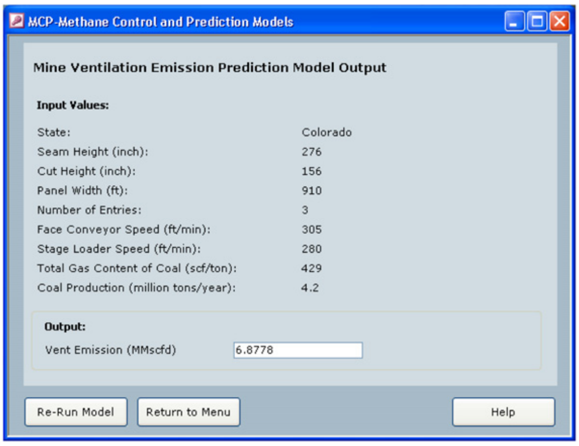
Fig. 6. Input screen for mine ventilation emissions prediction model.

The output screen gives the values of the input parameters and the predicted methane emissions in millions of cubic feet of methane per day (MMsfc/day). To run the model again with different conditions, the user can select the “re-run model” option (Fig. 7).

Fig. 8 shows information from application of the mine ventilation emissions prediction model conducted for mines operating in different states with different mining and geological conditions.

Mines in West Virginia, Alabama, and Virginia have the highest gas content, and therefore a higher emissions rate from their respective ventilation systems. These mines have lower yearly coal production and a higher ventilation air flow to lower the concentration of methane in the ventilation air. The gas content of the coal seams mined in Pennsylvania, Ohio, Maryland, Kentucky, Illinois, and Colorado are relatively lower, and thus the mines in these states have lower ventilation emissions and higher production compared to the West Virginia, Alabama, and Virginia mines.

The output of this module, total predicted ventilation emissions in millions of cubic feet per day, can be helpful in determining the needs of multiple projects in the mine. For example, having a good estimate of the total methane output can provide the operator with information to size a ventilation fan or to determine a ventilation strategy.



Mine Ventilation Emission Prediction Model Output

Input Values:

State: Colorado
Seam Height (inch): 276
Cut Height (inch): 156
Panel Width (ft): 910
Number of Entries: 3
Face Conveyor Speed (ft/min): 305
Stage Loader Speed (ft/min): 280
Total Gas Content of Coal (scf/ton): 429
Coal Production (million tons/year): 4.2

Output:

Vent Emission (MMscfd) 6.8778

Fig. 7. Output screen for mine ventilation emissions prediction model.

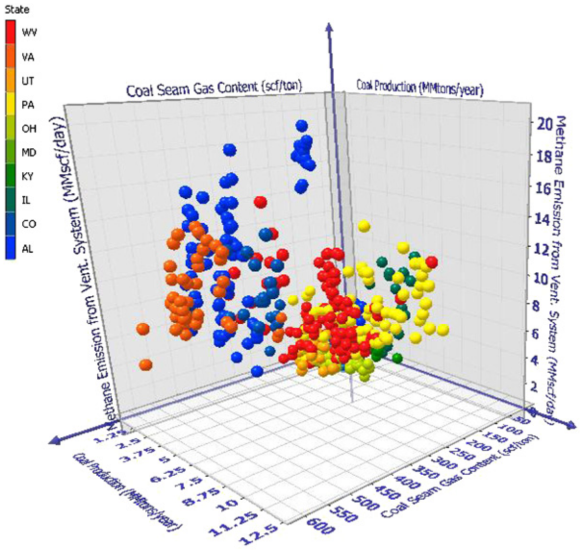


Fig. 8. 3-D graph showing the predicted mine emissions (MMscf/day) from mines in various states as a function of coal seam gas content (scf/ton) and coal production (MMtons/year).

3.3. *Module: degasification system selection*

Since ventilation alone may not be sufficient to control the methane levels on a longwall operation, gob gas ventholes (GGV, or G), horizontal (H) and vertical drainage boreholes (V), or combinations of these systems (HG or VHG) are drilled and used as supplementary methane control measures. In most cases, mining operations base their choice of degasification system on previous experiences, sometimes without analyzing the different factors that may have affected these decisions.

