

BAROMETRIC-INDUCED GOB BREATHING: ROOT CAUSE, EFFECT AND RECOMMENDED BEST PRACTICES

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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 events 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 (Loane et al., 1975; Lynn et al., 1986; Elkins, et al., 2001; McKinney et al., 2001; Dziurzynski and Wasilewski, 2012; Brune, 2013). 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 most common cause is the fluctuating barometric pressure. Atmospheric pressures change regularly every day but 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 will 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 (Hosler, 1948; Boyer, 1964; Kissell et al., 1973; Fauconnier, 1992; Hemp, 1994; Wasilewski, 2014; Belle, 2014; and Lolon, 2017). 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.

ROOT CAUSE AND EFFECT OF GOB BREATHING

Gob breathing is the result of the pressure differential between gob internal and external pressures caused by external atmospheric pressure fluctuations that occur naturally as a result of gravitational and thermal forces in the atmosphere (Lindzen and Chapman, 1969). Other major and sudden pressure changes may be caused by fan failures, failures of 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 so gob pressures have sufficient time to equilibrate. More extreme fluctuations associated with cyclonic weather systems and storms often result in more rapid and larger drops or rises in barometric pressure (Hosler, 1948; Fauconnier, 1992). A study by Lolon (2017) found that the timing of historical mine explosions showed consistency with the occurrence of abrupt and intense barometric variations.

The volume of a gas is inverse proportional to its pressure, causing an EGZ cloud to expand as the atmospheric pressure drops. During this expansion, the clouds can also move, especially if the pressure change is not symmetric across the gob volume. 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 loose air and equilibrates with its environment faster.

Lolon (2017) determined this time lag in gob breathing. Figure 1 shows a graphical representation of pressure conditions inside the gob vs. outside in the bleeder entries. As the atmospheric pressure falls

(Figure 1a) or rises (Figure 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 Figure 1(a), or ingassing from the mine workings into the gob, if ΔP_b increases as represented in Figure 1(b).

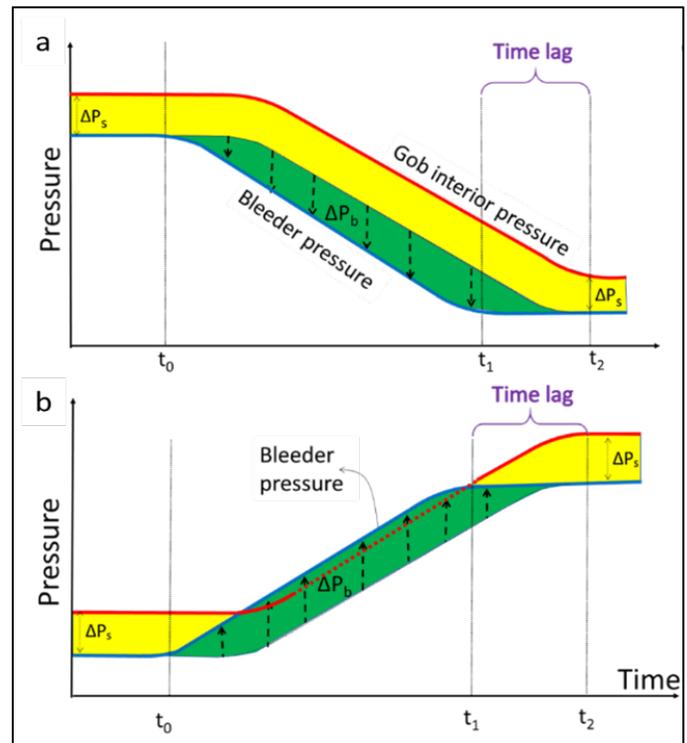


Figure 1. Pressure conditions of gob and tailgate return entry during barometric pressure (a) drop and (b) rise (Lolon, 2017).

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 inert gas body inside the gob, this air inflow will increase the size and location of the EGZ fringe between the bleeder entries and the inner gob that is fuel-rich inert.

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 (Lolon, 2017). The following section discussed this modeling effort and what researchers learned from it.

