Evaluation of the relative importance of coalbed reservoir parameters for prediction of methane inflow rates during mining of longwall development entries

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Abstract

This study presents a reservoir modeling approach to investigate the relative effects of different coalbed parameters on the migration of methane into development entries. A base coalbed reservoir model of a three-entry development section, where grids were dynamically controlled to simulate the advance of mining at a constant section advance rate, was created and calibrated for a Pittsburgh Coalbed mine in the Southwestern Pennsylvania section of the Northern Appalachian Basin. The values of coalbed parameters were varied to evaluate their effects on predicted methane emissions for various development distances.

The results of these parametric simulations were then used to derive linear expressions relating these parameters to methane emissions into the workings. These models were analyzed to assess their significance and adequacy for predictive purposes. This work shows that coupling reservoir simulations with linear modeling yield a technique that can be applicable to different coalbeds. The reservoir parameters used by the linear models (coalbed thickness, pressure, sorption time constant, Langmuir parameters, permeability) can be determined by running relatively simple laboratory tests, such as adsorption equilibrium and permeability determination, on coal samples obtained either from the mining operation or from the exploratory boreholes drilled ahead of mining.

1. Introduction

High methane liberation rates experienced during development mining can result from the intrinsic properties of the coalbed reservoir or from properties of the mining operation such as mining rate, mining height, and entry length, to name a few. In the case of unexpectedly high methane emissions and subsequent increases in methane levels, mining activity must be either slowed or stopped until these high levels are diluted and removed from the active workings by the ventilation airflow. Unfortunately, the emission rates are controlled not only by changes in mining parameters, but also by changes in the coalbed reservoir parameters. Other than increasing ventilation airflow, there are few means available for offsetting the effects of high methane

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emissions originating as a result of the intrinsic properties of the coalbed. Since all coalbeds differ in their gas storage and flow characteristics, the ability to predict the methane emissions based on a wide range of coalbed reservoir parameters can lead to more efficient ventilation system designs.

The recognition of methane in coalbeds as a valuable resource has led to the development of different numerical approaches for modeling the storage and flow mechanisms of gas and water in coal seams (King and Ertekin, 1991). The gas storage and transport mechanisms of coalbeds are complex and interacting. In order to simplify these mechanisms and the resultant model, Gilman and Beckie (2000) developed a coalbed methane model whose parameters were combined into a few dimensionless parameters. They used that model to evaluate the importance of some coalbed parameters on methane migration. Due to the complexity and non-linearity of the equations, Zhao and Valliappan (1995) have proposed a finite-element approach instead of the commonly used finite-difference schemes where the pressure and concentration of methane due to gas migration in the coalbeds were simulated (Valliappan and Wohua, 1996). However, finite-difference-based, pseudo-steady and unsteady-state models described by King and Ertekin (1991) continue to be the most widely accepted and applied techniques for simulating the complex storage and transport processes in coalbeds, since these type of models can realistically represent the complex matrix-fracture transport processes in the coalbeds.

The application of reservoir models for predicting field performance of production wells was proven to be successful in different field cases and helped develop this additional energy resource (Ertekin et al., 1988; Zuber, 1998; Young et al., 1991). These models offered advanced predictive capabilities for the benefit of the mining industry through evaluation and design of degasification wells (King et al., 1986; Brunner et al., 1997; Maricic et al., 2005). The reservoir modeling techniques, incorporating strata disturbances and moving boundary conditions have also been applied to the complex situations of methane control from gob areas and for predicting the performances of gob gas ventholes under different completion and panel design situations (Karacan et al., 2005, 2007). Reservoir modeling was also demonstrated as a versatile technique for prediction of methane inflow into development entries (Zuber, 1997). Karacan (2007) used a coalbed reservoir modeling approach with moving boundary formulation to optimize ventilation air requirements with and without degasification boreholes in the case of development mining and integrated the results with artificial neural network approach as an optimization method. As an alternative approach, Lunarzewski (1998) developed and used the "Lunagas" method of gassiness prediction based on research results and on empirical results of the intensity of gas release per unit area of exposed coal and the decay of gas release with time.

Field demonstrations of coalbed methane reservoir simulators for project development and economics led to investigations into the impacts of various coalbed parameters as controlling factors for the performance of production wells. The impacts of coalbed parameters on methane production were investigated using commercial and research reservoir simulators (Zuber et al., 1987; Young, 1998; Remner et al., 1986; Young et al., 1992). It was reported that some parameters were more influential than others. As a result of their parametric studies on a field case, Zuber and Olszewski (1992, 1993) stated that the coalbed parameters with the greatest impact on methane simulation forecasts were adsorbed gas content, desorption isotherm, water saturation, coalbed thickness, permeability, and porosity.

Similar parametric studies have not been conducted for determining the relative importance of coalbed parameters for controlling methane on longwall or development mining sections. Reservoir models can be extended to include the properties of the mining environment and can define the effects of each coalbed parameter or combination of parameters on methane inflow into mine workings. Such simulations can help answer specific questions related to mine ventilation. However, reservoir modeling may require sophisticated simulation packages and expertise to use and interpret them, which may not be available to most mine operators. Simpler, yet predictive, models will be helpful to mine operators to quantify emissions into mine entries from a coalbed whose critical properties can be determined through simple laboratory testing. Thus, multiple-factor linear models augmented by reservoir simulations can be valuable tools for predicting methane inflow into entries during development mining. Such models allow the assessment of the relationships between methane inflow rates and several independent coalbed parameters.

During the analysis, a linear combination of coalbed parameters that is maximally correlated with the methane inflow rates is developed. This gives a linear equation that predicts methane inflows using available coalbed parameters.

Multiple regression analysis allows assessment of the relationship between one dependent variable and several independent variables. However, when multiple independent variables contribute to the same dependent variable, it is sometimes difficult to predict how the dependent variable will change based on the changes in the independent variables. Also, the independent variables should be uncorrelated. In the case of highly correlated independent variables, large changes in the estimated regression parameters may occur when a variable is added or deleted (Sokal and Rohlf, 1994; Devore and Peck, 2001). It is also important to include significant variables and to exclude the non-significant ones that may mask the interpretation of the importance of the independent variables. Backward elimination is one of the multiple regression techniques that judges the importance of each independent variable based on its contribution to the dependent variable. This technique has an advantage over forward selection and stepwise regression because it is possible for a set of variables to have considerable predictive capability even though any subset of them does not. Forward selection and stepwise regression may fail to identify them. Because the variables do not predict well individually, they may never enter the model to have their joint behavior evaluated. Backwards elimination starts with all independent variables in the model, so their joint predictive capability can be evaluated (Motulsky and Christopoulos, 2004).

The objective of this work is to develop simple-to-use, yet accurate, predictive models for methane inflow into the entries during longwall development mining of coal seams by using reservoir simulation and multiple regression analysis techniques. This objective quantifies the sensitivity of methane inflow to different coalbed parameters and extends the predictions of the base model to other three-entry developments operating in different coalbeds as well as evaluating their significance and adequacy for predictions.

2. Reservoir modeling of development mining and methane emissions

The reservoir model was constructed using Computer Modeling Group's (Computer Modeling Group Ltd., 2003) compositional reservoir simulator (GEM) to simulate development mining of a three-entry tailgate and headgate and calibrated using the methane emission data measured in a mine operating in the Pittsburgh Coalbed (Fig. 1) operating in the Southwestern Pennsylvania section of the Northern Appalachian Basin. The grid values were controlled and the models were run "dynamically" to simulate advancing entry development. The models were calibrated for various entry lengths using in-mine measurements of methane inflow rates obtained during tailgate and headgate entry developments. In collecting this data, monthly averaged ventilation flow rates and air quantities were measured by mine personnel using methanometers and anemometers at the monitoring locations in belt and return entries shown in Fig. 1. Using airflow rate and methane concentrations in both sets of data, they calculated monthly averaged methane inflow rates during mining of headgate and tailgate entries. They also reported total linear distances advanced during mining and the clean and raw tonnages produced. The length of each

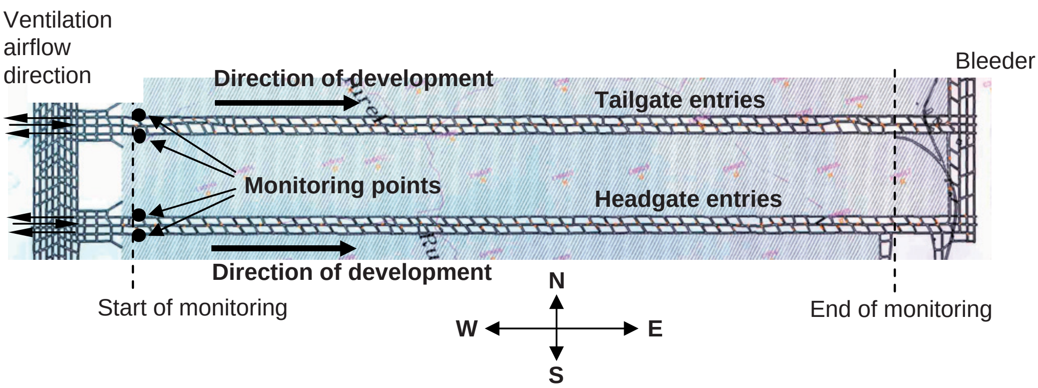

Fig. 1. Modeled longwall panel showing entry sections where mining and ventilation data were gathered during development mining.

entry section was around 11,000 ft (3353 m) and took 8 9 months to mine.

2.1. Coalbed reservoir and modeling parameters

The base model was a coalbed methane reservoir model where a single-layer coalbed was modeled in cartesian coordinates to simulate fluid flow in the unmined sections of the coalbed. In model construction, the base parameters given in Table 1 were used for the Pittsburgh Coalbed. These base parameters were used to match the predicted methane emissions during mining with the in-mine measurements.

The gas content and adsorption related data for the Pittsburgh Coalbed was obtained from the results of methane adsorption and direct method of gas content determination tests on various coal samples (Diamond et al., 1986). The spatial distributions of fracture permeabilities of the Pittsburgh Coalbed have not been previously established or reported. However, based on a large-scale modeling study involving estimation of some coalbed parameters (Karacan et al., 2005, 2007), the average permeabilities for the Pittsburgh coalbed were estimated to be 4 md in the face cleat direction and 1 md in the butt cleat direction. In the simulations, these values were taken to be uniform throughout the layer.

Table 1
Coalbed properties and their ranges used in simulations of development mining and statistical analysis of results

Parameter	Regression variable name	Values used in predictions
Coalbed thickness (ft)	Thick	5, 6[a], 7
Coalbed pressure (psi)	Pres	90[a], 200, 400
Sorption time (days)	S.Time	20[a], 125, 250
Permeability anisotropy (K_x/K_y)	Anisot.	4[a], 8
Face cleat permeability K_x (md)	K_x	4[a], 20, 40
Butt cleat permeability K_y (md)	K_y	0.5, 1[a], 2.5, 5, 10
Langmuir volume (scf/ton)	L.Vol.	200, 392, 490[a], 600
Langmuir pressure (psi)	L.Pres.	126, 326[a], 526
Initial water saturation S_{w_i} (%)	W.Sat.	40, 60[a], 100
Effective porosity (%)	Por.	0.5, 2, 4[a], 5
Irreducible water saturation $S_{w_{irr}}$ (%)	Irr.W.Sat.	10, 30, 40[a], 58
Relative permeability to gas (K_{rg}) at S_g 1 $S_{w_{irr}}$	G.Rel.Perm.	0.35[a], 0.5, 0.7, 0.9

[a]Base reservoir values used in developing the base simulation model.

