The methane-air explosion hazard within coal mine gobs

by Jürgen Brune

Abstract

This is a shortened version of the paper "The Methane-Air Explosion Hazard Within Coal Mine Gobs published in the 2013 volume of *SME Transactions* (Brune, 2013, pp. 376-390).

This paper analyzes the explosion hazard resulting from the formation of methane-air mixtures in the mined-out gobs of underground longwall coal mines. Evidence from numerous mine explosions suggests that explosive methane zones can form within longwall gobs. Explosions and fires resulting from these methane accumulations have led to severe and fatal injuries to the miners, including the explosion of the Upper Big Branch Mine in West Virginia, where 29 miners lost their lives April 5, 2010.

The paper also reviews current research on numerical modeling of gas flows in longwall gobs and outlines how targeted injection of nitrogen into gobs can effectively reduce the volume of such explosive methane zones. The paper concludes that comprehensive monitoring of gas compositions, along the accessible fringes of the gobs along with inertization, improved ventilation schemes and further research are necessary to control this explosion hazard and make mining operations safe.

Keywords: Longwall, gob, methane, EGZ, explosive gas zones, underground, coal, explosion, fire

Introduction

Investigation reports of a number of mine fires and explosions in recent years have suggested that accumulations of methane-air mixtures in longwall gobs have been ignited and or exploded, causing fatal injuries to miners. The most recent such explosion happened in 2010 at the Upper Big Branch (UBB) Mine on April 5, 2010 resulting in the death of 29 miners.

Figure 1 shows a frame from an illustration video published by the U.S. Mine Safety and Health Administration (MSHA) (MSHA, 2011) to visualize the conditions that led to the UBB explosion. In MSHA's UBB investigation report, Page et al. (2011) suggest that explosive methane-air mixtures migrated from the gob area into the longwall tailgate where it was ignited, likely by the shearer cutting into sandstone roof.

This paper will discuss the following:

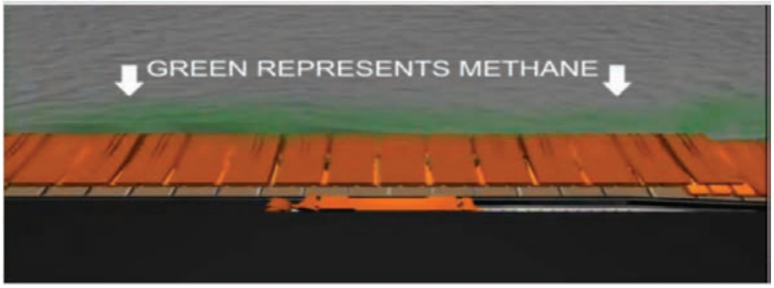
- Longwall ventilation with bleeder systems or bleederless, sealed gobs.
- A brief review of recent mine fires and explosions caused by explosive gas zones (EGZs) in longwall gobs.
- Known and unknown factors about the location and size of EGZs in longwall gobs.
- The influence of mine ventilation and nitrogen injection on EGZs.
- Ongoing research about EGZs; and recommendations for further research.

Bleeder and bleederless (sealed gob) longwall ventilation systems

Bleeder systems. In the United States, most underground longwall coal operations are required by Title 30, Code of Federal Regulations (CFR), § 75.334(b)(1), to use bleeder systems in pillar recovery operations to ventilate the mined-out, caved area (the gob). Figure 2 shows a typical longwall ventilation scheme with bleeder ventilation. The bleeder fan creates a pressure sink that causes a general flow of air within the gob and the bleeders directed away from the face so that contaminated air (CH_4, CO_2, CO) from the gob does not circulate back into the active mining areas.

Figure 1

Depiction of methane explosive fringe in the longwall gob behind the shields at the Upper Big Branch Mine. Not to scale. Source: MSHA (2011).



