Modeling Methane Emissions and Ventilation Needs by Examination of Mining Induced Permeability Changes and Related Damage to Ventilation Controls

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ABSTRACT: Understanding methane emissions in underground coal mines is critical for a safe and productive mine. In addition to reasonable estimation of initial coalbed reservoir parameters, it is also crucial that changes in effective stress due to mining and pore pressure reduction are taken into account due to their effects on porosity and permeability. Primary parameters for estimation of emissions or modeling of the mining environment for this purpose are porosity and permeability which can change dramatically as a result of stress redistribution associated with mining and gas desorption from a large coal volume. These parameters affect the emission rates and ventilation requirements, as well as water inflow into the working environment. Stopping leakage, on the other hand, is a secondary stress dependent factor in estimation of emissions, as convergence of the roof and floor strata, compromising the integrity of the stopping, may result in leakage, making prediction of ventilation requirements difficult.

This paper aims to examine the effects of porosity and permeability changes of the coal seam on methane emissions in an underground continuous miner section. The models were developed and executed in a dynamic fashion to simulate an advancing section. Through this process, the changes of effective stress in coal, particularly their change paths, on porosity and permeability were incorporated into the models and methane emissions, concentrations, air requirements, water inflow and possible leakage from the stoppings were investigated using a conventional coalbed methane reservoir model.

1. INTRODUCTION

Coalbed methane (CBM) is both a valuable domestic energy source in the United States and a safety concern in underground coal mines. In 2007, US underground coal mine operators reported 73 methane ignitions in underground coal mines. In unfortunate situations, these ignitions may lead to an explosion and to a major mining disaster. Thus, the ability to model methane emissions in underground coal mines as realistically as possible allows for the optimization of coalbed methane degasification systems ahead of mining, appropriate design of the mining geometry, and appropriate design of the mine and section ventilation systems, providing for enhanced safety and productivity.

There are various parameters involved in coalbed methane reservoir modeling that span from depth of seam, coal thickness, porosity, permeability, pressure, methane content and isotherms. Particularly, the influence of in-situ and mining induced stresses on coal porosity and permeability during mining cannot be underestimated for effective degasification and ventilation of coal mines.

Additionally, mining-induced and the resultant effective stress on a coal seam plays an important role in the integrity of ventilation controls, such as stoppings, in underground mines. Roof and floor convergence will usually result in some structural damage to stoppings, allowing leakage of air from intake to return and reducing the quantity of air at the working face.

By accounting for the influence of in-situ and mining-induced stress on the reservoir parameters, methane emissions in an active continuous mining section can be forecasted more accurately.

2. BACKGROUND

2.1. Coalbed Methane Emissions and Production

Methane is formed in coal during the coalification process and also as a result of bacterial activity. It is stored in coal both as a free gas and an adsorbed gas. The free gas and adsorbed gas exist in equilibrium in an undisturbed reservoir, but the introduction of a borehole or mine entries will disturb this equilibrium and cause gas to flow into the open area. Flow occurs both in the micropores and in the fracture network or cleat system, which comprise of butt (short, discontinuous cleats) and face cleats (continuous cleats) [1]. The effects of stress on both the micropores and particularly on fracture network are important in characterizing the ability of the coal to store fluid and to allow gas and water flow. The ability of a dual-porosity porous medium storing fluid and allowing fluid flow within are directly related to its porosity and permeability, respectively, which both are dependent on the effective stress level of the coal seam. Effective stress can be defined as the resultant stress due to in-situ and mining induced stresses collectively, and impacts the porosity and permeability of the cleat system more than the microporous matrices.

2.2. Coalbed Methane Reservoir Modeling

Coalbed methane reservoir modeling is necessary, both for the design of appropriate mining geometry and ventilation and for the design of degasification systems. Reservoir simulators require a large number of interrelated parameters for model building. Reasonable estimation of these parameters is essential in producing a realistic simulation.

Young gives a summary of the minimum data required for coalbed methane reservoir modeling [2]:

- Reservoir description (geometry, structure, depth, thickness, stratification, water saturation, and pressure)
- Fluid Pressure-Volume-Temperature (PVT) data (gas viscosity and composition)
- Time dependent well data (fluid flow rates and bottom-hole pressures), in other words recurrent data.

Porosity and permeability are important descriptors in the characterization of storage and flow of coalbed methane. Coalbed methane reservoirs are unique due to their pore structure. Pore structures in coal are divided into macropores (>50 nm), mesopores (2-50 nm), and micropores (<2 nm) [3]. The majority of methane stored in a coal seam is adsorbed on to the walls of these micropores, while some gas is present as a free gas in the fracture, or cleat, network. This network is comprised of nearly orthogonal fractures distributed within the seam; it stores almost all of the water and plays a critical role in gas production and methane emissions due to its permeability and porosity.