MODELING ENVIRONMENT AND SETUP

Mine Layout and Stratigraphy

A CFD computational model was developed based on data available from two cooperating mines in the Western U.S. (Grubb, 2008; Worrall, 2012; Gilmore, 2015). The model shown in Figure 2 was designed based on actual mine panel geometry. The model panel is 6,800 m (22,400 ft) long and 370 m (1,200 ft) wide, consisting of mine entries, longwall face, the gob and a 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 gateroad entries placed every 61 m (200 ft) inby.

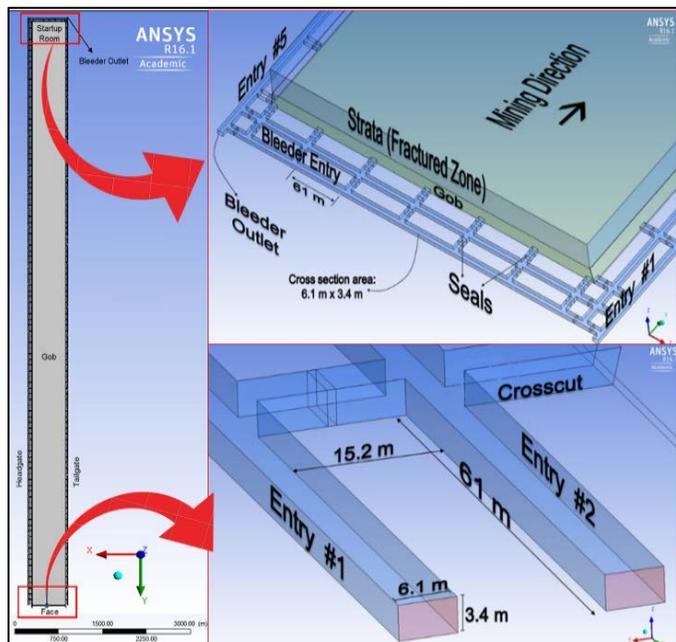


Figure 2. Mine layout and geometry used in this study.

The three-dimensional representation of longwall panel incorporates shields and a shearer models to obtain a realistic air flows and pressure drops across the face. The individual design of shields and shearer was provided by and used with the permission of Caterpillar, Inc. Figure 3 shows the shield design in detail. The model contains 175 shields along the face 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. The base case ventilation simulation results in a pressure drop of 130 Pa (0.53-inch WG) across the face, a common value reported by several cooperating mines (Lolon, 2017).

Figure 4 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 rubble zone. Gob porosity ranges from 14% to 40% and permeability ranges between $2.0 \times 10^{-7} \text{ m}^2$ and $5.0 \times 10^{-6} \text{ m}^2$ based on research by Marts et al. (2014) is applied to the gob zone. The permeability of the overlying strata model is $9.87 \times 10^{-14} \text{ m}^2$, based on work by Karacan (2009). 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.

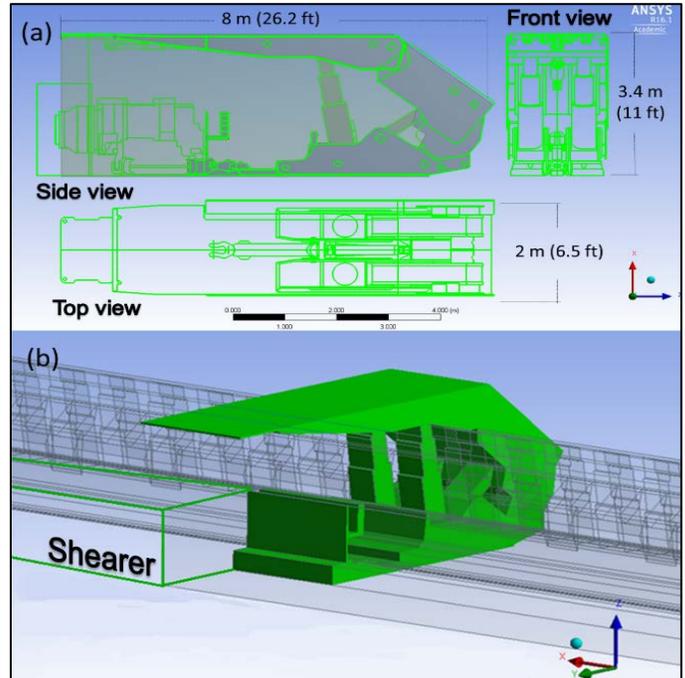


Figure 3. Shearer and shield model (a) manufacturer's design and (b) ANSYS DM® output