Table 4 shows the rotated matrix for five components (PC_R) and the factor loadings for each variable during PCA. This table also shows how the variables are separated between columns according to their characteristics. Table 4 shows that the first PC_R is mostly related to gas content of the mined coalbed, overburden rank, and the methane emissions. The highest loading is from total gas content (0.962), followed by lost plus desorbed gas (0.949), rank (0.917) and overburden thickness (0.817). Emissions measured from the ventilation system have a loading of 0.646. Selection of a degasification system is a direct consequence of emissions or the capacity of the ventilation system. Thus, it should be included in any model. The second PC_R is weighted by longwall panel dimensions, cut depth, and coal production. In this group, panel width and coal production have the highest loadings (0.820 and 0.755), followed by longwall panel length (0.751), and cut depth (0.721). The third PC_R in Table 4 represents the coalbed and mining heights, where their loadings are 0.939 and 0.917, respectively. The fourth PC_R in Table 4 is related to geographical location of the mine determined by state and coal basin. They are the only variables in the database that may be linked to the impact of underground geology on emissions from overlying strata. Their loadings in this PC_R are 0.952 and 0.907, respectively. However, since a coal basin can be present in more than one state and underground geology may change based on geographical location, the state variable is more localized and seems to be a better identifier for this purpose. The fifth PC_R represents the number of gateroad entries.

Based on the results given in Table 4, and comparison tests performed with the ANN, total gas content, panel width, coal production, state, seam height, cut height, overburden thickness and ventilation emissions were selected as the input variables for the degasification system identification model.

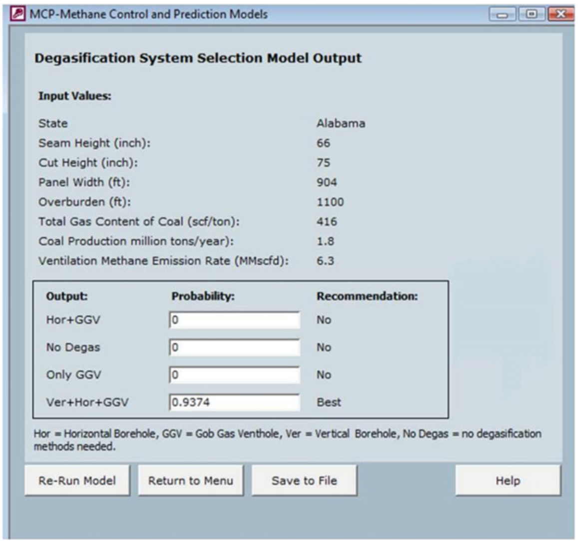
The ANN-based classification model was built using a multilayer perceptron (MLP) approach to map the inputs to four different degasification options outputting the “best” option with the highest probability. Such a model can be used as a decision tool

Table 4
Factor loadings of the variables after rotating the principle component matrix using Kaiser's varimax rotation. Bold entries show the most influential variables in each rotated principle component (PC_R).

Variables	PC_R 1	PC_R 2	PC_R 3	PC_R 4	PC_R 5
Basin	−0.296	0.010	−0.137	**0.907**	−0.133
State	−0.004	0.037	−0.198	**0.952**	−0.020
Seam height	0.070	0.076	**0.939**	−0.078	−0.070
Cut height	0.054	−0.036	**0.917**	−0.211	−0.067
Panel width	0.100	**0.820**	0.035	0.011	−0.059
Panel length	−0.187	**0.751**	−0.192	0.105	−0.035
Overburden	**0.817**	−0.083	0.112	−0.124	0.131
Number of entries	0.276	−0.158	−0.168	0.022	**0.853**
Cut depth	0.186	**0.721**	0.118	0.064	−0.272
Lost+desorbed gas	**0.949**	−0.054	0.067	−0.173	−0.031
Residual gas	−0.212	0.279	0.042	**0.777**	0.285
Total gas	**0.962**	0.002	0.080	−0.016	0.029
Rank	**0.917**	−0.011	−0.082	−0.163	0.193
Coal production	−0.173	**0.755**	0.121	0.213	0.061
Ventilation emission	**0.646**	0.339	0.104	−0.251	0.369

Table 5
Testing performance of the final ANN model (Figure C-10) after optimizing network parameters.