Hunt and Steele (1991) indicated that the coalbeds in the Central and Northern Appalachian Basin are desaturated and depressurized due to geological history, extensive coal mining, and the presence of many oil and gas wells. Thus, initial water saturation and pressure of the Pittsburgh Coalbed in the Northern Appalachian Basin were estimated to be 60% and 90 psia (6120 kPa) for this study, respectively. These numbers correspond to 60% of the available coalbed porosity, mainly cleat porosity, as water saturated and 90 psia (6120 kPa) as the initial fluid pressure in the coalbed.

The gas relative permeability curve of the coalbed was estimated by matching the average gas production rate from the simulated boreholes in the models to the reported average methane production rates of three horizontal degasification boreholes in the mining area [8.42 scf/day/ft (0.782 m^3/day/m) from simulations vs. 8.70 scf/day/ft (0.807 m^3/day/m) from field measurements]. A similar field-data-based adjustment could not be made to the water relative permeability curve because no data was available. Thus, the relative permeability of water at initial water saturation was set low so the wells would experience low amounts of water [0.0016 bbl/day/ft (0.0015 m^3/day/m)] as saturation changes. Although this is an assumption for a desaturated coalbed and the number may not be exact for water production in this specific field, the real-life practice in the study mines proved that there was not a major water inflow or accumulation problem in the entries during longwall mining or during development mining.

In the Pittsburgh Coalbed in the Northern Appalachian Basin, face and butt cleats are perpendicular and parallel, respectively, to the fold axis. In this mine, in the plane of mine roof, the major horizontal principle stress is 2370 psi at North 78° East, and the minor horizontal principle stress is 2200 psi. The gate road orientation and sequencing of longwall panel extraction relative to the in situ horizontal stress field can have a major impact on the gate road stability. Thus, mining direction is approximately in the E W direction in the study mine. Furthermore, in this field face cleats were oriented nearly in the E W direction and butt cleats nearly in the N S direction. This information indicates that the direction of mine advance is approximately parallel to the face cleats and perpendicular to butt cleats. When positioning the simulation grids and assigning the permeabilities, attention was given to cleat directions.

2.2. *Modeling of development mining process and performing the simulations*

For modeling advances of tailgate and headgate entries, a three-entry development model around a longwall panel was studied. Fig. 2a shows a snapshot of mining advance, pillar layout, and ventilation scheme. The middle entry was modeled as the ''track'' or haulage, and intake entry, where intake air flowed to the mining area. In this entry, ventilation air injection and mine pressure assignments to the grids were performed using an injector well. The entry to the left of ''track'' was designated as the ''belt'' entry. The third entry was designated as the ''return'' entry carrying away a majority (>90%) of the methane emissions and the methane-loaded ventilation air. The producer wells used in these entries both assigned the mine pressures and monitored the amount of methane in the produced gas stream.

During mining of the headgate and tailgate developments, entries were extended and interconnected by

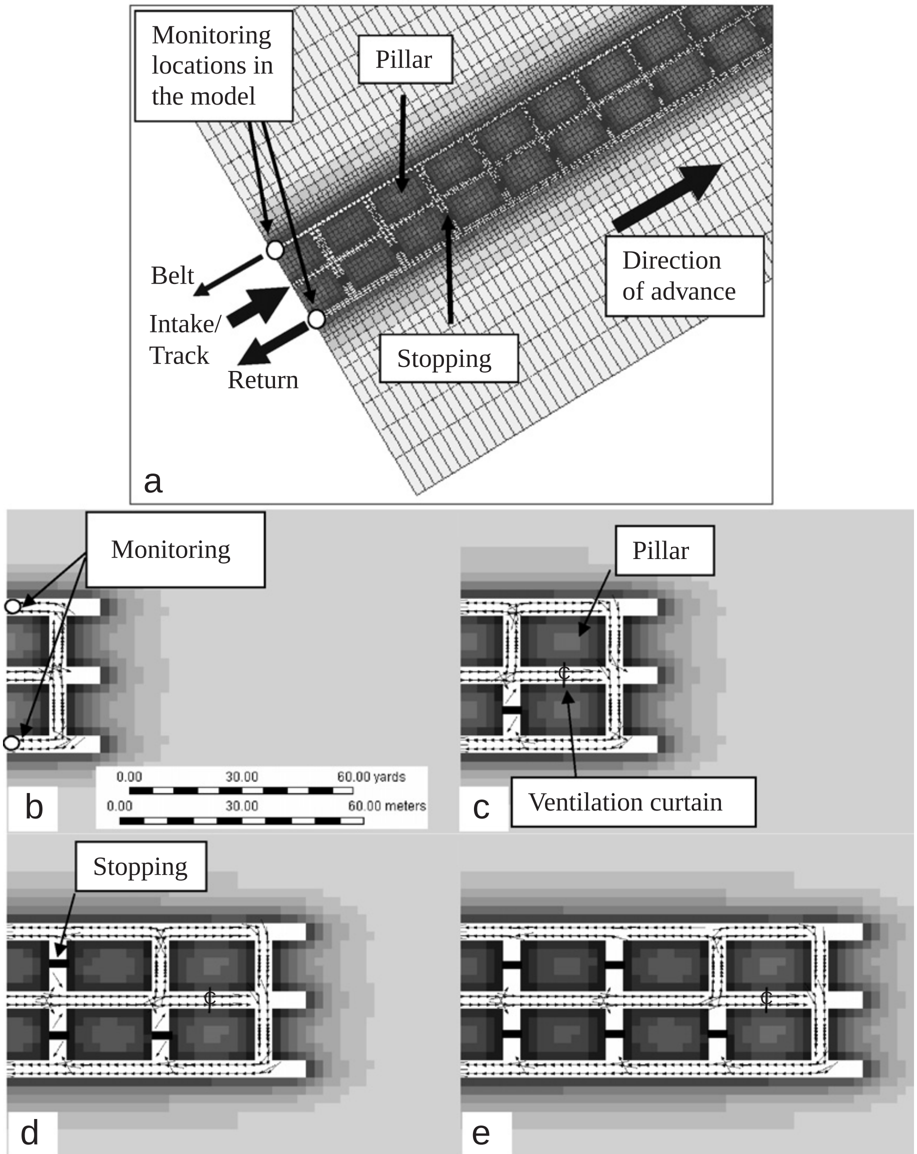

Fig. 2. A snapshot of mining advance, pillar layout and ventilation scheme in coalbed reservoir model. Ventilation arrows schematically represent flow magnitude (thicker arrows represent higher flow). Locations where total methane inflow is monitored are also shown (a). (b e) Progress of mining in coalbed between four successive section advance steps. Figures show entries, cross cuts, stoppings and location of ''curtains'' dynamically created during simulations plus path of ventilation airflow occurring during simulations.

cross-cuts. The amount and rate of methane emission into the developed entries depended upon the extent of the continually created new surfaces. As the continuous mining machine advanced, new volumes were created that required ventilation, while new surfaces were created that liberated gas into that volume. This constituted a moving boundary value problem, which was handled using "restart" model runs. These models were run sequentially, with each run characterizing an advance in entry development using a specified development rate. Coalbed properties were replaced with the assigned properties of the entries in the models, and ventilation-related features were constructed as required. Each restart run was performed so that entries would advance on a determined rate. This approach was used by Karacan (2007) to model development mining in coal seams to estimate ventilation air requirement with and without degasification/shielding boreholes drilled along the entries. Karacan et al. (2005, 2007) also used this approach to model the longwall mining process and the performances of gob gas ventholes, which are drilled from the surface on the active mine panel to control methane emissions into the mine as a result of extensive fracturing of the overlying strata.

In building the restart models, all three entries were developed simultaneously to a specific distance in a predefined amount of time, allowing calculation of the mining advance rate. For different rates, the times in the recurrent data set were changed. Thus, the rates reported in this study are not linear mining rates, but instead represent the rates that the mine section advanced. Based on this approach, a 150 ft (45.7 m) section advance corresponded to 570 ft (173.7 m) of linear mining distance in the model, which included developing three entries and required cross-cuts.

As the entries advanced, the pillars and cross-cuts were simultaneously developed. The pillars between the entries were 125 ft (38.1 m) in length and 75 ft (22.9 m) in width and were assumed to have the same properties as the coalbed. During the development of entries, each of which was 20 ft (6.1 m) in width and the same height as the coalbed, the permeability was replaced with a high permeability [10^9 md (10^{-6} m^2)] in all three directions. Also, the coal-matrix pressures in the mined grids were assigned to atmospheric pressures to simulate the mining process.

The development of the cross-cuts was modeled the same way as the entries. However, during each simulation run only the last set of cross-cuts was left fully open for ventilation airflow. In the model, stoppings (block walls) between track-belt and track-return were automatically constructed between the restart runs to force ventilation flow through the last open cross-cuts at each section advance. A permeability of 100 md was assigned to the stoppings to represent a low leakage, a common occurrence in underground mining. This value was selected in the absence of measured permeability data for the stoppings. A "curtain" resistance created in the last section of the "intake", or "track", diverted some of the intake air towards the "belt" entry to ventilate both belt and face (Figs. 2c e) as it happens in the mining environment. Figs. 2b e show the progress of mining between four successive section advance steps. These figures show the entries, cross-cuts, stoppings and the location of the "curtains" created during simulations plus the path of the ventilation airflow during simulations.

2.3. Matching reservoir model predictions of methane inflow with in-mine measurements

Various factors control methane emissions during development mining. Among these factors, coalbed parameters and mining parameters are probably the most important. In this study, the base coalbed parameters for the Pittsburgh seam (Table 1) and the mining parameters reported by the mine were used to calibrate and test the capability of the developed model for predicting the monthly, averaged in-mine methane emissions.

During mining, the linear advance distances and lengths of exposed rib were reported as monthly totals. The mining distances were reported as linear distances mined (including entries and cross-cuts), which were around 4500 6500 ft (1372 1981 m) per month, rather than the daily advance rate of the three-entry sections. In order to establish a comparison between measured data and the reservoir model formulation, linear mining distances were converted to net advance of the section. For this purpose, a ratio was calculated using the measured lengths of cross-cuts and entries and the net monthly advance of the entries determined from the mine maps. This approach revealed a ratio of 0.27 (1 section ft = 3.7 linear ft) between these two-length scales. Thus, the linear mining distances were converted to distances in the direction of mine advance. The advance rates, using the lengths in the direction of mine advance, were calculated based on two eight-hour production shifts and one maintenance shift per day for six days per week. The majority of calculated section advance rates were between 70 and 110 ft/day (21.3 33.5 m/day) during production shifts and working days. The average rate of mining to develop both sections to full length was approximately 80 ft/day (24.4 m/day).

The predictive performance of the reservoir model was compared with in-mine measurements of methane inflow, reported as monthly averages, during development of the tailgate and headgate entries. The simulation results using the base reservoir data (Table 1) and calculated advance rates of 70 and 110 ft/day for 2000 12,000 ft (610 3658 m) development distances were compared with the in-mine methane inflow rates.

Fig. 3 shows the simulator predictions and measured methane inflows into the headgate and tailgate entries. The solid markers and the trendlines show the simulator predictions for methane emissions with the upper and lower advance rates as a function of development distance. Since the simulations use constant mining and coalbed parameters, its methane inflows show a continuous increase with distance, as opposed to the scattered increase in measured data. However, the developed base model closely predicts the range of the measured data.