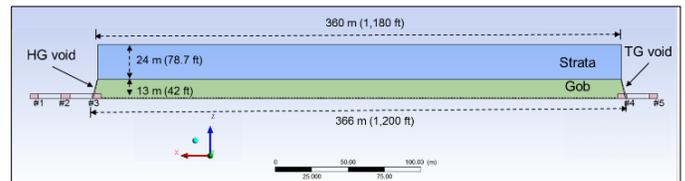


Figure 4. Cross-section view of gob and strata - looking towards the gob from the longwall face

MINE VENTILATION PARAMETERS

The simulated mine uses a three-entry bleeder ventilation system with both headgate and tailgate sides serving as air intakes, as shown in Figure 5. 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 entries #7. Entries #1 to #3 supply a total of $43 \text{ m}^3/\text{s}$ (90,000 cfm) to the panel of which about $10 \text{ m}^3/\text{s}$ (20,000 cfm) leaks into the gob past the headgate. The remaining $33 \text{ m}^3/\text{s}$ (70,000 cfm) ventilate the longwall face. Entries 4 and 5 each add another $4.7 \text{ m}^3/\text{s}$ (10,000 cfm) of fresh air from the tailgate side. A bleeder shaft is assumed to be located near outlet 7.

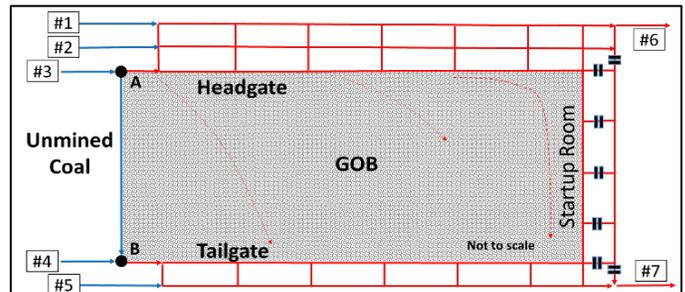


Figure 5. Simulated bleeder ventilation system.

The methane inlet placed at the top of the strata emits methane at a rate of $1.0 \text{ m}^3/\text{s}$ (2,100 cfm) down into the gob. This methane source is assumed to be infinitely available as a large reservoir. The methane

concentration at outlet 7 reaches 1.9%. The pressure boundary conditions at the inlets and the outlet are shown in Table 1.

Table 1. Pressure boundary conditions of the base case model.

Location	Boundary Condition Type	Pressure Values (Pa)	Flow Rate ¹	
			(m ³ /s)	(cfm)
Entry 1	Pressure-Inlet	3,332	+4.91	+10,400
Entry 2	Pressure-Inlet	3,332	+4.89	+10,350
Entry 3	Pressure-Inlet	3,467	+38.00	+80,500
Entry 4	Pressure-Inlet	3,335	+1.48	+3,100
Entry 5	Pressure-Inlet	3,328	+3.64	+7,700
Methane Inlet	Pressure-Inlet	4,630	+1.01	+2,150
Outlet 7	Pressure-Outlet	2,241	-49.63	-105,150

Note: ¹ Positive and negative signs represent flow entering and exiting the model, respectively

SUMMARY OF EGZ OUTGASSING SIMULATION RESULTS

Figure 6 shows the color scheme used to characterize the explosibility of methane in the gob atmosphere. Figure 7 shows the initial condition, balanced condition of EGZs in the gob. These EGZs are typical of most bleeder ventilated gobs (Brune, 2013; Gilmore, 2015). 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 towards 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.