In most longwall operations, gob ventilation boreholes (GVBs) are installed to extract methane gas from the upper fractured zones of the mined-out gob area. Initially, these holes frequently yield more than 80 percent methane, while some reach close to 100 percent (Moore et al., 1976). Mucho et al. (2000) documented with tracer gas studies that the gases in the longwall gob communicate with those in the GVBs, the active face

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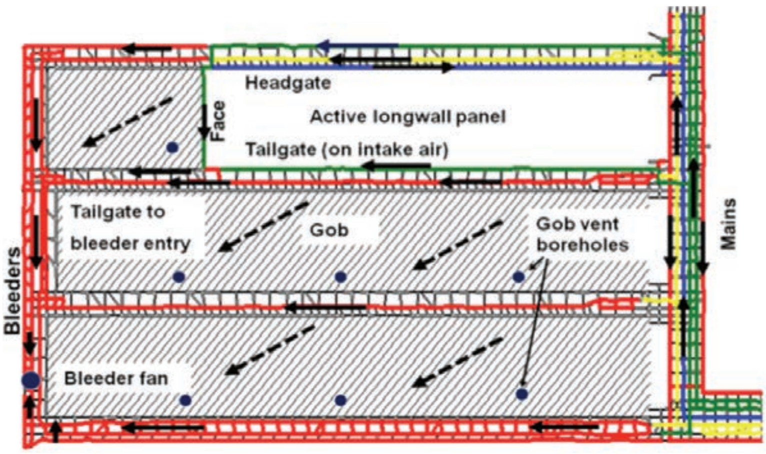
Figure 2

Typical longwall mine bleeder ventilation scheme. Arrows indicate direction of air flow. Colors indicate fresh air (intake): green; track: yellow; belt: blue; return or bleeder air: red. After Brune et al. (1999); not to scale.



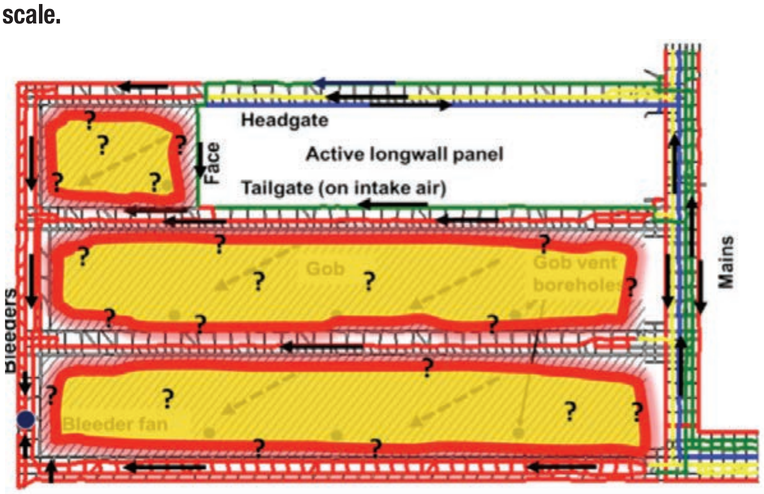
areas and the bleeder entries.

Therefore, if the methane concentration near the GVBs is far above the explosive range of methane, while in the surrounding airways, it is below 2 percent by statute, it follows that explosive gas zones (EGZs, about 5 to 16 percent methane) must exist inside the gob area. EGZs are likely located somewhere between the fringes and the locations of the GVBs. Figure 3 illustrates these EGZs in the longwall gob. In the bleeder entries the methane concentration must be kept below 2 percent. Toward the center of the gob there likely exists a methane-rich region (shaded in yellow) where the methane concentration is far above 16 percent.

The exact locations of these EGZs have not been determined directly, and their size and extent is not well-understood.

Figure 3

Presumed location of zones of explosive gas zones (EGZs) within the longwall gob. The EGZs in the gob contain methane mixed with air at explosive concentrations between 5 and 16 percent and are shown in red (note the colors of the gob areas are to be confused with those of the mine entries). The "?" indicate that the exact location of the zones is not known. The yellow shading indicates fuel-rich zones of methane-air mixture between 16 and 100 percent methane content. Gob fringe areas outside the orange perimeters are between 0 and 5 percent, i.e., fuel-lean inert. Not to scale.



