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## Critical Analysis of Longwall Ventilation Systems and Removal of Methane

Robert B. Krog

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# **Critical Analysis of Longwall Ventilation Systems and Removal of Methane**

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**Dissertation submitted to the  
College of Engineering and Mineral Resources  
at West Virginia University  
in partial fulfillment of the requirements for the degree of**

**Doctor of Philosophy  
in  
Mining Engineering**

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Frequency; Bleeder systems**

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# **Abstract**

## **Critical Analysis of Longwall Ventilation Systems and Removal of Methane**

**Robert B. Krog**

Bleeder systems are an important component for ventilation and the control of methane. The bleeder system of a coal mine contains a mixing zone for methane-laden air from the mined-out portions of the seam to mix with fresh air and the methane concentrations in the bleeders can often be elevated. Bleeders also provides a pathway for coalbed methane-laden ventilation air to quickly flow out of the mine through low resistance airways of a mine, such as supported gateroads, along the un-compacted outer perimeter of the gob, etc. Substantial quantities of coalbed methane are typically removed from underground workings. Although it is a relatively simple task to determine the methane quantities exiting the mine through direct measurements, a clear understanding of the exact manner and associated concentrations in which bleeder entries accumulate and transport methane-air mixtures is not known. The benefit of this improved understanding will decrease the likelihood of an explosion due to unknown accumulations of explosive gases in the bleeder entries, thereby improving worker safety.

In order to provide a better understanding of how a bleeder system works in moving methane through the mine, several field monitoring studies have been designed and completed using a tube bundle system and tracer gas releases. The tube bundle system was installed at a bleederless (progressively sealed) underground coal mine. The tube bundles monitoring points were located at different critical locations surrounding the longwall to specifically monitor gas concentrations and barometric pressures on a 30 minute interval for a period of two years. The tracer gas studies, on the other hand, were conducted at an underground coal operation with a traditional bleeder system. The objectives of these tracer tests were to determine transportation pathways and retention times of tracer gasses to better understand the exact gas movements in longwall gobs. The tracer gas was sampled from different headgate and tailgate entries through sample tubes of different lengths using vacutainers. The gas samples were analyzed using gas chromatography for determining concentration measurements for tracer and other gasses, including methane.

The tube bundle system results showed that falling barometric atmospheric pressure can cause the caved material to outgas higher concentrations of contaminants into the bleeder system. During prolonged atmospheric pressure drops, the gas concentrations leaving the caved material via the bleederless system were measured to increase by over two times the average values. These results strongly suggest that to effectively monitor and detect these outgassing events, the bleeder system requires collecting data more often than the once-a-week regulation stated in the 30 CFR Part §75.364.

The tracer gas testing showed locations of high methane in the bleeders, but the practice in multi panel longwall districts of use premixing of the airflow exiting the longwall panels with cleaner airflow to dilute the methane concentrations to below allowable levels before passing through bleeder evaluation points masked the high methane concentrations. Specifically, samples with methane concentration above 4% were collected from the middle entry of the tailgate, but these airflows were diluted to below 2% just before reaching the bleeder evaluation points, and the mine was unaware of the higher methane levels. This result indicates that premixing of explosive airflow as soon possible, as it exits from the tailgate entries

in this case, is beneficial to reducing possible explosions, sampling locations need to be closer to the caved material to better monitor and record the actual conditions existing within the inaccessible bleeder locations.

The explosive mixtures of methane in the bleeder are not theoretical but exist and are measurable with direct and indirect methods within both bleeder and bleederless ventilation system. Obtaining measurements of these mixtures is the first step to be able to better engineer longwall ventilation safety.

The conclusions for this research are: 1) Long duration atmospheric pressure drops of a day or more in length are the controlling factor in increased emission from the caved material. 2) The practice of pre-mixing airflows leaving the middle entries between longwall panels with low methane airflow before reaching the bleeder evaluation points, can mask the existence of explosive mixtures of methane at other locations in the bleeders. 3) Without knowledge of the precise locations of high methane in the bleeder entries, the bleeder system cannot be optimized for minimizing explosive methane concentrations and improve miner safety. To solve the atmospheric pressure drop issue it is recommended that a continuous monitoring system should be installed on surface to record these mine-wide changes in total methane emissions. It is also recommended that bleeder evaluation points should be moved closer to the caved material or the sample tubes should be used to monitor critical locations before mixing occurs. Both of these recommendations will improve the understanding of the nature of gas transportation within the bleeder system and thereby lead to improved worker safety.

# Dedication

The author wishes to dedicate this thesis to my parents, my friends and family for their support, encouragement, and understanding through the years.

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## 1 Introduction

Longwall coal mining supplies about half the underground coal tonnage in the United States. In 2015, 37 underground longwall mines mining 42 faces collectively produced over 181 million tons of bituminous coal (Coal Age, 2016). Further, underground longwall operations are more productive and have a lower accident rate than traditional room-and-pillar operations and continue to have an increasing share of underground production. Improvements in longwall equipment have enabled panel width to increase consistently over the last 25 years. Average panel widths have increased from 210 to 370 m (700 ft to 1,200 ft) while average lengths have increased from 2,100 m (7,000 ft) to approximately 3,400 m (11,000 ft). These increased panel sizes and extraction rates have increased the total amount of methane liberated from a typical longwall panel that needs to be controlled by the mine ventilation system.

In the US, a bleeder ventilation layout is used in the majority of underground longwall mines because of the Code of Federal Regulations (CFR) Title 30 §75.334. A bleeder layout system is designed to provide a pathway for coalbed methane-laden ventilation air to flow out of the gob and mine, through low resistance airways, such as supported gateroads, along the uncompacted outer perimeter of the gob, and wrap-around bleeder entries. These airways are typically connected to the surface through either a main mine fan or a bleeder fan. Figure 1-1 shows a simplified 3-panel longwall district that is ventilated by a bleeder system. In the figure, gateroads of the 4<sup>th</sup> panel are being developed, whereas the gateroads of all previous panels are not sealed, and are being used as airflow pathways in the bleeder system. A common bleeder system, Figure 1-1, uses the previous gateroad entries in the tailgate as pathways to transport the contaminants from the active working faces to a bleeder fan, typically located near the first longwall panel in a district. A negative pressure differential is created from the active working areas to the back of the bleeder by the bleeder fan and controlled through the use of stoppings and regulators. It is common for some of the airflow from the longwall headgate corner to be ventilated towards the startup of the active panel and to be used to pre-mix with the higher methane airflow before passing through Bleeder Evaluation Point (BEP) or Measuring Point locations (MPL) to dilute airflow to comply with statutory limits set by the CFR.

Figure 1-1 also shows a potential airflow pathway in the LW #3 panel behind the shields and away from the longwall tailgate corner as part of the bleeder system operation. Multiple regulators are shown as well along the front and back sides of the longwall districts. These

regulators can also be used as the BEP to determine the effectiveness of the bleeder system. This idealized operation of a bleeder system as shown in Figure 1-1 would comply with 30 CFR § 75.334(b)(1) to remove methane and other contaminants from the working environment.

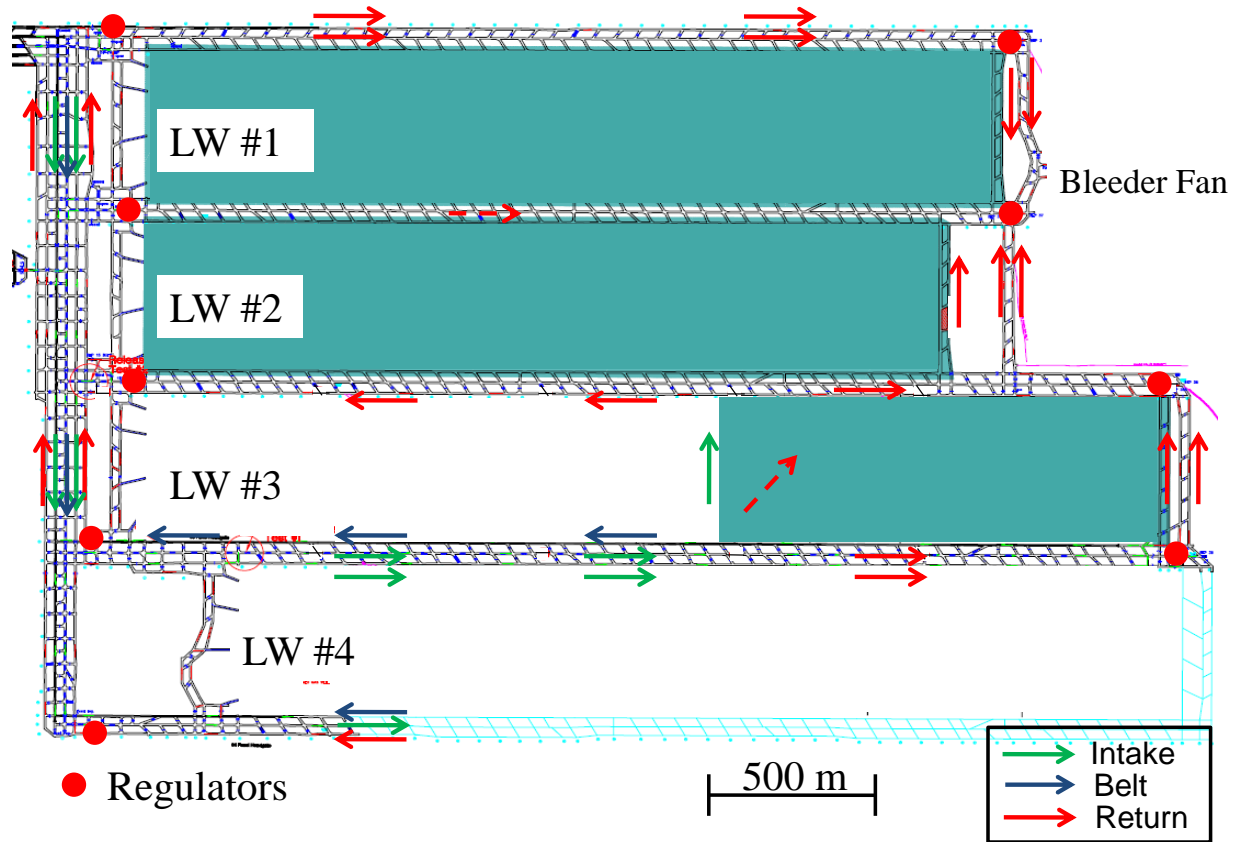


Figure 1-1. Simplified bleeder ventilation layout.

Two sections of the 30 CFR are described below, but they have different outcomes on the bleeder ventilation system design. Part 75.334(b)(1) states that “during pillar recovery, that a bleeder system shall be used to control the air passing through the worked-out area and to continuously dilute and move methane air mixtures and other gases, dusts, and fumes away from active workings into a return or to the surface of the mine”. Part 75.323(e) states that the “concentration of methane in a bleeder split of air immediately before the air in the split joins another split of air shall not exceed 2.0 percent”.

The first section, Part 75.334(b)(1), covers the main intent and goals of the bleeder system, but the second section, Part 75.323(e), is simple to measure and therefore the more enforceable section of the law and thus ends up being the main design criteria of the ventilation system for

many mines. If the primary goal of designing the bleeder system is to keep measureable methane concentrations below 2% at all mixing points, the mine operators would (and do) benefit from coursing large amounts of fresh air around the gob directly to the mixing point, and not much actually through the gobs to “continuously dilute” as stated in Part 75.334(b)(1).

## 1.1 Statement of the problem

The bleeder system of a coal mine contains a mixing zone between solid and mined-out portions of a seam where methane concentrations can be elevated; however, a clear understanding of the exact mechanisms by which bleeder entries accumulate coalbed methane and transport gas-air mixtures to the main or bleeder fans and how mining and natural variables (geology and atmospheric changes) impact these movements does not currently exist.

Despite the widespread use of bleeder systems in the United States their effectiveness depends on how well they are maintained. In most underground longwall operations bleeder systems are monitored once a week at the BEPs by certified examiners using handheld methanometers to see if they meet minimum regulatory requirements. However, once weekly measurements may not be enough to evaluate the bleeder system.

The bleeder system is composed of both caved material and supported entries within and surrounding the caved material. Measuring the methane concentration within the caved material itself is a difficult task due to the crushing and destructive nature. Measuring the methane concentrations at least in the immediate surrounding entries will give an indication as to how well the bleeder system is functioning. However, these bleeder systems may be designed primarily for regulation compliance and not necessarily for effective and safe operations. As longwall panels become larger, the inner air paths within the gobs remain the same but methane emissions could overwhelm current bleeders system’s capacity. Without a better understanding of the possible airflow paths within the inaccessible locations of the bleeder system, the buildup of methane to dangerous levels may occur anytime.

The primary design criteria for engineering an effective bleeder ventilation system should be that it can handle all situations by effectively diluting and removing contaminants from the worked out areas to increase safety. However, in practice the primary design criteria can be compromised by different factors. One of the most important driving factors that cripples the intended effectiveness of the bleeder system is the motivation to comply with the statutory limits of less than 2% methane after mixing points. The practice of using low methane airflow wrapping around the active panel from the headgate side to pre-mix the possible high methane

airflow exiting from the tailgate entries before reaching the monitoring locations can mask the bleeder system is perceived to be operating. This is often referred to as “sweetening the bleeder air”.

If multiple parallel dilution air paths can be utilized within the bleeder system before the mandated measuring points, the better the bleeder ventilation system will appear from the measuring point, but explosive mixtures of methane may still be in the gob or the entries adjacent to the gob. If fresh air can be directed to mix with higher methane airflow inside the inaccessible regions of the bleeder system directly before exiting the gob at the BEPs, then the ventilation system will appear to be operating more effectively, which clearly may not be the case. Therefore, for effectively designing a ventilation system for safety and compliance, the monitoring locations are critically important and a detailed understanding of the methane movement in the bleeder system would help alleviate the problem of pre-mixing not giving a methane concentration that indicates the safety of the bleeder system.

The other factor that affects the ventilation system effectiveness is the changing atmospheric pressures, which may cause the volume of air within the caved material to breathe in and out more than once week. Therefore, it is clear that weekly reading could easily miss an outgassing event, during which an explosive mixture could be liberated into the bleeder entries and possibly the bleeder fan. The volume of air within the caved material of a longwall panel is a large gas reservoir with varying methane concentrations that when exposed to atmospheric pressure changes due to changing weather the air volume within the caved material can expand or contract multiple times within a weekly period. Therefore, the frequency of sampling is critically important to determine the capability of the bleeder system to safely remove methane during the worst case atmospheric pressure changes.

Addressing the importance of increased monitoring rate and optimizing the monitoring locations can lead to a better understanding of the bleeder system and the future design to meet both safety and compliance criteria, which should be the ultimate goal.

## **1.2 Research approach**

This dissertation evaluated and quantified the impact of atmospheric pressure changes on the emissions from the caved material, the importance of a sampling frequency less than one hour to detect the concentration and the amount of methane entering the bleeder entries. The appropriateness of moving the monitoring point location, at least one entry closer to the caved material, with respects to pre-mixing was also investigated.

In order to achieve these objectives annual MSHA field reports, ventilation data and previous NIOSH publications were searched to determine the methane production and concentrations at the back of longwall panels. The MSHA reports were analyzed, based on direct measurement or mass balance calculations, to determine the location that methane entered the outer bleeder system. These results were used to determine the most likely pathways by which the methane and pre-mixing of airflows traveled before reaching the BEPs. However without knowing the timing or order that the samples were taken, the exact locations of the samples and the timing of the atmospheric events, the studies on the MSHA reports did not provide enough data to accurately describe system behavior. Similarly any potential numerical model had to be built with exact information which was not available and was not possible to obtain in great detail.

The review of annual mine ventilation plans did show by using mass balance of recorded airflows that there existed a zone of methane concentration in the explosive range, the size of which could not be determined with the given data. Therefore, in lieu of numerical simulation to study bleeder system behavior under various conditions, field experiments were designed at two underground coal mines to collect data in realistic mining conditions.

The experimental design covers two different mines: Mine A had a tube bundle system that was able to record the changes in emission from the caved material based on changes in the atmospheric pressure. Mine A used a bleederless (progressively sealed) ventilation system and converted from an exhausting to a blower system during the monitoring period. Mine B used a conventional bleeder system at the start of the study, but converted to an internal bleeder system while mining the last panel in the district. During this research, three tracer gas tests at mine B were conducted to help in determining internal airflow pathways of a longwall district, before the longwall retreated, with the aid of pre-installed sample tubes.

### **1.3 Outcomes**

Longwall bleeder systems need to be designed primarily for safety for the bleeder entries and then for compliance to regulations. This dissertation concluded that these two objectives can be achieved: 1) by increased sample frequency rate to every half hour with a tube bundle system or better yet with the installation of a continuous monitoring system, 2) by moving the sampling locations closer towards the caved material to reduce the masking effect of pre-mixing that dilutes high methane samples. These objectives will allow ventilation engineer the ability to design future bleeder systems bases off of accurate methane values with the goal of eliminating or at least reducing the size and frequency of explosive mixtures in the bleeder entries.

This research found that explosive mixtures do exist in longwall bleeder ventilation systems. The outgassing of gobbs during falling atmospheric pressure drops can lead to increased emissions that are as much as twice the average emission rate. A bleeder ventilation system can be operating with multiple parallel entries along the back of the bleeder system, which allow transportation of high methane concentrations exiting the tailgate entries while all BEPs located near the outsider walkable entry are within compliance. The finding of this dissertation showed that the use of multiple pre-mixing of the high methane concentrations as close to the source as possible should continue, but the BEP locations need to be moved into these mixing locations (possibly by sample tube lines) so that data can be collected to allow proper engineering of the bleeder system. However, it should be emphasized that making industry-wide recommendations regarding the physical changes to the ventilation layout is premature at this time, since the information is based on only two longwall mines.

During the course of the field studies it has been experienced that the instruments required for continuous monitoring of the underground BEP locations are problematic because of the requirement for permissible equipment limitations and the requirement of the transfer of the results to the mine's data management system. It has also been experience that the tube bundle system is capable of performing this task, but it poses limitations due to freezing of the sampling line during cold weather.



## 2 Literature Review

A Literature review on the effectiveness of bleeder and bleederless ventilations systems was conducted. The review covered a set of issues that are pertinent to longwall ventilation using bleeder and bleederless (progressively sealed) systems, including:

1. Explosions in active longwall gobs,
2. Longwall panel sizes,
3. Ventilation approaches: bleeder and bleederless,
4. Pre-mixing,
5. Acceptable methane concentrations,
6. Engineering design,
7. Methane production and transfer paths into the caved material,
8. Static and dynamic ventilation conditions,
9. Atmospheric pressure changes,
10. Permeability and porosity of caved material,
11. Tracer gas tests,
12. Boundary conditions,
13. CFD small scale and large scale models,
14. Ventilation network models.

A coal mine ventilation system requires a sufficient capacity of air to remove and dilute, hence rendering harmless all potential methane emissions. These emissions would usually originate from the coal face, ribs, floor and overlying strata. The ventilation system must also be able to incorporate any reasonable expected or unforeseen increases in emissions. The main ventilation system cannot handle the increases of higher gas content associated with deeper coalbeds, and increasing panel widths without support (Diamond and Garcia, 1999).

Degasification systems are the most common supplemental support used in coal mines to maintain methane levels within statutory limits (Thakur, 1997). Pre-drainage of the coal seam prior to mining can effectively reduce the in-situ gas content and allow increase gateroad development and longwall retreat rates. Post-drainage of the coal seam and upper strata layers can dramatically reduce the methane burden on the primary face and bleeder ventilation system (Karacan et al., 2007; Schatzel et al., 2008). The in-place methane content of all strata affected by the longwall will dictate the need and design of degasification systems, pre- and/or post-mining. Degasification systems remain vital components to an effective modern longwall ventilation system (Schatzel et al., 2008).

Countries other than of the United States predominantly use bleederless ventilation systems for modern longwalls. Previously, Canada used a 'sewer' ventilation system for the eastern longwalls under the Atlantic Ocean that did not have travelable bleeder entries but acted similar to modern bleeder systems (Young and Bonnell, 1997). Australia and South Africa exclusively use bleederless ventilations systems because of spontaneous combustion concerns. Australian research on longwall ventilation systems with progressive sealing, gob ventilation holes and inertization is extensive (Ren, 2009). The Polish system uses both retreating and advancing longwall systems. Current international research is primarily focused on bleederless ventilation systems. The United States is the only major world coal producer that uses bleeder ventilation systems in coal mines (Noack, 1998).

Previous work by Thakur (2006) on bleeder-type ventilations systems did indirectly address the theoretical or practical effectiveness of methane removal which would be greater for a bleeder than for a bleederless system. The accepted practice of allowing large amounts of fresh air into the back of the panels to premix with the high-methane-concentration air exiting from the gob before passing through a bleeder evaluation point is mentioned in the closing comments of one paper (Young and Bonnell, 1997). The acceptance of "sweetening" the bleeder system with pre-mixing does not appear to have been based on engineering design but a requirement to pass legislative requirements. The practice of mixing fresh air with the higher methane airflow for the gob as soon as possible to get below the lower explosive limit (5% methane) is prudent from an engineering safety perspective, but it should not be used to mask or conceal these possible explosive methane concentrations originating from the tailgate entries.

## **2.1 State of US longwall coal ventilation**

In this section the state of the US longwall coal industry with regards to ventilation is discussed. The primary focus of this discussion is the most important accident due to methane explosions in and around longwall faces, recent trends in longwall panel sizes and its impact on ventilation. Also the most common ventilation layouts, e.g. bleeder and bleederless (progressively sealed) are discussed with the most important and recent literature as well as MSHA regulations governing these systems.

### **2.1.1 Explosions in active longwall gobs**

This dissertation addresses the accumulation of explosive methane gas mixtures bleeder systems on active panels. The ignition source could vary from a frictional ignition by the shearers, a large ground fall behind the shields, or numerous unknown sources that could

cause an explosive mixture of methane to ignite. The most recent underground longwall mine explosions in active panels in the United States are listed below (Brune 2014, MSHA database 1983-2013):

1. Sunnyside mine No 1, 1987, (no fatalities)
2. Willow Creek mine, 1998 and 2000, (0 and 2 fatalities)
3. Pinnacle mine, 2003, (no fatalities)
4. Buchanan No 1 mine, 2005 and 2007 (no fatalities)
5. Upper Big Branch South mine, 2010 (29 fatalities)

Mine explosions in sealed areas or room-and-pillar mines have not been counted in this list, most notably the Sago mine explosion in 2006 (sealed area) nor the Jim Walters No 5 mine in 2001 (continuous miner development section). The time required for sealed areas to become inert either by low oxygen or by becoming methane rich (above 15% methane, 20% practical range) is not covered in this dissertation. While there are similarities in the air-methane mixtures and the physical layout between sealed panels and active panels, the sealed panels are not being actively ventilated and, therefore, excluded from research except for the leakage rates into the active workings. The adoption of 120-psi seals at mines should dramatically reduce future explosion damage originating from within sealed areas in United States coal operations (Zipf et al., 2007). Sealing of large inactive sections of longwall mines is a common practice in the United States but this dissertation will be focused on the actively ventilated sections of coal mines.

#### *2.1.1.1 Recent mine explosions resulting in fatalities*

Methane accumulations at coal mines will always create the potential for a disaster, and therefore, mine safety depends on an improved understanding and monitoring of the risk factors involved. In January 2006, a methane explosion at the Sago Mine in West Virginia resulted in 12 fatalities and 1 injury. The Darby No. 1 Mine explosion in Kentucky in May 2006 led to 5 miners losing their lives. The Upper Big Branch South (longwall) Mine explosion in April 2010 caused the deaths of 29 workers and injured two. All of these disasters were determined to have started with an ignition of methane gas. This dissertation will be focused on methane explosions and fires occurring at longwall operations. The following is a partial list of explosions that have occurred at longwall operations.

### ***2.1.1.2 Sunnyside Mine No 1 May 1987***

Sunnyside Mine No 1 located in Utah mined the Lower Sunnyside coal seam with the unfortunate characteristic that the overlying strata caused liquid hydrocarbons to leak from the roof. The petroleum vapor and methane caused problems with the gob. There were two different events during May 1987. The narratives of the two events are listed below and come from the MSHA database.

“May 18<sup>th</sup>, 1987-A LIGHT CRUDE OIL IS BEING DISCHARGED FROM IN THE GOB AREA OF 20 LEFT LONGWALL. A CAVE OCCURRED WHICH IGNITED THE OIL AT THE BACK OF THE SHIELDS. THIS OIL IGNITED 3 DIFFERENT TIMES AND TOOK ABOUT 45 MINUTES TOTAL TIME TO EXTINGUISH. THE IGNITION SOURCE IS UNDETERMINED.THERE WAS NO DAMAGE OR INJURIES”.

“May 27<sup>th</sup>, 1987-A LIGHT CRUDE OIL HAS BEEN DRAINING FROM ROOF IN CAVE AREA OF LONGWALL. A LARGE CAVE OCCURRED AT HEADGATE WHICH IGNITED THE VAPORS FROM THIS OIL. FLAMES CAME OUT OF THE CAVE AT THE HEADGATE THEY WERE ABOUT 32 FT HIGH. FLAMES CAME OUT OF THE GOB AT SHIELD 1, AND 28. AFTER THE IGNITION 2 SMALL FIRES WERE FOUGHT FOR ABOUT 20 TO 25 MINUTES. FACE WAS VERY SMOKEY AND HOT, NO DAMAGE OR INJURIES”.

In both instances, a large cave occurred in the gob, ignited vapors from the oil and caused a fire behind the shields. Flames migrated from behind the shields and onto the active face. The duration of the fires and the location is of great concern to the safety of the workers. It was fortunate that no one was injured in either incident.

### ***2.1.1.3 Willow Creek Mine, 1998 and 2000***

The Willow Creek ignition and fire events of November 1998 and again in July 2000 show that material caving into a gob could cause a frictional ignition, along with possible spontaneous combustion, that then leads to methane explosions followed by fires. This mine had similar hydrocarbons to the Sunnyside mine. In November 1998, a sudden caving in the gob caused an air rush onto the longwall face and caused a subsequent mine fire. The initial MSHA observation described the event as follows: “FIRE, BELIEVED THAT A ROOF FALL IN THE GOB IGNITED HYDROCARBONS OR METHANE”. An orange glow was reported behind the shields by workers.

The July 2000 and November 1998 events started out similarly, with a large cave-in causing methane or hydrocarbons to explode and to start a fire. Unfortunately the 2000 fire triggered three more subsequent explosions killing two and injuring eight miners, and ultimately closing the mine.

“The Mine Safety and Health Administration (MSHA) determined that the bleeder ventilation system did not adequately control the air passing through the worked-out area of the D-3 Panel. The system did not dilute and render harmless concentrations of methane and other gaseous hydrocarbons in the worked-out area where potential ignition sources existed (McKinney et al., 2001)”.

The statement by MSHA that the bleeder system was not adequately controlling methane buildup was expected. What was not expected though was the implication that potential ignition sources existed inby the longwall face in the caved zone at this mine. These potential ignition sources (overlying strata caving) cannot be eliminated if longwall mining is to occur. Therefore, the only option is to guarantee that explosive mixtures of methane will not accumulate, or can be minimized, in the active caving zones of the longwall panels.

#### *2.1.1.4 Pinnacle Mine, 2003*

Between August 31 and September 7, 2003 a series of methane explosions occurred around the active longwall panel of the Pinnacle Mine in West Virginia (NIOSH, 2004). After the Labor Day weekend, explosion damage was found near the tailgate corner of the active panel and the travelable bleeder walkway near the active panel’s BEP. Pressure spike data on the main mine and bleeder fans showed what appeared to be three separate methane explosions spaced out over a two-minute period.

One single event followed by burning methane fronts could explain all three explosions. Three separate methane explosions in close succession occurring at three different locations surrounding a longwall panel seemed unlikely unless they were related. One possible connection could be a burning event propagating through the caved material (Figure 2-1). The first explosion occurred inby the tailgate corner. This caused the burning front moving towards the headgate corner which caused a smaller secondary explosion. The flame front moving down the length of the active panel reached the active panel BEP (near 8H14 of map below) one minute later. The burning front would have the effect of expanding gases within the caved zone pushing a methane-rich body of air towards the active panel’s BEP. This methane-rich cloud would then mix with fresh air in the travelable bleeder entries. This would create an explosive

mixture of methane close by the BEP. When the flame front reached this location the largest of the three methane explosions would occur in the travelable walkway. Unfortunately this data and findings were never published by NIOSH because supporting evidence could not be obtained. Nevertheless the Pinnacle events of 2003 are convincing enough to be examples that methane-rich zones could and most likely would exist in modern longwall bleeder systems.

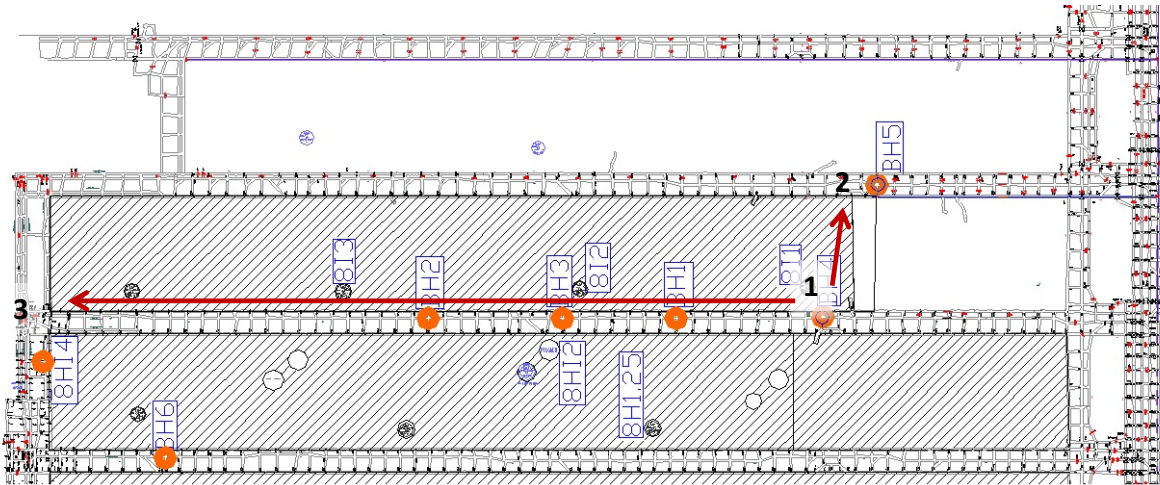


Figure 2-1. Pinnacle 2003 Labor Day explosions with the locations of the damage. Number 1 is the approximate location of the first explosion, the red arrows show the two flame front pathways, 2 shows the minor damage on the headgate, and 3 is the larger explosion at inby end of tailgate.

#### ***2.1.1.5 Buchanan No 1 Mine, 2005 and 2007***

Buchanan No 1 mine in Virginia had similar characteristics as the Pinnacle Mine had in 2003. Both mines operate in the Pocahontas #3 coal seam and had similar panel dimensions with similar weighting events that can cause large caves in the gob. These large cave-ins could displace higher methane concentrations in the gob and push them on to the active longwall.

“February 14, 2005-The 001 longwall shearer was preparing to "cut out" on the tail side of the face when a bump occurred that apparently forced a pocket of methane from the gob onto the face at the shearer resulting in an ignition that caused a mine fire.”

The 2007 events were similar to the 2005 event with a large cave in the gob which led to an explosion followed by a mine fire.

### *2.1.1.6 Upper Big Branch South Mine, 1997 and 2010*

The deadliest mining disaster in the last two decades occurred on April 25, 2010 at the Upper Big Branch South Mine in West Virginia. A self-propagating coal dust explosion started on the longwall face and enveloped two other working sections of the mine, killing 29 miners and injuring two others. While the coal dust explosion was the event that killed and injured the miners the most likely initiation was a methane ignition/explosion at the longwall shearer while cutting the tailgate corner. The MSHA report (Page et al., 2011) indicated the most likely occurrence was methane flowing out of the gob to the tailgate corner. This outgassing could only exist if MSHA investigators believed that there was a methane rich zone behind the longwall shields. This is not the first time the Upper Big Branch mine had an ignition that caused a flame front behind the shields. On January 4, 1997, an ignition occurred in the gob area near the tailgate side of the active longwall panel when “the bright orange glow was observed behind the shields in the gob area” (MSHA 1997). These two events demonstrate that there at least existed a flammable mixture of gas in close proximity to the longwall shields at or near the tailgate corner.

The statement that methane concentration in the explosive range might exist within the caved area of the gob can be proven by considering a gob ventilation borehole (GVB) that is drawing air close to the caved material. For example, a GVB can theoretically have 50% methane and over 5% oxygen, which has to have come from the main ventilation system. By design the longwall face and surrounding travelable entries have less than 1% methane, therefore there has to be a zone of explosive gas somewhere behind the longwall face and the bottom of the GVB (Brune, 2008; Schatzel, 2007). The explosive zone could be close behind the shields or high up in the separated roof tensional zone. If the inner cores of longwall panels become methane rich and non-explosive, there must be a 3-dimensional explosive mixing zone of air surrounding the inner core that is being diluted and removed by the bleeder entries. These zones of explosive methane can theoretically be located anywhere within the caved zone: along the perimeter, along the roof line, in the open fracture system above the shields, within the low permeability compacted inner core or down the supported gateroads prior to being mixed with fresh air. The latter location is the most troubling because any explosive mixture in the supported gateroads could quickly transition from a methane ignition to a methane detonation given the turbulent disruptive nature of air movement created by any standing support in the entry.

The theoretical proposition of the existence of zones of explosive methane within the gobs is not in doubt. However, a more important question is, where and how large these zones of explosive methane are. A ventilation system can be designed to shift these zones of methane into a more safe/optimum location within the caved material once the methane concentrations are known in the inaccessible locations.

Even with the history of fires and explosions from within caved portions of longwall operations (Lolon, et al., 2015), the mining industry has been lulled into a state of complacency as to the possible explosive hazard of methane accumulation within the gob. This shows that there still exists the possibility of a large methane explosion risk to miner's safety.

### **2.1.2 MSHA definition of bleeder and bleederless ventilation systems**

30 CFR § 75.334(b)(1) states that, "During pillar recovery a bleeder system shall be used to control the air passing through the area and to continuously dilute and move methane-air mixtures and other gases, dusts, and fumes from the worked-out area away from active workings and into a return air course or to the surface of the mine".

A common bleeder system used the previous gateroad entries as pathways to transport the contaminants from the active working faces to a bleeder fan located near the first longwall panel in a district. A negative pressure differential is created from the active working areas to the back of the bleeder by the use of stoppings and regulators. A representative bleeder ventilation system is show in Figure 1-1 with all airflow through the caved material and the incorporated gateroad entries traveling towards the bleeder fan.

Figure 2-2 shows a longwall operation's bleeder system methane load based on the required weekly ventilation measurements (Part 75.364). Knowing the airflow and methane concentration at each of the Bleeder Evaluation Point (BEP) locations and comparing them to the known methane liberation from the surface bleeder fan, the calculated methane release amounts of each BEPs is shown. It is known that greater quantities of methane are released from the active longwall panel than previously mined panels. The mine was able to keep all BEPs below 4.5% CH<sub>4</sub> and below 2% after mixing. The interesting part of Figure 2-2 is that the BEP #3 on the active tailgate only liberated 1% of the methane recorded at the Bleeder Fan but BEP #2, located on the tailgate of the second panel, liberated 58%. (The percentages do not add up to 100% because only the BEP were measured while the leakage through the stoppings was not measured). The methane transfer from the active third panel to the second panel by using



internal pathways that parallel the outer walkable bleeder entry the methane bypasses the BEP on the active panel.

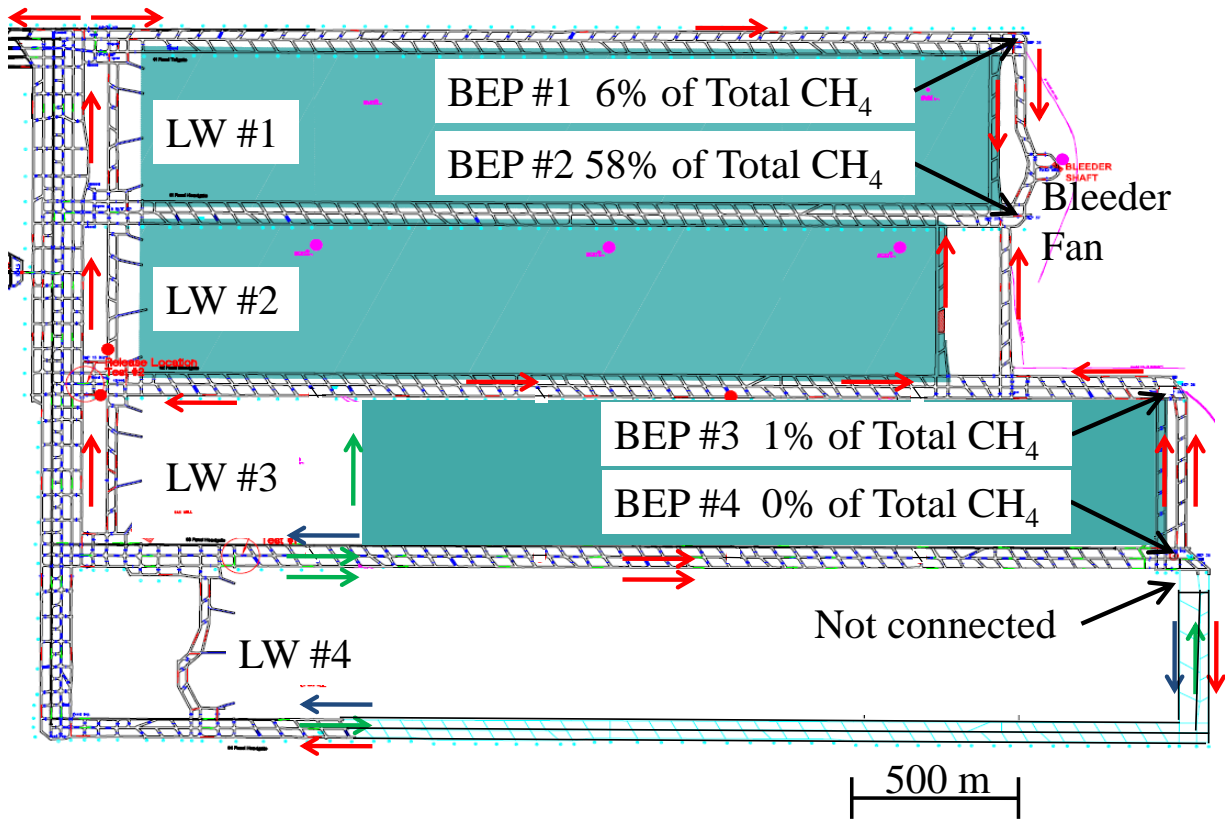


Figure 2-2. Percentage of total methane measured at Bleeder Fan that passed through each BEP (three panels).

Nine months later, the same mine had the methane distribution in its bleeder system as shown in Figure 2-3. There is so much fresh air being brought around the start of the panel from the headgate entries that both BEP #4 and BEP #3 show little to no methane liberation (below the 0.1% methane detection limit of handheld unit). Three quarters of the total methane emissions of the Bleeder Fan is passing through BEP #2. The bleeder system is now moving the majority of the methane liberated in the active gob to a BEP located two panels away from the active longwall face by using internal entries that may have much higher methane concentrations, possibly explosive, then would be allowed by the outer walkable entry.

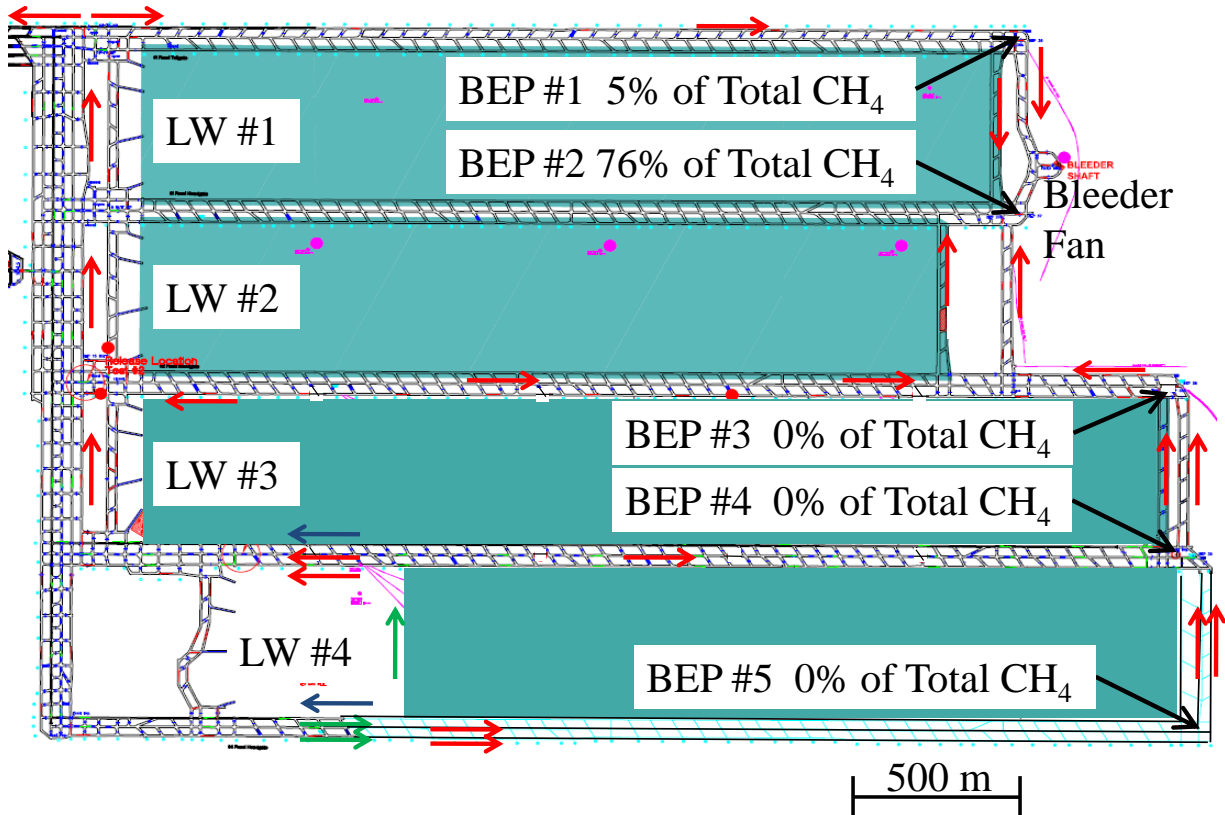


Figure 2-3. Percentage of total methane measured at Bleeder Fan that passed through each BEP (four panels).

### 2.1.3 Reason for bleederless (progressively sealed) ventilation systems

Spontaneous combustion is the most common reason for the adoption of a bleederless ventilation system over a bleeder system (Hartman et al., 1997). A bleederless system is simple in design and cannot mask an ineffective ventilation system. With this system, if there is not enough airflow along the longwall face then problems of high methane or low oxygen will occur at or near the longwall tailgate corner. In order to partially address this adverse effect, bleederless systems can be modulated by nitrogen injection and the removal of high methane by the use of gob vent boreholes. Nitrogen injection has been shown to be most beneficial if injected on the headgate side (Belle, 2010). The removal of methane at or near the tailgate is preferred. However, nitrogen injection and methane removal, while both beneficial, will not hide possible explosive mixtures in the bleeder entries. Figure 2-4 shows how the same mine layout could be converted to a progressively sealed bleederless ventilation system. Gob isolation stoppings would be installed at each crosscut of the headgate entry (between entry #1 and #2) as the longwall retreats. A corresponding stopping would be installed across the middle tailgate (entry #2) to restrict airflow from the caved material to the longwall return.

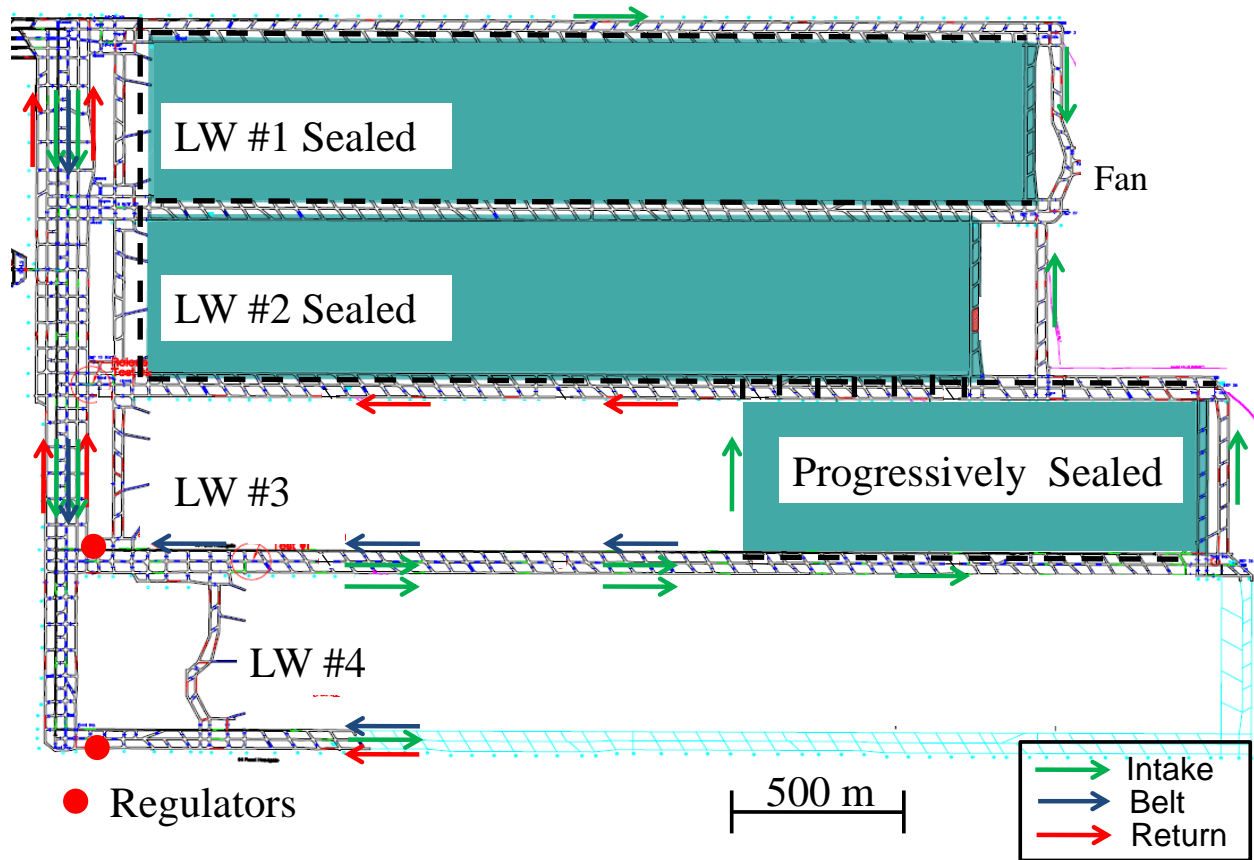


Figure 2-4. Simplified bleederless (progressively sealed) ventilation layout with travelable outer intake entries.

The main advantage of a bleeder system is its ability to remove larger amounts of methane than a bleederless system, given the same pressure differential. The reason for this is that gateroads are used multiple times throughout their lives. The headgate gateroad is used to supply fresh air to the headgate corner during the mining of the first panel. During mining of the second panel the headgate entry is now the tailgate entry that is used to remove return air from the tailgate corner, possibly in both directions. The multiple pathways of a bleeder system have a lower overall resistance when compared to the standard bleederless ventilation system.

In previously mined panels, the old gateroads are used to transfer air between the two isolated adjacent gobbs towards the back bleeders and eventually the bleeder fan. Noack (1998) calculated that the increased abilities of bleeder ventilation systems to remove methane in a gassy operations to be 150% to 180% that of the standard 'U-type' bleederless ventilation system shown in Figure 2-5. Predicted methane emissions into the active zone are proportional to daily coal production. Therefore, bleeder ventilation systems permit greater daily production

versus bleederless ventilation systems if methane production and removal is a limiting factor for safe mining.

Bleederless ventilation systems, on the other hand, are simpler in design and implementation than bleeder systems. The progressive sealing of the gob during retreat (common) or advanced (rare) mining of the panel leaves few open entries for airflow besides the active face. Therefore spontaneous combustion is limited by the reduction of the opportunity for oxygen to enter the gob, except close to the shields.

Some bleederless systems utilize single intake and exhaust entries connected by the longwall face. Bleederless ventilation systems, while simple in concept, still have many varieties of layouts. Noack (1998) showed selections of ventilation layouts shown in the Figure 2-5. The 'Y, U and Z' schemes are normally associated with bleederless systems, while the 'H' is associated with bleeder systems. The 'W and Double Z' which utilize an extra entry driven through the middle of the panel, are found in Eastern Europe's gassy operations, however, are not practiced in the United States (Smith et al., 1994). In all cases the longwall faces shown are being mined from right to left and predominantly retreat mining except in the following cases which are advancing (Y = 1-4, 1-5, 1-6, U = 4-1, Z = 5-1, W = 6-1, 6-3, Z = 7-1, 7-3).

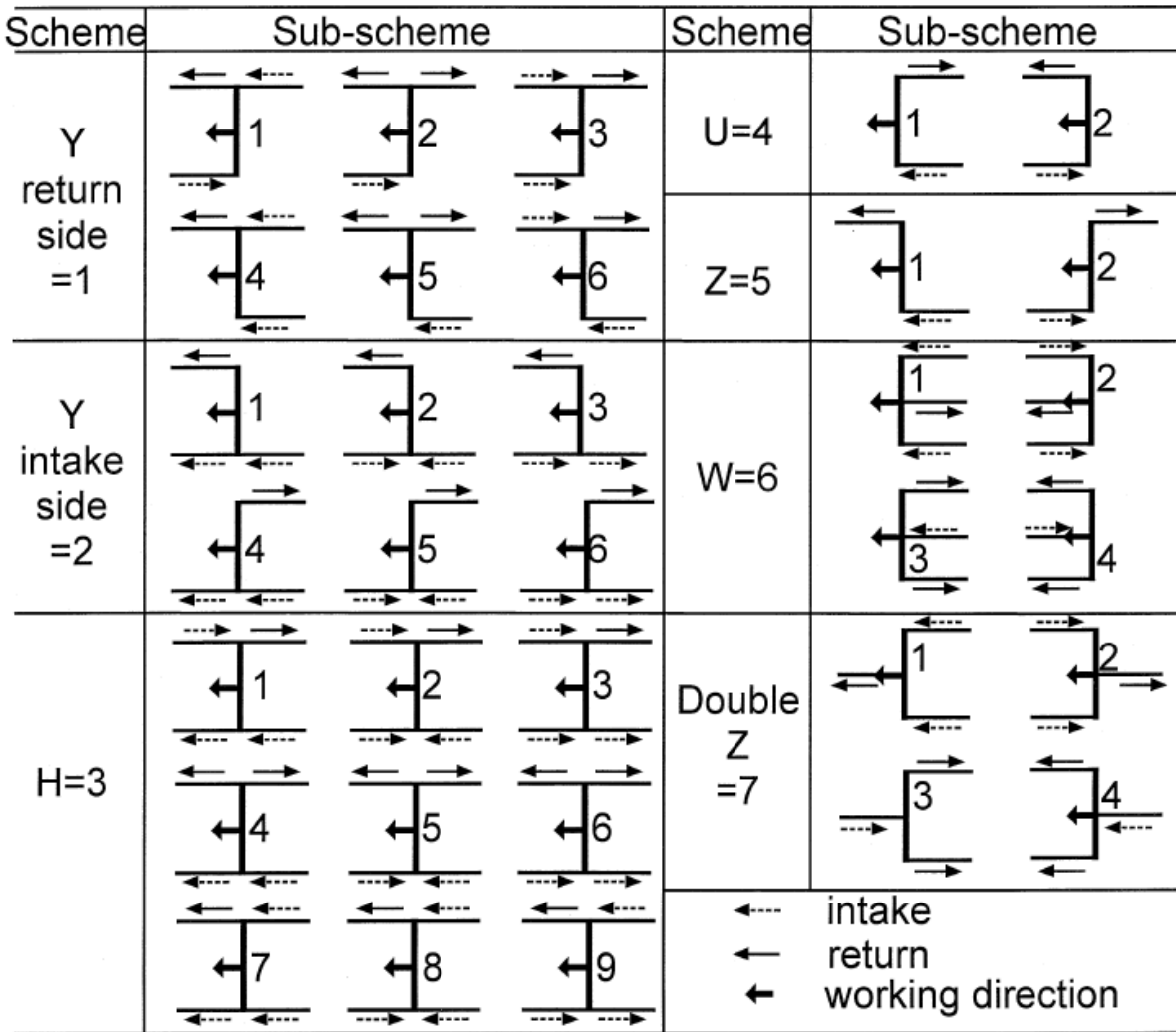


Figure 2-5. Ventilation-related panel design variants for longwalls (Noack, 1998).

Single wire frame diagrams in Figure 2-5 do not show airflow paths through the caved material. The representation that airflow moves diagonally across gobs is shown by Hartman et al. (1997), Barletta (2007) and Brune (2014) in Figure 2-6. This simplification is for visual purposes and should not be interpreted to be actual measured airflow paths. The fact that airflow does migrate from high-pressure locations (longwall face) to lower-pressure locations (bleeder entries and bleeder fan) is known. A large unknown is which flow paths are used and in what quantities. Previous work to determine the effective size opening of the gateroad entry surrounded on both sides by gobs was investigated by Brune et al. (1999). The gateroad size opening is affected by rock strata structural properties, depth of cover, supplemental standing support, age of opening, discontinuities and multiple other factors that make each gateroad unique. The various effective size openings over the life of the gateroad will have a dramatic effect on the amount of airflow

that can be transported from the longwall tailgate corner down the middle entry towards the back of the panel. This quantity of airflow can be the limiting factor to the bleeder system ability to remove methane from the longwall face and to not allow methane rich airflow to enter the tailgate corner from behind the shields.

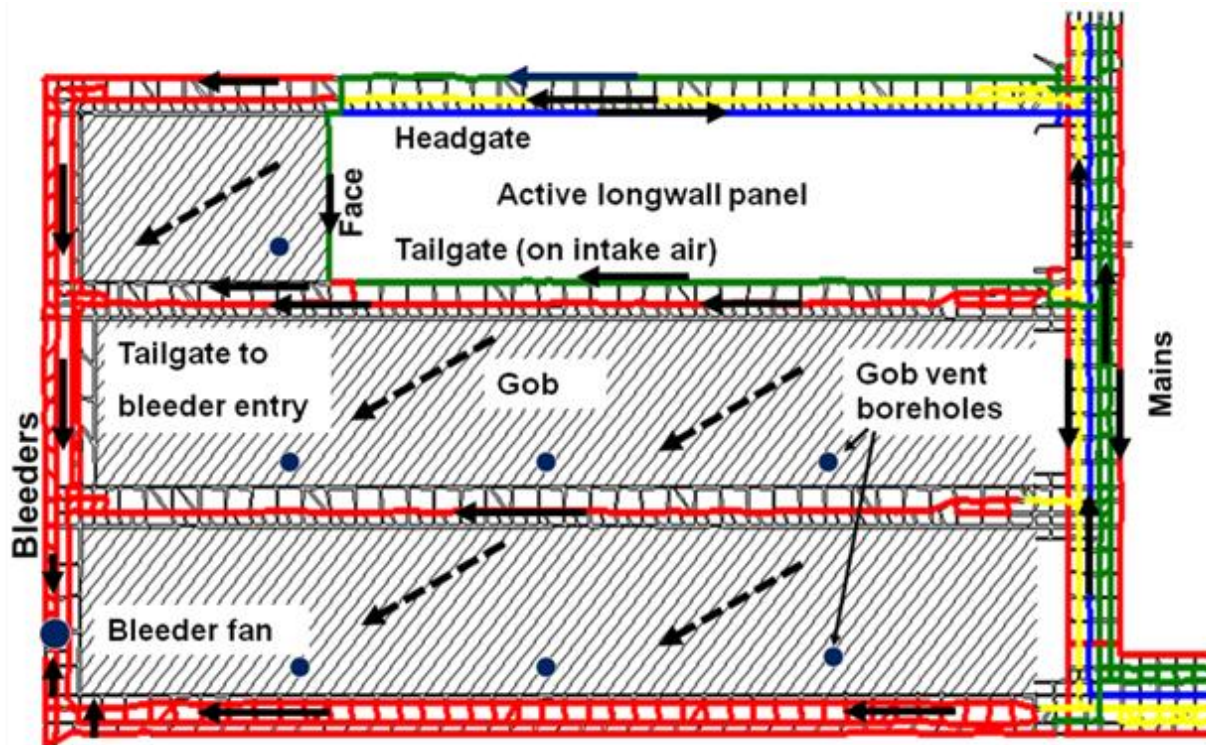


Figure 2-6. Representative Bleeder longwall ventilation scheme (Brune, 2014); not to scale.

Regardless of which longwall ventilation system is used (bleeder or bleederless) there are some common problems such as gas accumulation in the caved material and the difficulty in measuring these gas concentration in critical locations. Therefore although coal properties may largely dictate the choice of ventilation system the problem of gas accumulation still has to be monitored.

#### 2.1.4 Longwall panel sizes

Improvements in longwall equipment have enabled panel width to increase consistently over the last 25 years. Figure 2-7 shows that the average size of US longwall panels has increased in length and width over the last 20 years. Average panel widths have increased from 210 to 370 m (700 ft to 1,200 ft) while average lengths have increased from 2,100 m (7,000 ft) to approximately 3,400 m (11,000 ft). The annual variability in average panel length is mainly caused by the addition or subtraction of a few of the longest panels to the yearly totals, but the

continued general increase in average panel length is still observed. A better indicator to the scale of longwall panel size increases over the last 20 years is to look at average acreage covered per panel. While panel length and panel width have both almost doubled over the last 20 years, the average panel acreage has tripled from 100 to 300 acres per panel. These threefold increases in panel sizes are still primarily being ventilated by the same gateroad systems.

Coal mining districts in the United States are designated: Northern Appalachian, Central Appalachian, Southern Appalachian (Black Warrior basin), Illinois basin and west of the Mississippi (multiple basins). As of 2015, all longwall's east of the Mississippi use bleeder ventilation systems while three out of nine operations in the west currently use bleederless systems (Signal Peak, San Juan, and West Elk).

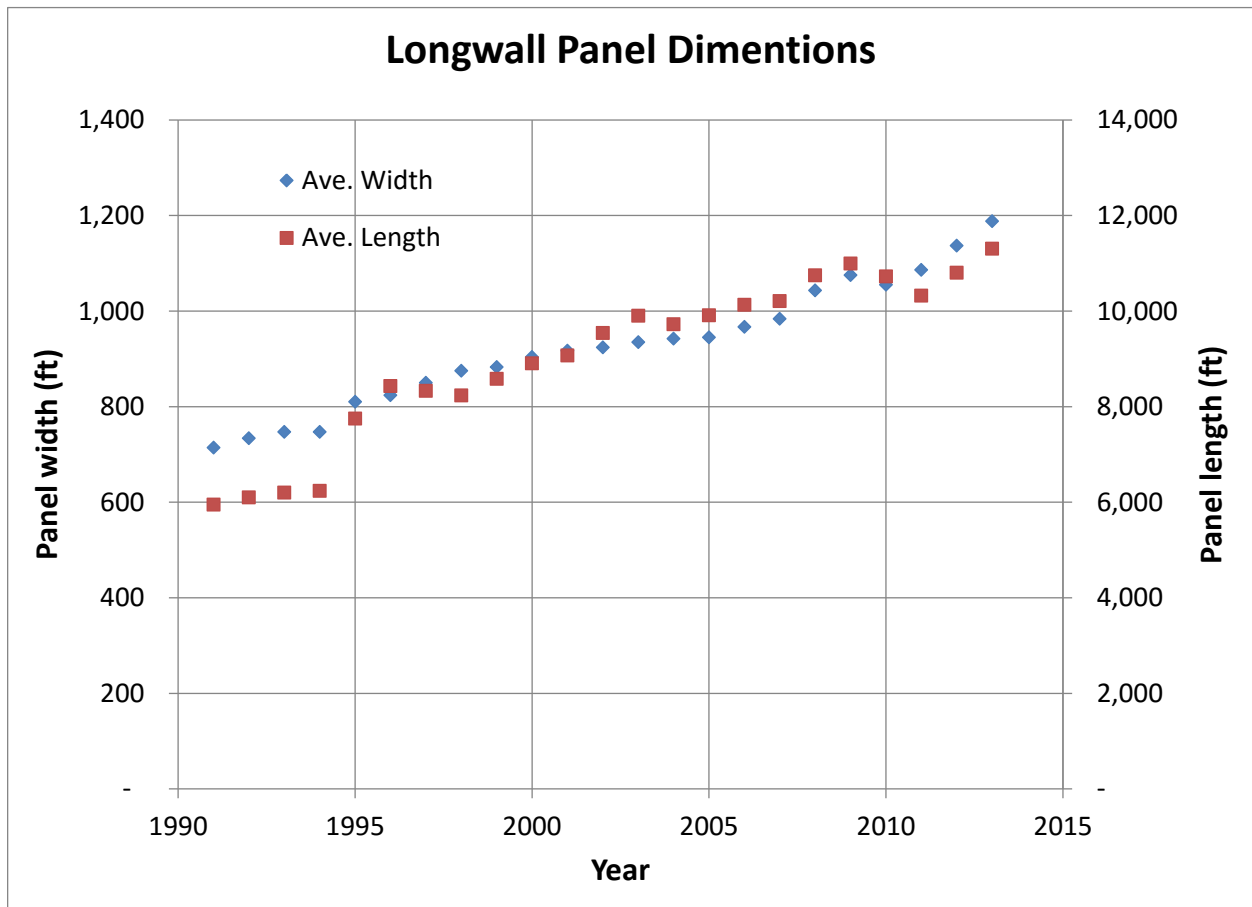


Figure 2-7. Longwall panel dimensions (CoalAge, multiple years)

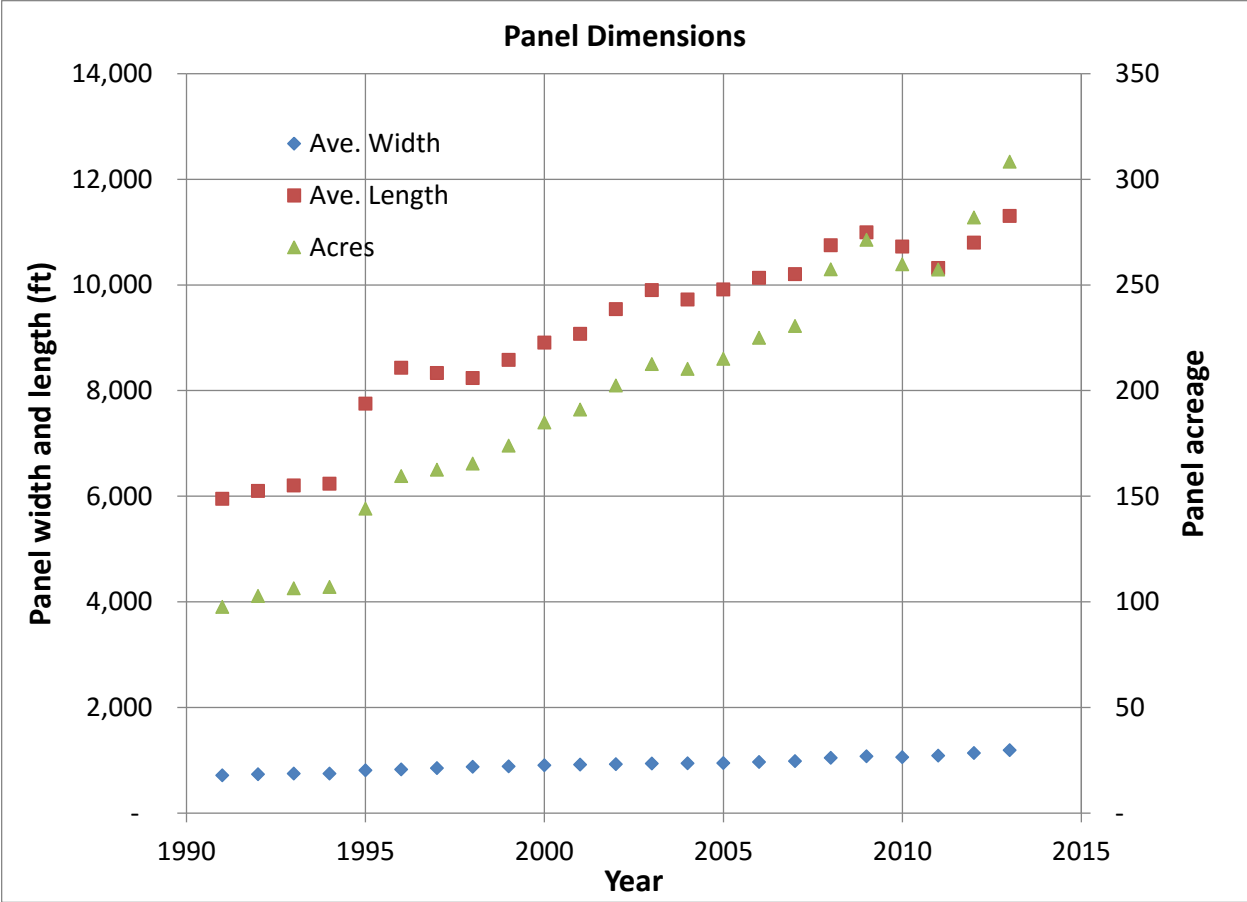


Figure 2-8. Average panel width, length and acreage longwall mines (CoalAge multiple years).

Figure 2-9 shows one mine’s history of increasing longwall dimensions over a 20-year period. Initial longwall panel sizes were 34 acres; eventually, they increased to 79 acres, then to 183 acres, and have since expanded to 422 acres in 2011. The initial 34 to 79-acre longwall panels were mined using four-entry gateroads which would be considered wasteful by today’s standards but the pillars were smaller with numerous crosscuts. The longwalls above 183 acres were mined using three-entry gateroads.