2.3. The Effects of Stress on a Coalbed Methane Reservoir

Understanding methane emission rates in underground mining is critical for the safety and productivity of a mine. Various factors control methane emissions during mining development, but the initial reservoir parameters and the mining parameters are the most important. Coal reservoir parameters that are sensitive to mining induced stresses and in-situ stresses include permeability and porosity. It is essential to consider stress and associated changes in porosity and permeability when modeling emissions from a coalbed methane reservoir [4].

Generally, a decrease in stress in a coal seam will result in desorption of gas followed by an increase in permeability due to matrix shrinkage and opening of cleats [5, 6]. Stress will generally have a more significant effect on macropores and on cleats while leaving mesopores and micropores less affected [7]. This effect changes the permeability of the coal seam, since the cleat structure is mainly responsible for permeability and its anisotropy. Therefore, gas may flow preferentially in one direction due to this structure, usually along the face cleats. The spacing and orientation of cleats are generally related to the orientation of the present or past principal stresses prevailing in the field.

It is important to note that the relative importance of stress with regard to permeability may differ significantly in different coal basins, and that coal seam composition and fracture also play a significant role. However, in general, the anisotropic permeability tends to decrease as effective stress increases, indicating that high in-situ stress will cause the cleat system to close and lower the permeability and porosity of the seam [8]. Therefore, a permeability decrease due to either in-situ or induced stresses, and a permeability increase due to matrix shrinkage may occur concurrently during mining.

Mining, when commenced, will have the effect of redistributing the in-situ stress. As coal is removed the existing stress will be transferred to the adjacent in-place coal, creating zones of relatively higher stress, referred to as abutment stresses. Considered independently, this stress will cause a decrease in porosity and permeability.

3. MODELING PROCEDURE

3.1. Reservoir Modeling Approach for Simulating Effects of Mining

The model used for this case study is a three-entry continuous miner development section, typically practiced by several mines operating in the Northern Appalachian basin. The mining geometry is displayed in Figure 1. The middle entry was modeled as the track entry, intaking air, and the entry to the left of it in the advancing direction was designated as the belt entry or a neutral entry. The third entry was designated as the return entry. Mine entries are modeled as boreholes; the borehole pressures are adjusted to match ventilation pressures found in the entries. Ventilation air input was modeled with an injection well, which injected air at a constant rate of 37.69 m^3/s (79,861 cfm). This value was determined from the pressure loss in the entries and allowing the injection pressure to increase to a maximum value of 102.4 kPa (14.85 psi). The return and belt entries were modeled with production boreholes operating at 100.7 kPa (14.60 psi) and 101.0 kPa (14.65 psi) bottom-hole pressures, respectively. These boreholes were used as monitoring points where the amount of methane and air in the produced gas stream were recorded by the simulator to calculate methane inflow. The injected air from the track entry was split into two at the face based on the pressure differences in the other two entries and the leakage across the stoppings, when it occurred.

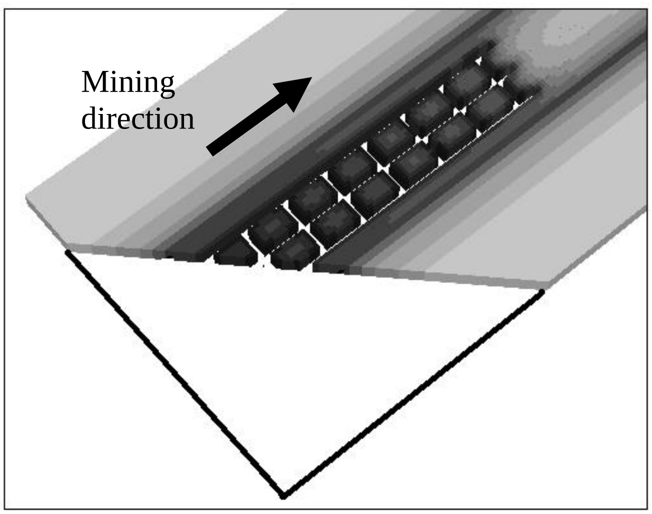

Fig. 1. A cut-away picture of the model showing entries, pillars and mining direction.

While methane inflow and its percentage in the ventilation air are of prime importance, water inflow into the mining environment from coal seam may be important also. The reservoir model was constructed as a two-phase flow model where water is mobilized as a result of effective stress reduction in the fractures following a relative permeability curve that was chosen and used for history matching in earlier studies [9]. Similarly, entries were assigned relative permeability values which would maximize gas flow while enabling water movement towards the monitoring points to quantify water inflow.