ANN Output	HG (Horizontal +GVB)	N (None)	G (GVB)	VHG (Vertical+ Horizontal+GVB)
HG	21 (True)	3 (False)	1 (False)	0
N	0	29 (True)	2 (False)	0
G	1 (False)	0	12 (True)	0
VHG	0	0	0	12 (True)
% Correct	95.5	90.6	80.0	100.0



MCP-Methane Control and Prediction Models

Degasification System Selection Model Output

Input Values:

State	Alabama
Seam Height (inch):	66
Cut Height (inch):	75
Panel Width (ft):	904
Overburden (ft):	1100
Total Gas Content of Coal (scf/ton):	416
Coal Production million tons/year):	1.8
Ventilation Methane Emission Rate (MMscfd):	6.3

Output:	Probability:	Recommendation:
Hor+GGV	0	No
No Degas	0	No
Only GGV	0	No
Ver+Hor+GGV	0.9374	Best

Hor = Horizontal Borehole, GGV = Gob Gas Venthole, Ver = Vertical Borehole, No Degas = no degasification methods needed.

Fig. 9. Output screen for degasification system selection model. This particular scenario resulted in a “best” recommendation for a system using vertical and horizontal boreholes plus GGVs.

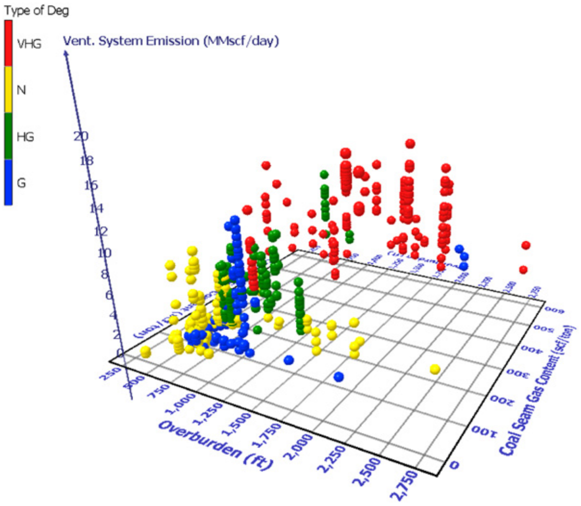


Fig. 10. 3-D scatter diagram showing the distribution of the type of degasification system (type of Deg) as a function of overburden depth (ft), coal seam gas content (scf/ton), and ventilation system emissions (MMscf/day).

for selection of a degasification system and can also be used as a screening or planning model. Based on the performance of the network with different elements, the final network had two-hidden layers with 48 and 28 processing elements, hyperbolic tangent and softmax axon as the transfer functions, a momentum term of 0.7 and a training epoch of 1500. Table 5 gives the performance of the classification network that was developed and implemented in the software for degasification system identification. The detailed explanation of the development of this model is included in Karacan (2009b).

Degasification systems have become necessary due to their ability to remove most of the gas from the coal seam prior to mining, allowing operations to safely extract the coal. Currently, mines use different methods to find the most cost-effective way to mine safely and efficiently. With a selection model now available to design degasification plans, the mining operation can more precisely and efficiently choose methods that will maximize degasification and minimize methane-induced ventilation issues.

This module uses an ANN-based expert classification system to identify the need and the type of degasification system best suited for a particular longwall operation. The ANN-based classification model was built using a multilayer perceptron (MLP) approach to map the inputs to four different degasification options and output the probabilities of each output options, as reviewed in the application section given in 3.3.1. The model can be used as a decision tool for selection of a degasification system and as a screening or planning model. For a detailed explanation of the development of this model, see Karacan (2009b).

3.3.1. *The use and application of degasification system selection model*

This expert classification system identifies the need and the type of degasification system for a longwall operation given mine-specific inputs. The model maps the inputs to four different degasification options:

- ○ N: No degasification needed
- ○ G: Gob gas venthole only
- ○ HG: Horizontal boreholes and gob gas ventholes
- ○ VHG: Vertical boreholes, horizontal boreholes, and gob gas ventholes.

As in the emissions prediction module, the user must select the state from the pull-down menu on the input screen, and enter additional coal and mining characteristics. When the model is executed, it calculates the choice probabilities for available degasification systems based on the inputs given, and maps the probabilities to the four degasification systems.

The output screen for this module shows input information, the calculated probabilities for each system, and whether the system is recommended (Fig. 9). The system with the highest positive probability calculated is labeled “best” in the recommendation column. Recommended “best” option in this module indicates the degasification system choice with highest probability of successfully removing methane from the mine environment.