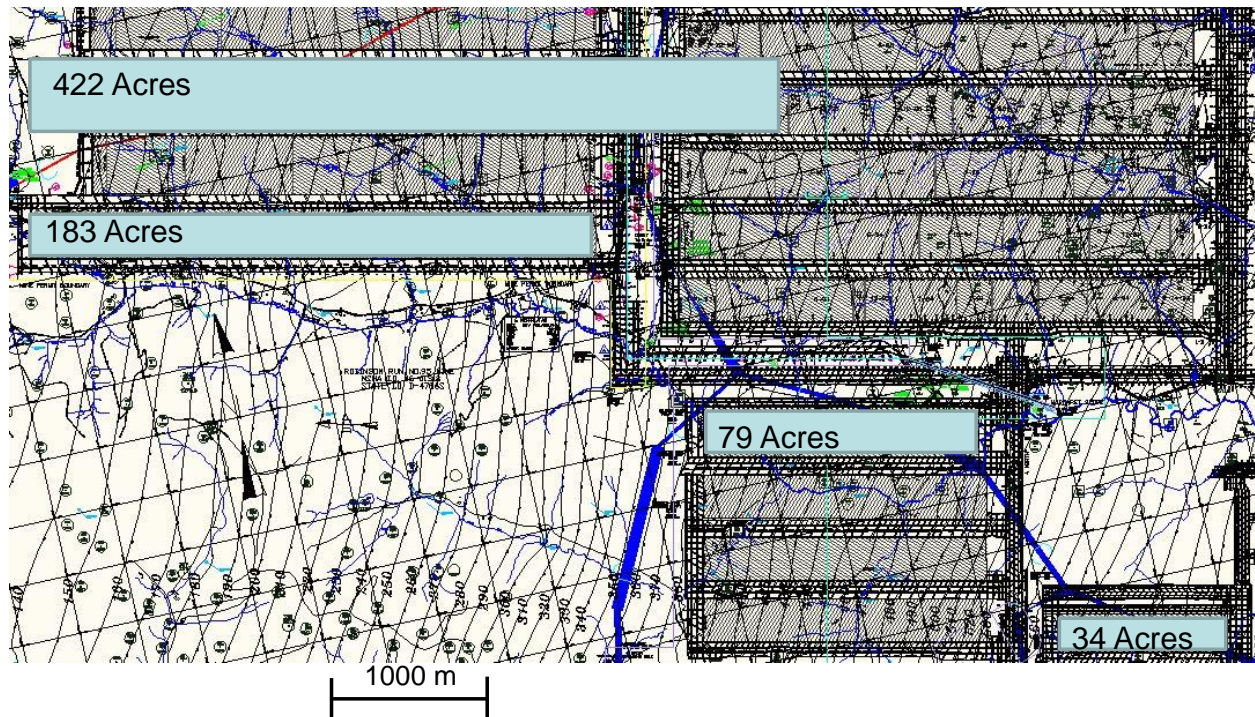


Figure 2-9. Increasing longwall panel size for a single mine, note the newest 422-acre panel was overlaid for visual comparison.

The increasing acreage of the longwall panels is being matched by the extraction rate which has similarly increased. A longwall panel 1,450 ft. wide can be retreated 60 ft. in only one 24-hour period. This subsides about 2 acres of overburden in one day  $(1,450 \times 60 / (43,560)) = 2.0$  acres. Given that in situ methane amounts of 1 to 2 million cfm per acre are common in overlying strata in the Northern Appalachian basin (Thakur, 1997), this mining rate generates large quantities of methane that have to be ventilated by the bleeder systems or by pre or post-production de-gas systems (e.g. in-seam degas holes, Gob Vent Boreholes).

#### 2.1.4.1 Critical vs. super-critical panel sizes

Ground subsidence of critical panels usually occurs when the panel width is 120% of seam depth, (Peng, 1992). Supercritical panels are defined by their surface subsidence profile (maximum subsidence) and controlled by the internal angle-of-draw, which is a function of the geology and stress fields. Supercritical panels are common in the northern and central Appalachia and Illinois basins. The Southern Appalachian (Warrior) basin, in Alabama, with depths greater than 400 m (1,300 ft) has sub-critical panels with reduced surface subsidence as well as in the west. The mines west of the Mississippi can also have minimal surface subsidence due to small panel widths and massively thick overhead stratigraphic layers that can span a single longwall panel.

In western coal mines in the US, the variation in depth of cover is high, with some mines operating in excess of 760 m (2,500 ft) of overburden and panel widths ranging from 240 to 420 m (800 to 1,400 ft); therefore subcritical panels. Supercritical panels will have a lower permeability compacted zone in the middle of the caved material because of higher stress concentrations (Esterhuizen and Karacan, 2007).

The Illinois basin (specifically the Herrin No 6 coal seam) can have highly blocky caved material in the immediate overburden that may not readily compact and remains porous throughout the life of the panel. An MSHA report indicates that a mine in the Illinois basin has half the airflow down the headgate entry transferring across the gob and appearing in the tailgate entry in by the longwall face. In this case, the airflow did not transfer around the gob rather it transferred through the gob (Figure 2-10) (Stoltz, 2009a).

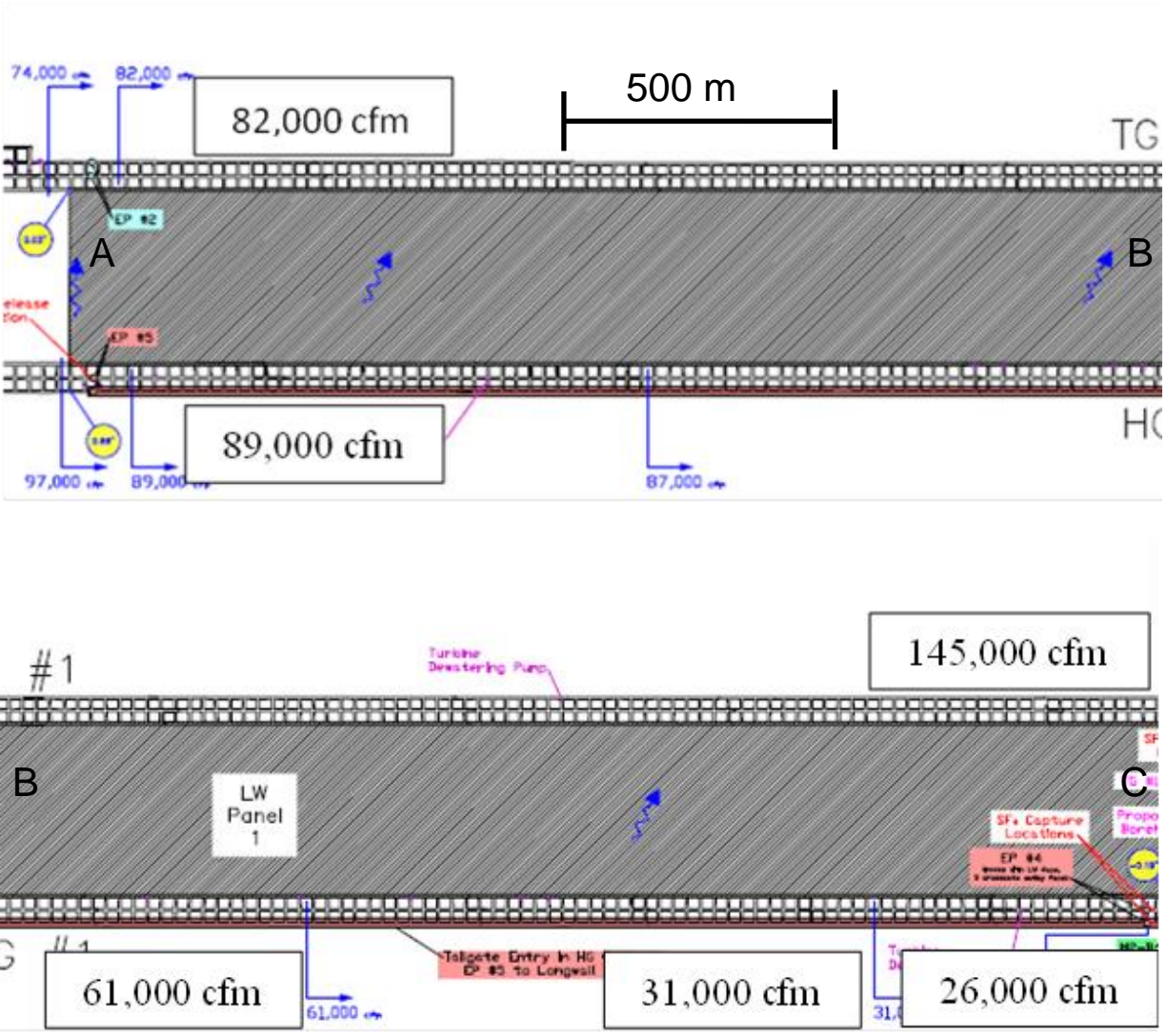


Figure 2-10. Split view of Illinois basin mine in the Herrin #6 coal seam showing extreme airflow across a gob from the headgate to tailgate entries. Approximately 28 m<sup>3</sup>/s (60,000 cfm) leaked through the gob (Modified from Stoltz, 2009a).

This is an extreme example of a supercritical gob with 380 m width and 150 m depth (1,250ft width and 500 ft depth) that did not readily compact after mining, but it does not represent the majority of underground longwall coal mines. MSHA prepared the report (Stoltz, 2009a) because this was not a common occurrence with previous eastern longwalls. This MSHA investigation reinforces the belief that each mine is unique with its own specific problems and conditions.

Panel sizes have increased by factor of 3 over the last 20 years but are still largely ventilated by the same 3-entry gateroad system utilizing a bleeder system at most underground longwall

mines. The majority of panels would be considered super-critical and therefore have central cores with lower porosity and permeability than the surrounding caved material.

## **2.2 Methane transfer within longwall panels and control**

Due to the nature of longwall mining process methane is produced not only from the mined coal but also from overlying and underlying strata. One of the most important functions of the ventilation layouts is to control this methane and render it harmless. This section discusses the pre-mixing of high methane concentration along the back bleeders, the acceptable methane levels at different stages of panel extraction, as well as engineer versus legislative design approaches in methane control by ventilation.

### **2.2.1 Pre-mixing along the back bleeders**

The following figures show the wide-spread problem that multiple parallel airflow paths can obscure the methane concentration and total amount of methane passing through BEPs. This out-of-compliance bleeder had a BEP recording of 0.8% methane, while 5% methane was being emitted down the middle entry of the active longwall's tailgate (Figure 2-11). The most disturbing fact about the measured 5% methane is that this is not a pure sample from the middle entry but a mixture of at least two airflows. One of these airflows had a methane concentration of 0.6% before passing through the corner gob of the setup room (Figure 2-12). What is the methane concentration of the airflow passing through caved setup room of the next panel? The transportation of large amounts of methane within the gob, allowing it to be emitted at a BEP located far away from the active gob, has not been addressed. Figure 2-12 shows the methane transportation in the three parallel entries with the outer walkable entry transporting less methane than the two inner non-accessible entries.

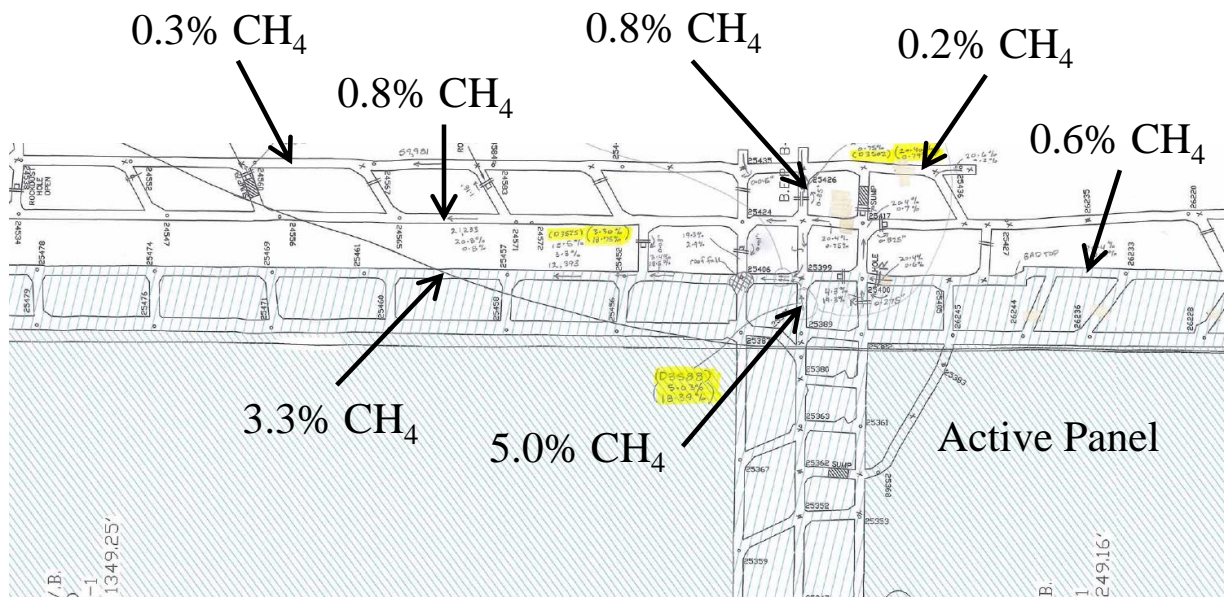


Figure 2-11. Increasing methane concentrations in bleeder entries surrounding gobs (modified from Stoltz, 2009).

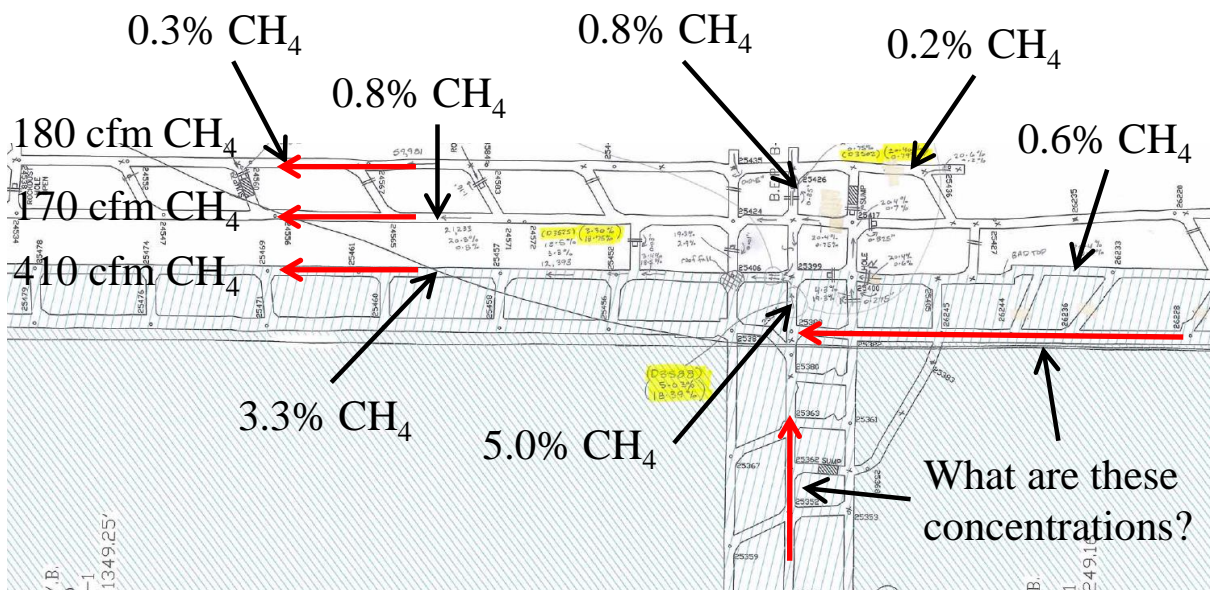


Figure 2-12. Two mixing airflows average to 5% methane (modified from Stoltz, 2009).

Figure 2-13 shows one current view on how the methane travels from the active tailgate entries to arrive at the BEP located closer to the bleeder fan. However, previous work on gob permeability does not support a ventilation model with so much air moving through the caved material as shown in Figure 2-13. This misconception about airflow pathways across caved material perpetuate the idea that methane just arrives at the back BEP by the most direct direction and not following a longer distance but lower resistance pathways surrounding the caved material. Declining gas production data from longwall panels and districts are shown in Figure 2-14 based on isolated panels that are progressively sealed during extraction. This figure shows the expected gas production based for each longwall panel dependent on activity and time. The methane produced in LW4 should be reporting to the BEP on the tailgate side of LW4 but instead reports to the BEP of LW1 using parallel internal entries that are not measured or monitored.

Monitoring of the BEP located outby where premixing occurs gives methane concentrations less than it actually exiting from the tailgate entries. Thus values taken from only the outer travelable entry give little indication as to the effectiveness of the bleeder system. Methane can be bypassing the active panel's BEP by the use of multiple parallel along the back of the bleeder system.

## Two Longwalls in Adjacent Panels

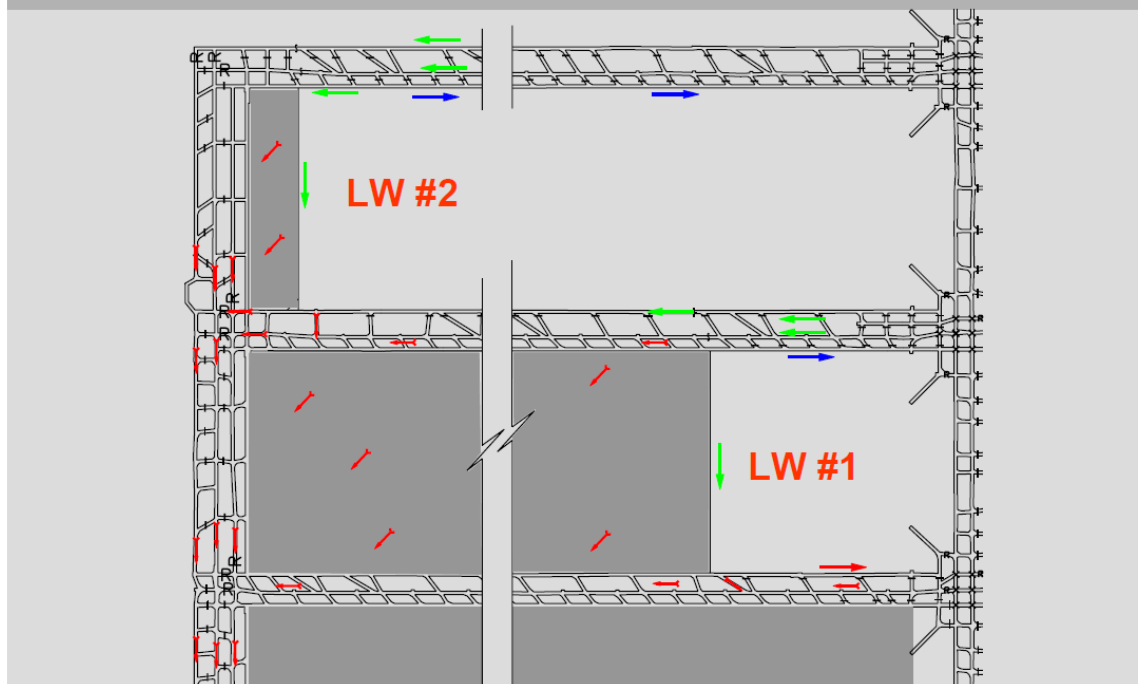


Figure 2-13. Belief that airflow moves through gob and not around them (Barletta, 2007).

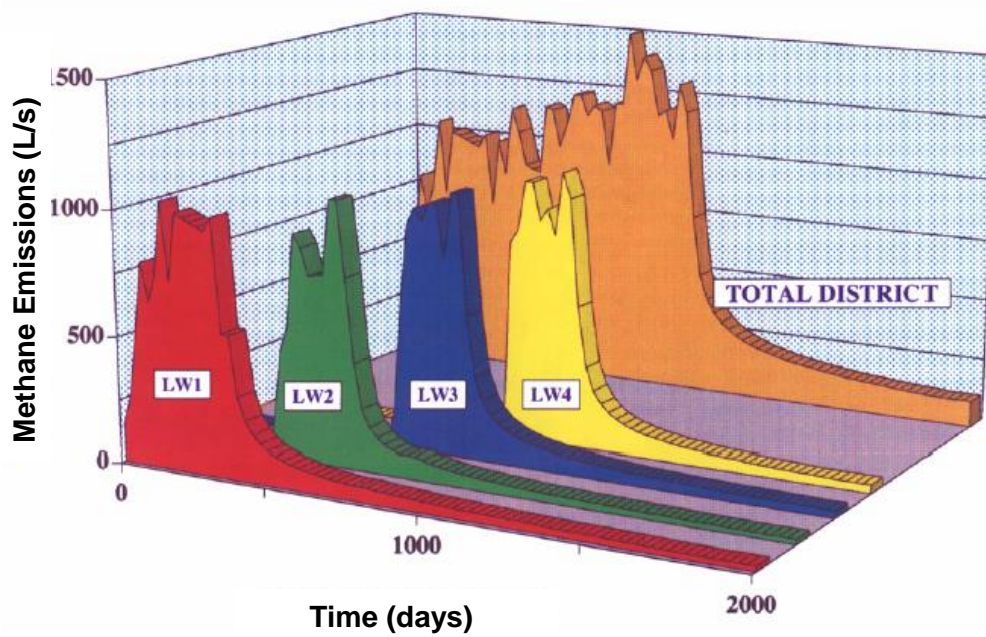


Figure 2-14. Methane production from each panel in a mining district (Lunarwenski, 2010).

### 2.2.2 Acceptable methane concentrations

It was interesting to see that ventilation beliefs as to what is considered safe and acceptable in the rest of the world are under debate in the United States. The notion that possible explosive levels of methane are acceptable within the bleeder systems because the letter of the law is being followed is disturbing. In 2007 MSHA presented a one-day symposium regarding bleeder systems. The following figures were two slides that were asking questions to the audience: “10% CH<sub>4</sub> in gob okay, 4.5% CH<sub>4</sub> in entries okay at the MPL (measuring Point Locations)?” The fact that these questions were being asked shows how differently methane accumulation opinions are viewed within the United States. Figure 2-15 and Figure 2-16 show two sets of possible philosophies as to what are acceptable methane concentrations within the gob by industry (Beiter, 2007). MSHA does not agree with these interpretations but is only able to enforce the law as stated in the Code of Federal Regulations (CFR). These theoretical figures would describe what technically is legal but not fundamentally a good engineering design.

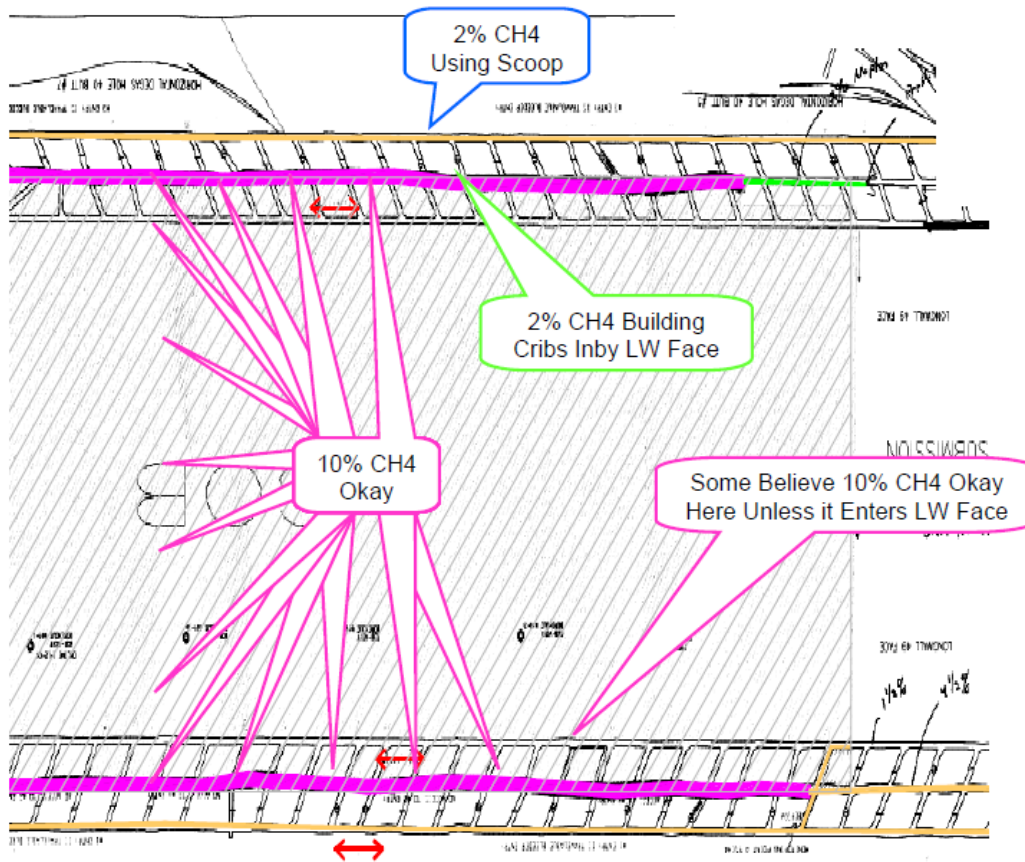


Figure 2-15. Question: regarding the possible acceptable methane concentrations in the gob (Beiter, 2007).



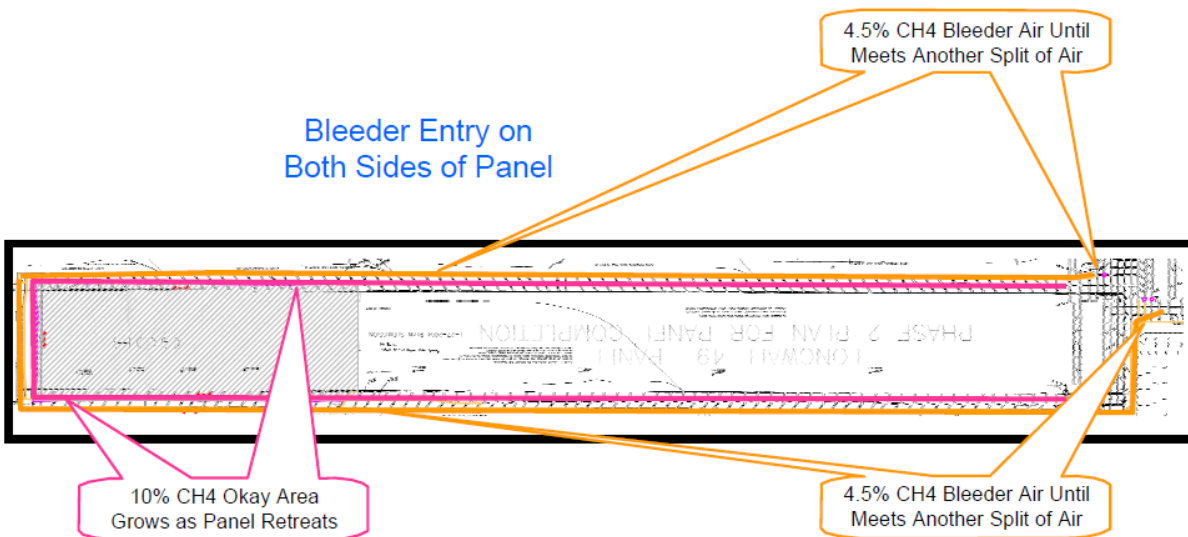


Figure 2-16. Question: High methane ok so long as it passes the MPL 4.5% and 2.0% levels. Pink color is the 10% methane question and gold color is the 4.5% methane bleeder split question (Beiter, 2007).

### 2.2.3 Engineering design vs. legislative design

“So long as we are below 4.5% methane at the statutory measuring locations we are in compliance” has been stated, off the record, by many ventilation personnel in the field. Industry has not measured the methane concentration in these inaccessible locations because there is no incentive to do so but in fact a disincentive exists. The only possible results will have negative consequences. What happens if 8% methane is shown to exist just in by the longwall tailgate corner? What does a mine do to fix this? Measurements are not done because the burden of proof to show that the bleeder system is operating safely does not rest with the engineering department of the operator, but is in fact a legislative procedure that has to be followed by the CFR. MSHA does have considerable leeway to interpret the law for practical reasons but fundamentally they are restricted to what the explicit letter of the law states. Some of the most experienced ventilation engineers in the country work at MSHA but they have to defer to the CFR in most matters. This can result in ventilation plans that meet the letter of the law, but have large areas of explosive mixtures of methane and are therefore, not the safest possible design.

An example of the legislative constraints placed on MSHA is shown from the text of one of the slides as follows: “Bleeder System Evaluation -an effective bleeder system with adequate ventilation pressure differentials and airflow distribution will not be substantially affected by

normal barometric pressure changes” (Stoltz, 2007). If the above statement is possible, then the engineering system required to evaluate such a rule requires, at a minimum, continuous measurement of methane at the bleeder fan to check if there are spikes in methane concentrations during normal barometric pressure changes. If these spikes are present, then each of the underground MPL have to be sampled to find out if any of them are out of compliance. Mining operations may be taking continuous methane measurements at main or bleeder fans for internal reference but not publishing these results.

There is a discrepancy between what engineering requirements would incorporate into the design of a ventilation system compared to how the system would be optimized to pass legislative requirements of lower methane concentrations at the MPL. This discrepancy, which needs to be addressed, may result in explosive mixtures of airflow being transferred within the bleeders system without being detected.

#### **2.2.4 Modeling methane generation and transfer paths within the caved material**

Researcher will use two common forms of ventilation modeling for the caved material: network circuit design or computational fluid dynamics. For any model that uses methane injection, the location and quantity of the methane is important. One large, single-source location might not be applicable; whereas, a large general area might be an oversimplification. Some models have used the longwall shearer as a point source of methane, whereas others have used the overlying strata (Marts et al., 2013). Strata emissions could be the full plan-view area of the longwall panel or just the cross-sectional area of the active subsidence zone behind the shields (Yuan et al., 2006). Actual methane emissions can also be from any solid coal source, for example the headgate ribs and overlying strata that attaches to the gob. The methane can also be released by the broken coal on the longwall face, the broken coal falling behind the shields, and along the perimeter of the gob.

Any of these choices is a simplification of the real world which would be governed by in-situ methane pressure, as well as fractures and major geological features, like faults of sandstone channels. From this perspective, an active longwall panel can be described as the world’s most efficient fracturing of strata for the release of methane. Each progressive caved section of the longwall panel likely will have its own declining-curve emission rate. All sections have to be summed up to determine the expected emission rate for a longwall panel as mining progresses.

Lunarzewski (2010) described a decline-curves method for methane emission from individual and district longwall panels. Production of methane in the active panel is closely related to the

short-term coal production rates on a weekly and monthly basis. When mining of a panel stops, there is a rapid reduction in the methane production of the panel. This rapid short-term reduction is based on the total methane emitted for each individual panel. As shown in Figure 2-14, the total methane emitted by for each of the four panels was approximately 1 m<sup>3</sup>/s methane (approximately 3 MMCFD) which matches a medium gassy operation in the US (Thakur, 2006)

Figure 2-17 shows an individual longwall panel production history, followed by the rapid short-term methane production reduction during the first 4-6 months after mining stopped, followed by a slower long-term decline afterwards. The condition shown is for a non-flooded caved panel.

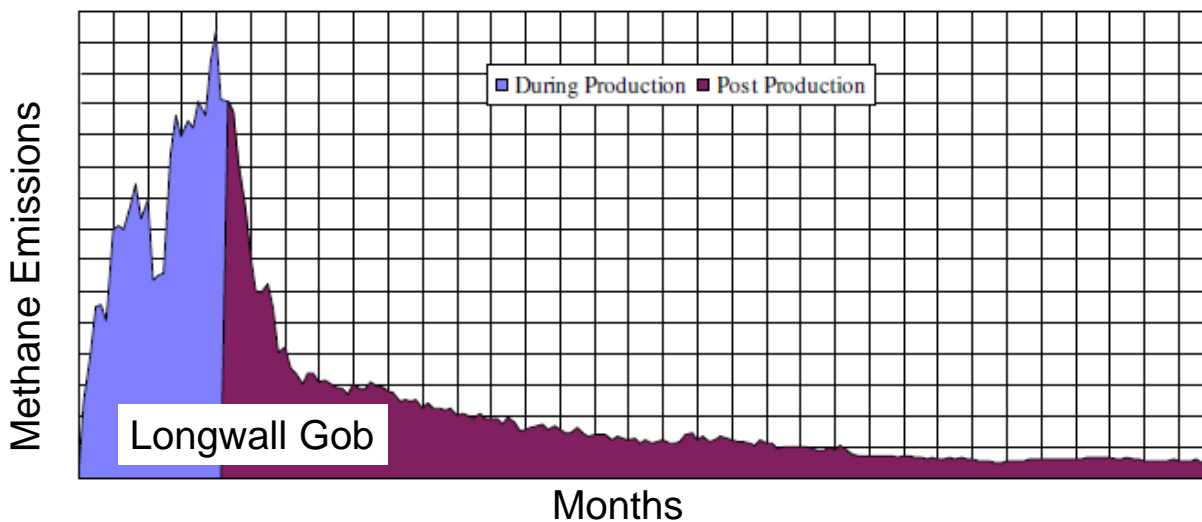


Figure 2-17. Methane emission versus time for an individual longwall panel with dry (non-flooded) conditions. (Lunarzewski, 2010).

Methane production in a longwall district is predominately from the active longwall panel not from previous mined panels. The methane production of a bleederless system is measurable at the longwall return or at the back for the panel because each panel is progressively sealed. However, a bleeder system can have methane transferred across panels from active to previous panels, therefore making measuring methane production for just the active panel by itself difficult. The multiple airflow pathways from the methane emission sources to exiting the mine via a bleeder fan, complicated modeling of a bleeder system.

### 2.3 Dynamic nature of methane emission in longwall panels during mining

Methane generation from the longwall face and also from strata during mining and non-mining periods are variable. In addition to the dynamic nature of these emissions changing atmospheric pressure will add additional complexity in the form of out gassing events from the caved

material. This section discusses with examples and with relevant literature the differences in the magnitude of the methane concentration during panel extraction and the effect of changing atmospheric pressures to those levels during outgassing events.

### 2.3.1 Static and dynamic methane release on longwall faces

Methane emissions into the active working areas are not constant. On a longwall face the emissions are generally controlled by the cutting of coal over the previous short-term (Krog et al., 2006). Methane-concentration data collected on longwall faces are not common in the publication history, but previous work by Mutmansky and Wang (1999) gives a compelling view as to the dynamic changes occurring during longwall operations. Figure 2-18 shows the methane concentration along an active longwall operation over a 2-hour period at a gassy longwall operation. The concentration ratio between methane peaks and the background emissions levels during non-mining activity was about 5:1 (Mutmansky and Wang, 1999). Krog et al., (2006) showed a similar 5:1 ratio during a study at a moderately gassy, Pittsburgh #8 seam mine where the methane emissions and the shearer movements were simultaneously tracked (Figure 2-19).

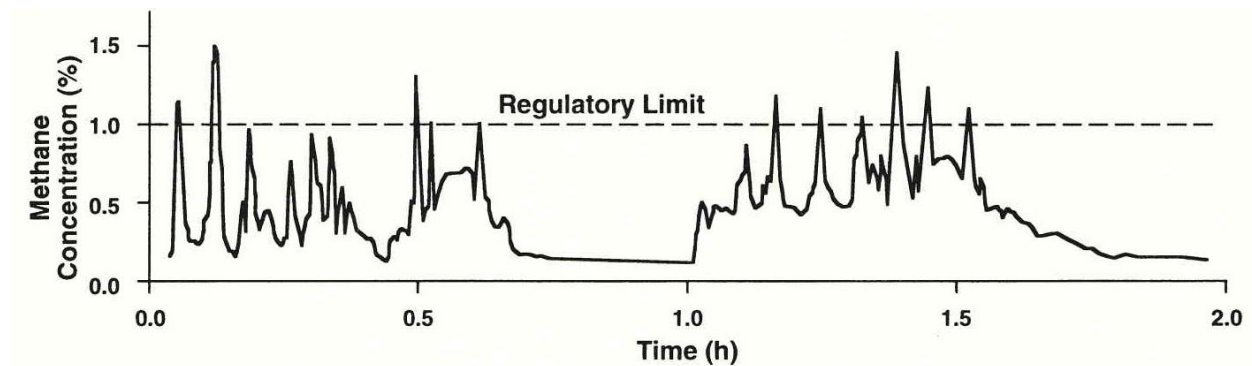


Figure 2-18. Pattern of methane concentration vs. time on a high-methane longwall face with gas stoppages (Mutmansky and Wang, 1999).

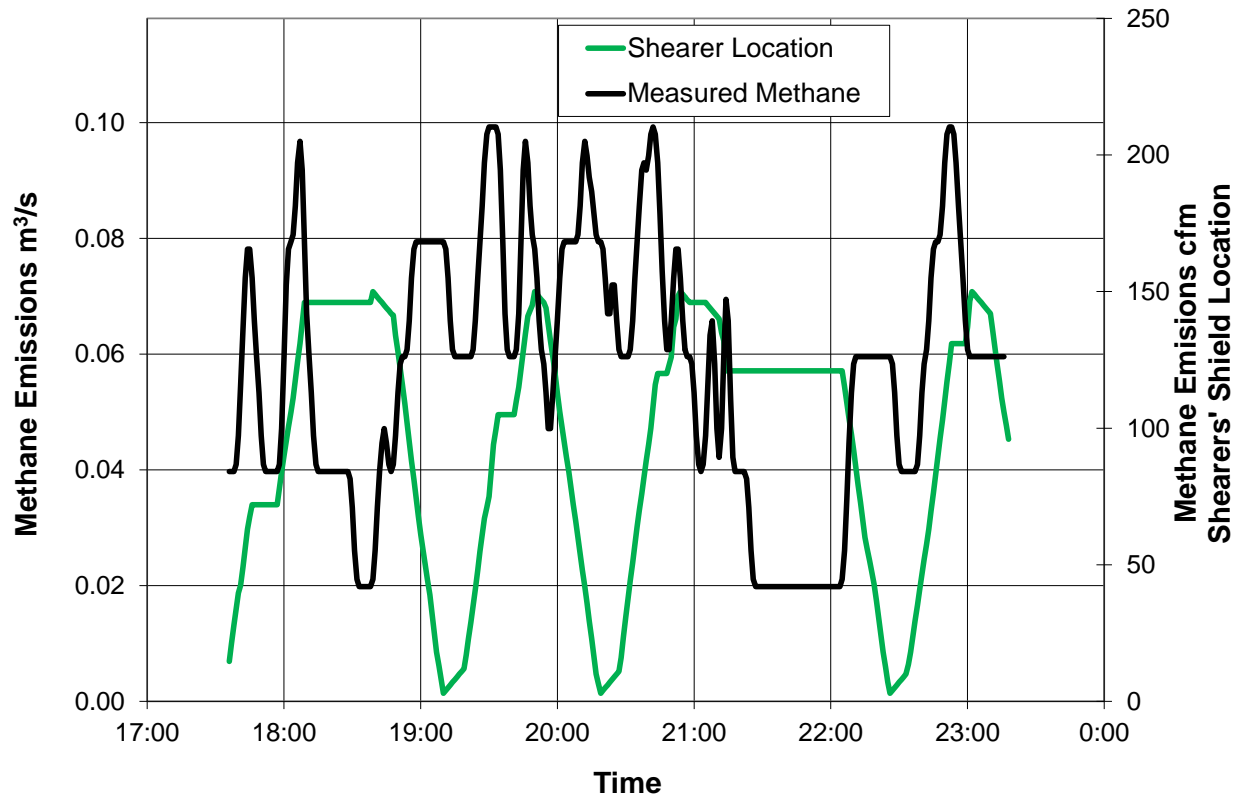


Figure 2-19. Methane emissions from a Pittsburgh #8 seam mine over a shift showing shearer shield location to determine if active cutting was occurring (Krog et al., 2006).

The two previous figures show that methane emissions on a longwall face are dynamic and can quickly rise and fall if the shearer is cutting and if there is coal on the armored face conveyor. Therefore, methane production from the longwall face is not uniform and a dynamic system based on mining rate. With airflow leaving the longwall tailgate corner to enter the caved material the approximation of a constant methane emission rate from the longwall face is not entirely correct. The fracturing of the strata by the retreating longwall face will also have non-uniform emission level of methane into the caved material. Therefore the methane emission exiting from the caved material will not be constant.

### 2.3.2 Atmospheric pressure changes

Methane emissions from the entire longwall panel are also dynamic and can be significantly controlled by atmospheric pressure. Most previous research done on mine ventilation systems assumes a static barometric pressure. The reasons for this are obvious. By eliminating barometric pressure fluctuation, researchers can simplify the problem and focus on other controlling factors of interest, such as the working GVB in a longwall panel, or airflow pathways

in a caved material. However, Diurnal changes along with large-scale barometric pressure effects on ventilation systems should be considered. Hemp (1998) defined the two main issues associated with changing barometric as: 1) changes to gas emissions from the strata, and 2) leakage into and out of sealed or poorly ventilated areas, including longwall gobs. Hemp's results showed that, when in-seam gas pressures are high, any changes in atmospheric pressure will have a negligible effect on methane outflow from the strata. These results were expected, considering that in-seam gas pressures are orders of magnitude greater than barometric pressure fluctuation. The second issue of sealed or poorly ventilated areas with regard to air inflow or outgassing/ingassing during changes of atmospheric pressure was investigated. Hemp's conclusions were that barometric pressure changes are one of many factors influencing atmospheric conditions within a mine and that further research was required. That fact that atmospheric pressure changes affect gas emissions from poorly ventilated areas is generally acknowledged (Hemp, 1998). Schatzel et al., (2015) correlated outgassing of a set of 7 mine seals from a sealed panel to the changes in atmospheric pressure over a 6-month period.

## **2.4 Modeling approaches to ventilation layouts, their features and limitations**

Numerical modeling is one of the most widely used methods for understanding system behavior in engineering. For methane control and ventilation, network modeling and CFD are the most common techniques. However, these techniques require critical data and simplification of complexities of mining environment. This section presents a literature review on distribution of porosity and permeability of caved material, the tracer gas technique to collect data from the inaccessible parts of the panel, and simplified boundary conditions of CFD models that are used for predicting gas concentration within the gob. Furthermore, the limitation of CFD modeling that arises from the dimensions of full size panels are also presented with relevant literature.

### **2.4.1 Permeability and porosity of caved material**

Accurate modeling of airflow in longwall operations by computational fluid dynamics (or network models) is highly dependent on the assumed permeability in the gob. Most CFD problems simplify the gob as a porous media block that has a uniform permeability in all three directions. More complex CFD modeling of a gob is done by using multiple horizontal layers of porous media blocks still has a major assumption of uniform permeability within each layer. This more complex CFD modeling still does not represent true permeability of the gob. A uniform porous media block would apply to the lower layers of the fallen caved material, but the transition zone

of the upper strata with bed separations will not have a uniform-permeability distribution instead, it will have preferential flow paths. The preferential flow would be along the edge of the gob, not across it or upper/down vertically. Visually this would be represented by an image of a race track around the perimeter of the panel surrounding a low permeability compacted middle gob (Mucho et al., 2000).

Esterhuizen and Karacan (2007) have created a FLAC model that determines gob permeability based on porosity determined by the compaction of the overlying strata. These probability distributions have been the basis of many computational fluid models to determine airflow paths in the gob, treating the blocks as porous media with changing permeability based on location within the caved material. While this appears to be an important improvement over previous models that just use large regional porous media blocks, the permeability developed by this method is still based on one particular coal seam and may not be applicable to all other mines in the United States. One of the problems with this model is that it uses a uniform permeability in all directions, which is not the case in dealing with the upper strata having bedding plane separations which then give a non-uniform directional permeability constant, orders of magnitude higher along the sides of the panel but not across it or vertically up or down. The communication between gob vent boreholes shown by Mucho et al. (2000) can only be possible if there is a non-uniform permeability in the overlying strata. A shut-in gob vent borehole had a static pressure 1.5 kPa (6" w.g.) lower than the bleeder fan was producing. The source of the lower pressure was the communication with an active GVB located over 1,300 m (4,300 ft) away and not mine ventilation system located 12 m (40 ft) below hole bottom.

Previous CFD work by Ren and Balusu (2009) and Yuan et al. (2007) used non uniform but symmetrical permeability to create a permeability graph of the gob as shown in Figure 2-20 published by Yuan et al. (2007). The caved material is symmetrical in two directions, both with and perpendicular to the mining direction (width = 150 m, and length = 1,000 m). The symmetrical distribution of the permeability for the panel's start-up room and recovery room is not consistent with subsidence data or the extraction process and progressive caving (Marts et al., 2014).

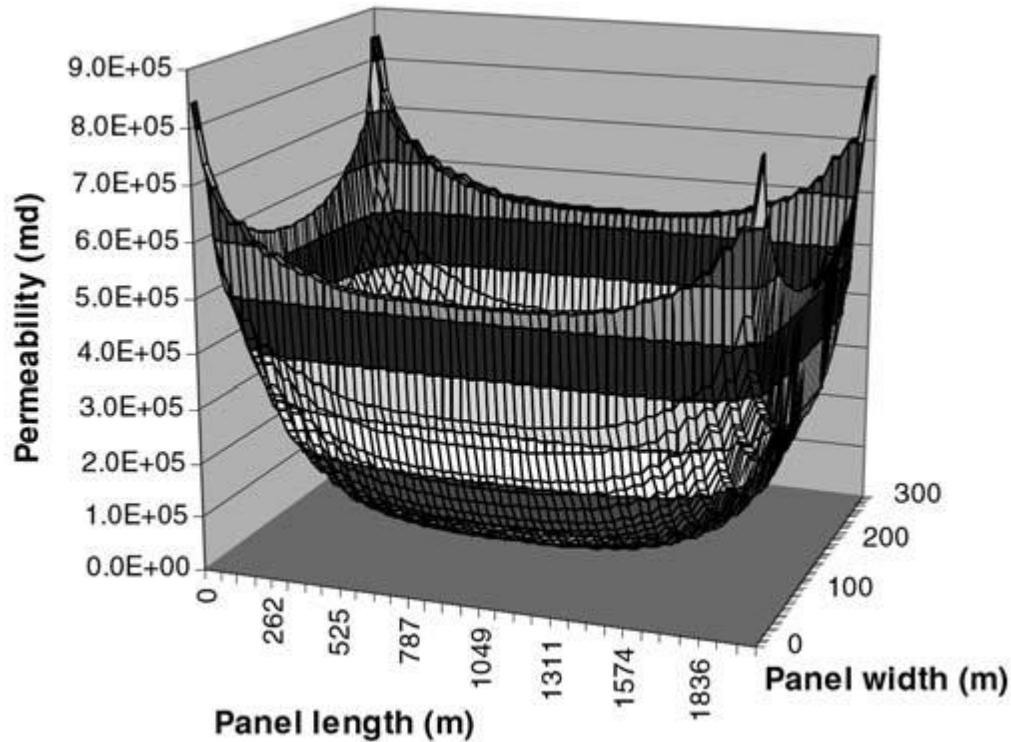


Figure 2-20. Permeability of a longwall panel during partial extraction, (Yuan et al., 2007).

Permeability of overlying strata above the coal seam after longwall extraction has been evaluated by ground-control researchers (Esterhuizen et al., 2005; Whittles et al., 2006). Geotechnical models were constructed in either  $FLAC^{2D}$  or  $FLAC^{3D}$  using various overlying strata layers to determine permeability based on initial longwall mining and, later on, partial and full re-compaction of the caved material. A list of possible ranges of gas fluid mobility for different caving zones is shown in Figure 2-21 from Whittles et al. (2006).



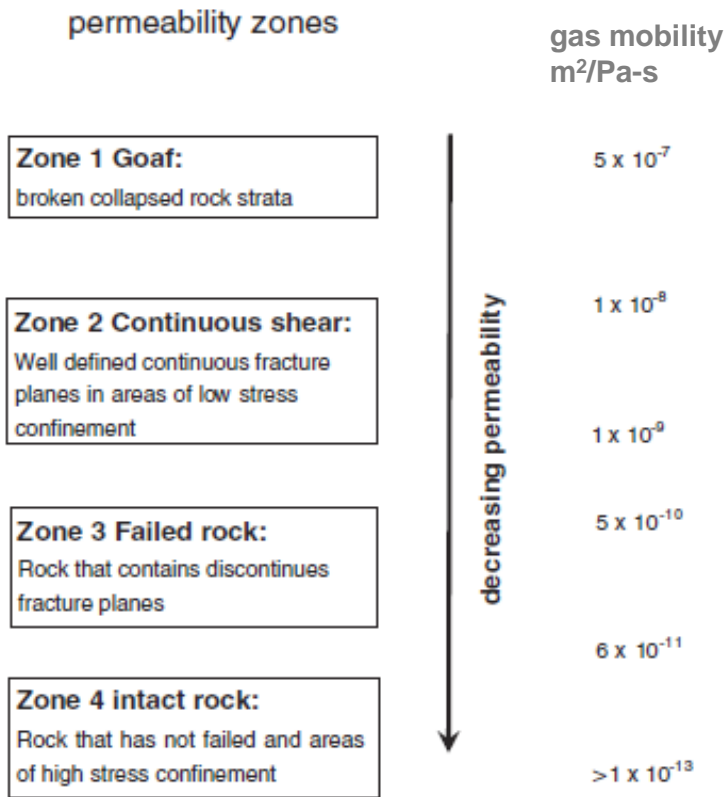


Figure 2-21. Zones of fluid mobility (Modified from Whittles et al., 2006).

The Whittles et al. (2006) model predicts that the majority of the methane airflow in the caved material occurs at or near the perimeter. Yuan et al. (2006) calculated that the velocity in the low-compaction cave material near the setup room is in the order of 0.02 m/s compared to less than 0.000002 m/s, or one-thousandth the velocity within the gob. The sharp contact of change in the airflow pathways within the gobs, as shown in Figure 2-22, is a product of the contact surfaces of different large blocks of different permeability making up the caved material within the model. Work done by Marts et al. (2013) derived a dramatically different porosity distribution of the gob based on narrower 10-meter mining increments of coal when compared to earlier symmetrical models. Porosity is the foundation for calculating the permeability of the gob, and most input permeability values are based on an empirical relationship using porosity (Karacan et al., 2006).

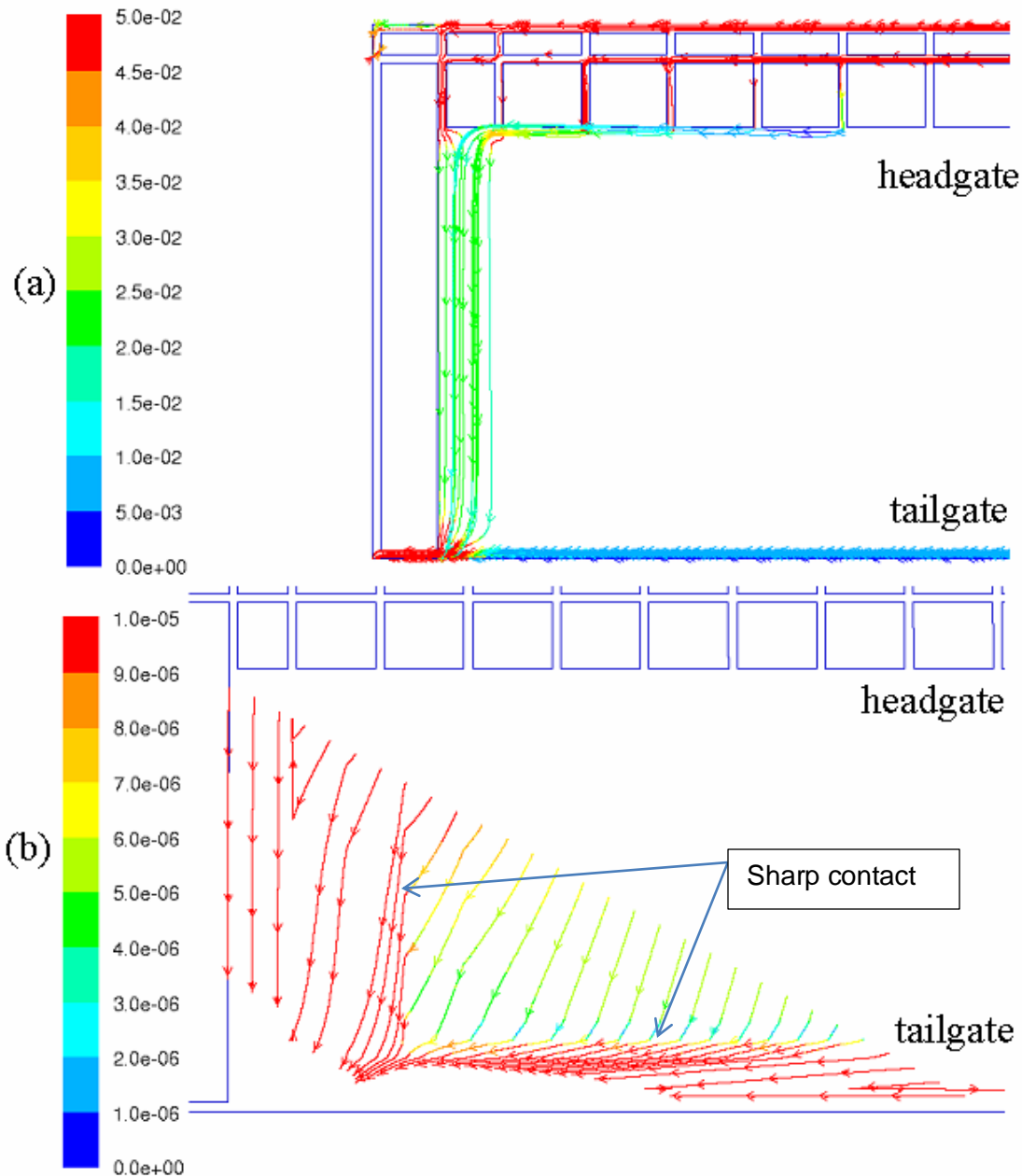


Figure 2-22. Flow path lines by velocity magnitude (m/s) for a three-entry bleeder system: (a) near the back end of the gob, and (b) away from the back of the gob (Yuan et al., 2006).

Marts et al. (2014) produced the volumetric strain of a gob that showed the benefit of a stepped extraction to better match actual centerline mine subsidence of a super-critical longwall panels (Figure 2-23). The stepped extraction method better approximates the observed centerline panel subsidence. These resulted in two different permeability distributions for two mines, as shown in Figure 2-24. The lower permeability (higher compaction) of Mine C is the closest gob

permeability distribution found in the literature that matched the airflow patterns recorded at a cooperating mine (Mine B).

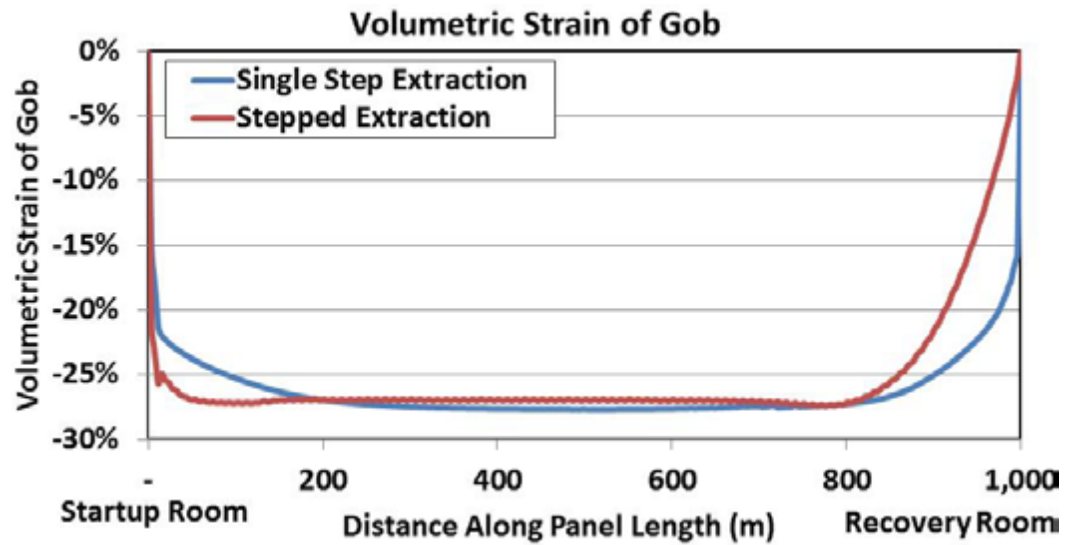


Figure 2-23. Centerline volumetric stain of gob showing two different extraction methods (Marts et al., 2014).

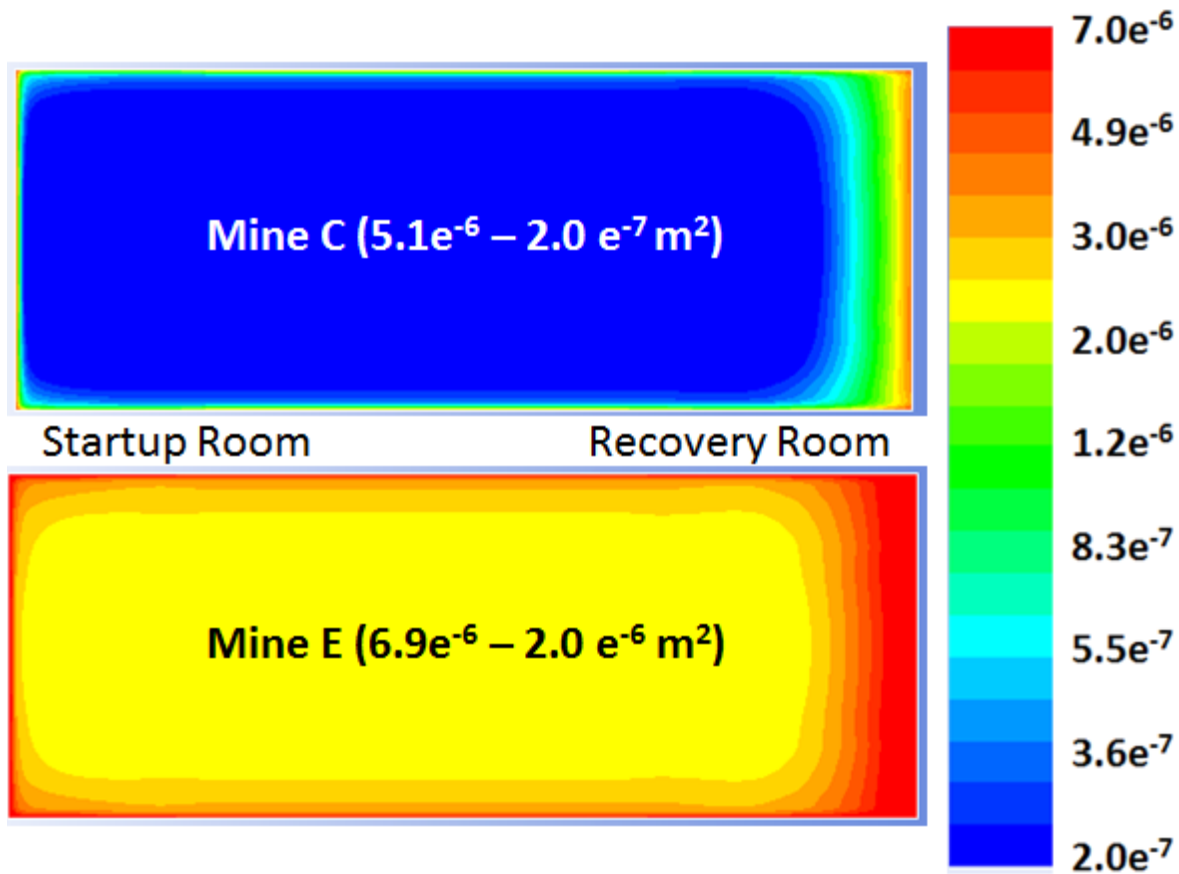


Figure 2-24. Permeability of two gobbs, Carman-Kozeny relationship (m<sup>2</sup>) (Marts et al., 2014).

While the previously modeled studies of gob permeability (Yuan et al., 2006) (Marts et al., 2014) were based on a closed bounded system and are site specific, what is not shown is the possibility that there exists an open or partially maintained opening surrounding the gob that can transport a much greater volume of airflow than the gob itself (Krog et al., 2014) (Figure 2-25). All three studies by Ren and Balusu (2009), Yuan et al. (2006) and Marts et al. (2014) dealt with partially or progressively sealed bleederless ventilation systems, with few if any airflow paths outside of the caved material. A bleeder system is much more complicated to model because of the possibility of open parallel pathways surrounding the gob and the interaction with previous mined panels that are not progressively sealed.

In a bleeder system, the setup room is assumed to be incorporated into the gob, but the setup-room access drift could be fully or partially open. Stoppings installed to isolate the setup-room access drift from the surrounding bleeder entries could be partially or fully damaged by the caving of the gob. In the mine shown in Figure 2-25, over 14 m<sup>3</sup>/s (30,000 cfm) of combined airflow was measured to be transported by the setup room access and inner bleeder entries. the

stair-step feature shown in Figure 2-25 is a function of mine design not an inherent design of bleeder systems.

The prevalence of large standing support in the tailgate entries at some coal operations can maintain viable airflow paths at the boundary of the tailgate entry and the gateroad pillars, as shown in Figure 2-26 (Zhang, 2012). The existence of a low-resistance pathway at the tailgate corner that extends hundreds of meters into the caved material would alter airflow pathways within the caved material of either bleeder or bleederless systems. The question becomes whether or not these tailgate entries are partially open or closed and what would their impact be on the effectiveness of a bleeder or a bleederless system with respects to longwall tailgate corner ventilation. The maintained openings allow longwall face airflow to leave the tailgate corner and enter the middle tailgate entry at the first inby crosscut. This causes a sweeping airflow pathway that keeps contaminants from behind the shields away from the tailgate corner.

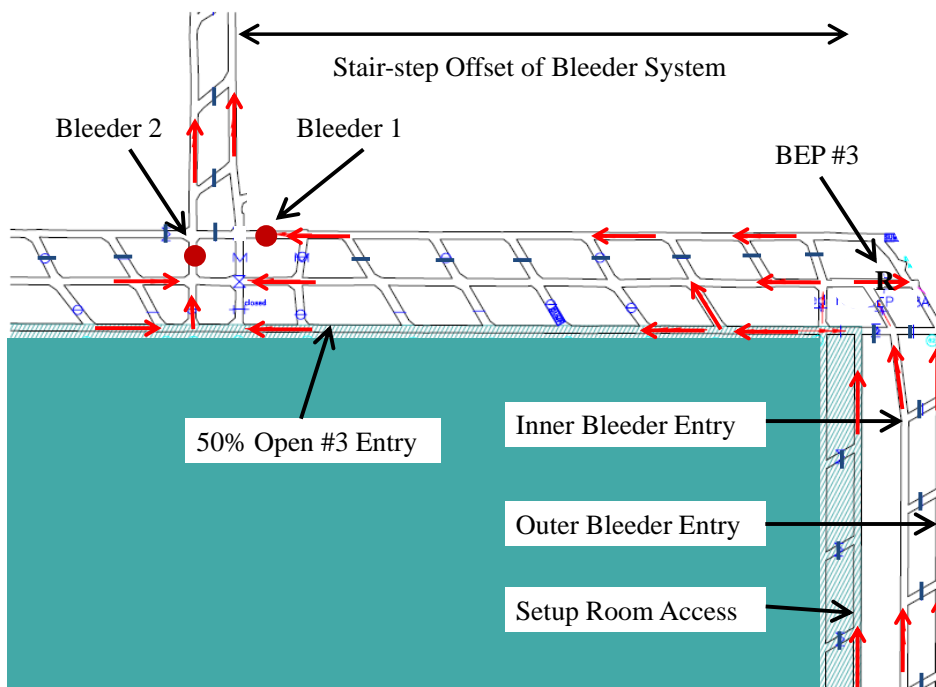


Figure 2-25. Possible open entries surrounding the gob in a bleeder system (Krog et al., 2014).



Figure 2-26. Pumpable cribs in tailgate entry inby the longwall face, looking inby showing a low resistance ventilation pathway into the gob (Zhang, 2012).

#### 2.4.2 Modeling using tracer gas

Since access to areas near the caved material is difficult due to unstable ground conditions, direct airflow and quality measurements at these locations are typically not safe or practical. Therefore, researchers have looked to indirect measurement techniques to determine the conditions in the inaccessible regions on longwall panels. Sulfur hexafluoride ( $\text{SF}_6$ ), a good ventilation tracer gas, has been previously used by the mining industry to determine airflow paths in inaccessible regions of mines. Thimons and Kissell (1974), Timko and Thimons (1982), and Vinson and Kissell (1989) introduced practical protocols for the use of tracer gas to aid in research at coal mines. Mucho et al. (2000) extended in mine work to show the communication between non-active gob vent boreholes and the underground working, with communication taking anywhere from one day to over a month. Schatzel et al. (2011) and Krog et al. (2011) used the tracer gas to help define airflow pathways and retention times in the inaccessible locations of an active longwall district. Xu et al. (2012) also used tracer gas to validate a simplified CFD model of a longwall panel, which simulated different ground falls blocking the airflow pathways (see Figure 2-27).