Both mining and ventilation are dynamic processes in nature, resulting in varying ventilation requirements based on changes in operating conditions. As the continuous miner advances, a new space must be ventilated, and new surfaces that liberate gas into that space are created. In terms of modeling, this situation is a moving-boundary-value problem. In this study, development of a three-entry continuous mining model was handled using "restart" model runs. These models were run sequentially, each characterizing an advance in entry development with a specified development rate, during which coal bed properties were replaced with the assigned properties of entries in the models. Each restart run was performed in such a way that entries would progress based on a rate of 15.2 m/day (~50 ft/day) that was scheduled in the recurrent data set. As the three-entry system was developed at the designated rates in the models by changing coalbed properties, the crosscuts were also developed at the same time. The resulting pillars were 38.1 m (125 ft) in length, 22.9 m (75.1 ft) in width and had the same properties as the coalbed. Entries and crosscuts were modeled as 7.62 m (25 ft) wide and 1.83 m (6 ft) in height. During development of crosscuts, two stoppings (between track-belt and track-return) were automatically created in the open crosscut of the previous restart run so that during each simulation the ventilation flow would always be circulated from the last open crosscuts. A relatively low permeability value of 98.7 μm^2 (100 darcies) was assigned to the undamaged stoppings to represent the minimum leakage, where 98,700 μm^2 (100,000 darcies) was used to simulate stress-related damage to stoppings in the model runs. These values were selected based on Bear [10] and correspond to lower and upper permeability ends of highly fractured rock material [10]. The formulation of this model was similar to the earlier work detailed by Karacan [9]. The initial properties of the coal seam prior to effective-stress-reduction induced changes are given in Table 1.

Table 1. Initial coalbed properties used in simulation of development mining.

Parameter	Values
Coalbed thickness	1.83 m (6 ft)
Coalbed pressure	2758 kPa (400 psi)
Sorption time	50 days
Permeability anisotropy (K_x/K_y)	4
Face cleat permeability (K_x)	0.00987 μm^2 (10 md)
Butt cleat permeability (K_y)	0.00247 μm^2 (2.5 md)
Langmuir volume	13.6 m^3/ton (490 scf/ton)
Langmuir pressure	2248 kPa (326 psi)
Initial water saturation (Sw_i)	60%
Effective porosity	5%
Irreducible water saturation (Sw_{ir})	10%
Relative permeability to gas (K_{rg}) at S_g= 1-Sw_{irr}	0.35

3.2. *Implementation of Stress Induced Changes*

Various factors control the methane emission rates during mining; the most important are the mining parameters and coalbed parameters [9]. As mining proceeds, the coal seam and the overlying strata are exposed to mining induced stress. These stresses may cause some deformation in the pillars and the ribs of the coal seam, as well as convergence of the roof and floor. The stresses in the ribs and pillars of the roadways result in deviations in the original permeability and porosity of the coal seam. These deviations eventually result in changes in methane and water inflow into the roadways that must be controlled with proper ventilation and pumping. Additionally, roof and floor convergence may result in damage to stoppings, causing intake ventilation air to leak to the return entries, reducing the volume of fresh air that can be utilized at the face. In this study, convergence was neglected due to the model limitations; however, its effect on stoppings was represented by increasing the stopping permeability three orders of magnitude from an original permeability of 98.7 μm^2 (100 darcies) to 98,700 μm^2 (100,000 darcies). These numbers are consistent with permeability values of 0.1 μm^2 to 100 μm^2 for undamaged cinderblocks in the literature [11] and those of highly fractured rock masses given in [10].

Griffith's crack theory was utilized to model changes in permeability at the entry boundaries due to mining-induced stress [12]. This theory describes an elliptical crack, which represents the mine opening in this case, and the stresses at its edges, which may represent the stresses occurring in pillars and in the ribs extending into the coal seam [13]. According to this theory, the vertical stress distribution along the edge of the opening is given by:

$$\sigma_{yy} = P \coth(e) \quad (1)$$

$$where \quad e = \cosh^{-1}(x/c) \quad (2)$$

σ_{yy}: *The vertical stress in the rib*

P: *Stress at infinity perpendicular to the crack, generally related to the overburden stress*

x: *Distance into the rib*

c: *Half the crack width, half the entry width in this case.*

It has been postulated previously by Hoch et al. [14] that the σ_{xx} curve had the same shape as the σ_{yy}; however, it was a fraction less in magnitude. This fraction amount could be approximated by the expression:

$$\sigma_{xx} = \gamma \sigma_{yy} \quad (3)$$

Where:

σ_{xx}: *horizontal stress*

σ_{yy}: *vertical stress*

γ: *Poisson's ratio, approximately 0.25 for coal.*

A simple elastic behavior concept was used to implement the stress level during extension of the opening. In addition, desorption of gas, and drainage of gas and water from coal cleats into the entries result in changes in pore pressure, which couple with mechanical stresses and cause compaction of coal, thus changes in fluid flow related properties, in relation to the pore-pressure stress path. For these cases, four different stress paths (SP), *or elastic response curves of the coal material to a given pressure*, were defined to change permeability and porosity of the coal seam in accordance with changes in the pressure for pillars and the ribs around the openings. Figure 2 illustrates the four cases and the resulting changes in porosity and permeability, as calculated in comparison with the initial values after mining induced stresses are incurred. In these cases, SP1 was considered the base stress path, where a stopping permeability value of 98,700 μm^2 (100,000 darcies) is also used, in addition to 98.7 μm^2 (100 darcies) for comparison of a damaged stopping with undamaged one. Damage to the stoppings was reflected in their permeability values, which was not a function of pressure; therefore all the damaged stoppings had permeability values of 98,700 μm^2 (100,000 darcies) in the model.

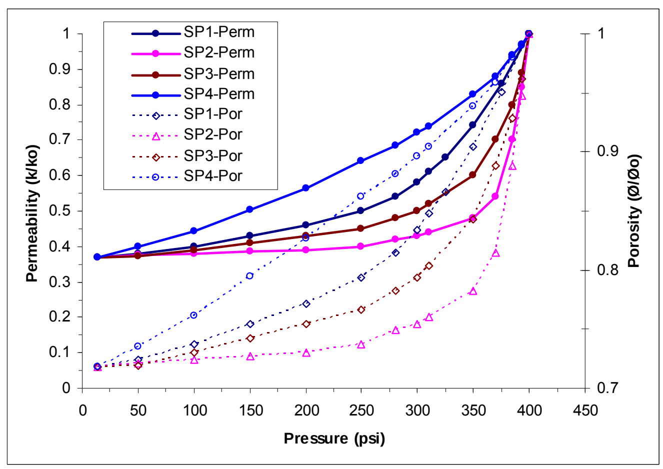

Fig. 2. Permeability and porosity change curves for different stress paths during entry development.

For porosity-dependent permeability changes, the following relation was used [15]:

$$\frac{k}{k_o} \approx \left(\frac{\phi}{\phi_o}\right)^3 \quad (4)$$

In Figure 2, all starting and end point values for different SPs in porosity and permeability were set to the same values. Thus, the effect of end points was eliminated and just the effect of SP change in elastic region was considered.

4. RESULTS AND DISCUSSION

Figure 3 displays samples from model runs. These pictures represent the last 137 m (449.5 ft) of development. A total of 518 m (1,700 ft) of development was modeled in this work. Figure 3A shows the pressure contours while 3B shows the effective porosity contours at the corresponding time step. In both figures, the arrows show the direction and magnitude of water velocity scaled by the logarithm in order to be able to show low and high values in the same figures. These figures illustrate that the velocity of water is highest at the headings where there are sudden drops in pore pressure and it declines around the entries and in the pillars. Conversely, porosity and the related permeability parameter reach the lowest values in the pillars and in the ribs. There is a high porosity and permeability zone ahead of the entries that result from the transient increase in pore pressure in this zone.