Bleederless ventilation. Bleederless longwall ventilation schemes are most common in European and Australian longwall mines, often due to the tendency for the coal to spontaneously combust. If the coal is susceptible to spontaneous combustion, the mine operator must limit or avoid introducing any oxygen from the active mine workings into the mined-out areas. Therefore, the gob must be sealed concurrent with mining and care must be taken to not allow any flow of fresh ventilation air into the gob. In the United States, bleederless or sealed gob ventilation systems are permitted only on an exception basis if a spontaneous combustion cannot otherwise be controlled (30 CFR §75.334). There are several mines currently operating in the United States with bleederless, sealed gobs.

Figure 4 (MSHA, 2007) shows a bleederless, sealed longwall gob where the face is ventilated in a "U" pattern. Fresh air (green arrows) enters the face at the headgate side (left) and return air (red arrows) flows out on the tailgate side (right). The gob area is progressively sealed following the advance of the longwall face. As Fig. 4 shows, on the headgate side (left), new seals are installed in each crosscut inby the face.

As indicated in Fig. 4, the goal of sealing the gob is to render the atmosphere in the active gob fuel-rich inert (marked "CH4 Non-Explosive"). This can be attained by either maintaining the CH4-content above 16 percent or by reducing the oxygen content to below 12 percent through the injection of nitrogen or other inert gases.

Dziurzyński and Wasilewski (2012) studied methane accumulations in a bleederless, sealed longwall gob with a "U" ventilation scheme in the Mysłowice-Wesoła coal mine in Poland. Dziurzyński's gob methane measurements are indicated in the contours in Fig. 5 and clearly demonstrate that there are potentially explosive conditions in the gob. The contours in Fig. 5 show the methane concentration in percentage and suggest that there are EGZs immediately inby the active face.

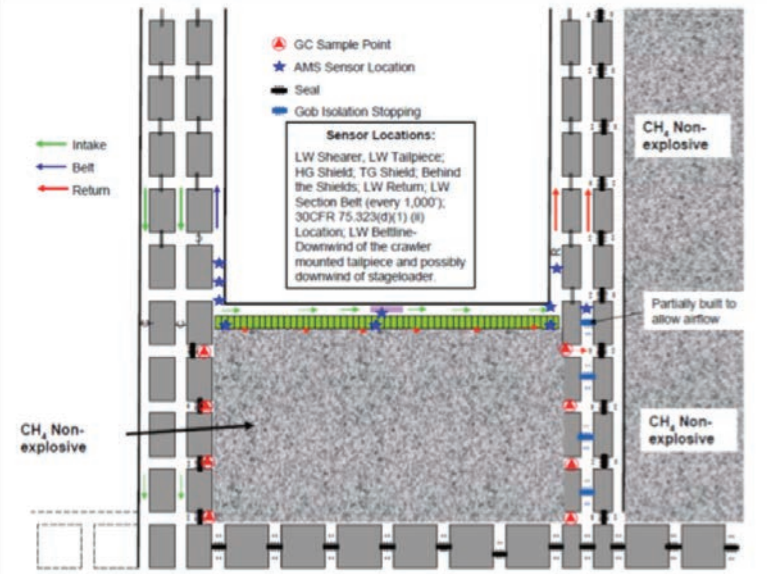
To reduce the oxygen content in the gob and render the gob atmosphere inert, it is common in bleederless longwalls inject nitrogen through the seals inby the headgate and tailgate. Figure 6 (MSHA 2007) depicts with gray shading what might happen during the inertization process. The red shaded area indicates the zone where the methane concentration is believed to be above 15 percent and the atmosphere is fuel-rich inert.

In conclusion, bleeder and bleederless longwall ventilation systems have the potential to accumulate methane gas in the gob areas. Zones with explosive methane-air mixtures (EGZs) can exist in both systems but the exact locations of these zones is unknown. It appears that leakage of fresh, oxygen-rich air into the gob along the face and through bleeder entries and gob seals can create mixing zones along the fringes where these EGZs form.