Fig. 10 shows that the mines operating in coal seams with higher gas content and under mid to high overburden depth require a more extensive degasification system comprised of vertical degasification holes, horizontal degasification holes, and gob gas ventholes (shown in red as VHG in this figure), while mines operating in coal seams with less gas content and in shallower depths do not need multiple degasification techniques (N: none needed or G: GGVs only) to supplement their ventilation system. Mines operating in overburden depths from 750 to 1250 ft and in coal seams with gas contents less than 200 scf/ton typically have ventilation emissions from 1 to 10 MMscf/day. These mines are good candidates for degasification systems shown in both blue (G: GGVs only) and green (HG: Horizontal boreholes and GGVs).

Fig. 11 shows the results of comparing the overburden (ft), panel width (ft), and production (tonnes/year) to the type of degasification system recommended. It can be seen that the program predicts

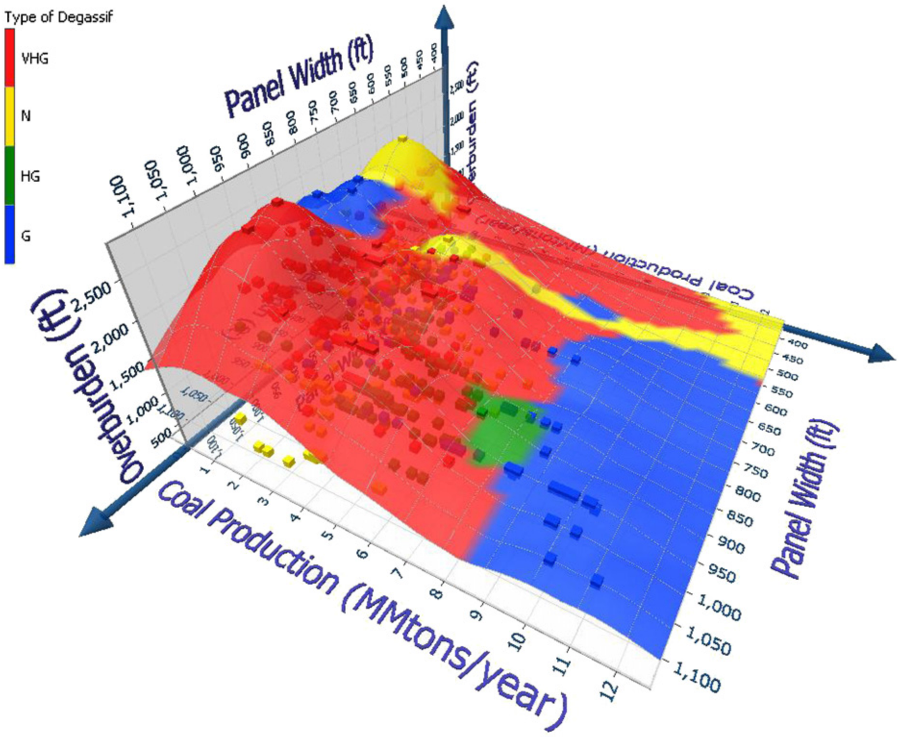


Fig. 11. 3-D Surface diagram showing the overburden (ft), coal production (MMtons/year), panel width (ft), and the type of degasification method suggested (type of degassif) using the degasification system selection module. The data points are shown under the surface as dots.

that mines in the mid to high range of overburden depths should have more extensive degasification systems, while mines in lower overburden have minimal degasification, which indicates that the coals have lower gas contents. This prediction is consistent with mining experience: deeper coals tend to be gassier than shallower coals. Fig. 11 also shows that mines with lower gas emissions have higher coal production rates and do not always need degasification systems.

3.4. Module: gob gas venthole production performance prediction

Gob gas ventholes are used to help control methane inflows into a longwall operation by capturing it before it enters the ventilation system. It is important to understand the effects of various factors, such as drilling parameters, location of borehole, applied vacuum, and mining/panel parameters to evaluate the performance of GGVs and to predict their effectiveness in controlling methane emissions. Until the development of MCP, a practical model for this purpose did not exist. This module develops an ANN-based methodology to predict GGV production rates and methane concentrations based on venthole location, mining parameters, borehole location with respect to panel and surface terrain, and exhauster pressure. Detailed information is given in Karacan (2009c).

