



Study of Methane Outgassing and Mitigation in Longwall Coal Mines

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Abstract

Historically, there have been many occurrences of mine fires and explosions recorded in the United States and other countries that have demonstrated the existence of explosive methane–air mixtures, herein referred to as explosive gas zones (EGZs). The risk of mine explosions can increase if the EGZs migrate out from the gob into the surrounding mine entries. Fluctuating barometric pressure is the common cause for EGZs outflowing or outgassing from the gob. Numerical analysis using a 3D computational fluid dynamics method was developed to fully understand the outgassing phenomenon. A number of simulations using various magnitudes and periods of barometric pressure changes indicated that the EGZ outgassing potentially occurs due to lags in pressure, which are strongly influenced by mine conditions and ventilation systems. An early warning system with a real-time pressure monitoring and the application of gob ventilation boreholes are recommended to detect and mitigate explosion hazards from gob outgassing.

Keywords Gob outgassing · Barometric pressure variation · Computational fluid dynamics (CFD) · Explosive gas zone (EGZ) · Methane gas

1 Introduction

In underground longwall coal mining, the mined-out areas or gobs frequently contain methane, which can form explosive methane–air mixtures. Historically, there have been many occurrences of mine fires and explosions recorded in the United States and other countries that have demonstrated the existence of such explosive mixtures, herein referred to as explosive gas zones (EGZs), inside and around the perimeter of bleeder-ventilated longwall gobs [1–6]. The risk of mine

explosions can increase if the EGZs migrate out from the gob into the surrounding mine entries. Several factors can induce EGZs outflowing from the gob, but the common cause is the fluctuating barometric pressure as it naturally occurs every day. This atmospheric pressure change can fluctuate abruptly and become increasingly hazardous in adverse weather conditions. Other sudden pressure changes can result from roof falls, failing ventilation controls, and fan outages. Any such fluctuation of mine ventilation pressure may disturb the pressure differential between the gob and the surrounding mine workings and may cause EGZs to outgas from the gob.

The correlation between major mine explosions and abrupt barometric pressure changes has been studied and confirmed for explosions in coal mining countries, including the United States, South Africa, Australia, and Poland [7–14]. Disastrous mine explosions appear to happen more frequently during stormy weather, which, in the United States, typically occurs during the late fall and winter seasons.

2 Root Cause and Result of Gob Breathing

Gob breathing is the result of the pressure differential between the inside and outside of the gob caused by external atmospheric pressure fluctuations that occur naturally as a result of gravitational and thermal forces in the atmosphere [15].

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Other major and sudden pressure changes due to failures of fan and ventilation controls or roof falls can also cause an unexpected gob breathing. Normal barometric fluctuations occur every day but usually do not pose an explosion risk as they occur gradually, and therefore gob pressures have sufficient time to equilibrate. Extreme fluctuations associated with cyclonic weather systems and storms often result in more rapid and larger drops or rises in barometric pressure [7, 10]. A study by Lolon [14] found that the timing of historical mine explosions showed consistency with the occurrence of abrupt and intense barometric variations.

The volume of a gas in the gob is inversely proportional to its pressure, causing an EGZ cloud to expand as the atmospheric pressure drops. Further drops would increase the pressure difference between the methane gas reservoir and the mine atmosphere, causing more methane to emanate from the strata. During the process, the EGZ clouds may outgas at specific locations if the pressure change is not symmetric across the gob region. After some time, pressures across the gob will equilibrate, but due to the low permeability of the gob material, this process may take several minutes. It can be compared to an air balloon that has a small leak and takes a long time to lose its air pressure. If the leak is larger, the balloon loses air and equilibrates with its environment faster.

Figure 1 shows a graphical representation of pressure conditions inside the gob versus outside in the bleeder entries. In a bleeder exhaust ventilation system, the pressure inside the gob is higher than that in the bleeder entries. ΔP_s represents the pressure difference between these two locations due to the

selected ventilation system. The barometric or atmospheric pressure change is represented by ΔP_b . As the atmospheric pressure drops (Fig. 1a) or rises (Fig. 1b), the pressure of air in the active working areas and bleeders will change almost instantaneously while the internal gob pressure lags behind because the low-permeability gob material slows the flow of gases required to reach equilibrium. This causes the change of internal gob pressure to lag behind the change of the active mine barometric or absolute ventilation pressure. The pressure differential during this time lag period induces outgassing from the gob into the surrounding mine workings if ΔP_b decreases as shown in Fig. 1(a), or ingassing from the mine workings into the gob, if ΔP_b increases as represented in Fig. 1(b).

If the external pressure changes instantly, for example, due to a fan failure, a roof fall blocking an airway or a crushed-out stopping, the pressure gradient ΔP_b can change almost immediately. If it causes an instant drop of air pressure in active mine working, the pressure differential grows instantly resulting in instantaneous EGZ out- or inflow. After the time lag, the pressure differential decays to the initial differential, ΔP_s . An instantaneous rise of external pressure, for example, a fan failure in an exhaust ventilation system, can cause an immediate positive pressure gradient ΔP_b by which external pressure becomes higher than the gob pressure. Fresh air will flow from the face and headgate entries into the gob and brief flow reversals may occur at the tailgate and bleeder sides. If fresh air mixes with the fuel-rich gas body inside the gob, this air inflow can potentially convert the fuel-rich methane–air mixture to an EGZ [5].

Computational fluid dynamics (CFD) simulation results confirm that the time lag depends on gob permeability, depth of the mine gob, magnitude and rate of the external pressure change.

3 Modeling Environment and Setup

3.1 Mine Layout and Stratigraphy

A CFD computational model was developed based on data available from two cooperating mines in the Western U.S. [16]. The model shown in Fig. 2 was designed based on actual mine panel geometry. The model panel is 6800 m (22,400 ft) long and 370 m (1,200 ft) wide, consisting of mine entries, longwall face, a 13-m (42-ft) high gob and a 24-m (79-ft) high fractured zone that develops above the gob as the coal is extracted. The mine entries for headgate, tailgate, and bleeder sections have identical, rectangular shapes with a height of 3.4 m (11 ft), determined by the height of coal seam, and width of 6.1 m (20 ft). There is a total of 104 crosscuts connecting the two gate road entries placed every 61 m (200 ft) in by the face.