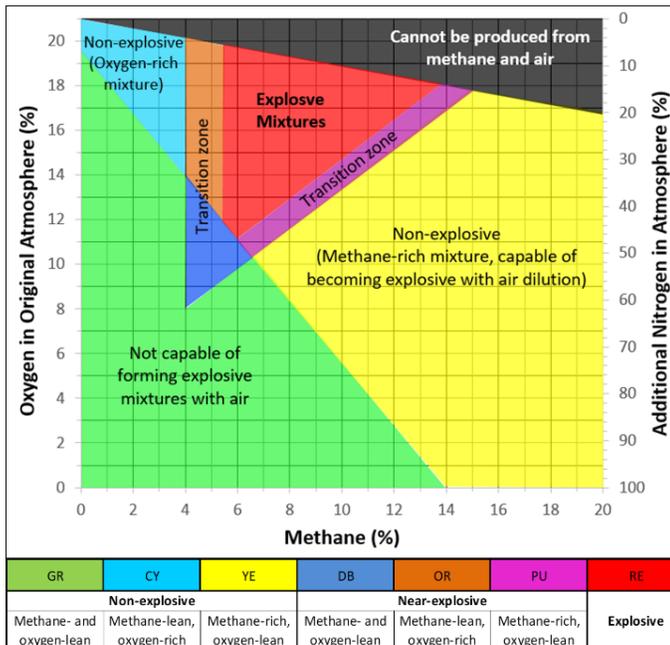


Figure 6. Color-coded diagram used in this modeling (modified after Gilmore, 2015).

Table 2 (see APPENDIX) shows the summary of simulation results for varying rates and magnitudes of atmospheric pressure drops. The time lag of the gob response to a gradual or instantaneous pressure changes depends on the gob's porous medium characteristics, mine depth, magnitude and rate of external pressure changes. Simulation results indicate time lags of 1.2, 1.8, 2.1, and 2.8 minutes respectively for 100, 500, 1,000, and 2,000 Pa drops. During these times, the EGZs expand into the surrounding mine entries where they can ignite and explode. Table 2 also indicates that total outgassing volume is a function of the magnitude of pressure changes, regardless of the rates of pressure change. 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. Simulations show that, for the ventilation scheme and pressure regime chosen in the model, outgassing occurs primarily in the last 10 crosscuts closest to the bleeder outlet #7.

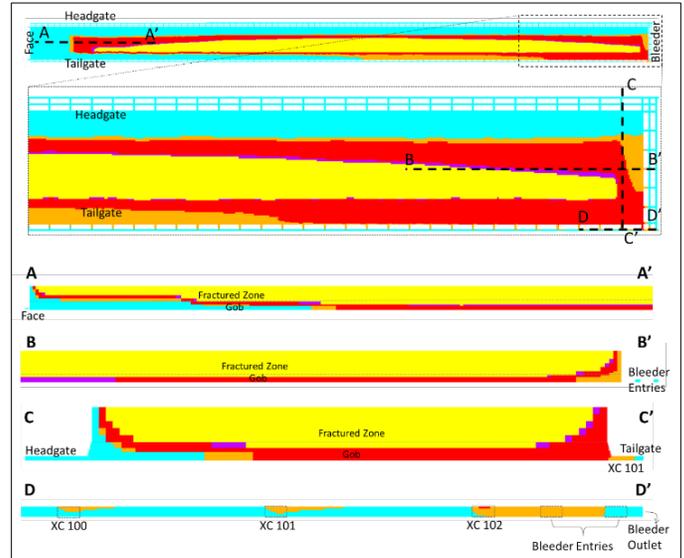


Figure 7. Initial condition of EGZ formation in the gob and tailgate return.

Figures 8-10 show the EGZ conditions and pressures returning back to equilibrium following a change in atmospheric pressure. In all cases, a decreasing barometric pressure induces an expansion of the EGZ within the gob, typically towards the tailgate as this is the pressure sink. In Figures 9 and 10, 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.