3. Effect of coalbed parameters on methane inflow into entries during development mining

This study investigated the impacts of selected coalbed properties on methane inflows for 2000, 6000, 10,000 and 12,000-ft-long (610, 1830, 3050, and 3660 m) development distances. For the parametric analyses, the values of key coalbed properties were varied around their base values that were used to match the field measurements as shown in Table 1.

For the parametric analyses, the calibrated reservoir model was run with 50 ft/day (15.3 m/day) section advance rate rather than the 70 or 110 ft/day rate mentioned previously in model calibration discussions for the study mine. The reason for simulating a lower mining rate is that most mining operations run their continuous mining machines fewer days per week or with fewer production shifts than the study mine of the base case. Mining fewer days a week or less number of hours within a day reduces the average daily section advance rate. This means that a section length to be mined takes longer time for when mining machines operate shorter periods, which is equivalent to decreasing linear advance rate in numerical models. Since the purpose of the study is to develop models with a more general applicability, a lower average daily section advance rate was selected. The following sections discuss the changes in methane inflow data resulting from variations (i.e., all other values

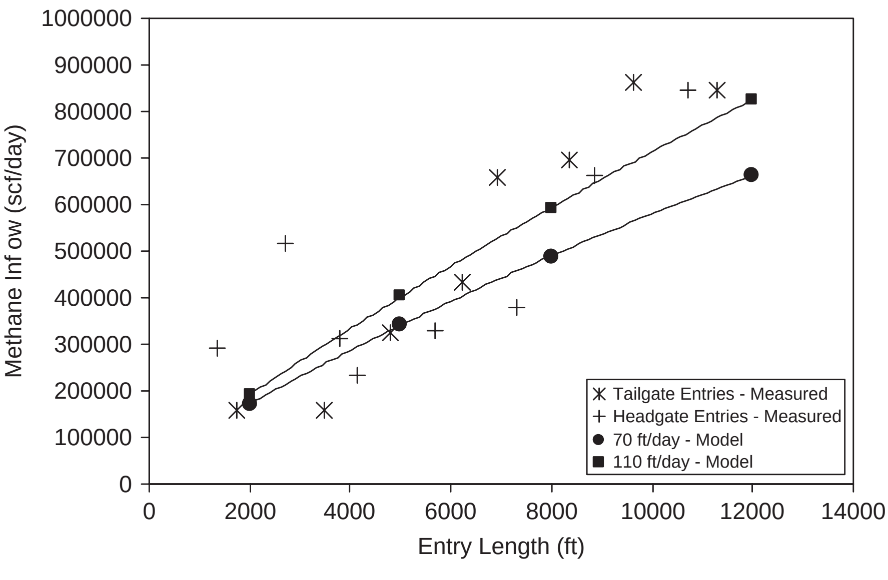

Fig. 3. Comparison of measured methane inflow into mine and reservoir simulator (GEM) predictions at two different average daily mining rates practiced during development of entries.

remaining constant at the base values) in coalbed parameters.

3.1. Effect of coalbed permeability and permeability anisotropy on methane inflow into development entries

Permeability is an intrinsic property of porous formations that relates to pressure drop and flow rate. In coalbeds, vertical permeability is usually significantly lower than horizontal permeability because of the presence of bedding. Thus, horizontal permeability and its direction (anisotropy) are more important in coalbed reservoirs. Horizontal permeability and its anisotropy in coalbeds are characterized with two orthogonal permeability components that run in the direction of characteristic fractures within the coalbed. These are termed the face and butt cleats. Face cleats are continuous and can extend for long distances. However, butt cleats are short and discontinuous, usually terminating at face cleats. Because of the nature of these two cleat systems, face cleats are more permeable to gas and water flow. The permeability anisotropy can be defined as the ratio of face cleat (K_x) to butt cleat (K_y) permeabilities.

The presence or lack, and direction of permeability has a profound effect on methane inflow into the wellbores (Remner et al., 1986), suggesting that any horizontal drilling in coalbeds should account for directional permeability. The average permeability for flow in coalbeds can be defined as

$$K_a = \sqrt{K_x K_y}, \qquad (1)$$

where K_a is the average permeability and K_x and K_y are the directional permeabilities of the cleats.

Direction and magnitude of permeability is important for control of methane emissions during mining. When mining advances perpendicular to the face cleats, where permeability is higher, much more gas is emitted into mine workings than when the advance is parallel to the face cleat. In fact, in one area of a mine operating in the Pittsburgh coalbed, the methane emissions from the solid ribs were significantly higher than the emissions from the working face as a result of the ribs intersecting the face cleats (McCulloch et al., 1975).

In this study, mining advance was oriented parallel to the face cleats to mimic the modeled mine. The effects of permeability anisotropy and directional cleat permeabilities on methane emissions into the development entries were evaluated. Both face and butt cleat permeabilities were varied between minimum and maximum values shown in Table 1. Permeability anisotropies were increased by decreasing the butt cleat permeability. Anisotropies could have been increased by increasing face cleat permeability rather than decreasing butt cleat permeability. However, since mining was parallel with face cleat permeability, the effect of this change would have been less compared to the changes obtained by varying butt cleat permeability, which were perpendicular to entries in this case. This argument is further supported by statistical analysis presented in the following sections.

Fig. 4 presents the simulated average methane inflow rates as a function of permeability anisotropy, average permeability calculated using Eq. (1), and development distance. This figure shows that increasing average permeability, while keeping the anisotropy constant, increases methane inflow into the entries. On the other hand, doubling anisotropy decreases methane inflow even though the face cleat permeability is unchanged. This is due to lower flow from the decreased butt cleat permeability, which is perpendicular to the entries in this study. Also, this figure shows that the effects of anisotropy or changes in butt cleat permeability are more pronounced for longer development distances. In a more general sense, the effect of butt cleat permeability observed in this study should be interpreted as the effect of coalbed permeability perpendicular to the entries, based on orientation of mining. Thus, cleats perpendicular to entries are more important than parallel ones for contributing to methane inflow.

3.2. Effect of porosity on methane inflow into development entries

The fracture or cleat system is the main source of porosity in coalbeds. Gas can exist as free gas in the fractures and cleat network or in a sorbed state in the coal matrices. However, cleat porosity is usually small and the amount of methane residing in the cleats as free gas is much less compared to the sorbed gas. The fine micropore structure of coal has a very high storage capacity for methane compared to a fracture volume of the same size (Zuber, 1996). Porosity in coalbeds is related mainly to water storage capacity (Young et al., 1992).

Fig. 5 shows the effects of changing coalbed porosity on methane inflow into the entries. The data in this figure show that increasing porosity

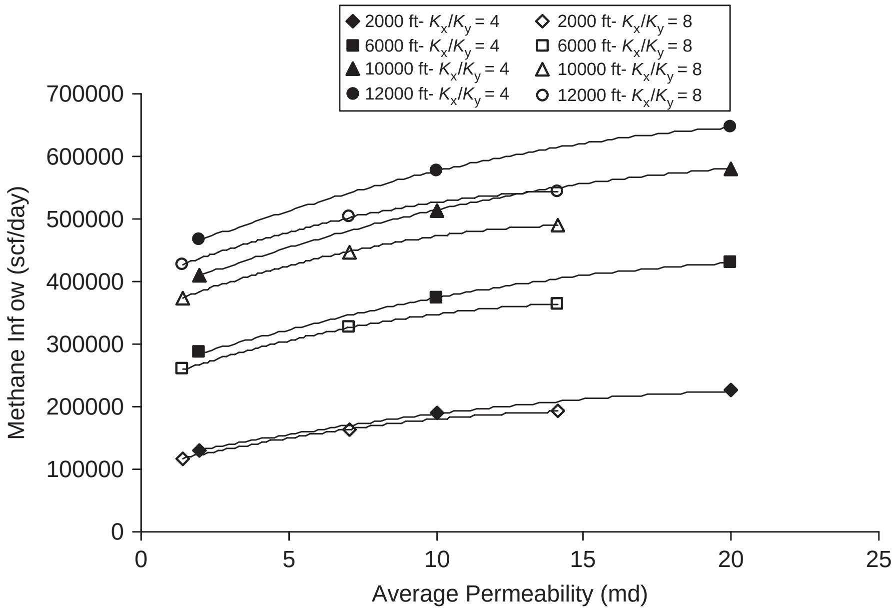

Fig. 4. Reservoir model simulations of methane inflow variability with permeability, permeability anisotropy, and development distance.

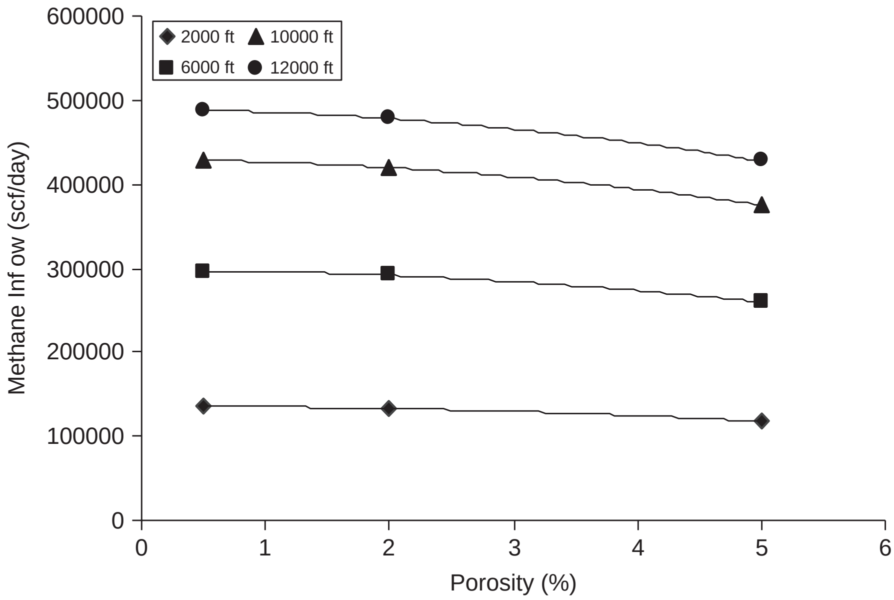

Fig. 5. Reservoir model simulations of methane inflow variability with cleat porosity and development distance.

slightly decreases average methane inflow into the entries. As porosity is increased in a constant reservoir volume, the fraction of the volume previously occupied by the high methane storage capacity matrices is replaced by fractures whose methane content is less. This is equivalent to decreasing the gas-in-place of the coalbed, which causes average flow rate to decrease. Fig. 5 also shows that the effect of increased porosity on methane inflow rate is greater when mining longer entries [12,000 ft (3660 m)] than when mining shorter entries [2000 ft (610 m)]. As longer entries are mined, more gas flows from the coalbed because of an increased drainage area and pressure sink. As a result, the impact of decreased methane in-place is more pronounced.