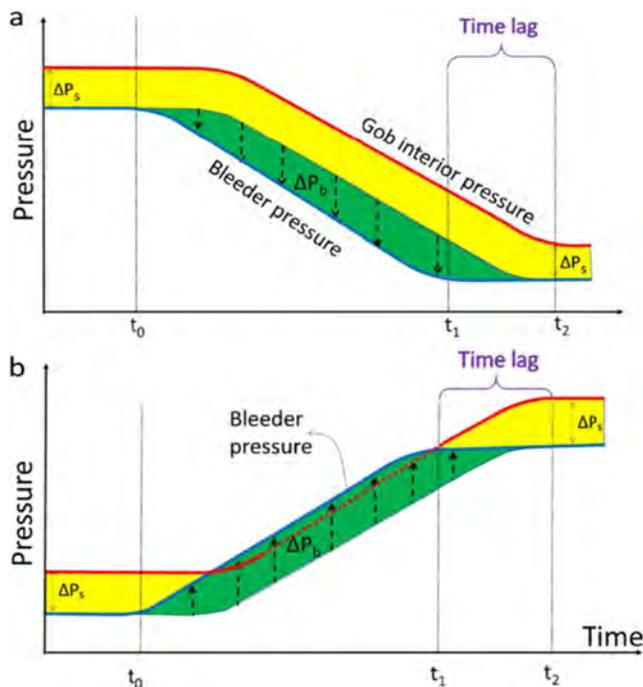


Fig. 1 Pressure conditions of gob and tailgate return entry during barometric pressure (a) drop and (b) rise [14]

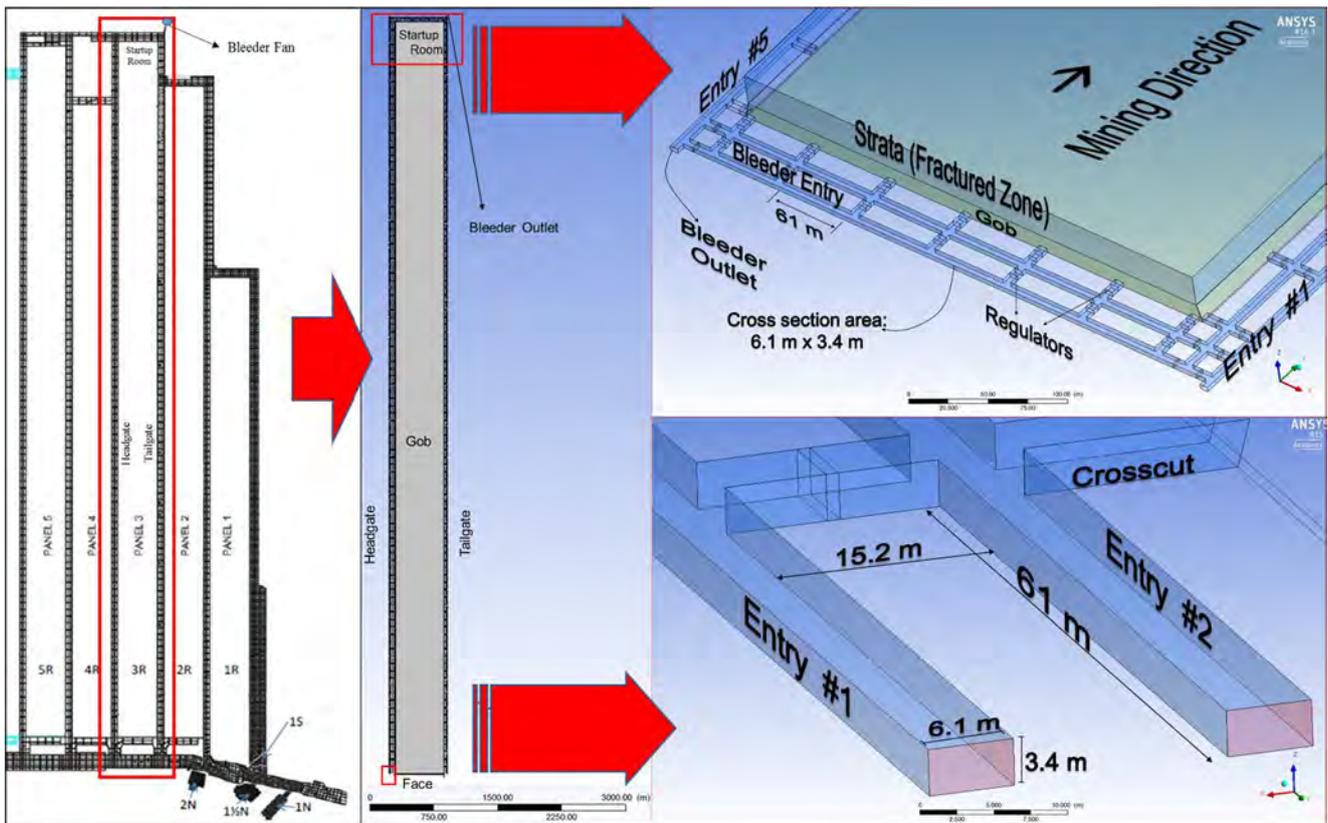


Fig. 2 Mine layout and geometry used in this study

The three-dimensional representation of the longwall panel incorporates shields and a shearer model to obtain realistic air flows and pressure drops across the face. The individual design of shields and shear was provided by Caterpillar, Inc., which were subsequently simplified for meshing purpose. Figure 3 shows the shield design in detail. The model contains 175 shields from headgate to tailgate in this model. The shearer model was simplified to a rectangular box 17 m (55.8 ft) long, 1.8 m (6 ft) wide and 1.4 m (4.5 ft) high, positioned in the center of the longwall face. This model also includes an armored-face conveyor. With approximately 38 m³/s (80 kcfm) of air across the face, the pressure drop is approximately 130 Pa (0.53 in. WG), a common value reported by several cooperating mines [14].

The back end of each shield is not completely closed, leaving a gap of approximately 0.6 m (1.95 ft) × 0.6 m (1.95 ft) between the lemniscate linkages at the back of the shield. The opening size was determined from a 3D model of the shield. This gap of ~0.36 m² (3.8 ft²) exists in every shield along the face, as shown in Fig. 4, and provides a pathway for air flow from the face to the gob. The thin gap between shields is not modeled, since it is considered insignificant for leakage compared to that of the shield gaps. In addition, the construction of this thin gap can result in poor quality meshes due to high aspect ratio.

In many cases, the geometry of the model parts must be simplified since it is near impossible to include all details such

as posts or cribs along the mine entry. Such exclusions are compensated by adjusting wall roughness in the CFD model.

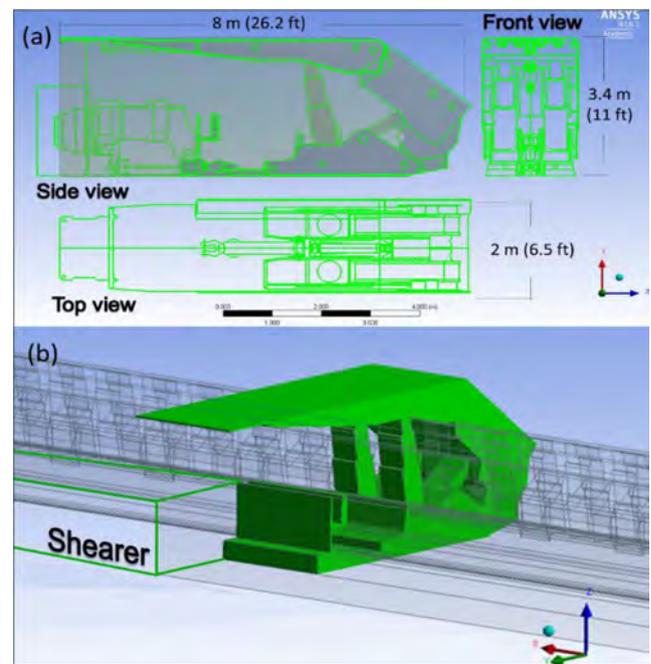


Fig. 3 Shearer and shield model (a) manufacturer’s design and (b) ANSYS DM® output