Various factors affect the performance of gob gas ventholes producing from an active or completed mine. Table 6 shows the sensitivity values of outputs to these various inputs, as well as the total sensitivity in standard deviations about the mean due to sensitivities of gas flow rate and methane percentage to inputs when they are considered together. The average total sensitivity was calculated as the arithmetic average of third data column in Table 6, which gave a value of 33.8. For the sake of this analysis, the total sensitivity values above this average of 33.8 were considered as high sensitivities of gob gas venthole performance to the corresponding input variables. According to this approach and the data in Table 6, (a) face advance (whether it is advancing or not), (b) percentage of the panel that has been mined, (c) surface elevation of the venthole (above sea level), (d) casing diameter, (e) distance of the venthole to the tailgate, (f) distance of venthole to panel start, and (g) panel length are more influential for the venthole performance.

Table 6
Sensitivity (in standard deviations) of performance parameters (gas flow rate and percent methane) to individual input parameters used in this model and the total sensitivity (third column) when both performance parameters are combined. Bold values are the total sensitivity above the average sensitivity value (33.8) calculated using all inputs.

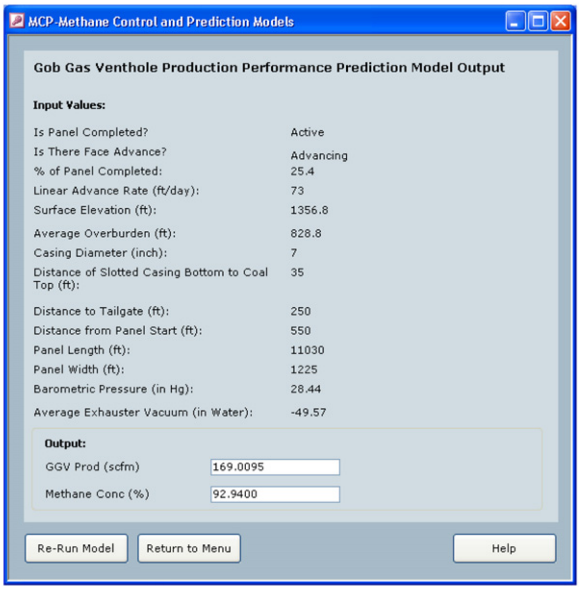
Input variable	Gas flow rate	Percent methane	Total (Std. dev.)
Panel completed (Yes)	13.1	8.1	21.2
Panel completed (No)	28.2	3.6	31.9
Is face advancing? (No)	24.3	10.3	**34.7**
Is face advancing? (Yes)	18.7	0.3	19.0
% of panel mined	45.2	3.1	**48.3**
Linear advance rate	7.5	1.4	8.9
Surface elevation	34.4	6.6	**41.0**
Overburden	16.1	4.2	20.3
Casing diameter	81.2	4.4	**85.6**
Casing distance to coalbed	7.7	2.2	10.0
Distance to tailgate	67.7	1.7	**69.5**
Distance from panel start	52.3	12.2	**64.5**
Panel length	37.7	4.3	**41.9**
Panel width	5.1	1.4	6.5
Barometeric pressure	14.0	0.6	14.6
Average vacuum at wellhead	22.1	1.9	24.0

It is important for methane control to have a practical model to decide the design parameters of a GGV before drilling it, or to respond to an emerging situation by changing some of the operating parameters. However, a practical model for these purposes currently does not exist. The aim of this software module is to develop an ANN-based methodology to predict gob gas venthole production rates and methane concentrations based on venthole location, mining parameters, borehole location with respect to panel and surface terrain, and exhauster pressure.

For this purpose, a two-layer ANN model with 22 processing elements in the first hidden layer and with 16 processing elements in the second hidden layer was developed. Hyperbolic tangent activation function, ''Tanh,'' between the layers with momentum parameters of 0.7 and 2500 iterations were also used. Table 7 gives the performance of the network model that was used and programmed into this module to predict production performance of the GGVs. Detailed information is given in Karacan (2009c).

Table 7
Predictive performance of the GGV performance prediction network obtained during testing phase.