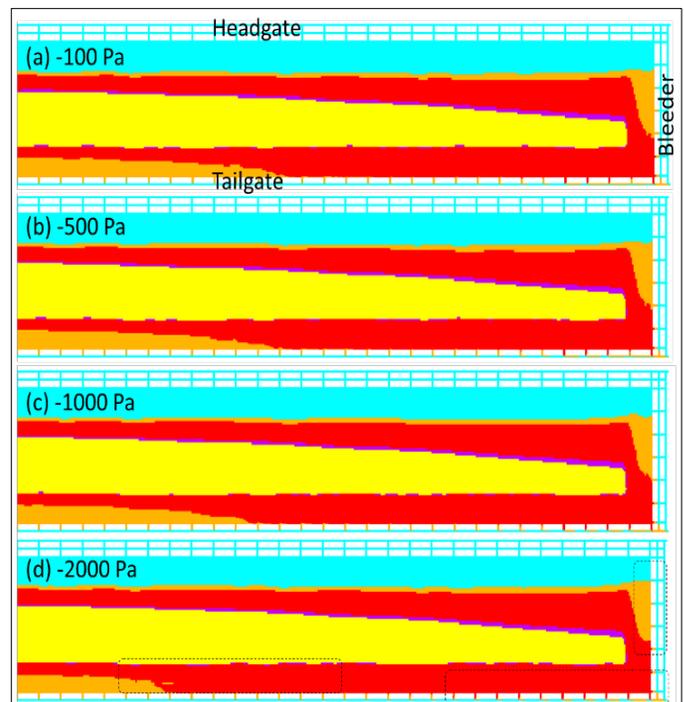


Figure 8. EGZ profile along the horizontal plane view at t=300 s of pressure drop

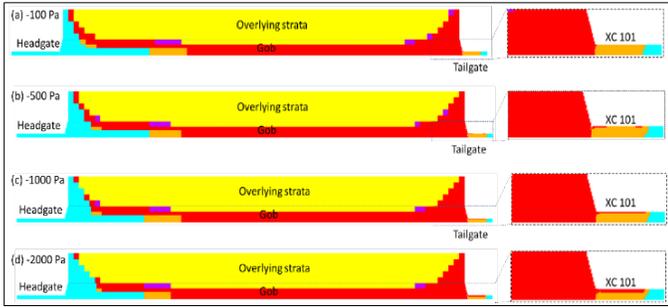


Figure 9. EGZ profile in the vertical section along XC 101 at t=300s of pressure drop.

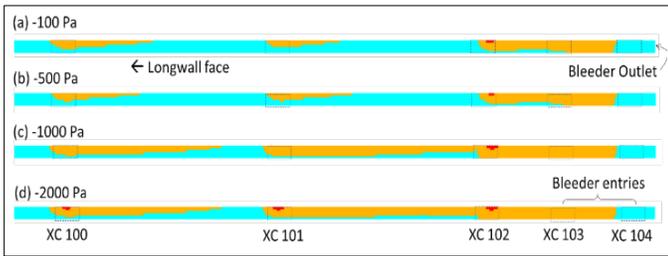


Figure 10. EGZ profile along the tailgate return at t=300s of pressure drop.

RECOMMENDED BEST PRACTICES FOR EXPLOSION PREVENTION

Barometric pressures fluctuate naturally so mine operators must have early warning systems and plans in place 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).

Risk Matrix for EGZ Outgassing

EGZ modeling demonstrates the influence of gob permeability, longwall panel layout, atmospheric and ventilation pressure conditions, methane sources and other mine specific parameters. 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 3. The risks are ranked based on suggested likelihood and consequence criteria presented in Tables 4 and 5. The likelihood of barometric changes can be 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.

Table 3. Example of a risk matrix for EGZ outgassing due to barometric pressure changes.

Likeli-hood	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

Table 4. 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

Table 5. Example of consequence criteria.