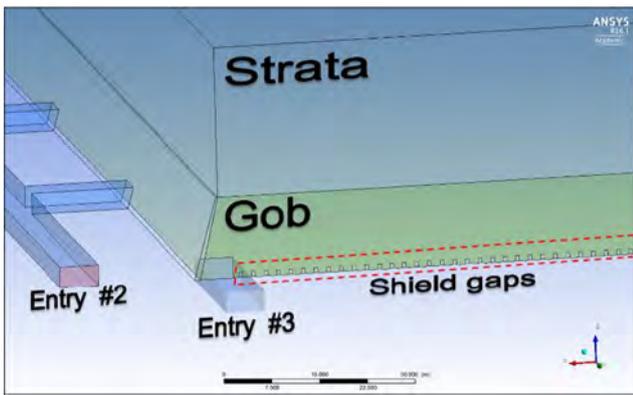


Fig. 4 Location of shield gaps along the face

3.2 Gob Permeability

Figure 5 shows a cross section through the gob zone behind the face. It shows the gob or rubble zone in green, overlaid by a zone of fractured strata shown in blue. The #3 entry on the headgate (HG) and #4 entry on tailgate (TG) are simulated to be mostly collapsed, leaving voids that extend along the rubble zone. The voids are roughly modeled as a continuously open trapezoidal prism of 0.3 m (1 ft) wide at the top and 0.9 m (3 ft) wide at the base, with the same height as the gob (Fig. 4). Gob permeability and porosity gradually vary in the x-y plane. Gob porosity ranges from 14% in the center of the gob to 40% immediately behind the face. Corresponding permeabilities range between $2.0 \times 10^{-7} \text{ m}^2$ and $5.0 \times 10^{-6} \text{ m}^2$, respectively. These values are based on research by Marts [17] and have been validated against data from cooperating mines. For the overlying strata, the permeability is modeled as a fixed value of $9.87 \times 10^{-14} \text{ m}^2$, based on work by Karacan [18]. In the model, a methane inlet is simulated at the top of the fractured zone, representing gas emitted from a rider coalbed above the strata. Both gob and overlying fractured strata are modeled as Darcy’s porous media.

3.3 Model Meshes

The full longwall model is comprised of seven parts meshed independently and imported into ANSYS Fluent® for assembly. The entire model has nearly 18.6 million cells. The

Fig. 5 Cross-section view of gob and strata—looking toward the gob from the longwall face

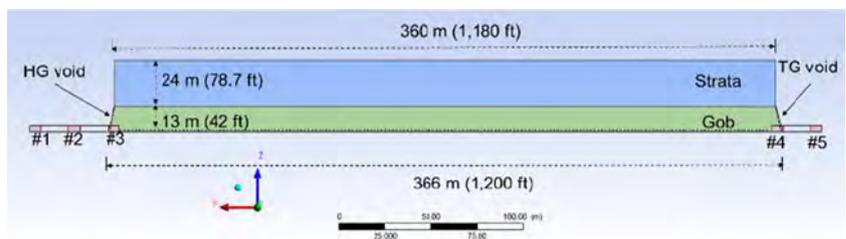


Table 1 Mesh type and quality of the longwall model parts

Model Parts	Dominant Mesh Type	Max. cell size (ft)	Number of Cells (in 1000s)	Mesh Quality		
				Maximum Skewness < 0.95	Aspect Ratio Range 0.2 – 5.0	Minimum Cell Quality > 0.01
Headgate Entry	Hex	2.0	1,057	0.68	1.0–4.7	0.34
Face	Tet	1.0	7,483	0.84	1.1–10.5	0.21
Tailgate Entry	Hex	1.0	2,883	0.32	1.0–4.6	0.65
Bleeder	Hex	2.0	47	0.74	1.0–4.0	0.67
Gob	Hex	4.0	6,442	0.78	1.0–7.72	0.32
Gob-Voids	Hex	1.0	123	0.32	1.4–4.0	0.45
Upper Strata	Hex	8.0	519	1.4E-10	1.0–1.0	0.99

summary of mesh type and quality for each part of the model in this study is given in Table 1.

Figure 6 shows the complete mesh of the model used in this study. The inlets are indicated in blue, outlets in red, and wall boundaries in white.

In a converged model, solutions must be independent from the mesh and no longer change as mesh sizes decrease. Therefore, a mesh-independence study was conducted to analyze the mesh sensitivity and ensure true solutions are achieved. Differences of less than 1% change in EGZ volume outputs after refining the mesh size two and four times smaller confirm mesh independence of the CFD models in this study.

3.4 Mine Ventilation Parameters and Boundary Conditions

The simulated mine uses a three-entry bleeder ventilation system with both headgate and tailgate sides serving as air intakes, as shown in Fig. 7. The ventilation parameters are obtained from cooperating mines in the Western U.S. that had been studied by earlier researchers of this project [17]. The outermost tailgate entry is not modeled as it is assumed to have fully caved along the edge of the previous gob. Entries #1 through #5 supply fresh air, which is then exhausted through entry #7. Entries #1 to #3 supply a total of

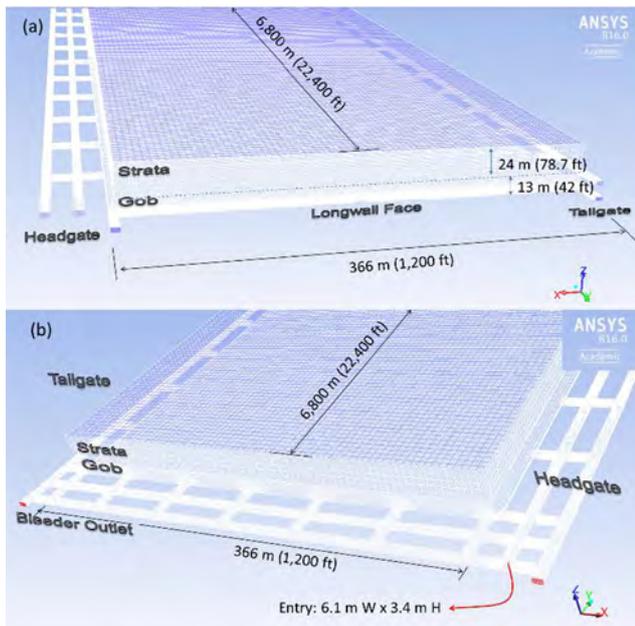


Fig. 6 The complete meshed model (a) front view and (b) rear view

47.8 m³/s (101,250 cfm) to the panel of which approximately 10 m³/s (21,200 cfm) leaks into the gob past the headgate. The remaining 37.8 m³/s (80,050 cfm) ventilate the longwall face. Entries 4 and 5 add another 5.1 m³/s (10,800 cfm) of fresh air from the tailgate side. A bleeder shaft is assumed to be located near outlet #7.