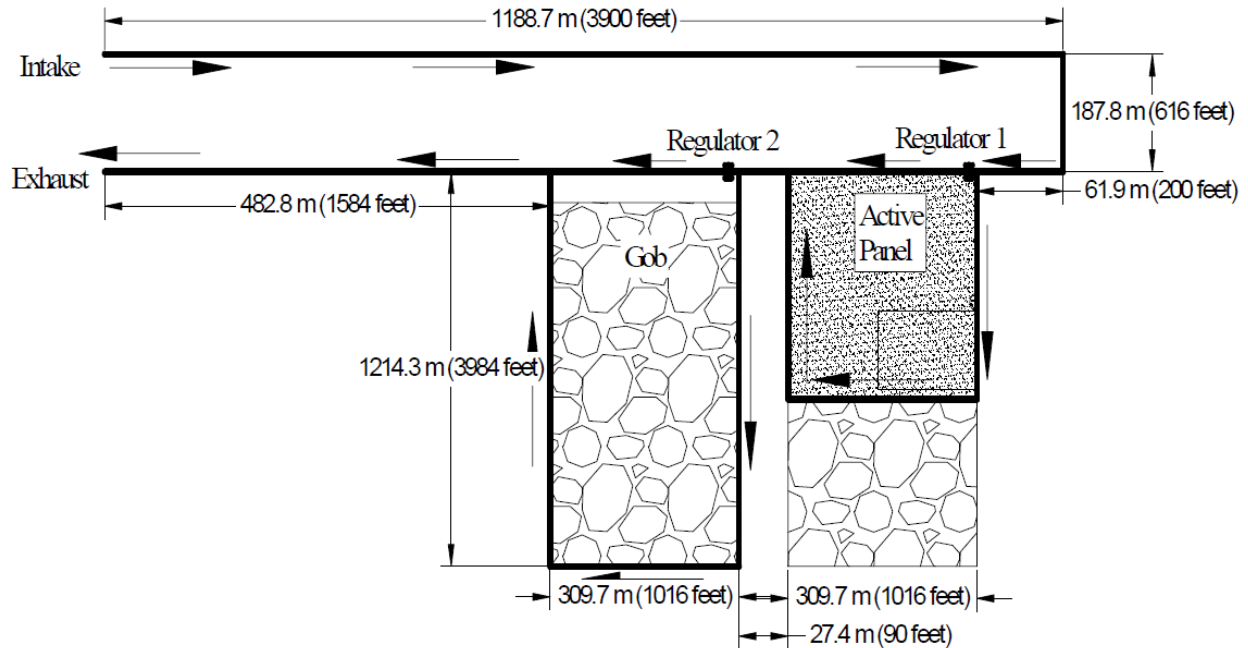


Figure 2-27. Ventilation layout used by Xu et al., (2012) for CFD and tracer gas releases. (Note the size is still less than one-tenth of the required needed to model a modern longwall district).

Non-destructive testing of mine seals using tracer gas was proposed by Brashear et al., (2014). Besides the normal first arrival and peak concentration of tracer gas to determine airflow velocity, the determination of the total volume of recovered tracer gas at each sample location can give considerable insight into any mixing and dilution occurring in the inaccessible locations. With the use of mass balances of methane, oxygen and tracer gas, any possible zones of explosive methane can be determined (Krog et al., 2014).

Tracer gas is still a reliable method for tracking airflow pathways in inaccessible location of underground coal mines when a known amount of tracer gas is released. Also mine operators are more amenable to tracer gas testing than to direct methane testing because of the legal implications of taking a high methane reading anywhere within the mine main or bleeder ventilation systems.

### 2.4.3 Boundary conditions

A bleederless ventilation model utilizing a “U” system can have as few as two boundary conditions one entry of intake and one entry of exhaust (Figure 2-5) and if this is a static system, then intake matches exhaust (Ren, 1997). Because of limited computing power the first CFD papers by Ren used this simplifying assumption to get workable results. Single inlet and single outlet boundary conditions are common in small-scale CFD models. Methane gas can be

injected at one or multiple locations, but this does not change the simplicity of the model design. Previous work by Ren and Balusu (2009) utilized the same two boundary conditions (single intake and single exhaust) with nitrogen injection. Balusu et al. (2005) modeled the use of a back fan or intake shaft at the startup room of the panel, adding a third boundary condition.

A bleeder system is much more complicated than a simple progressively sealed bleederless panel utilizing a 'U' ventilation system. The following is a list of possible fresh-air intake locations for a common bleeder longwall district that may need to be represented by boundary conditions in a CFD model (Figure 2-28):

1. Headgate belt entry,
2. headgate track entry,
3. headgate dual intake,
4. tailgate intake for secondary escapeway,
5. intake evaluation point (IEP) for all previous gateroads, and
6. tailgate entry of first panel in district,

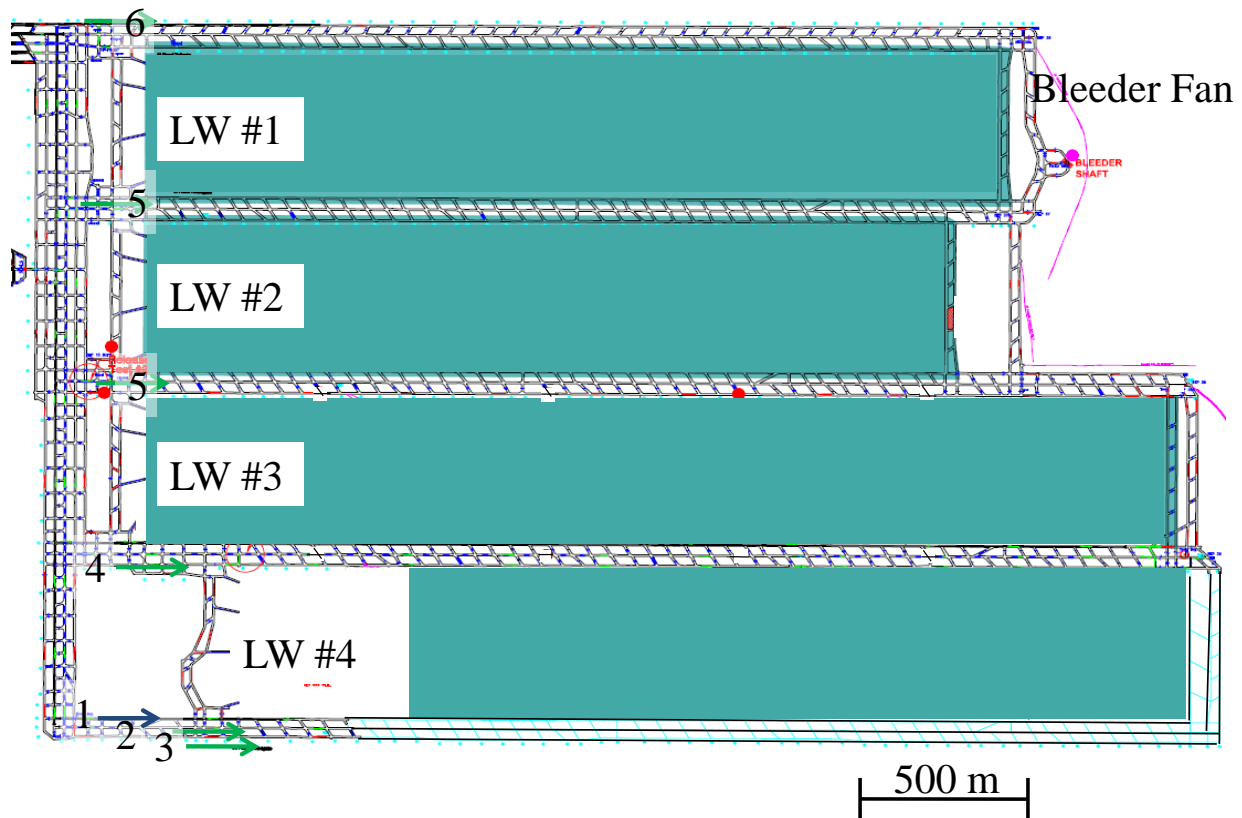


Figure 2-28. Possible intake locations in a longwall district requiring boundary conditions, (numbers refer to text above).



The boundary conditions for the exhaust entries are also quite numerous for each ventilation district. Depending on how the model is developed the following locations could all be exhausting boundary conditions as show in Figure 2-29:

1. Headgate belt entry outby to regulator at mouth of the section,
2. head gates entries inby longwall face towards back bleeders,
3. tailgate entry outby to main mine fans,
4. tailgate entry out by to internal bleeder system via the recovery room access drifts,
5. tailgate entry inby to back bleeders,
6. return air in the main's dumped into the number one tailgate panel,
7. return air to main fan, and
8. return to bleeder fan,

The possible zones within the caved material for the highest methane productions are shown in Figure 2-29 below and represent the newest caved material just behind the retreating longwall face and along the side of the gob with the undisturbed coal and strata which represent the largest reservoir of methane closest to the active panel. Note that the zones of highest methane production do not infer the highest methane concentrations within the caved material.

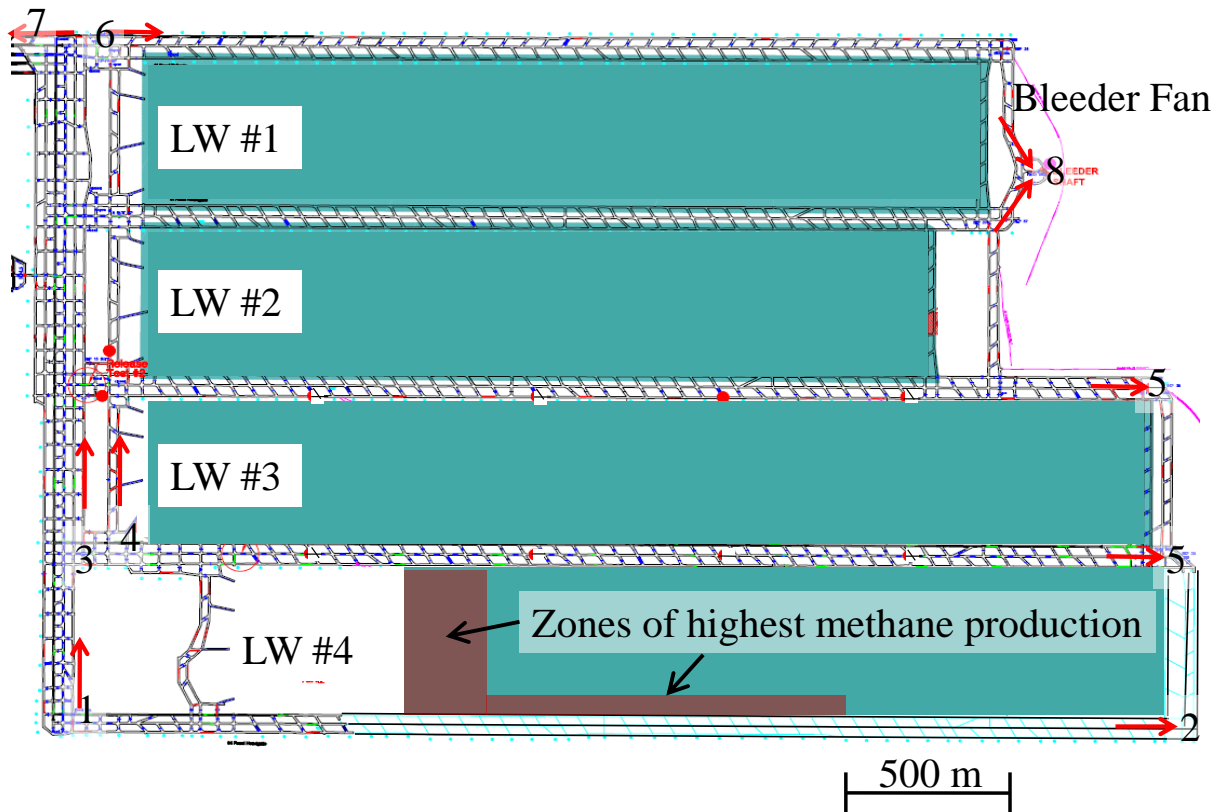


Figure 2-29. Possible exhaust locations in a longwall district requiring boundary conditions. (Numbers refer to the text above). Zones of likely highest methane production.

The difficulty with accurately measuring the multiple boundary conditions required to model a CFD of a longwall district is hard enough, but also given that these boundary conditions would alter with changes to atmospheric pressure make calibration of these model problematic. What is required is better monitoring of the boundary condition locations (e.g. BEP or bleeder fan) to help calibrate possible CFD models of bleeder ventilation systems.

#### 2.4.4 CFD small scale and large scale models

CFD models can be categorized into two groups: 1) Small auxiliary ventilation models and 2) large-scale system-wide ventilation models. Auxiliary ventilations refers to: ventilation of continuous miners, roadheaders, LHDs, dust levels, methane around miner, DPM of trucks, single entry intersection or fan ducts (Silvester et al., 2002; Kollipara et al., 2012; Figure 2-30; Sasmito et al., 2012; Figure 2-31) and are important to general mining ventilation practices. While these models have been quite useful for engineering purposes, they are less than 1% of the physical size required to model a typical modern-longwall panel with dimensions of 370 m x 3,400 m (1,200 x 11,000 ft). Full-scale 3D CFD models of modern sized longwall panels would

be limited by the economic availability of sufficient computing power. Xu et al. (2012) modeled a simplified single-shortened longwall panel with single entries, which is still one-tenth the size of a typical longwall panel in 2012. To properly model the asymmetric nature of a multi-panel district bleeder system, as shown in Figure 2-6, the model size (over 10 million cells) would be prohibitively difficult for small-scale computer cluster.

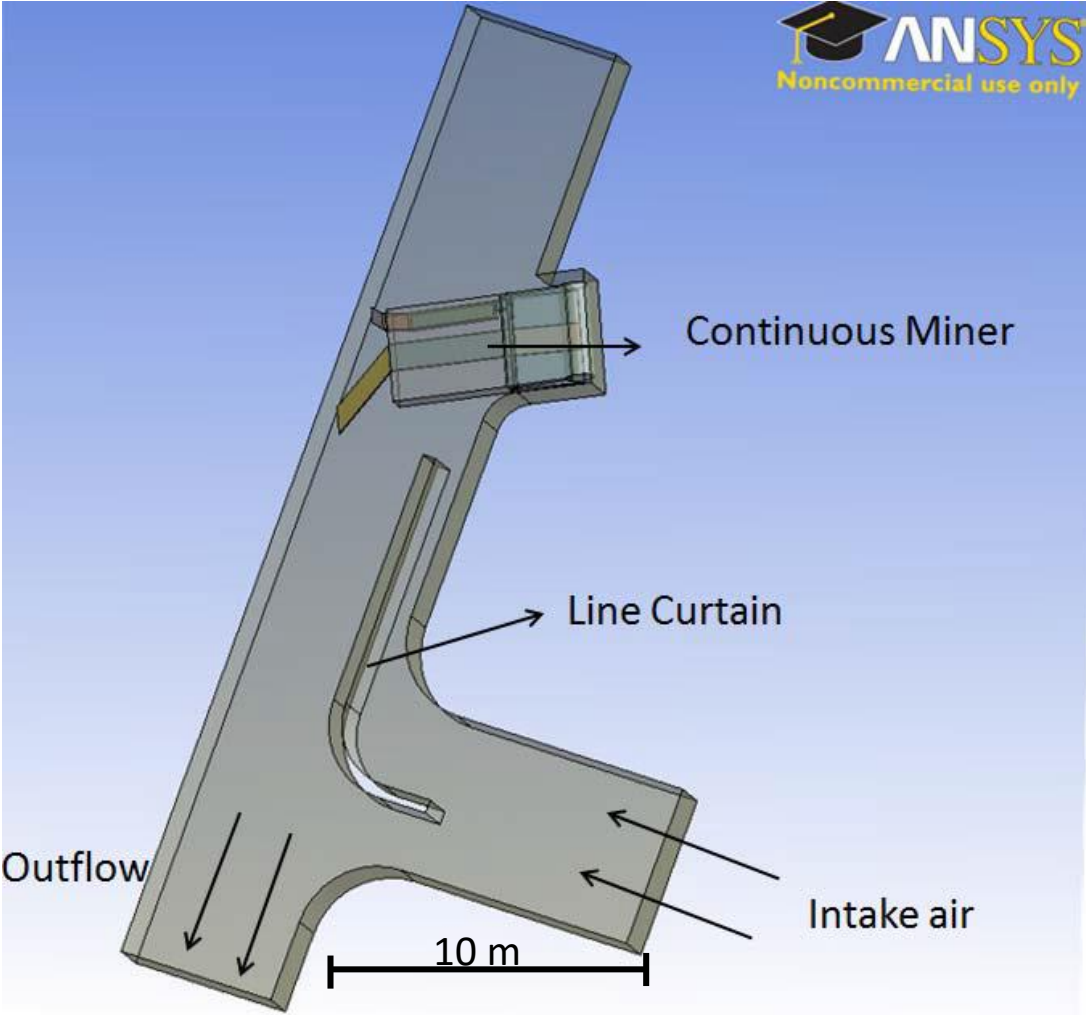


Figure 2-30. Small scale CFD model of a continuous miner, (Kollipara et al., 2012).

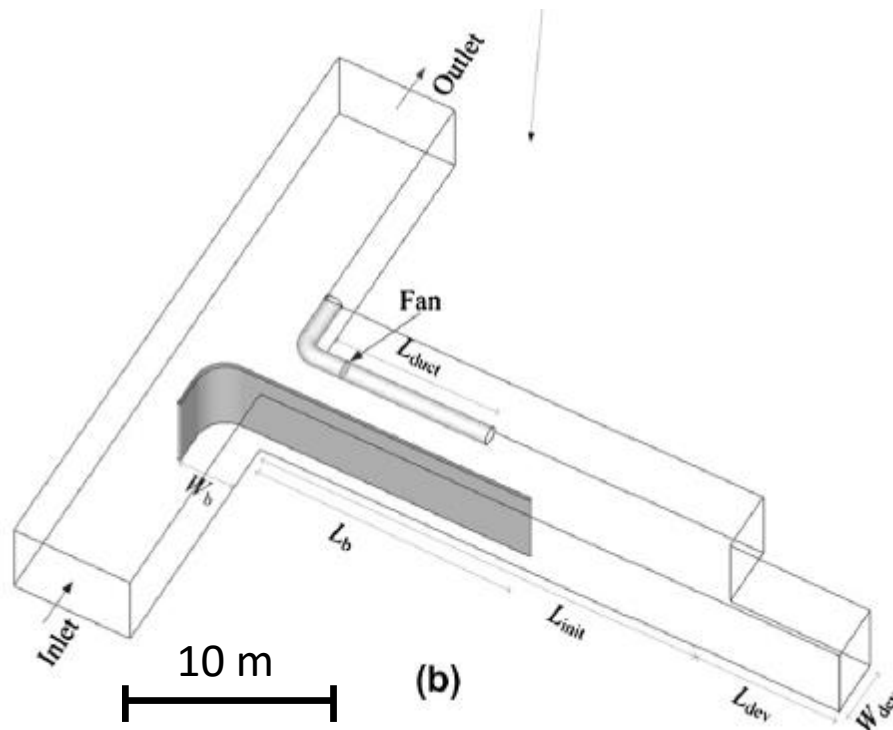


Figure 2-31. Ventilation of small scale crosscut using brattice and exhausting fan (Sasmito et al., 2012).

With increasing computer power being more available to researchers each year modeling of longwall panels will soon be able to handle a full scale panel and then eventually a longwall district utilizing a bleeder system. When that happens the conditions of the regulators/stoppings located within the inner entries of the bleeder system will have the most effect as to the airflow distribution within the bleeder system.

#### 2.4.4.1 CFD model for bleederless only systems

CFD models of longwalls represent mostly bleederless (progressively sealed) ventilation systems (Yuan, 2006; Ren, 2009; Marts et al., 2013) The reason for this is twofold: 1) bleederless systems are the most common system used in the rest of the world (Ren, 2009) and 2) the bleederless CFD model is simple in design enabling large-scale models to be created that have few boundary conditions that interact to the atmosphere (Figure 2-32).

The limitation of modeling a longwall ventilation system using CFD is model size (meshing) so single progressively sealed panels are modeled. Accuracy limitation of CFD modeling of bleeder ventilation systems is boundary conditions.

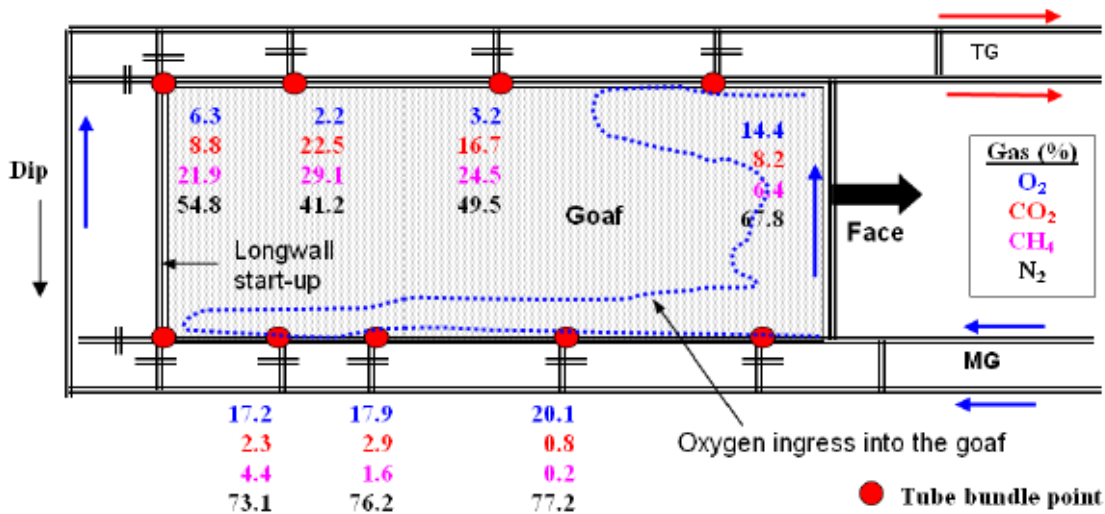


Figure 2-32. Bleederless CFD model of longwall gobs (Australian) showing oxygen ingress into the gob which is representative of the majority of the longwall ventilations in the world (Ren, 2009).

CFD modeling has been primarily used to investigate the chances of spontaneous combustion (oxygen concentration) by determine gas concentrations in the gob as a result of the injection of inert gasses along the headgate side of the longwall panel (see Figure 2-33).

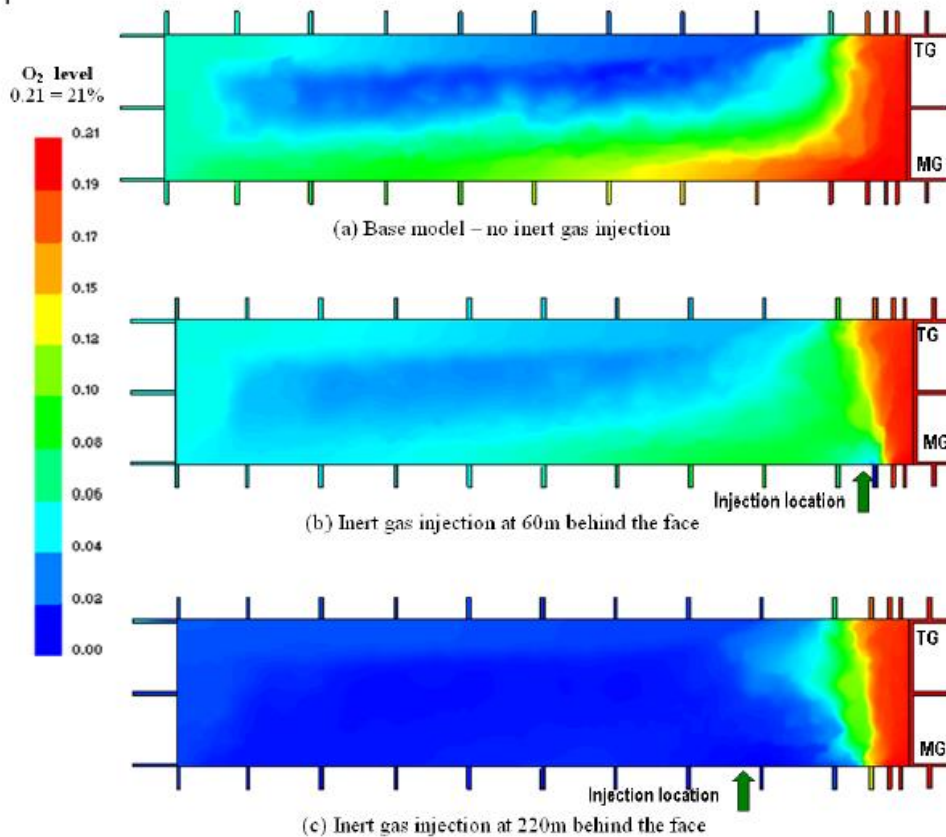


Figure 2-33. Inertization locations on a bleederless ventilation gob (Ren, 2009).

CFD modeling has progressed to the level where coal-seam inclination and major discontinuities are being modeled and compared with field experiments (Balusu, 2002) (Figure 2-34). The international research community has a great desire to be able to predict if any explosive methane mixture exists throughout any parts of the sealed gobs. Papers have been also published dealing with the ventilation issues of short-term sealing of longwall panels and with the proper techniques to minimize any potential explosive hazard during shield recovery (Balusu, 2002) (Figure 2-35); (Ren and Balusu, 2009) (Figure 2-36); (Marts et al., 2013) (Figure 2-37).

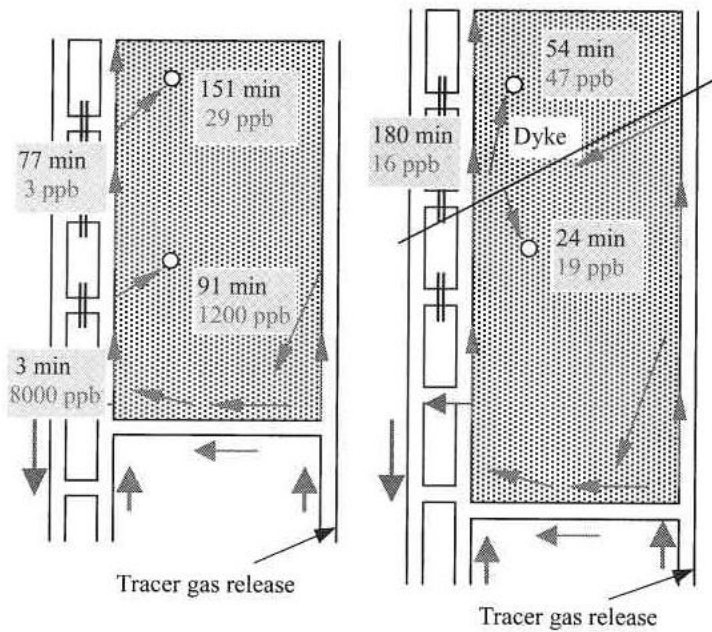


Figure 2-34. Gob flow with discontinuities (dyke) (Balusu, 2002).

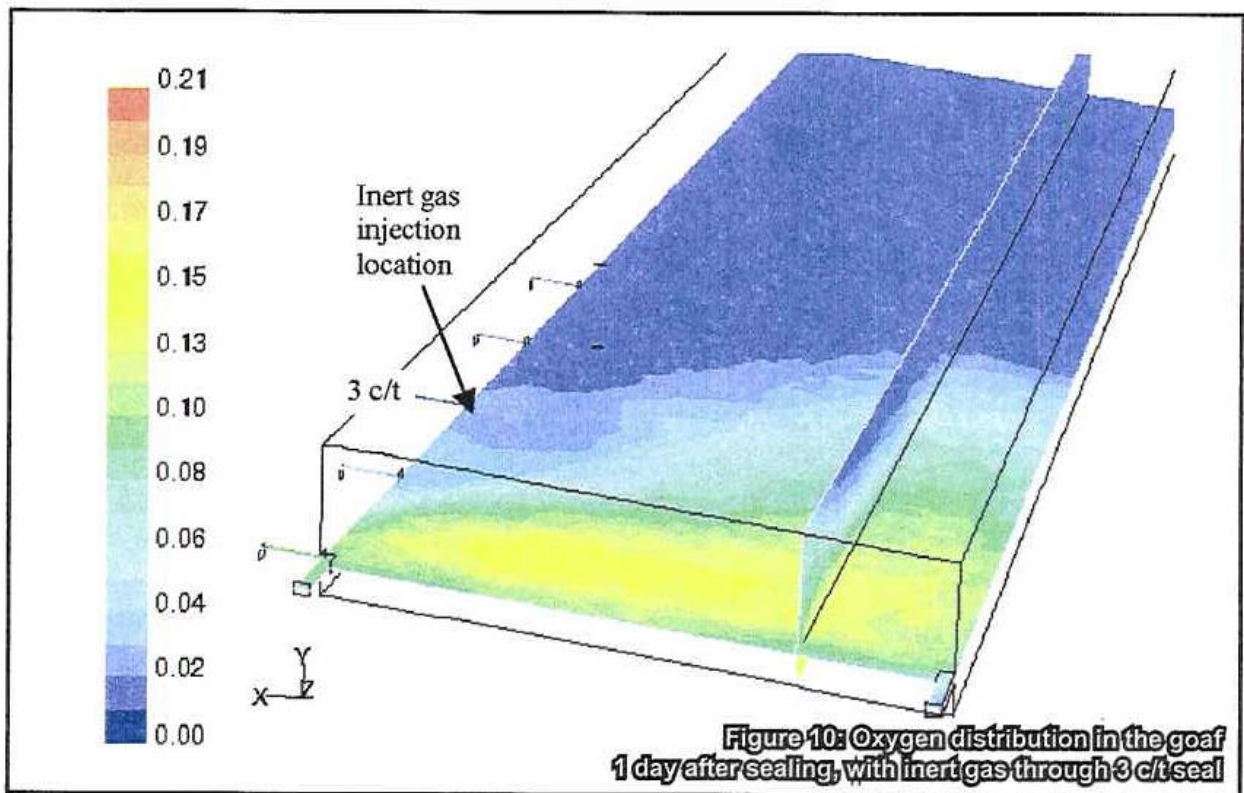


Figure 2-35. Injection strategies for panel sealing (Ren and Balusu, 2009).

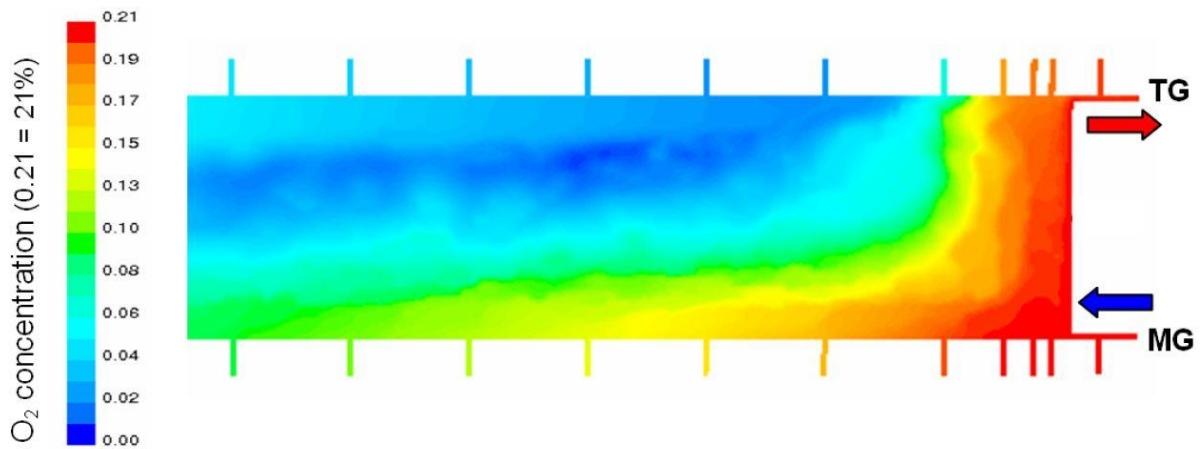


Figure 2-36. Low flow zones with lower oxygen in a bleederless system (Ren, et al., 2009).

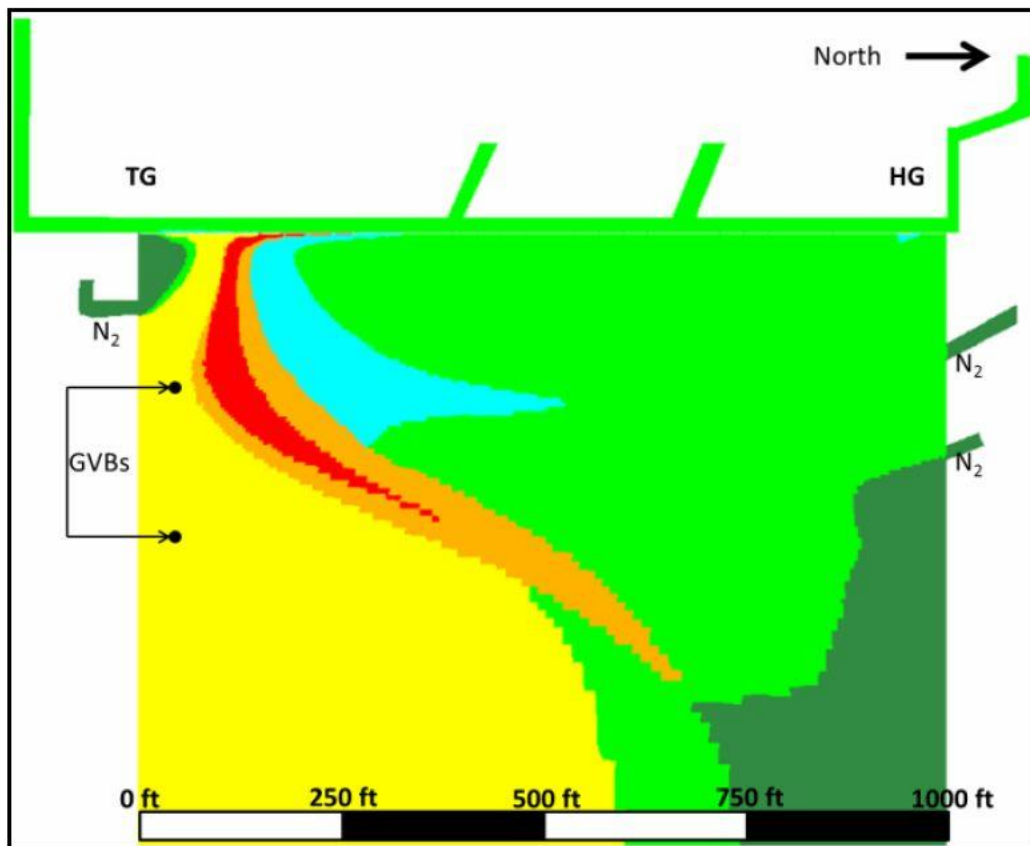


Figure 2-37. Nitrogen injection with explosive regions shown with a bleeder system (Marts et al., 2013).

Marts et al., 2013, describe a bleederless longwalls with nitrogen injection just inby both the head and tailgate corners is a great representation of the likely explosive zone at a bleederless



system. This was based off a static ventilation model of a single longwall panel. A multiple panel longwall district would be over 8 times larger in size and with over 50 stoppings with unknown leakage across both setup and recovery rooms.

Full scale CFD modeling of a bleeder system is a very complicated task and one that requires multiple field measurement surrounding the longwall district to properly calibrate the model. The tube bundle system operating at Mine A and the tracer gas testing done at Mine B did not have the required extra information to properly calibrate a model because of the mine not wanting compliance sampling to be done.

#### **2.4.5 Ventilation network models**

CFD models have problems with accurate boundary conditions and with accurately simulating the gob. Similarly, wire-frame network models have trouble accurately modeling the gob. Wire-frame network models are used extensively for full-mine ventilation simulation in underground mines. Modeling all known entries in underground mining operations, like a hard-rock mine, results in effective ventilation simulations that are beneficial to mine operators (Hartman et al., 1997). Similar to CFD model, underground coal mines with caved zones that alter traditional open-entry underground mine characteristics are also much harder to simulate with wire-frame. Inaccessible regions of the caved material, as well as the unknown current conditions of ventilation control devices (stoppings, regulators, etc.) within the caving area and bleeder system, make any modeling inherently inaccurate. Prosser and Oswald, (2006) depicted a simplified bleeder network with leakage vectors in a three-panel district using a network model (Figure 2-38). Krog et al. (2011) used a network model to show the possible airflow pathways within the bleeder system and caved material of a partially developed longwall panel (Figure 2-39). Dziurzyński and Wasilewski (2012) created a detailed ventilation network model of a two-panel bleederless district to model methane concentration near the longwall face by varying the longwall face airflow rate (Figure 2-40). The model was a closed system with no changes in atmospheric pressure effecting methane emissions rates from the caved material. What were recorded underground were the dramatic methane concentration fluctuations near the tailgate corner over a one-week period. The results by Dziurzyński and Wasilewski (2012) showed the large horizontal extent of possible explosive mixtures of methane behind the longwall face based on different amounts of longwall face ventilation.

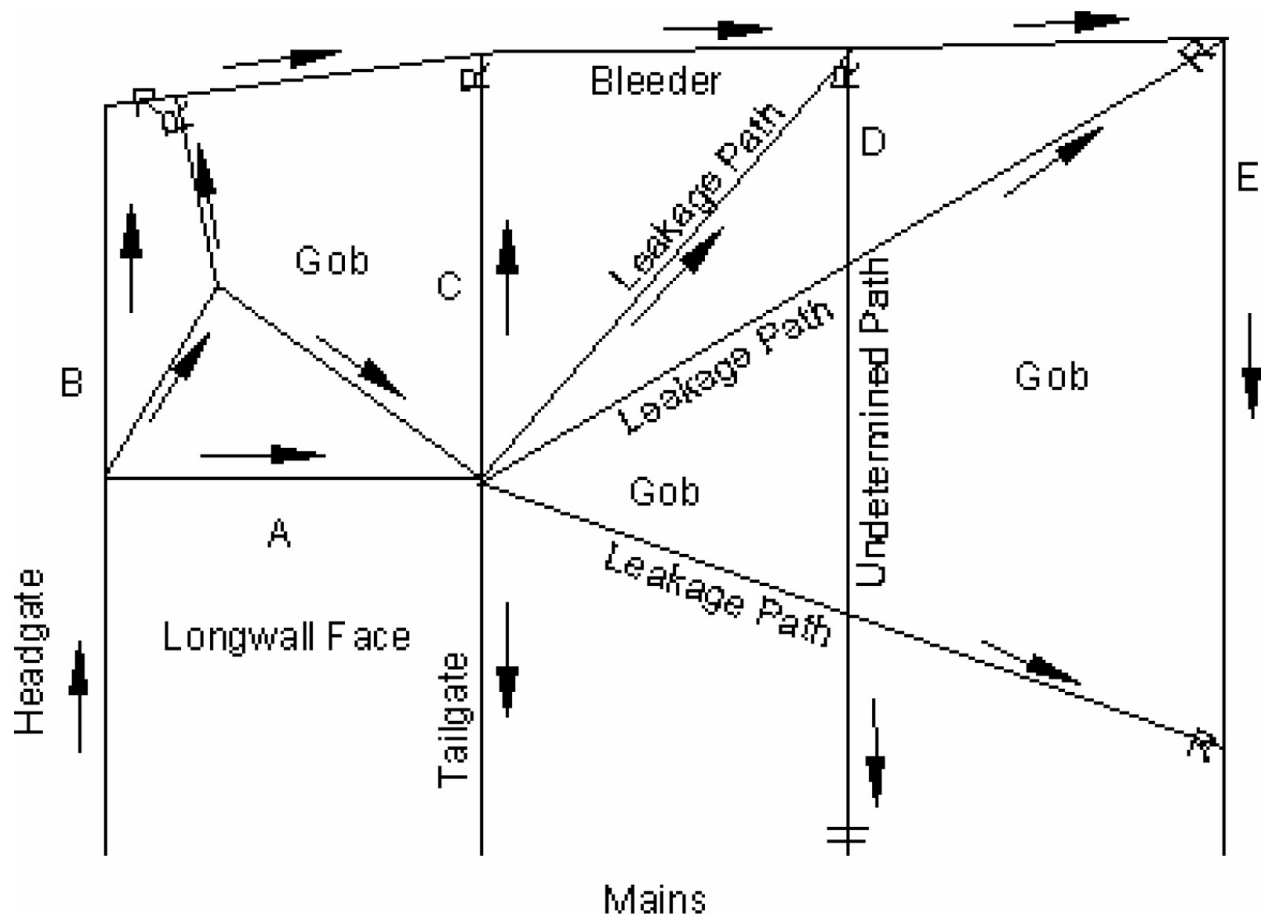


Figure 2-38. Simplified ventilation network model of a bleeder longwall district (Prosser and Oswald, 2006).

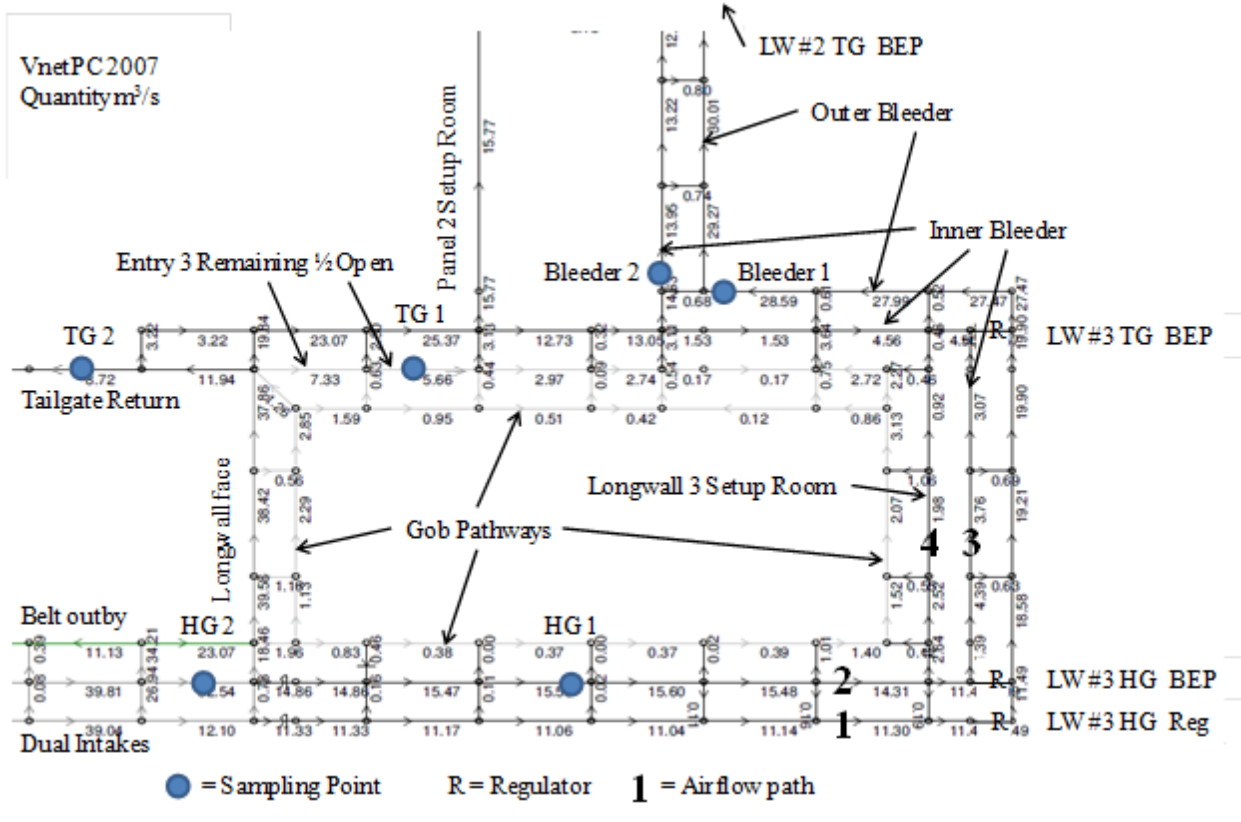


Figure 2-39. Network model showing possible airflow rates ( $m^3/s$ ) of a partial longwall panel (Krog et al., 2011).

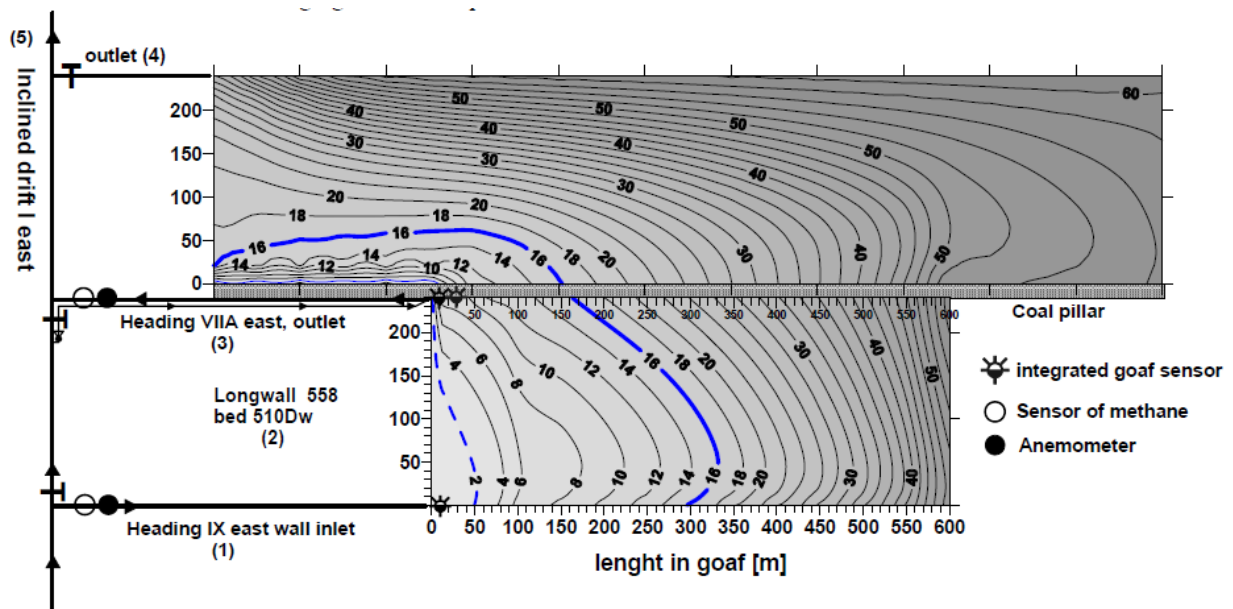


Figure 2-40. Isolines of methane concentrations from a ventilation network model (Dziurzyński and Wasilewski, 2012).

Ventilation network modeling is a logical starting point for the modeling of a mine's ventilation system due to its speed of convergence. However, the main drawback of network modeling is the lack of critical physics (momentum) and the simplification of mixing at all nodes of the network. This approach eliminates modeling the ability of the ventilation system to sweep contaminants away with high flow, but it instead only dilutes them to lower concentrations.

## **2.5 State-of-the-art**

Research investigating the dynamic nature of methane accumulation within the caved material of longwall gob originally had to simplify the problem to achieve workable models and the use of bleederless, progressively sealed, ventilation systems over the more complicated bleeder systems. The modeling of a falling atmospheric pressure drop had shown a possible increase in emissions levels from the caved material (Lolon S. et al. 2015). What was missing was a physical study that emissions directly monitored from the caved material were related to atmospheric pressure changes. This dissertation covers that deficiency in knowledge related to atmospheric pressure changes as well as the sample frequency required to capture these high emission events.

Previous work on bleeder systems primarily used the weekly methane values recorded at the BEPs to calibrate both network and CFD models. What was lacking in the literature reviews was the dramatic effect that the use of clean airflow to sweeten the bleeder system covered up possible high methane emission exiting from the caved material. The practice of multiple airflows pre-mixing in front of the BEPs with the goal of reducing the methane concentration to below statutory limits, made it difficult to get an accurate value of the methane concentration exiting the caved material. This dissertation shows the limitation of knowledge to the possibility of explosive methane concentrations in the middle entries of the bleeder systems being covered up by premixing.

### 3 Experimental Design

Bleeder ventilation systems are required to remove contaminants from the working face and to maintain methane concentrations at safe levels throughout the caved material and surrounding entries. The removal of other contaminants, such as dust, diesel particulate matter, and smoke from the active face, is simple to verify with equipment and personally mounted sensors. After the contaminants leave the working faces and enter the return or bleeder system, they generally do not interact with workers and require little further monitoring.

Methane removal within a longwall district is more problematic because any occurrence of explosive mixtures of methane within a bleeder system is a potential hazard. The ability to accurately predict the location and size of explosive mixtures of methane within a bleeder system cannot be determined with just weekly readings at intake evaluation points (IEP) and bleeder evaluation points (BEP). Sample locations within the inaccessible regions of the gob and a higher sampling frequency rate are required to determine the location and size of any potential explosive mixtures of methane.

The experimental design of the research in this dissertation covers two sections: the first section addresses the variation of emission rates for longwall operations. Operators need to know not only the average emission rate for the longwall district but also the variation in the peak emission rates to determine the factor of safety. In this first study, a tube bundle system (TBS) collected underground atmospheric concentrations at various accessible and inaccessible regions of a bleederless ventilation system over a two-year period. The TBS was able to take underground atmospheric measurements about every half hour and relate the emissions back to changes of outside atmospheric pressure. Diurnal and longer duration atmospheric pressure changes both affected the measured emission rates from both the active and sealed gobs.

In the second research section, three field experiments collected tracer gas and underground atmospheric concentrations (methane, oxygen, carbon dioxide) at various accessible and inaccessible regions of a bleeder system over a one-year period. This enabled the determination of airflow pathways and the retention/travel times of these pathways. The tracer gas tests along with traditional ventilation measurements (pressure, flow rate and gas concentration) enabled for the determination of an airflow path's effective cross-sectional areas and resistances. The mapping of parallel pathways and their ratio of airflows, resulted in the ability to calculate possible methane concentration within the inaccessible portions of the bleeder system.

### 3.1 Tube bundle systems

The first section of the experimental design was the installation of a tube bundle system (TBS) at a western United States longwall coal operation (Mine A) that was experiencing possible spontaneous combustion. The mined seam is a Subbituminous B ranked coal that has not undergone the methane production stage of coalification. Rather, the coal has solely produced carbon dioxide as a retained gas.

Carbon dioxide is readily dissolved and transported by groundwater, and this shallow coal seam outcrops within 300 m to the south and west. Therefore, any carbon dioxide emitted during the coalification process has not accumulated in the coal seam or overlying strata. Carbon dioxide emissions are not seam gas related but come from the active oxidation of the mined and overlying coal seams that fall into the caved material. As such, the operation does not have detectable levels of methane in the mine but does have a high propensity for spontaneous combustion.

The mine had developed and mined three panels at the completion of this study, which covered the extraction of the second and third panels (Figure 3-1). At the start of the study, the second panel was being mined, and the slope connection to the surface at the back of panel 3 is on intake airflow. A mine diagram showing the general outline of the exhausting ventilation system during the extraction of the second panel is also shown in Figure 3-2. All three panels have the same width of 380 m (1,250 ft), but the first and second panels have shorter lengths of 4,900 m (16,000 ft) and 6,700 m (22,000 ft). The third panel's dimensions are close to the maximum found in the United States and are listed below:

- Width: 380 m (1,250 ft)
- Length: 7,160 m (23,500 ft)
- Cutting height: 3-4 m (10-13 ft) depending on coal thickness and proximity of rider seam
- Surface acreage: 2.73 km<sup>2</sup> (674 acres)
- Run-of-mine coal near 11 million tonne (12 million tons) for a single panel

Gateroads were developed with three entries on 67-m (220 ft) centers for crosscuts, with equal-sized pillars. The overburden thickness varied greatly from 60 to 260 m (200 to 850 ft) with the shallowest depths experienced at the setup up and recovery rooms for each panel. The shallow depth and complete fracturing to the surface causes the creation of air pathways from both the setup and recovery rooms to the surface. These pathways can bring airflow in or out of the active caved areas of the mine depending on whether an exhausting or blowing ventilation

system is used. A sealed panel with this high permeability fracture connection to surface would have near atmospheric pressure throughout the caved material. The pressure differential across the underground gob isolation stoppings would then become close to the mine's relative atmospheric pressure to surface; in other words, with the exhausting ventilation system the mine had negative pressure across the gob isolation stoppings and air from the sealed panel would tend to leak into the mine's atmosphere.

### **3.1.1 Longwall development and support**

Secondary standing support in the headgate consists of the following: in the first entry a double row of 0.76 m (30") pumpable cribs are installed on 3 m (10-ft) centers; in the middle entry, 10" diameter wooden posts were installed along the ribs and intersections ahead of the initial longwall on 3 m (10-ft) centers or less depending on conditions. During longwall retreat, a single row of 0.76 m (30") pumpable cribs were installed in the middle entry after the power center and shield pumps have been advanced.

The bi-directional cutting longwall utilizes a Joy 7LS5 DDR 2,400 shearer and 1.75-m 1,060-tonne (5.75-ft 1,170-ton) shields. The installed Armored Face Conveyor (AFC) was a 48-mm twin strand inboard chains powered by three 1,230 kW (1,650 hp) motors, two at the headgate and one at the tailgate. Because of the thickness of the coal seam, the shearer's cutting traversing speed has been reduced slightly to limit strain on the outby equipment (crusher, stageloader, and conveyor belts). This mine consistently mined over 1 million tons of raw coal per month during the time of this study covering two panels.

The continuous miners sections that develop the gateroads and mains utilize the Joy 12CM12 miners. A single CM developed the gateroad 7-days a week while a second CM developed the mains on approximately half as many shifts per week. Joy 10SC shuttle cars and Fletcher CHDDR twin boom bolters work with the CM on development.

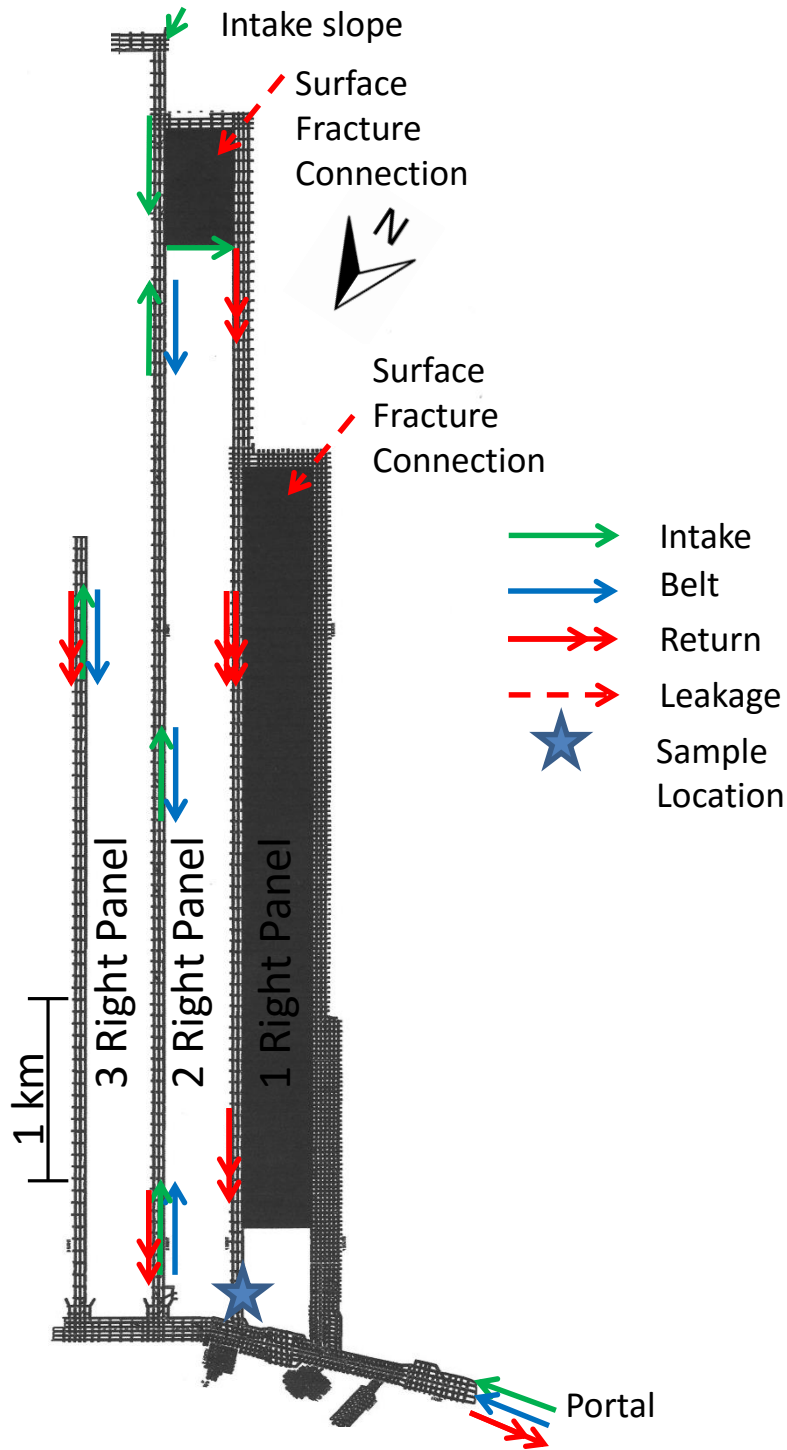


Figure 3-1. Mine layout during the mining of panel 2 showing leakage into panels from surface cracks.

The mine used a modified bleederless ventilation system that progressively sealed the active panel with 'GOB isolation stoppings' which are comprised of two Kennedy stoppings filled with a



lightweight concrete mixture. The thickness of the gob isolation stoppings was a function of the mining height and varied from 1.2 to 2.4 m (4 to 8 ft) thick corresponding to entry heights of 2.1 to 4.2 m (7 to 14 ft). These gob isolation stoppings were not as thick as mainline seals (120-psi) located near the mains to finally seal the panels after extraction. The regulator in the #2 entry of the tailgate entry was a partially completed Kennedy stopping that got completed once the longwall panel retreated past the next intersection in the tailgate, about every 67 m (220 ft). The mine utilized a “back-return” ventilation system at the tailgate that caused some of the longwall face airflow to leave the face at or near the tailgate corner and migrated towards the first inby open crosscut where it was directed into the middle entry (Figure 3-2). The purpose was to keep the low oxygen airflow from within the caved material from reaching the active tailgate corner directly but rather to have the low oxygen air flow to the first inby crosscut. Normally, this system would also have been able to prevent higher methane airflow from reaching the tailgate shearer, but, as previously stated, this operation did not have significant methane. The majority of the longwall face airflow reached the middle entry in the tailgate and traveled down the seal line of the previous panel to the section regulator.

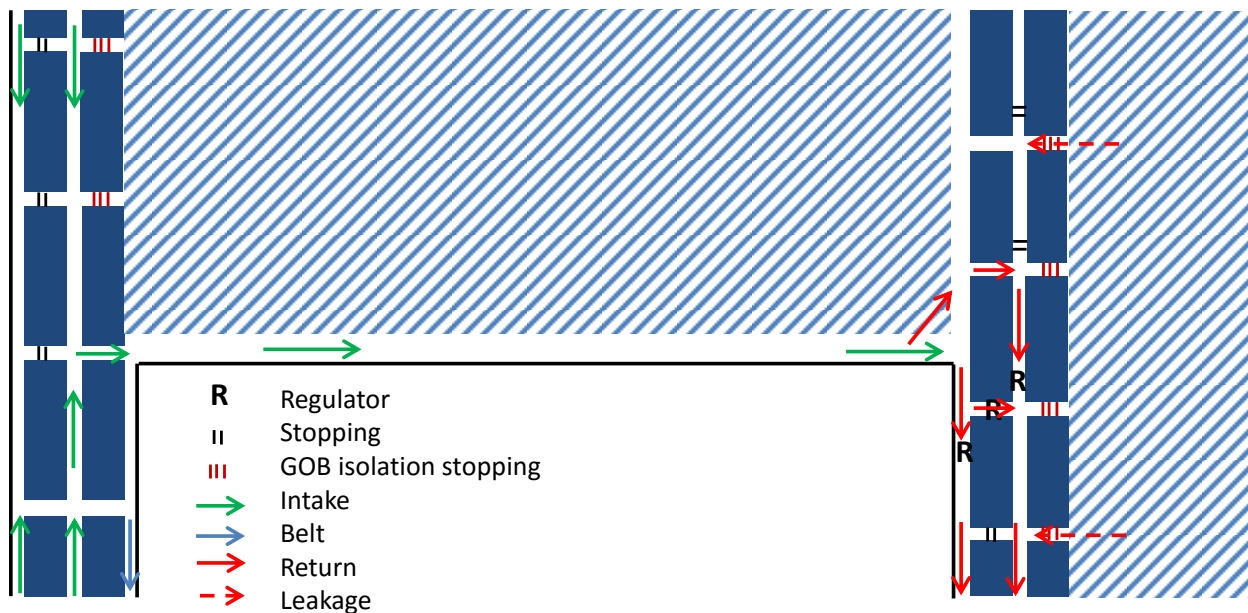


Figure 3-2. Longwall ventilation showing gob isolation stoppings and back return ventilation at the tailgate corner (not to scale).

### 3.1.2 Description of the TBS used at Mine A

A TBS is a monitoring system that continuously draws gas samples from underground locations by the use of pre-installed tubes. The vacuum pumps draw the samples to the surface where

they are analyzed to determine underground atmosphere gas concentrations. The most common gasses tested by a TBS are oxygen, carbon monoxide, carbon dioxide, and methane. The results are recorded and analyzed for trends in the data that could be early indications of problems underground. Increased levels in carbon monoxide could indicate spontaneous combustion occurring, whereas, increases in methane concentrations can be corrected before explosive mixtures accumulate underground. Tube bundle systems are a mature technology with over 50 years of use around the world, most notably Australia (Zipf et al., 2013a). Tube bundle systems are not the primary ventilation monitoring system in an underground coal mine as dictated by regulations, but they are a useful supplement that can be used to verify an inert atmosphere in sealed areas or in the early detection of spontaneous combustion.

Currently in the United States, there are two installed TBS at longwall operations; the first is at BHP-Billiton's San Juan coal mine in New Mexico (Bessinger et al., 2005), while the second is at Signal Peak Energy's, LLC, Bull Mountains No. 1 Mine in Montana (Zipf et al., 2013b). The system described in the following section is the system installed at Mine A (Figure 3-3).



Figure 3-3. TBS trailer showing three large purge pumps (front), smaller sample pump (back), calibration cylinders for analyzer.

The installed system consisted of up to 16 sample tube lines which had an outside diameter (OD) of 16 mm (5/8") with an inside diameter (ID) of 13 mm (1/2"). The longest installed tube line was over 7,900 m (26,000 ft) in length and the vacuum purge pumps were able to effectively draw samples at this length. The default condition of the sample lines is to be under constant negative pressure by the purge pumps with the suctioned air samples vented to the atmosphere, if not sampled. This default condition ensures that freshest samples are consistently available at the surface trailer. The tube bundle control systems are located on the surface and use programmable-logic-controllers (PLCs) to open and close solenoid valves that divert an individual sample of tube gas from going to the purge pumps. The diverted airflow is instead condition by the removal of dust and moisture before sending it to the gas analyzers.

The Sick Maihak Model S715 gas analyzer can measure gas ranges between 0-25% oxygen, 0-100% methane, 0-30% carbon dioxide and 0-1000 ppm carbon monoxide. The stated accuracy is  $\pm 0.5\%$  of full scale. The analyzer cycle rate is about 90 seconds, so when 20 samples lines are analyzed, each tube is being tested about every half hour. The analyzer also utilizes two background sample locations, one inside the trailer and the other outside the trailer to test ambient atmospheric conditions. The TBS monitors and records other information for each sample, including temperature, sample pump vacuum pressure, and outside barometric pressure.

### **3.1.3 TBS layout during the mining of Panel 2**

The tube lines were initially installed to test the atmospheric conditions of the first two panels during active mining and after being sealed (Zipf et al., 2013b). Most lines were fixed, except for Line 9 and Line 10 which followed the longwall during retreat and were cut and moved after each intersection was passed in the tailgate (Figure 3-4). The most important sample location during mining of the second panel that records changes in emission levels is Line 15 - LW return. The longwall return sample line (Line 15 LW return), while not a regulatory sample location, is important to understanding the variation in emissions from the longwall panel. This location, in the middle entry, is the lowest pressure pathway on the active longwall panel's gateroad and, therefore, the majority of the carbon dioxide will pass through this location. Also, any leakages along the seal line of the previously sealed panel will enter this entry and pass this location. This sample location does not get diluted by mixing with other cleaner airflows, like the main return (Line 8 Main Return). If there is a rise in carbon dioxide emissions from the longwall system, it has to pass by the Longwall return (Line 15 LW return) sample location.

As stated before, the previous sealed #1 panel had a fracture connection to the surface located in the shallow depth of cover at both the setup and the recovery rooms; therefore, the gob is at or near atmospheric pressure. Figure 3-5 shows the diurnal changes in carbon dioxide for the setup room of the first panel which would not occur from a fully sealed gob. Also, the longwall tailgate relative pressure is negative, 0.5 to 0.7 kPa (2 to 3"), to atmosphere and that gob-isolation-stopping's leakage normally flows from the sealed panel into the middle tailgate entry, all insinuating that a connection to surface exists.