3.3. Effect of Langmuir volume, Langmuir pressure, and coalbed pressure on methane inflow into development entries

In coalbeds, the major portion of the gas exists in adsorbed state, rather than in a free state. As the pressure is lowered due to fluid production from the cleats, gas starts to desorb from the micropore surfaces and diffuse into the macropores (Remner et al., 1986). Adsorption and desorption of methane from coal is described by a Langmuir isotherm, which defines the relationship of coalbed pressure to the capacity of a given coal to hold gas at a constant temperature. More specifically, the Langmuir isotherm for coals relates matrix gas content, $V(P)$, to the coalbed cleat pressure, P, according to

$$V(P) = \frac{V_L \times P}{(P + P_L)}, \qquad (2)$$

where V_L is the Langmuir volume or maximum amount of gas that can be adsorbed. P_L is the Langmuir pressure or a characteristic measure of residence time for a gas molecule on the surface and represents the pressure at which gas storage capacity is half of the maximum storage capacity, V_L (Young, 1998). Both V_L and P_L can be determined from gas sorption measurements on the coal core samples. The Langmuir Eq. (2) provides a necessary boundary condition at the matrix cleat interface (Young, 1998). For non-equilibrium diffusion sorption models, it is assumed that the concentration of methane at the surface of the micropore matrix blocks is in equilibrium with the free gas pressure in the cleats. This implies that the external boundary condition of the micropore equation is the equilibrium sorption isotherm (King et al., 1986).

The shape of this isotherm is important for manipulating the boundary condition between matrix and cleats and to control desorption of gas from coal. The shape of the isotherm is largely affected by V_L and P_L. These two quantities dictate the gas content of the coal at a certain cleat pressure and gas release rate as pressure decreases.

Cleat pressure is also important for determining the gas content of the coalbed for a given V_L and P_L. However, it should be noted that, initially, the actual amount of gas in the coalbed (gas content) may not be on the desorption curve defined by the Langmuir isotherm and may be below this curve. In this case, coalbed cleat pressure needs to be reduced further until it reaches a critical desorption pressure where gas starts to desorb and gas release follows the Langmuir isotherm as pressure declines. V_L and P_L also determine how quickly the critical desorption pressure is going to be reached at such a condition.

Fig. 6 shows the effect of coalbed pressure on methane inflow during development mining of entries. Since coalbed pressure is related directly to the methane content, higher pressure results in higher methane inflow rates at constant values of V_L and P_L. The dependency of inflow rate on pressure is nearly linear for each of the entry length studied. Also, it should be noted that the inflow rate is higher when mining longer entries, as expected, since longer entries create a larger drainage area into which gas can flow. Furthermore, a much larger portion of the coal seam is depressurized sooner which triggers gas desorption from greater distances, a similar phenomena observed in longer horizontal production wells (Ertekin et al., 1988;

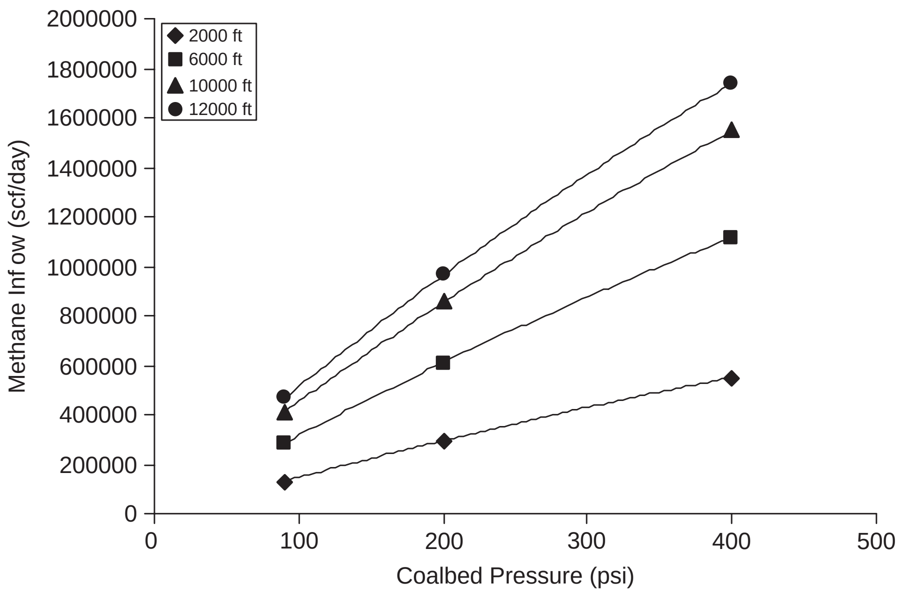

Fig. 6. Reservoir simulations of methane inflow variability with coalbed pressure and development distance.

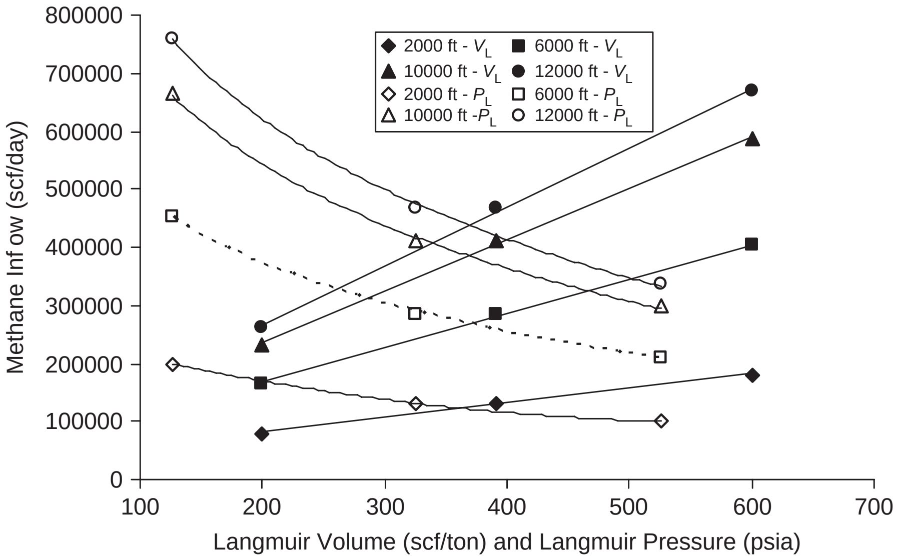

Fig. 7. Reservoir simulations of methane inflow variability with Langmuir pressure (P_L) and Langmuir volume (V_L) and development distance.

King et al., 1986). A steeper slope of the graph for longer entries can be explained by the same reasons.

The effects of V_L and P_L on simulated methane inflow into the entries during development mining are shown in Fig. 7. This figure shows that methane inflow rate is almost a linear function of V_L. Since V_L represents the maximum gas capacity of coal, higher V_L ensures the availability of more methane and promotes higher methane emissions when pressure and P_L are kept constant.

The effects of P_L on methane inflow rates show inverse relations (Fig. 7) when both V_L and coalbed pressure are constant. The slope of the isotherm, or the change of gas capacity with pressure, is largely controlled by P_L. If P_L is high, then the isotherm will be flatter compared to the isotherm with a lower P_L value, especially where $V(P) < V_L/2$. This means that when mining a coalbed with a higher P_L, the change in gas capacity or change in gas desorption from the coal will be less compared to a seam with a lower P_L for the same pressure drop. Thus, the rates of desorption and methane inflow into entries in a higher-P_L coalbed decrease as development distances increase.

3.4. *Effect of sorption time constant on methane inflow*

Once methane desorbs from the micropore surfaces of the coal matrix, it flows towards the cleat system in response to a methane concentration gradient defined by a combination of Knudsen, bulk and surface diffusion processes (Smith and Williams, 1984; Kolesar and Ertekin, 1986). In coalbed modeling, unsteady-state diffusion effects can be quantified by determining a sorption time, τ (days), which is proportional to cleat spacing, s_f, and the diffusion coefficient, D, that can be determined by laboratory tests:

$$\tau \sim \frac{s_f^2}{D}. \tag{3}$$

In effect, τ is the time constant that regulates the rate at which gas is released from the micropores into the macropore system. For small values of τ, or larger values of D, the diffusion and sorption process is faster and a higher cumulative gas production and a higher production rate peak is observed at degasification boreholes (Remner et al., 1986; Spencer et al., 1987). Later in the life of the coalbed methane reservoir, sorption time, together with desorption, may also act as an internal pressure maintenance mechanism.

Instead of separately investigating the effects of cleat spacing and diffusion coefficient on methane inflow into entries, the effect of τ was evaluated. The simulated effects of different sorption times, shown in Fig. 8, demonstrate that small sorption times cause higher methane inflow rates, a phenomenon observed in coalbed gas production using horizontal boreholes (Remner et al., 1986). It is also evident that the change in inflow rates between short and long sorption times is more significant for longer entries than shorter ones (2000 vs. 12,000 ft).

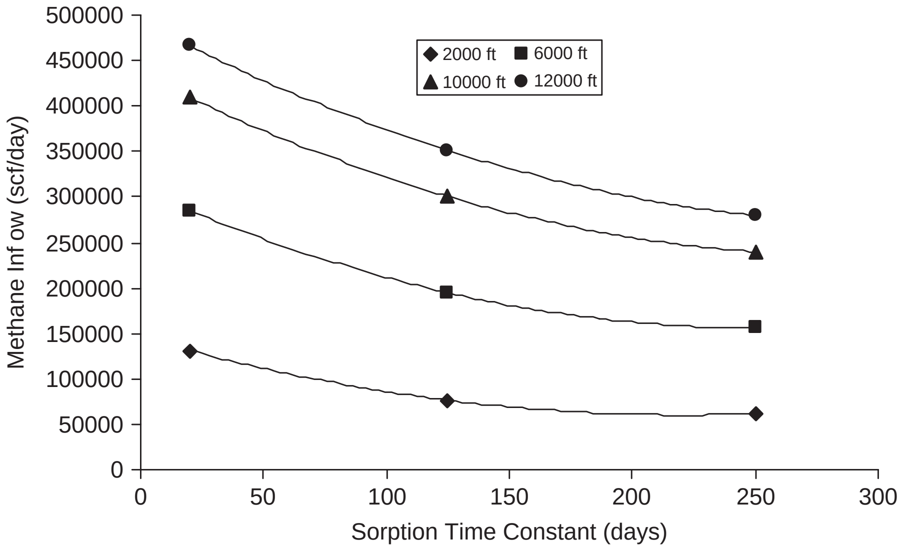

Fig. 8. Reservoir simulations of methane inflow variability with sorption time constant and development distance.

This may be related to regulation of the rate of gas release from micropores to cleats and pressure maintenance in the reservoir while mining is progressing. During mining of shorter entries, the pressure disturbance within the coalbed is limited and the area of drainage is less. A short sorption time, τ, results in high flow rates from the areas surrounding the entries and from the areas that pressure transients can propagate. In the case of longer sorption times with other reservoir parameters being constant, the flow rate will be less due to slow diffusion from the coal matrices into the cleats. Also, the pressure transients will travel further since there will not be enough pressure maintenance in the coalbed. However, when the sorption time is even longer, its effect is less pronounced since there will be a semi-steady-state condition established between diffusion/desorption, cleat pressure, and flow rate at the existing coalbed permeability.

When mining longer entries, the inflow rates are higher because the pressure disturbance affects a larger area for a longer time and a larger surface area is exposed. The methane inflow with a short sorption time constant is higher. However, with a longer sorption time constant, the flow rate is less due to slower diffusion rates into the cleats. This causes the pressure transients to propagate further due to the lack of sufficient pressure maintenance within the reservoir. Mining longer entries affects larger areas for longer periods, increasing sorption time, and reducing average flow rates even further.