Performance indicator	Total flow scf/day	Percent methane
Nominal MSE	0.13569	0.08595
Mean Abs error	1235.92	3.52427
Min Abs error	166.91	0.02904
Max Abs error	20,628.04	24.2980
R	0.930	0.956



Gob Gas Venthole Production Performance Prediction Model Output

Input Values:

Is Panel Completed?	Active
Is There Face Advance?	Advancing
% of Panel Completed:	25.4
Linear Advance Rate (ft/day):	73
Surface Elevation (ft):	1356.8
Average Overburden (ft):	828.8
Casing Diameter (inch):	7
Distance of Slotted Casing Bottom to Coal Top (ft):	35
Distance to Tailgate (ft):	250
Distance from Panel Start (ft):	550
Panel Length (ft):	11030
Panel Width (ft):	1225
Barometric Pressure (in Hg):	28.44
Average Exhauster Vacuum (in Water):	-49.57

Output:

GGV Prod (scfm)	169.0095
Methane Conc (%)	92.9400

Fig. 12. Output screen from the gob gas venthole production performance model, showing the predicted total gas flow rate (scfm) and methane concentration (%) from a GGV and the associated input data.

3.4.1. *The use and application of GGV production performance prediction model*

This module calculates the total gas production rates and the methane concentrations in the produced gas stream of the GGV based on venthole location in the panel, mining parameters, venthole location with respect to panel and surface terrain, and applied exhauster pressure. The input screen requires the panel status (active or completed), face status (advancing or idle), venthole location data, venthole completion parameters, and the operational properties of its exhauster. The model output is GGV total production in scfm and methane concentration percentage (Fig. 12).

Scenarios with various input parameters were analyzed to test the outputs and the sensitivity of the model. One scenario analyzed the relationships between distance of the GGV from the start of the panel, GGV total production rate, panel length, and linear face advance (Fig. 13). The analysis shows that the GGV has a higher production rate when operating above a longwall with a length of 9500–12,000 ft and with a linear advance rate greater than 30 ft/day. When varying the length of the longwall block and linear advance rate, the variable ''GGV distance from the start'' did not seem to have a great impact on the output values. MCP allows the user to keep the other variables constant while changing the GGV distance from the panel start, and therefore can show how this variable can influence both GGV production and methane percentage.

Another scenario analyzed methane concentration (Fig. 14). The highest predicted methane concentrations occurred at the start and end of the longwall panels. The largest concentration was predicted at the beginning of the panel and with a linear advance rate between 25 and 30 ft/day. This is not surprising, because the first GGV in a panel has a larger reservoir of easily accessible methane primarily due to abutment effects at the ends of the longwall panel than GGVs in other locations along the panel. A higher predicted concentration of gas and production rate is also visible at the end

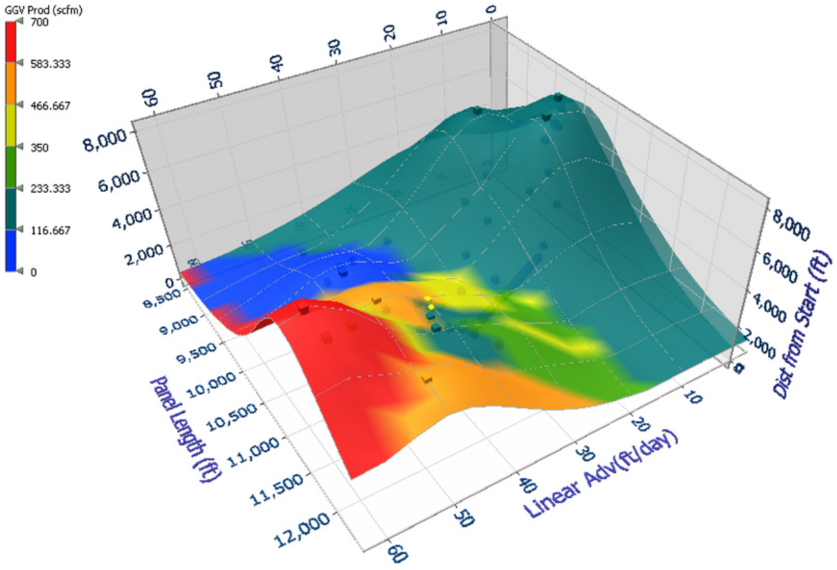


Fig. 13. Surface diagram showing the distance of the GGV from the start of the panel (ft), gob gas venthole (GGV) total production rate (scfm), panel length (ft) and linear face advance (ft/day) obtained using the GGV production performance prediction module. The data points are shown under the surface as dots.