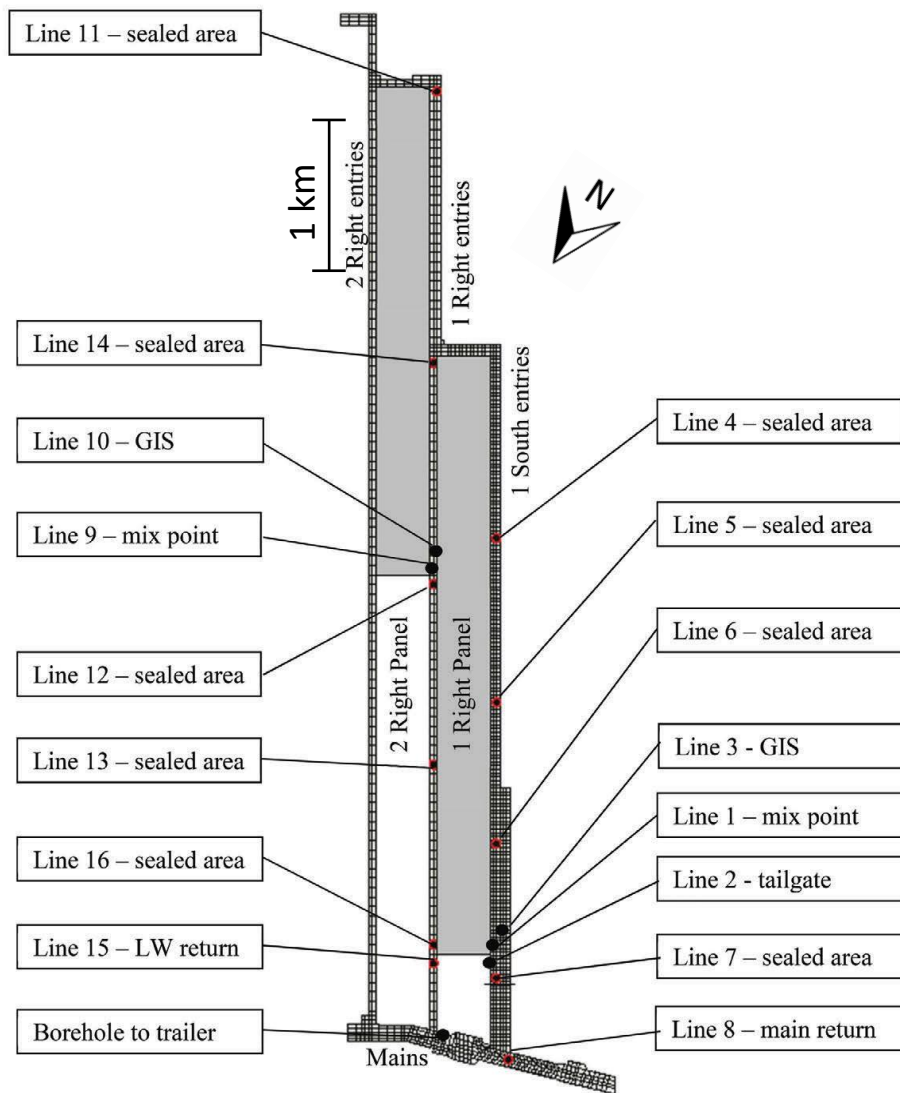


Figure 3-4. Mine layout showing the layout of sample tubes lines installed to monitor the gas composition of the first two panels at about March, 2012 (Modified after Zipf et al., 2013b).

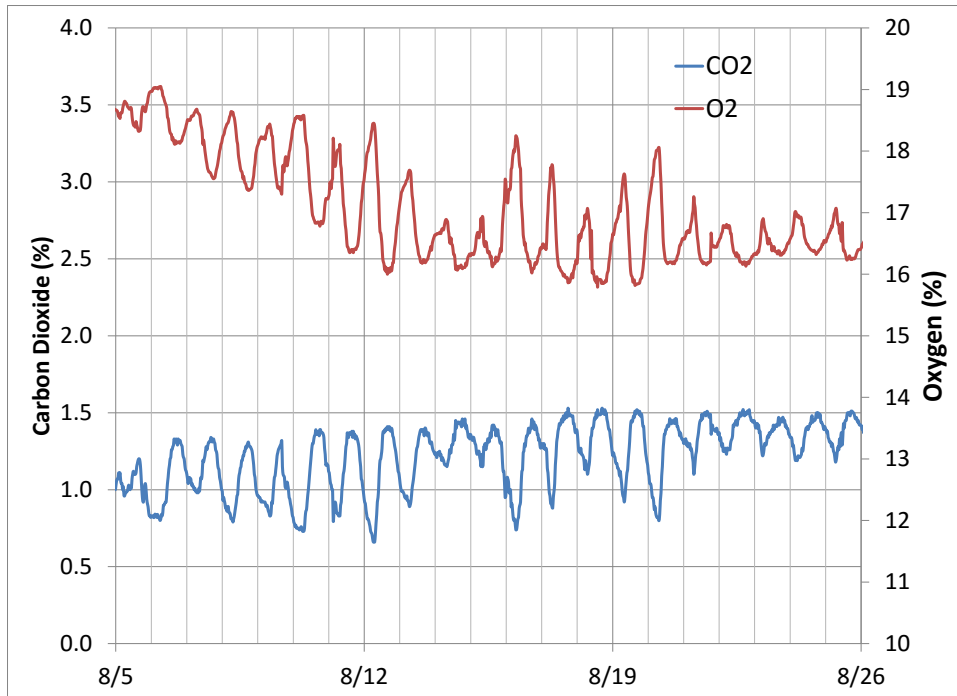


Figure 3-5. Carbon dioxide and oxygen concentrations at the Panel 1 setup room showing diurnal changes because of the fracture connection to the surface.

The ventilation system utilized for panel 2 is a modified bleederless exhausting system with secondary fresh air supplied to the longwall face from the inby headgate entries. The main mine fan was located at the portals and removed all of the mine airflow. The slope installed at the back of the third panel was used as an alternate escapeway using intake airflow (Figure 3-6). The active panel was progressively sealed with the addition of gob isolation stoppings installed at every crosscut between the #2 and #3 entries during longwall extraction. Leakage across the gob isolation stoppings was from the previously sealed panel into the middle entry of the active tailgate, due to the exhausting ventilation system and the atmospheric air leaking into the previous sealed gob. Because the sealed gob had oxygen levels below 2% and carbon dioxide level above 18%, leakage from the gob could seriously affect the air quality in the middle walkable tailgate entry. The first entry is the secondary escapeway and is ventilated with the longwall face airflow and separated from the middle entry with Kennedy stoppings. Leakage is from first entry into the middle entry.

### 3.1.4 TBS layout during the mining of Panel 3

The ventilation system utilized for panel 3 started as a modified bleederless exhausting system. For the first four months of panel extraction, the main mine fan was located at the portals and removed all of the mine airflow, except for the small amount of approximately 21 m<sup>3</sup>/s (45,000

cfm) exhausted by a fan located at the back of panel 3 that maintained airflow around the perimeter of the sealed panel and provided an alternate escape way (Figure 3-6). The slope fan is not a bleeder fan as the airflow is classified as intake air up to the return fan. The active panel was progressively sealed with the addition of gob isolation stoppings installed at every crosscut between the #2 and #3 entries during longwall extraction. The key longwall sampling location had moved to the start of the 2 Right gateroad just outby the Panel 2 recovery room marked as the blue star. Any leakage across the gob isolation stoppings from panel 2 would enter the middle entry of the active longwall tailgate (Figure 3-2).

The ventilation system for the third panel changed after four months of production from an exhausting to a blowing system. A shaft and blowing-fan were installed between the 3 Right and 4 Right gateroads in the mains. Entry doors were placed at the portals and the old exhaust main mine fan was removed. The small exhausting fan at the back of the panel 3 was also disengaged and become an exhaust regulator (Figure 3-7). Since the panel was progressively sealed, the airflow moving around the active panel was considered fresh air.

The dramatic changes of going from an exhausting system to a blowing system had a measureable effect on the air quality at the longwall return sample location. The main ventilation in the mine was now at a higher pressure than the sealed panels, so airflow leakage would now be from the tailgate entry into the sealed area (Figure 3-8). Airflow direction at the headgate entries remained the same but now the installation of a temporary regulator to maintain the correct pressure balance. There would be little if any carbon dioxide added to the middle entry from the tailgate corner out to the mains. Therefore, the only carbon dioxide that arrived at the main sample location at the 2 Right middle entry would have come from the active longwall panel. The average carbon dioxide concentration would be reduced, but the mine will still be affected by large atmospheric pressure changes that caused the gob to breathe out onto the tailgate corner of the open gob.

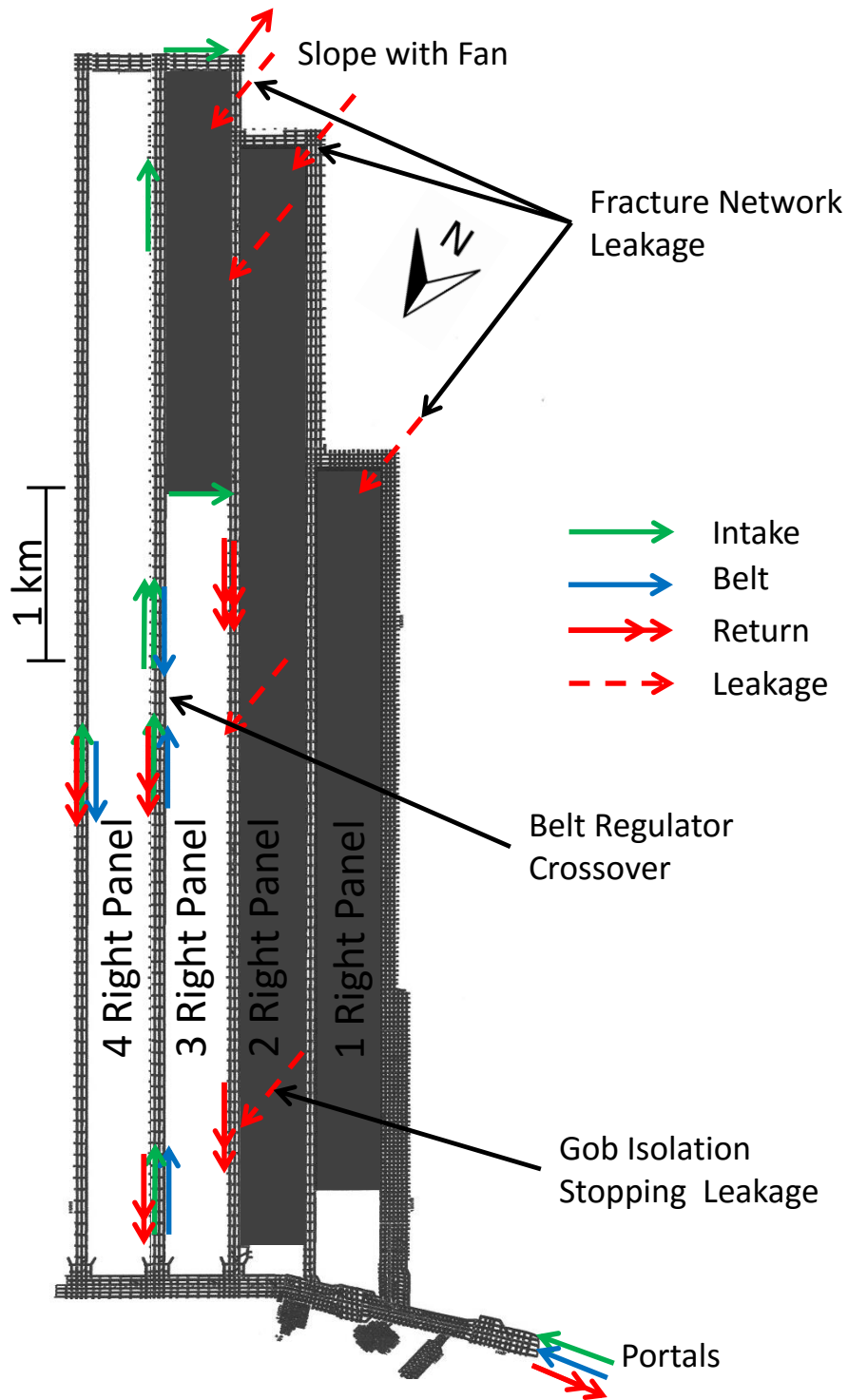


Figure 3-6. Exhausting ventilation layout during the initial mining of Panel 3 with small exhaust fan located at the back of the panel.



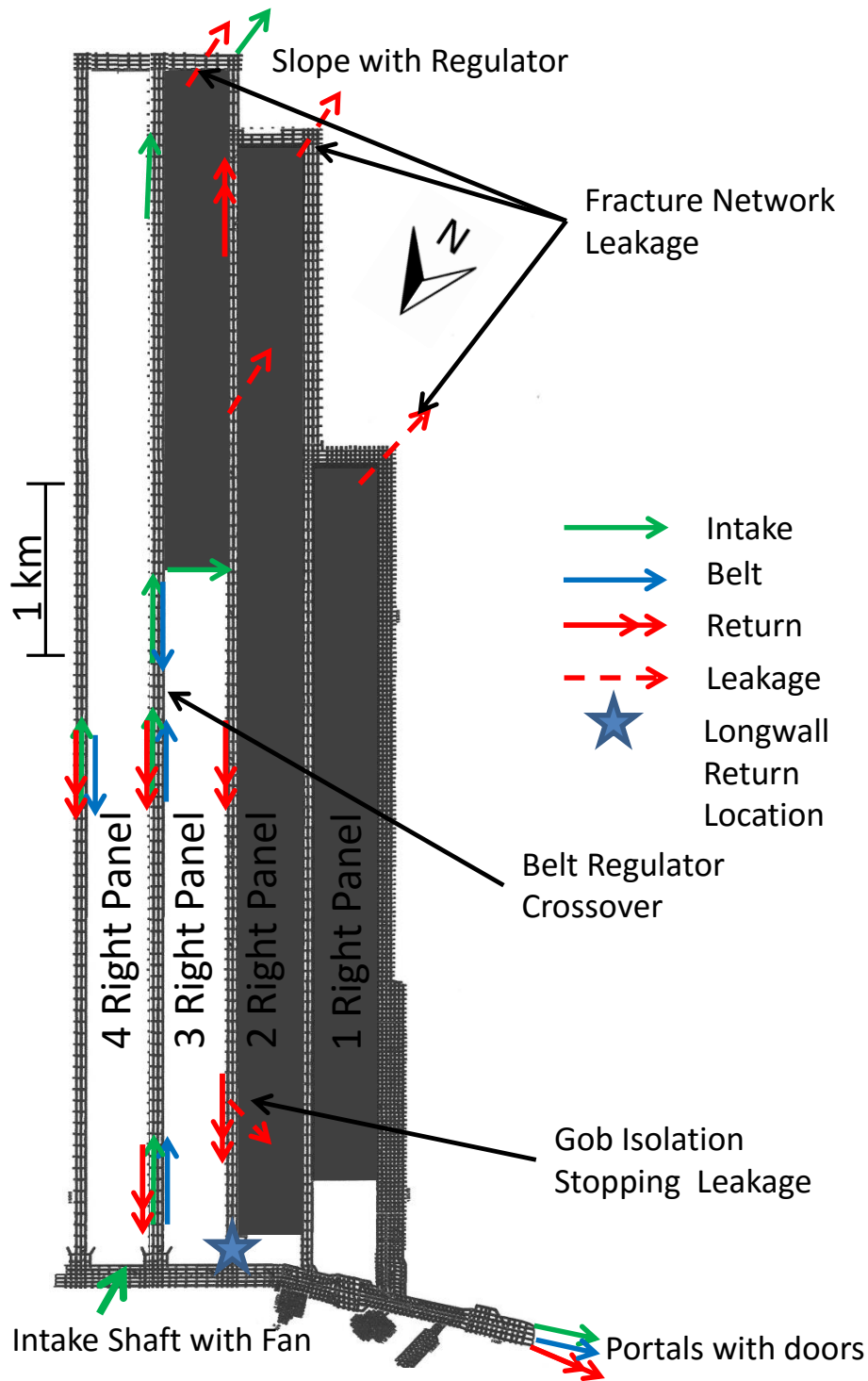


Figure 3-7. Blowing ventilation system of Panel 3 after the installation of an intake shaft and fan (May 27, 2013).

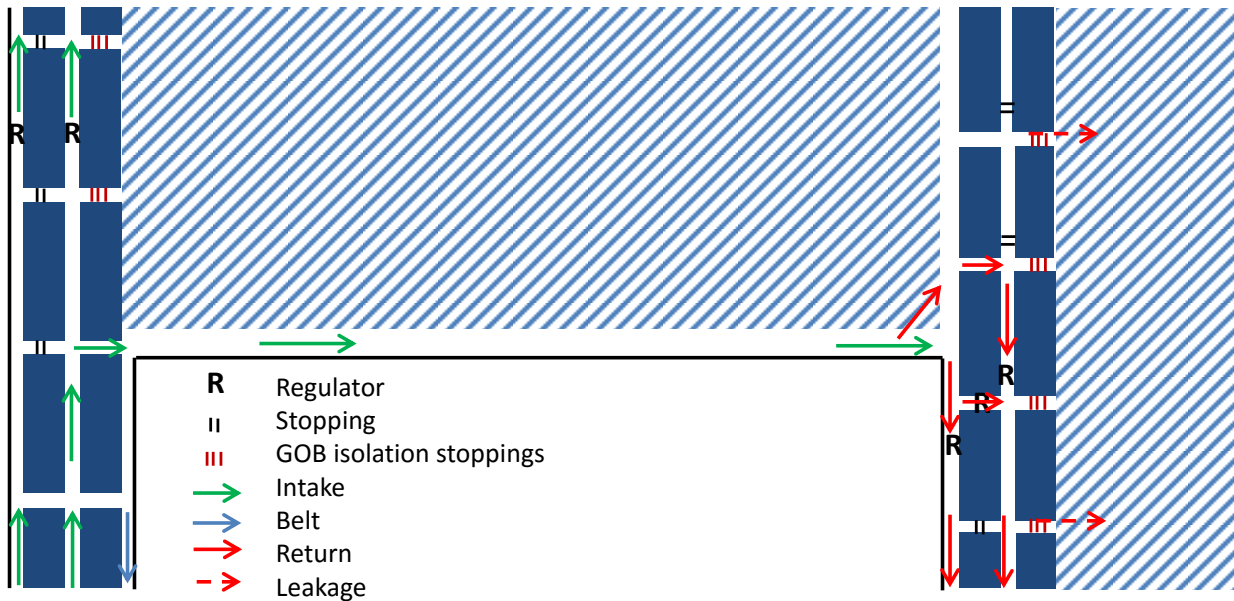


Figure 3-8. Ventilation layout at the longwall face after blowing fan installed. Back return at tailgate shown (not to scale).

### 3.2 Tracer gas study of a bleeder ventilation system

The second part of the field experiment was a series of three tests using tracer gas and hydrocarbon gas analysis to determine the airflow pathways in the inaccessible parts of a longwall district. The fact that methane is produced by the longwall system is not in doubt; however, it is unclear which airflow pathways in the gob are used and the methane concentrations of the air, as it travels to the bleeder fan and out of the mine.

The underground coal mining operation where the three tracer gas studies were conducted had a single longwall operating in the Pittsburgh #8 seam in southwestern Pennsylvania. This mine which will be referenced as Mine B. The four-panel district (see Figure 3-9) was developed using a typical three-entry gateroad system with overburden depths ranging from 240 to 300 m (800 to 1,000 ft). This longwall district had the interesting feature of being bounded on all four sides by previously mined longwall panels. The Eastern and Southern ends had flooded longwall panels that limited methane inflow but increased water inflow from the east (back bleeder sections). The North and West directions were bounded by previous longwall districts of Mine B.

The four longwall panel's widths were all 410 m (1,350 ft), but lengths varied from 2,100 to 2,650 m (6,900 to 8,700 ft) with all four startup rooms offset from each other (Figure 3-9). The first three recovery rooms were in line with each other while the fourth panel was cut short

because of surface subsidence constraints (Figure 3-10). This caused the back bleeders to have a stair-step offset design that is covered in more detail in the results and discussion section.

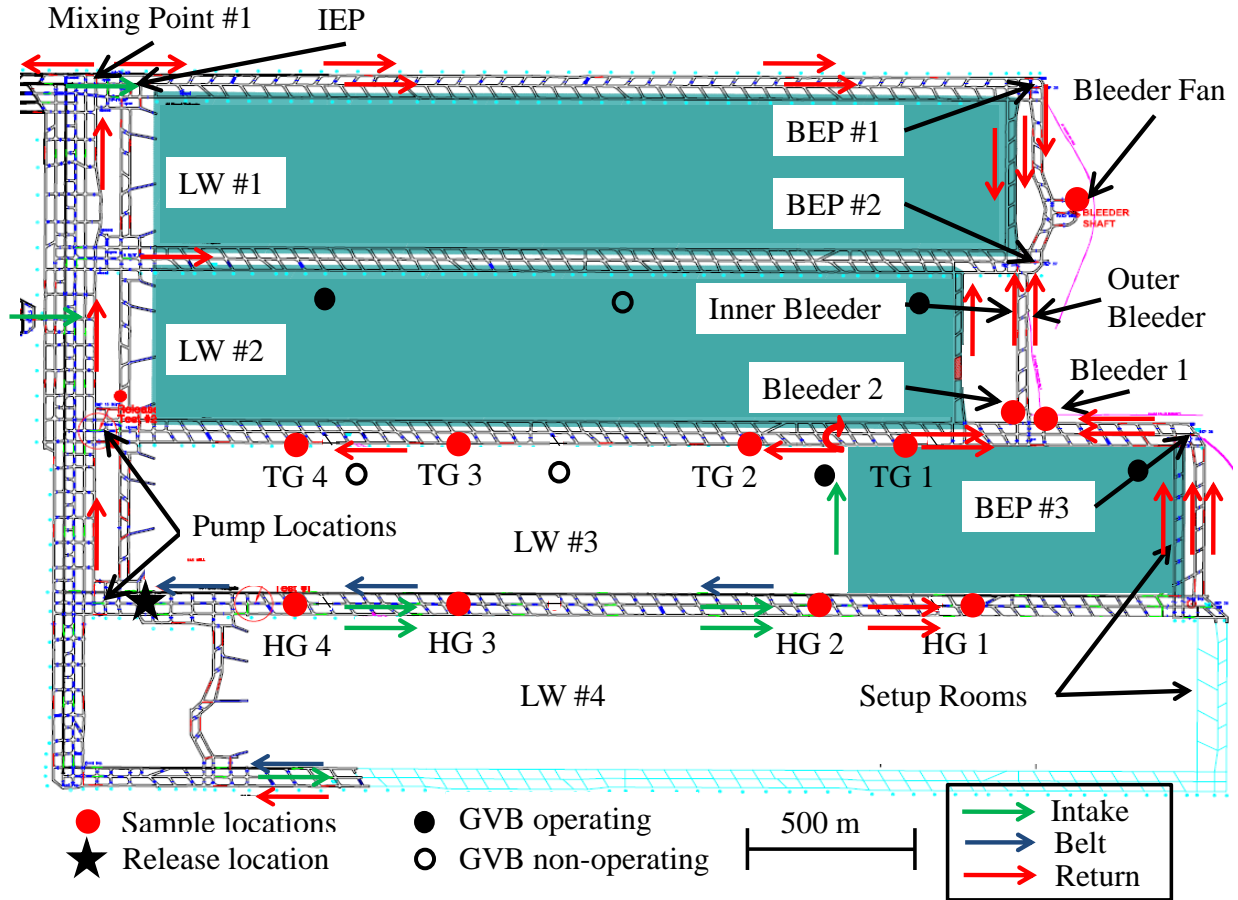


Figure 3-9. Mine B district layout for Test 1 with sample tube placements shown and operating GVBs.

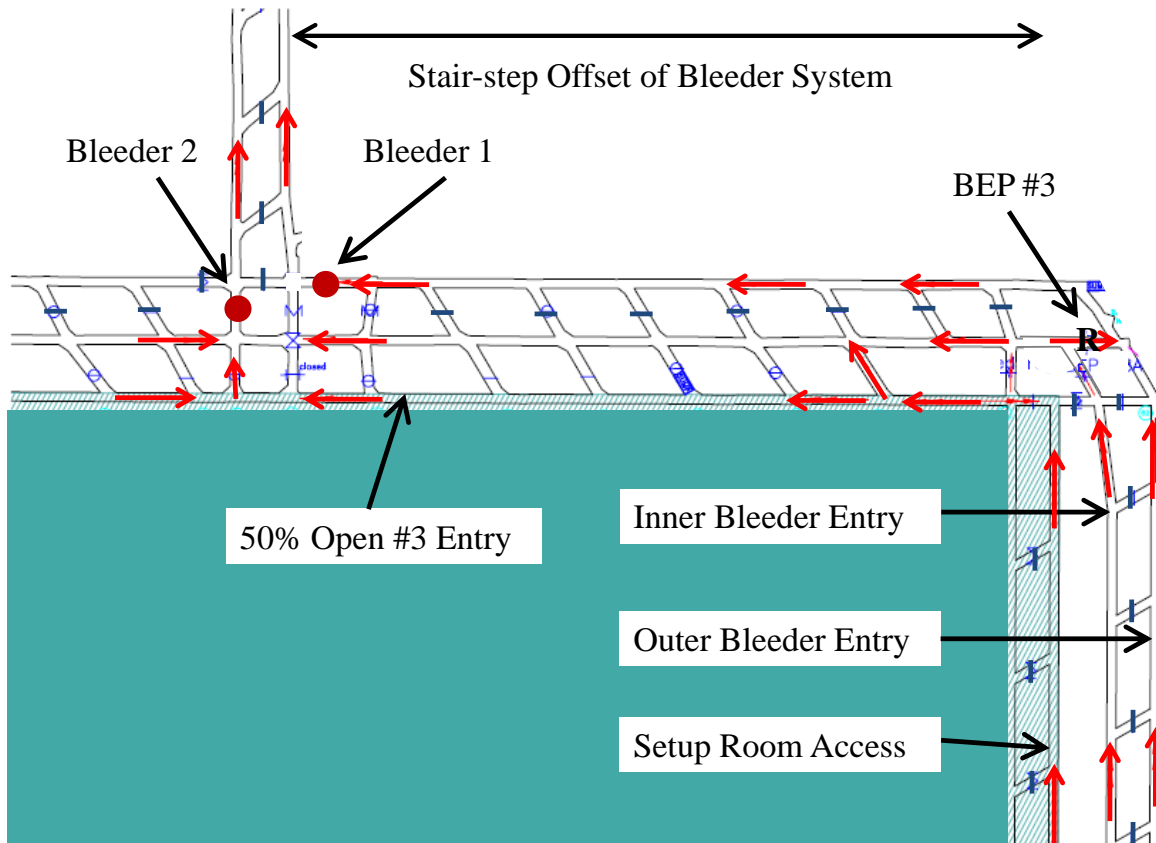


Figure 3-10. Close-up of Longwall Panel #3 tailgate flow direction for Test 1.

The three entry gateroads numbered 1, 2 and 3 (left to right looking inby) housed the belt, track and return entries respectively. All entries were developed by full-face miner bolters developing 4.9m x 2.6m (16' x 8.5') entries profiles. The #3 return entries had a double set of 0.76 m (27 inch) pumpable cribs installed on 3.6 m (12 foot) centers for added standing ground support in the tailgate entry (Figure 2-26 photo from Zhang, 2012). The same pumpable cribs were installed in the travelable outer bleeder entry. The parallel inner bleeder did not have the same installed supplementary standing support but remained fully open throughout the three test studies based on visual observation.

The bi-directional cutting longwall utilizes a Joy 7L2A DDR 1,666 shearer and 1.75-m 994-tonne (5.75-ft 1,096-ton) shields. The installed Armored Face Conveyor (AFC) was a 42-mm twin strand inboard (TIB) chains powered by three 1,230 kW (1,650 hp) motors, two at the headgate and one at the tailgate.

Sulfur hexafluoride ( $\text{SF}_6$ ) was selected as the tracer gas for use in this study because it is a colorless, odorless, non-reactive, inorganic compound with a detection limit at less than 1 part per billion (ppb). Samples from the underground sampling were analyzed using the NIOSH 6602 (NIOSH, 1994) method and a gas chromatograph with an electron capture detector for the ability to measure Sulfur hexafluoride. A portable gas chromatograph was used to measure some samples collected at the surface locations (bleeder fan and gob vent boreholes) to confirm the presence of the tracer gas in the ventilation system and its interaction with the gob vent borehole drainage system. No tracer gas reported to the active gob vent boreholes during all three tests; however, tracer gas was still detectable at the bleeder fan 8 hours after the release. The gob vent boreholes' high methane concentration and lack of oxygen (below 1%) indicate that mine air was not being pulled towards the gob vent boreholes and; therefore, it is reasonable that no tracer gas was detected. This was consistent for all three tests.

The mine utilized a bleeder design with parallel entries but separate airflow paths that have been labeled the travelable outer bleeder (lowest pressure) and the parallel inner bleeder (Figure 3-9 and Figure 3-10). The inner bleeder entries brought airflow from the headgate gateroads across the back of LW #3 (via the inner bleeder entry and the longwall setup room access entry) up to Bleeder 2 location and then into the outer bleeder entry at BEP #2. Both bleeder sample locations were situated approximately 365 m (1,200 ft) from the start of LW #3. Figure 3-9 shows a schematic of the longwall district, ventilation system, release  $\text{SF}_6$  location, sample pumps, sampling tube locations, Mixing Point #1 (MP #1), Intake Evaluation Point (IEP), and Bleeder Evaluation Points (BEP #). The Mixing Point #1 regulator was located in entry 1 of the tailgate for LW #1, which was partially open and delivered main return airflow into the outer entry of the bleeder system. The five-entry mains are shown in the top left of the figure as well as bleeder shaft converted to an intake shaft.

The installed bleeder system design created multiple layers of parallel bleeder airflow across the back side of the longwall panels. The system is all considered to be part of the same bleeder split of air, but each entry has a different function from a ventilation engineering perspective. Because of the use of parallel but separated entries across the back side of the longwall panels, the system can be defined as an inner bleeder system design. The stair-step offset feature of the back bleeders is shown in both Figure 3-9 and Figure 3-10.

### 3.2.1 Layout during Test 1 tracer gas release

Three experiments were conducted at Mine B. In Test 1, the active panel was #3, while the panel #4 headgate was being developed (Figure 3-9). Panel 3 was developed as a 2,650-m-long (8,700-ft-long) and 410-m-wide (1,350-ft-wide) block of coal and had retreated 850 m (2,800 ft) from the setup room, just passing the stair-step offset feature between LW #2 and LW #3 where the back bleeders do not align. The longwall district employed a classic bleeder-type ventilation system with a bleeder shaft at the back end of LW #1. Each gateroad was developed with three entries and the entries were numbered 1 to 3, left to right, looking inby.

During the startup of mining panel #3, sampling tubes were installed in the #2 entry of the headgate (HG1, HG2, HG3 and HG4, see Figure 3-9) and the #3 entry of the tailgate (TG1, TG2, TG3, and TG4) to measure the arrival times and quantities of SF<sub>6</sub> during the tests. As the longwall retreated, the tubing lines became situated within the inaccessible regions of the gob area. The #3 entries of the gateroads had double rows of standing supports (pumpable cribs) that maintained the entries about 50% open after the longwall panel was extracted (Figure 3-10). The standing supports (single row of pumpable cribs) in the #2 entries were assumed to maintain the entries open and limit deterioration, while allowing these airways to be the primary transportation pathway for airflow on the tailgate and on the headgate.

Four polyethylene sampling tubes were installed ahead of the retreating longwall face in the #3 entry of the tailgate labeled TG1 through TG4. The sample tubes were hung between the two supports with the support closest to the removed block of coal almost fully collapsing after extraction. Four additional sampling tubes were installed in the #2 entry of the headgate, labeled HG1 through HG4, with all ended at the mouth of the section. Tube locations HG 1 and TG 1 were the longest at 2,290 m and 2,100 m (7,500 ft and 6,900 ft), respectively. HG 2, HG 3, and HG 4 and TG 2, TG 3, and TG 4 were located outby the face at the time of the release, with HG 4 and TG 4 being the shortest at 460 m (1,500 ft). The sample tubes were 1.3-cm (0.5-in) OD polyethylene tubing, 1.0-cm (0.375-in) ID, each attached to an intrinsically safe, MSHA-approved, permissible SKC Airchek Samplers 224-44XRM vacuum pump (Figure 3-11). The two sample pump locations for both the headgate and tailgate, were located near the sub mains (Figure 3-9) and were in fresh air. All samples were collected in 15-ml glass vacutainers which had been previously re-evacuated because the original manufacturer's evacuation was not complete. A summary of the sample tube locations, sample volumes, and transit times of samples in each of the tubes is shown in Table 3-1, as well as in previous papers by Schatzel et al. (2011) and Krog et al. (2011). Pump flow rates and tubing volumes were calibrated in the lab

together before the tests by measuring the transit time of methane slugs in known length of tubing at different flow rates. The calculated transit times shown were rounded to the nearest minute based on the significant figures of the pump flow rate and to match the SF<sub>6</sub> sampling frequency. All other sample locations were collected at in-mine locations and therefore have no transit time through tubes.

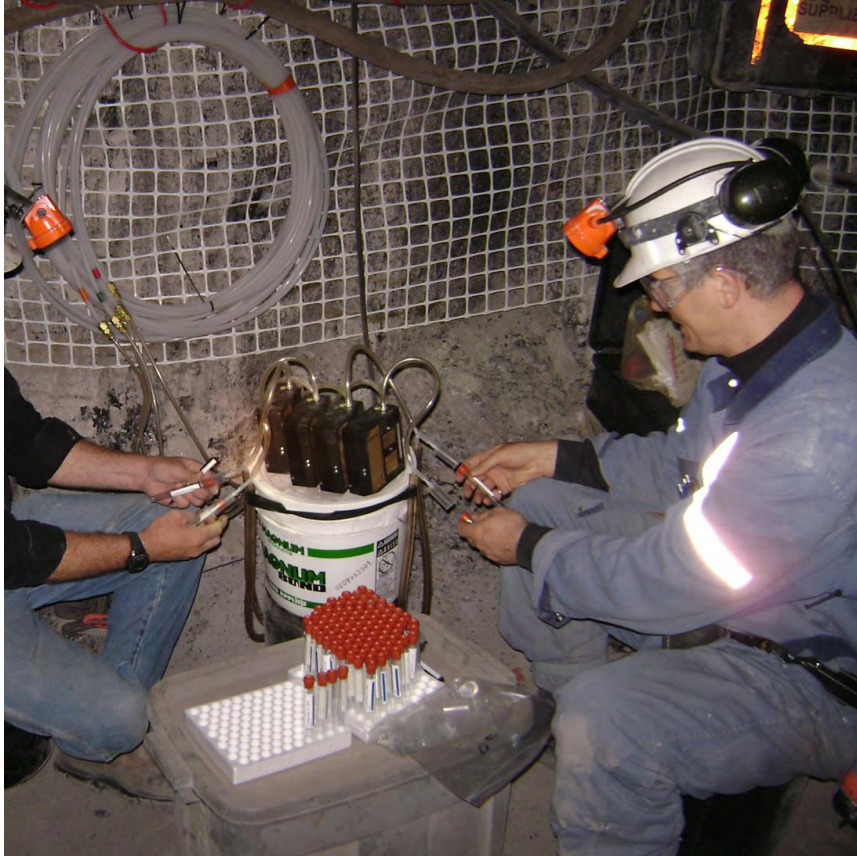


Figure 3-11. Underground sample pump location (4 pumps and sample tubes coiled on rib) with 15 mL vacutainers with syringes on the positive outlet side of the sample pumps.

Table 3-1. Initial tube length, volume, and calculated transit times in the tubes for Test 1

Location	Length m (ft)	Pump rate L/min (ft <sup>3</sup> /min)	Volume L (ft <sup>3</sup> )	Transit time minutes
<b>Headgate</b>				
HG1	2290 (7500)	3.1 (0.12)	190 (6.8)	63
HG2	1830 (6000)	3.7 (0.13)	160 (5.5)	42
HG3	920 (3000)	4.2 (0.15)	77 (2.7)	19
HG4	460 (1500)	4.9 (0.17)	38 (1.4)	8
<b>Tailgate</b>				
TG1	2100 (6900)	3.3 (0.12)	180 (6.3)	55
TG2	1650 (5400)	3.3 (0.12)	140 (4.9)	42
TG3	920 (3000)	3.5 (0.12)	77 (2.7)	22
TG4	460 (1500)	4.3 (0.15)	39 (1.4)	9

For the first test, 149 L (5.27 ft<sup>3</sup>) of SF<sub>6</sub> at standard temperature and pressure conditions (STP) of 101 kPa and 16°C (14.7 psia, 60°F) was released over a three-minute time period. This relatively high concentration of SF<sub>6</sub> was released into the main ventilation air stream (~9,000 ppb on a volume basis) to achieve a measurable concentration over the large longwall bleeder area. All of the fresh air (90 m<sup>3</sup>/s -191,000 cfm) supplied to the longwall headgate section entered through a single entry at the mouth of the section (shown as “release location” in Figure 3-9). The intake air traveled down a single entry for over 120 m (400 ft) before splitting between the #2 and #3 intake entries within the next two open crosscuts. Next, the #2 and #3 intakes were separated by a stopping line for 1,540 m (5,060 ft) up until the longwall headgate corner. The #3 headgate entry outby the longwall face (normally a return entry on development) was used as a secondary intake during panel extraction. The tracer gas was released in the single intake at the release location, and mixing was assumed to be complete before the intake air split into the isolated #2 and #3 entries.

### 3.2.2 Layout during Test 2 tracer gas release

At the start of Test 2, the longwall had progressed about 1,250 m (4,100 ft) from Test #1 as shown in Figure 3-12. For this second test, the release location was not changed. The volume of SF<sub>6</sub> released was 68.8 L STP (2.43 ft<sup>3</sup>). Mixing Point #1 shown near the LW #1 tailgate introduced SF<sub>6</sub> from the main return into the bleeder system. Belt air from the LW #3 headgate and the LW #3 return air passing sample location TG 4 were both transported by the main return out to Mixing Point #1 (Figure 3-12), where a portion of the return air entered the bleeder system in LW #1 tailgate. This fast moving airstream reached the bleeder fan before airflow



reached the Bleeder 1 or 2 sampling locations. The headgate gateroad development for LW #4 had not yet been connected to the back bleeder system during Test 2. During extraction of the LW #3 panel between Test 1 and Test 2, the headgate and tailgate sample tube lines were damaged. The two longer sample tube lines in the headgate (HG 2A and HG 1A) were cut to a length of 1,280 m (4,200 ft), while the previous longest sample tube line in the tailgate was cut to 920 m (3,000 ft). A description of the sample tube locations, sample volumes, and transit times to the collection point for tracer test 2 are shown in Table 3-2. (Arrival times of the tracer gas, corrected for sample tube transportation times at all the sampling locations, are shown in Figure 3-12.)

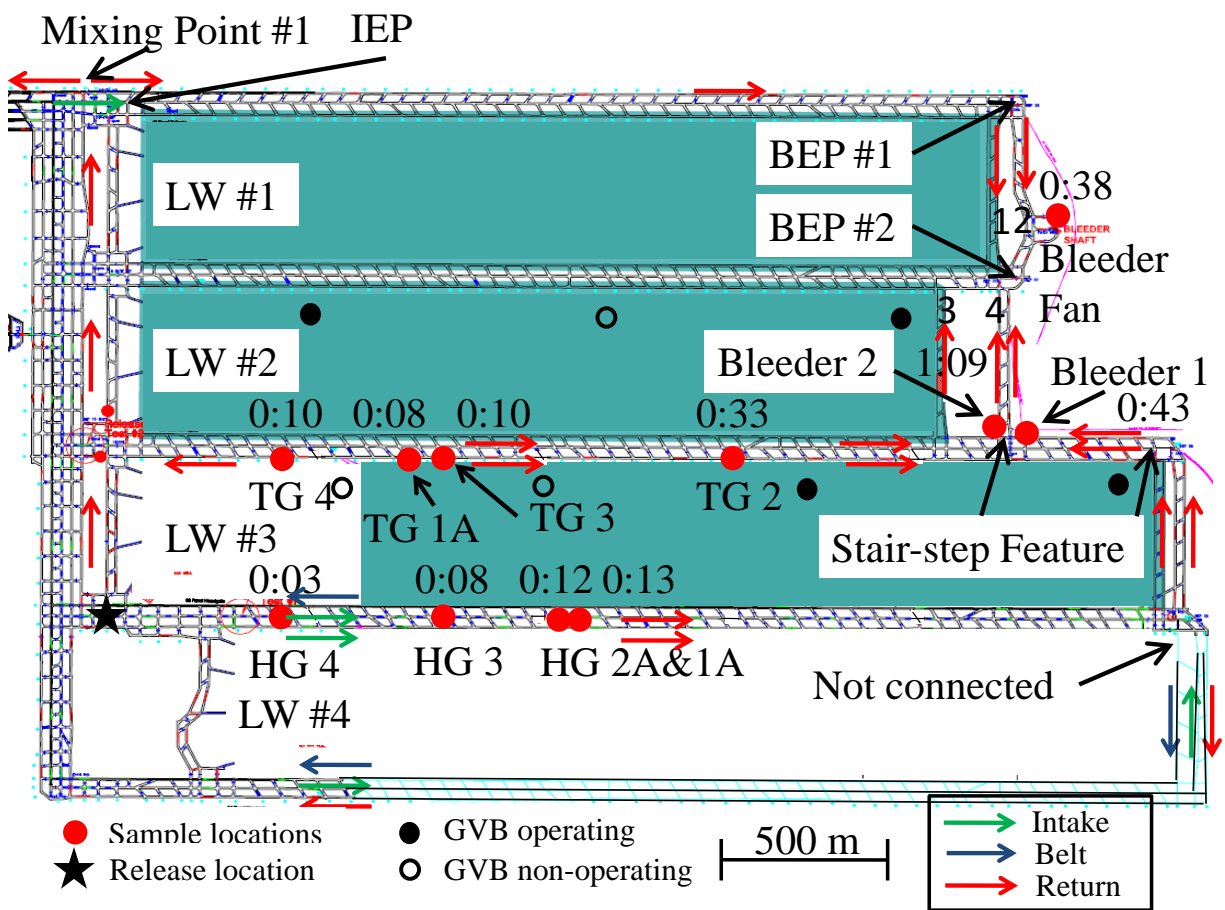


Figure 3-12. Test 2 sample lines locations and corrected tracer arrival times.

Table 3-2. Test 2 tube lengths, volumes, and calculated transit times in the tubes.

Location	Length m (ft)	Volume L (ft <sup>3</sup> )	Pump Rate L/min (ft <sup>3</sup> /min)	Transit time minutes
<b>Headgate</b>				
HG 1A	1280 (4200)	110 (3.8)	3.7 (0.13)	29
HG 2A	1280 (4200)	110 (3.8)	3.7 (0.13)	29
HG 3	920 (3000)	77 (2.7)	4.3 (0.15)	18
HG 4	460 (1500)	39 (1.4)	4.8 (0.17)	8
<b>Tailgate</b>				
TG 1A	850 (2800)	72 (2.6)	4.7 (0.17)	15
TG 2	1650 (5400)	140 (4.9)	3.6 (0.13)	38
TG 3	920 (3000)	77 (2.7)	4.5 (0.16)	17
TG 4	460 (1500)	39 (1.4)	5.0 (0.18)	8

### 3.2.3 Layout during Test 3 tracer gas release

At the start of Test 3, longwall panel 3 was completed and the longwall system had moved to longwall panel 4 and mined approximately 2,040 m (6,700 ft) from the setup room (Figure 3-14). The longwall #4 face was located just behind the location of the adjacent longwall #3 face during Test 2. SF<sub>6</sub> was released with a total volume of 69.4 L STP (2.45 ft<sup>3</sup>). The release location was changed for Test 3 to shield 19 (38 m from headgate corner) on the longwall #4 face and the lengths, volumes, and transit times for the sample tubes are shown in Table 3-3. The sample line labeled TG 3B was cut at or near the sample pumps and recorded no tracer gas. This release differs from the previous two tests as all of the intake airflow to the district did not pass the release location. After completion of LW #3, the original sample tube lines in the tailgate entry were pinched closed and no airflow was able to be pulled by the sample pumps. Repairs to the lines were not successful due to limited access, so direct measurement of airflow travel between two completed gobs by tracer gas was not performed. Note that the locations for Bleeder 1 and Bleeder 2 were moved closer to the bleeder fan to measure the different tracer gas pathways during this test and a third sample location (Bleeder 3 Inner) was installed (Figure 3-14).

Changes made to the ventilation system altered the airflow for the third and final tracer gas test at this mining district since the mine operator removed the last continuous miner unit from this district and redistributed airflow on a mine-wide basis. An internal bleeder design was utilized during the extraction of LW #4, where the majority of the longwall tailgate airflow was directed

towards the main return and then diverted towards the bleeder system using the recovery rooms and access entries of the previous panels, also referred to as an internal ladder design (Barletta, 2007). A previous paper on internal bleeders indicates the advantages and disadvantages of this system design (Brune et al., 1999) and should not be confused with the use of an “inner bleeder” system running parallel to the single-entry outer bleeder system at the back of the panels for the first two tests. The inner bleeder system was still being used for Test 3, but now the mine operator was also using an internal bleeder system to direct return airflow, approximately 21 m<sup>3</sup>/s (45,000 cfm), from the longwall tailgate corner towards the mains, around the previous recovery rooms, and back towards the bleeder fan by using the tailgate of the first panel.

The internal bleeder system created a dramatic alteration to the airflow pattern at the longwall tailgate corner and throughout the longwall district. In the previous two tests, the majority of the airflow at the longwall tailgate corner traveled inby towards back entries of the bleeder system and pulled the airflow behind the shields away from the face. During Test 3, about 70% of the airflow on the longwall face was sent outby the longwall tailgate corner via the two remaining tailgate entries with most then dumped into the wrap-around bleeder system at the previous panel’s recovery room. Most of the 70% was transferred through the #2 entry (bleeder airflow) which is separated from the #3 entry (section airflow) by a row of stoppings. This indicated that only 30% of the longwall face ventilation traveled inby back towards the entries at the back of the panel.

The Mixing Point #1 regulator located in entry 1 of the tailgate for LW #1, which was partially open for the first two tests, was fully closed for the third test, but now an even greater airflow of 41 m<sup>3</sup>/s (87,000 cfm) quantity was being directed down tailgate #1 towards the bleeders coming through the recovery room access entries (internal bleeder). Most of the airflow moved by the internal bleeder passed through the Intake Evaluation Point (IEP) located on LW #1 tailgate (Figure 3-13).

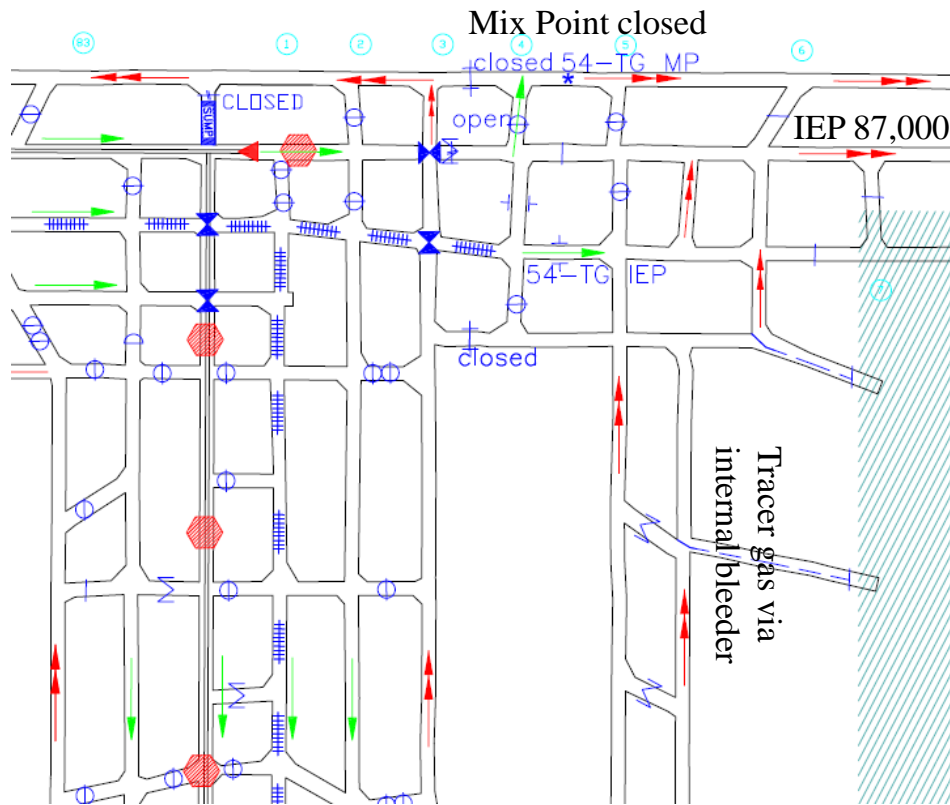


Figure 3-13. Intake Evaluation Point location during Test 3 with the mixing point located in the outer entry closed.

The originally planned tracer test #3 was to measure the airflow traveling between two completed gobs, LW #2 and LW #3, but the loss of the sampling tube lines eliminated that option. Therefore, the third test was modified to determine the longwall tailgate corner airflow distribution and the capacity of the internal bleeder by releasing the tracer gas on the longwall face. Under these conditions, the airflow traveling behind the longwall at shield 19 would not be mixed with the released tracer gas and carried no tracer gas, which enabled the determination of the origin of the air reaching sampling locations inby the longwall face (TG 2B and TG 1A of Figure 3-14).

Table 3-3. Test 3 tube lengths, volumes, and transit times.

Location	Length m (ft)	Volume L (ft <sup>3</sup> )	Pump Rate L/min (ft <sup>3</sup> /min)	Transit time minutes
Tailgate				
TG 3B	0	0	Line Cut	0
TG 1A	1280 (4200)	110 (3.8)	3.7 (0.13)	29
TG 2B	1160 (3800)	98 (3.5)	3.7 (0.13)	26
TG 4	460 (1500)	39 (1.4)	4.0 (0.14)	10

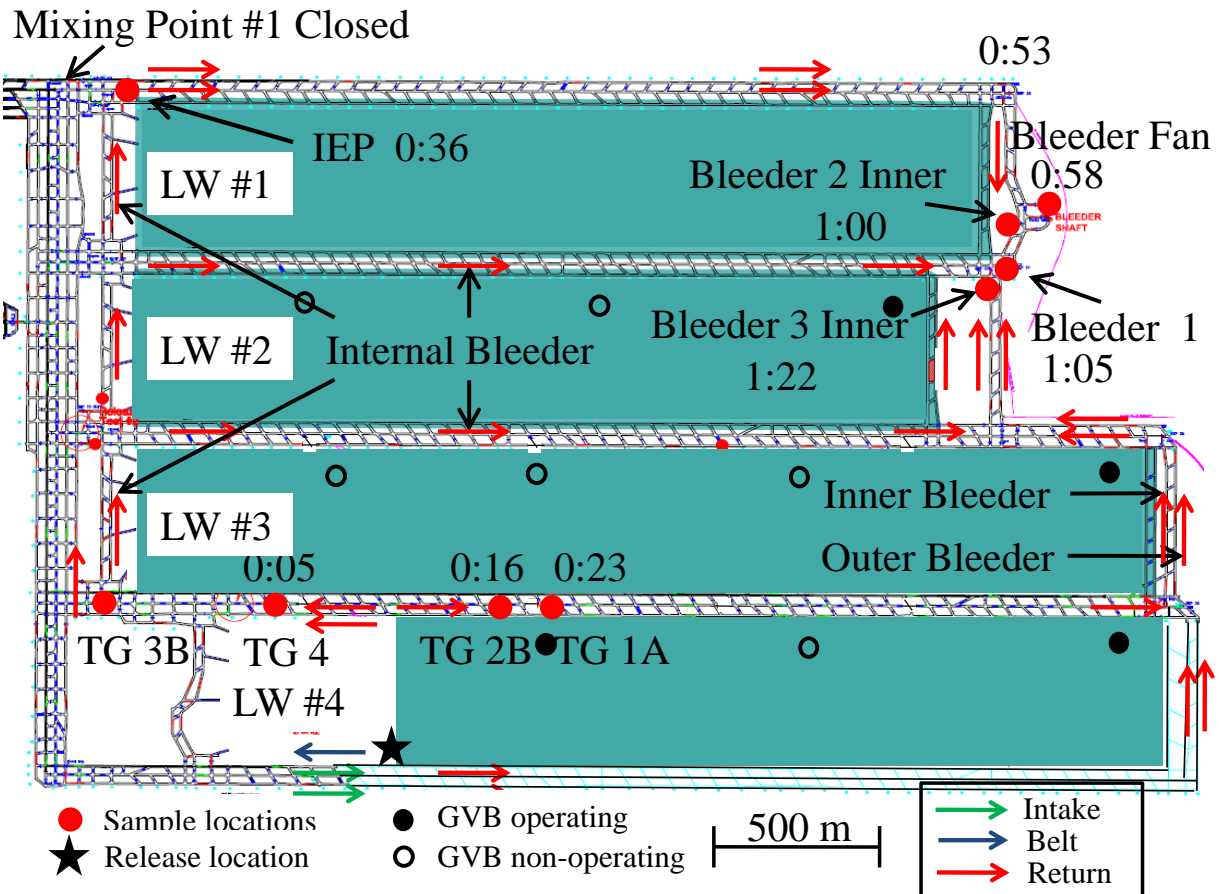


Figure 3-14. Test 3, showing internal bleeder ventilation system, along with arrival times. TG 3B was cut near the sample pumps and all four previous TG sample lines were pinched off.

Thousands of vacutainer samples were taken for each of the three tests (2,500, 3,000, and 2,000 respectively) A sample frequency schedule for each location was developed with a low of 2 minutes for the start of the faster moving airflow locations. Sample frequency then decreasing to 5 then 10 minutes as the time from tracer gas release increased. Not all samples were analyzed but the majority of the samples were tested by a gas chromatographic with an electron

capture detector (ECD). Once the SF<sub>6</sub> was determined to have passed a location the later samples do not have to be tested. Over 500 SF<sub>6</sub> samples were analyzed for Test 1, over 400 samples for Test 2 and over 350 for Test 3. Samples were also sent to an outside laboratory for verification and cross checking of sample procedure. Blanks (normal air, Nitrogen) and spike samples (1, 10 and 100 ppb calibration gasses) were also sent as control samples.

With thousands of unused vacutainers from each experiment not being analyzed for tracer gas, there were hundreds of samples available to be tested for methane and other higher hydrocarbons. The most important gas results were for C<sub>1</sub> (methane), oxygen, carbon dioxide and to a lesser extent C<sub>2</sub> (ethane). Samples were sent for partial and full hydrocarbon (helium, hydrogen tested and argon removed from the oxygen balance) testing that incorporating the following compounds: In order: Helium (He), Hydrogen (H<sub>2</sub>), Argon (Ar), Oxygen (O<sub>2</sub>), Carbon Dioxide (CO<sub>2</sub>), Nitrogen (N<sub>2</sub>), Carbon Monoxide (CO), Methane (CH<sub>4</sub>), Ethane (C<sub>2</sub>H<sub>6</sub>), Ethylene (C<sub>2</sub>H<sub>4</sub>), Propane (C<sub>3</sub>H<sub>8</sub>), Propylene (C<sub>3</sub>H<sub>6</sub>), Isobutane (iC<sub>4</sub>), Butane (C<sub>4</sub>H<sub>10</sub>), specific gravity, and BTU. The values for all the higher carbon chained gasses above butane were insignificant or zero and therefore could be removed. The detection level for carbon monoxide is 100 ppm and all samples were below this detection limit. Blank samples containing normal air or nitrogen, along with duplicates and spiked samples (various concentrations of CH<sub>4</sub> and balance N<sub>2</sub>, 10% CO + 10% H<sub>2</sub> balance N<sub>2</sub>) were sent out as control samples. These are the values that will be used for the remainder of the dissertation.

The experimental design for the two mine sites enabled the collection of a data set that was able to analyze and determine the following conditions of a longwall's ventilation system:

1. The effect of sampling frequency on capturing increased emissions during low pressure atmospheric events.
2. Airflow pathways within the inaccessible parts of the gob.
3. Quantity and retention times of these inaccessible pathways
4. The gas concentration within the inaccessible parts of the gob and the mass balance to show total methane migration within the gob.

## 4 Results

The two studies, completed at Mine A and Mine B, are unique and independent from each other, but also complementary in the sense that they increased the understanding of the complex problem of ventilating a longwall gob. The first study covers the operational results of a tube bundle system installed at Mine A. The study's objective was to determine and quantify the variations of gas emission levels from active and inactive longwall panels during changes in atmospheric pressure and to investigate the sampling frequency required to capture significant movements.

The second study, which was completed at Mine B, helped explaining airflow pathways within the inaccessible regions of active longwall panels. While methane concentrations within the zones of the caved material are important, it is best to first understand the atmospheric conditions that exist within the multiple maintained entries surrounding the caved material. The use of pre-mixing of multiple airflows before Measurement Point Locations (MPL) or Bleeder Evaluation Points (BEP) can dilute possible higher methane readings before the MSHA required monitoring locations. The objective of the study was to determine how and where methane was produced in a longwall district and how it was removed by the ventilation system. Since the measurement of just methane would not allow for the determination of the quantity and qualities of the airflows in the inaccessible entries of the bleeder system due to the uncertainty about the location and generation of methane, the release of tracer gas allowed determination of transit time and quantity as a proxy. Using a combination of tracer gas, methane, oxygen, and carbon dioxide sampling, as well as direct airflow measurements (quantity and pressure), the study was able to determine both quantity and quality of the airflows in inaccessible pathways of the active gob. Along with the ventilation measurements taken from the travelable outer bleeder entry as well as the inner entry, the use of the principle of mass balances for oxygen, methane and carbon dioxide allowed for accurate determination of quantity and concentration of the airflows within the inaccessible locations. Mass balances were done for the longwall tailgate corners, middle entry between longwall panels, and balances of airflow at the back BEPs. The data obtained through these studies was used to calibrate a wire-frame ventilation model that successfully predicted the airflow rate and methane concentration within the inaccessible regions of the bleeder system. The travelable outer-bleeder entry by itself does not give a good representation as to the atmospheric conditions that exist within the inaccessible regions of the bleeder system.

## 4.1 Tube bundle system at Mine A

The tube bundle systems installed at Mine A shows that the gas emissions of an active longwall panel are not static but a highly dynamic system predominantly controlled by atmospheric barometric pressure changes and volume of the void space remaining within the caved material. The measurements showed that gas emissions from the gob are not consistent on a day-to-day comparison let alone on a weekly basis. Measurements showed that increased emissions during decreasing atmospheric pressures, can be 2 to 3 times higher than the monthly average. Therefore, the current assumption of a ventilation system design using a static atmospheric case along with a factor of safety, to cover unexpected emission levels, may not be as conservative as once thought. A factor of safety of 2 used during engineering of the ventilation system may initially seem conservative but if the peak emission levels are over 4 times the static case, then the designed system will not be able to handle the high emission events.

The preferred design philosophy of any engineering discipline is to have a maximum expected value for a design parameter, and then multiple that by a factor of safety to determine the final design criteria to fulfill the conditions under which that parameter may attain under unexpected condition. Examples of this are common in mining, such as, determining wire rope thickness to support the skips, determining standing support density in a gateroad, determining rock bolt diameter to suspend overlaying rock layers. In other forms of engineering the worst case scenario does not have to be measured directly but can be determined ahead of time and considered in the designed, e.g. bridge design with only parked, fully-loaded tractor trailers across a span. In this situation, the worst-case design value can be reasonably determined and all succeeding engineering can be done based on this value. If the maximum expected value is not known; however, then the expected value can be substituted with a corresponding higher factor of safety to incorporate the added uncertainty. This expected value should have a known mean and standard deviation to allow for variation. If the standard deviation is not know because the sampling frequency is too low to catch variations, then an even higher factor of safety is required to be applied to the input average design value.

### 4.1.1 Sampling frequency

The sampling frequency rate in collecting data is important because it should be high enough to capture the significant variations in the measured value. A mine design ventilation question would be: how often does the gas concentration have to be measured to determine the highs and lows on a daily, weekly, monthly or annual basis? Would taking a recording at noon each day be enough to determine the daily high? The answer is obviously no, because the high value



most days is not known. In mining ventilation, we do not have this knowledge or experience on the daily gas emissions profile throughout the day, so a better answer would be to measure at each hour. This would determine the daily high for each day, week, month or year. In mining, the daily changes in emission levels from the caved material into the remaining open entries of the bleeder systems are not known to have been published so ventilation engineers are left with incomplete information to design a ventilation system. Therefore the less preferred method of engineering design (taking an average emission value and multiplying by a factor of safety) is generally being used by longwall operations to design their ventilation system.

The tube bundle system at Mine A has up to 36 sampling port locations and only 12 to 15 were being utilized at any given time. Therefore, extra tube lines were installed at the mouth of the section of the active longwall return (Figure 4-1). This point, while not a regulated MSHA sampling location, is ideal for gas monitoring from an engineering perspective because all airflow from the active tailgate and all leakage from the previous panel stopping line has to pass this location. Furthermore, this location at the mouth of the section has not been diluted with other airstreams, so a direct relationship between atmospheric pressure changes and gob emissions could be established from this measurement. An equivalent location for a bleeder ventilation system would be a single idealized BEP for the whole district without any fresh air pre-mixing with the sample point.

The tube bundle installed at Mine A operated over a two-year period collecting air sample data at multiple points throughout the mine (Figure 4-1). Data from 998,489 initial measurements were analyzed along with the corresponding system operating conditions: such as, barometric pressure, vacuum pump pressure, and analyzer flow rate.

The tube bundle system had a difficult time with line blockages predominantly from line freezing during the winter months as well as the water trapping effect of sagging sample lines. Sample data with corresponding system operating conditions indicating that the line had a blockage were removed. If multiple sample locations had line blockages at the same time the system as a whole was also not evaluated because of possible cross-contamination of lines. Frozen line data were removed and the final result was a database with over 300,000 sample points over a two-year period.

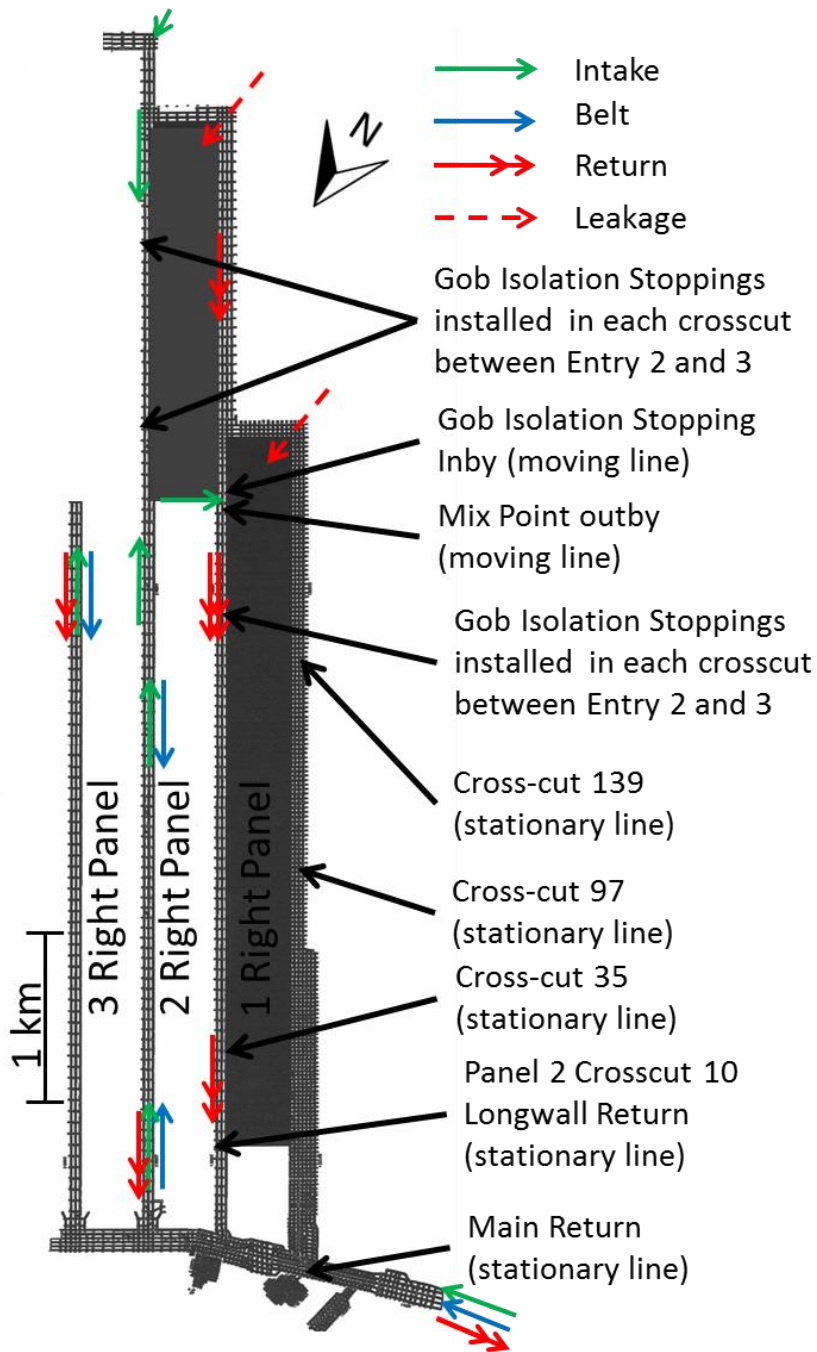


Figure 4-1. Mine A showing multiple sample locations for the tube bundle system during mining of Panel 2.

Currently, mining regulations require sampling of all ventilated areas at least once a week with common practice to be taken on Sunday. The tube bundle system allowed for a sample frequency of half an hour or less. To better describe the role of sample frequency has on monitoring the quality of the gasses leaving a longwall district the following three figures will

show the same set of data for a 43 day period. Figure 4-2 has weekly samples taken at noon on Sundays, Figure 4-3 has samples taken at noon each day, and Figure 4-4 has samples are taken on 30-minute intervals. In all samples, oxygen concentration and carbon dioxide concentration were measures since this coal mine does not have detectable methane.