3.5. *Effect of coalbed thickness on methane inflow*

Fig. 9 shows that the methane inflow rates increase almost linearly with the coalbed thickness. The figure also shows that, as expected, mining longer entries in thicker coalbeds results in higher inflow rates. This is due to a combination of the two factors suggested by Ertekin et al. (1988) for fracture-stimulated horizontal boreholes: larger reservoir volumes and the increased surface area for flow in horizontal boreholes stimulated by hydraulic fractures whose lengths are equal to the coalbed thickness. They report that methane production from horizontal boreholes increases as the coalbed thickness increases even if the borehole surface area is the same due to larger volumes of reserves encountered due to the presence of hydraulic fractures. Also, in the case of fracture-stimulated boreholes, the flow rates are even higher compared to the non-fractured counterparts due to the increases in surface area (Ertekin et al., 1988).

During development mining in thicker coalbeds, larger volumes of methane reserves are encountered. Also, the increased thickness of the coalbed results in an increased area of flow, which is a similar to and even more significant than vertical fractures in the boreholes. Thus, mining longer entries in thicker coalbeds increases both the size of the methane reservoir encountered and the surface area created, which increases methane inflow rates even further.

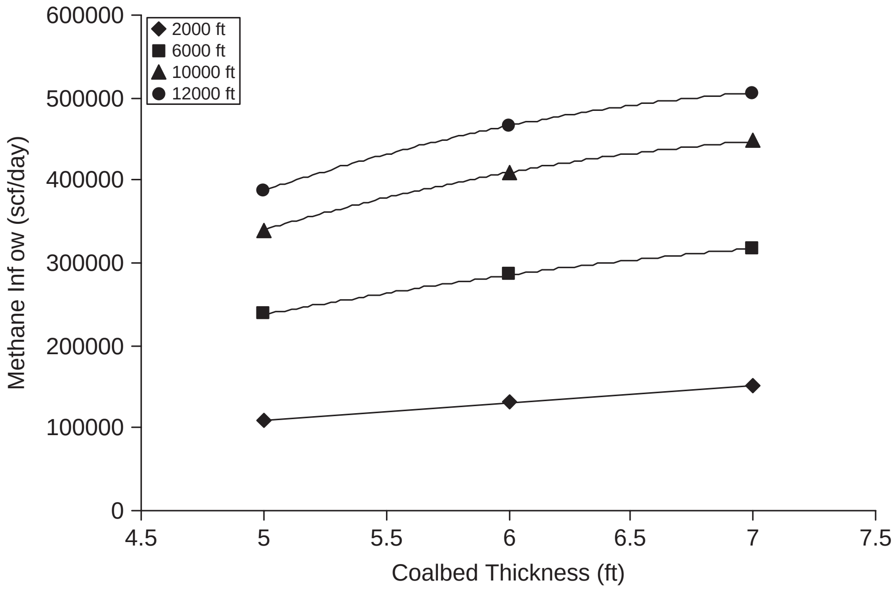

Fig. 9. Reservoir simulations of methane inflow variability with coalbed thickness and development distance.

3.6. *Effect of initial and irreducible water saturation of the coalbed on methane inflow*

The saturation of a given phase or fluid in any porous medium represents the fraction of the total pore volume occupied by that phase or fluid. Coalbeds are almost always partially or completely saturated with water. However, since the porosity and permeability of coal matrices are extremely low, almost all of the water resides in fractures and cleats in the coalbed. Thus, any water saturation for coalbeds represents the fraction of cleat porosity that is occupied by water. Since this saturation definition is based on the total pore volume of cleats, part of the pore volume may be occupied by immobile water, where water saturation cannot be reduced further. Thus, water saturation in cleats may vary between a minimum value (immobile water saturation) and a maximum of 100% saturation, at which water has maximum relative permeability and mobility. Intermediate values denote mobile saturation where water can flow in the cleats.

Besides decreasing the available cleat volume for methane, saturations are particularly important for affecting the permeabilities of the coalbed to water and methane. If there are two fluids flowing simultaneously through a porous medium, then each fluid has its own effective permeability. These permeabilities are dependent on the saturations of each fluid (Dake, 1978). When water saturation, S_w, is equal to one, then the cleats are entirely filled with water and the effective permeability to water is equal to the absolute cleat permeability and the effective permeability to gas is zero. Likewise, if the saturation of water is at irreducible water saturation ($S_{w_{irr}}$) here water is immobile, then the effective permeability of water is zero and the effective permeability of gas is a maximum. The practical range of variations of gas saturation, S_g, is

$$S_{g_{irr}} \leqslant S_g \leqslant 1 - S_{w_{irr}}. \tag{4}$$

However, irreducible gas saturation ($S_{g_{irr}}$) is not appreciable in the cleats and gas saturation may change between 0 and $1 - S_{w_{irr}}$. Critical gas saturation where gas becomes mobile may be important; however, this value is expected to be small, or equal to irreducible gas saturation.

Effective permeability can be normalized to absolute permeability to give relative permeability, which is commonly used for mathematical convenience (Dake, 1978). Relative permeabilities of each phase as a function of their saturations can be interpreted the same way as the effective permeabilities.

In methane production from coalbeds using boreholes, increases in initial free gas saturation result in recovery that is greater than the additional gas volume stored in the cleats alone due to the impact of saturation on relative permeability (Young et al., 1992). As the initial free gas saturation is increased (and water saturation is decreased), reservoir conditions favor gas flow over water flow since the relative permeability to gas increases with increasing gas saturation. Similarly, as the irreducible water saturation is decreased, more water is allowed (or considered mobile in a wider saturation range) to flow in the cleats, which potentially can reduce relative permeability to gas. Thus, gas and water flow at different initial and immobile water saturation conditions and follow distinctly different "paths" on the relative permeability functions.

Initial water saturations were changed while keeping the irreducible water saturation constant, and irreducible water saturations were changed while keeping the initial water saturation constant to evaluate the possible effects of water saturations (and thus gas saturations) on methane inflow. Fig. 10 displays simulated methane inflow rates at different initial and irreducible water saturations and shows that reducing irreducible water saturation to 10% for a development distance of 2000 ft reduced the methane inflow rate. For other irreducible saturation levels and entry lengths, reducing irreducible water saturation did not make any significant difference in gas inflow.

Fig. 10 shows that increasing initial water saturation, while keeping irreducible water and other parameters constant at their base values, had a more significant effect on methane inflow rates. With development distances of 2000 ft (610 m) and 6000 ft (1830 m), increasing initial water saturation decreased the methane inflow rate mostly due to decreased initial gas saturations and gas relative permeabilities. A similar decrease was observed in the longer entries when initial water saturation was changed from 40% to 80%. Increasing water saturation puts the reservoir initially in an unfavorable situation for gas flow. However, when mining 10,000 and 12,000-ft (3050 and 3660-m) long entries, gas inflow rate started to increase when water saturation increased from 80% to 100%. When mining begins in a coalbed that is 100% saturated with water, first water will start flow into the entries rapidly and trigger a high initial gas desorption and the "negative decline" period as observed in the production wells, thus increasing average inflow rate into the entries. These high-methane-inflow periods are repeated as the mine face is progressively advanced in the coalbed for longer distances in the reservoir. Shorter entry developments may not experience the repeated effect of these periods and methane inflow remains at lower values. However, mining longer entries gives enough time, longer coalbed exposure and more face-advance steps for the initial high gas inflow rates and negative declines to impact average methane inflow rates, as seen when progressively extending entry lengths in Fig. 10. Overall, initial water saturation seems to be more influential and negatively correlated with methane inflow for shorter entry developments.

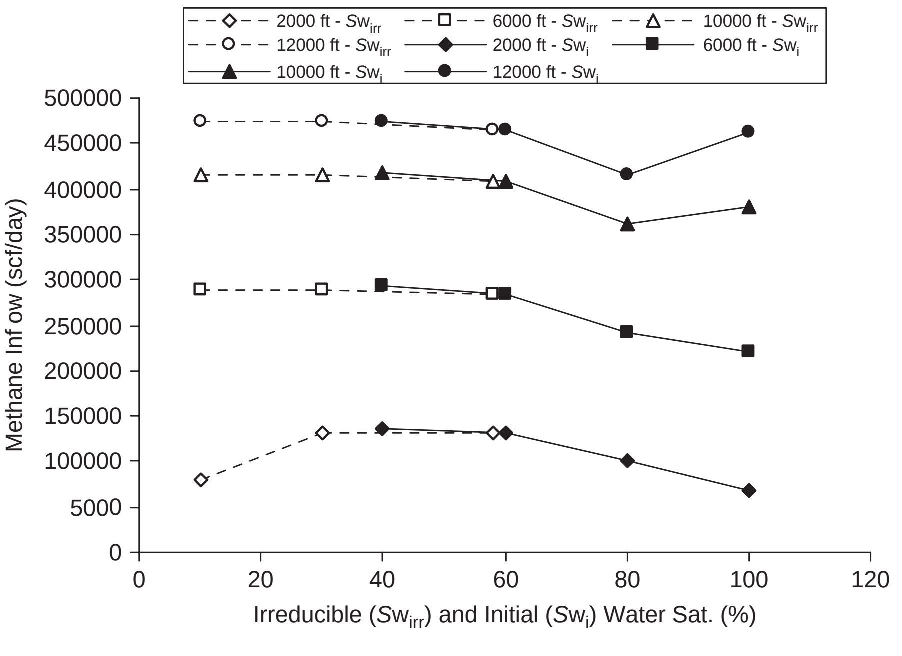

Fig. 10. Reservoir simulations of methane inflow variability with irreducible ($S_{w_{irr}}$) and initial water (S_{w_i}) saturations and development distance.

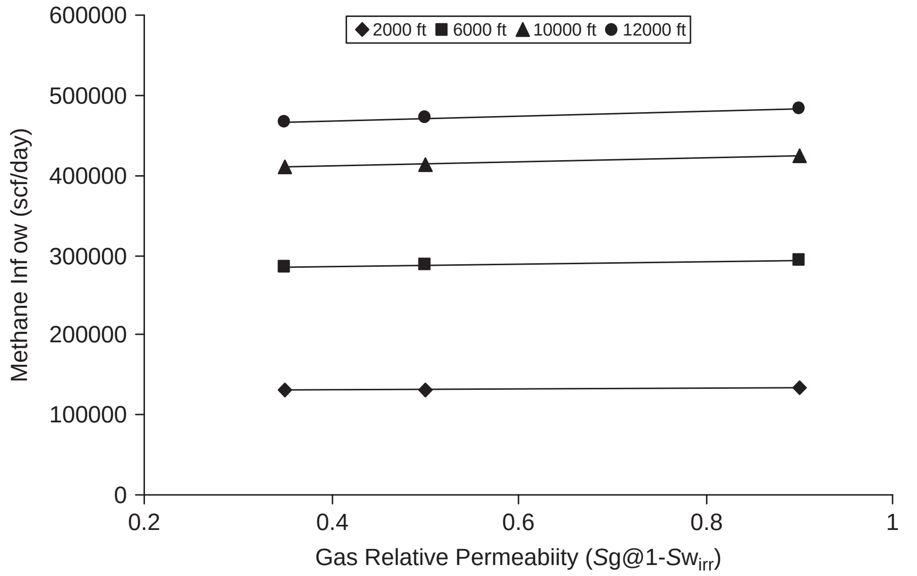

Fig. 11. Reservoir simulations of methane inflow variability with end point gas relative permeability and development distance.