The pressure boundary conditions at the inlets and outlets are shown in Table 2. These are obtained and adjusted in the modeling to achieve the specified target flow rates at each entry. To simulate the methane source, a pressure inlet of 4630 Pa is placed at the top of the strata to emit methane at a maximum rate of 1.0 m³/s (2,100 cfm) down into the gob, ensuring a methane concentration of 1.9% at outlet #7, not to exceed 2% as regulated by 30 CFR 75.323. This pressure value is in the proximity of the gob venthole shut-in pressures reported by other field studies [19, 20]. This methane source is assumed to be infinitely available as a large reservoir.

Several regulators for ventilation control are set up in the bleeder entries near the start-up room based on observations in the cooperating mines. In practice, the condition of the inner

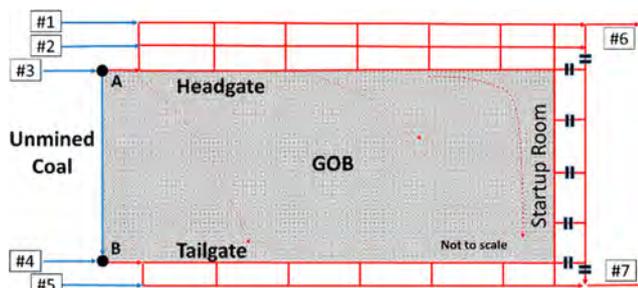


Fig. 7 Simulated bleeder ventilation system

Table 2 Pressure boundary conditions of the base case model

Location	Boundary condition type	Pressure value (Pa)	Flow rate [1]	
			(m ³ /s)	(cfm)
Entry 1	Pressure-inlet	3332	+4.91	+10,400
Entry 2	Pressure-inlet	3332	+4.89	+10,350
Entry 3	Pressure-inlet	3467	+38.00	+80,500
Entry 4	Pressure-inlet	3335	+1.48	+3100
Entry 5	Pressure-inlet	3328	+3.64	+7700
Methane inlet	Pressure-inlet	4630	+1.01	+2150
Outlet 7	Pressure-outlet	2241	-49.63	-105,150

Positive and negative signs represent flow entering and exiting the model, respectively.

bleeder entry next to the start-up room can be wholly or partially caved, limiting the passing air flow.

3.5 Explosibility Diagram

Figure 8 shows the color scheme used to characterize the explosibility of methane in the gob atmosphere. The diagram is based on Coward’s triangle but has been modified to include the additional nitrogen as a result of inertization application and near-explosive transition zones of fuel-rich, fuel-lean or both fuel- and oxygen-lean [16]. This mixture’s explosibility is calculated in CFD using the user-defined functions (UDFs).

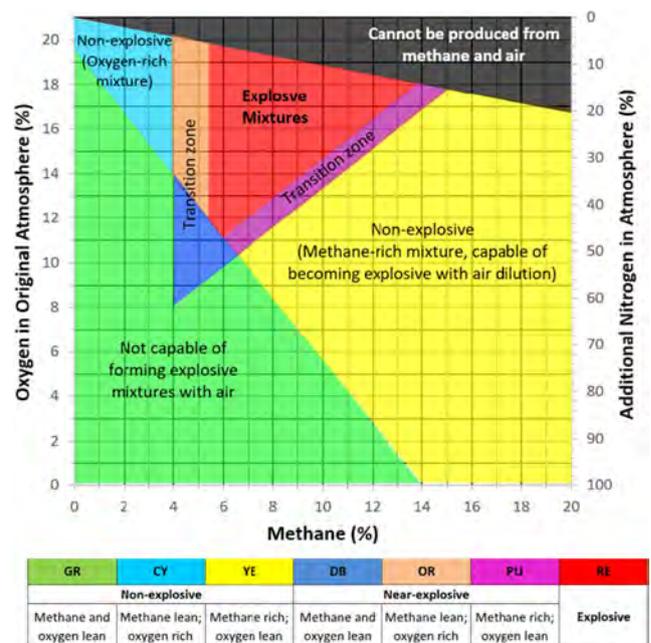


Fig. 8 Color-coded diagram used in this modeling (modified after [16])

4 Summary of Simulation Results

4.1 Initial EGZ Condition

Figure 9 is a plane view at 3 m above mine floor showing the initial condition of potential EGZs in the gob before pressure changes with boundary conditions specified in Table 2. These EGZs are typical of most bleeder ventilated gobs [5, 16]. Cross sections A-A', B-B', and C-C' show that the EGZ fringe (red color) has a “tub” shape with a gradually wider profile toward the top of the gob. Gob zones directly behind the face and along the headgate side are shown as cyan color indicating

ventilation air ingress into the gob. In the tailgate return (section D-D'), EGZ fringes and near-explosive mixtures (orange) are observed along the roof due to the buoyancy of methane.

4.2 Simulation Results: Time Lag

Several studies have reported barometric pressure changes within a range of 100 to 1000 Pa prior to major mine explosions ([7, 10–12] [13, 14]). Pressure data obtained from the National Climatic Data Center’s land-based station near one of the cooperating mines indicated fluctuations with the largest swing of nearly 2000 Pa in 2013 due to a major storm that