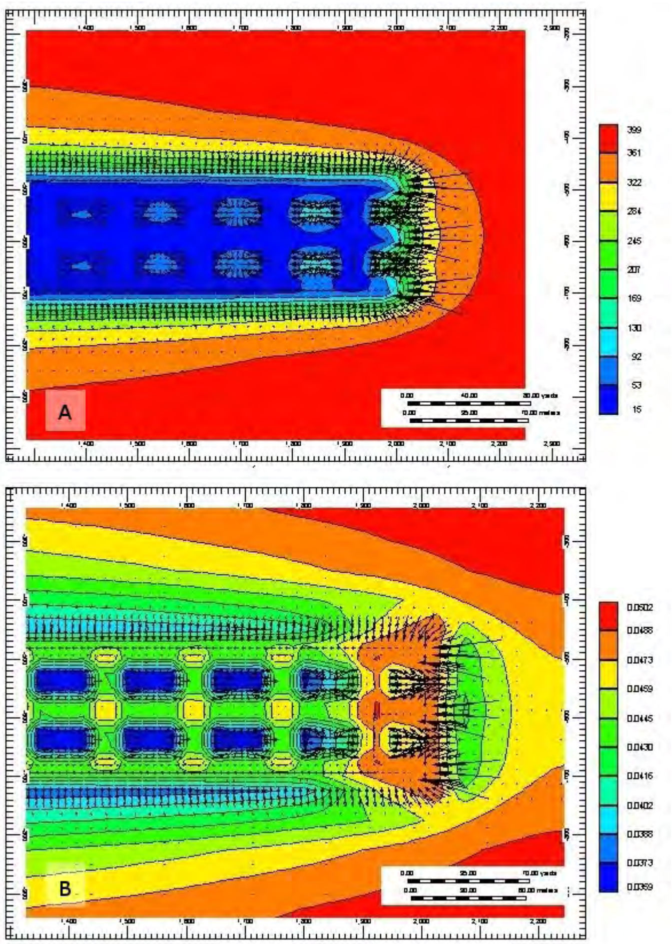

Fig 3. Reservoir pressure contours (A) and porosity contours (B) for the last 137 m (450 ft) of development. Mining is advancing towards right side of the figures. Color legends are and the values are in pressure units, psia.

The results of the simulations for different stress paths (SP) were evaluated for their effects on methane and water inflow into the entries. Figure 4 shows the daily methane inflow rates into the belt and return entries (A) and the daily cumulative emissions from these two entries (B) while a constant air injection rate of 37.69 m^3/s (79,861 cfm) has been provided from the middle (track) entry. Figure 4A shows that the highest methane emissions were obtained from the return entries when SPs of 4, 1, 3 and 2 were followed, respectively. The emission level from the belt entry followed the same SP trends. This was due to the fact that when SP4 was being followed the porosity and permeability of coal in pillars and in ribs around the entries followed a gradually compacting trend with decreasing pressure, as opposed to a sudden compaction and decrease in directional permeability that was experienced in SP2. Therefore, during mining of the entries, a more gradual compaction resulted in a higher gas inflow rate due to a slower decrease in absolute and effective permeabilities. On the other hand, methane inflow rates were about two times higher in the return as compared to the belt entry because the pressure was 0.34 kPa (0.05 psia) lower in the return entry. The cumulative methane emission rates from these two entries were calculated to reach values of about 15.7 m^3/min (557 cfm) at the end of 518 m (1,700 ft) development, when SP4 was followed during mining (Figure 4B)

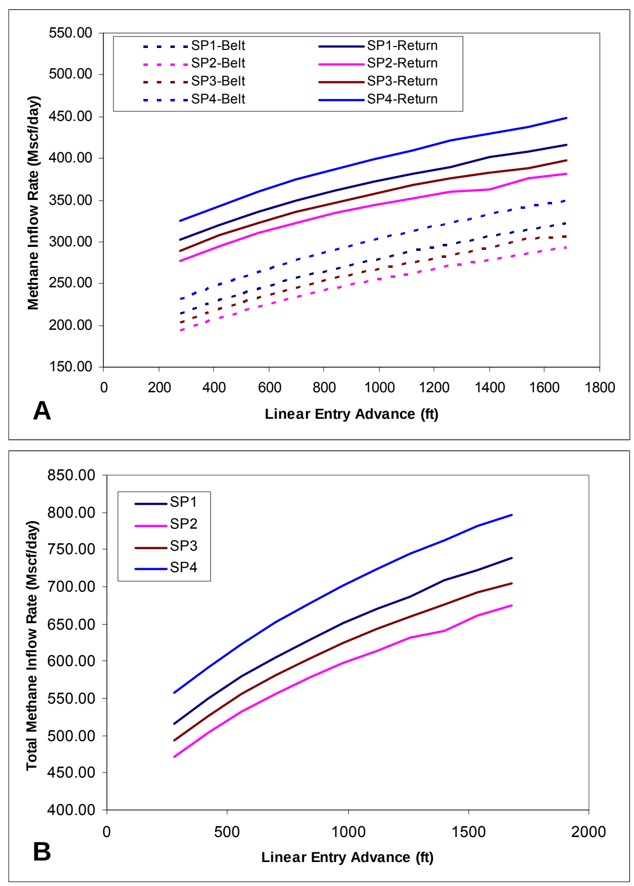

Fig. 4. Daily methane inflow rates into the belt and return entries (A) and the daily cumulative emission from these two entries (B) as a function of development distance and stress path results during mining.

Figure 5 shows the methane percentages in the cumulative ventilation air as measured at the monitoring points at return and belt entries as a function of linear entry distance and the stress paths given in Figure 2. This figure shows that the methane percentage increased in the ventilation air in accordance with the methane inflow rates as developed distance increased. In all SP conditions the ultimate methane percentage at 518 m (1,700 ft) is <1%, which is the statuatory limit. However, as discussed before, the methane content in the air increased more when the compaction of the coal did not occur abruptly as a result of decrease in coal seam pressure as mining continued. From these data, it appears that for longer linear developments the percentage of methane in ventilation air may exceed the 1% limit, especially in the SP4 case.