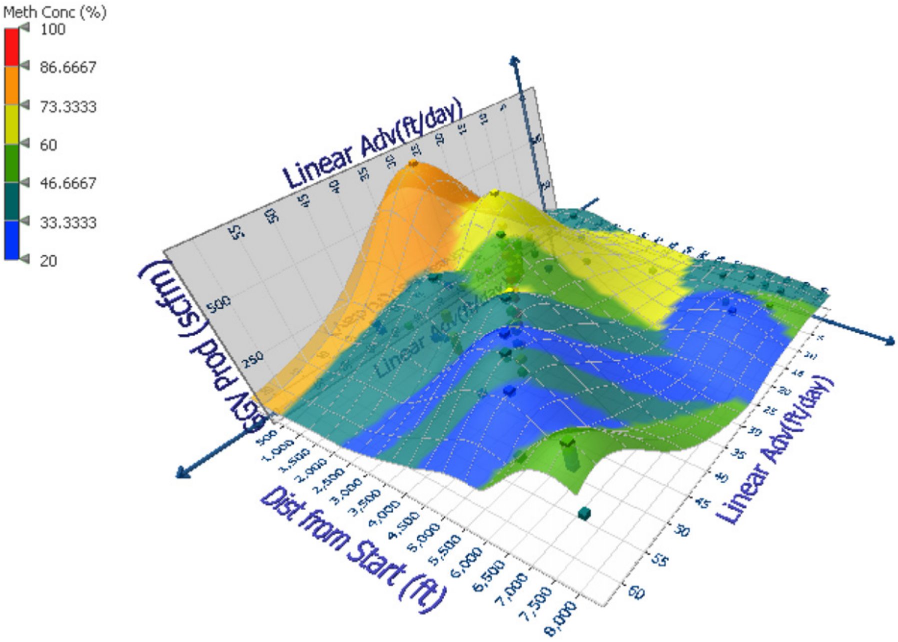


Fig. 14. Surface diagram showing the distance of the GGV from the start of the panel (ft), gob gas venthole (GGV) total production rate (scfm), linear face advance (ft/day), and methane concentration (meth conc) from GGV (%) obtained using the gob gas venthole production performance prediction module. The data points are shown under the surface as dots.

Table 8
Conversion factors for converting English units to SI units

Name of unit	Symbol	Definition	Relation to SI units
atmosphere (standard)	atm		≡101 325 Pa
cubic foot	cu ft	≡1 ft × 1 ft × 1 ft	≡0.028 316 846 592 m^3
cubic foot per minute	CFM	≡1 ft^3/min	=4.719474432 × 10^{-4} m^3/s
foot (International)	ft	≡(1/3) yd≡0.3048 m≡12 inches	≡0.3048 m
foot per minute	fpm	≡1 ft/min	=5.08 × 10^{-3} m/s
inch (International)	in	≡1/36 yd≡1/12 ft	≡0.0254 m
inch of mercury (conventional)	inHg	≡13 595.1 kg/m^3 × 1 in × g	≈ 3.386 389 × 10^3 Pa
inch of water (39.2 °F)	inH_2O	≈ 999.972 kg/m^3 × 1 in × g	≈ 249.082 Pa
pound per square inch	psi	≡1 lbf/in^2	≈ 6.894 757 × 103 Pa
ton, short	sh tn	≡2 000 lb	=907.184 74 kg

of the panel further from the start. As with the first GGV, this indicates that there is a larger gas reservoir from which the GGV can produce.

4. Conclusions

In this paper, NIOSH's new MCP (methane control and prediction) software has been introduced with brief details of its development and with applications of methane control and methane emissions predictions. The software modules, used together or separately, can help mining operations predict and control longwall methane drainage. MCP software can calculate the elastic and shear moduli of coal-measure rock and the total ventilation output of methane. Both can help to determine if the methane can be captured and controlled safely and allow time to develop control measures to more effectively ventilate working areas. The degasification system selection module determines the safest way to degasify a longwall mine with given characteristics using proven techniques. Finally, MCP can predict the performance of gob gas ventholes and accurately determine the impacts of drilling/exhauster parameters, borehole location, and mining parameters on GGV performance.

Previously, there were no simple ways to estimate and plan for methane drainage and emissions, other than from past experience in a specific coal seam or at a certain operation. Numerical modeling techniques were available, but could be very time consuming and could require expertise to use them. The MCP software is a practical, new way to predict methane drainage, estimate ventilation emissions, plan methane drainage techniques, and predict the effectiveness of GGVs. The applications of the MCP software modules for methane control-related problems can help improve the safety of mines and the underground workforce.

5. International unit conversions

See Table 8.

Disclaimer

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company or product does not constitute endorsement by NIOSH.

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