Rating	Definition
Insignificant	Magnitude of drop ≤ 50 Pa; Instantaneous or gradual. Negligible outgassing
Minor	Magnitude of drop between 50 – 100 Pa Instantaneous drop, gradually decreases < 50 Pa/hour. Methane concentration at tailgate Bleeder Evaluation Point (BEP) reaches 2%
Moderate	Magnitude of drop between 100 – 1000 Pa Instantaneous drop, gradually decreases > 50 Pa/hour. Methane concentration at tailgate BEP reaches 2-5.5%
Severe	Magnitude of drop $> 1,000$ Pa, Instantaneous drop; Gradually decreases > 50 Pa/hour. Methane concentration at tailgate BEP exceeds 5.5%

The recommended mitigation plan should be developed based on the pre-determined risk matrix rank. For example, to respond a low-risk rank the mine operator should closely monitor methane readings at the tailgate return and BEPs, 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 back 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.

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 (MSHA, 2008). 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 (Brady, 2008; Zipf et al., 2013) are equally suited to detect explosive atmospheres but cannot detect pressure changes resulting from roof falls or failing ventilation controls. Also, tube 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.

Use of Gob Ventilation Borehole (GVB)

If a longwall gob is considered a “black box” ventilated with 50 m³/s (~100,000 cfm) of fresh air, the system can absorb 1 m³/s (~2,000 cfm) of methane if a maximum methane concentration of 2% in the bleeder exhaust must be maintained. 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 1,500 m (1,500 to 5,000 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.

CONCLUSIONS

This research presents a new approach of 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 follow:

1. Fringes of EGZs exist within the gob – in agreement with other studies and observations made from a number of bleeder-ventilated mine fires and explosions.
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. 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.
4. CFD simulations in a sample case showed that gob pressures lag up to 3 minutes behind for external pressure changes of up to 2,000 Pa. The greater the magnitude and rate of pressure changes, the longer the resulting time lag, inducing more EGZ outgassing.
5. 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.
6. A sudden, abrupt drop of barometric pressure 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.
7. EGZ outgassing volume depends on the magnitude of a pressure drop, regardless of the drop rate. CFD simulations showed a 13-32% increase of EGZ volume in the tailgate return as a result of 100-2,000 Pa drop. For comparison, Belle (2014) reported a significant increase of methane in Australian mine's tailgate return with pressure decrease greater than 500 Pa, while Fauconnier (1992) suggested a potential explosion hazard for South African mines if pressure drops in excess of 270 Pa.
8. 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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APPENDIX

Table 2. Summary of outgassing as a function of barometric pressure changes magnitudes and rates.

Simulated Condition	Magnitude of Pressure Change (Pa)	Rate of Pressure Changes	Time Lag (mins)	After Two Hours of BP Changes				Potential Location of EGZ Outgassing
				Total EGZ Outgassing in TG Return (m ³)	Total EGZ Outgassing (%)	Methane Inflow (m ³ /s)	CH ₄ Conc. at Bleeder Outlet (%)	
Scenario 1: Instantaneous Pressure Drop	-100	Instantaneous	1.2	700	13.2	1.10	2.0	Tailgate return, bleeder entry
	-500		1.8	790	14.7	1.30	2.1	Tailgate return, bleeder entry
	-1,000		2.1	1,110	20.7	1.50	2.2	Tailgate return, bleeder entry
	-2,000		2.8	1,730	32.3	2.10	2.4	Tailgate return, bleeder entry
Scenario 2: Instantaneous Pressure Rise	+500	Instantaneous	1.2	-110	-2.1	0.80	1.0	No outgassing observed
	+1,000		2.1	-120	-2.2	0.80	1.0	No outgassing observed
Scenario 3: Gradual Pressure Decrease of 100 Pa	-100	-50 Pa/hour	< 0.5	700	13.2	1.10	2.0	Tailgate return, bleeder entry
	-100	-100 Pa/hour	< 0.5	710	13.4	1.10	2.0	Tailgate return, bleeder entry
Scenario 4: Gradual Pressure Decrease of 1,000 Pa	-1,000	-500 Pa/hour	1.0	1,110	20.7	1.50	2.2	Tailgate return, bleeder entry
	-1,000	-1000 Pa/hour	1.3	1,110	20.8	1.50	2.2	Tailgate return, bleeder entry