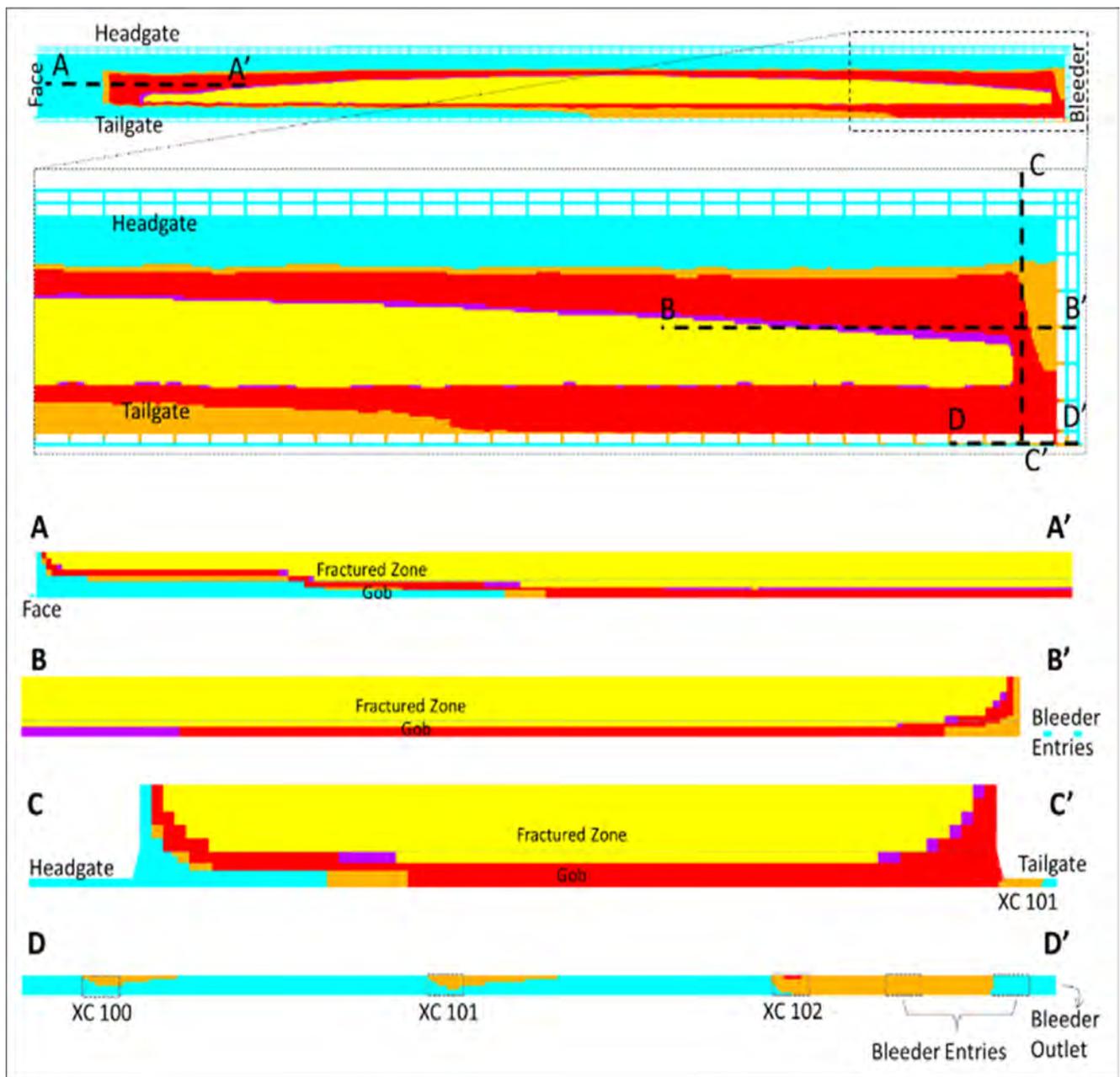


Fig. 9 Initial condition of EGZ formation in the gob and tailgate return

occurred in the region [21]. The rates of pressure change reached over 100 Pascals per hour at times. Based on these studies, pressure changes in this modeling were simulated at various magnitudes ranging from 100 to 2000 Pa and rates from 50 Pa per hour (slowest) to instantly. Near instant pressure changes may occur during a roof fall or a main fan failure. A rate slower than 50 Pascals per hour did not show significant increase in EGZ outgassing. Such small rates would only cause infinitesimal pressure differences, for which gob pressure is able to quickly reach equilibrium, preventing significant and continuing outgassing.

In each simulation, all barometric pressure boundary conditions shown in Table 2, except the methane inlet, are concurrently dropped or raised by the same magnitude and rate using scripted UDFs. Pressure changes at several locations inside and outside the gob are recorded before and after the event. Figure 10 shows six pressure evaluation locations inside the gob and three outside the gob at the tailgate return and crosscuts. Some of these sampling locations are not physically accessible but serve as markers in the CFD model. Evaluation points are located 3 m (9.8 ft) above the mine floor, i.e., approximately 0.3 m below the roof.

As shown in Fig. 1, when the atmospheric pressure rises or drops, the ambient pressure in the active working areas will change almost instantaneously while the internal gob pressure will change more slowly, causing a time lag. This lag in gob response to external pressure changes depends on the gob’s permeability as well as magnitude and rate of pressure changes.

This study simulated scenarios for different magnitudes of pressure change and recording the resulting time lags. For instantaneous drops, Fig. 11 shows the trends at locations A through F and outlet #7, denoting time lags of 1.2, 1.8, 2.1, and 2.8 min, respectively for 100-, 500-, 1000-, and 2000-Pa

drops. The time lag begins when the outside pressure stops changing and lasts until the gob pressure reaches equilibrium.

In all four cases, the bleeder outlet pressure instantaneously drops from 2240 Pa before remaining steady at $t = 0$ s, resulting in additional pressure gradient, ΔP_b , into the system. Over time, the pressure in the gob slowly decreases and reaches equilibrium at the end of time lag. Simulations indicate that the time lag is proportional to the magnitude of pressure decrease. The greater the pressure drops, the longer the time lag.

In addition to instantaneous drops, scenarios with gradual decreases and increases were also simulated. Table 3 summarizes the simulation results. The (+) and (–) signs on the pressure magnitude and rates represent the increase or decrease, respectively. Modeling shows a smaller time lag if atmospheric pressure decreases at a small rate. In other words, if mine pressure drops gradually, the gob pressure will not lag far behind, keeping ΔP_b minimal, and thus limiting methane outgassing.

4.3 Simulation Results: Explosive Gas Zones (EGZ)

Figure 9 depicts the initial EGZ condition, highlighting that some gob outgassing occurs as a result of the bleeder ventilation system. This outgassing is driven by the bleeder system’s pressure differential, ΔP_s (yellow-colored area in Fig. 11). The outgassing increases instantly at $t = 0$ s due to the addition of ΔP_b to the system. Outgassing during the time lag is driven by the total of $\Delta P_b + \Delta P_s$. During these times, the EGZs expand and outgas into the surrounding mine entries where they create an ignition hazard. The magnitude of ΔP_b decreases over time as the gob pressure catches up, causing the outgassing to taper off gradually and eventually stop when gob pressure reaches equilibrium. When atmospheric pressures no longer change, the equilibrium mimics the initial condition where $\Delta P_b = 0$ and only ΔP_s exists.

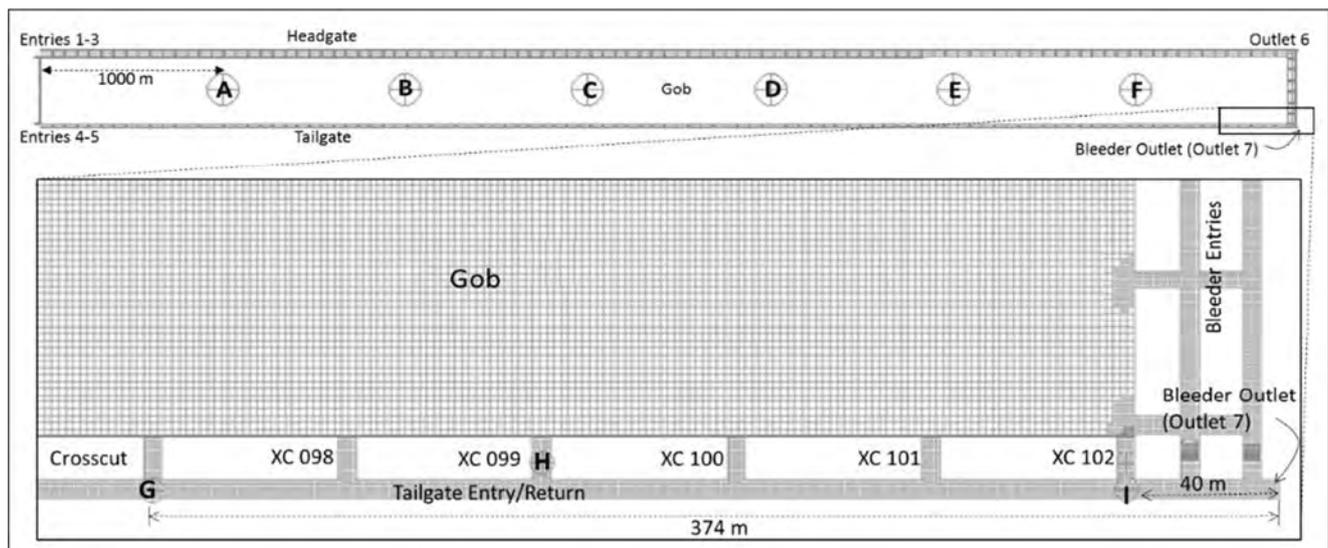


Fig. 10 Locations of sampling points A–F in the gob and G–I outside the gob along the bleeder entries