3.7. *Effect of end-point-relative permeability of gas on methane inflow into entries*

The maximum relative permeability to gas that can naturally occur at the irreducible water saturation is called the end-point relative permeability, K'_{rg}, and is defined as (Dake, 1978)

$$K'_{\mathrm{rg}} = K_{\mathrm{rg}}(\text{at } S_{\mathrm{w}} = S_{\mathrm{w_{irr}}} \text{ or } S_{\mathrm{g}} = 1 - S_{\mathrm{w_{irr}}}). \qquad (5)$$

In this definition, K_{rg} is the relative permeability to gas. End-point relative permeabilities can be determined by core-flow tests (Crotti et al., 1998; Gash, 1991).

Fig. 11 shows the impact of different end-point relative permeability values on methane inflow. The simulation data shows that, although the impact of end-point relative permeability value for gas flow increases slightly for longer entries; in general, this factor does not have a significant effect on the methane inflow rates. However, it should be mentioned that the effect of relative permeability "curves" on the whole saturation range, relative permeability path and how it changes with saturation, may be more important than the effect of only end-point relative permeability values (Price and Ancell, 1993; Young et al., 1992).

4. Multilinear models for prediction of methane inflows and their diagnostics for utility and adequacy

In this paper, the main coalbed parameters shown in Table 1 that control gas storage and flow in coalbed reservoirs and that may have significant effects on the methane inflow were considered as the independent parameters. The importance of each parameter from a coalbed reservoir engineering, gas flow, and gas storage point of view and the relative importance of each on simulated methane inflows were evaluated in the previous sections. These data showed that these changes usually created linear or close-to-linear relations with respect to methane inflow with no significant non-linearities for the various development lengths.

The dependent variables used for these regressions were the simulated methane inflow rates into the 2000, 6000, 10,000, and 12,000 ft developments using a calibrated reservoir model with a 50 ft/day (15.3 m/day) section advance rate. By using 11 coalbed parameters, 57 observations (simulations) were created for each of these development distances by changing the values of individual coalbed parameters within the range of values listed in Table 1 while keeping the others at their base values. A separate regression analysis for methane inflow prediction was carried out for each development distance. Table 1 shows the symbolic names of all variables used in multiple regression analysis.

The methane inflows were modeled by including many parameters in the simulations, since the outputs were expected to mimic a number of reservoir and mining conditions. In this modeling study, the independent variables investigated were those major gas flow and storage-related coalbed properties impacting methane inflow. However, a predictive model may not contain variables whose statistics prove them to be insignificant in the presence of the other significant ones. Using a variety of techniques, insignificant variables are excluded so that the final models are composed only of significant variables. Apart from a statistical point of view, this is important from a practical point of view since fewer significant variables will make data collection easier and more economical.

In this study, backward elimination was used, due to its advantages over forward selection and stepwise regression to evaluate joint predictive capability (Motulsky and Christopoulos, 2004), as the multiple regression technique to judge the importance of each independent variable based on its contribution to the dependent variable. This technique was used to develop a linear model to predict methane inflows using 57 observations for each of the four development distances (2000, 6000, 10,000 and 12,000 ft). In selecting the coalbed parameters for their relative importance on methane inflow, care was taken to ensure that there would not be a high degree of correlation between them. For this reason, face cleat and butt cleat permeabilities were selected in lieu of anisotropy, which is defined by the ratio of these two variables. Thus, multiple regressions were performed with 11 independent variables shown in Table 1, by excluding permeability anisotropy. During these analyses, the significance cutoff value, α, and the confidence interval of regression were set as 0.05 and 95%, respectively.

4.1. *Model equations, analysis of multiple determination coefficients, and ANOVA*

Table 2 shows the linear models of methane inflow rates for the four development distances derived using backward elimination. The table also shows the multiple determination coefficient, R, the square of multiple determination coefficient, R^2, and the adjusted determination coefficient, aR^2, for the regression models presented. These coefficients are high for each model, indicating successful fitting of the models to the observations. The value of aR^2 is adjusted for the number of parameters in the equation and the number of data observations (Motulsky and Christopoulos, 2004). Thus, it is a more conservative estimate of the percent of variance, especially in the case of many independent variables. This parameter ranges between 0.9096 and 0.8705, for 2000 ft (610 m) and 12,000 ft (3660 m) models. In other words, the models account for roughly 0.91 and 0.87 of the variance,

Table 2
Linear models for predicting methane inflow rates into development entries of various lengths using key coalbed reservoir parameters

Development length (ft)	Methane inflow rate[a] (scf/day)	R	R^2	aR^2	F
2000	9025.0349 + (18,676.8392 × Thick) + (1367.1790 × Pres) + (581.1950 × S.Time) + (13,100.6770 × K_y) + (121.6918 × L.Vol.) + (197.1251 × L.Pres.) + (1280.3404 × W.Sat.)	0.9597	0.9209	0.9096	81.538
6000	193,021.3700 + (49,697.1335 × Thick) + (2734.4987 × Pres) + (997.3667 × S.Time) + (19,103.2963 × K_y) + (298.3296 × L.Vol.) + (544.3628 × L.Pres.)	0.9493	0.9011	0.8893	75.945
10,000	256,242.0600 + (73,838.2649 × Thick) + (3764.7566 × Pres) + (1256.0067 × S.Time) + (21,052.8924 × K_y) + (457.1441 × L.Vol.) + (867.7456 × L.Pres.)	0.9432	0.8896	0.8764	67.169
12,000	283,185.5900 + (85,055.0763 × Thick) + (4219.7519 × Pres) + (1357.3077 × S.Time) + (21,403.8583 × K_y) + (532.4142 × L.Vol.) + (1023.3603 × L.Pres.)	0.9404	0.8844	0.8705	63.736

(Thick: thickness; Pres: pressure; S.Time: sorption time constant; K_y: butt cleat permeability in this study, but can be interpreted as cleat permeability perpendicular to entries; L.Vol: Langmuir volume; L.Pres: Langmuir pressure; W.Sat: water saturation). Multiple, squared multiple and adjusted multiple determinations coefficients as well as F test results are also shown.

[a]The units of coalbed parameters are as presented in Table 1. The calculated inflow rates using these linear models are compared with simulator predictions in Fig. 12.

respectively, and suggest that these formulations are reasonably good.

Table 2 also presents the utility of the model using ANOVA (analysis of variance) tests. The reported "F" statistics and the "Prob F" values test the overall significance of the regression model. The probability value of F is the probability that the null hypothesis for the full model is true. More specifically, it tests the null hypothesis that all of the regression coefficients are equal to zero in the model (Devore and Peck, 2001). A low probability value for F (<0.05 in this study) implies the high possibility of having non-zero coefficients and that the regression equation does have validity in fitting the data. In this study, "Prob F" values for all linear models were computed to be zero, which suggests that all models have very high possibility of having non-zero coefficients for the independent variables and thus they have validity in fitting the data.

The models presented in Table 2 do not contain all of the initially selected coalbed parameters. For instance, the model for the 2000 ft (610 m) case does not contain four of these parameters, namely 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. However, it may be surprising to see that face cleat permeability is not as important for methane inflow during development mining. 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.

4.2. Significance tests and analysis of results

In order to further test the validity of these equations and the significance of the regressions

Table 3
Coefficients of independent variables in models, tolerance of independent variables, beta (β) weights, correlation coefficients, semi partial correlations, t value, and probability t for testing the significance of model variables for different entry lengths

Development length (ft)	Variables	Model coefficients	Tolerance	β	Corr.	Semi partial corr.	t	Prob t
2000	Thickness	18,676.8392	0.9574	0.1041	0.1117	0.1019	2.536	0.0145
	Pressure	1367.1790	0.8897	0.9172	0.8204	0.8651	21.537	0.0000
	S.Time	581.1950	0.9021	0.4525	0.1699	0.0863	10.698	0.0000
	K_y	13,100.6770	0.9415	0.2407	0.0449	0.2336	5.815	0.0000
	L.Vol.	121.6918	0.8700	0.0885	0.2244	0.0825	2.055	0.0453
	L.Pres.	197.1251	0.8732	0.1438	0.2587	0.1344	3.345	0.0016
	W.Sat.	1280.3404	0.9685	0.0877	0.1377	0.4297	2.150	0.0366
6000	Thickness	49,697.1335	0.9829	0.1359	0.1437	0.1347	3.030	0.0039
	Pressure	2734.4987	0.8923	0.9001	0.8369	0.8503	19.121	0.0000
	S.Time	997.3667	0.9025	0.3810	0.1029	0.3619	8.139	0.0000
	K_y	19,103.2963	0.9441	0.1722	0.0164	0.1674	3.763	0.0004
	L.Vol.	298.3296	0.8704	0.1064	0.2690	0.0993	2.233	0.0301
	L.Pres.	544.3628	0.8736	0.1948	0.3248	0.1821	4.095	0.0002
10,000	Thickness	73,838.2649	0.9829	0.1435	0.1587	0.1423	3.029	0.0039
	Pressure	3764.7566	0.8923	0.8808	0.8380	0.8321	17.710	0.0000
	S.Time	1256.0067	0.9025	0.3410	0.0663	0.3240	6.896	0.0000
	K_y	21,052.8924	0.9441	0.1349	0.0459	0.1311	2.790	0.0074
	L.Vol.	457.1441	0.8704	0.1159	0.2901	0.1081	2.302	0.0255
	L.Pres.	867.7456	0.8736	0.2207	0.3565	0.2063	4.391	0.0001
12,000	Thickness	85,055.0763	0.9829	0.1461	0.1639	0.1448	3.011	0.0041
	Pressure	4219.7519	0.8923	0.8723	0.8370	0.8240	17.134	0.0000
	S.Time	1357.3077	0.9025	0.2300	0.0525	0.3093	4.470	0.0000
	K_y	21,403.8583	0.9441	0.1212	0.0564	0.1178	2.449	0.0179
	L.Vol.	532.4142	0.8704	0.1193	0.2975	0.1113	2.314	0.0248
	L.Pres.	1023.3603	0.8736	0.3256	0.3677	0.2150	6.432	0.0000

coefficients, "t" tests were performed on the model equations presented in Table 2. Table 3 presents the coefficients of independent variables in the models, tolerance of independent variables, beta (β) weights, correlation coefficients, semi-partial correlations, t values, and probabilities.

The tolerances represent the regression of the corresponding independent variable on all the other independent variables, ignoring the dependent variable. The higher the intercorrelation of the independents, the more the tolerance will approach zero (Lewis-Beck, 1980). Generally, if tolerance is less than 0.20, a problem with multicollinearity is indicated. Table 3 shows that the tolerances exceed 0.85 for all independent variables. This indicates the absence of multicollinearity between the independent variables, which is one of the prerequisites of multiple regression analysis.

The beta weights, β, presented in Table 3 for each independent variable, are the average amounts (in standard deviations) that the dependent variable increases when a specific independent variable increases one standard deviation and other independent variables are held constant. The higher the β value, the greater the impact of that independent variable is on the dependent variable. Thus for a 2000 ft (610 m) development length, the β values in this analysis show that pressure, sorption time constant, butt cleat permeability, and Langmuir pressure are the more important independent variables for prediction than Langmuir volume and coalbed thickness. But sorption time and Langmuir pressure are negatively correlated with methane emissions rates, since increasing values of these two variables results in slower diffusion rates and desorption rates, respectively. Water saturation is also negatively correlated with methane emission rates, as discussed before, indicating that higher cleat saturations impede gas flow in mining shorter entries.