From Figure 5 it is also evident that a sudden compaction of the coal with small decreases in pressure during mining, the case in SP2, may be desirable since this will result in less methane inflow.

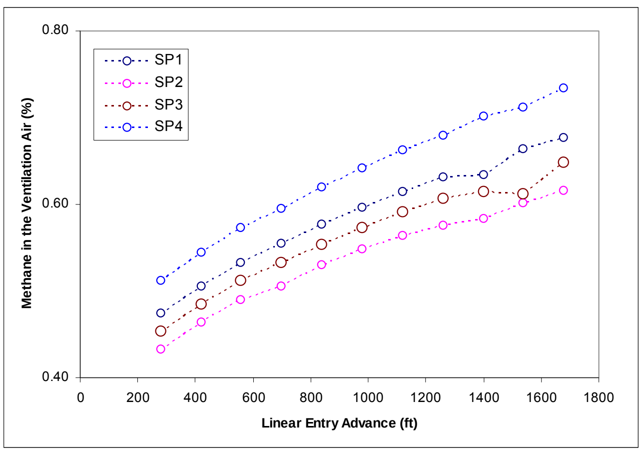

Fig. 5. Methane percentages in the cumulative ventilation air as measured at the monitoring points in return and belt entries as a function of linear entry distance and the stress paths given in Figure 2.

The reservoir model was developed with two-phase flow formulation; water was also flowing in the coalbed due to changes in stress variations and effective permeability to water during mining. In some situations, water inflow into the mine may be high enough to require pumping. In this study, the results of water inflow into entries associated with changes in SP during mining were determined and the data are displayed in Figure 6. Figure 6-A shows the difference in water inflow into return and belt entries, as well as the effect of SP. More water was measured in the return entry, about 11.9 m^3/day (75 bbl/day). The rate in the belt entry was approximately 8.74 m^3/day (55 bbl/day). The values did exhibit an increasing trend with advance distance, similar to observations for methane in Figures 4 and 5. As expected, water control in longer developments is less of an issue than methane control. However, more importantly, the water inflow trend is opposite of the methane inflow trend with respect to SPs. This is due to two mechanisms that occur simultaneously in this model. Normally, in a coal seam reservoir free of any major compaction due to mechanical effects, or similar sorptive tight gas reservoirs, most gas resides in micropores, and most water resides in cleats or fractures. In these reservoirs, gas is released from the microporous matrix as water removal causing the pore pressure to drop. Thus, the faster the pressure drops, the more gas desorbs from coal and diffuses into the cleats, where eventually the relative permeability to gas increases and the gas rate increases at the expense of water rate, which initially was higher. In this model, since fractures deform continuously as well with the stress changes, water residing in fractures has been forced out of the pillars and ribs. So, as a result of the combined effect of compaction of fractures and coal matrix, water rate increased when compaction occurred abruptly, opposite of what was observed in the methane inflow case. The cumulative water flow rate from return and belt entries was approximately 21.5 m^3/day (135 bbl/day) when the development distance was 518 m (1,700 ft).

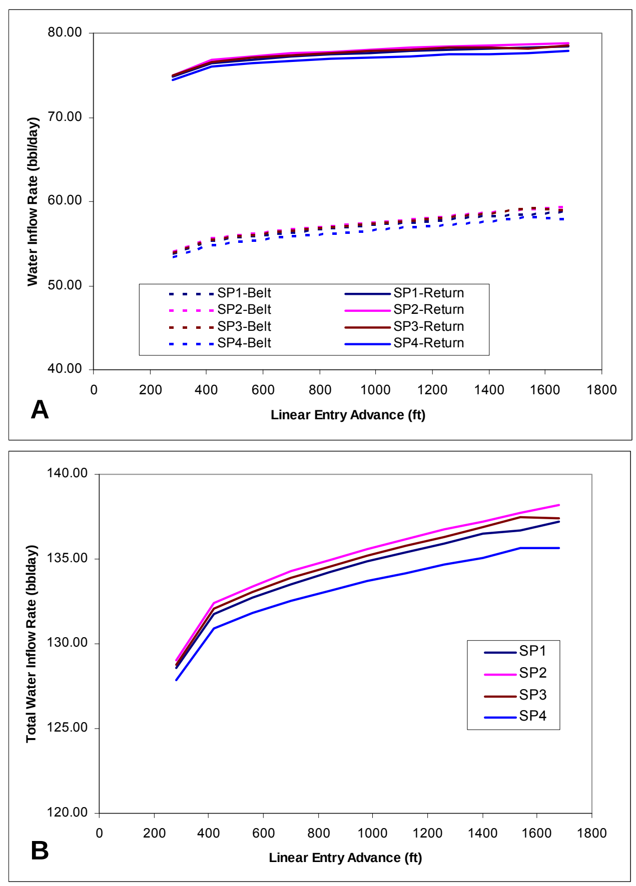

Fig. 6. Daily water inflow rates into the belt and return entries (A) and the daily cumulative water production from these two entries (B) as a function of development distance and stress path results during mining (bbl: barrels).