Table 3 shows that total outgassing volume is a function of the magnitude but not of the rate of the pressure change. For instance, total EGZ outgassing volume for 1000-Pa atmospheric pressure decrease is 1100 m³ for both instantaneous and gradual pressure rate scenarios. This is the EGZ volume found in the bleeder entries alongside the gob. As shown by Fig. 9, EGZ has been observed to occur in the tailgate return initially. The % EGZ outgassing is an

indication of the relative increase or decrease of its volume from the initial volume. While the falling pressure scenarios result in increasing outgassing, rising barometric pressures will push the EGZ toward the center of the gob. The 1000-Pa pressure rise scenario shows a 2.2% lower EGZ outgassing volume, indicating that the rising atmospheric pressure negates the ΔP_s , the pressure difference generated by the ventilation system.

Fig. 11 Pressures recorded at several sampling locations within the gob during instantaneous atmospheric pressure drops by (a) 100 Pa, (b) 500 Pa, (c) 1000 Pa, and (d) 2000 Pa

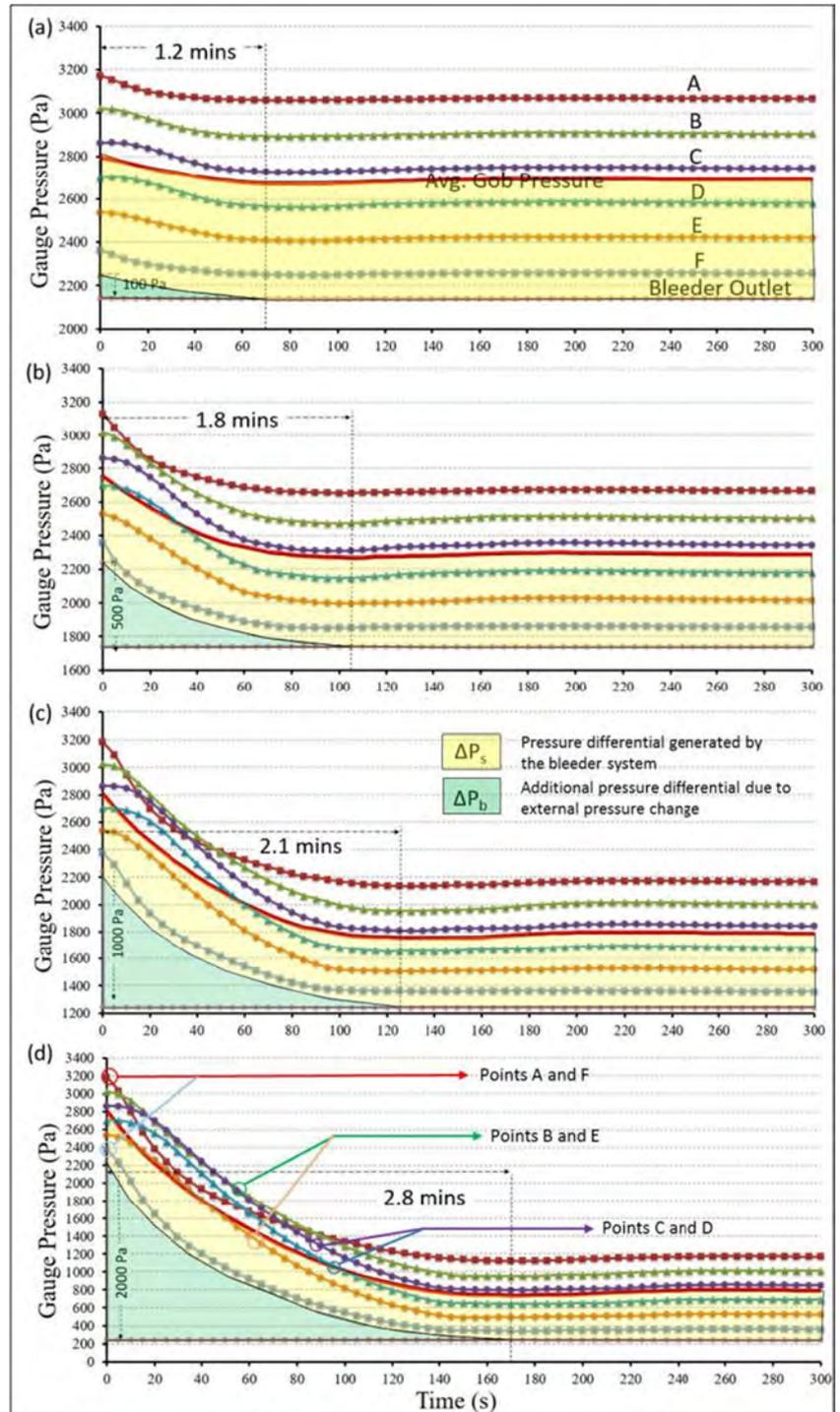


Table 3 Summary of outgassing as a function of barometric pressure changes magnitudes and rates

Simulated condition	Magnitude of pressure change (Pa)	Rate of pressure change	Time lag (mins)	After Two Hours of BP Changes			Potential location of EGZ outgassing
				Total EGZ outgassing (m ³)	Total EGZ outgassing (%)	Methane inflow (m ³ /s)	
Scenario 1: Instantaneous pressure drop	-100	Instantaneous	1.2	700	13.2	1.10	Tailgate return, bleeder entry
	-500		1.8	790	14.7	1.30	Tailgate return bleeder entry
	-1000		2.1	1110	20.7	1.50	Tailgate return bleeder entry
	-2000		2.8	1730	32.3	2.10	Tailgate return bleeder entry
Scenario 2: Instantaneous pressure rise	+500	Instantaneous	1.2	-110	-2.1	0.80	No outgassing observed
	+1000		2.1	-120	-2.2	0.80	No outgassing observed
Scenario 3: Gradual pressure decrease of 100 Pa	-100	-50 Pa/h	<0.5	700	13.2	1.10	Tailgate return, bleeder entry
	-100	-100 Pa/h	<0.5	710	13.4	1.10	Tailgate return, bleeder entry
Scenario 4: Gradual pressure decrease of 1000 Pa	-1000	-500 Pa/h	1.0	1,000	20.7	1.50	Tailgate return, bleeder entry
	-1000	-1000 Pa/h	1.3	1110	20.8	1.50	Tailgate return, bleeder entry

The simulation also indicates that the change rates determine the rates of outgassing over time. An instantaneous pressure drop causes an abrupt, early outgassing that slows down over time, while a gradual pressure drop causes steadier outgassing over time.