Furthermore, the β weights show that the predictive importance of the independent variables changes with increasing entry length. For instance, the β value for pressure is ~0.91 for a 2000 ft (610 m) development distance compared to ~0.87 for a 12,000 ft (3660 m) distance, suggesting a decrease in the importance of coalbed pressure on methane inflow for longer developments. A greater decrease in the relative influence of sorption time (β values from ~-0.45 to ~-0.23) is also observed between 2000 and 12,000 ft (610 and 3660 m) entry lengths. On the other hand, the importance of coalbed thickness and Langmuir pressure on methane emissions increases with entry length, suggesting that the shape of the adsorption isotherm and the area of exposed coal surfaces are becoming more important.

The correlation coefficient reported in Table 3 is the percent of variance in the methane inflow data explained by the corresponding independent variable when all other independent variables are allowed to vary. This value is different than β weights. Statistically, the magnitude of correlation includes not only the covariance it shares with the dependent variable, but also the covariance shared with other independents in the model and its uncontrolled effects on the dependent variable. A correlation value >0.90, or several values >0.7, may be indicative of multicollinearity, which is a concern as it inflates standard errors and makes assessment of the relative importance of the independents unreliable using β values (Devore and Peck, 2001). The correlation values given in Table 3 show that the independent variables do not fall into this category.

The relative importance of the independent variables on the dependent variable can be assessed by computing the semi-partial correlations. The linear effects of the other independents are removed from the given independent variable before computing the remaining correlation of this variable with the dependent variable. Interpreting the relative importance of coalbed parameters on methane inflow, in conjunction with the β weights, shows the same importance grouping between coalbed parameters considered; that is, pressure, sorption time constant, butt cleat permeability and Langmuir pressure are highly correlated with methane inflows and their importance changes with entry length as discussed before.

The "t" and "Prob t" values give an indication of the significance or impact of each predictor variable. The smaller the value of Prob t, the more significant the parameter is and the less likely that the actual parameter value is zero. In other words, the terms of the regression equations containing the independent parameter having a low "Prob t" cannot be eliminated without significantly affecting the accuracy of the regression (Devore and Peck, 2001). As seen in Table 3, the probability t values for all the coalbed variables are smaller than the cutoff α, 0.05, indicating that all are significant and cannot be removed from the models without significantly affecting the accuracy.

4.3. Durbin– Watson test for autocorrelation

Absence of autocorrelation of residuals indicates the independence of variables, which otherwise leads to biased estimates of standard deviations and significance. A Durbin Watson test is performed to check the autocorrelation (association between successive residuals) of errors. The value of the Durbin Watson coefficient (*d*) ranges from 0 to 4. Values of *d* close to 0 indicate high positive autocorrelation, whereas *d* values close to 4 indicate high negative autocorrelation. When *d* is close to 2, the result indicates that there is no serial autocorrelation of errors (Savin and White, 1977). The values of *d* between 1.5 and 2.5 indicate the independence of observations. In this study, the Durbin Watson coefficients were 1.8812, 1.7579, 1.7951, and 1.8101 for the methane inflow models presented in Table 2 for development mining of 2000, 6000, 10,000, and 12,000-ft entries, respectively. The *d* values obtained for the models show that there is no apparent autocorrelation problem.

4.4. Adequacy of multiple regression models

Figs. 12a d show the comparison of predicted methane inflow rates using the GEM model with the rates calculated from the linear models. These figures indicate that the models can predict the observations reasonably well for all the entry lengths studied. However, some cases have more residuals than others.

A plot of standardized residuals against fitted values is helpful in identifying unusual or highly influential cases and gives an idea about the adequacy of the proposed models (Devore and Peck, 2001). While, in a perfect prediction, the value of standardized residual is zero, in predictive modeling it is nearly impossible to achieve this for all observations. Thus, a desirable residual plot exhibits no particular pattern and distributes points randomly between -2 and 2. Any outside data may be considered an error in measurement. Also, any point on the plot that is very far from the rest of the data in the horizontal direction may have had a

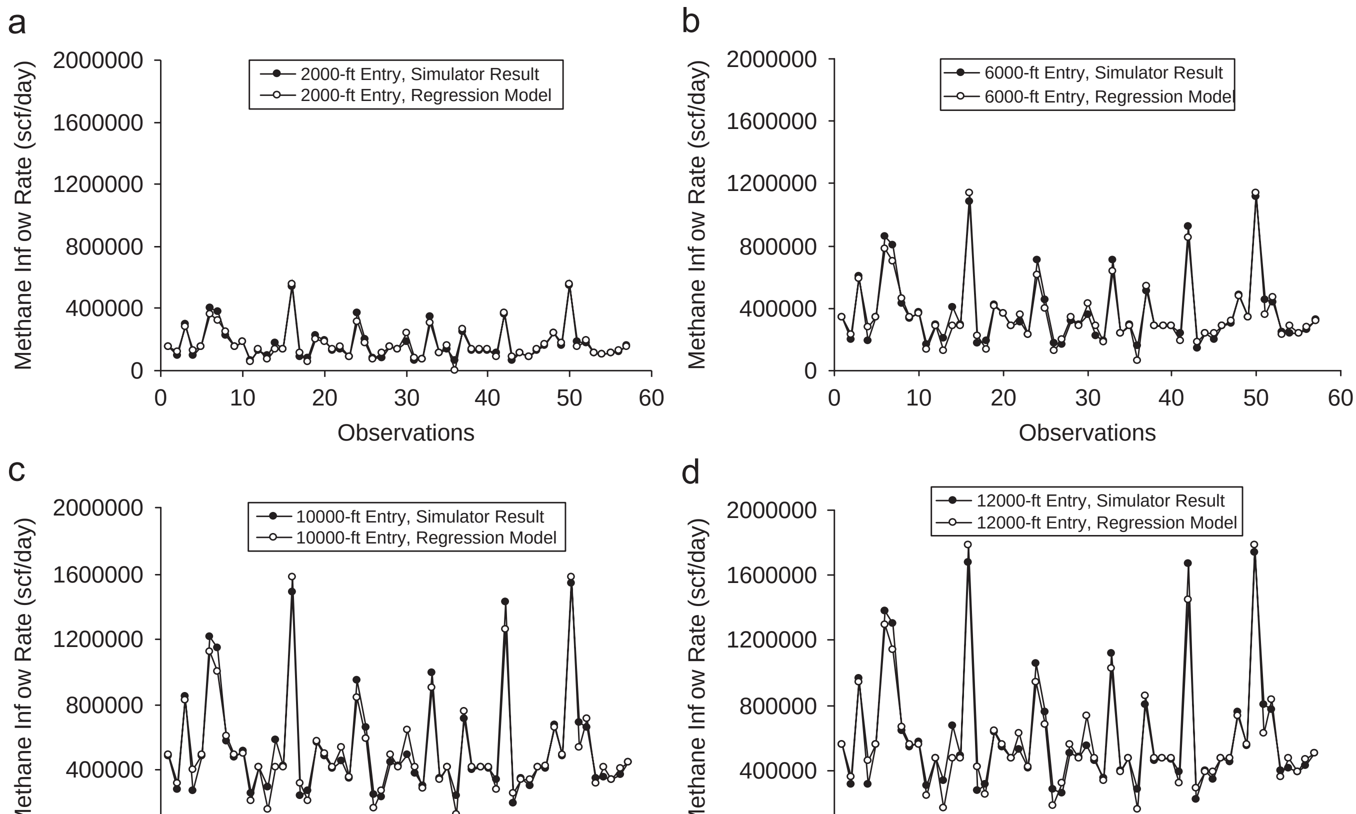

Fig. 12. (a d). Comparison of simulated methane inflow rates for different combination of coalbed parameters with the predictions of linear equations for mining of different development distances.

major influence in determining the fitted line (Devore and Peck, 2001).

Figs. 13a d show the standardized residual plots for each prediction model. These plots show that a few of the observations exhibit values very close to or slightly more than ± 2. However, even with these data in the models, the values of the adjusted regression coefficients and other statistical parameters were quite acceptable. Thus, they were kept in the data set in order to include their effects in the results.

A closer look at the residual plots for mining 10,000 and 12,000 ft (3050 and 3660 m) entries (Figs. 13c and d) suggests that curvilinear models may be better fits for these cases compared to linear models presented in this study, possibly because of the slightly curvilinear relations between some coalbed parameters and calculated methane inflows. However, considering the comparative graphs in Figs. 12a d and the distribution of the residuals, simpler linear models may be as helpful and adequate for predicting the methane inflows.

5. Summary and conclusions

This study coupled "dynamic" reservoir models to linear models to predict methane inflows during development mining of a coal seam. The base reservoir models were developed for a typical three-entry system in the Northern Appalachian Basin section of the Pittsburgh Coalbed. Model data and reservoir simulation results were calibrated using the in-mine measured methane inflows during mining of the headgate and tailgate entries. The base model that was developed for a 50 ft/day (15.3 m/day) section advance rate was used to predict methane inflows into these entries for different coalbed reservoir conditions by varying

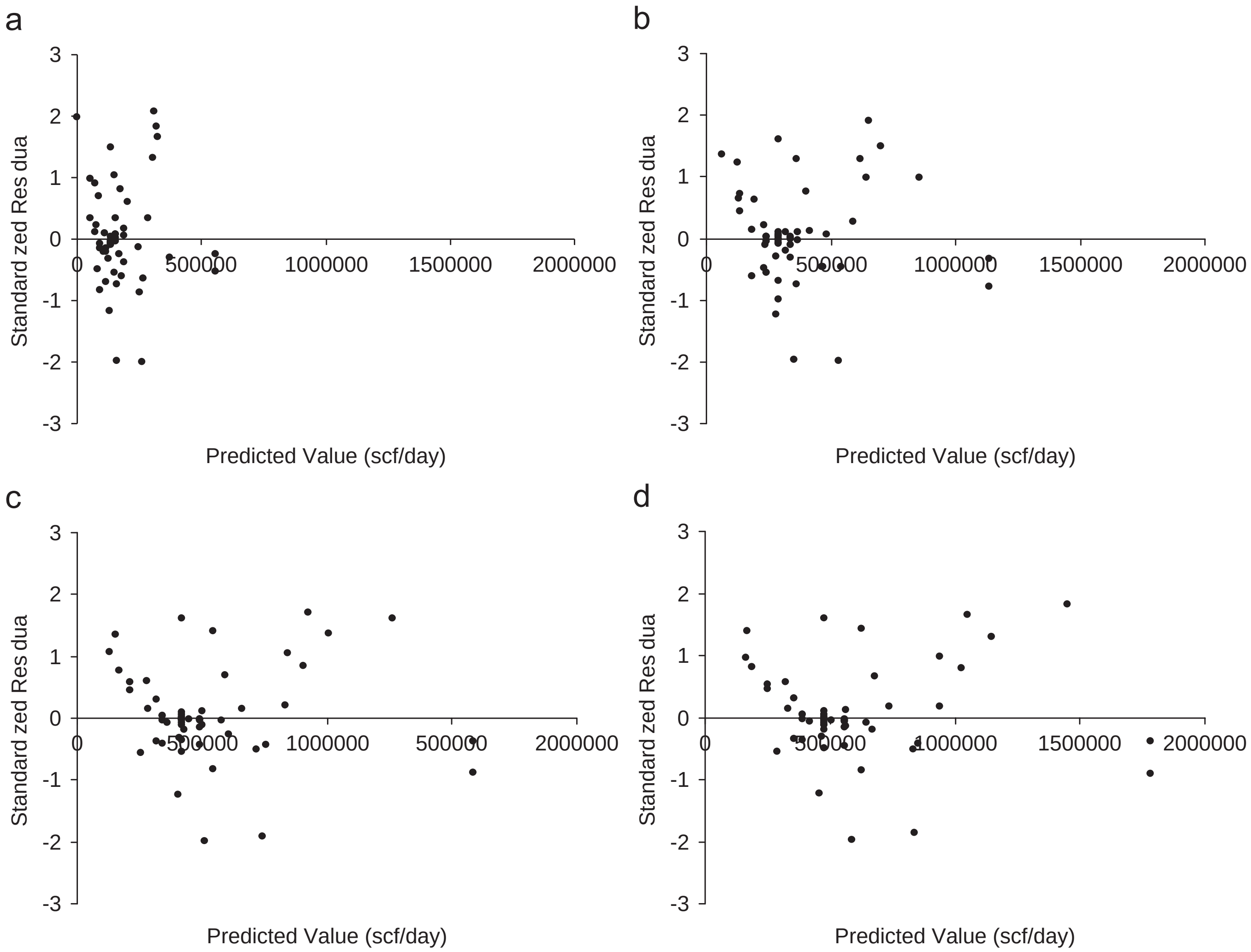

Fig. 13. Plots of standardized residuals vs. predicted methane inflow values during mining using linear models developed for mining of different development distances: (a) 2000 ft, (b) 6000 ft, (c) 10,000 ft, and (d) 12,000 ft.

key reservoir parameters. Thus, 57 simulation cases were performed for each of the 2000, 6000, 10,000, and 12,000 ft (610, 1830, 3050, and 3660 m) development distances.