The discussion thus far has included examination of how changes in SP with mining affect methane and water inflow. In these cases, all stoppings were given permeability values of 98.7 μm^2 (100 darcies). In other words, all stoppings were considered undamaged. A model case was created to compare the effect of permeability of stoppings by using the stress path SP1. In this case, the stoppings were assigned a permeability of 98,700 μm^2 (100,000 darcies), which was considered a damaged stopping for comparison purposes. The main effect of this change was expected to be a increase in leakage across the stoppings and a increase in the ventilation air in return entries, and a consequent decrease in belt air rate, which will either be insufficient to maintain statutory methane levels as mining continues at the face with constant ventilation air capacity, or will increase the ventilation costs significantly in order to provide desired amount ventilation air at the face for effective dilution. The result is displayed in Figures 7 and 8.

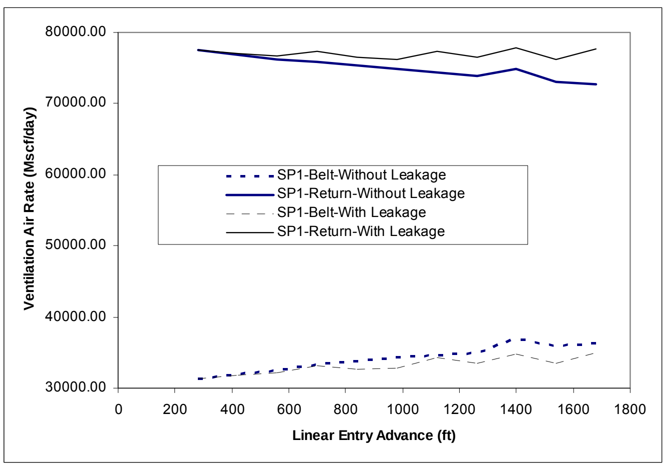

Fig. 7. Comparison of two different stopping permeabilities on the ventilation air quantity in return and intake entries.

In Figure 7, the air rates measured in return and belt entries as a function of development distance are shown. It can be observed that the change in stopping permeability resulted in an increase in air quantity in the return, and a decrease in air quantity in the intake, as air leaked from intake to return.

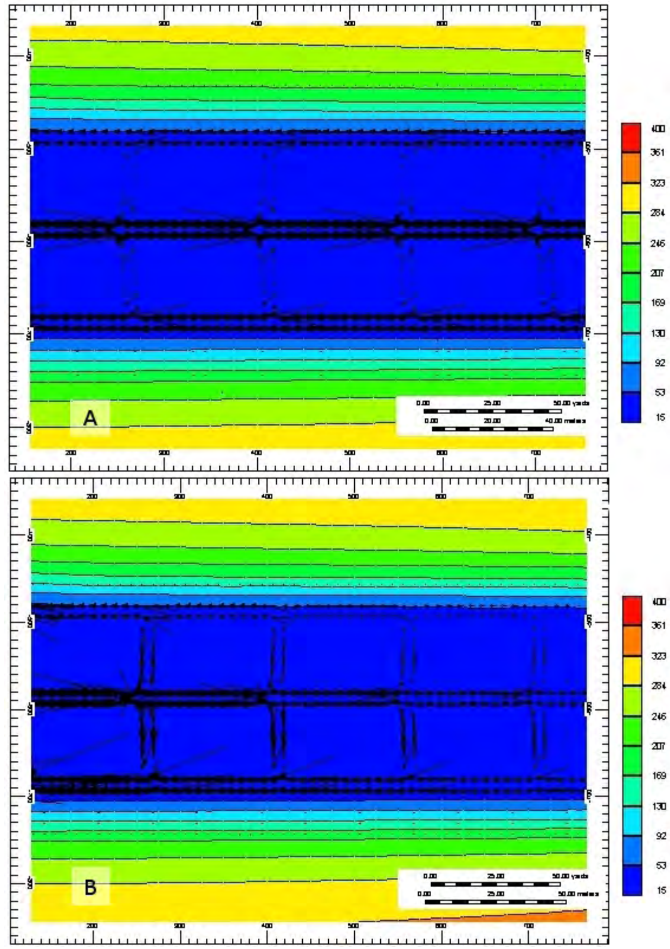

Fig. 8. Comparison of leakage paths for undamaged (A) and damaged (B) stopping permeabilities. Velocity vectors are shown in black, mining is from left to right. Denser cross entry vectors in B indicate more leakage due to stopping damage.