For the ventilation scheme and pressure regime chosen in the model, outgassing occurs primarily in the last ten crosscuts closest to the bleeder outlet #7. Figures 12 through 14 depict the EGZ conditions when pressures reaching equilibrium following a change in atmospheric pressure (at t = 300 s). In all cases, a decreasing barometric pressure induces an expansion of the EGZ within the gob, typically toward the tailgate as this is the pressure sink. In Figs. 13 and 14, EGZ expansions into the tailgate crosscuts and bleeders are associated with greater pressure drops. The EGZs are found to expand mostly along the roof due to buoyancy effects.

In addition to EGZ volumes, methane concentration is also monitored at bleeder outlet #7. The simulation results show that, despite increased EGZ volumes found in the tailgate return, the methane concentration increases at the bleeder outlet are relatively small, within 0.5%. The worst scenario simulated, a 2000-Pa instantaneous pressure drop, pushes EGZ into the adjacent bleeders with an increase of 32%, yet methane concentration at the outlet only increases by 0.5% from 1.9%.

5 Model Validation

The geometry and ventilation data used in this study are obtained from the cooperating mines and thus the resulting EGZ and airflow are expected to show the general direction of what would happen in a real situation.

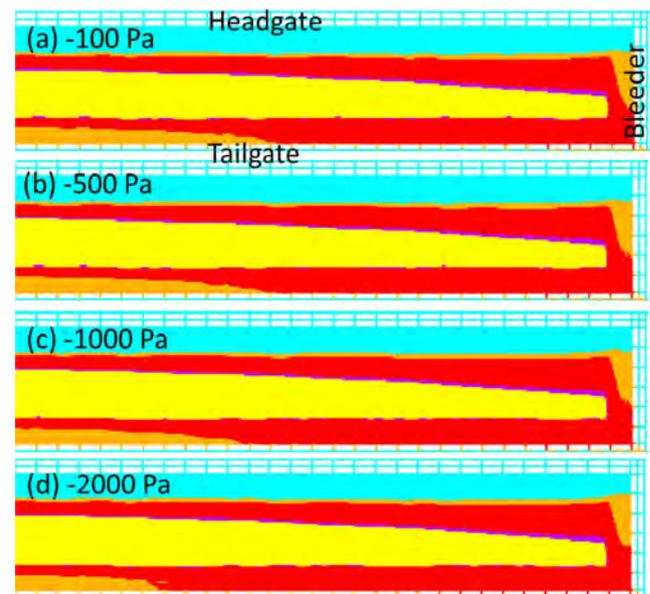
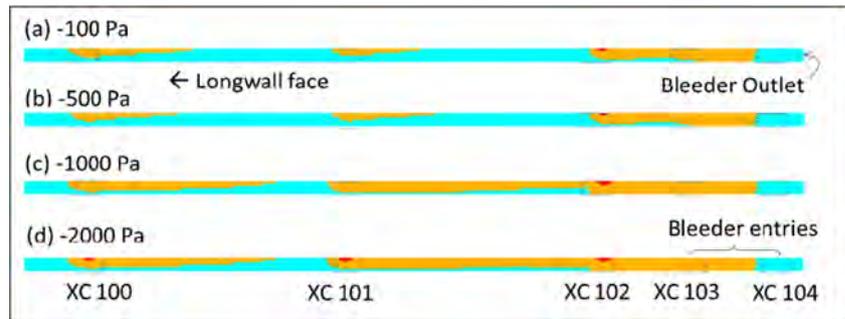


Fig. 12 EGZ profile along the horizontal plane view at 3 m above mine floor, at t = 300 s of pressure drop

Fig. 14 EGZ profile along the tailgate return (section D-D' in Fig. 9) at $t = 300$ s of pressure drop



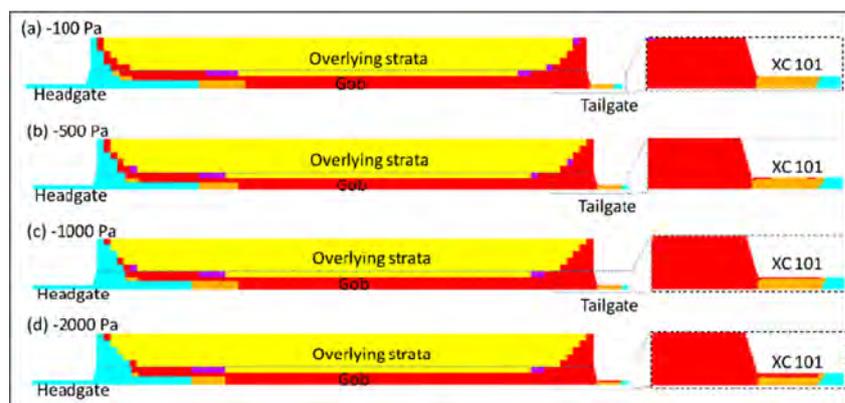
In addition, the modeling results such as flow velocity in the gob, pressure of methane inlet and increased methane concentration at tailgate entry after a barometric pressure drop are validated against mine measurements and reference values obtained from several actual mines. Due to the inaccessibility and continuous caving of the gob, field measurements are impossible to conduct directly in the gob; thus, many studies estimated velocity using a tracer gas. Diamond et al. [19] used sulfur hexafluoride, SF_6 , in several longwall panels in the Pittsburgh coalbed and found the velocity to be 0.002 m/s (0.36 ft./min). Comparable values are indicated in this study, ranging between 0.0001 and 0.04 m/s (0.019 and 7.9 ft./min) across the entire gob.

EGZ outgassing volume depends on the magnitude of a pressure drop, regardless of the drop rate. Belle [13] conducted an extensive field investigation at a highly gassy coal mine in Australia and reported an increase of 0.5–0.94% methane content in tailgate return after a 500-Pa drop. In this study, the simulation on the 500-Pa instantaneous drop scenario indicates an immediate methane increase in tailgate bleeder by 0.8%, within the range reported from Belle's field investigation.

6 Recommended Best Practices for Explosion Prevention

Barometric pressures fluctuate naturally, and therefore mine operators must have early warning systems and plans in place

Fig. 13 EGZ profile in the vertical section along XC 101 (section C-C' in Fig. 9) at $t = 300$ s of pressure drop



to detect and mitigate the explosion hazards from gob outgassing. Hazard evaluation and mitigation include the development of a risk matrix, barometric and fan pressure monitoring, and the operation of gob ventilation boreholes (GVBs).