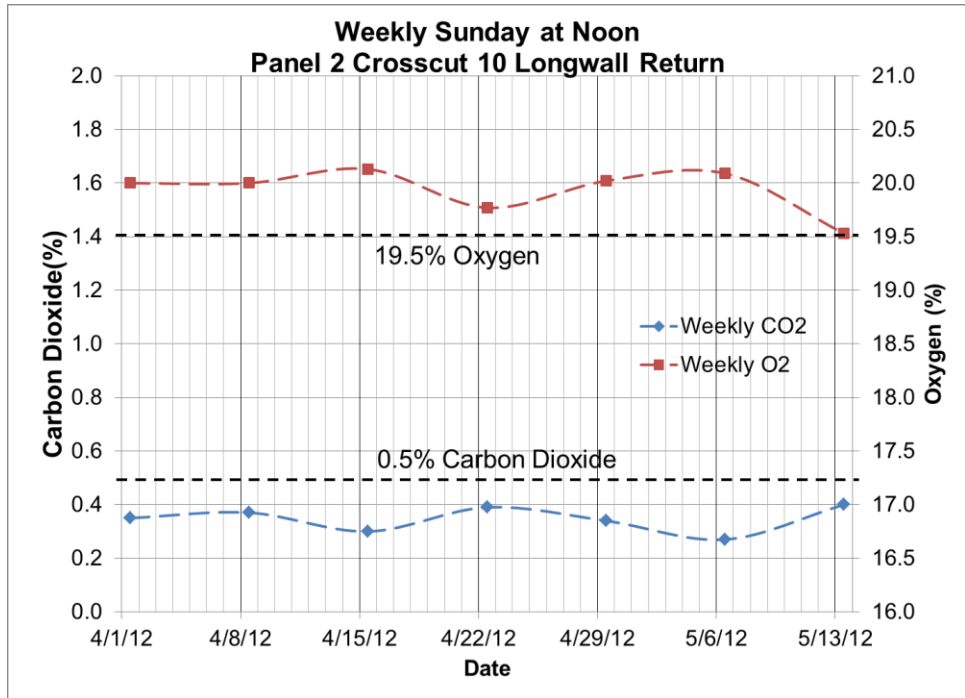


Figure 4-2. Weekly sample frequency over a 43 day period.

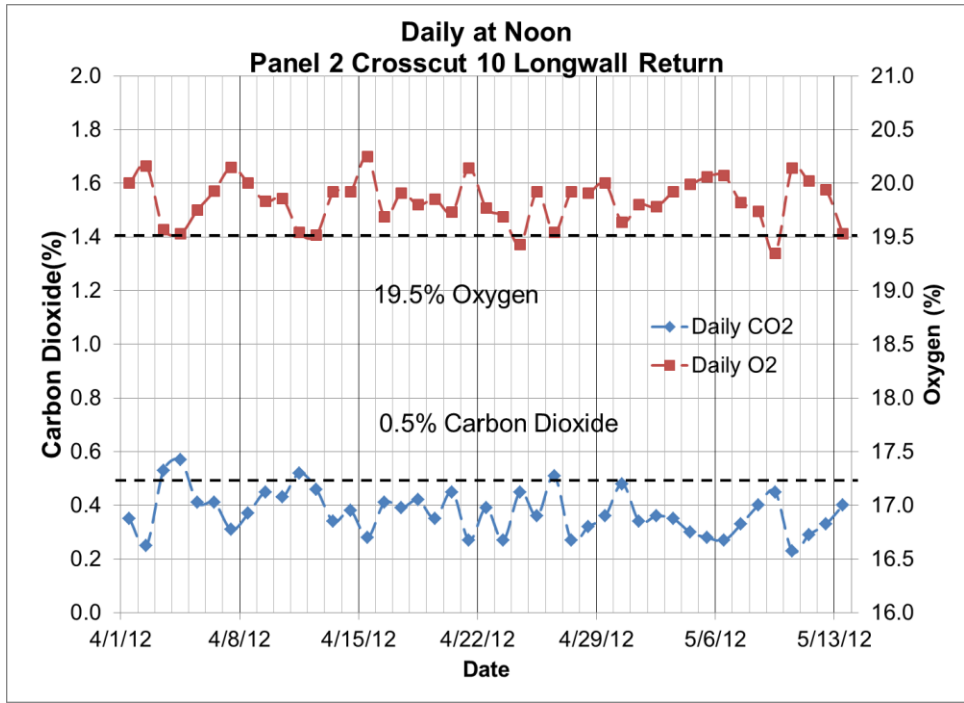


Figure 4-3. Daily sample frequency over a 43 day period.

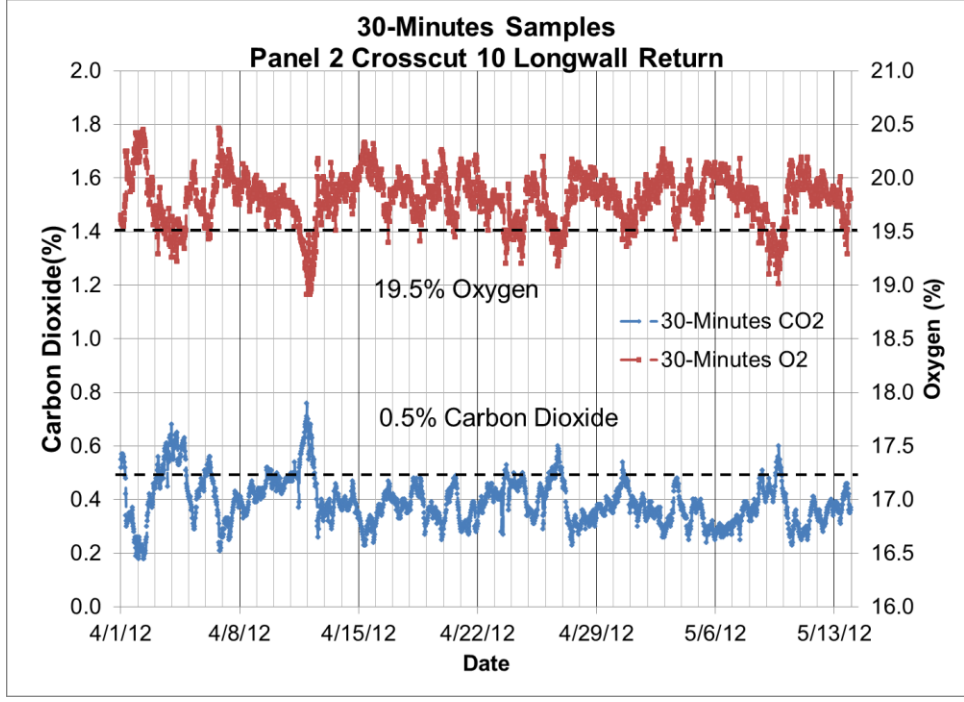


Figure 4-4. 30-minute sample frequency over a 43 day period.

From the three figures above show that a sample frequency rate of once a week is too low to be able to capture the highs and lows in emissions from a longwall panel or district. It is of interest

to note that the four highest-concentration events of carbon dioxide also correspond to the lowest levels of oxygen over the 43-day as shown in Figure 4-4. Plotting the same data with barometric pressure results shows a clear connection between persistent falling atmospheric pressure and a dramatic rise in carbon dioxide levels that rapidly reduce once the atmospheric pressure starts to rise as shown in Figure 4-5 with pointing arrows.

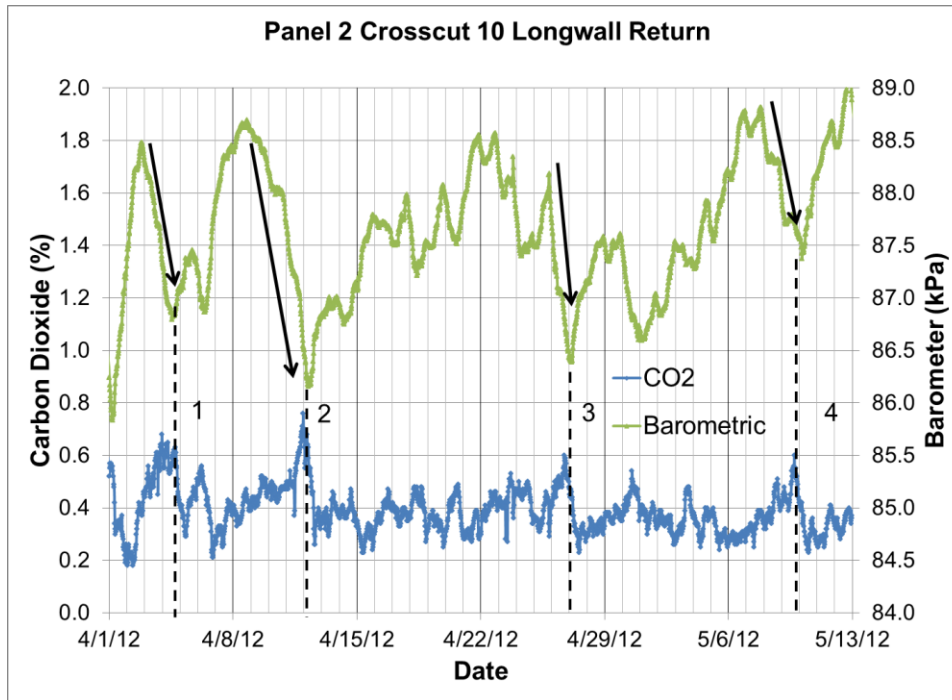


Figure 4-5. Carbon dioxide levels primarily being controlled by changes in atmospheric pressure.

Measurements taken by previous experiments with the tube bundle systems at Mine A during the extraction of Panel 1 showed the following readings and conclusions (Zipf et al., 2014):

1. Panel 1 had fractured connections to the surface at the startup room and recovery room (Figure 4-6).
2. The gas concentrations throughout the sealed Panel 1 had a near uniform distribution with approximately 20% carbon dioxide and less than 2% oxygen (Figure 4-7 and Figure 4-8)
3. The leakage rates across the gob isolation stoppings (installed in each crosscut of the headgate between entries 2 and 3) were proportional to the pressure drop across the stoppings (Schatzel et al., 2015)

4. Differential pressure across the gob isolation stoppings on the tailgate side averaged approximately 0.5 to 1.0 kPa (2 to 4" w.g.)
5. The longwall tailgate corner relative pressure differential to surface was between 0.5 to 0.75 kPa (2 to 3" w.g.)
6. Many parts of the ventilations system show a daily (diurnal) change in carbon dioxide levels and atmospheric pressure

The initial ventilation system for the start of the mining of Panel 2 is shown in Figure 4-6 and represents leakage from the surface into both panel setup rooms as well as a regulated intake at the back of Panel 3. The 1 Right Panel has been sealed and still has three sample tube lines able to monitor the gas concentration within.

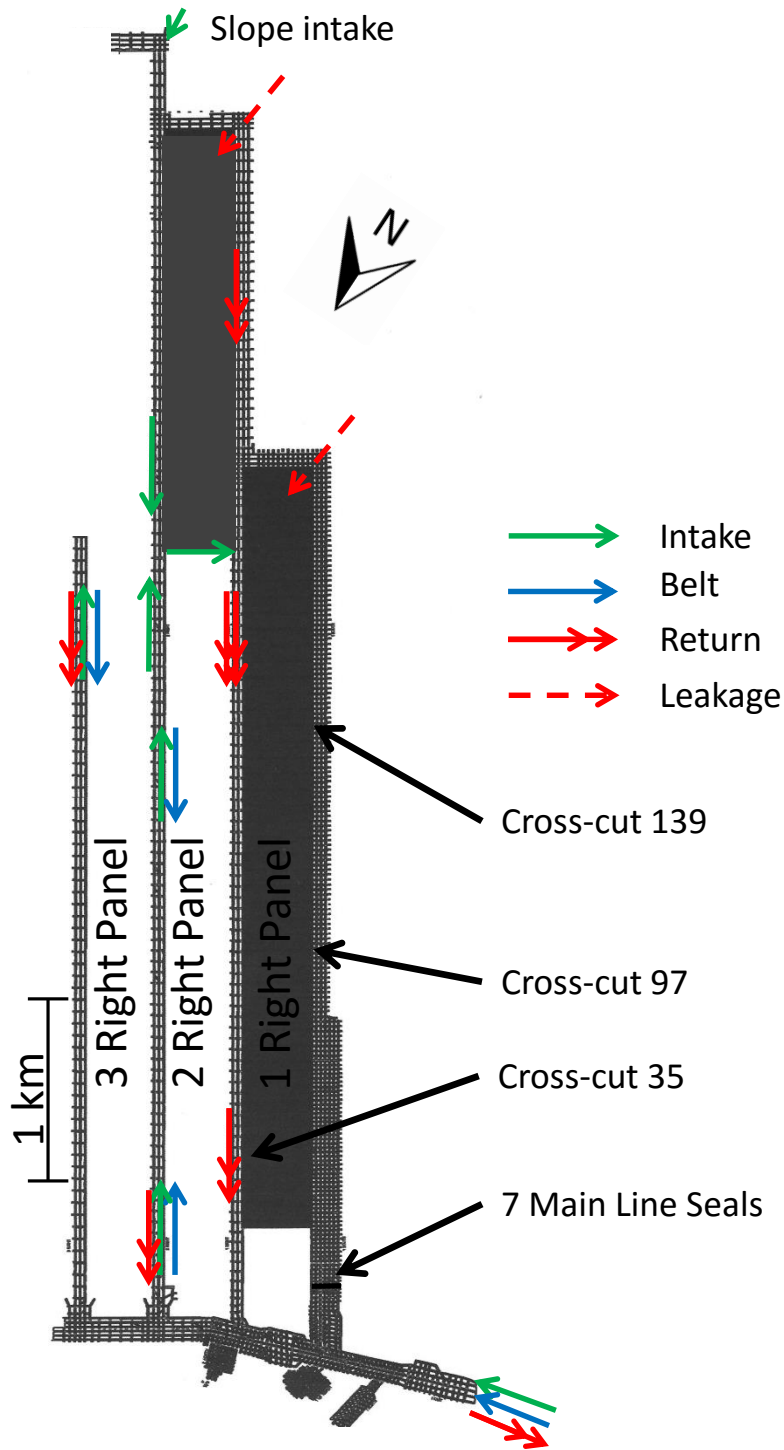


Figure 4-6. Layout of Mine A showing three samples locations within the sealed gob of Panel 1 during the mining of Panel 2.

## 4.2 Results of TBS for Mine A

Mine A used a bleederless ventilation system during this study with progressive sealing of the active panel during mining using a double set of Kennedy stoppings filled with a concrete mixture. After Panel 1 was mined, the panel was sealed on the tailgate side by 7 seals (Figure 4-6). A total of 73 gob isolation stoppings remained along the newly active Panel 2 tailgate as potential leakage pathways into the return air from the longwall tailgate corner. Atmospheric composition conditions in the sealed Panel 1 when Panel 2 started mining June 2011, began to show high carbon dioxide levels with little oxygen (Figure 4-7, Figure 4-8 and Figure 4-9). The static pressure differential between the tailgate of Panel 2 and the sealed Panel 1 was measured at between 0.5 to 1.0 kPa (2 to 4" w.g.) dependent on the longwall current length and how far down the tailgate return the pressure was measured. The highest pressure is closest to the mouth-of-the-section at the outby end of the panel when the ventilation lengths are greatest. Therefore, any leakage from the sealed Panel 1 into the active tailgate return would greatly increase the measured carbon dioxide levels in the longwall return near the mouth of the section. It should be noted that this sealed gob does leak out into the middle entry of the active tailgate and has higher emissions during atmospheric pressure drops. While this sealed gob does have high carbon dioxide and low oxygen levels it is still separated from the active panel 2 by gob isolation stoppings which are approximately 1.5 m (5 ft) thick. There are no such isolation stoppings installed in the common bleeder ventilation systems used throughout the Eastern United States, and any remaining stoppings are single thickness, non-sealing stoppings.

As shown in Figure 4-7, the gas concentration within Panel 1 stabilized at near 20% carbon dioxide and less than 2% oxygen. There were no diurnal changes in concentration within the gob even before the panel was fully sealed. After the mainline seals were installed the gob took less than 2 months to reach equilibrium. During the winter months of mining Panel 2 some of the sample lines froze and this complication brings into question the accuracy of the results without proper air exchange between samples. Figure 4-8 and Figure 4-9 show a constant atmospheric condition in the sealed Panel 1 gob at other locations in addition to Figure 4-7, which allows for the assumption that gas leaking through the 80+ gob isolation stoppings between Panel 1 into Panel 2 will have a constant composition.



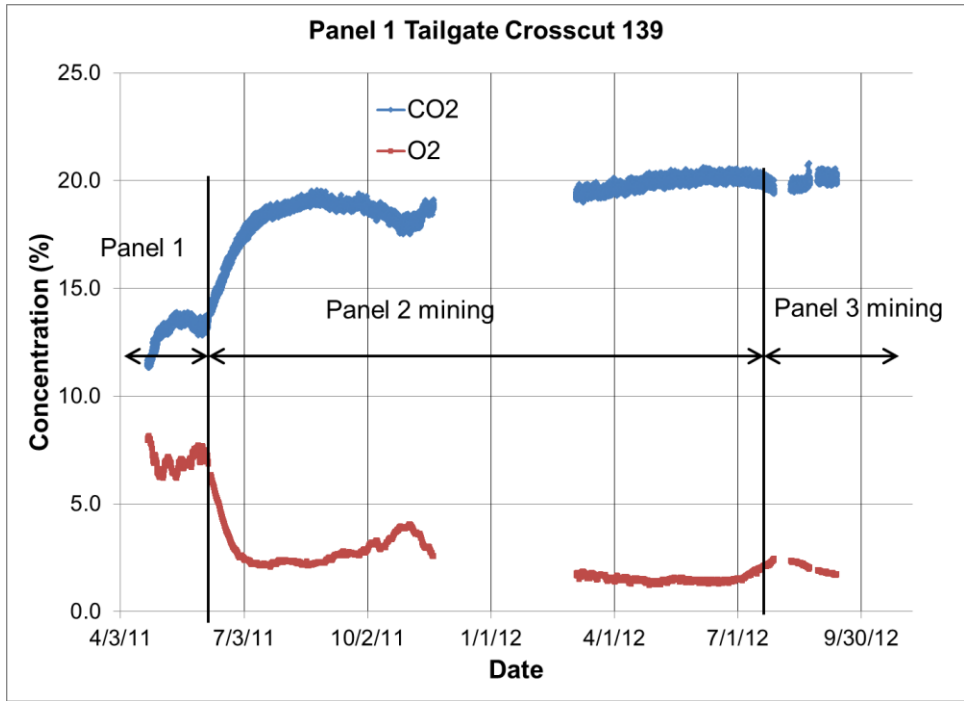


Figure 4-7. Panel 1 gob sample location cross-cut 139, during mining of panels 1, 2 and 3. The panel was sealed just before the mining of Panel 2. The gap in data is when the sample tube lines were frozen.

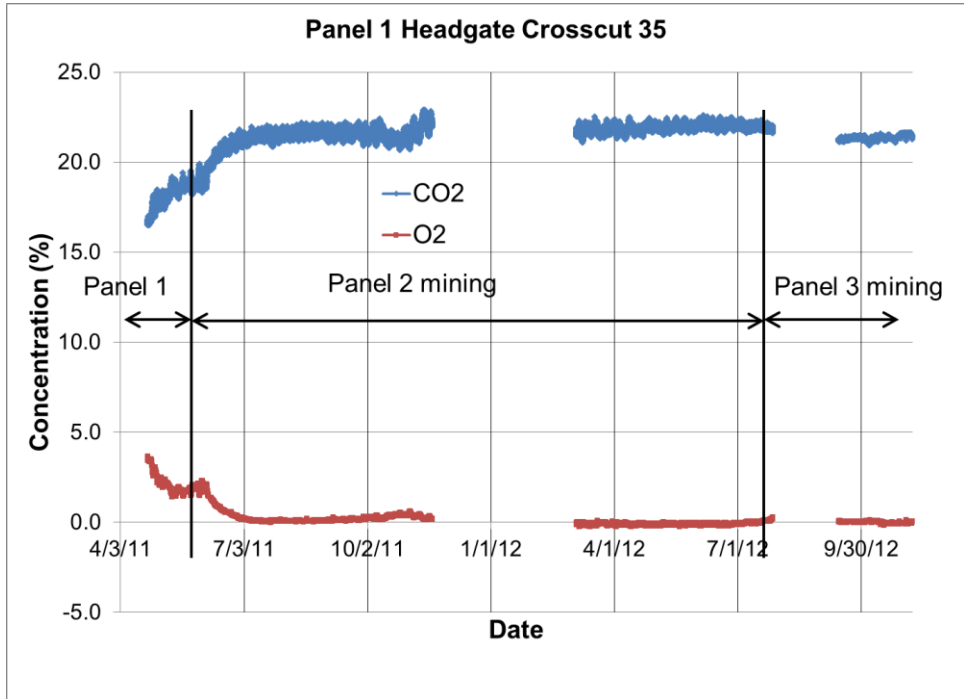


Figure 4-8. Panel 1 gob sample location cross-cut 35, during mining of panels 1, 2 and 3. The gap in data is when the sample tube lines were frozen.

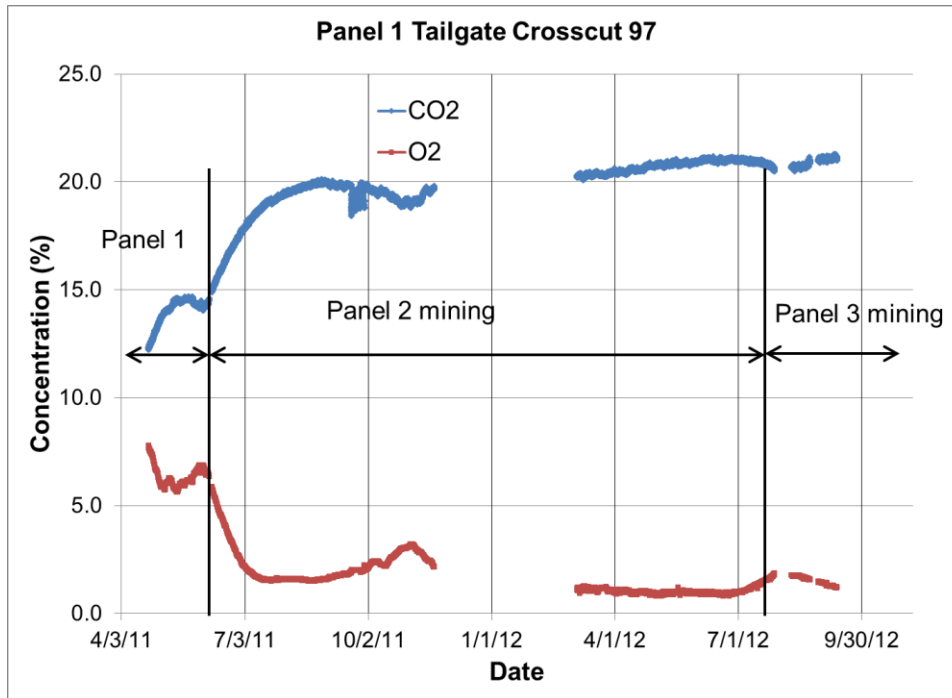


Figure 4-9. Panel 1 gob sample location cross-cut 97, during mining of panels 1, 2 and 3.

#### 4.2.1 Coal oxidation vs. seam gas

The measured carbon dioxide at Mine A is believed to be a function of coal oxidation, not from coal seam gas emissions. The highly reactive coal at this mine has created a low oxygen environment where nearly all the oxygen has been converted to carbon dioxide within the gob. The coal seam is highly reactive and with the progressive sealing of the panel during extraction the following conditions were observed. The oxygen level drops first followed by a rise in carbon dioxide level (Table 4-1). The atmospheric composition of gob was nearly at 21% when oxygen and carbon dioxide are summed together. Only during the initial rapid reduction of oxygen do the two components gas components not add up to 21%. On Sept 19, 2011, ten samples were taken in a row from the TBS auxiliary sample port as it cycled. The samples were sent for full gas analysis that included hydrogen and argon. The other gasses of hydrogen, methane and higher carbon chains are not shown because they were insignificant or undetectable.

Table 4-1. Full gas analysis of samples from the tube bundle system 9/19/2011

Samples	O2	CO2	O2 + CO2	Ar	N2
1	20.6	0.37	21.0	0.945	78.1
2	19.5	0.90	20.4	0.955	78.7
3	20.4	1.07	21.4	0.944	77.6
4	12.6	7.90	20.5	0.953	78.5
5	3.34	13.5	16.8	0.992	82.2
6	2.26	14.5	16.8	0.980	82.2
7	3.27	16.6	19.8	0.944	79.2
8	3.18	17.0	20.2	0.954	78.9
9	2.37	17.3	19.7	0.962	79.3
10	0.60	19.5	20.1	0.958	79.0

The analysis for argon allows the determination of what is occurring within the gob. Given that argon gas is not a byproduct of the coalification process, it cannot be a coal seam gas emission. The argon could be naturally occurring though but highly unlikely to be greater than the natural 0.94% in natural air. The sample arranged by increasing carbon dioxide levels shows that the argon concentration starts off about 0.95% (near background levels) but increase to over 0.98% during the oxidation by the caved material, when the oxygen levels were falling quickly (Figure 4-10). Argon increased from 0.95% to 0.98% for the samples at the same time as the sum of oxygen and carbon dioxide fell from 21% to about 17%. Since oxygen and carbon dioxide have the same specific volume, the coal must have removed more oxygen from the air before the carbon dioxide was released. This 4% reduction in total air volume within the caved material would cause the nonreactive Argon gas concentration to increase from 0.95 to 0.99%.  $[0.95/(1-0.04) = 0.99\%]$ . Given time in the slow moving air of the caved material the carbon dioxide level eventually plateau at 21%, while the Argon levels fall back to the initial 0.95% level. Figure 4-11 uses the same 10 gas samples as does Figure 4-10 but shows the increases in nitrogen concentration that would be explained by the same removal of oxygen that effected the Argon concentrations. Because both argon and nitrogen gas concentrations return to normal atmospheric levels once carbon dioxide levels plateau around 21%, the carbon dioxide recorded cannot be from coal seam emissions. Coal seam emissions cannot have the same ratio of nitrogen and argon found in the atmosphere because both these gasses are not byproducts of the coalification process. Argon, being a noble gas, is not found anywhere in the coalification from peat to anthracite. Therefore the carbon dioxide recorded in the caved material was determined to not be from coal seam gas emissions, but a product of the coal oxidation process.

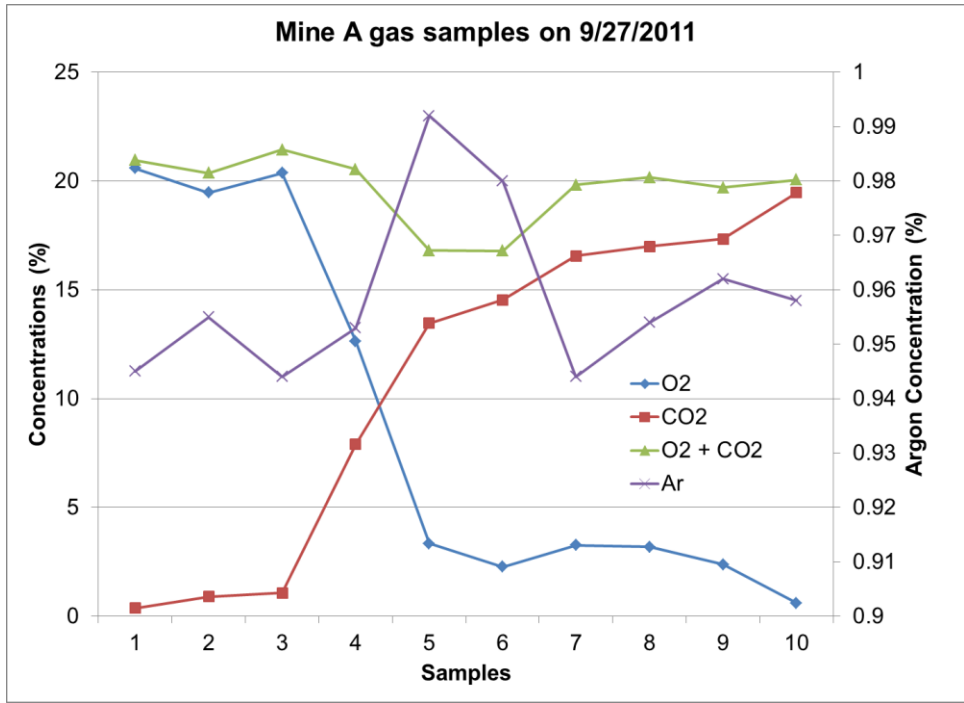


Figure 4-10. Multiple samples taken at Mine A on September 19, 2011, showing the gas concentrations during the oxidation of the caved material and removal of oxygen. Note background argon level increased during rapid oxidation.

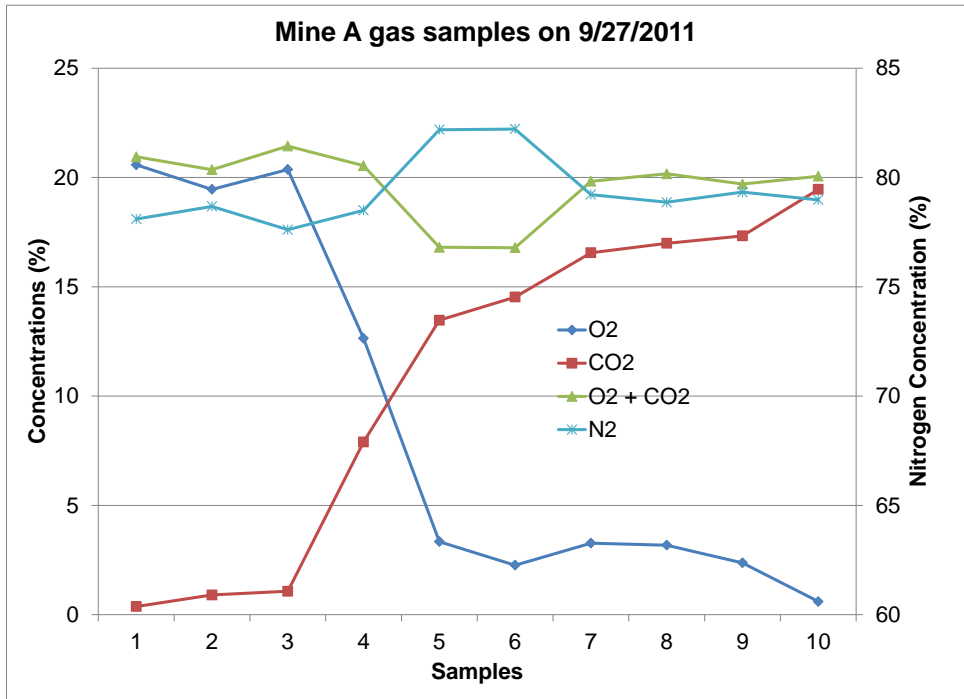


Figure 4-11. Samples showing increased nitrogen gas levels during the coal oxidation process within the caved material. Note this was before nitrogen injection plant was installed in early 2012.

#### 4.2.2 Diurnal pressure changes

The tube bundle system had many sample locations that experienced daily changes to atmospheric compositions and this is indicating communications with the primary ventilation system. Figure 4-7 to Figure 4-9 show that the sealed Panel 1 has little, to no, indications that there is a connection to the primary ventilation system and this condition is expected with the gob isolation stoppings and seals installed. The surface fresh air location shows both diurnal changes to oxygen and carbon dioxide but also the drifting of the base line for expected values of 20.9% oxygen and 0.04% carbon dioxide (Figure 4-12).

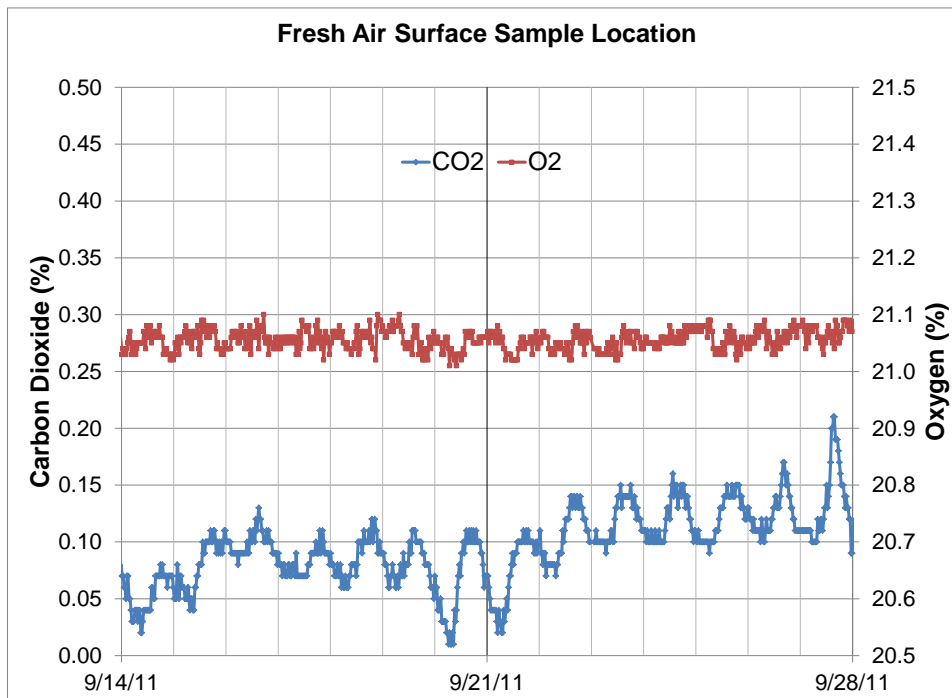


Figure 4-12. Fresh air sample location showing daily variation in values as well as drift for the oxygen sensor.

Figure 4-13 shows some of the sample locations during the mining of Panel 2 as of October 2011. The panel had retreated 2,050 m (6,730 ft) of its planned length of 6,480 m (21,260 ft). The main return and Panel 2, crosscut 10, longwall return are both stationary sample locations (Figure 4-13). The gob isolation stopping and mix point sample locations are both moving/trailing sample locations that retreat with the longwall face. Traveling sample tube lines are to be cut each time a crosscut is mined passed. The previous gob isolations stopping, utilizing the back return ventilation system, are to be fully closed and a new gob isolation stopping erected one crosscut further outby (Figure 4-14). The gob isolation stoppings built across the middle entry, first acts as a regulator then as a stopping once mining has passed.

The gob isolation sample tube lines are to be cut before the stopping is completed. Also the longwall mix point line is to be cut and moved outby one crosscut as well. Failure to do so will show a quick rise in carbon dioxide levels and a reduction in oxygen because the sample tubes will be left behind within the caved material. The sample tub lines will not be in the correct location and will giving high gas concentration readings of CO<sub>2</sub>.

One of the primary issues with a TBS is keeping the sample tube lines operating during the freezing temperatures of winter. Figure 4-15 depicts the sample results of the main return over a one-year period and shows the times in the winter when the sample lines were frozen. In January and February 2012 a nitrogen injection plant was utilized to reduce oxygen levels within the active gob. During the spring of 2012 when the two bundle system came back online, the carbon dioxide levels in the main return were lower than in the previous fall.

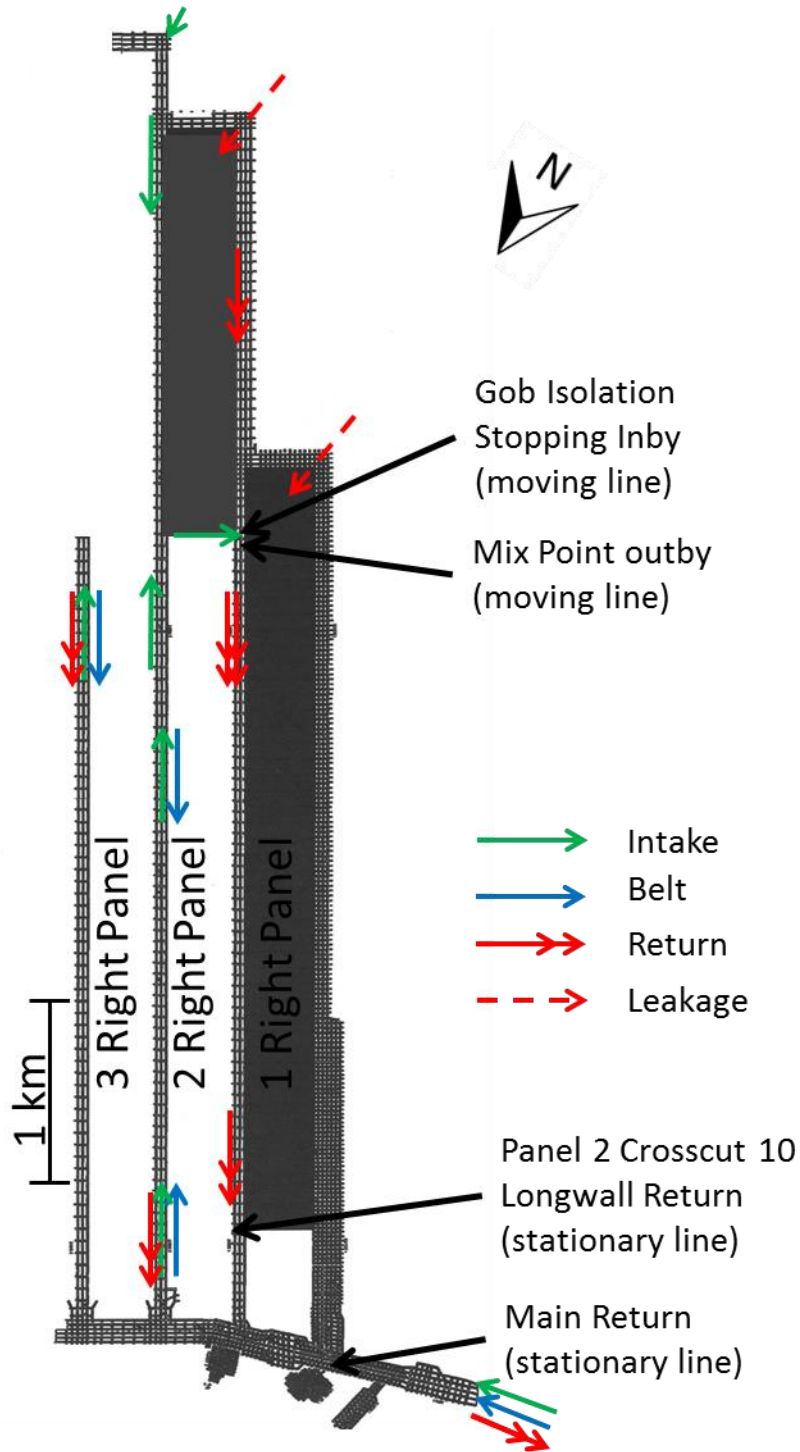


Figure 4-13. Sample locations during mining of active Panel 2 as of October 2011.

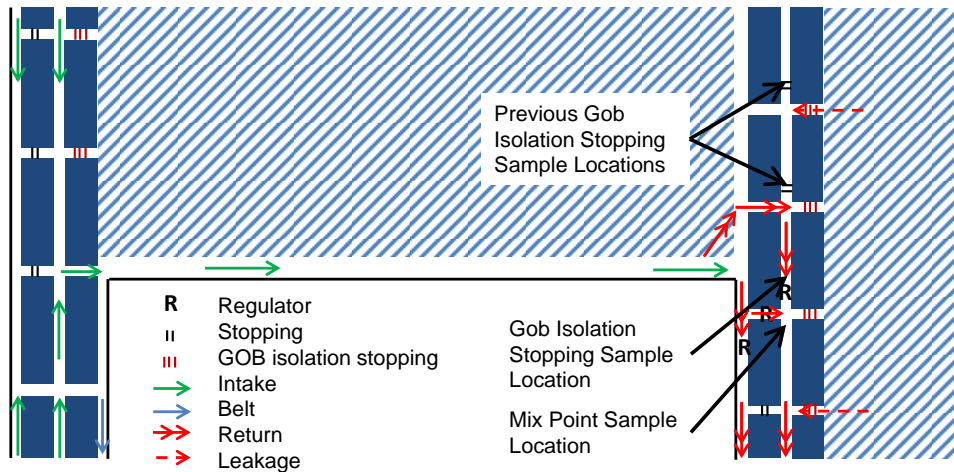


Figure 4-14. Moving locations for the Gob Isolation Stopping and Mix Point sample locations. Sample tube lines are to be cut each time a crosscut is mined passed.

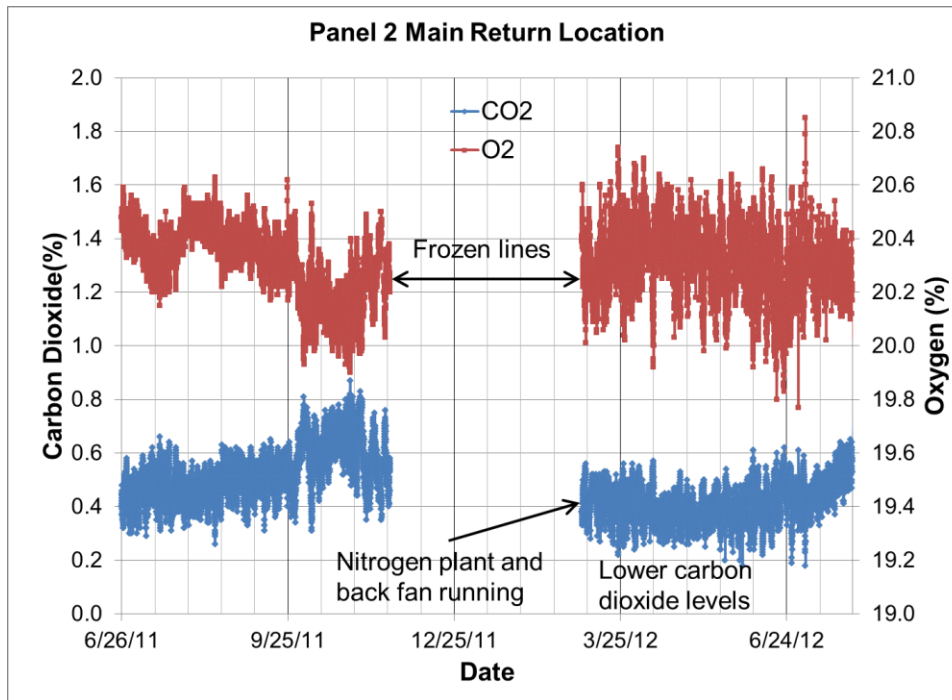


Figure 4-15. Sample location of the Main Return depicting mine wide gas concentrations.

The tube bundle results in the fall of 2011 were complicated by the fact that the gob isolation stopping sample location and the longwall mix point were not strictly kept up to date during mining past the crosscuts. The two sample tube lines were laid in the middle entry and on more than one occasions got switched with each other. Also, the sample tube lines were not always cut at the correct time and were sometimes left within the caved material for a few days before the error was corrected. Figure 4-16 shows the gob isolation stoppings sample location in the



fall of 2011, with the sample tube line cut after the gob isolation stopping was completed. The gob isolation stoppings were completed before the sample tube line was cut, the oxygen levels drop quickly over a two day period. Once the line was cut the oxygen contact jumps back over 20% and the carbon dioxide levels drop. From 10/6/11 to 10/24/11 the gob isolation stopping sample tube and the longwall mix point sample locations were switched. Late cutting of the sample tubes as well as mixing the two sample locations makes any statistical interpretation of these two locations inappropriate during the mining of panel 2. One advantage that was gained by the lines being cut late was that the atmospheric concentrations behind the longwall face could be measured. The mining rate of the longwall is known to average between 15-18 m/day (50-60 ft/day) and a crosscut is mined every 3 to 4 days. Therefore approximately 50 m behind the longwall face it appears that the atmospheric concentrations were 12% oxygen and 3% carbon dioxide.

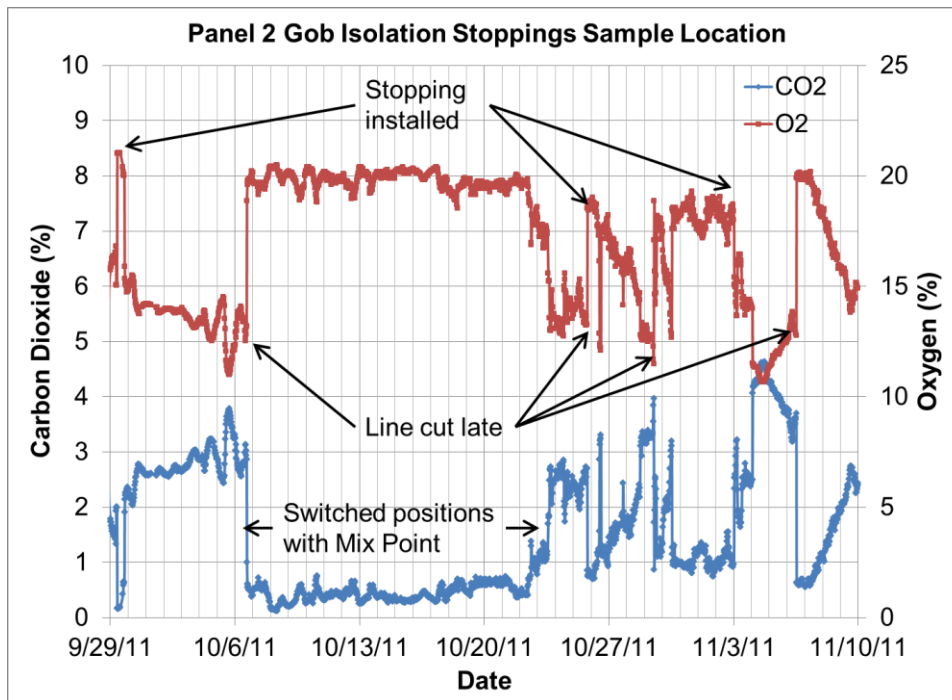


Figure 4-16. Gob Isolation Stopping longwall trailing sample point showing gas concentration within the gob, if the trailing sample line was not cut when next GIS stopping installed.

The longwall mix point Figure 4-17 also shows the same issues of the sample tube lines being cut late as well as switching positions between the mixing point and the gob isolation stopping. With both tube lines the same color the unfortunate occurrence of switching the sample tubes lines did occur during the movement of the sample lines after each cross cut was mined past.

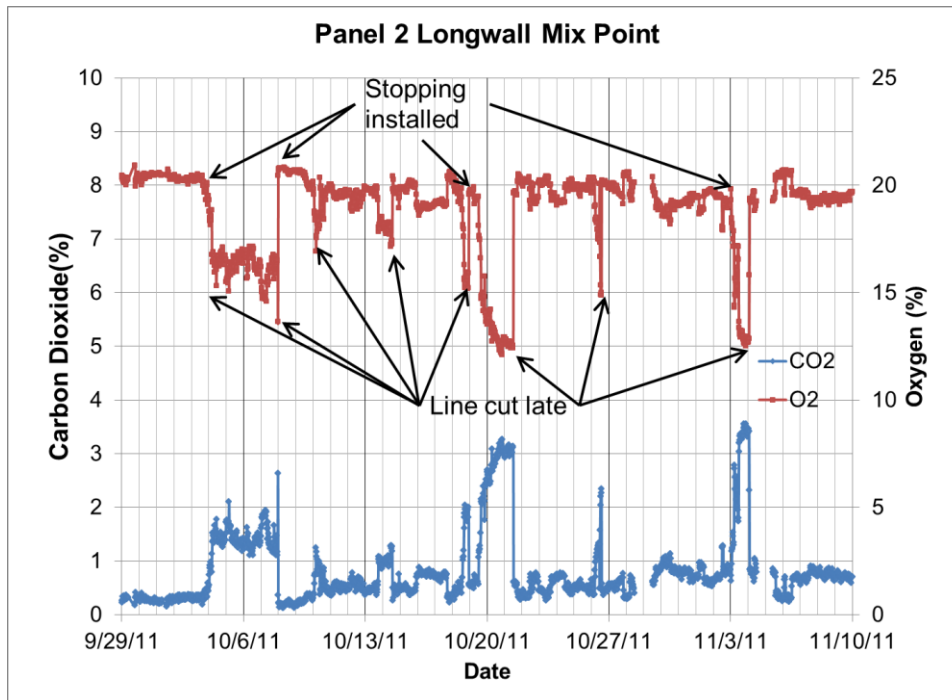


Figure 4-17. Longwall Mix point sample location showing the line being left within the gob multiple times and being switched with the GIS sample location.

During the same 6 week period from 9/29/11 to 11/10/11 the main return sampling location did not show any of the large changes in gas concentration as the longwall mix point and gob isolation stopping showed (Figure 4-18). As expected, the main return during the same time period had a characteristic much narrower gas concentration range as the longwall return accounted for approximately 25% of the main return. Panel 2 crosscut 10 longwall return located near the mouth of the section also had a large variation in oxygen and carbon dioxide gas concentrations but these step-changes do not match up with the gob isolation or the longwall mix point sampling locations (Figure 4-19).

The controlling factor for oxygen and carbon dioxide levels in the longwall return appears to be barometric pressure changes as shown in Figure 4-20. During falling atmospheric pressure the emissions increase but rapidly decrease during the rising barometer. There are some exceptions to these general observations most notable on 10/17/2011 when the barometric pressure was rising and there was a step function in gas emissions from the gob. The range of gas sample results of the longwall return for the 6-week period between 9/29/11 to 11/10/11 is summarized in Table 4-2.

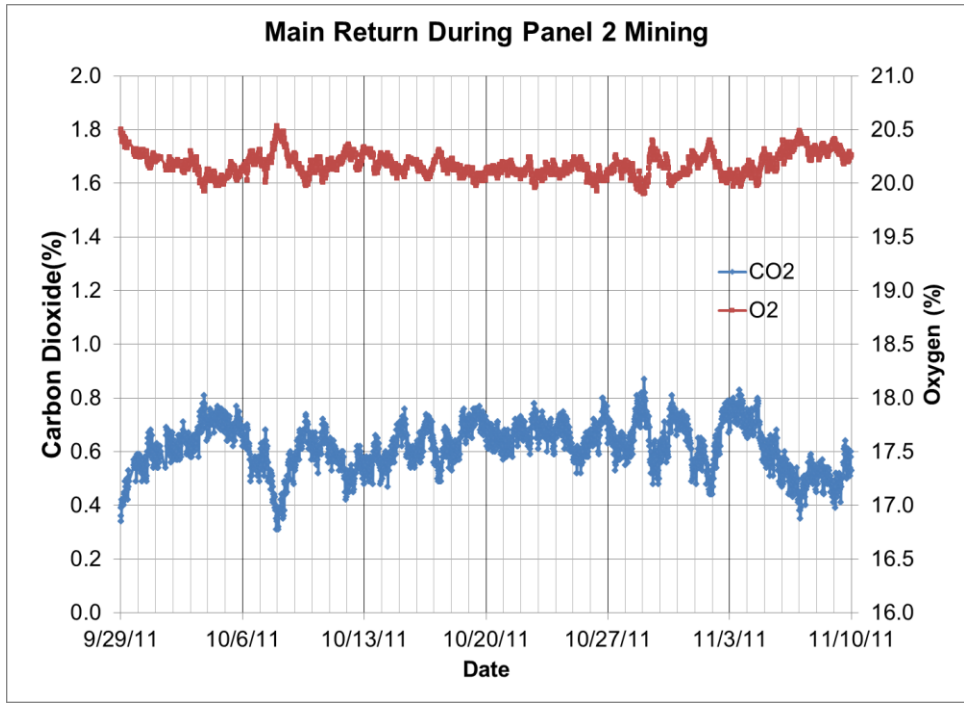


Figure 4-18. Mine main return showing some variations in gas concentrations during mining of the first half of Panel 2 (fall of 2011).

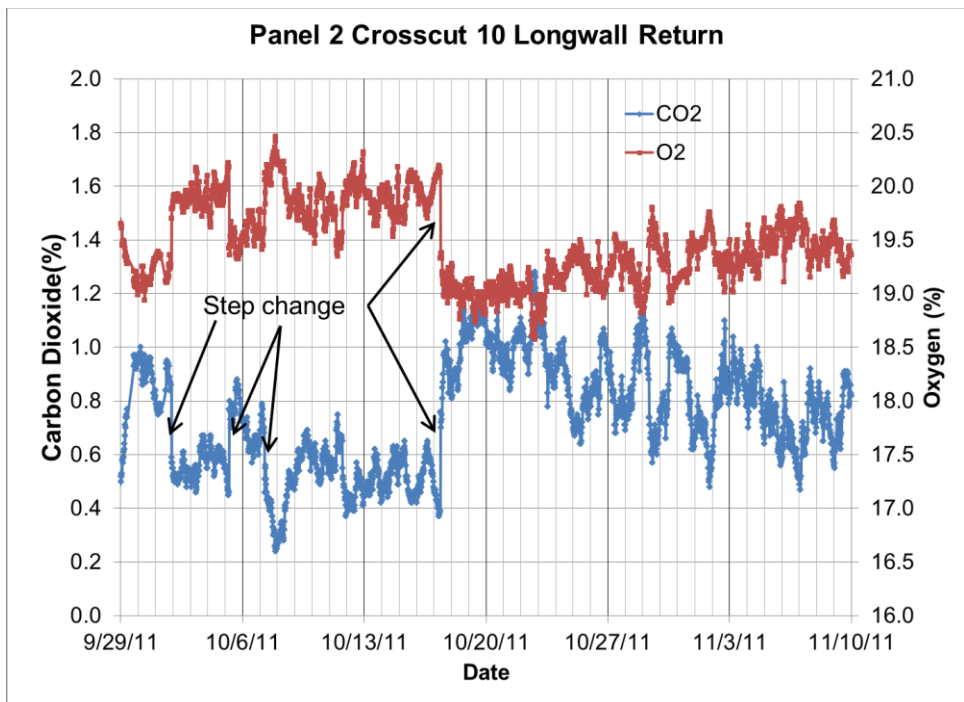


Figure 4-19. Panel 2 crosscut 10 longwall return with large variations in oxygen and carbon dioxide concentrations coming off the longwall tailgate return.

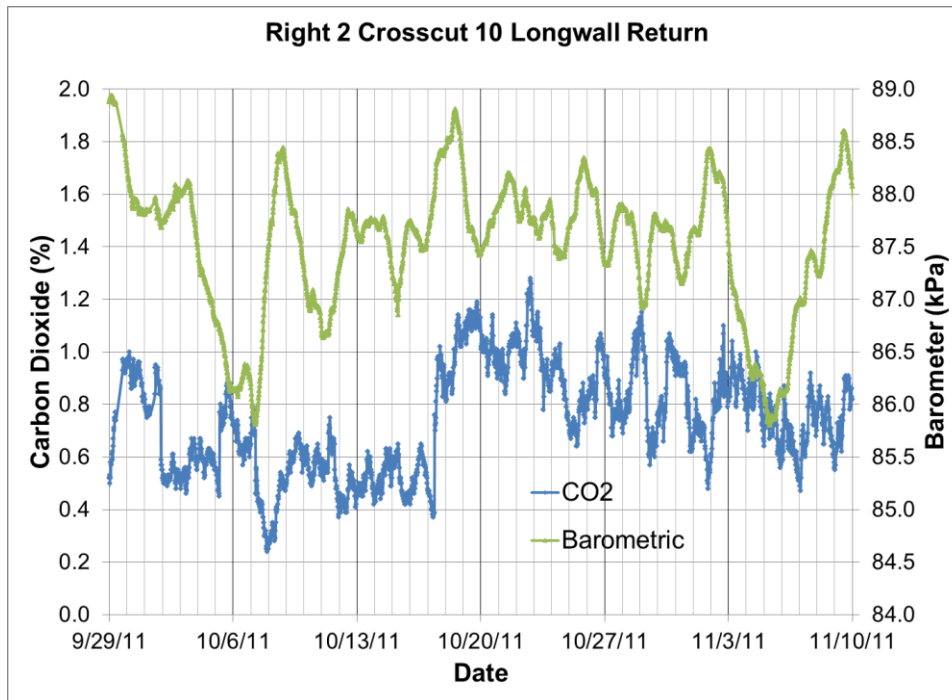


Figure 4-20. Panel 2 crosscut 10 longwall return showing large variations in carbon dioxide concentrations explained by barometric pressure changes. The correlation is not perfect but indicates the impact of the barometric pressure as an underlying controlling factor in gas concentration.

Table 4-2. Longwall return gas composition from 9/29/2011 to 11/10/2011.

Longwall Return	CO <sub>2</sub>	O <sub>2</sub>
Average	0.74	19.5
Max	1.28	20.5
Min	0.24	18.6
Standard Deviation	0.20	0.37

In January of 2012 a nitrogen plant was installed and gas concentrations of less than 3% oxygen (the balance nitrogen) were injected into the caved material from the headgate side near the setup room. It is assumed that Panel 2 has a similar fracture network connection to surface at or near the setup room as did Panel 1, and with the addition of about 0.8 m<sup>3</sup>/s of low oxygen gas from the nitrogen plant would lower overall carbon dioxide levels within the caved material (Figure 4-21). The introduction of nitrogen at the headgate side of the longwall panel would displace oxygen from entering the caved material. Lower oxygen levels slow down coal oxidation and the production of carbon dioxide. Because carbon dioxide is not a seam gas at this mine, any active system that reduces oxygen levels should also reduce average carbon dioxide levels as shown in Figure 4-15.

Panel 2 gob, which had a length of 4,250 m (13,960 ft) as of April 1 2012 and was over 70% extracted, has a much larger volume (reservoir) of caved material to allow significant air exchange during breathing/outgassing events (falling pressure) when compared to the January event.. Longwall retreat for April was 532 m (1745 ft) for daily average of 17.7 m/day (58 ft/day). Longwall retreat for May 2012 was 535 m (1755 ft) 17.3 m/day (57 ft/day). For the months of April and May the longwall was running consistently with no major disruptions.

During April and May, the gob isolation stopping sampling location was again left within the gob multiple times. It can be clearly seen in Figure 4-22 that the construction of a gob isolation stopping every 3-4 days as a crosscut is mined by and sometimes the sample tube is cut and transferred to the next outby location. During 4/19/12 a second stopping was installed without the gob isolation stopping sample tube cut, therefore the measured gas concentration dropped to about 5% oxygen and 6% carbon dioxide. This indicated the atmosphere within the gob up to 134 m (440 ft) inby (2 crosscuts depths) from the longwall face along the tailgate entries. Then, on 4/22/12, the sample line was cut and the gas concentrations quickly increased to 19.5% oxygen and 0.5% carbon dioxide. This pattern is repeated 10 times over the next 6-week period.

The longwall mix point only had two episodes of high gas concentrations over the same 6-week period (Figure 4-23). A short duration event on 4/16/12 and a longer day-long event on 5/11/12 indicating a higher level of maintenance of the longwall mix point compared to the gob isolation stopping location. This is expected as there would be action taken if the gas concentration were high at the longwall mix point due to its importance as the secondary escapeway for the longwall face.

The two traveling samples lines nearest the longwall (gob isolation and longwall mix point) are the ones that in which MSHA was most interested to detect possible heating source, but these two lines clearly show errors in sampling. The high gas reading from the two traveling locations do not show a corresponding spike at the main return (Figure 4-24) or the longwall return (Figure 4-25) sample locations indicating that they were not moved before the next crosscut was mine through. Therefore the two major spikes recorded at the longwall mix point over the 6-week period were both false readings and any rapid response would have discovered the sample tube line in the wrong location. These spikes demonstrate one of the primary problems with a tube bundle system, the requirement for ongoing maintenance.

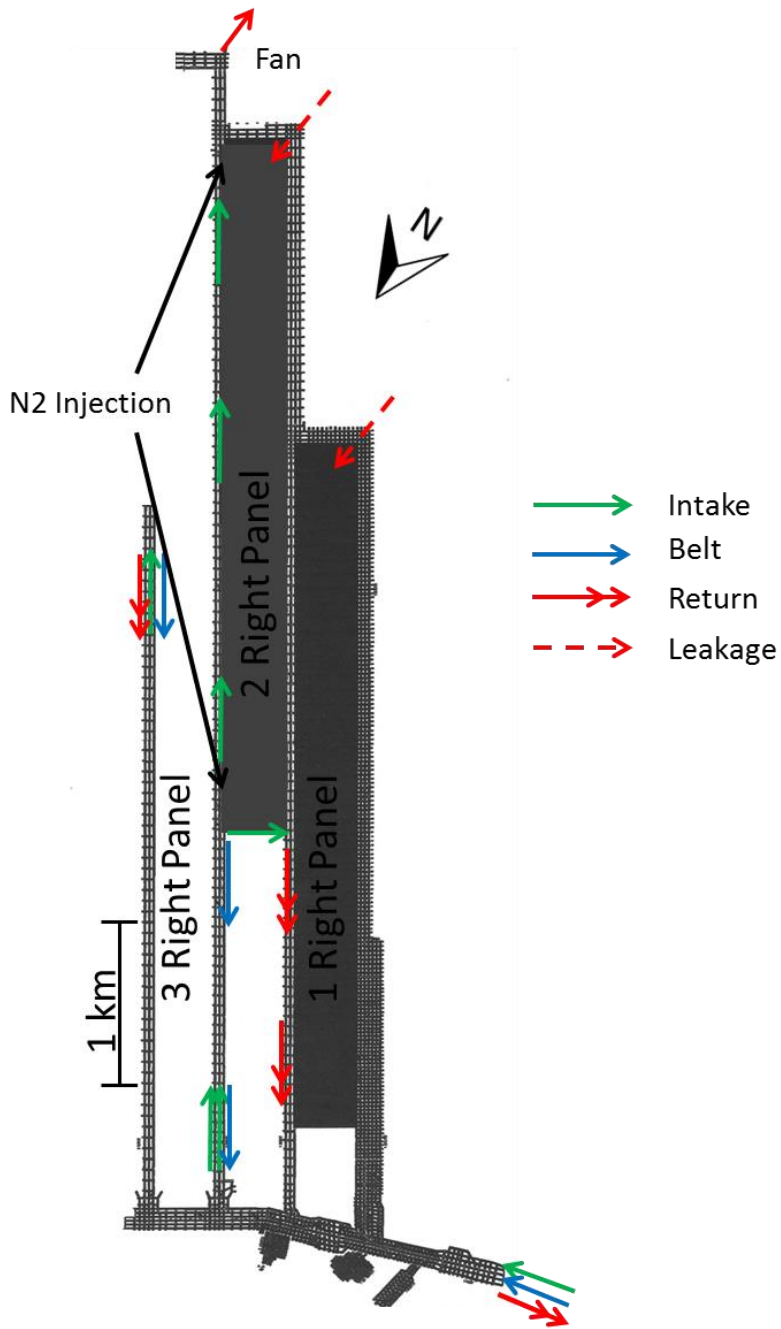


Figure 4-21. Ventilation layout as of April 2012, back return fan installed and nitrogen gas being injected behind the gob isolation seals on the headgate in two locations: at the start of the panel and behind the active longwall face.

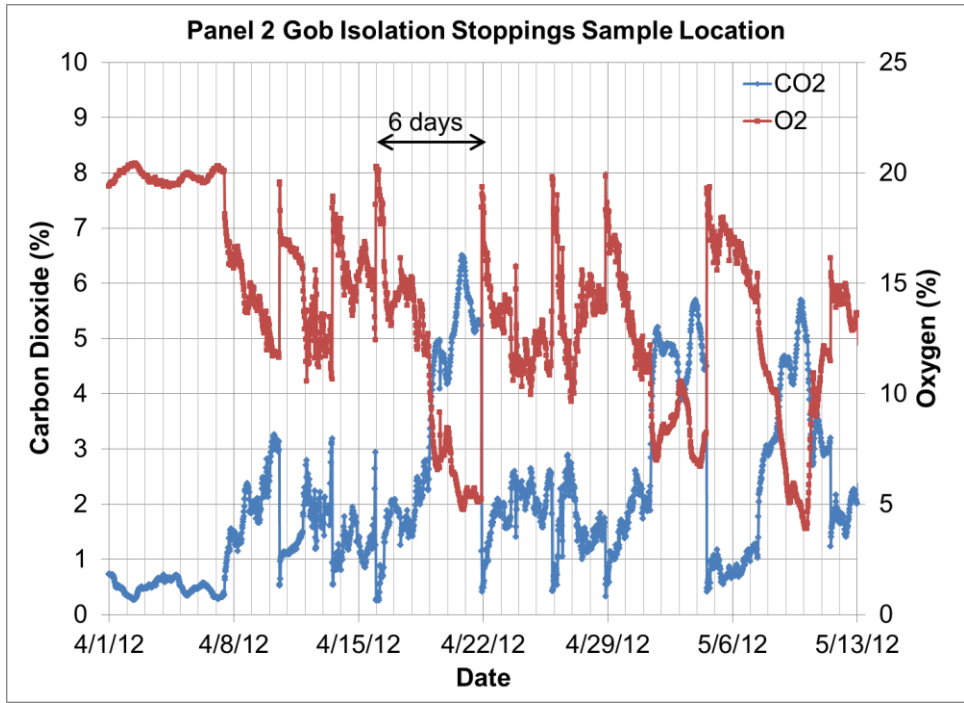


Figure 4-22. Panel 2 gob isolation stopping sampling location left within the gob multiple times. Note the rapid reduction in oxygen concentrations within a few days of installation of stopping across the middle entry.

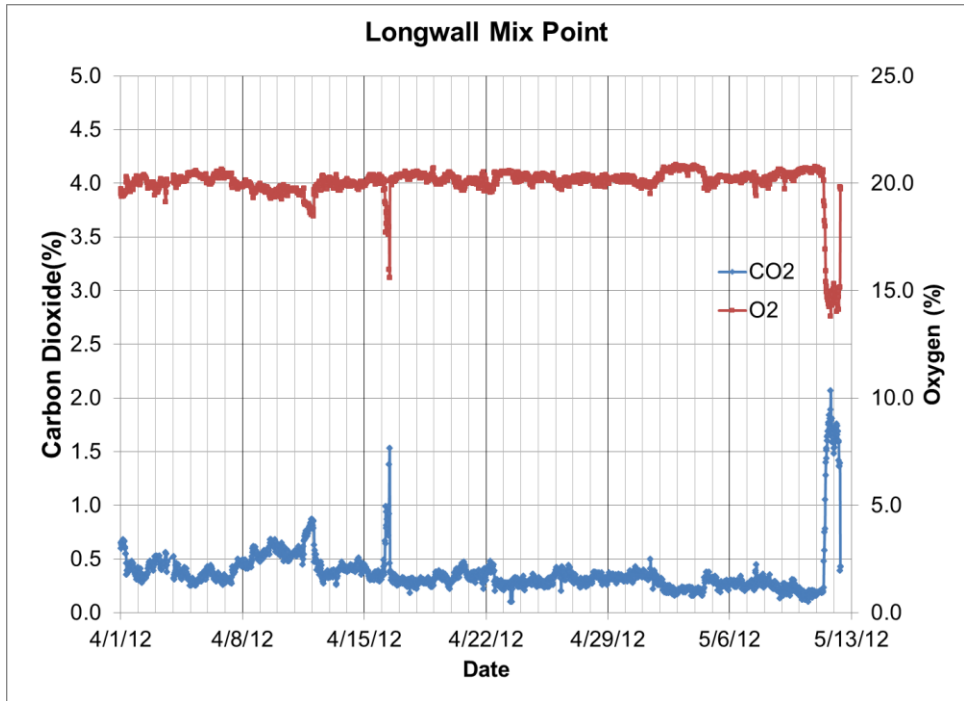


Figure 4-23. Panel 2 mix point showing only two short-term incidences of the sample line being left in the gob.