The methane inflow data were then used to develop linear models using the backward elimination technique. The linear models predicted the methane inflows by using these key coalbed reservoir properties. The models and their parameters were analyzed to evaluate their significance and adequacy for prediction.

This study made the following conclusions:

1. Reservoir simulation was used effectively for modeling development mining in underground coal mines. It predicted methane inflows into the entries based on various coalbed and operating parameters.
2. Methane inflow rate increased with entry length because of increases in the surface area of the coalbed exposed to the mine environment.
3. Among all the coalbed parameters evaluated, coalbed thickness, pressure, sorption time constant, permeability perpendicular to entries and adsorption parameters were found to be the most influential on methane inflow rate. For shorter development distances, initial water saturation was also found to be influential too.
4. Statistical analyses to evaluate the significance of the linear regression model parameters showed that, for all development distances, pressure, sorption time constant, butt cleat permeability, and Langmuir pressure were the more important independent variables for prediction rather than Langmuir volume and coalbed thickness. For shorter development distances, initial water saturation was also found to be influential with a lesser degree. It was further shown that as the development distance increased, the relative importance of coalbed variables changed.
5. Statistical tests suggested that the linear models and their independent parameters did not reveal any statistical problems that would indicate autocorrelation or multicollinearity. Also, hypothesis testing showed that the models had predictive significance.
6. Standardized residuals plotted against predicted parameters indicated that there were only a few data points outside ± 2 interval. In longer development distances, slightly increasing non-linearity was observed, suggesting that non-linear models may be more appropriate.
7. Considering the results of all analyses, comparison of simulator and linear-model predicted rates, low residuals, and high regression coefficients, linear models using influential coalbed parameters can be adequate models and can be used to predict methane inflows in entries during development mining.

References

Brunner, D.J., Schwoebel, J.J., Li, J., 1997. Simulation based degasification system design for the Shihao Mine of the Songzao coal mining administration in Sichuan China. In: Proceedings of the Sixth International Mine Ventilation Congress, Pittsburgh, Pennsylvania, pp. 429 433.

Computer Modeling Group Ltd., 2003. Generalized Equation of State Model GEM User's Guide. Calgary, Alberta, Canada.

Crotti, M.A., Inlab, S.A., Rosbaco, J.A., 1998. Relative permeability curves: the influence of flow direction and heterogeneities. Dependence of end point saturations on displacement mechanisms. In: Proceedings of the SPE/DOE Improved Oil Recovery Symposium, SPE Paper No. 39657, Tulsa, Oklahoma.

Dake, L.P., 1978. Fundamentals of Reservoir Engineering. Elsevier Scientific Publishing, Amsterdam, The Netherlands, 443pp.

Devore, J., Peck, R., 2001. Statistics: The Exploration and Analysis of Data. Duxbury Thomson Learning Inc., Pacific Grove, CA, 713pp.

Diamond, W.P., La Scola, J.C., Hyman, D.M., 1986. Results of direct method determination of the gas content of the US coalbeds. US Department of Interior, Bureau of Mines, Information Circular No. 9067, 95pp.

Ertekin, T., Sung, W., Schwerer, F.C., 1988. Production performance analysis of horizontal drainage wells for the degasification of coal seams. Journal of Petroleum Technology 40, 625 631.

Gash, B.W., 1991. Measurement of rock properties in coal for coalbed methane production. In: Proceedings of the 66th Society of Petroleum Engineers Annual Technical Conference and Exhibition, Paper No. 22909, Dallas, Texas, pp. 221 230.

Gilman, A., Beckie, R., 2000. Flow of coalbed methane to a gallery. Transport in Porous Media 41, 1 16.

Hunt, A.M., Steele, D.J., 1991. Coalbed methane development in the Appalachian Basin. Quarterly Review of the Methane from Coal Seams Technology 1, 10 19.

Karacan, C.Ö., 2007. Development and application of reservoir models and artificial neural networks for optimizing ventila tion air requirements in development mining of coal seams. International Journal of Coal Geology 72, 221 239.

Karacan, C.Ö., Diamond, W.P., Esterhuizen, G.S., Schatzel, S., 2005. Numerical analysis of the impact of longwall panel width on methane emissions and performance of gob gas ventholes. In: Proceedings of the 2005 International Coalbed Methane Symposium, Paper 0505, Tuscaloosa, Alabama.

Karacan, C.Ö., Esterhuizen, G.S., Schatzel, S.J., Diamond, W.P., 2007. Reservoir simulation based modeling for characterizing longwall methane emissions and gob gas venthole production. International Journal of Coal Geology 71, 225 245.

King, G., Ertekin, T., 1991. State of the art modeling for unconven tional gas recovery. SPE Formation Evaluation 3, 63 72.
King, G.R., Ertekin, T., Schwerer, F.C., 1986. Numerical simulation of the transient behavior of coal seam degasifica tion wells. Society of Petroleum Engineers (SPE) Formation Evaluation 4, 165 183.
Kolesar, J., Ertekin, T., 1986. The unsteady state nature of sorption and diffusion phenomena in the micropore structure of coal. In: Proceedings of the SPE Unconventional Gas Technology Symposium, Paper No. 15233, Louisville, Kentucky, pp. 289 314.
Lewis Beck, M.S., 1980. Applied Regression: An Introduction. Sage Publications, Beverly Hills, California, 84pp.
Lunarzewski, L.W., 1998. Gas emission prediction and recovery in underground coal mines. International Journal of Coal Geology 35, 117 145.
Maricic, H., Mohaghegh, S.D., Altun, E., 2005. A parametric study on the benefits of drilling horizontal and multilateral wells in coalbed methane reservoirs. In: Proceedings of the 2005 SPE Annual Technical Conference and Exhibition, Paper No. 96018, Dallas, Texas.
McCulloch, C.M., Diamond, W.P., Bench, B.M., Deul, M., 1975. Selected geological factors affecting mining of the Pittsburgh Coalbed. US Department of Interior, Bureau of Mines, Report of Investigations No. 8093, 72pp.
Motulsky, H., Christopoulos, A., 2004. Fitting Models to Biological Data Using Linear and Nonlinear Regression: A Practical Guide to Curve Fitting. Oxford University Press, New York, NY, 351pp.
Price, H.S., Ancell, K., 1993. Performance characteristics of high permeability saturated and undersaturated coals. In: Proceed ings of the 1993 International Coalbed Methane Symposium, Birmingham, Alabama, pp. 497 509.
Remner, D.J., Ertekin, T., Sung, W., King, G.R., 1986. A parametric study of the effects of coal seam properties on gas drainage efficiency. SPE Reservoir Engineering 1, 633 645.
Savin, N.E., White, K.J., 1977. The Durbin Watson test for serial correlation with extreme sample sizes or many regressors. Econometrica 45, 1989 1996.
Smith, D.M., Williams, F.L., 1984. Diffusional effects in the recovery of methane from coalbeds. Society of Petroleum Engineers Journal 24, 529 535.
Sokal, R.R., Rohlf, F.J., 1994. Biometry: The Principles and Practice of Statistics in Biological Research, third ed. W.H. Freeman and Company, New York, NY, 859pp.
Spencer, S.J., Somers, M.L., Pinchewski, W.V., Doig, I.D., 1987. Numerical simulation of gas drainage from coal seams. In: Proceedings of the 62nd SPE Annual Technical Conference and Exhibition, Dallas, Texas, pp. 217 229.
Valliappan, S., Wohua, Z., 1996. Numerical modeling of methane gas migration in coal seams. International Journal of Numerical and Analytical Methods in Geomechanics 20, 571 593.
Young, G.B.C., 1998. Computer modeling and simulation of coalbed methane resources. International Journal of Coal Geology 35, 369 379.
Young, G.B.C., McElhiney, J.E., Paul, G.W., McBane, R.A., 1991. An analysis of Fruitland Coalbed methane production. In: Proceedings of the 68th SPE Annual Technical Conference and Exhibition, Houston, TX, pp. 263 279.
Young, G.B.C., Paul, G.W., McElhiney, J.E., 1992. A parametric analysis of Fruitland Coalbed methane producibility. In Proceedings of the 67th SPE Annual Technical Conference and Exhibition, Washington, DC, pp. 461 473.
Zhao, C., Valliappan, S., 1995. Finite element modeling of methane gas migration in coal seams. Computers and Structures 55, 625 629.
Zuber, M.D., 1996. Basic reservoir engineering for coal. In: Saulsberry, J.L., Schafer, P.S., Schraufnagel, P.S. (Eds.), A Guide to Coalbed Methane Reservoir Engineering. Gas Research Institute, Chicago, Illinois.
Zuber, M.D., 1997. Application of coalbed methane reservoir simulators for estimation of methane emissions in long wall mining. In: Proceedings of the Sixth International Mine Ventilation Congress, Pittsburgh, Pennsylvania, pp. 435 440.
Zuber, M.D., 1998. Production characteristics and reservoir analysis of coalbed methane reservoirs. International Journal of Coal Geology 38, 27 45.
Zuber, M.D., Olszewski, A.J., 1992. The impact of errors in measurement of coalbed methane reservoir properties on well production forecasts. In: Proceedings of the 62nd SPE Annual Technical Conference and Exhibition, Paper No. 24908, Washington, DC.
Zuber, M.D., Olszewski, A.J., 1993. Coalbed methane produc tion forecasting: measurement accuracy required for key reservoir properties. In: Proceedings of the 1993 International Coalbed Methane Symposium, Birmingham, Alabama, pp. 549 559.
Zuber, M.D., Sawyer, W.K., Schraufnagel, R.A., Kuuskraa, V.A., 1987. The use of simulation and history matching to determine critical coalbed methane reservoir properties. In: Proceedings of the SPE/DOE Low Permeability Reservoirs Symposium, Denver, Colorado, pp. 307 316.