CONCLUSIONS

The results indicate that a gradual change in reservoir permeability and porosity (SP4) as a result of mining induced stress produces the highest quantity of methane emissions, while water production is actually higher with a sudden decrease in permeability and porosity (SP2) as a result of mining induced stress. This phenomenon is most likely due to two mechanisms that occur concurrently. Gradual compaction will cause water to flow out of fractures, lowering the pore pressure and causing gas to desorb from the coal and diffuse into the fracture network, eventually increasing the relative permeability of the reservoir to gas. However, a sudden compaction will force water out too quickly and also cause the fracture network to compress, effectively lowering the permeability of the reservoir to gas.

Stopping damage due to mining induced stress was modeled by increasing the permeability of the stopping to simulate air leakage, and determine the effects of this leakage on methane presence in the ventilation air. This increase in permeability affected the ventilation air quantity, increasing air in the return and decreasing it in the belt entry, as expected. Also, stopping leakage becomes more significant as a section advances. A damaged stopping with a permeability of 98,700 μm^2 (100,000 darcies) was set and applied all the way along the section because convergence could not be integrated into the reservoir simulator and applied to the stoppings. A more realistic approach might be to apply a high permeability at the most outby stoppings (farthest from the mining face) and gradually reduce stopping permeability as they move closer to the face.

Although a sudden compaction will produce less methane to the ventilation air it may also cause further damage to stoppings, which will either reduce the ventilation air quantity that is available to dilute the methane or require higher fan costs to effectively dilute the methane. It is evident from these results that the effects of mining induced stress on both the reservoir properties and the ventilation controls should be considered when designing mining geometry (layout?) and ventilation in a gassy mine.

Future research will involve improving the simulation of leakage across damaged stoppings as detailed above. Additionally, more advanced modeling of mining induced stress would also improve the model, most likely with software such as FLAC [16].

REFERENCES

1. McPherson, M. 1993. *Subsurface Ventilation Engineering (Online Edition)*: Mine Ventilation Services.
2. Young, G. 1998. Computer modeling and simulation of coalbed methane resources. *International Journal of Coal Geology*. : p. 369-379.
3. Crosdale, P., B. Beamish, and M. Valix. 1998. Coalbed methane sorption related to coal composition. *International Journal of Coal Geology*. : p. 147-158.
4. Gu, F. and R. Chalaturnyk. 2005. Sensitivity study of coalbed methane production with reservoir and geomechanic coupling simulation. *Journal of Canadian Petroleum Technology*. (10): p. 23-32.
5. Harpalani, S. and G. Chen. 1997. Influence of gas production induced volumetric strain on permeability of coal. *Geotechnical and Geological Engineering*. : p. 303-325.
6. Bell, J. 2006. In-situ stress and coal bed methane potential in Western Canada. *Bulletin of Canadian Petroleum Geology*. (3): p. 197-220.
7. Wang, G., P. Massarotto, and V. Rudolph. 2009. An improved permeability model of coal for coalbed methane recovery and CO2 geosequestration. *International Journal of Coal Geology*. : p. 127-136.
8. Li, H., S. Shimada, and M. Zhang. 2004. Anisotropy of gas permeability associated with cleat pattern in a coal seam seam of the Kushiro coalfield in Japan. *Environmental Geology*. (1): p. 45-50.
9. Karacan, C.Ö. 2008. Modeling and prediction of ventilation methane emissions of U.S. longwall mines using supervised artificial neural networks. *International Journal of Coal Geology*. : p. 371-387.
10. Bear, J. 1972. Dynamics of Fluids in Porous Media. New York; Dover Publishing.
11. Wang, F. and I. Ward. 2000. The development of a radon entry model for a house with a cellar. *Building and Environment*. : p. 615-631.
12. Griffith, A. 1921. The Phenomena of Rupture and Flow in Solids. *Philosophical Transactions of the Royal Society of London, Series A, mathematical and Physical Sciences*. : p. 163-198.
13. Jaeger, J. and N. Cook. 1979. *Fundamentals of rock mechanics*. New York: Chapman and Hall.
14. Hoch, T., G. Karabin, and J. Kramer. 1991. *Simple Technique for Predicting the Stress Distribution in a Mine Panel*: MSHA.
15. Reiss, L. 1980. *The Reservoir Engineering Aspects of Fractured Formations*. Houston, TX: Gulf Publishing Co.
16. Itasca Consulting Group. 2000. Fast Lagrangian analysis of continua (FLAC). *Minnesota*.