The main return (Figure 4-24) shows 4 significant events with increased emission levels during the 6-week period. These 4 higher emission recordings from the main return match up extremely well with the longwall return sample location (Figure 4-25). The main return was always above 19.5% oxygen and only above 0.5% carbon dioxide during the 4 high events. The longwall return showed the same 4 events but the oxygen levels were lower at 19.0% and carbon dioxide was higher above 0.6%.

The controlling factor for emission levels on the longwall return appears to be barometric pressure changes over the previous 2 days (Figure 4-26). When the barometric pressure was falling steadily, the carbon dioxide levels in the returns rose steadily. But once the barometric pressure started to level off or rise there was a sharper reduction in emission compared to the falling pressure. This means that gas emissions from the gob rose consistently during falling barometric pressure events but returned to baseline background levels rapidly during a static or rising barometric pressure as the caved material starts to ingas. The sample gas concentration for the longwall return during the 6-week period between 4/1/12 to 5/13/12 is summarized in Table 4-3.

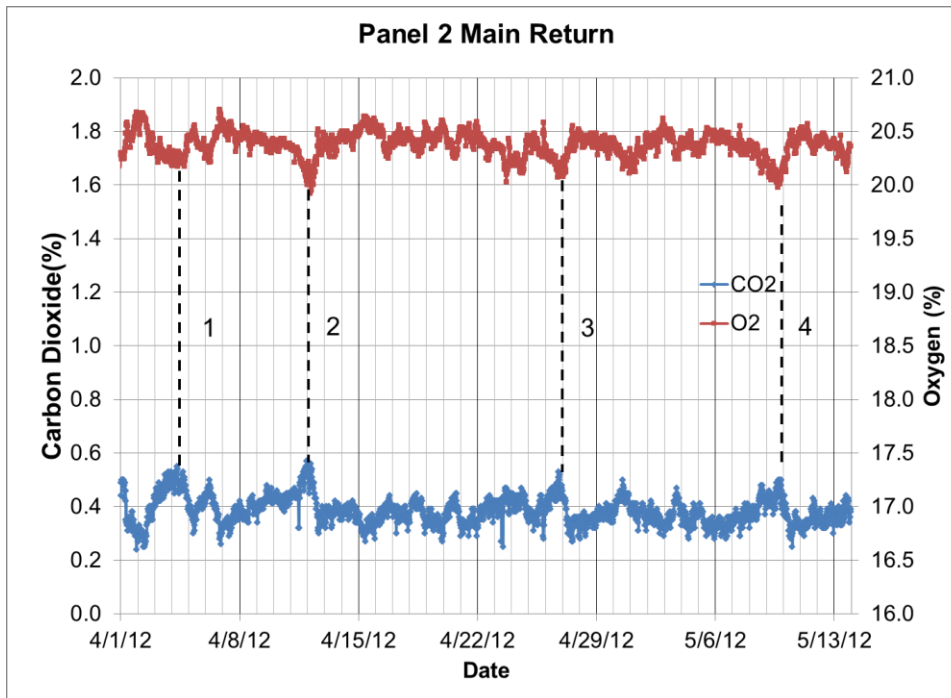


Figure 4-24. Panel 2 main return showing a tighter range of gas concentrations with four label occurrences of higher carbon dioxide and lower oxygen concentrations.



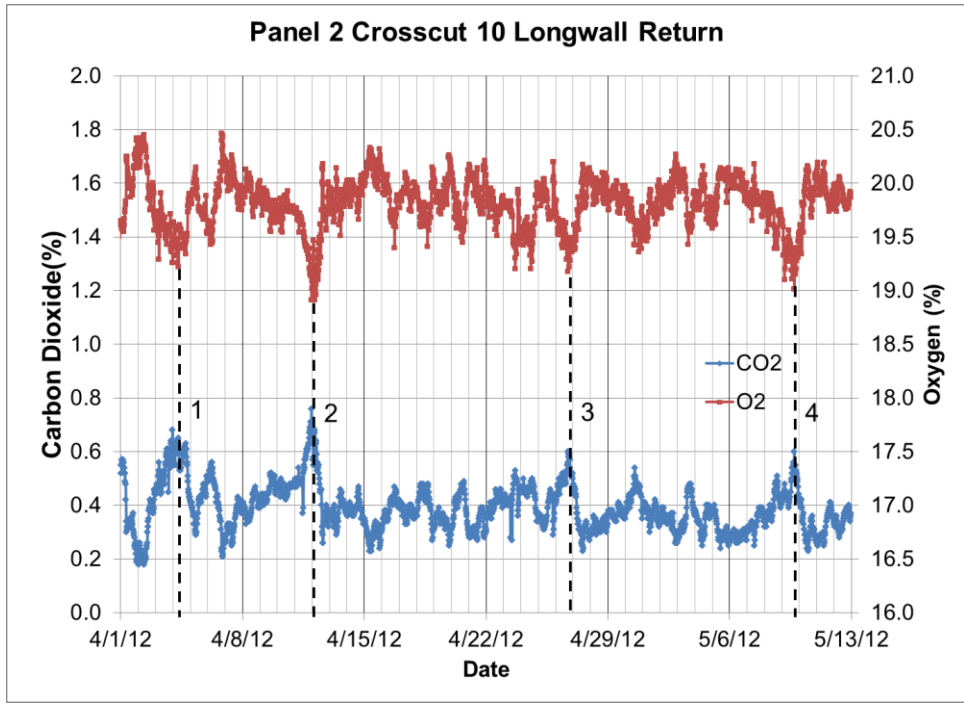


Figure 4-25. Panel 2 crosscut 10 longwall return has a greater range of gas concentrations compared with the main return along with the same 4 labeled occurrences.

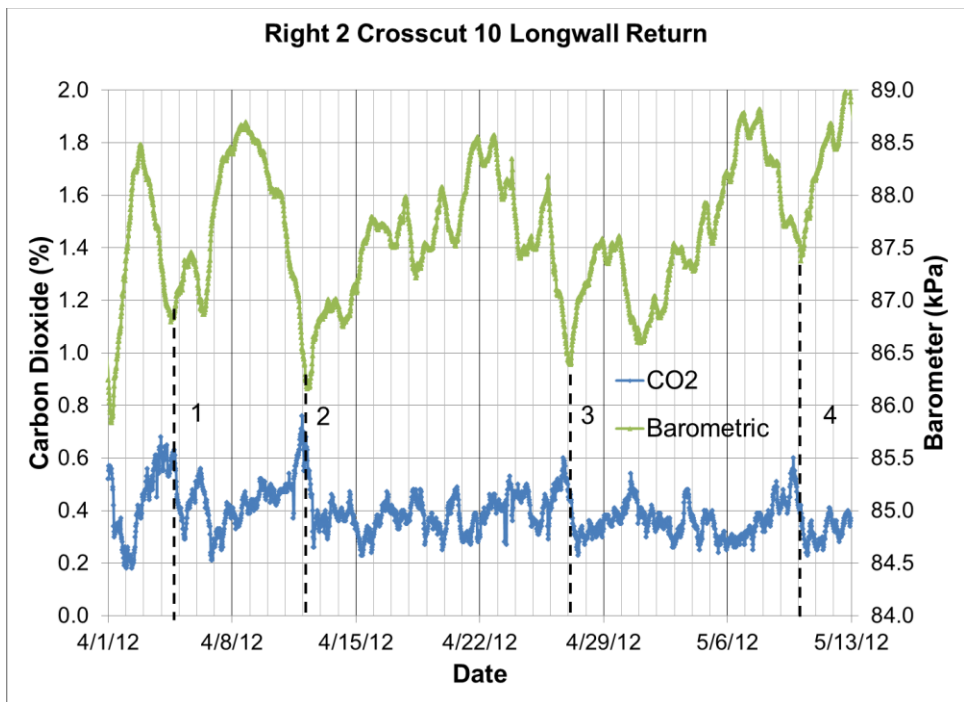


Figure 4-26. Panel 2 crosscut 10 longwall return showing the four highest values of carbon dioxide and the lowest values of oxygen all correspond to rapid and sustained drops in atmospheric pressure.

Table 4-3. Ranges in Longwall return gas composition during test from 4/1/12 to 5/13/12.

Longwall Return	CO <sub>2</sub>	O <sub>2</sub>
Average	0.39	19.81
Max	0.76	20.46
Min	0.18	18.91
Standard Deviation	0.09	0.24

#### 4.2.3 Extraction of the start of Panel 3

The third panel's extraction is significant because the mine transferred from an exhausting ventilation system, using two fan locations, to a blowing ventilation system using a single fan location on 5/27/13 after approximately one third of the panel was mined out (Figure 4-27). The tube bundle system was not operating effectively over the winter months due to freezing of the sample lines. After a trip to the mine site on 4/20/12, the system was brought back on line and the longwall return and section return sample tube lines were installed (Figure 4-28). Given the results from Panel 2, it was determined that the longwall return sample location would again be the most important location. The section return sampling location was added to serve multi purposes. First, as a backup to the longwall return in case it was damaged or offline, second to act as a check for single high spike readings recorded by the longwall return. Third, because the section return takes all the airflow from the longwall return as well as pre-mixing with higher oxygen, lower carbon dioxide airflow it creates a better view of the ventilation system. If a BEP is placed at this location, it will show the perceived benefits of 'adding sweetener' to the return airflow to make the sample airflow to appear to be cleaner. This is a common occurrence with bleeder ventilations systems.

It is important to understand the operating condition of the ventilation system prior to the conversion to a blowing system. During the mining of the start of Panel 3, the ventilation system was under the greatest strain yet for this operation. The mine uses a belt regulator at crosscut 50 to transfer airflow from the #3 belt entry into the #1 entry return. This is done to allow belt airflow to be used outby from the longwall face for the mining of the first half of the panel. With panel lengths of over 5 km, a single belt regulator at the start of the panel would have too much leakage to maintain belt ventilation at the longwall face to be outby and not onto the longwall face. So, the belt regulator crossover at crosscut 50 limits the belt length needed to be ventilated by the belt regulator. The main problem with this setup is that it only used a single intake (#2 intake entry) for the first 50 crosscuts (approximately 3.1 km, 10,200 ft.) of the gateroad. With the back return fan also removing airflow from the longwall headgate location, an

ever greater supply of airflow is required to be pulled from the single intake entry. Relative pressure from the surface to the longwall headgate and tailgate entries increased greatly from 0.5 kPa for Panel 2 to over 0.75 kPa for Panel 3.

The mine still had a fracture network connection to surface near both the startup and recovery room or each of the three mined panels. Also, because of the similar lengths of Panel 2 and 3, there are now over 90 gob isolation stoppings between the two panels some with up to 0.75 kPa (3" w.g.) of pressure across them. The total predicted airflow from these two airflow pathways (fracture network and gob isolation stoppings between panels) was calculated to be between 4-6 m<sup>3</sup>/s (8,000-13,000 cfm).

Leakage through a fracture network and through gob isolation stoppings (laminar flow) is linearly related to differential pressure. Increasing the relative pressure drop from surface to the longwall tailgate location by 50% will increase measured carbon dioxide at the outby longwall mix point and longwall return sample locations. The measured gas concentration in the sealed Panel 2 is similar to the sealed Panel 1 with oxygen concentrations below 2% and carbon dioxide above 18%.

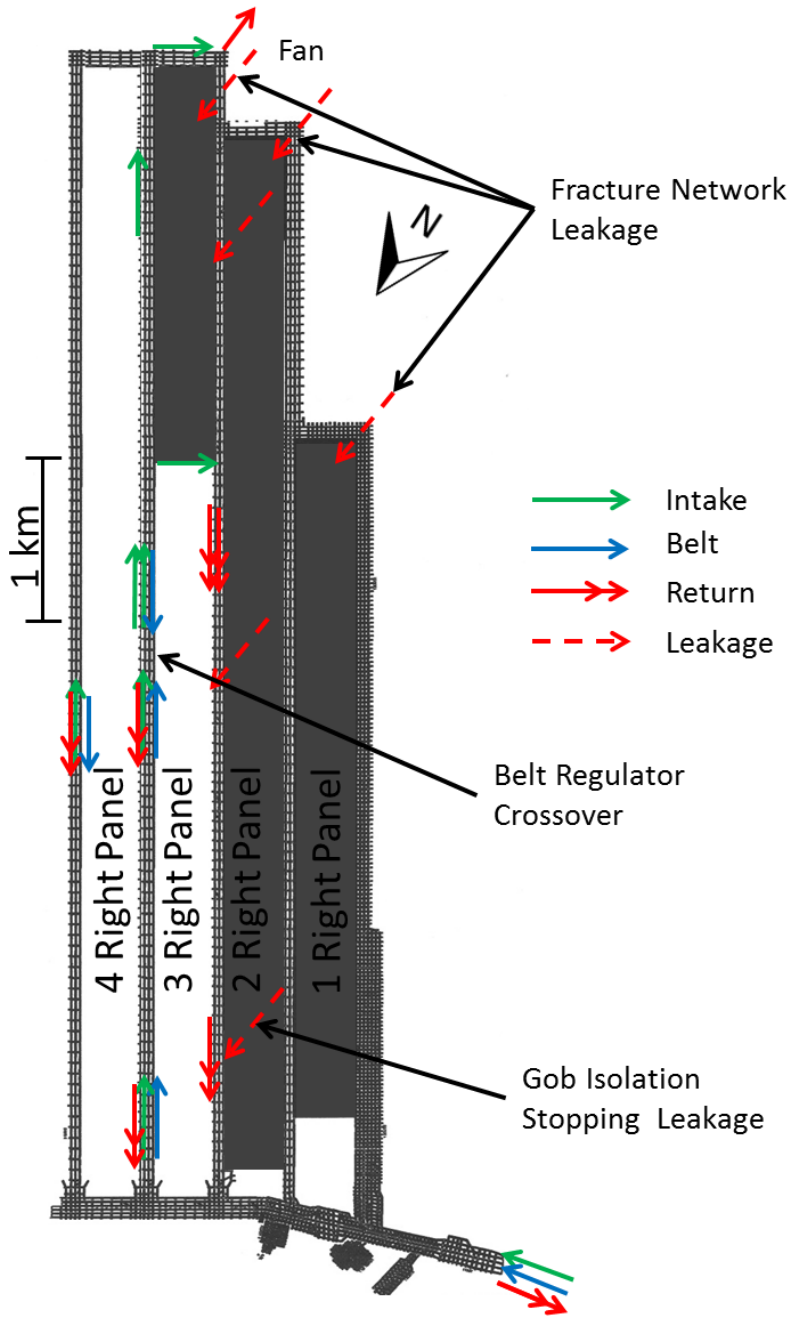


Figure 4-27. Panel 3 mining with exhausting system. The belt regulator crossover limited intake air to only one entry for the first 3.1 km (10,200 ft) of the gateroad. The back return auxiliary fan (not a bleeder fan) also reduced longwall airflow.

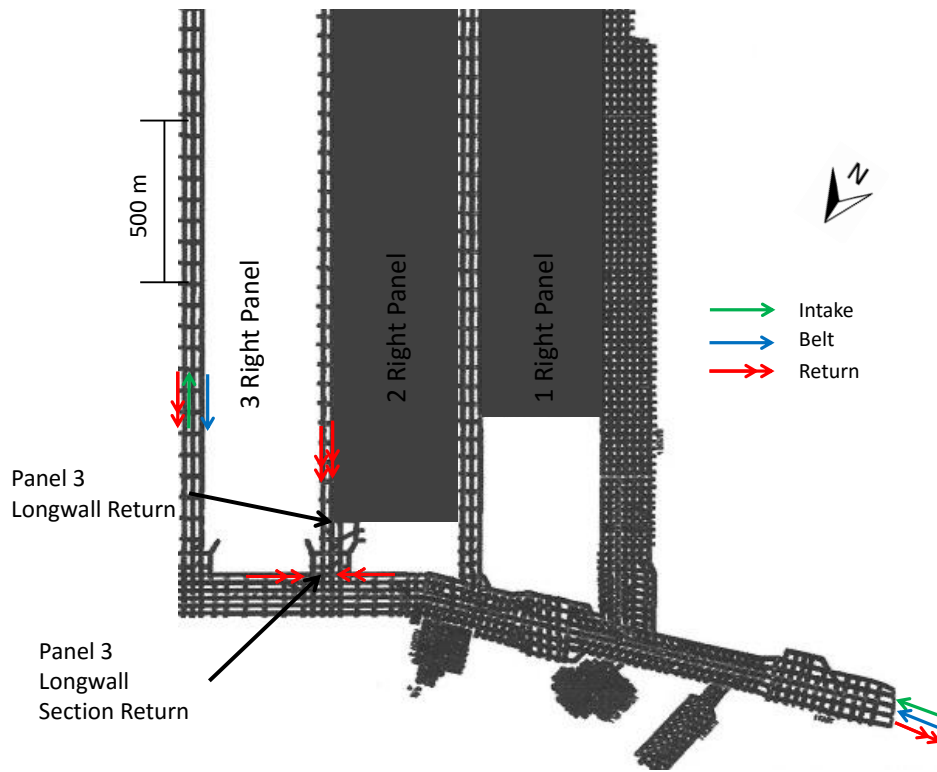


Figure 4-28. Panel 3 layout with longwall return and section return sample locations.

During the mining of Panel 3 from January to May 2013 the longwall extracted approximately 2,200 m (7,200 ft.), or one third of the expected panel length. The ventilation conditions in the middle entry of the tailgate return were ‘problematic’ because of low oxygen readings and changes had to be made. The gob isolation stopping sample location showed high carbon dioxide concentrations for the 19-day period prior to the main ventilation change (Figure 4-29). Sampling showed an inert atmosphere with oxygen concentrations of around 4% and carbon dioxide concentration above 8%. The low oxygen concentrations closely behind the active longwall were a positive sign for reducing the potential of spontaneous combustion. This is one of the primary goals of the injection of nitrogen behind the active longwall face on the headgate side it to create a low oxygen zone that inhibits coal oxidation and heating. The change to a blowing ventilation system on 5/27/13 is also shown in Figure 4-29.

The longwall mix point (Figure 4-30) for the same 19-day period only had one occurrence when it was allowed to remain in the gob and showed a much larger and more dynamic drop in oxygen and higher carbon dioxide (10% and 4%), than was experienced during the mining of Panel 2 (15% and 2%) (Figure 4-23).

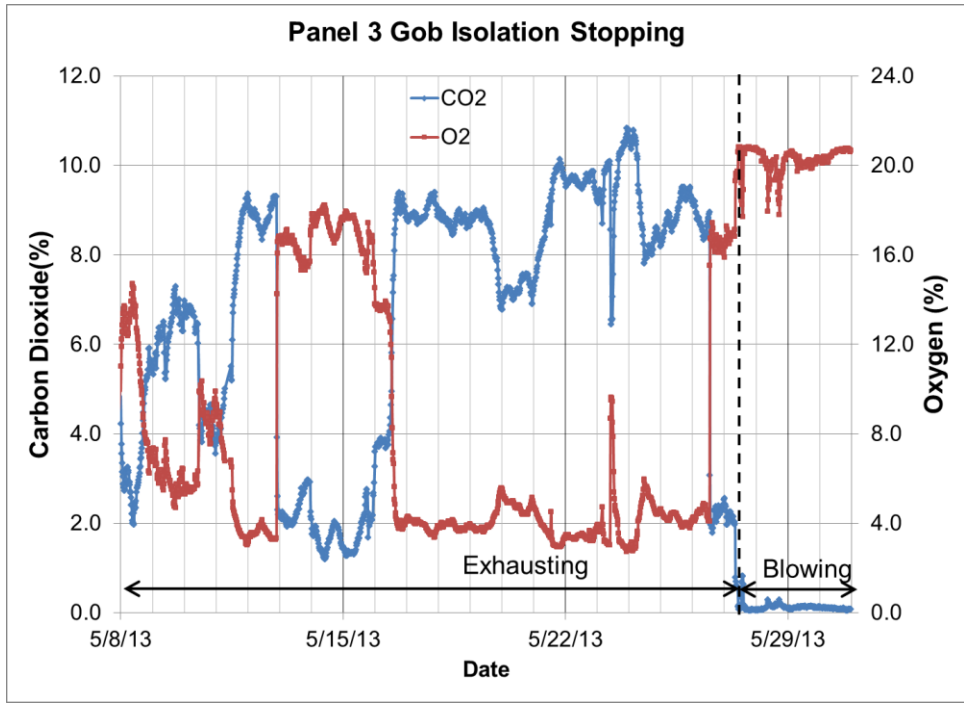


Figure 4-29. Panel 3 exhausting ventilation system at the gob isolation stopping locations showing an inert atmosphere close to the active longwall.

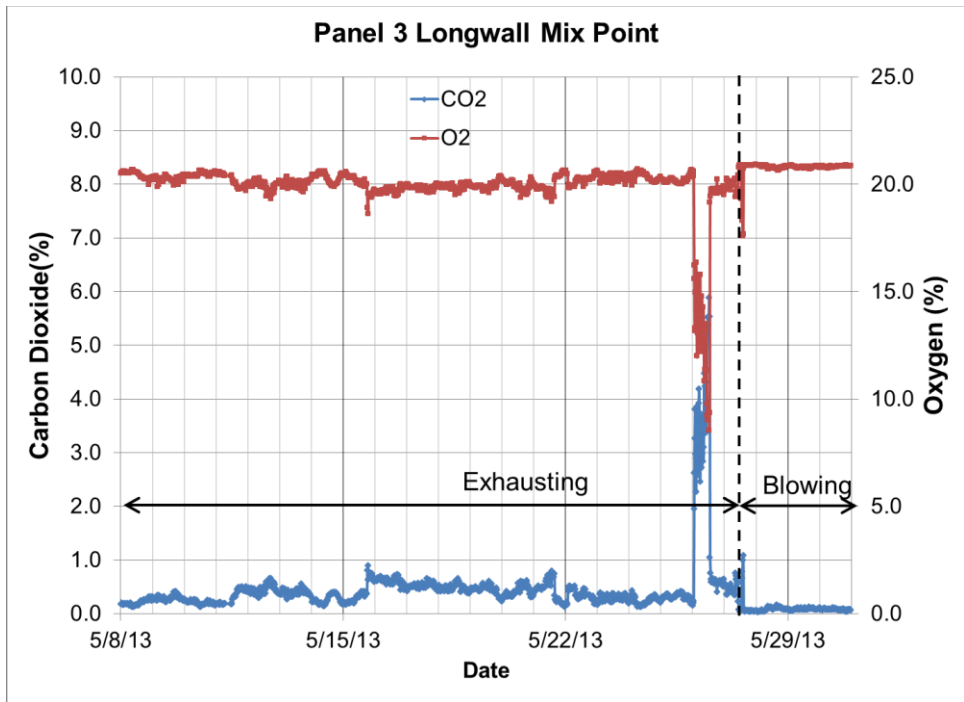


Figure 4-30. Panel 3 exhausting ventilation, longwall mix point.

The longwall return during the mining of Panel 3 had a much higher average and peak carbon dioxide concentration than while mining Panel 2 (Figure 4-31). Oxygen concentrations below

19.5% carbon dioxide occurred 91% of the time for the 19-day period, while on two occasions falling to below 18%. This was unacceptable to the mine. Therefore, on 5/27/13, the mine converted to a blowing system. The controlling factor for the gas concentration in the longwall return was again the barometric pressure changes. Even the smaller pressure drops shown in Figure 4-32 of 0.5 kPa, over a 24-hour period, caused carbon dioxide concentrations to nearly double. A rising barometric pressure would cause the carbon dioxide concentration to drop from 1.8% to 0.6% in a 12-hour period.

The main return sample tube that was used during the mining of Panels 1 and 2 was not available for the mining of Panel 3. A second sample line (section return), located 150 m (500 ft) from the longwall return, was used as the backup sample location (Figure 4-33). Two other return airflows from the #7 entry (belt return access drifts from either side of the longwall return) added 12 m<sup>3</sup>/s (25,000 cfm) of low carbon dioxide airflow (measured at 0.1% or less with hand-held sensors). This mixing of cleaner airflow with higher concentration airflow from the longwall return creates a sample location which shows improved atmospheric conditions for the section return (Figure 4-34).

It should be repeated that this is not a required MSHA measuring location and the mine had no intention of trying to use a sweetener in this ventilations system. This is simply a common way of ventilating a mine and using an overcast multiple times during many phases of the ventilation system history. The fact that this setup at the mouth-of-the-section looks similar to the back side of a bleeder ventilation system that uses sweetener to lower high concentrations of airflow being emitted from entries between panels, could not be discounted. The section return location is equivalent to a sample location downstream of pre-mixing airflows, which reduces gas concentrations and makes the ventilation system appear to operate more effectively. For example, in Figure 4-34 the longwall return had oxygen concentrations above 19.5% only 9.2% of the time over the 19-day period, while the section return was above 19.5% oxygen 41.9% of the time. This is a significant increase in average atmospheric concentration just by moving the sampling location 152 m (500 ft) outby with is in effect a single crosscut that allows pre-mixing of airflows to produce a higher average oxygen content.

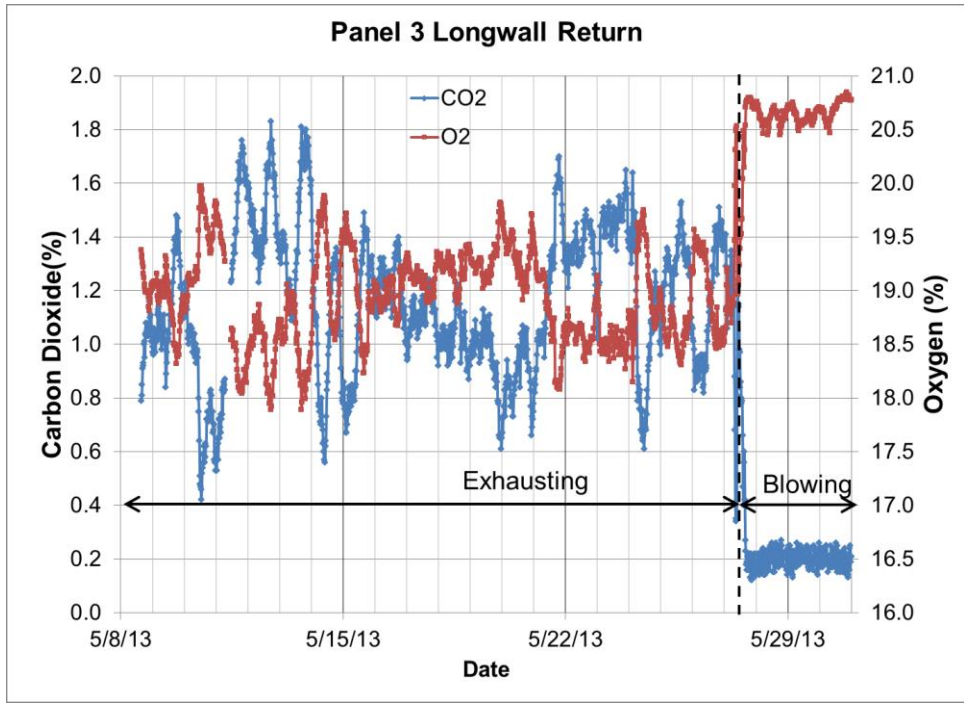


Figure 4-31. Panel 3 longwall tailgate return during exhausting ventilation. Excessive leakage from the Gob Isolation Stoppings reduced oxygen and elevated carbon dioxide levels in this entry.

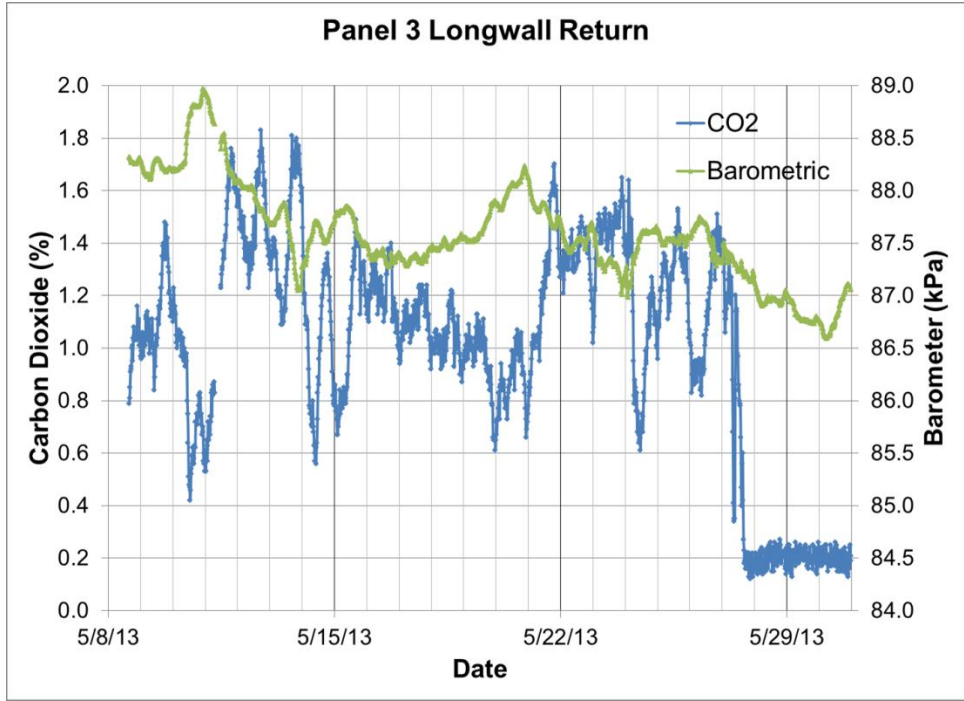


Figure 4-32. Panel 3 carbon dioxide concentration related to barometric pressure changes during mining of Panel 3 with the exhausting ventilation system.



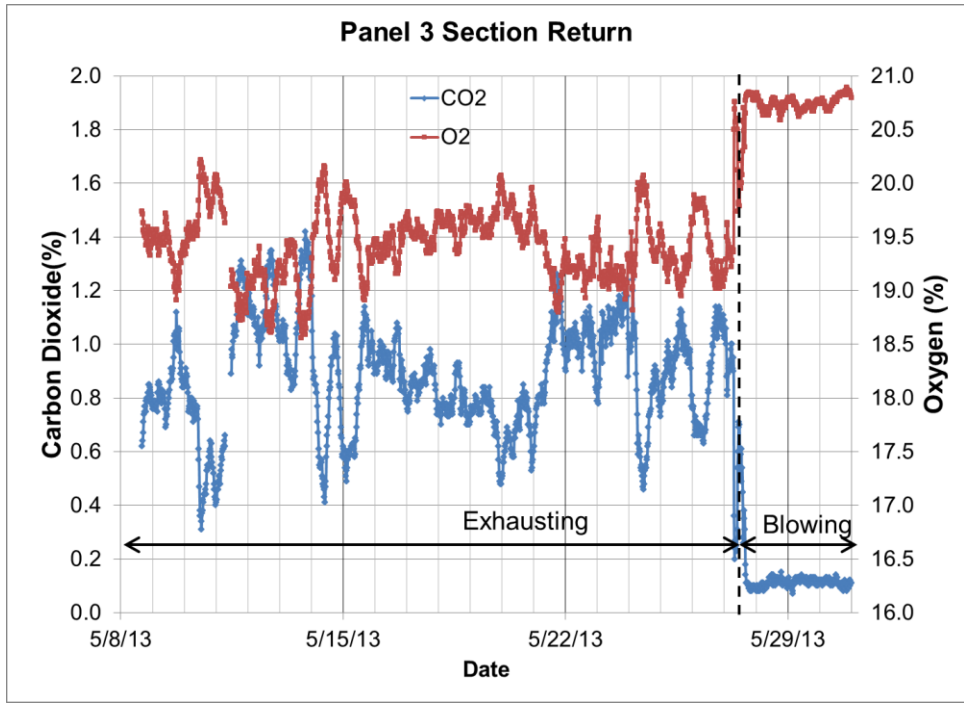


Figure 4-33. Panel 3 Section Return showing that the mixing of fresh air with longwall return air improves the quality and reduces the standard deviation.

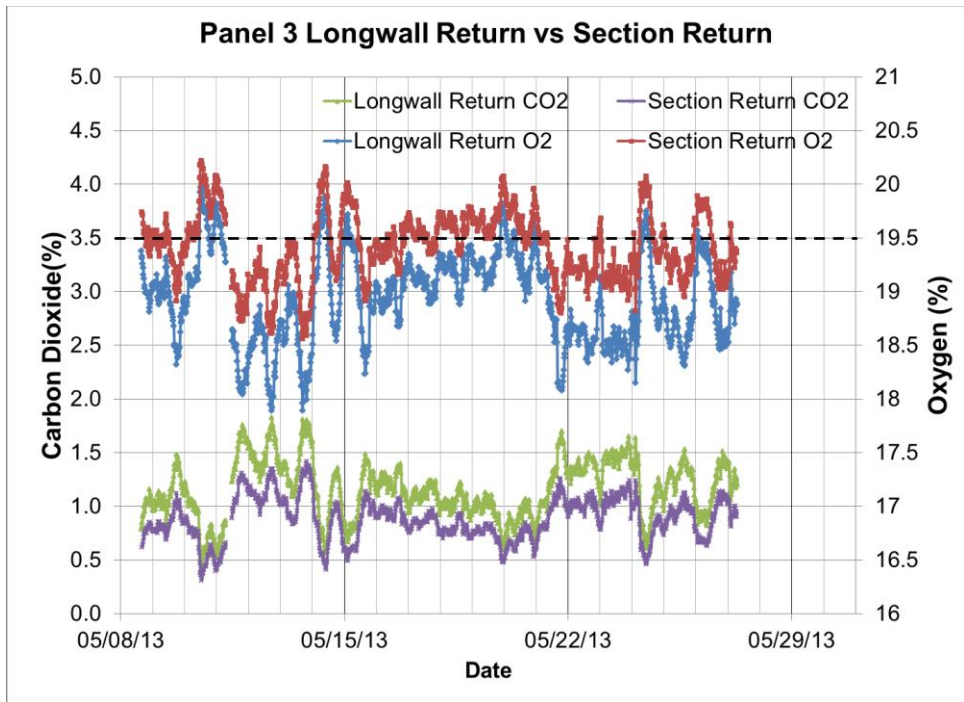


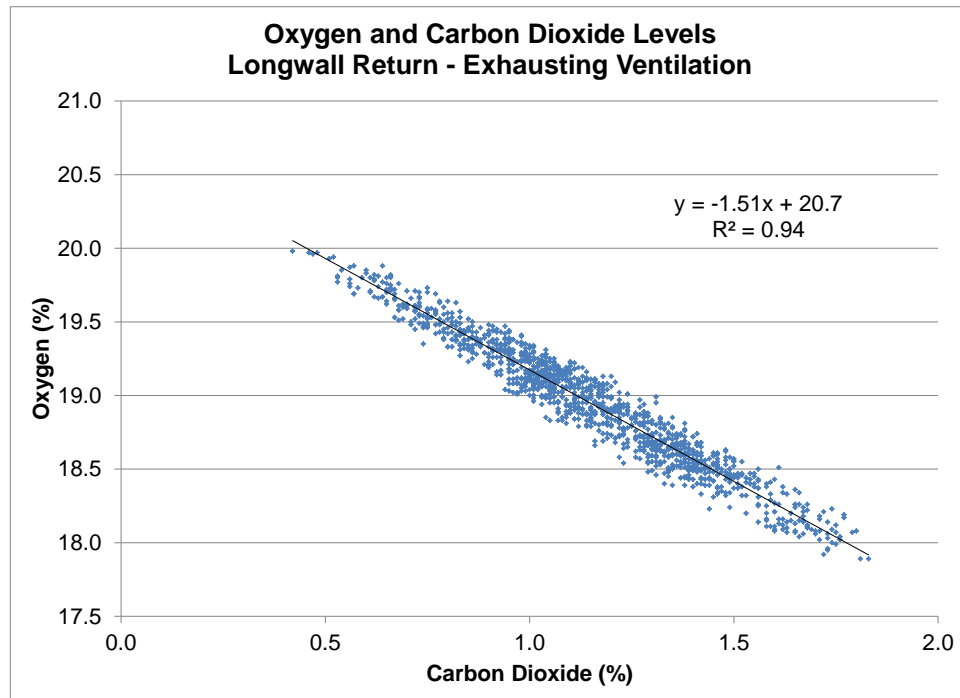
Figure 4-34. Oxygen concentration between the longwall return and the section return with added cleaner air. The 19.5% oxygen level is achieved more often with sweetener added.

During the 19-day period between 5/8/13 to 5/27/13, the difference between the longwall return and the section return gas concentrations is summarized in Table 4-4. Because of the pre-mixing of multiple airflows before the section return sampling location, its average, maximum, minimum concentrations as well as the standard deviation are all improved from an engineering management perspective. But, the sample airflow recorded in the longwall return is the preferred location to determine the effectiveness of the bleeder ventilation system.

Table 4-4. Three weeks of gas concentration data of longwall return and section return, during mining of panel 3 with exhausting ventilation system. 5/8/13 to 5/27/13

Longwall Return	CO <sub>2</sub>	O <sub>2</sub>
Average	1.16	18.9
Maximum	1.83	20.0
Minimum	0.42	17.9
Standard Deviation	0.27	0.42
Section Return	CO <sub>2</sub>	O <sub>2</sub>
Average	0.88	19.4
Maximum	1.42	20.2
Minimum	0.31	18.6
Standard Deviation	0.20	0.32

In Figure 4-34, oxygen and carbon dioxide for both the longwall and section return follows the same trend because of the high correlation between oxygen and carbon dioxide in the longwall



return as shown in

Figure 4-35 with a  $R^2$  of 0.94. In this situation either carbon dioxide or oxygen can be used to quantify the quality of the airflow leaving the longwall return.

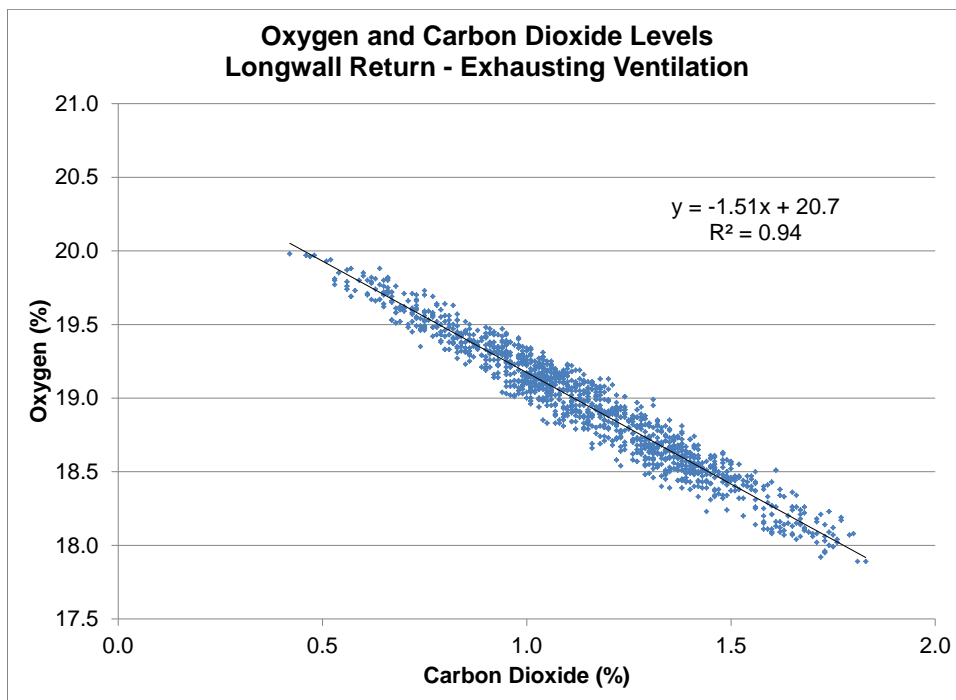


Figure 4-35. Correlation between oxygen and carbon dioxide at the LW return during mining of Panel 3 with exhausting ventilation between 5/8/13 to 5/27/13.

#### 4.2.4 Exhausting to blowing ventilation system

An intake shaft was installed in the mains between the gateroads of the future Panel 4. Figure 4-36 shows the layout of the ventilation system on 5/27/13 when the switch to a blowing system was completed. The ventilation change outcome was a dramatic reduction in total carbon dioxide emission level in the Panel 3 longwall return as well as higher oxygen levels (Figure 4-41). The probability that the previous fracture networks from the start and end of the panels to the surface remains in the current and all future panels; therefore, with the blowing system the airflow direction will now be from the gob to surface. This reversal of airflow direction would have a dramatic reduction in average carbon dioxide concentration levels measured at the longwall return. In a truly static atmospheric case, 4-6  $m^3/s$  would be leaving the gob via the fracture network system and through the almost 90 gob isolation stoppings to the previous panel, and will not arrive at the longwall mix or longwall return sample locations. Assuming that the gob's gas concentration would be at least as high as the inby samples taken by the gob isolation stopping when left within the gob after the next stopping is installed. The concentration would be at least 10% carbon dioxide and below 5% oxygen and, at the low end of 4  $m^3/s$ , that

equals 0.4 m<sup>3</sup>/s carbon dioxide not being channeled to the longwall return. The flow rate in the middle #2 entry in the longwall gateroad return was measured at 40-45 m<sup>3</sup>/s (85,000-93,000 cfm) during exhausting ventilation with 8 to 10 m<sup>3</sup>/s (17,000-21,000 cfm) exhausting down the parallel #1 (secondary escapeway). After the conversion to a blowing system, the airflow in the #2 entry increased to 50-53 m<sup>3</sup>/s (105,000-112,000 cfm), while the airflow in the #1 entry remained the same. Therefore, using the conservative values of 4 m<sup>3</sup>/s of 10% carbon dioxide being diluted by 45 m<sup>3</sup>/s of airflow, the expected average carbon dioxide concentration reduction measured at the longwall return in entry #2 would be expected to drop by  $0.4/45 \text{ (m}^3\text{/s} / \text{m}^3\text{/s)} = 0.9\%$  carbon dioxide. The average carbon dioxide concentration at the longwall return during exhausting ventilation was calculated to be 1.16% (Table 4-4). The change to a blowing system was predicted to reduce average carbon dioxide concentration in the longwall return to under 0.25%.

As of 5/27/13, Panel 3 had been mined approximately 2650 m (8700 ft.) which is close to 40% of the total panel length of 6860 m (22,500 ft.). In Figure 4-36, the fracture networks to surface are shown along with the leakage across the 90 gob isolations stoppings between Panels 3 to 2. The small fan at the back of the bleeder system was removed and replaced with a regulator. Airflow through the caved material is shown flowing away from the longwall face and towards the surface fracture network near the start of Panel 3. This airflow in the caved material was not directly measured. The belt regulator and overcast in the headgate at cross-cut 50 is also still in operation.

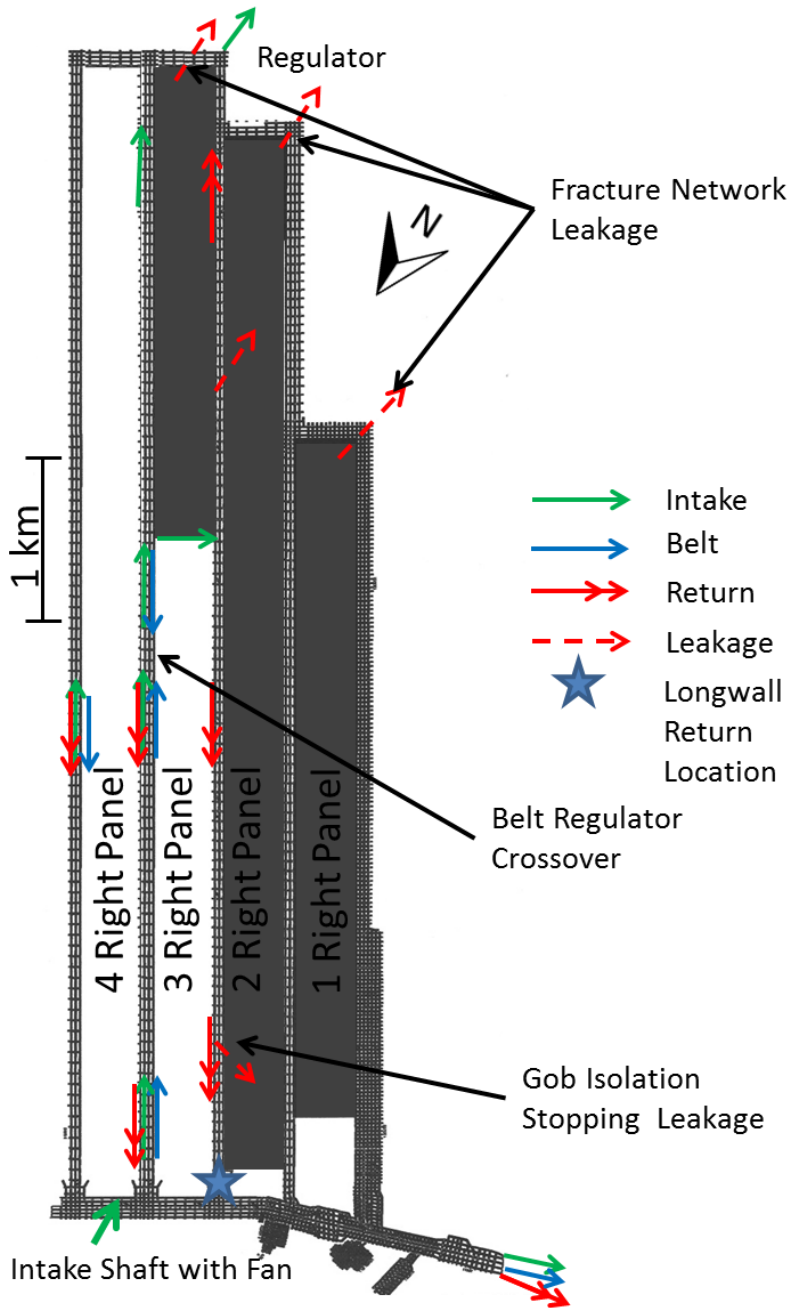


Figure 4-36. Location of intake shaft with blowing fan.

The gas concentration at the gob isolation stopping sample location were much lower during the 4-week period after the blowing ventilation was in operation (Figure 4-37). Oxygen concentrations dip to below 12% but the carbon dioxide remained below 2.5%. Of note are two events on 6/14/13 and 6/19/13. The first is an expected spike in emissions and the other has the

previous look of a line being cut after a stopping was installed. However, the 6/19/13 is not related to a stopping installation or the gob isolation stopping sample line being cut.

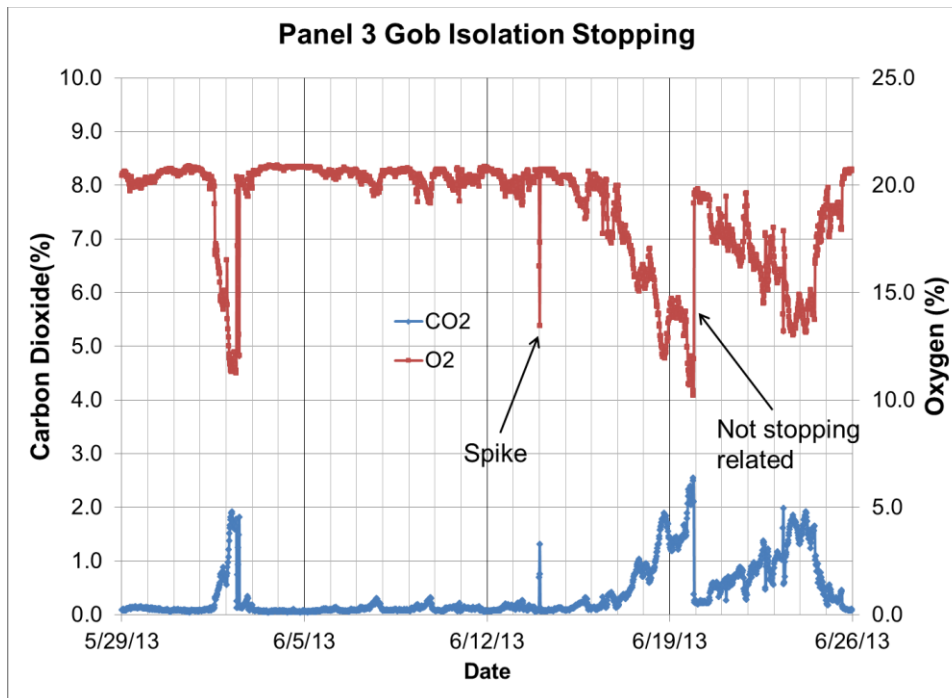


Figure 4-37. Panel 3 blowing the gob isolation stopping has reduced carbon dioxide levels but also with similar low oxygen levels. The rapid drop in Carbon dioxide and corresponding increase in oxygen on 6/20/13 is not related to the installation of gob stopping or cutting of the sample tube.

After conversion to a blowing system, the longwall mix point shows a single case of the sample tube being left behind in the gob, on 6/2/13, along with two spikes as shown in Figure 4-38. The average oxygen levels are much higher than during the exhausting system (Figure 4-30). The two spikes at the time were caused by an unknown event but because of previous examples of the lines being left in the gob before cutting this was assumed to be the reason.

The longwall return also shows a dramatic improvement in air quality with oxygen well above 19.5% for the majority of the 4-week period (Figure 4-39). Further, the reduction in carbon dioxide concentration was extreme when compared to the exhausting system (Figure 4-31). The same two spikes show up at the longwall return as seen at the longwall mix point indicating that they are not caused by the sample tube line being cut late. The rapid increase in oxygen at the end of 6/29/13 was also recorded at the longwall return as well as the gob isolation stopping. This was not caused by a stopping being installed.

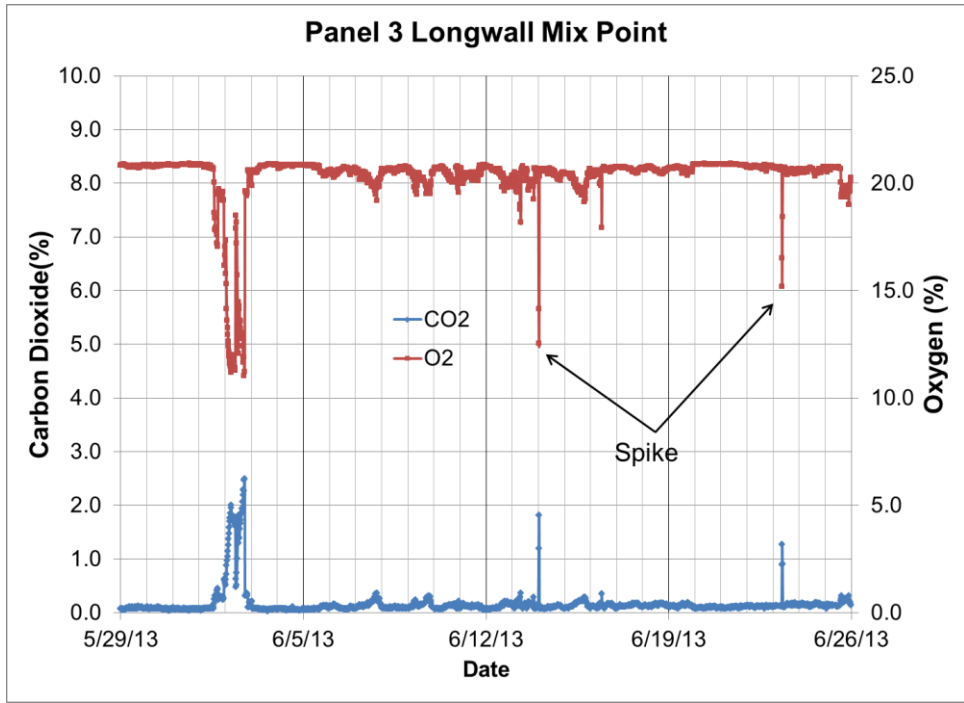


Figure 4-38. Panel 3 blowing, mix point with two short term spikes and one case of the tube not being moved up during mining for a day (6/2/13).

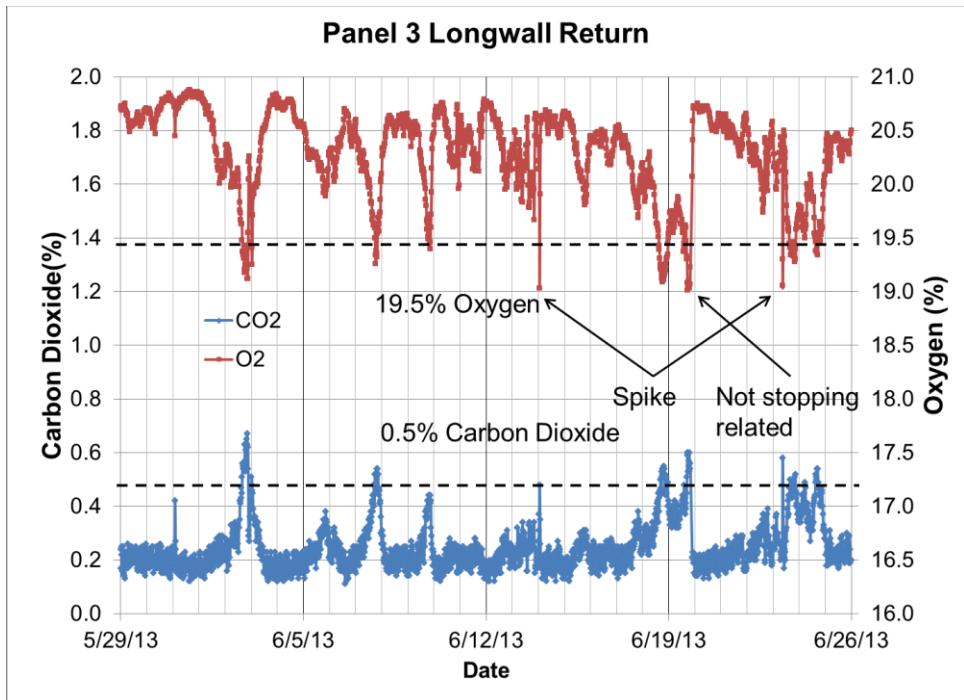


Figure 4-39. Panel 3 longwall return after the blowing ventilation system was operational with lower carbon dioxide levels and higher oxygen levels.

The section return, as shown in Figure 4-40, perfectly mirrors the longwall return after mixing with cleaner airflow from the #1 entry the recovery rooms. The air quality results for the section return and the longwall return are shown in Table 4-5. The longwall return average value of 0.24% carbon dioxide during blowing ventilation is 21% of the average value of 1.16% under exhausting ventilation. The longwall section return for the same period had average carbon dioxide that fell from 0.88 to 0.16%. This is 18% of the previous value.

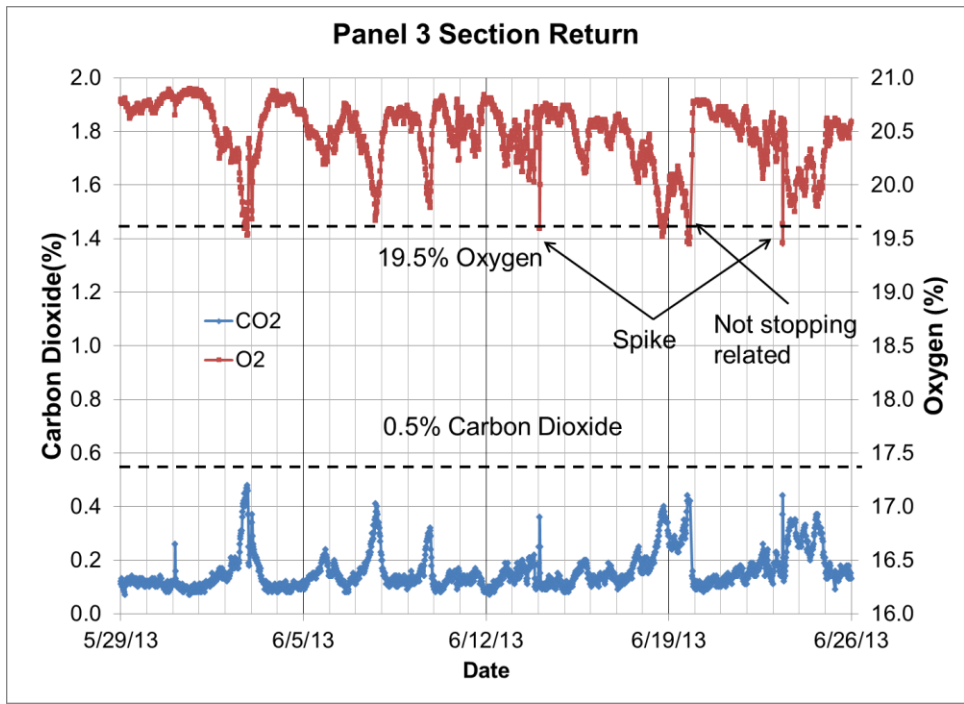


Figure 4-40. Panel 3 blowing, section return with approximately 25% mixing of clean air reduced almost all samples to below required levels. This would be a classic case of adding 'sweetener' to the ventilation system.



Table 4-5. Panel 3 gas concentration during blowing ventilation for the longwall return and section return during a 4-week period between 5/29/13 to 6/26/13.

Longwall Return	CO <sub>2</sub>	O <sub>2</sub>
Average	0.24	20.32
Maximum	0.67	20.88
Minimum	0.11	19.01
Standard Deviation	0.09	0.38
Section Return	CO <sub>2</sub>	O <sub>2</sub>
Average	0.16	20.48
Maximum	0.48	20.9
Minimum	0.07	19.45
Standard Deviation	0.07	0.28

Figure 4-41 shows the easily recognizable connection between dropping barometric pressure and increased gas emissions from the gob. Once the barometer stops falling and stabilizes or starts to rising, there is a rapid reduction in emissions back to the baseline. During stable and rising barometric pressures, the emissions from the gob appear to be quite stable and formed a baseline emission level of approximately 0.2% CO<sub>2</sub>. During the evening of June 19<sup>th</sup>, after 2.5 days of the barometer steadily falling from 88.36 to 86.278 kPa, the atmospheric pressure started to rapidly increasing 0.5 kPa in 3 hours, from 86.278 to 86.578 kPa. Carbon dioxide concentration dropped from 0.56% to 0.21% in 2 hours, which is a 62.5% reduction. Previously, during a sharp pressure rise after a persistent drop in pressure, the carbon dioxide levels would drop quickly but not to the same extreme rate as shown in 6/19/13. The rise in carbon dioxide concentration at the longwall return after the blowing system was installed, is not just a function of the average drop in barometric pressure over the previous 12 hours. It appears, that any increase in barometric pressure resets the carbon dioxide emissions to the baseline within 2 hours. This is an outcome due to the normal movement of longwall face airflow being pulled back towards the setup room by the surface fracture network give the fact that now the caved material is at a higher relative pressure to atmosphere due to the blowing ventilation system. Only during long and consistent falling barometric pressure events does the gob now exhaust onto the longwall tailgate corner and into the longwall return.

The ventilation setup 5/27/13 was in fact a hybrid ventilation system that has both the properties of a bleederless and a bleeder system. The gob is kept in a low oxygen environment (bleederless) with a consistent amount of airflow being pulled (syphoned) from the back of the panel by the fracture network (similar to bleeder). The system currently has excellent airflow at

the longwall tailgate return, and from sampling around the Panel 3 gob a low oxygen concentration within the gob.

The lower carbon dioxide concentration recorded at the longwall return mean that the correlation between oxygen and carbon dioxide is not as high with the blowing system as the exhausting system (see Figure 4-42).

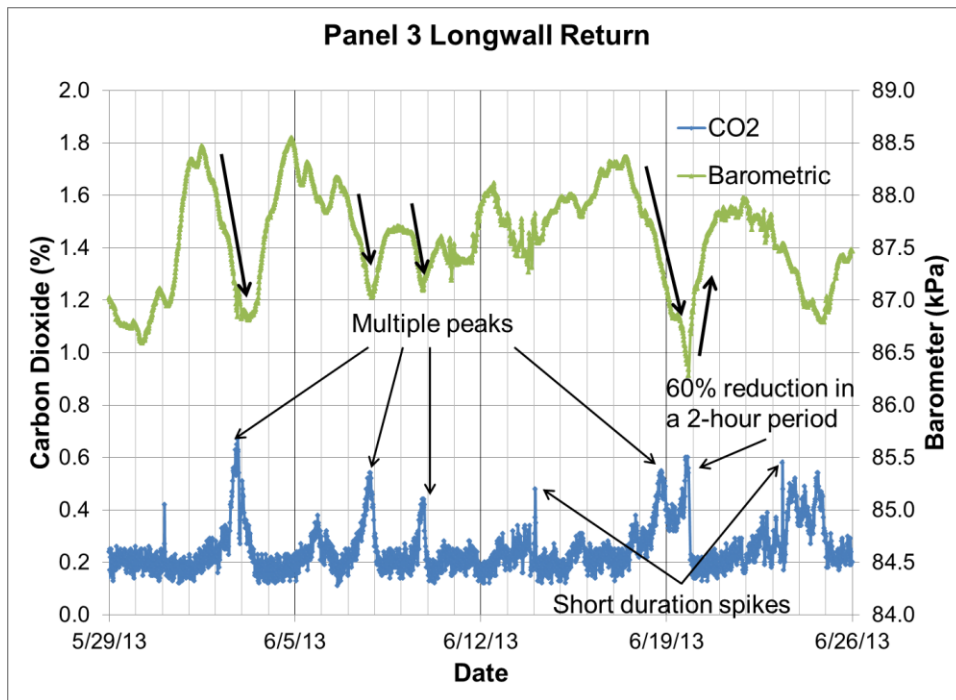


Figure 4-41. Panel 3 blowing, longwall return showing the control that barometric pressure changes had on emission levels. The 60% reduction in carbon dioxide levels in less than 2 hours was a function of rapid atmospheric pressure changes and not the installation of a gob isolation stopping.

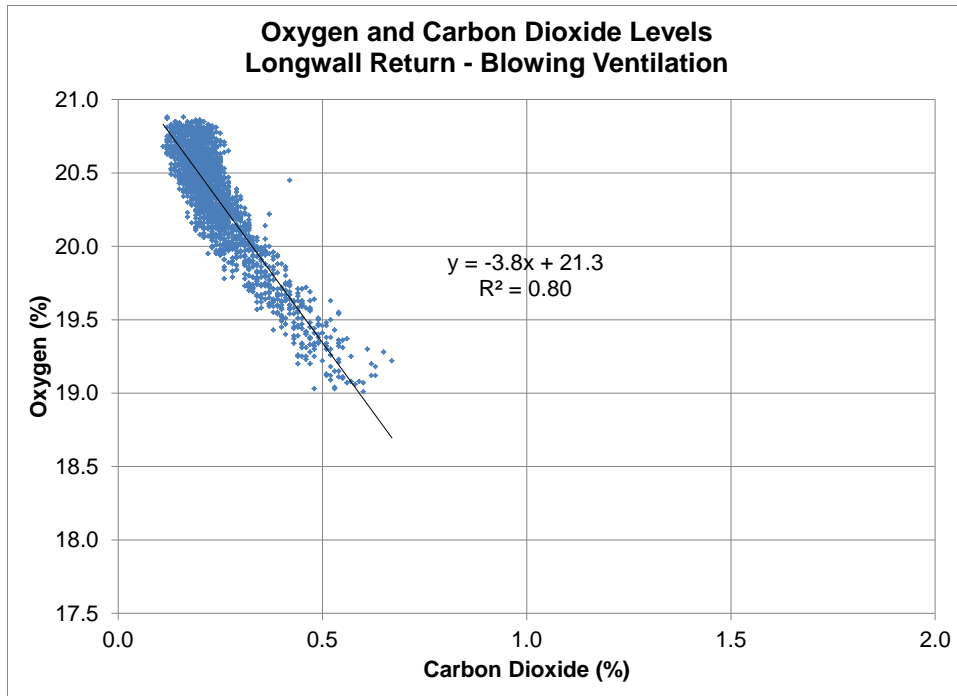


Figure 4-42. Correlation between oxygen and carbon dioxide at the LW return during mining of Panel 3 with blowing ventilation.

#### 4.2.5 Fan stoppage or startup

Any system that takes over 1 million samples is going to have a few unexpected measurements spikes. The two unknown spikes recorded in Figure 4-38 and Figure 4-39 are not explained by stopping construction or barometric pressure drops. These spikes were interesting because they were not just isolated readings, but appeared over many sampling locations at the same time. The reason for these anomalous readings became clear on 8/18/13. Figure 4-43 shows the longwall return for Panel 3 mining with a clear spike on 8/18/13 when oxygen drop to 15%. Since the conversion to a blowing ventilation system on 5/27/13, the average oxygen concentration was rarely below 19.5% and the recorded value of 15% oxygen on 8/18/13 looks like an unexpected spike. Similarly, the gob isolation stoppings (Figure 4-44) and the longwall mix point (Figure 4-45) were investigated and found to have similarly low oxygen levels of 10% and 12% respectfully, therefore, this was not an isolated spike reading at the longwall return. The longwall section return (Figure 4-46) also showed the same low oxygen spike.

It was determined that the cause for the outgassing at the tailgate corner of the longwall was a fan stoppage for maintenance, which took 4 hours to complete. The reduction in pressure of the gob when the fan stopped blowing caused a rapid outgassing on to the longwall tailgate corner and possibly onto the face as well. The low oxygen slug of airflow that covered the gob isolation

and longwall mix point did not reach the longwall return until after the main fan was re-started (Figure 4-46). Once the blowing fan restated, the caved void re-compressed and returned to normal while the low oxygen slug left the mine via the tailgate entry and main return. This event had no significant change in barometric pressure prior to the spike and in fact the pressure was rising the previous 6 hours (Figure 4-47).