6.1 Risk Matrix for EGZ Outgassing

EGZ modeling demonstrates the influence of barometric pressure changes for a bleeder ventilated longwall panel, with specific gob permeability, ventilation conditions, and methane sources. While EGZ outgassing and changes caused by barometric or external pressure fluctuations are considered to be similar from one mine to another, quantitative indicators such as outgassing volume and absolute methane concentration can be different. Therefore, each mine operator should conduct their own analysis, preferably with CFD, on the impact of barometric pressure fluctuations typical for their location. Understanding the effects of barometric pressure fluctuations on gob breathing does not itself prevent EGZ outgassing from occurring, particularly because bleeder systems are designed to flush explosive gases from the gob. However, such understanding is the basis for appropriate response and emergency planning to prevent mine explosions.

One element of a response plan is a risk matrix similar to the one shown in Table 4. The risks are ranked based on suggested likelihood and consequence criteria presented in Tables 5 and 6. The likelihood of barometric changes can be

Table 4 Example of a risk matrix for EGZ outgassing due to barometric pressure changes

Likelihood	Consequence			
	Severe	Moderate	Minor	Insignificant
Likely	Extreme	High	Medium	Medium
Possible	High	Medium	Medium	Low
Unlikely	Medium	Medium	Low	Low
Rare	Medium	Medium	Low	Low

determined from historical data of pressure fluctuations within the region that are available from meteorological services. The consequence rank is determined by the magnitude and rate of drop and the methane concentration at the tailgate return based on measurements and/or CFD modeling. The recommended mitigation plan should be developed based on the pre-determined risk matrix rank. For example, to respond to a low-ranked risk, the mine operator should closely monitor methane readings at the tailgate return and bleeder evaluation points (BEP) and adjust ventilation to ensure any outgassing is well diluted. In the more extreme cases, the operator may need to temporarily shut down and evacuate the mine until methane readings return to normal.

It is noted that the ranking presented above is based on the CFD modeling conducted for this paper. Other mine settings and situations may require specific risk and consequence schemes to be developed.

6.2 Real Time Monitoring System

In most underground longwall operations, bleeder systems must be monitored once a week at the BEPs using a handheld gas detector [22]. Handheld gas detectors are typically used in U.S. mines to measure mine gas concentrations. These readings cause the mine examiner to be directly exposed to potentially explosive methane–air mixture while measuring. A real-time, telemetric atmospheric monitoring system (AMS) records atmospheric composition and pressures continuously, including detecting rising or falling trends, without exposing miners to the EGZ. Non-electric tube bundle air quality monitoring systems [23, 24] are equally suited to detect explosive atmospheres but cannot detect pressure changes resulting from roof falls or failing ventilation controls. In addition, tube

Table 5 Example of likelihood criteria

Rating	Definition
Rare	Frequency of occurrence ≥ 100 Pa expected to be less than 2 times per year
Unlikely	Frequency of occurrence ≥ 100 Pa expected to be 2–5 times per year
Possible	Frequency of occurrence ≥ 100 Pa expected to be 5–10 times per year
Likely	Frequency of occurrence ≥ 100 Pa expected to be ≥ 20 times per year

bundle measurements have an inherent delay based on the length of the tubes and may not capture a brief outgassing event before pressures equilibrate again. Mine operators should also continuously monitor and record atmospheric pressures and install a warning system that detects small changes in all main fan pressures as such changes will reveal unintended changes in the ventilation system.

In addition, the methane must also be monitored continuously either at regulated BEPs or other locations where the methane will most likely accumulate such as at the face tailgate corner in the absence of enough diluting air. Fiber optic methane sensors are examples of real-time monitors that can be used. In addition to real-time measurement, sensors must be reliable, fast, accurate, and tough in the harsh mining environment.

6.3 Use of Gob Ventilation Borehole (GVB)

If a longwall gob is considered a “black box” ventilated with $50 \text{ m}^3/\text{s}$ (~106,000 cfm) of fresh air, the system can absorb $1 \text{ m}^3/\text{s}$ (~2100 cfm) of methane if a maximum methane concentration of 2% in the bleeder exhaust must be maintained according to the 30 CFR 75.323 [25]. Any excess methane must be extracted through the face ventilation system or via methane removal systems in the coalbed or gob.

GVBs have been used to effectively reduce EGZ formation in the gob and prevent methane emission to the active working areas. GVBs are primarily operated in the range of 500 to 1500 m (1500 to 5000 ft) behind the face. In many cases, GVB lines break due to the gob collapsing and compacting after the coal has been extracted. Therefore, GVBs become less effective the farther they are from the face. Modeling indicates that GVBs should be operated and maintained active as long as possible to reduce methane concentrations in the gob.

7 Conclusions

This research presents a new approach regarding using a computational fluid dynamics ventilation model to analyze the gob breathing phenomenon and its correlation with external pressure changes. Key findings from this research, based on trends observed from modeling outputs, are as follows:

1. Fringes of EGZs exist within the gob, which is in agreement with other studies and observations made from a number of bleeder-ventilated mine fires and explosions [2–6].
2. During atmospheric or pressure drops, the EGZ most likely outgasses through crosscuts along the tailgate return and the bleeder entries near the back end of a panel.
3. When external pressures change, air pressures in mine workings and entries change almost instantaneously.

Table 6 Example of consequence criteria

Rating	Definition
Insignificant	Magnitude of drop ≤ 50 Pa; Instantaneous or gradual. Negligible outgassing
Minor	Magnitude of drop between 50 and 100 Pa Instantaneous drop, gradually decreases < 50 Pa/h. Methane concentration at tailgate bleeder evaluation point (BEP) reaches 2%
Moderate	Magnitude of drop between 100 and 1000 Pa Instantaneous drop, gradually decreases > 50 Pa/h. Methane concentration at tailgate BEP reaches 2–5.5%
Severe	Magnitude of drop > 1000 Pa, Instantaneous drop; gradually decreases > 50 Pa/h. Methane concentration at tailgate BEP exceeds 5.5%

Pressure changes within the gob follow with a delay due to the low permeability of the gob material. This delay or time lag can last several minutes depending on permeability, magnitude, and rate of pressure change.

- CFD simulations in a sample case showed that gob pressure lags up to 3 min behind for external pressure changes of up to 2000 Pa. The greater the magnitude and rate of pressure changes, the longer the resulting time lag, inducing more EGZ outgassing.
- CFD simulations show that rising atmospheric pressure induces more oxygen ingress to the gob, but it does not necessarily increase EGZ volume in the gob. The ingressing air dilutes the outer EGZ fringes becoming less explosive and pushes the areas with higher methane concentrations further into the gob.
- A sudden, abrupt drop of barometric pressure, which commonly occurs during stormy weather, immediately generates a large pressure differential and can induce severe EGZ outgassing to the tailgate return. In contrast, a gradual pressure drop causes steady, continuous outgassing over time, which must be diluted and rendered harmless by the ventilation air.
- EGZ outgassing is strongly influenced by the specific mine conditions and ventilation systems. CFD studies and meteorological evaluations should be conducted for each mine to evaluate the EGZ outgassing risk. Along with this risk assessment, atmospheric gas and pressure monitoring systems are recommended throughout the mine to provide early warning and evacuation alerts if barometric pressure changes suddenly, roof falls occur, or ventilation controls are damaged.

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Conflict of Interest The authors declare that they have no conflict of interest.

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