The 4-hour long fan stoppage was much longer than the previous shorter weekly tests. However, it was found that these short fan tests can explain the short duration spikes caught previous. With a sampling rate of approximately 30-minutes during the mining of Panel 3, it is expected that any short term fan stoppage of less than 15-minutes, will not be detected by the tube bundle system. The 4-hour long stoppage on 8/18/13 clearly shows one possible side-effect of a blowing system, the outgassing of the gob during a fan outage. Therefore, it seems clear that all efforts must be made to remove all personal from the longwall face and any personal in the longwall tailgate return if any fan stoppage occurs.

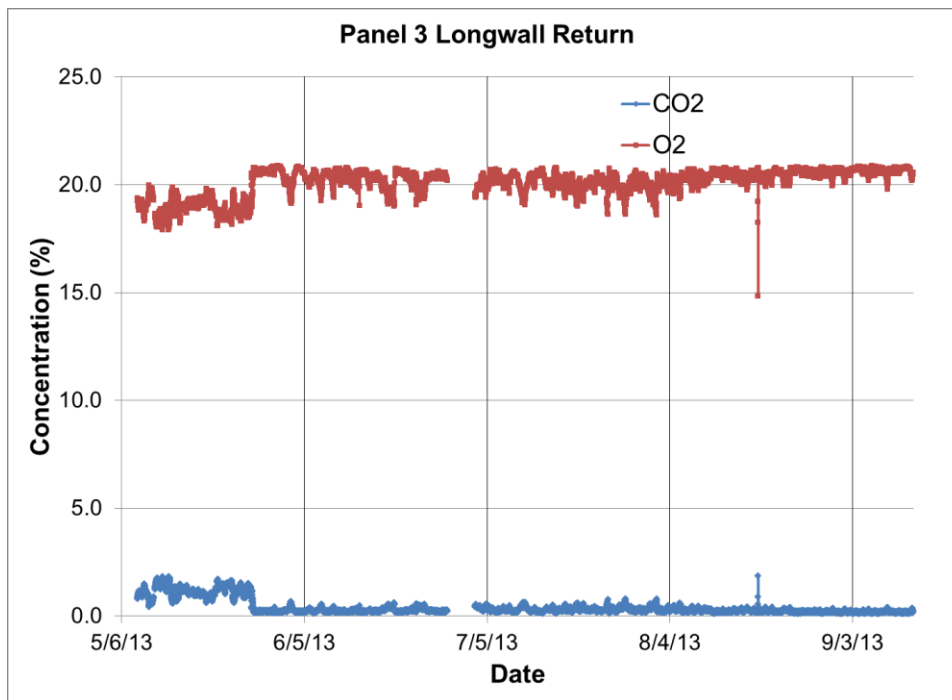


Figure 4-43. Gob outgassing during a fan stoppage (8/18/13) at the longwall return.

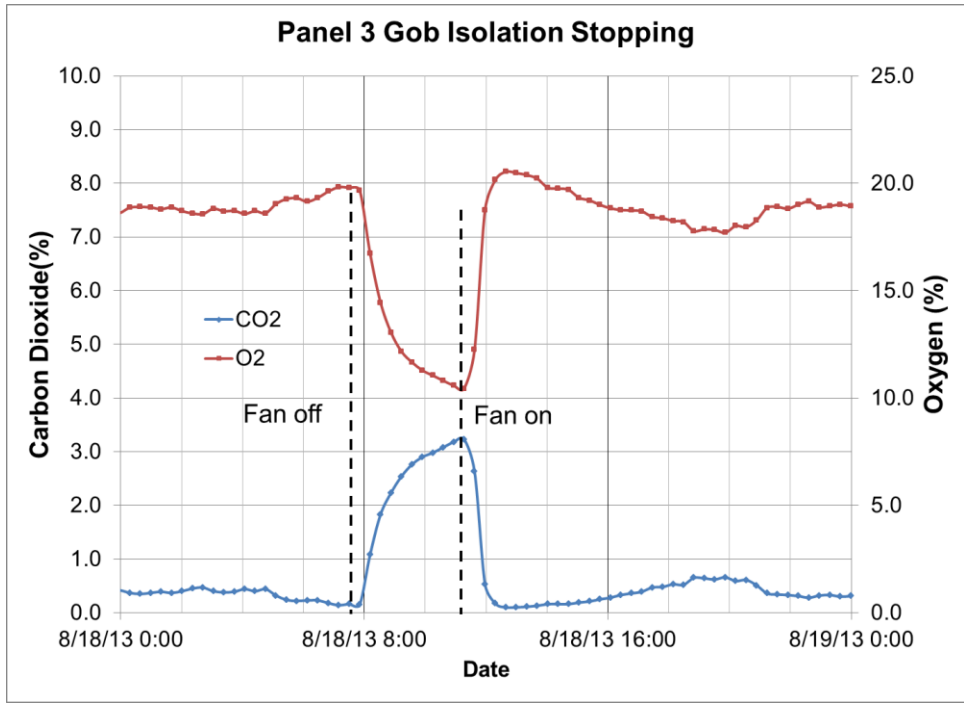


Figure 4-44. Gob outgassing during a 4-hour long fan stoppage at the gob isolation stopping. Note the almost half hour transit delay along the sample tube lines.

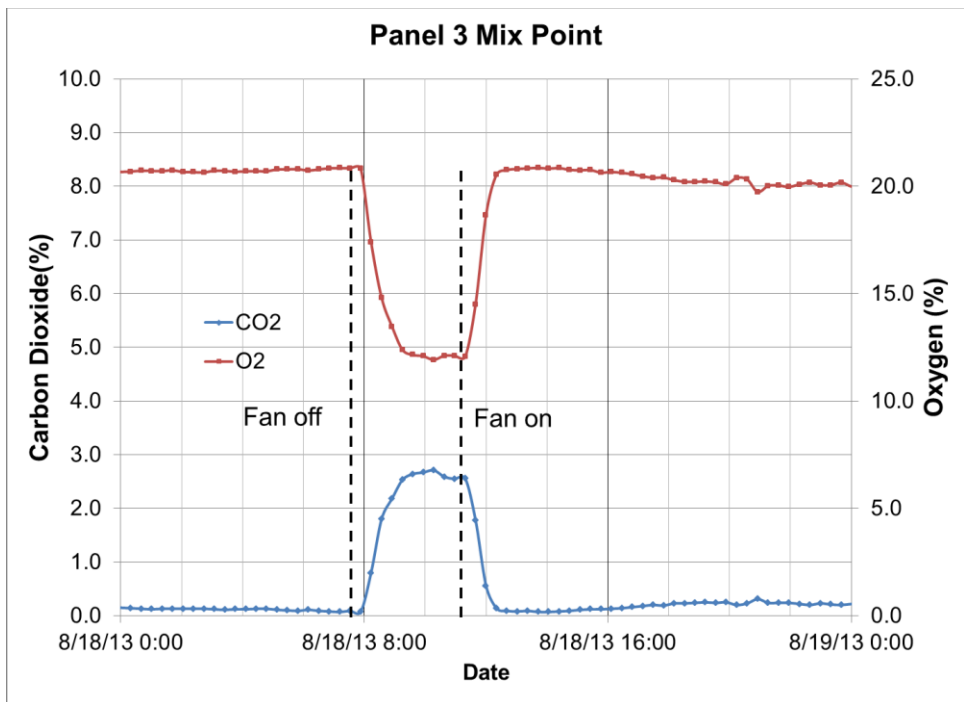


Figure 4-45. Gob outgassing during a fan stoppage at the Panel 3 mix point. Note the almost half hour transit delay along the sample tube lines.

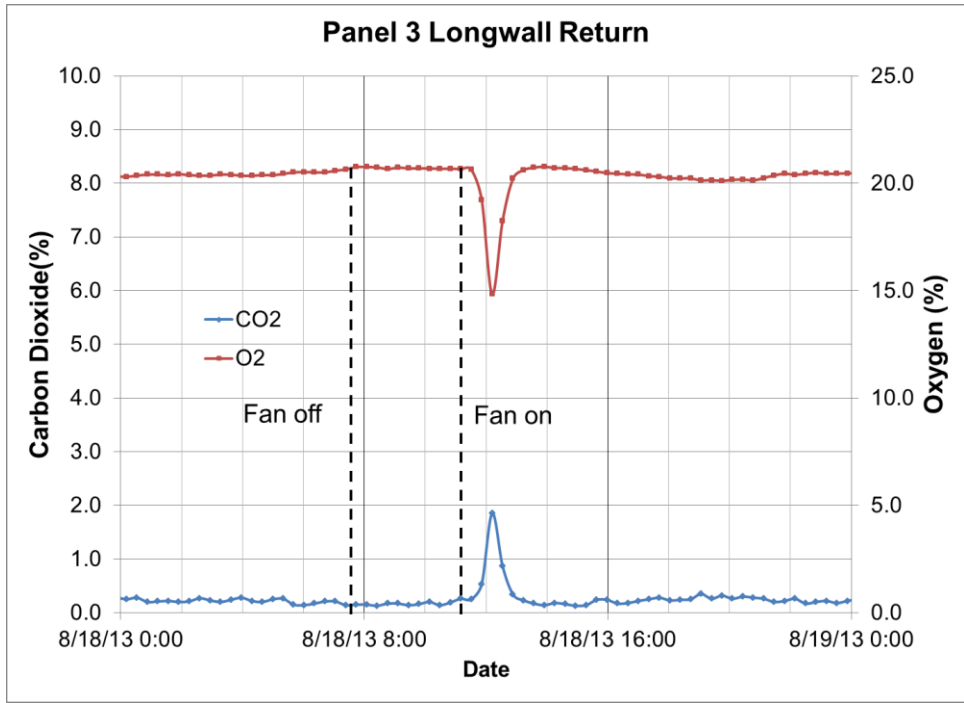


Figure 4-46. Gob out gassing event at the longwall return. Note the low oxygen did not arrive at this location until after the main fan was turned back on.

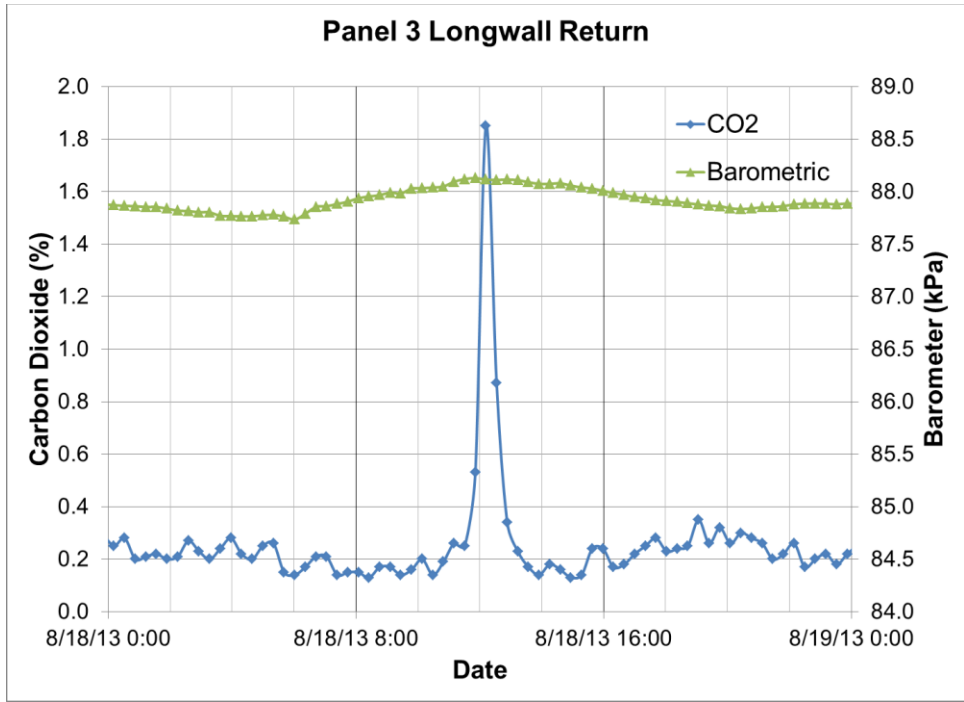


Figure 4-47. Panel 3 Longwall return with barometric data showing a rising pressure during fan stoppage.

### 4.3 Lessons learned from Mine A

The tube bundle system, over the 3-years it was in operation, shows highly variable emission levels from the active panel on a daily, and even hourly, basis that would not be recorded with just daily or weekly gas readings. Gas emission levels from longwall panels are not static and have a high variability that may not be adequately addressed by a ventilation system that assumes a static case while using a factory of safety. Further, the large range in emissions levels of the 3-year study show a high correlation to atmospheric pressure changes. Long-term falling barometric pressures were shown to regularly double the emission levels for the active longwall panel, and from the mine as a whole. Within an hour of the barometric pressure holding steady or rising, the measure emission rate would rapidly return to the normal.

### 4.4 Bleeder system operating at Mine B

Mine B extracts the Pittsburgh #8 coal seam using a four panel district and a bleeder ventilation system. During this investigation, three tracer gas tests along with methane/oxygen/carbon dioxide samples, were used to analyze potential airflow pathways and methane migration through the bleeder system. The tracer gas releases determined the retention times and pathways of the inaccessible regions of the bleeder system, while methane gas concentration data and total flow rate allowed for the determination of the mass balance of methane, which ultimately allowed for the determination of the airflow rates and methane concentrations within the caved material itself.

The bleeder system at this mine has many parallel entries that can transfer airflow from the walkable outer bleeder, inner bleeder, middle entry between two panels, caved material-pillar intersection, and finally the non-uniform caved material itself (see Figure 4-48). The three tracer gas tests show that bleeder evaluation points located close to the walkable outer bleeder entry gives little indication as to the gas concentration being released from the caved material due to multiple pre-mixing of airflows before the BEP is encountered.

The release point, which is shown in Figure 4-48 for Tests 1 and 2, was important because all intake airflow for every sample point except the bleeder fan passed through this location. This property allowed for calculation of recovery percentages of the tracer gas at all locations, including the bleeder fan, based on the following assumptions: perfect mixing at the release location, a closed system with no other intakes except at the IEP (Intake Evaluation Point) at LW #1 TG, and minor stopping leakage. These assumptions are reasonable with airflow velocities of over 6.1 m/s (1,200 ft/min) at the release point, and with no other intake path

besides minor stopping leakage and the airflow passing through Mixing Point #1, which was dumped directly into the low-pressure outer bleeder entry with no possibility to interact with other sampling points. Every sampling location, regardless of airflow quantity and given enough time, should have the same integrated area under the SF<sub>6</sub> concentration vs. time curve (Figure 4-49 and Figure 4-50). This integrated area function is a result of all the intake airflow passing through the release point, for the first two tests, and the assumption that bleeder system generates a preferred airflow pathway throughout the bleeder system without recirculation. Each location will not receive the same quantity of SF<sub>6</sub> but will receive the same integrated concentration and time area. These integrated areas multiplied by the measured airflow quantity determine the standard recovered volumes of SF<sub>6</sub> at each location. These are compared to the expected recoveries that are based on the integrated area of the release location. Direct airflow quantity measurements were not possible at the sample locations within the caved zone (TG 1 and HG 2) but could be estimated based on arrival times and assumed cross-sectional areas.

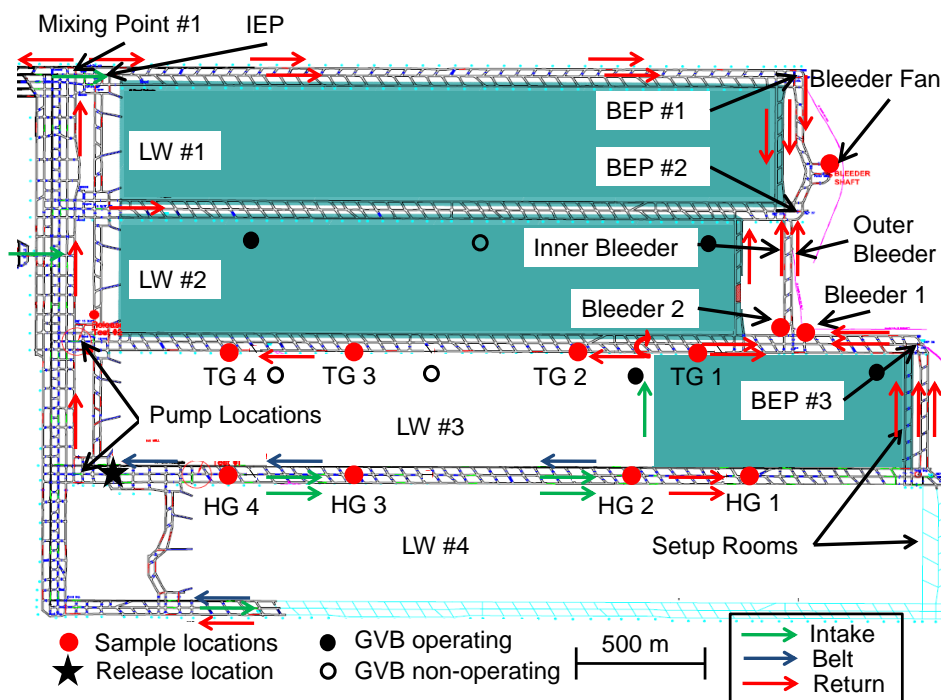


Figure 4-48. Mine B ventilation layout during Test 1.

#### 4.4.1 Test 1

Arrival times of the tracer gas, corrected for sample tube transportation times, at all the sampling locations, are shown in Figure 4-49. The high-speed airflow (over 3.6 m/s (700 ft/min) traveling down the headgate carries the tracer gas to the sample locations. No tracer gas were



detected in any of the samples at the four operating gob vent boreholes during Test 1 but their operation is important to the total methane emission for the district (Figure 4-48).

The SF<sub>6</sub> concentrations over time are shown in Figure 4-50. The HG 1 sample location was in the longwall headgate corner and shows little exchange of ventilation airflow between the gob and the intake airflow (HG 2), as represented by the same decline rate as HG 2. If there was a significant interaction with the caved material between HG 2 and HG 1 a second arrival time at HG 1 would have been observed but it was not. A curtain in the #2 entry close to the longwall headgate causes little air interaction with the longwall gob corner as airflow passed through this corner to reach HG 1 located in the #2 entry.

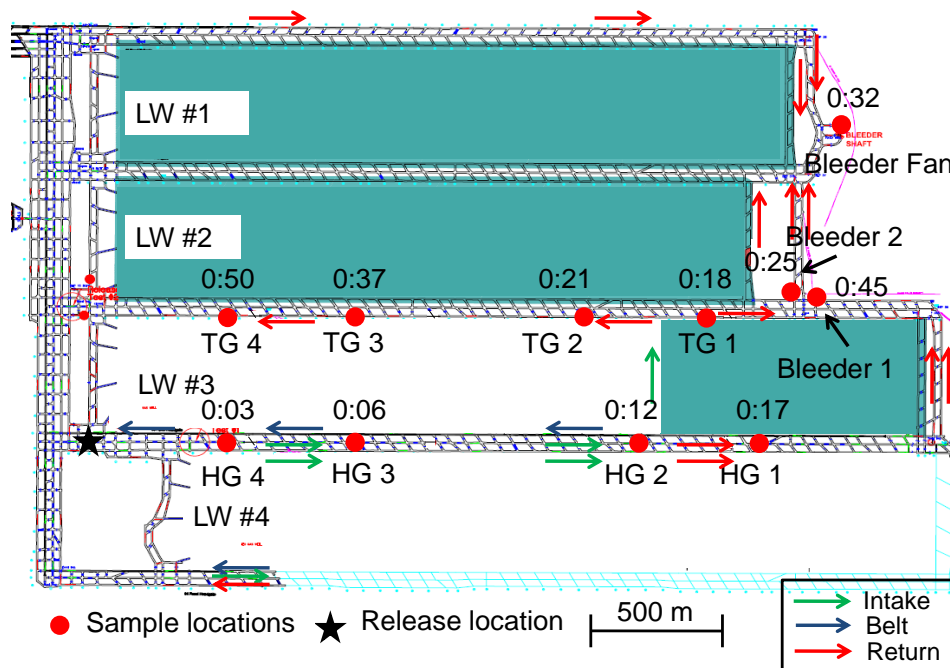


Figure 4-49. Test 1 first arrival times (h:mm) for sample locations.

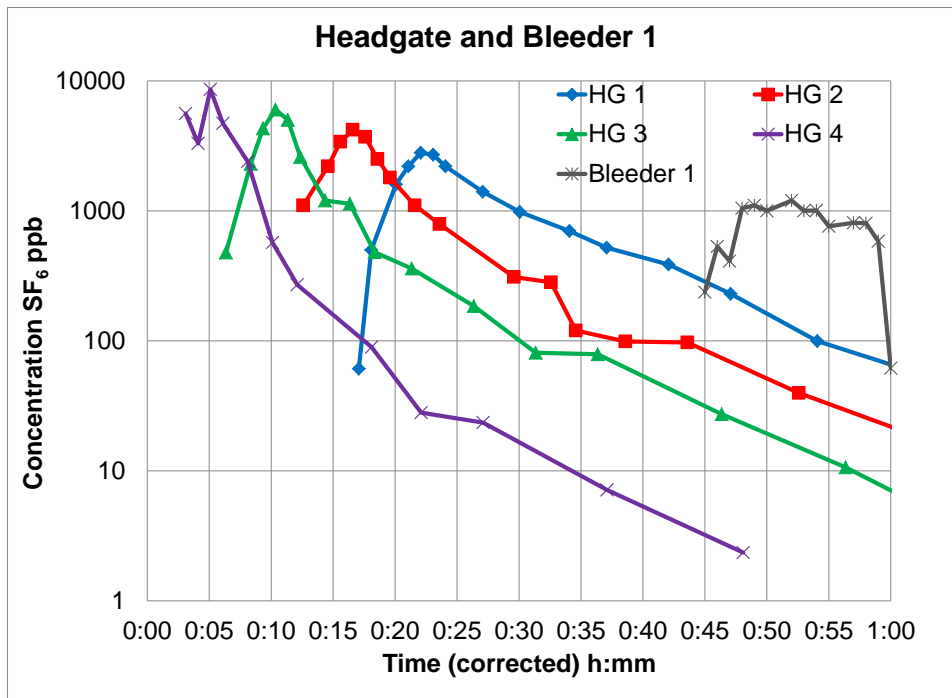


Figure 4-50. Test 1 concentrations for the headgate samples.

A ventilation survey at the start-up of the third panel extraction showed that the longwall tailgate corner was ventilated primarily by the bleeder fan, with the majority of the longwall face airflow pulled back towards the bleeder fan (Krog et al., 2011; Schatzel et al., 2011) (Figure 4-48). The concentrations of the SF<sub>6</sub> detected as a function of time after arrival in the tailgate entry in Test 1 are shown in Figure 4-51. The results showed that the inby TG 1 location had half the peak concentration compared to those sampling locations outby the tailgate (TG 2). This indicates that half of the airflow at TG 1 came directly from the longwall face, traveling down the supported #3 entry that is open to the gob, with initial dilution from slower moving air without SF<sub>6</sub> behind the shields (Figure 4-51). The secondary rise in SF<sub>6</sub> concentration at time 0:28 indicates that the other half of the airflow came from the broken rock mass behind the shields. Test 1 showed the ability of the tube line sampling system to record fast-moving SF<sub>6</sub> slugs in the main ventilation airflow, as shown in the headgate tracer gas samples where airflow velocities of over 3.6 m/s (700 ft/min) were measured and differentiate between slower-moving airflow behind the shields.

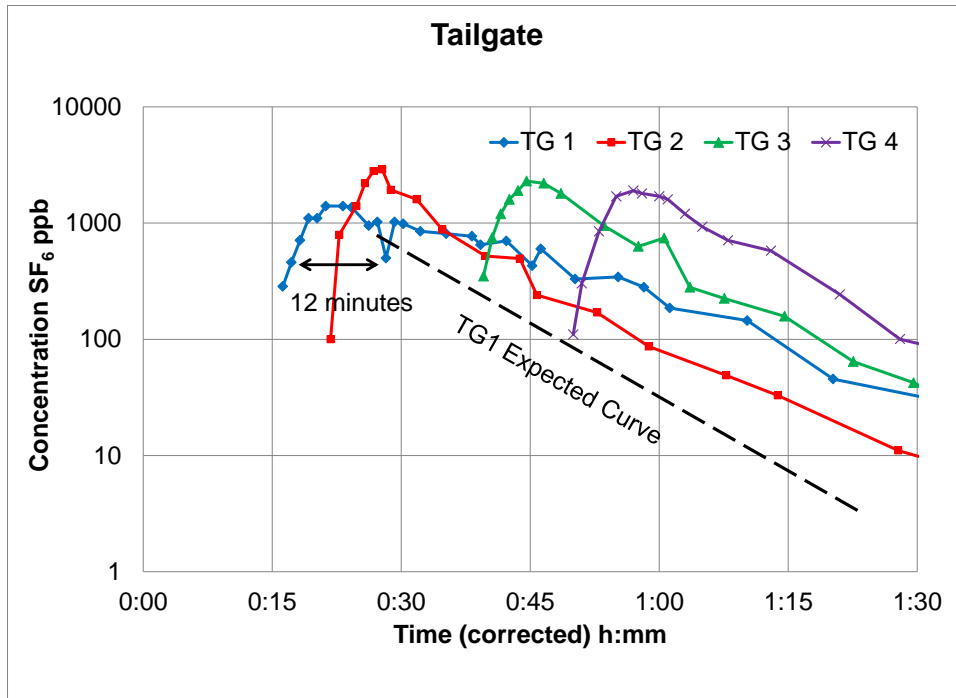


Figure 4-51. Test 1 tracer gas concentrations for the tailgate samples corrected for tube sample transit times. Also shown is TG 1 expected decline curve without mixing.

Along with measuring concentrations of tracer gas collected by the thousands of vacutainers, the same samples were also tested for mine gas concentrations. It should be noted that these samples are not compliant MSHA collected samples for enforcement, but for research purposes only. The samples were taken at both accessible and non-accessible locations within the bleeder system. For Test 1, the average concentrations of O<sub>2</sub>, CH<sub>4</sub> and CO<sub>2</sub> (minimum of three samples) along with sampling locations are shown in Figure 4-52. These data show that the mine was producing little methane (0.35%) at the bleeder fan with a flow rate of 118 m<sup>3</sup>/s (250,000 cfm). The methane emission rate of the bleeder fan was calculated to be 413 L/s (1.26 mmcf/d) (Table 4-6).

The airflow from the longwall tailgate corner passed by TG1 onto the bleeder fan. The methane concentration at TG1 was 0.57% and this increased to 1.88% at point Bleeder 2 (inner bleeder) while the Bleeder 1 sample point (walkable bleeder) only had 0.58%. Therefore, the parallel inner bleeder had over 3 times the methane concentration as outer bleeder and over 5 times the methane concentration of the bleeder fan. The slow moving airflow 8 m<sup>3</sup>/s (17,000 cfm) in the tailgate longwall return (TG2, TG3 and TG4) had rising methane concentrations as well, assumedly attributed to coal rib emissions.

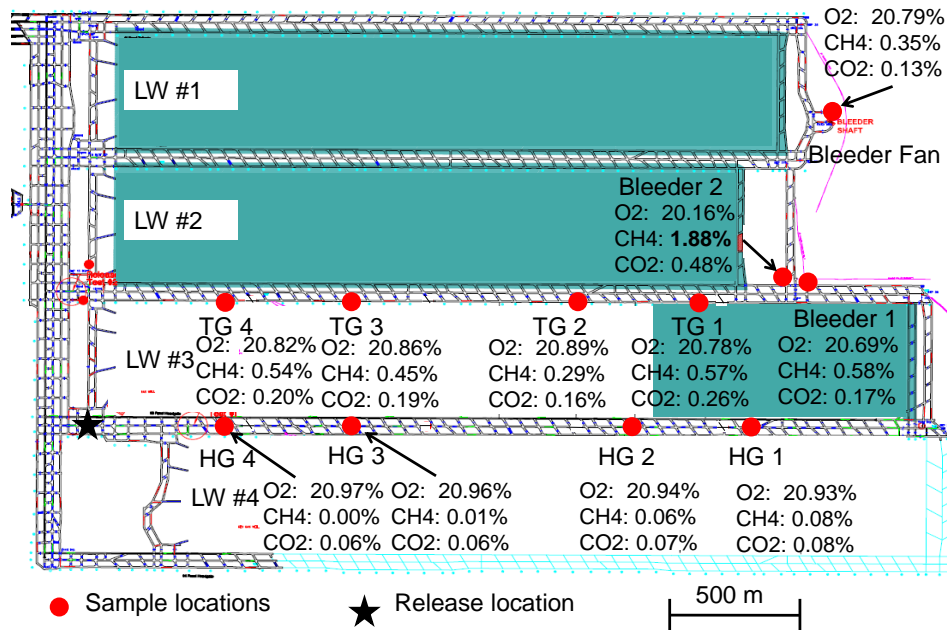


Figure 4-52. Test 1 gas concentrations, note that Bleeder 2 location (inner bleeder) has three times the methane concentration than Bleeder 1 (the walkable bleeder).

Table 4-6. Test 1 gas concentrations, airflow data and calculated methane flow rate.

	Location	O <sub>2</sub> %	CO <sub>2</sub> %	N <sub>2</sub> %	CH <sub>4</sub> %	Airflow m <sup>3</sup> /s	CH <sub>4</sub> L/s
Test 1	TG 1	20.78	0.26	77.46	0.57	26	148
Test 1	TG 2	20.89	0.16	77.73	0.29	8	24
Test 1	TG 3	20.86	0.19	77.58	0.45	8	38
Test 1	TG 4	20.82	0.20	77.51	0.54	8	46
Test 1	Bleeder 1	20.69	0.17	77.62	0.58	26	150
Test 1	Bleeder 2	20.16	0.48	76.50	1.88	14	266
Test 1	HG 1	20.93	0.08	77.97	0.08	33	27
Test 1	HG 2	20.94	0.07	78.00	0.06	85	47
Test 1	HG 3	20.96	0.06	78.04	0.01	87	5
Test 1	HG 4	20.97	0.06	78.04	0.00	90	2
Test 1	Bleeder Fan	20.79	0.13	77.79	0.35	118	413

#### 4.4.2 Test 2

The second tracer test was performed, when the longwall had progressed 1,250 m (4,100 ft) over 3.5 months. The operating gob vent boreholes and tracer gas arrival times are shown in Figure 4-53. No tracer gas was detected at any of the operating gob vent boreholes during Test 2 but their operation is important to the total methane emission for the district. In test 2, all three inby sample locations in the headgate entry showed similar gas concentrations and quantities indicating little air exchange from the gob to the sample locations as well as any migration from

the #3 entry to the #2 entry (sample locations) because the headgate #3 entry is at a lower pressure than the #2 entry.

In Figure 4-54, the sharp initial tracer gas release slug is indicated by HG 4, with similar decline curves for the three inby sample locations. The rapid decline for HG 4 (primary intake) is more rapid than for three inby locations because of the higher flow rates and matches the results from Test 1. For lines that have been cut, the labeling is altered by adding a suffix to the location name, e.g. HG 1A. Because of the location that the tubes lines were installed in the #3 entry of the tailgate of LW #3 and exposed to the caved material it was expected that some damage may occur to the sample lines due to the high convergence at these locations. Arrival time data along with gas concentration data (methane, oxygen and carbon dioxide) indicated that TH 1 was cut at the location shown.

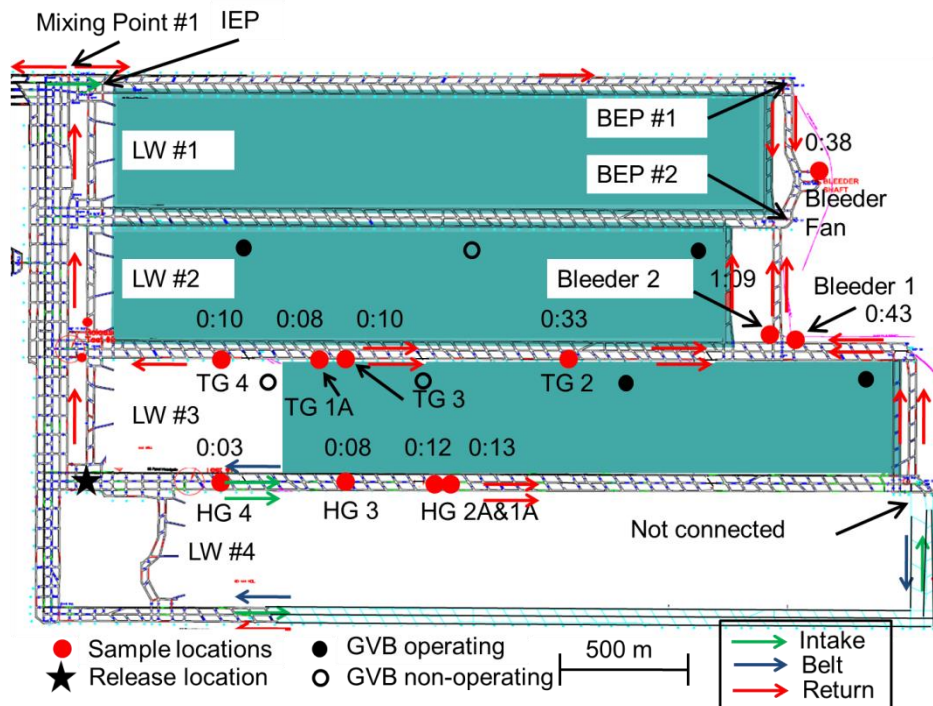


Figure 4-53. Test 2 mine layout, showing ventilation, sample locations and arrival times.

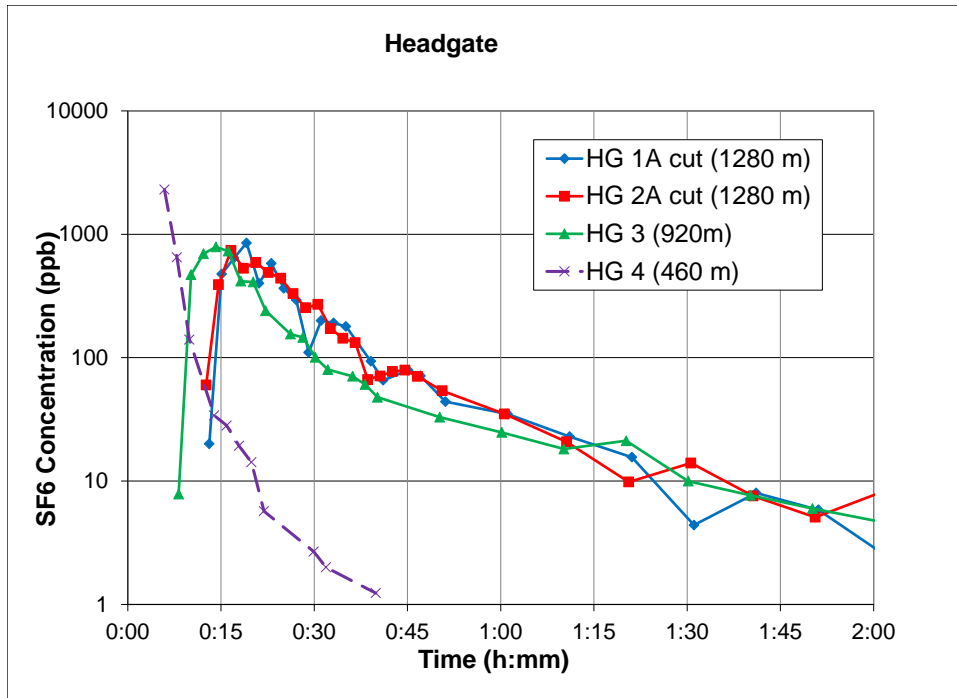


Figure 4-54. Test 2 HG corrected with HG 1 and HG 2 lines cut at 1280 meters, relabeled HG 1A and HG 2A.

In Figure 4-55, SF<sub>6</sub> concentrations for TG 1A and TG 3 match closely for the first two hours but then diverge afterwards assumedly due to airflow that traveled slowly behind the shields and within the gob arriving at the more distant TG 3 sample location. This longer interaction period with airflow from the gob caused the flatter tail of TG 3 when compared to the closer TG 1A. TG 4 shows the highest tracer gas concentration, which is expected from a sample location that had little possible interaction with the gob. The three inby locations (TG 1A, TG 3, TG 2) had much lower peak concentrations and increasing tail lengths, compared to TG 4, showing a greater mixing interactions with airflow paths within the gob. If the airflow leaving the longwall tailgate corner towards the back bleeders had no interaction with airflow from within the caved material, then the concentration-time curves of TG 1a to 2 would be similar to TG 4.

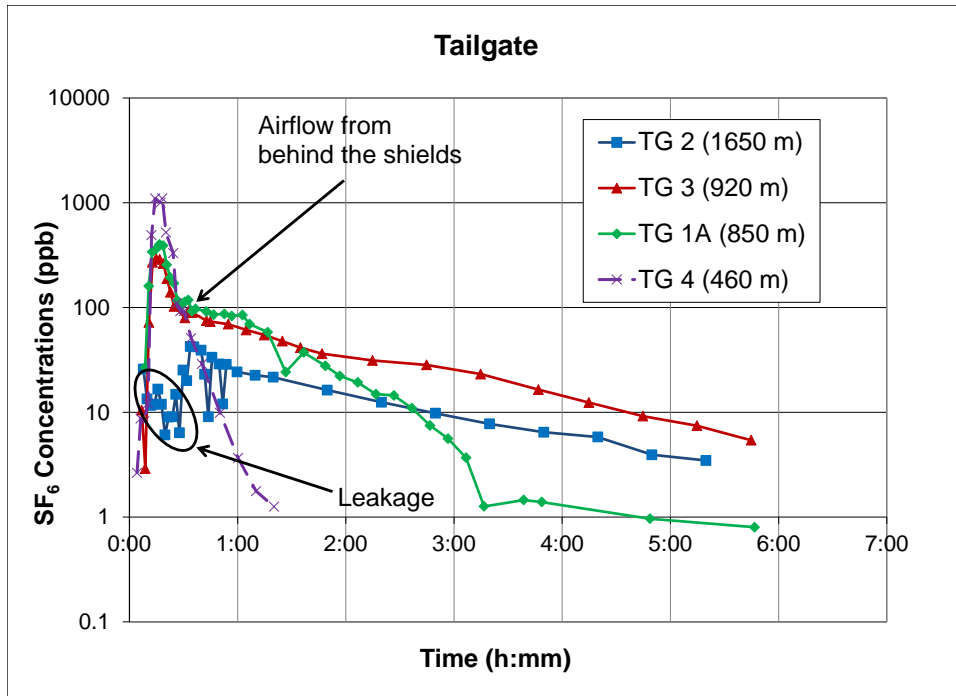


Figure 4-55. Test 2 tailgate with tube leakage shown in TG 2.

The travel pathways determined from the tracer gas tests give an internal view as to the design of the inner bleeder entries and the transportation of gob gas to the measuring locations (BEPs). Airflow velocity down the #2 entry of the headgate was calculated to be 1.22 m/s (240 ft/min) and was maintained until reaching the back end bleeders (Figure 4-56). At the tailgate, the airflow velocity in the #3 entry started at 0.95 m/s (190 ft/min) from the longwall face to TG 3, and slowed to 0.51 m/s (100 ft/min) between TG 3 and TG 2. The airflow velocity from TG 2 to Bleeder 2 was calculated to be 0.34 m/s (67 ft/min). Airflow velocity decreased between TG 3 and TG 2 as compared to between LW face and TG 3 due to air leaving the #3 entry airflow path and entering the #2 entry airflow path because of the lower resistance. This would be expected as flow resistance was lower in entry #2 due to the likelihood that entry #3 was obstructed, being adjacent to the gob. The calculated airflow velocity in entry #2 increased as it flowed in by the longwall tailgate corner due to potential blockages in entry #3, as corroborated by the SF<sub>6</sub> arrival time at the bleeder fan compared to the Bleeder locations (Figure 4-57). The airflow traveling down tailgate entry #2 of LW #3 was predicted by network models to be pulled across the setup room of LW #2. This airflow did not arrive at sample point Bleeder 2 but bypassed this location and arrived at BEP 2 (Figure 4-56). The inner bleeder system is designed to bring four different airflow streams: (1) Panel #1 setup room access, (2) Panel #1 inner bleeder entry, (3) Panel #2 setup room access, (4) Panel #2 inner bleeder entry, together

just before BEP 2, then to pass this airflow to the outer bleeder entry (shown in Figure 4-56). BEP 2 is responsible for over one-third of the total airflow of the surface bleeder fan, and all interior airflow entries flow toward this location. Therefore, to accurately describe the major airflow pathways of this bleeder system, a better understanding of the role the longwall's setup room access entries play in transferring and diluting methane has to be measured. This analysis was incorporated in designing Test 3, which focused more attention to the pre-mixing of airflows before they passed through the BEPs.

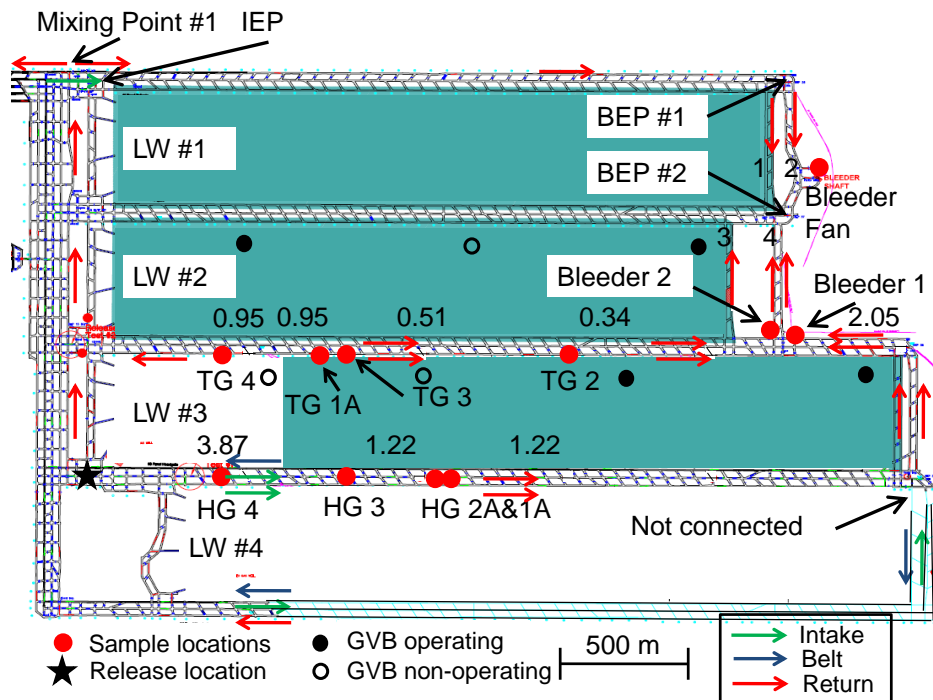


Figure 4-56. Test 2 showing calculated airflow velocities between sample locations in the supported #3 entry of the tailgate and the middle #2 entry of the headgate (m/s). The four airflows that pre-mix before BEP #2 are shown.

The cumulative SF<sub>6</sub> totals in bleeders 1 and 2 and at the bleeder fan, and the expected cumulative amounts are shown in Figure 4-57. The expected cumulative amounts, based on full recovery, were calculated based on known airflow measurements in the accessible locations of the mine. Predicted SF<sub>6</sub> amounts were calculated using ventilation network models for the inaccessible locations and then compared to the recorded SF<sub>6</sub> amounts. Bleeder 1 reached its peak total while both Bleeder 2 and the bleeder fan were still increasing when sampling stopped. Indicating that the SF<sub>6</sub> had not yet reached Bleeder 2 locations because of the slow moving multiple airflow pathways between the release location and Bleeder 2. The sampling times for Test 2 were extended underground based on the results from Test 1, but it was



determined after data analysis that equilibrium had still not been achieved at some locations, indicating that low-velocity high-retention airflow paths existed in some portions of the bleeder system. During Test 3, the underground sample times were extended even further to try to capture all SF<sub>6</sub> released, but longer gob retention times and the long pathways between gobs made completing the test in one extended shift impossible given personal constraints.

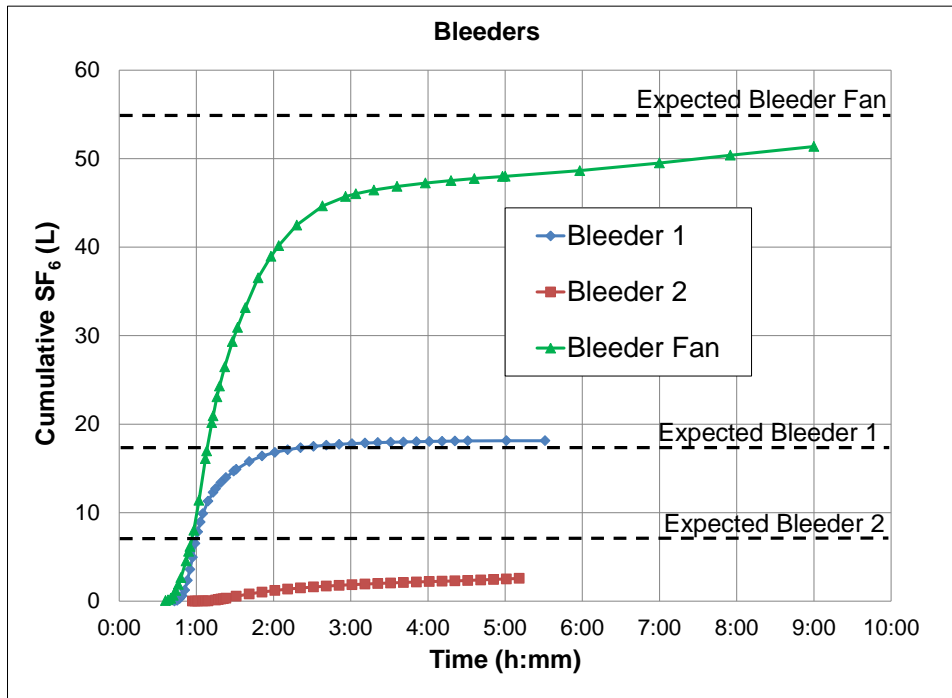


Figure 4-57. Test 2 cumulative tracer gas recovery totals along with expected recovery amounts.

The concentration of SF<sub>6</sub> reporting to Bleeder 2 was still increasing after 5 hours and had not reached its expected cumulative tracer gas amount, while Bleeder 1 had leveled off after 4 hours. Actual tracer gas recovery at Bleeder 2 was only 31% of that expected (Table 4-7) at that time but was still rising. Some of this tracer gas was captured at the bleeder fan which was observed for a longer period. The high expected recovery in the outer bleeder (Bleeder 1) shows that this airflow path had little interaction with the gob, while the lack of tracer gas return in the inner bleeder (Bleeder 2) indicated that it had airflow paths with longer retention times within the gob. This was not unexpected because the airflow from the longwall tailgate corner passed through the inaccessible tailgate towards Bleeder 2 and the low-velocity zone along the caved material of the gob.

The percentage tracer gas recovery at any location is related to the interaction with the gob and the amount of air traveling in the predominant and faster flowing paths of the main ventilation

system (entries). Tailgate #2 (TG 2) had only 33% of the expected recovery of SF<sub>6</sub>, indicating that 2/3 of the expected tracer gas did not pass this location within the sampling time frame but instead remained in or was slowly traveling in the gob (Table 4-7). The long retention time of tracer gas passing TG 2 is reproduced by network models and reveals a slow outgassing from the gob along the entire length between TG 3 to TG 2 and up to the offset step feature of the bleeder system between longwall panels 2 and 3.

Bleeder 2 had a low expected recovery of tracer gas (31%), which is consistent because it was located downstream of TG #2, which also had a similar low expected recovery of tracer gas. The quick part of the airflow traveled from TG 2 to Bleeder 2 (730 m) in 36 minutes at 0.34 m/s (2400 ft / 36 min = 67 ft/min). Four hours after the tracer gas release, Bleeder 2 experiences a second arrival of tracer gas (Figure 4-58) that did not show up at TG 2, indicating a pathway not past TG 2. The longer pathway was determined to be from the LW 3 setup room which then traveled back towards the stair-step bleeder feature and then to Bleeder 2 using the inner bleeder entries (Figure 4-53 and Figure 4-48). The airflow total in Table 4-7 is for the combined entries listed in the “Comments” column.

Table 4-7. Test 2 tracer measure and expected recovery totals, bold air quantity values are from network models or based on arrival times.

Location	Air Quantity (m <sup>3</sup> /s)	Comments	Measured SF <sub>6</sub> (L)	Expected SF <sub>6</sub> (L)	Recovery of Excepted SF <sub>6</sub>
Release point	97	Entry 2	68.8	68.8	
HG 4	85	Entries 2 and 3	45.7	60.4	76%
HG 3	32	Entries 2 and 3	21.3	22.7	94%
HG 2	32	Entries 2 and 3	22.2	22.7	98%
HG 1	32	Entries 2 and 3	21.5	22.7	95%
TG 4	14	Entry 3	9.9	10.2	97%
TG 1A	<b>19</b>	Entries 2 and 3	13.2	13.7	96%
TG 3	<b>19</b>	Entries 2 and 3	14.7	13.7	107%
TG 2	<b>19</b>	Entries 2 and 3	4.5	13.7	33%
Bleeder 1	24	Outer Bleeder	18.1	17.2	105%
Bleeder 2	12	Inner Bleeder	2.6	8.3	31%
Bleeder Fan	127	Surface	52.2	54.8	95%

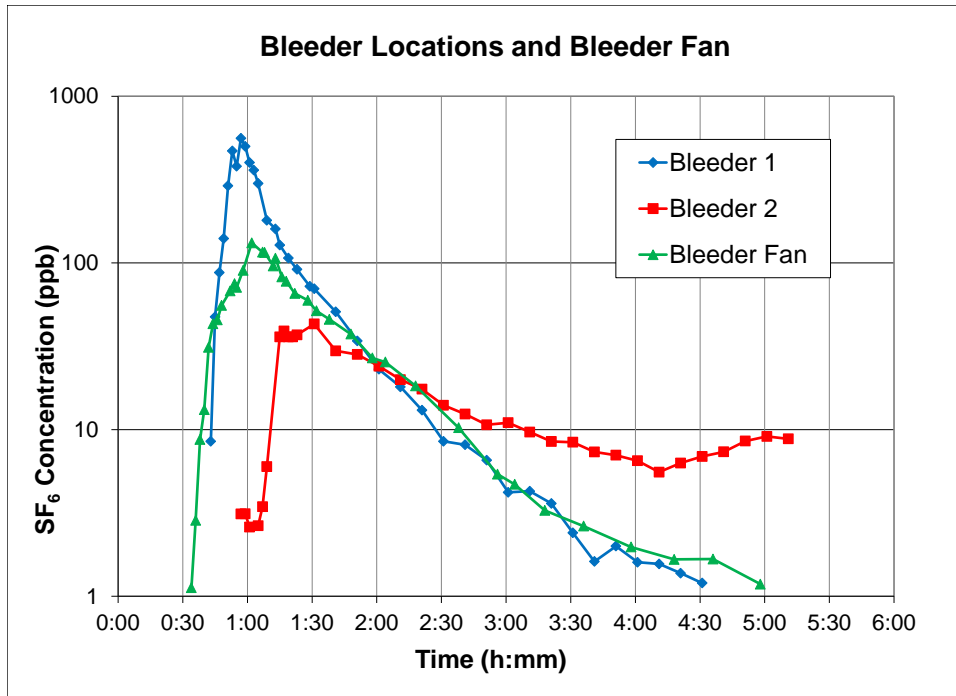


Figure 4-58. Test 2 note that Bleeder 2 recovery is low because the entire tracer slug has yet to arrive indicated by the rising at time 4:10.

The exposure to the gob and the possibility that a short section of the supported #3 entry in the tailgate could be completely blocked and enveloped by the gob would have the following consequences; a) Airflow quantities down the #3 entry would be much lower than at the longwall tailgate corner. b) Airflow traveling down the #3 entry after reaching the blockage would transfer preferentially to the #2 entry, which was assumed to remain open. c) Assuming a well-compacted gob, after the blockage was passed, the airflow in the #3 entry would predominantly flow from the periphery of the gob, since the general airflow pattern in this district was towards the bleeder fan. Therefore, airflow traveling down the #3 entry would likely come from the surrounding gob. Tracer gas traveling along the periphery of the gob in #3 entry would have a much longer retention time than tracer gas traveling down the #2 entry. These conclusions are supported by the data shown in Figure 4-59 and **Error! Reference source not found.**

The peak concentrations and flatter tails in Figure 4-55 show that the longwall tailgate corner is ventilated with 40% of the air at TG 1A coming directly from the longwall face. The remainder takes the slower path through the corner of the gob and from behind the shields. The airflow leaving the tailgate side of the longwall face splits and travels to both TG 4 and TG 1A. The SF<sub>6</sub> concentration at TG 4 (Figure 4-55) has a non-diluted (pure) peak concentration of 1,000 ppb, while TG 1A has a diluted (mixed) peak of 400 ppb. The peak ratio indication of 40% of the

airflow at TG 1A came directly from the longwall face and traveled inby down entry #3. Table 4-7 shows that both TG 4 and TG 1A had the same high recovery of expected SF<sub>6</sub>, indicating that all SF<sub>6</sub> had passed these sample locations. The results of Test 2 show that the bleeder system was still able to effectively ventilate the longwall tailgate corner of the longwall panel #3 after mining the majority of the longwall panel, 2,100 m (6,900 ft) from the setup room. Airflow at the longwall tailgate corner split and effectively removed the higher methane gas concentrations from behind the shields and transported them towards the back bleeder via the remaining openings of the inby tailgate entries.

The recorded methane concentrations throughout the mine during Test 2 were much higher than during Test 1 (Figure 4-59). The measured methane concentrations at the bleeder fan increased to 1.23% while total exhausting emissions increased to 1445 L/s methane (4.41 mmcf/d) (Table 4-8). This is an increase of 3.5 times the emission levels at the bleeder fan compared to that of during Test 1. Bleeder fan methane Figure 4-59 shows the average measured gas concentrations (minimum 3 samples) throughout the bleeder system during Test 2.

The gas concentration in the longwall tailgate #3 entry increase from 1.07% at TG 1A to 2.89 at TG 3 to 4.22% at TG 2 as well as a falling oxygen concentrations indicating outgasses from the caved material. Since it was shown that the full amount of tracer gas passed through both TG 1A and TG 3 (Table 4-7) and that the calculated airflow for these locations was 19 m<sup>3</sup>/s (40,000 cfm) therefore some highly rich methane left the caved material. The distance between sample locations TG 1A to TG 3 was calculated to be only 70 m as they had similar tracer gas arrival times as shown in Figure 4-55. The mass balance shows that approximately 344 L/s (730 cfm) of methane entered the supported entries between TG 1A and TG 2. If the addition of 344 L/s of methane was at 10% concentration, that would be 3.44 m<sup>3</sup>/s of additional airflow. This would decrease the travel time to the back bleeders. Since this increased overall flow rate was not recorded, the most logical conclusion is that air with a methane concentration greater than 10% as well as low oxygen, flowed out of the caved material between TG 1A and TG 3.

The difference in methane concentration between the walkable outer bleeder and the inner bleeder is higher during test 2, with Bleeder 2 concentrations over 9 times that of Bleeder 1 (3.46% vs. 0.38%). Using the methane flow data from Table 4-8, the combined methane transported through Bleeder 1 and Bleeder 2 was calculated to be 537 L/s (1,140 cfm) which is only 37% of the methane being exhausted by the bleeder fan. Therefore, the setup room access

drift of LW #2 must be transferring airflow from the tailgate of LW #3 between sample locations TG 2 and Bleeder 2. This would also account for the reduced tracer gas recovery at Bleeder 2 (Table 4-7).

After Test 2 it became evident that to determine the controlling factors of the bleeder ventilation system, the sampling of BEP #2 will be required to accurately determine all total methane airflow pathways at this operation.

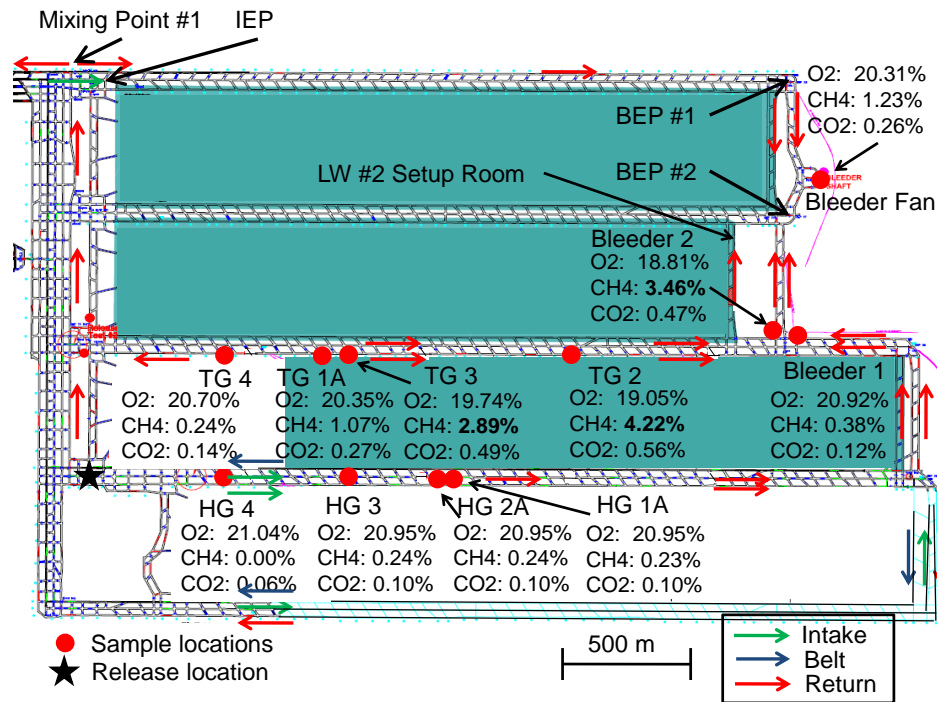


Figure 4-59. Test 2 gas concentrations.

Table 4-8. Test 2 gas concentrations, airflow data and calculated methane flow rate.

	Location	O <sub>2</sub> %	CO <sub>2</sub> %	N <sub>2</sub> %	CH <sub>4</sub> %	Airflow m <sup>3</sup> /s	CH <sub>4</sub> L/s
Test 2	TG 2	19.05	0.56	75.18	4.22	19	796
Test 2	TG 3	19.74	0.49	75.92	2.89	19	546
Test 2	TG 1A	20.35	0.27	77.38	1.07	19	202
Test 2	TG 4	20.70	0.14	77.98	0.24	14	34
Test 2	Bleeder 1	20.92	0.12	77.66	0.38	25	97
Test 2	Bleeder 2	18.81	0.47	76.29	3.46	13	440
Test 2	HG 1A	20.95	0.10	77.78	0.24	26	62
Test 2	HG 2A	20.95	0.10	77.79	0.23	26	61
Test 2	HG 3	20.95	0.10	77.78	0.24	26	61
Test 2	HG 4	21.04	0.06	77.97	0.00	90	3
Test 2	Bleeder Fan	20.31	0.26	77.26	1.23	118	1445

### 4.4.3 Test 3

As outlined in Chapter 3, the ventilation system during Test 3 is dramatically different than from Test 1 and Test 2, because of the use of the internal bleeder system. With the removal of the last continuous miner unit and with the start of the fourth and final panel in this district, the mine altered the ventilation system so that recovery rooms of the previous panels (labeled as internal bleeder in Figure 4-60) were used to transfer the airflow from the longwall tailgate return to the tailgate of panel 1. There was no SF<sub>6</sub> detected at any of the operating surface GVB but given the high methane concentration levels above 80% this was anticipated by still verified.

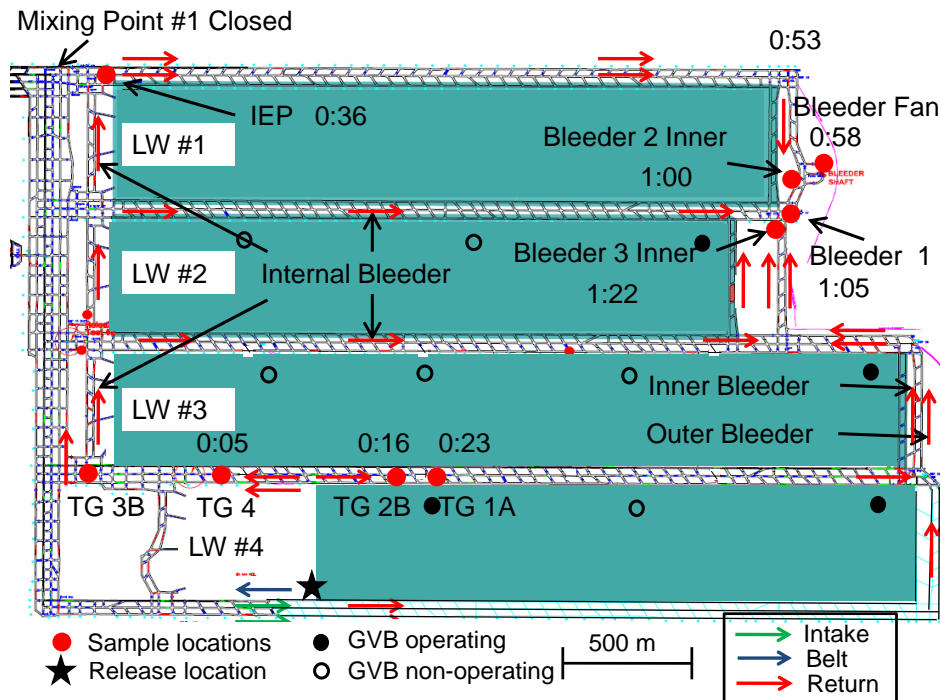


Figure 4-60. Test 3 ventilation layout utilizing an internal bleeder system. Arrival times are also shown.

Test 3 results in Table 4-9 can be used to determine the airflow distribution at the longwall tailgate corner and throughout the longwall district. The tracer gas was released at shield 19 of the active longwall panel 4 and the measured or calculated airflow quantities are shown in Table 4-9. The recovered tracer gas at the tailgate shows that while longwall face airflow flowed inby through the bleeder system at the longwall tailgate corner, about one-half of the air at the inby locations TG 2B and TG 1A did not pass the longwall face at shield 19 but traveled behind the shield line and through the gob (Figure 4-61). This indicates that the airflow enters the gob between the longwall headgate corner and shield 19, before passing behind the shields and then through the gob towards the back bleeders.

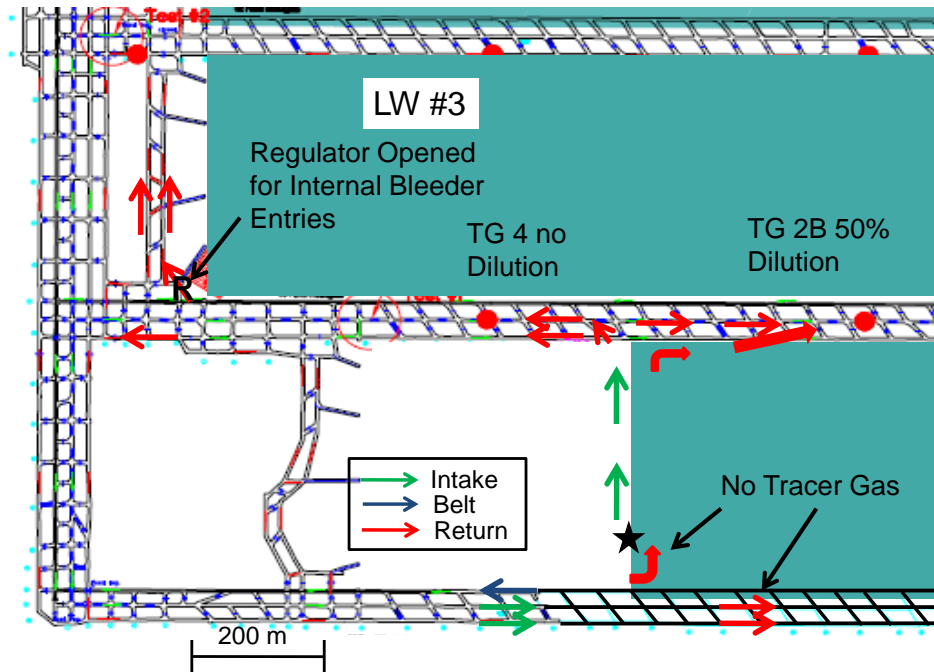


Figure 4-61. Test 3 tracer gas-free airflow behind shields and the location of the internal bleeder regulator.

Table 4-9. Test 3 tracer measure and expected recovery totals, bold air quantity values are from network models or based on arrival times.

Location	Air Quantity (m <sup>3</sup> /s)	Comments	Measured SF <sub>6</sub> (L)	Expected SF <sub>6</sub> (L)	Recovery of Expected SF <sub>6</sub>
Release point	35	Shield 19 LW #4		69.4	
TG 4	21	Entries 2 and 3	50.7	41.6	122%
TG 2B	<b>14</b>	Entries 2 and 3	12.1	26.8	45%
TG 1A	<b>14</b>	Entries 2 and 3	13.7	26.8	51%
TG 3A	0	Line cut		0.0	
IEP	41	Panel 1 TG Entry 2	41.1	41.6	99%
Bleeder 1 New	43	BEP 2	32.8	41.6	79%
Bleeder 2 New	9	Inner Bleeder	9.6	9.4	103%
Bleeder 3 New	9	Inner Bleeder	0.9	9.2	10%
Bleeder Fan	127	Surface Fan	55.2	60.1	92%

The SF<sub>6</sub> concentration chart from Figure 4-62 shows the depressed peaks and slow concentration declines for the two sampling locations inby the longwall tailgate corner. The TG 4 sample line shows the high-peak SF<sub>6</sub> concentration experienced on the longwall face followed by a decline, indicating some interaction with a longer retention airflow traveling in the longwall

tailgate corner gob. The expected result for TG 4 based on the decline curves from the first two tests is shown to represent the difference when an internal bleeder system is operated.

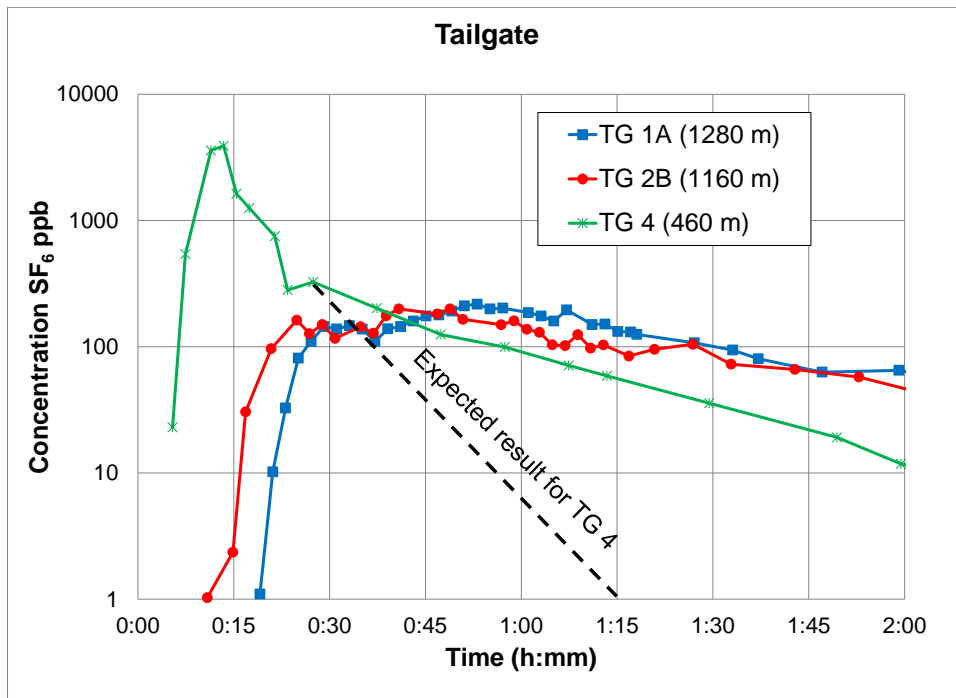


Figure 4-62. Test 3 tailgate sample concentrations and tubing lengths.

The data in Figure 62 differed from data in the two previous tests. For instance, the levels at TG 4 in Test 3 took over one hour to drop to 1% of peak concentration while it took less than 30 minutes in Test 2 (Figure 55), indicating that some of the tracer gas remained behind the shields or there was an interaction with the adjacent worked-out area of the previous longwall panel. In both previous tests, the concentration of tracer gas had fallen off rapidly, indicating little exchange with the gob and with the airflow at or near the longwall tailgate corner. In Test 3, the inby sample locations (TG 1A and TG 2B) both have flatter peaks and slower decline curves, indicating a greater retention of tracer gas at the longwall tailgate corner.

The majority of the tracer gas released on the longwall face passed through the IEP sample location, towards Bleeder 2 and Bleeder 1, and then to the bleeder fan (Figure 4-60). Figure 4-63 shows the SF<sub>6</sub> concentrations for airflow traveling this path. The majority of the SF<sub>6</sub> that passed through the IEP reached Bleeder 1 via Bleeder 2 and the parallel air path of the setup room of LW #1 (Figure 4-64). The expected amounts of SF<sub>6</sub> for the IEP and Bleeder 1 are the same at 41.6 L (1.47 ft<sup>3</sup>) but do not represent the same SF<sub>6</sub> at both locations.



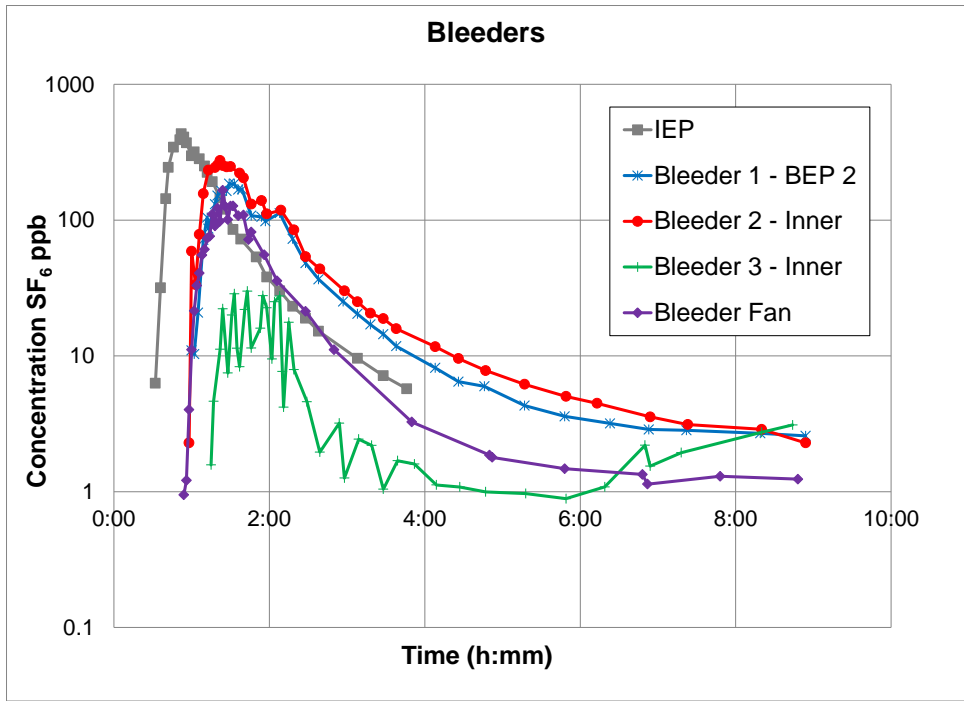


Figure 4-63. Test 3 Bleeder concentrations and IEP.

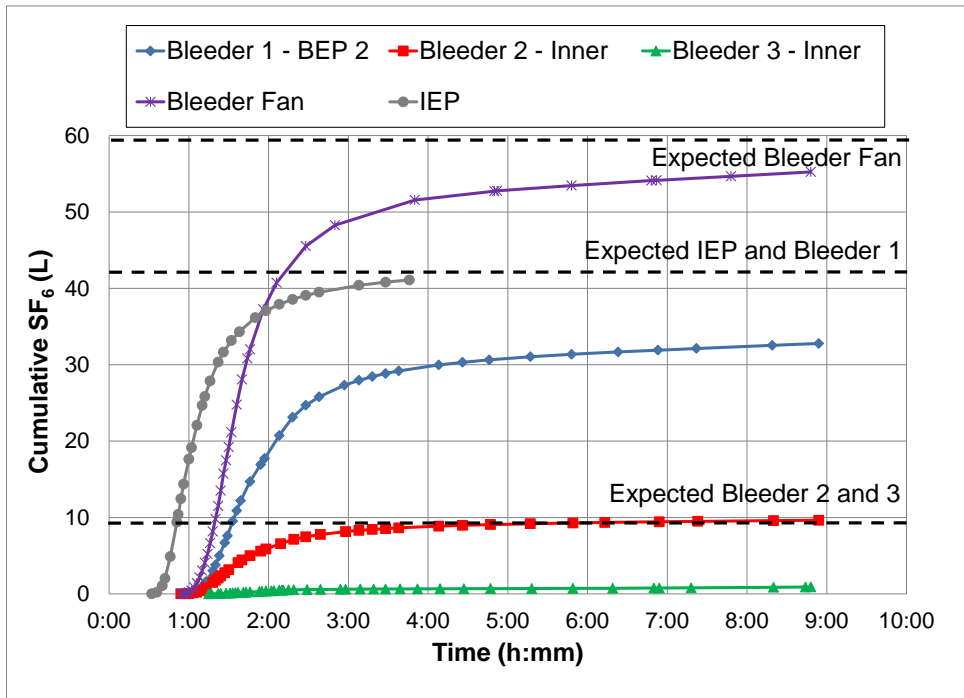


Figure 4-64. Test 3 cumulative tracer gas at sampling locations.

In Test 3, the recovered SF<sub>6</sub> concentration vs. time curves at the two inby locations, TG 2B and TG 1A, were only 45-51% of those expected (Table 4-9). The two sample locations were

located in entry 2 of the tailgate and the data indicate that one-half of the airflow being pulled from the longwall tailgate corner came from the longwall face, and one-half came from airflow traveling behind the shields that entered the gob before shield 19 (38 m, 125 ft). The implications are that while the total amount of airflow being pulled in by from the longwall tailgate corner was reduced by the use of the internal bleeder system, the longwall tailgate corner and longwall face were still being ventilated and contaminants behind the shields were being pulled away from the face towards the back bleeder system. However, half of the airflow traveling down the middle entry arrived via the caved material where it diluted methane from behind the shields.

The methane concentration of the sample locations corresponds well with the tracer gas recoveries from Table 4-9. The two inby longwall tailgate sample locations (TG 2B and TG 1A) both indicated methane concentrations just above 3% methane (Figure 4-65). The determined 50% dilution factor from airflow that traveled behind the shield to arrive at these locations creates a difficult question to answer. If airflow is being pulled from behind the shields in a 1:1 ratio with longwall face gas and given that the methane concentrations on the longwall face are at or below 0.47%, then the expected methane concentration of the airflow behind the longwall shields must average 5.81% ( $3.14\% \times 2 - 0.47\% = 5.81\%$ ) to mass balance out the methane and tracer gas. This is an interesting condition because at the first glance, the bleeder ventilation system appears to be adequately ventilating the tailgate corner by removing high methane concentration from the behind the longwall shields and transporting it down the middle entry. This is how a bleeder ventilation system is supposed to operate. By taking both methane and tracer gas reading at the same time, it is possible to calculate the methane concentration of the airflow behind the shield without taking a direct sample which is hard to do in such a destructive and crushing environment as the caved material re-compacts.

The methane concentrations at the back of the panel at the Bleeder locations also shows similar results of high methane concentrations in airflow mixing with higher-oxygen airflow before passing through the BEP #2 (Table 4-10). The single BEP #2 (Bleeder 1) emit 74% of the total methane that is emitted by the Bleeder Fan. How that methane was transported from the actively mined longwall panel (Panel #4) and transported to the BEP #2 located between Panels 1 and 2 demonstrates that methane concentration taken in the walkable outer bleeder show little indication as to the methane concentration within the bleeder system.

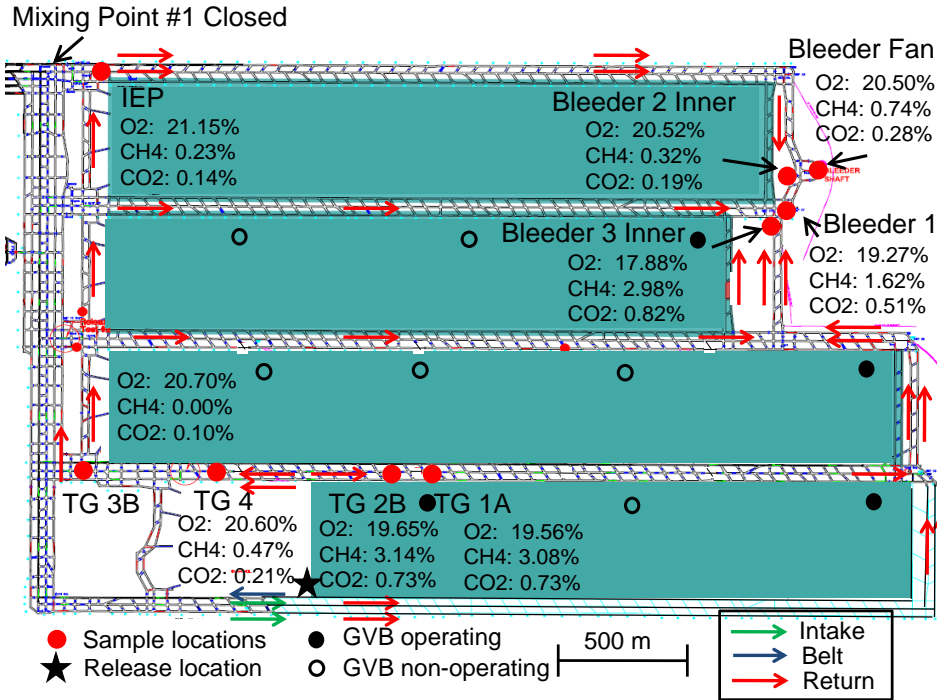


Figure 4-65. Test 3 gas concentrations, note that Bleeder 1 location (BEP #2) has over double the methane concentration than the bleeder fan, while Bleeder 3 is almost double Bleeder 1.

Table 4-10. Test 3 gas concentrations, airflow data and calculated methane flow rate.

	Location	O <sub>2</sub>	CO <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>	Airflow	CH <sub>4</sub>
		%	%	%	%	m <sup>3</sup> /s	L/s
Test 3	TG 3 Cut	20.72	0.10	78.25	0.00	Cut Line	
Test 3	TG 1A	19.56	0.73	75.63	3.08	14	436
Test 3	TG 2B	19.65	0.72	75.48	3.14	14	444
Test 3	TG 4	20.60	0.21	77.77	0.47	21	101
Test 3	Bleeder 1	19.27	0.51	77.63	1.62	43	699
Test 3	Bleeder 2	20.52	0.19	78.04	0.32	9.2	29
Test 3	Bleeder 3	17.88	0.82	77.30	2.98	8.6	256
Test 3	Panel 1 IEP	21.15	0.14	77.55	0.23	34	77
Test 3	Bleeder Fan	20.50	0.28	77.53	0.74	127	942

A closer examination around Bleeder 1 (BEP #2) can show the condition of pre-mixing before mandated sample locations (Figure 4-66). The ventilation survey measured the airflow rate around Bleeder 1 (BEP #2) and determined the airflow rate for Setup Room #1 to be 14 m<sup>3</sup>/s (29,700 cfm). 6 sets of gas analysis were done at hourly intervals around Bleeder 1 to determine the gas concentration data of the remaining airflow coming out between Panels 1 and 2. The airflow rate was determined to be 11.4 m<sup>3</sup>/s (24,200 cfm) and gas concentrations similar to that measured at Bleeder 3, averaging just above 3% methane as shown in Table 4-11. This

corroborated previous higher airflow rates ( $15 \text{ m}^3/\text{s}$ , 31,800 cfm) traveling down the inner bleeder before Bleeder 3 ( $8.6 \text{ m}^3/\text{s}$ , 18,200 cfm) with some of the airflow traveling back towards the caved material before reporting to Bleeder 1.

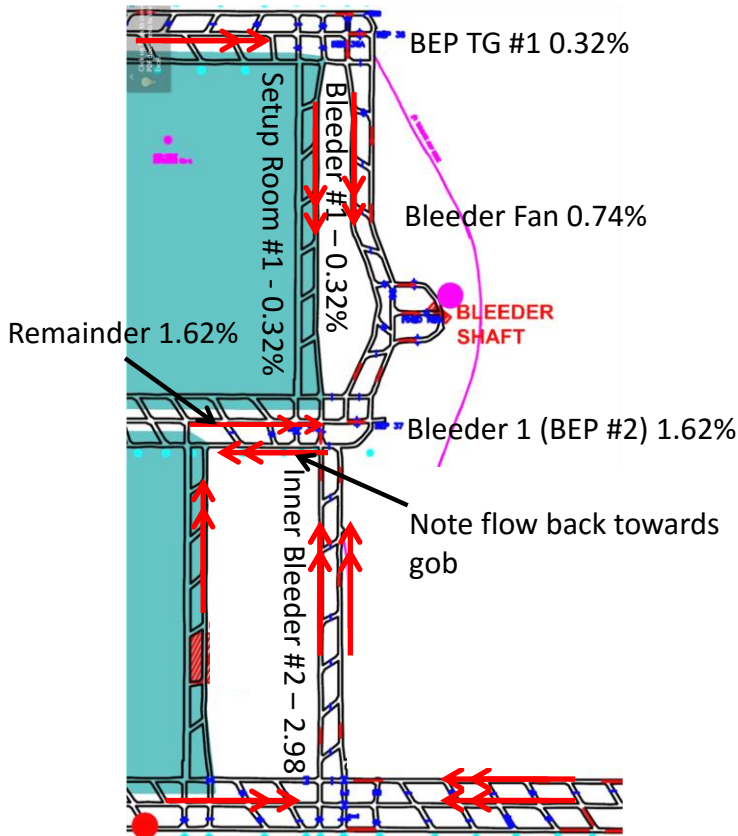


Figure 4-66. Test 3 Close-up of airflows near the bleeder fan showing pre-mixing. Note that some airflow from Bleeder 2 flows back towards the gob and makes a 180 degree turn and flows towards Bleeder 1.

Table 4-11. Test 3 mass balance of remaining airflow at Bleeder 1, from 6 sets of gas analysis.

Location	Time (h:mm)	O <sub>2</sub> %	CO <sub>2</sub> %	N <sub>2</sub> %	CH <sub>4</sub> %	Flow (m <sup>3</sup> /s)
BEP 1	10:01	19.28	0.51	77.63	1.6	43.2
BEP 1	11:02	19.22	0.54	77.56	1.7	43.2
BEP 1	11:15	19.1	0.47	77.82	1.65	43.2
BEP 1	11:59	19.17	0.5	77.77	1.59	43.2
BEP 1	13:02	19.35	0.52	77.52	1.63	43.2
BEP 1	14:01	19.51	0.51	77.48	1.53	43.2
BEP 2	10:01	20.5	0.19	78.06	0.315	23.2
BEP 2	11:02	20.6	0.19	77.95	0.315	23.2
BEP 2	11:17	20.35	0.17	78.27	0.286	23.2
BEP 2	12:00	20.38	0.18	78.18	0.325	23.2
BEP 2	13:02	20.59	0.2	77.93	0.34	23.2
BEP 2	14:02	20.67	0.2	77.85	0.331	23.2
BEP 3	10:02	17.91	0.89	77.06	3.1	8.6
BEP 3	11:03	17.91	0.9	77.05	3.1	8.6
BEP 3	11:21	17.92	0.77	77.31	2.99	8.6
BEP 3	12:00	17.61	0.91	77.29	3.16	8.6
BEP 3	13:03	17.97	0.84	77.21	2.95	8.6
BEP 3	14:02	18.24	0.83	77.07	2.83	8.6
Remaining	10:01	17.83	0.87	77.18	3.08	11.4
Remaining	11:02	17.40	0.98	77.15	3.46	11.4
Remaining	11:15	17.45	0.85	77.29	3.42	11.4
Remaining	11:59	17.88	0.84	77.30	2.98	11.4
Remaining	13:02	17.87	0.93	76.92	3.26	11.4
Remaining	14:01	18.11	0.90	77.04	2.99	11.4

The weekly bleeder system ventilation survey done the Sunday before Test 3 was completed is shown in Figure 4-67. The hand-held methane sensor found less than 0.1% methane at BEP 5 and intake on the headgate side of the active panel. This was expected as this is the fresh air supply to the back bleeder system. The below 0.1% methane reading at both BEP 4 and BEP 3 show that there is an abundance of pre-mixing before the BEPs. The methane concentration traveling down the middle entry between Panels 3 and 4 is at least 3.1% methane with total airflow rates calculated to be 14 m<sup>3</sup>/s (30,000 cfm) (Table 4-10). Therefore the mixing between this airflow and the fresh air traveling in the inner bleeder before BEP 4 is not a 'mixing zone' but a 'displacement zone'. The methane exiting from the middle entry completely bypasses BEP 4 and travels towards BEP 3 via the setup room access drift or possibly the inner bleeder. The low airflow rate of only 5.6 m<sup>3</sup>/s (12,300 cfm) at BEP 4 compared to the calculated air flow rate of the middle entry clearly show this to be a displacement zone not a pre-mixing zone. Displacement zone being the case where a larger airflow intersects a smaller airflow and before mix and dilution it pushes the airflow into a different entry. An example of a displacement zone

would be an exhaust hood above a stove, smoke does not mix in the room it is pulled away. This displacement process is repeated in front of BEP 3 indicated by the same low flow rate and no recorded methane. In fact airflow is moving away from BEP 3 down the middle entry towards the 'stair-step feature' and mixing with airflow exiting from the middle entry between Panels 2 and 3.

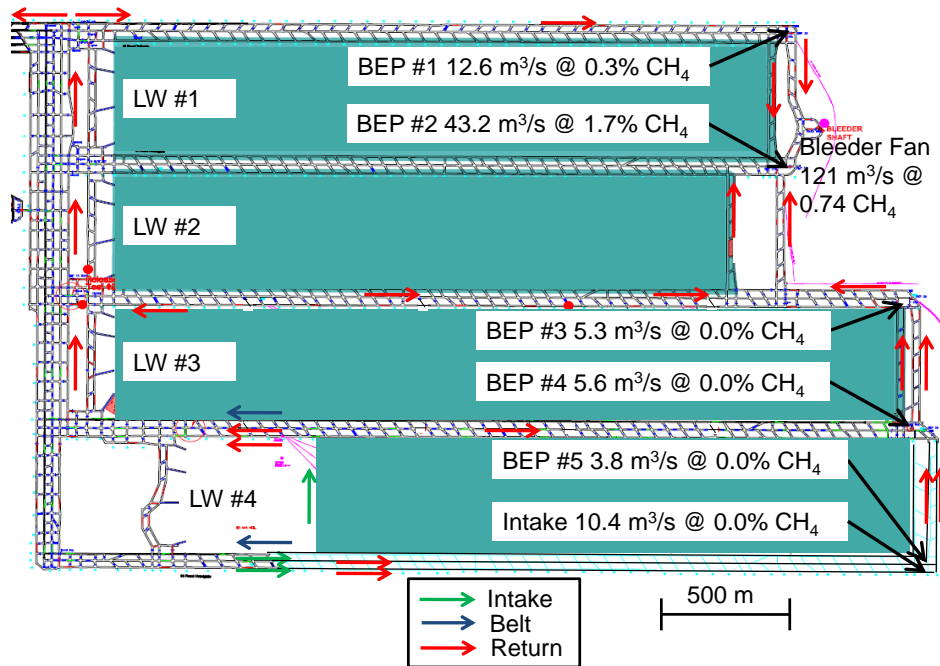


Figure 4-67. Weekly ventilation survey done the Sunday before Test 3 was conducted. The results are from a handheld methane device, but these are the weekly MSHA recorded values.

This interpretation of Test 3 tracer gas concentrations in the inby locations in conjunction with the cumulative recovery data indicated that while the bleeder system does pull a majority of the airflow from behind the shields, there is a greater retention of tracer gas at the longwall tailgate corner when an internal bleeder system is paired with an inner bleeder design. The flatter tail of the concentration plot at TG 4 indicates that there is a greater retention of tracer along the longwall face that continues for hours after the initial tracer gas release (Figure 4-62). This flat tail was not observed in the previous two releases, and indicated that while an internal bleeder system can increase longwall face ventilation, it also increases the exchange between face airflow, any airflow movement behind the shields, and longwall tailgate corner airflow moving towards the mains. This is a known feature of the internal bleeder system and Test 3 confirms previous work (Brune et al., 1999).

With the concurrent use of tracer gas (arrival times, peak concentration, recovery and dilution) along with gas concentration data (methane, oxygen and carbon dioxide) the ability to determine the inaccessible airflow pathways, retention time, airflow rate and gas composition is possible. A 4-panel bleeder system was investigated and determined that the measured and calculated gas compositional data within the bleeder system has little correlation to the measured methane reading recorded during weekly survey in the walkable outer bleeder. The bleeder ventilation system that was used transferred the bulk of the methane produced during longwall mining from the active panels (Longwall #3 and #4) by the use of the inner bleeders and setup room access entries. The majority of the methane entered the walkable bleeder within 100 m of the bleeder fan at BEP #2 after being pre-mixed with multiple low methane airflows to reduce methane concentrations. Any ventilation modeling done using just the airflow and methane recorded values from weekly BEP survey may not give an acceptable representation as to the bleeder system operating conditions.

## 5 Discussion

The results of Chapter 4 laid the foundation for the main discussion topics of this chapter: gas emissions quantities from longwall gobs for both bleederless and bleeder systems, and the premixing of airflows before monitoring locations.

Gas emissions from caved material are not constant and have been observed and quantified to have peak hourly emissions levels 1.5 to 2 times higher than weekly or monthly averages. Atmospheric pressure changes account for the majority of the variability in emission levels especially during peak emissions, followed by the longwall extraction rate. Peak emissions from the active longwall panels were recorded to occur not during the short-term period of the most rapid pressure drops but to have occurred at the end of long-duration pressure decrease events. The net outgassing quantity from the caved material was found to be proportional to the short-term pressure drops. Similarly, the short-term gas concentration of the outgassing airflow from the caved material during falling atmospheric pressure, was found to be proportional to both the duration and magnitude of the pressure drop. Any leveling out or increase in atmospheric pressure quickly restored the emissions level to the lower long-term average. Therefore, continuous monitoring is an important consideration for ventilating mines effectively, for understanding methane flows in the bleeders accurately, and for ventilating mines safely.

Another noteworthy observation related to ventilation quality is that the bleeder ventilation systems, with the addition of large amounts of fresh air along the headgate entries of the active panels, can cause methane emissions from the active panel to be transferred to bleeder evaluation points not on the active panel. Without rebuilding stoppings that are usually removed during the first caving of the active panel, the longwall setup room access drift, as well as the inner bleeder entry, can transfer low methane airflow that will parallel the measured outer ventilation system. This potentially masks the true methane quantities and/or concentrations within these inner bleeder entries.

The following sections provide a more in-depth discussions of some of the main observations and quantifications of the monitoring data that were presented in previous chapters.

### 5.1 Importance of atmospheric pressure changes

Almost all ventilation models used to design ventilation systems are based on the simple premise of static mine and atmospheric conditions. This applies to both network models and computational fluid dynamics for modeling ventilation networks. Static conditions allow for



simplification of the modeling exercise and are valid for conditions such as when smaller quantities of air are modeled that do not expand or contract. For example; modeling of the ventilation of gateroad development, dead-end entries, crusher stations or any other small scale ventilation sections, about which numerous CFD papers have been written over the last decade. On the other hand, longwall gobs represent a large volume of fairly static air that can easily expand and contract due to atmospheric pressure changes, changes to regulator settings or fan interruptions.

The maximum free space volume held within a panel or longwall district can be readily approximated, if the overall subsidence factor is known. Given the known average mining height of the longwall panel and ignoring the edge effects and minimal rock expansion due to lower stress fields in the gob, a super critical longwall panel's maximum remaining volume can be determined. With a known volume, the ideal gas law can be used to approximate the amount of outgassing that will occur during a known pressure drop. This extra outgassing has to be accommodated by the ventilation system for proper dilution. The added complication that arises during outgassing is that the air composition within the caved material is not homogenous with higher concentrations of contaminants deeper in the gob. Therefore, not only does the quantity of air flow leaving the gob increase during a pressure drop, but also the concentration of contaminants as the outgassing continues.

As shown by Figure 4-22 the gas composition within the caved material at Mine A is not homogeneous, but if static atmospheric conditions are assumed then the amount of contaminants release stays constant. When a dynamic ventilation case is considered in which the pressure is dropping, after a short amount of time the lower contaminant concentration surrounding the perimeter of the caved material is outgassed first, followed by higher concentrations of contaminants from within the deeper parts of the caved material. During a falling barometer, not only the rate of pressure drop has to be considered but also the duration of the event should be taken into account. As shown in chapter 4 for Mine A, the highest carbon dioxide values occur not during the steepest pressure drop, but at or near the end of the falling barometer event. The quantity of the exhausting airflow can be estimated by the simplified gas law and controlled by the rate of pressure drop, and would remain near constant with a constant falling barometer. Therefore, the exhausting gas concentration must be changing to account for the increased gas concentrations recorded at the sampling locations.

Once the barometer levels off or starts to rise, the carbon dioxide emissions rapidly fall back to the long-term background emissions levels. If the caved material had been homogenous in its air contaminant concentrations, emissions recorded at the longwall section return would have directly corresponded to the rate of pressure change. However, this is not the case for Mine A. Instead, the gas concentrations in the active gob in Mine A indicated increasing carbon dioxide levels further within the caved material. The sample tube line that was left in the gob at the tailgate corner over a two week period shows a rapid increase in carbon dioxide and reduction in oxygen as the longwall face continuously retreats.

The effect of increased emission rate from a gob during a prolonged drop in atmospheric pressure was numerically shown numerically by Lolon et al. (2015). The rapid increase of the size of the modeled explosive gas zone, during the second half of the 24-hour falling barometer (Figure 5-1) closely matched with the increasing gas emissions for Mine A during a similar 48-hour falling barometer event monitored in this study (Figure 5-2). These two figures, although for different gas concentrations within the bleeder system, both show an increase with increasing duration of atmospheric pressure drops. The paper by Lolon et al. (2015) clearly demonstrated the use of CFD to model the theoretical increase in size of the possible explosive zone within the caved material, whereas the monitoring results from Mine A of this study showed increasing emission rate from the active longwall panel, partially validating the CFD models of Lolon et al., 2015.

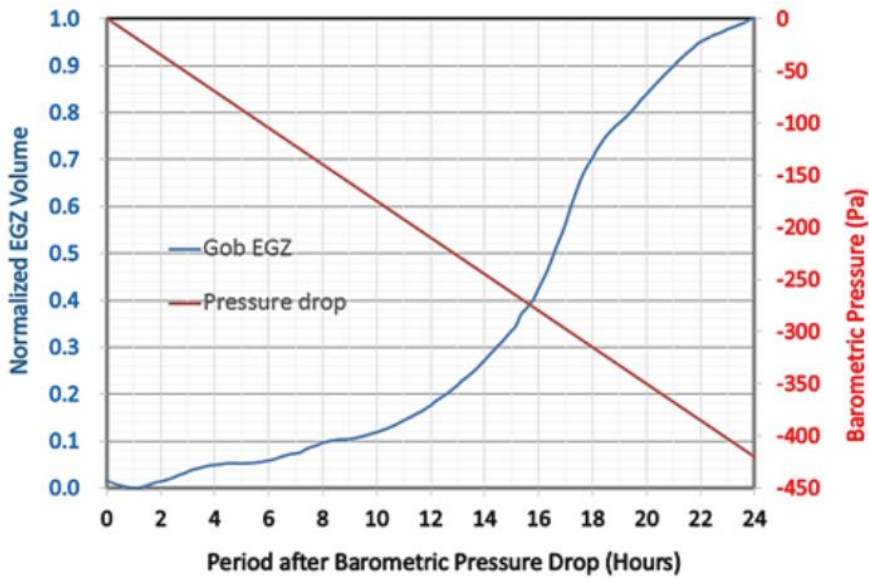


Figure 5-1. Normalized explosive gas zone volume predicted in the gob as a function of barometric pressure drop (Lolon et al., 2015)

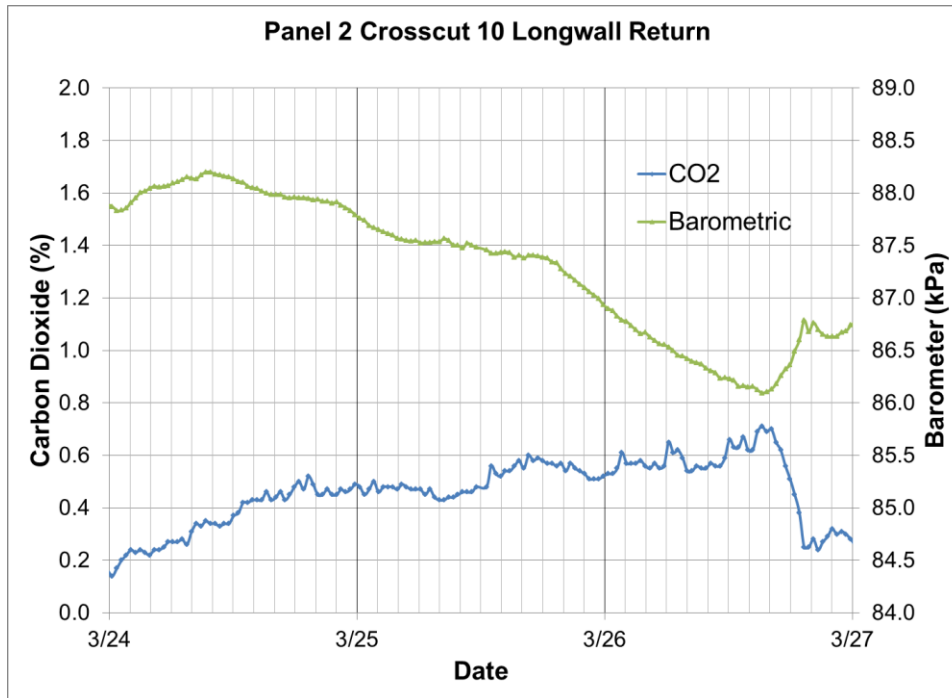


Figure 5-2. Mine A Panel 2 longwall return showing carbon dioxide concentrations more than doubling during a two-day falling barometer event. Concentrations drop back to the average quickly after the barometer rises.

The non-homogenous gas concentration near the longwall face along with in- and out-gassing events explains why the gas emission levels recorded at the section return do not have a normal distribution but a log-normal distribution. In other words, when the caved material is exhausting airflow, the concentrations of the emissions also increase with time. This is not a result of the bleederless system or of the use of an exhausting or blowing ventilation system, but is common to all longwall mines that having a large void space open to the active ventilation system.

When the active longwall panel is progressively sealed, as in Mine A, it can still breath onto the active face. Previous panels have been semi-sealed from the active panel but there is still leakage around the high number of gob isolation stoppings (over 90). When the standard bleeder system layout is considered, there is no restriction for airflow of the previous panels in the district to expand during falling pressure events and flooding the bleeder ventilation system with progressively high concentration of contaminants as the pressure drop event duration length increases.

The rising contaminate concentrations recorded during a falling barometer events at Mine A indicated that emissions increase with duration length. With peak emissions more than double the mean measurements and given that the air within the caved material expands and contracts regardless of if the ventilations system is a bleeder and bleederless. Why are these outgassing events as shown at Mine A not being recorded at other longwall operations utilizing a bleeder systems? The answer is simple, the sampling frequency of once a week is too low.

## **5.2 Importance and effects of sampling frequency**

Typically, a mechanically rotating disk functions in bleeder fans as a pressure log and would capture any changes to the static pressure of the fan and could detect if there was a significant mine explosion or groundfall causing a blockage which increases the pressure of the fan. Therefore the only practical use of continuous pressure monitoring, of a bleeder fan, would be in a post disaster investigation. Considering that explosive methane mixtures might exist somewhere in the mine bleeder system, a sampling frequency rate that will allow for the detection of potentially high methane concentrations as the result of atmospheric pressure changes, should be selected.

Typically, one has to first be able to measure and quantify any issue before being able to engineer the system to an optimum solution. This quantify and optimize approach has been done before in underground coal mining with the installation of continuous methane monitoring

of continuous miners and longwall shearers, which have greatly enhanced the safety of the face ventilation designs. It seems logical to apply a similar approach to optimize underground bleeder locations or bleeder fans on the surface. The continuous miners and shearers are nominally mining in fresh air, whereas the bleeder locations would be expected to have higher methane in return air. The installation of continuous methane monitoring within the “return air” of the bleeder system itself is difficult given the MSHA permissibility requirement for instrumentation in the bleeder system. The ability to just sample this airflow for methane concentration with a tube system is a simpler task that would not involve introducing a possible ignition source. The requirement that the sampling instrument pose no explosive hazard to the airflow poses a paradox. The airflow is either in the explosive range or not. If the air cannot be explosive, then there should not be an issue installing the instrument. If there is a possibility that the airflow could be explosive, then the installation of the instrument should be a requirement to monitor if the gas is explosive. In either case, it is highly beneficial that both the airflow and gas concentration be monitored at points within the bleeder system, but permissibility is a difficult requirement to meet.

As shown in Chapter 3 the required weekly sampling of the bleeder system does not capture the highly variable nature of the emission level leaving the active longwall panel. Even daily sampling will miss most peak occurrences as the high emission event durations are typically less than 24 hours. The sampling frequency rate at Mine A ranged from 14 to 30 minutes and was able to capture all atmospheric changes but not the weekly fan shutdowns. With this system, the weekly fan shutdown on Sundays were recorded as single sampling anomalies except for the one occurrence when the fan was down for over three hours (Figure 5-3). The sampling system was able to record the gas concentrations from the caved material flooding the tailgate location. When the fan turned back on this slug of CO<sub>2</sub> laden air left the mine via the longwall section return, but only three samples was taken of this high concentration of carbon dioxide airflow and the peak was most likely missed. So even with a sample frequency of every 20 minutes, some high gas reading of likely short duration events may pass by unrecorded.

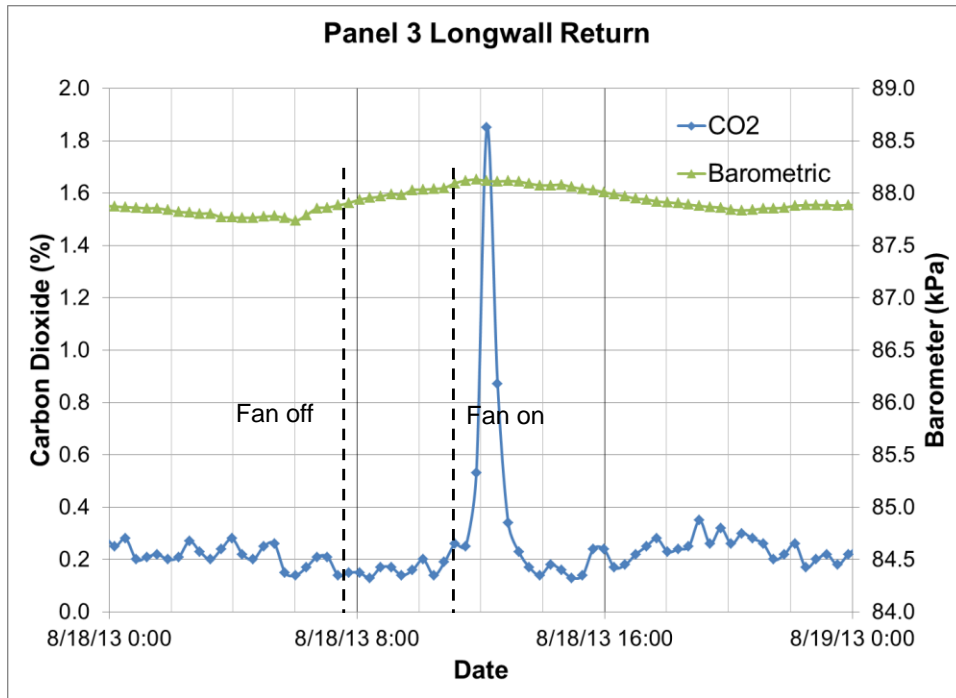


Figure 5-3. High outgassing event at longwall return caused by the main mine fan shutting down for 3 hours.

The first level of any more effective sampling system would be to simply monitor the surface bleeder fan locations for gas concentrations and have a sample frequency of an hour or less. This would be able to definitely show if there are high outgassing events and then the events could be correlated to atmospheric pressure changes. If high outgassing events are observed at the bleeder fan, then a second set of underground sampling locations closer to the caved material should logically be installed, with the BEP and MPL the obvious starting locations.

### 5.3 Effect of conversion of ventilation system from exhausting to blowing

If there is surface leakage to surface via fractures at the back of the active bleederless panel, then the total emission levels will be similar to a bleeder system, as discussed in Chapter 4. These fracture networks act as a low resistance pathway that allows leakage into the caved material that then transports the high concentration from the caved material towards the tailgate corner (primary exhausting pathway). This fracture network extending to the surface acts similar to the remaining middle gateroad entries of between the panels of a bleeder system, which transports the higher methane airflow from the caved material towards the back of the bleeder system (BEP or MPL).

It should be restated that the bleederless ventilation system used at Mine A had a fracture network connected to the surface, which allowed the active panel to have an extra flow path towards the tailgate and allowed previous sealed panels to slowly breathe with changes in atmospheric pressure. The sealed panels with the surface fracture connection and higher resistance leakage through the gob isolation stoppings was kept roughly at outside atmospheric pressure. The fracture network to surface existed because the start room and recovery rooms only having about 60 m (200 ft) of overburden cover at the start and the end of the panel. This is not a common characteristic of longwalls in the USA with Powhatan No. 6 mine in Ohio (Pittsburgh #8 coal seam) at 90 m (300 ft) having the second shallowest overburden thickness.

When the longwall face is at a lower or higher relative pressure compared to the atmosphere outside, leakage will either enter or leave the caved material into the mine. Since the main mine exhausting fan at this mine placed the longwall face between to 0.5 to 0.7 kPa (2 and 2.5 inches) negative pressure relative to surface, the two general flow paths were; through the caved material from the setup room of the active panel to the tailgate corner of the longwall face, and from the previous sealed panel leaking through the strata around the gob isolation stoppings. The number of gob isolations stoppings leaking depends on the level of extraction of the active panel and can range from 10 at the start to over 90 when nearing full extraction. Because the gas concentration within the first two sealed panels is less than 1% oxygen and approximate 20% carbon dioxide any substantial volume of leakage (5% of total longwall return airflow) from the first two sealed panels can quickly and easily overwhelm the ventilation of the longwall tailgate or longwall section return. 5% leakage with 20% carbon dioxide equates to a 1% increase of measured carbon dioxide in the longwall section return.

Because of this ventilation leakage, during mining of the 4th panel, the mine changed to a blowing ventilation system which increased the relative pressure at the tailgate corner to positive 0.7 to 0.9 kPa (2.5 to 3.5 inches) relative to surface. This caused a dramatic reduction in measured gas emissions at the tailgate corner, as well as in the longwall section return. The reason for this is that the airflow leakage was now from the caved material back towards the startup room surface cracks of the active panel and leakage through the seals would be from the active panel toward the sealed areas. The reversal of carbon dioxide leakage caused an over 70% reduction in the average carbon dioxide measured at the longwall section return after the conversion. This was the primary justification for converting from an exhausting to a blowing system.

The major disadvantage with the conversion to a blowing system at this mine was the introduction of increased oxygen levels behind the headgate shield that could lead to a heating event. The mine overcame this issue by the continued use of the nitrogen generation plant injecting airflow just inby the longwall panel on the headgate side through the gob isolation stoppings.

The primary reason for the installation of a bleederless system at Mine A was to reduce the possibility of spontaneous ignition of the reactive coal. A surface nitrogen generator installed while mining Panel 3, would inject approximately 0.5 m<sup>3</sup>/s of below 3% oxygen airflow behind the headgate gob isolation stoppings located inby the headgate corner. This nitrogen injection greatly increased in effectiveness after the conversion from an exhausting to a blowing system. Before the conversion most of the nitrogen injected would soon migrate towards the tailgate corner and leave the mine because the general airflow pathway in the gob was towards the tailgate corner. After conversion to a blowing ventilation system, the increase in effectiveness of the nitrogen plant was due to the new airflow pathway that was from the longwall face back towards the setup room. The nitrogen injected into the caved material on the headgate side of the longwall panel would now stay within the caved material and because of lower oxygen, suppress coal heating and carbon dioxide generation. The blowing system changed the airflow path direction pushing the N<sub>2</sub> back into the gob and lowered initial oxygen concentration in the active panel and hence reduced the final carbon dioxide level after the panels were sealed. The increased oxygen levels on the longwall tailgate side, after the conversion, could not be controlled by nitrogen injection alone, the mine operators make it a priority that the longwall face did not stay idle for long periods of time. The mining rate did not increase, but shutdown durations were minimized.

What should be noted is that the dramatic change in switching from an exhausting system to a blowing system was significantly a function of changing the leakage from the longwall face towards the setup room and then towards the surface. With the blowing ventilation system installed, leakage reversed from the caved material towards the longwall section return during low pressure events. During these events the airflow from the caved material reversed itself and caused dramatic increases in carbon dioxide levels and reduced oxygen levels at the longwall section return. This dramatic airflow reversal is not just a function of the bleederless ventilation system. The same dramatic increase of emissions can happen in a bleeder system as well: dramatically higher emissions from the caved material are transported towards the BEPs and MPLs, but they are missed due to infrequent sampling.



## 5.4 Effect of multiple mixing zones in a bleeder systems and sample locations

Current bleeder ventilation systems have been designed to dilute highly contaminated airflow originating between two gobbs as quickly as possible with cleaner low concentration airflow supplied by the headgate entries of the active panel and by the tailgate entries of the first panel (see Figure 5-4). The higher methane concentration air exiting from the inby end of the middle entry of the tailgate between two panels, is first diluted by airflow that wraps around the active panel via the caved material of the setup room that does not fully re-compact during retreat mining. Next, dilution airflow comes from the longwall setup room access drift unless stoppings are reconstructed after the first cave, which may have partially knocked over the stoppings, there now exists a direct open pathway from the middle headgate entry to the middle entry between the two panels. Even with partial or near complete roof falls in the longwall setup room access drift, the ability to transfer 10 to 20 m<sup>3</sup>/s of relatively low methane airflow to be used as a sweetener to mix with the higher methane airflow exiting the caved material from the middle entry of the active panel has to be considered.

There are no active systems measuring the gas concentrations airflow traveling down the middle entry between two mined-out panels and knowledge of the methane load in this entry is crucial to effectively designing the bleeder system. The simple installation of a 300-m sampling tube running from the travelable outer bleeder entry into the caved material via the middle gateroad entry prior to retreat mining, would allow samples to be drawn before any dilution could occur. These un-diluted samples would give a clear knowledge of high methane, possibly explosive, airflows are traveling down the middle entries. This sampling tube line is being proposed as a requirement by MSHA in District 2 (Western Pennsylvania) for new longwall districts (private conversation with CONSOL Energy). The installation of the tube line may give a better indication for the methane concentrations traveling down the middle entry of the tailgate entry at the start of mining but, as previously discussed, only if the sample frequency is greater than once a week. As shown in chapter 4, the emissions fluctuate greatly from a longwall panel or district and therefore requiring a sample frequency of 30 minutes or less to get the most useful information

It is commonly accepted that the use of multiple parallel bleeder entries surrounding the longwall districts along with pre-mixing can mask higher concentrations within the bleeder system. It is a common practice to have more airflow flowing from the active headgate to a location in front of the active tailgate BEP than being pulled through the panel BEP. For

example, a typical situation might be a total of 30 m<sup>3</sup>/s of clean air from the headgate may use the setup room access drift and the inner bleeder entry to travel to just in front of the tailgate BEP.

As shown in Figure 5-4, which assumes perfect mixing in network modeling, 15 m<sup>3</sup>/s of contaminated airflow traveling down the middle entry of the tailgate mixes with 10 m<sup>3</sup>/s airflow from the setup room access drift to form a 25 m<sup>3</sup>/s of mixed concentration. After this mixing, 10 m<sup>3</sup>/s transfers towards the active BEP where it then mixes with 20 m<sup>3</sup>/s airflow from the inner bleeder. After this second occurrence of pre-mixing, only 5 m<sup>3</sup>/s of airflow finally passes through the BEP. In this situation, the airflow leaving the middle entry between the two caved panels could have a methane concentration of 5%, and yet the airflow concentration of the active BEP would only be 1.1%.

One key result of this scenario is that the active BEP does not see the full amount of airflow coming from between the panels to the walkable outer bleeder. Since only 5 m<sup>3</sup>/s is transferred and recorded at the active BEP, the remaining 40 m<sup>3</sup>/s travels via the previous panels' setup room access drift and via inner bleeder to mix with the airflow exiting from between the previous two longwall panels. This process of diluting the airflow exiting from between two previous panels with only minor amounts of airflow (5 m<sup>3</sup>/s) passing through the BEPs is repeated across the longwall district until the first panel is reached. Here, a large amount of clean airflow is transferred from the tailgate side of the first panel towards headgate where it mixes with the high methane concentration airflow arriving from the active longwall panels. Once mixed at the headgate of the first panel, it is then passes through the BEP located between panels 1 and 2. The total airflow passing through this single BEP can be greater than the combined airflow of all the newer BEPs including the active panel's BEP. Minor amount of airflow passes through the active panel's BEP to allow a greater airflow to move along the inner bleeder entry pre-mixing the higher methane concentrations.

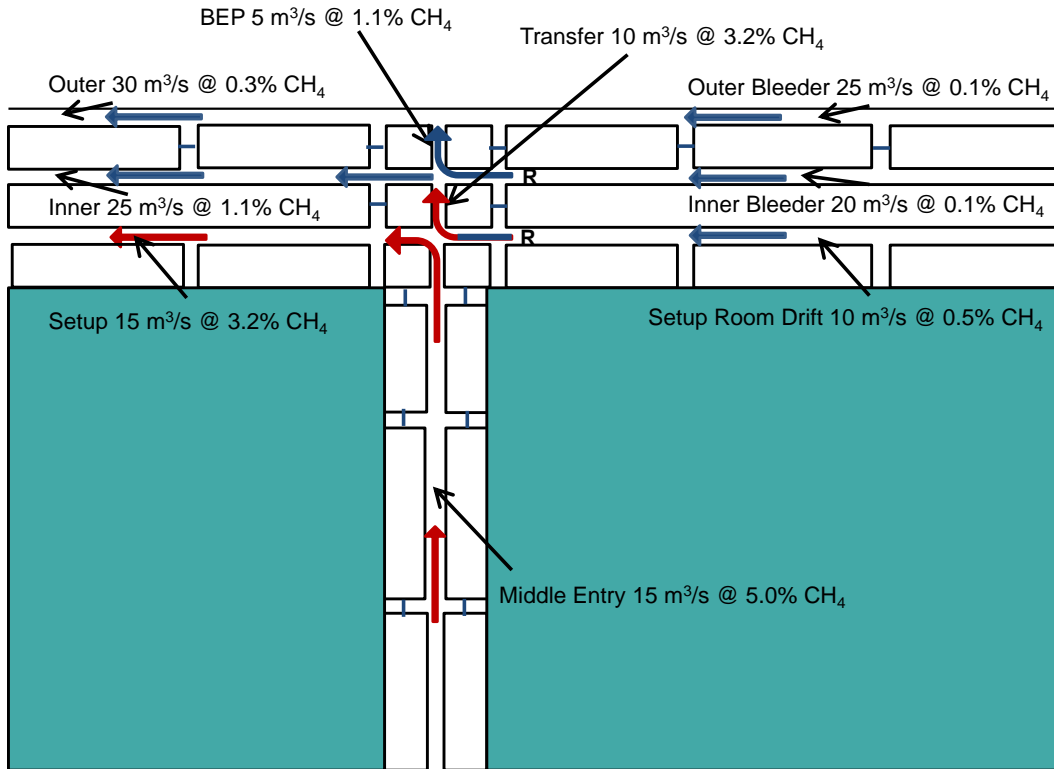


Figure 5-4. Methane concentrations in front of active panel BEP showing perfect dilution at interactions (ventilation network models).

Ventilation network models use simple perfect mixing conditions for any node intersection between two or more airflows as shown in Figure 5-4. On the other hand, CFD models use momentum to determine the level of mixing that occurs in these intersections. If a significant higher airflow quantity enters an intersection, it can displace a lower airflow crossing its path. This form of interaction is not perfect mixing but a form of displacement ventilation, which is more accurate than the idealized perfect mixing. This momentum-driven ventilation can be similar to water jets and sprays on the shearers suppressing and transferring dust and methane away from the shearer operators.

If the same example of perfect mixing of a ventilation network described in Figure 5-4 is repeated for a more realistic approximation of the real world using CFD modeling, a totally different concentration of methane is recorded at the BEP, and is shown in Figure 5-5. In this scenario, the same  $10 \text{ m}^3/\text{s}$  airflow traveling towards the BEP meets up with  $20 \text{ m}^3/\text{s}$  of airflow from the inner bleeder. Given that the cross sectional areas of the entries are the same, the airflow from the inner bleeder would have 4 times the momentum. In an actual displacement interaction, all of the  $10 \text{ m}^3/\text{s}$  of 2.0% methane airflow would be pushed into making a left hand

turn and travel down the inner bleeder with none of the 10 m<sup>3</sup>/s airflow appearing at the active BEP. In this case, the active BEP would only see the low methane concentration airflow from the inner bleeder and therefore give no indication as to higher methane concentration exiting from the middle entry between the two panels. This is a case of displacement airflow imperfectly mixing in front of the BEPs and gives a closer approximation to the real world when two airflows of different momentums interact.

While reviewing yearly ventilation maps submitted by mining companies at the MSHA offices, it was noticed that there were multiple occurrences of the BEP of the active mine registering little or no methane because of excessive airflow being transferred by the inner bleeder and setup room access drifts, while higher recorded methane concentrations were reported at the older BEP from the previous panels that are closer to the bleeder fan.

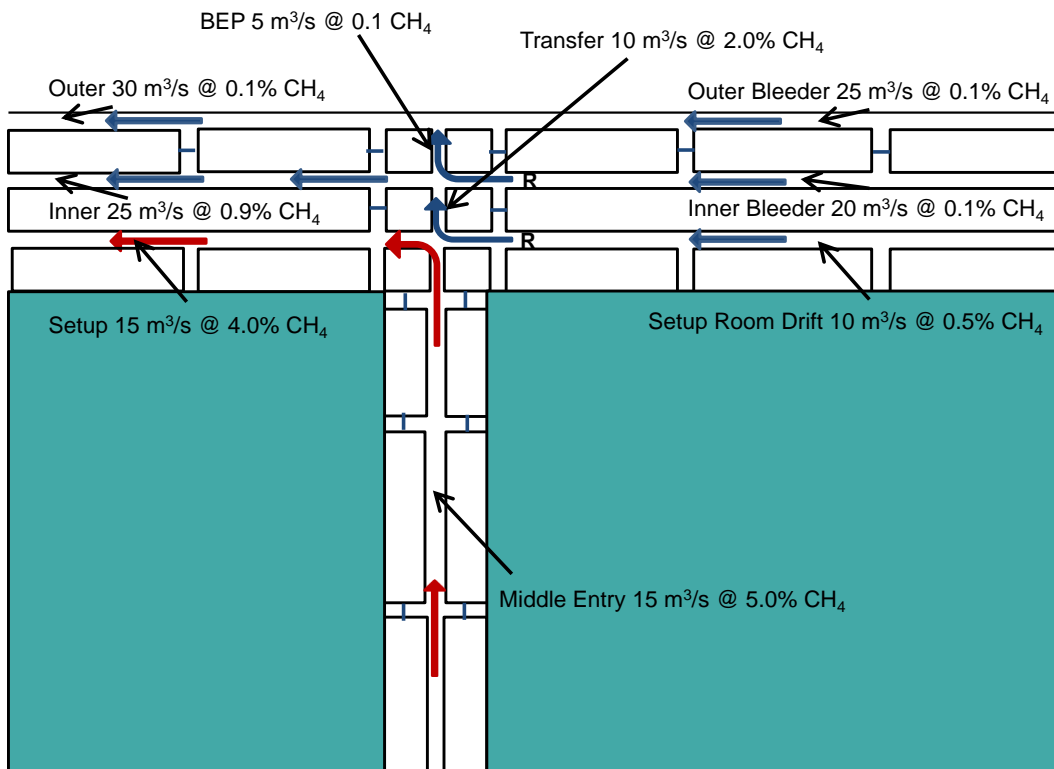


Figure 5-5. Methane concentrations in front of active panel BEP showing displacement ventilation at interactions (CFD models).

This multiple mixing in front of the BEP locations does have the benefit of diluting possible explosive concentrations as quickly as possible, but can mask the actual concentration of the airflow leaving from between longwall panels in a bleeder system. With premixing allowed the

weekly recorded gas concentrations at the BEP locations give little indication as to the health and effectiveness of the bleeder system.

One potentially obvious solution is to move the BEP locations closer to the caved material and to the actual middle entry between longwall panels. The problem is that these locations are some of the higher ground stress locations in the mine and fire boss's (mine employee) safety has to be considered for roof safety. The pre installation of sample tubes or possibly fiber optic sensor lines before the commencement of longwall retreat mining can reduce this ground fall hazard while supplying the necessary information. However, the unknown integrity of the sample lines will always be an issue from a legal and enforcement point of view.

## **5.5 High concentration methane airflow behind longwall shields at tailgate corner**

The three tracer gas test at Mine B were able to approximately determine the airflow rate behind the longwall shields from the airflow that entered near the headgate corner, traveled behind the shields towards the tailgate and then towards the back bleeders away from the longwall tailgate corner. The airflow pathways were demonstrated to be sweeping the tailgate corner as expected, and were functioning as designed in all three tracer test (Chapter 4). The tracer gas tests showed that the possible high methane concentration behind the shields nether entered the tailgate corner, nor got near the possible ignitions source from the shearer. By analyzing the tracer gas concentrations, the quantity of this airflow behind the shields was determined to be approximately 7 m<sup>3</sup>/s (15,000 cfm) with retention times of 15 to 30 minutes for all three tests. During the third tracer gas test a concentration of 5.8% methane for this airflow was calculated to be required to balance out the known concentrations from the longwall face and the measured concentrations down the middle entry. The increase in CO<sub>2</sub> levels along with reduced O<sub>2</sub> levels indicates that there is an interaction with air flowing behind the shields and the air in the caved material itself.

It should be noted that calculating the methane level for the airflow behind the shields, by the mass balance method, was not a primary goal of the initial tests. The hydrocarbon testing of the vacutainer samples was used as a check to make sure the sample tubes lines were labeled correctly. The vacutainers were not taken as valid compliance monitoring samples but do give a representation as to the conditions behind the shields for all three tests. The obvious result from this testing is that airflow with greater than 5% methane was an occurrence close to behind the shields. These tests did not determine the depth into the caved material, in which the explosive

methane mixtures were found. The result of the high methane near the tailgate corner was an outcome of determining the airflow pathways at the tailgate corner and the mixing ratios in the entries leaving the tailgate corner.

The tracer gas releases performed at this mine appear to be a repeatable experiment to determine if other operations have a similar methane concentration behind the shields. However, finding a mine operator who was willing to repeat this experiment was not possible. Mine operators have little incentive to ever do such a test that can cause immediate regulatory problems. However, from a safety perspective, the possible safety improvement of collecting accurate data on the increased emissions that occur during falling atmospheric pressure has to outweigh the collective short term compliance issues for both the ventilation operators and regulators.

## 6 Conclusions and recommendations

Previous ventilation research in underground coal longwall operations had been focused on determining if and where explosive mixtures of methane are located within the caved material. Knowing the explosive mixtures do exist, one of the goals of this research was to show that more frequent and better located monitoring would reduce the likelihood of explosions, since the underground ventilation system is not a static case but a dynamic system. Throughout this dissertation this research shows that, while explosive conditions may exist within the caved material and warrants further research, an issue of far greater concern is the likelihood of explosive mixtures in the maintained bleeder entries themselves. The dynamic nature of emissions from the caved material during falling atmospheric pressure along with the practice of premixing of airflows before BEP locations makes the current weekly ventilation assessment of bleeder system effectiveness for eliminating explosive mixtures questionable. With the demonstrated existence of explosive air mixtures behind the longwall shields, the underground coal industry should be concerned with the proximity of those locations to possible ignitions sources, such as the shearer.

The doubling of emissions from the gob during large atmospheric pressure drops recorded at Mine A have to be considered as the overriding condition for the design of any bleeder or bleederless ventilation system. With peak emissions recorded from the caved material at over twice the average value, previous factors of safety used in longwall ventilation mine design have to be reevaluated. During long-term atmospheric drops, the concentration of contaminants exhausting from the caved material increases, thereby confirms the theory that gobs have higher concentration of contaminants in the middle section.

Emission rates from the active gob were shown to be predominately controlled by long-term (days) atmospheric pressure changes that rapidly returned to average emission rate with a short-term (hours) rise. The first level of any reasonable sampling system would be to monitor the surface bleeder fan exhaust for methane concentrations and have a sample frequency of an hour or less, with continuous monitoring preferred. This would show if there are large outgassing events and if they are controlled by atmospheric pressure changes. If high outgassing events are observed, then a second set of sampling locations closer to the caved material would be recommended for installation, with the BEP and MPL as the obvious starting locations. This second set of locations would be more difficult to install because of the need for a permissible system in the bleeder locations in the US. Tube bundle systems, or fiber optic sensors could instead be used for this purpose.

To complicate the sampling process from just the BEP or MPL, there is an additional issue with bleeder system ventilating longwall districts by using multiple parallel pathways along the backside of the bleeder. These parallel pathways inby the outer bleeder entry and BEPs are used to transfer large quantities of cleaner air to pre-mix and dilute with the higher concentration airflow exiting from the middle entry between two panels. In some cases, so much clean air is brought to pre-mix at these air intersections that the clean airflow overwhelms and displaces the entire smaller volume exiting from the panels. When this happens, little or no methane is recorded at the active BEP, even though there are high concentrations of methane exiting from the adjacent panels. In these situations the diluted methane airflow is transferred further inby toward the first panel's BEP, just in front of the bleeder fan, by the use of the inner bleeder entry or setup room access drifts. In most cases, the weekly methane concentrations and airflow rate measurements at the underground BEP give little to no accurate indication of the quality of contaminants exiting from the middle entry between two panels.

One recommendation is to move the BEPs closer to the caved material before the pre-mixing occurs. How close the new BEP can be placed has to consider the safety of the mine worker required to install and maintain those structures. The practices of mixing the high methane airflow exiting from between the panels as soon as possible should be continued. The goal should still be to dilute the high methane concentration as quickly as possible, but not to just to mask the issue of high methane concentrations in the middle entries by pre-mixing.

Therefore, to get a useful reading, the installation of a continuous sampling system should not be at the current BEP locations but further within the bleeder system. This can be accomplished with the installation of sample tube lines of various lengths prior to longwall mining of the panel. These tubes of lengths of a few tens to hundreds of meters, can be installed to end in the outer walkable entry for added safety. The sample tubes along with a sample frequency of less than half an hour would be better to be able to properly define the true emission rate especially as it relates to falling atmospheric pressures. These sensitive measurements have to be recorded and analyzed at multiple mines prior to any country-wide engineering recommendations for re-design of ventilation systems.

The tailgate entry next to the longwall tailgate corner typically have increased support (standing or intrinsic) for the requirement of maintaining the secondary escapeway open, and to maintain an open return airflow pathway into the caved material to at least the first inby crosscut. This open entry allows for the removal of airflow away from the longwall tailgate corner in both a



bleeder and bleederless ventilation system through the use of a 'back return'. In this approach, the rationale is to quickly remove the high methane concentrations coming from the gob away from the longwall face and into the returns.

Research into ventilation of longwall mines supports the hypothesis that there must exist an explosive mixture of air within the caved material and also closely behind the longwall shields. It is hard to take direct air concentration measurement within the caved material during the re-compaction of the gob. One of the tests conducted at Mine B using both methane and tracer gas measurements at the longwall face and in the center entry of the longwall both inby and outby the tailgate corner, indicated airflow of about 7 m<sup>3</sup>/s (15,000 cfm) of airflow at 5.8% methane behind the shields. Measuring the airflow and methane concentration behind the shields was not the primary purpose of the tracer gas test, but this single test result confirms that explosive mixtures exist closely behind the shields and is occasionally measurable.

The indirect measurement of the airflow behind the longwall tailgate shield can be easily duplicated at any longwall operations by the installation of 150 to 300 m (500 to 1,000 ft) sampling tubes in the tailgate's middle or side entries ahead of the retreating longwall face. After the longwall has retreated past the ends of the tubing, samples can be taken with the use of a sample pump to measure the methane concentration. Along with the airflow rate of both the longwall face near the tail gate and the outby tailgate entries and corresponding methane reading, a simple mass balance will be able to determine if an explosive concentration is present behind the shields. Tracer gas testing is not required but would give a greater accuracy to airflow rates and therefore a better approximation to airflow and concentration behind the shields, if done at the same time.

This dissertation has shown that Mine A with the quantity of emissions exhausting from the active longwall panel to be primarily controlled by cave void volume and by falling atmospheric pressure, for a progressively sealed bleederless ventilation system. Mine B was shown to have high concentrations of methane in the airflow behind the longwall tailgate shields as well as down the middle tailgate entries, than for a typical bleeder ventilation system.

One possible suggested ventilation system change at longwall mines could be the adoption of progressively sealed panels with nitrogen injection, which is beneficial for coals showing a propensity of spontaneous combustion, such as in Mine A. Progressively sealed panels are not recommended for non-spontaneous combustion prone coal seams. The perceived increase in safety using a progressivity sealed active panel has to be weighed against the disruption and

additional cost of coal production from building gob isolation stoppings and injecting nitrogen. As shown by Novak (1998), the advantage of a bleeder system over a traditional bleederless system is a 160 to 180% increase in airflow rate which directly leads to increased coal extraction rate. Any industry-wide recommendation of the conversion of mine ventilation systems to switch from bleeder to bleederless systems, must first be based on information gathered from more than two mines.

## 6.1 Suggestions for future research

Future research in longwall ventilation needs to be conducted with the assistance of a continuously monitored sampling system so as to have a better understanding of the normal and peak methane concentrations and the volume of these mixtures in the inaccessible entries of the longwall district. Future research should be focused on understanding the airflow in the inaccessible entries next to the caved material that are maintained open with supplemental ground support (notably standing support). These areas are an ideal situation to initiate a methane explosion.

The U.S. coal mining industry and researchers cannot ignore the likelihood that explosive mixtures of methane exist within the caved material but are not being measured or controlled. Explosive mixtures of methane can, and do, exist in bleeder and bleederless systems. Explosive mixtures are not theoretical and therefore they need to be accurately measured and located so that proper engineering can be done to reduce the likelihood of an explosion and to increase miner safety.

At this time it would not be prudent to abdicate industry-wide recommendations on mine layouts of ventilations design based on only two mines. However, these case histories have clearly demonstrated the potential safety benefit of continuous methane monitoring at surface bleeder fans, and permissible (tube bundles, fiber optics, etc.) underground airflow and methane monitoring at critical locations in the bleeder system. If, and when, high methane concentrations are recorded at the surface fan one of the following three precautions can be taken: 1) a re-design of the ventilation system can be engineered, 2) the mine may simply delay longwall mining until the event ends, 3) if the need be, the mine can be evacuated.

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