Current research has not advanced far enough to understand where the EGZs are located and how they can be controlled to prevent mine explosions and fires. The following section will examine the fire and explosion hazards resulting from EGZs using well documented investigation reports.

Figure 4

Schematic of a bleederless longwall ventilation system (MSHA, 2007, not to scale). It should be noted that the characterization "CH4 Non-Explosive" is one made by MSHA and has not been scientifically documented.



Review of mine explosions caused by methane-air accumulations in longwall gobs

This section presents a review of several recent mine explosions that document that EGZs must have existed in longwall gobs, and where gas from the EGZ exploded in the gob or migrated into active mine workings. There is frequent anecdotal reference from miners hearing or feeling "pops" (perhaps explosion concussions) and seeing ignition flashes in the gob, yet few of these events have been fully investigated and understood by scientists. Since longwall gobs are not accessible, small ignition events that happen deep enough inside the gob are unlikely to get noticed. Even if an airblast or concussion is felt by the miners, it may often be interpreted as a consequence of a major roof fall rather than a methane explosion.

Willow Creek Mine explosions, 1998 and 2000. On Nov. 22, 1998, an explosion and subsequent fire occurred at the Willow Creek Mine in Utah. No injuries were reported from this incident but a large airblast knocked down four miners at the longwall face and temporarily reversed the air flow at the longwall face (Elkins et al., 2001). After the explosion, miners observed an orange colored flame in the gob behind the shields that appeared to move toward the face and then back into the gob. This is evidence that an EGZ must have existed in the gob that was either close enough to migrate into the active face or was pushed into the face area by the caving gob.

In a nearly identical accident in 2000, a series of four explosions occurred at the Willow Creek Mine, killing two miners and injuring eight more, with some of them severely burned. According to the MSHA investigation (McKinney et al., 2001), "Most likely, a roof fall in the worked-out area of the D-3 longwall panel gob ignited methane and other gaseous hydrocarbons." From this investigation, it is again evident that an EGZ existed in the gob and was ignited.

Figure 5

Methane percentages in a bleederless longwall gob (Dziurzynski, 2012, dimensions as indicated).

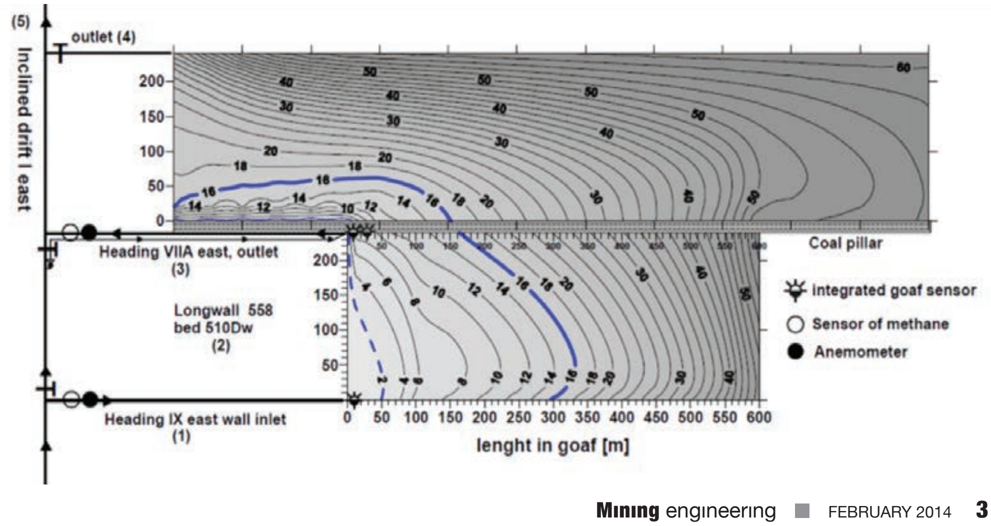
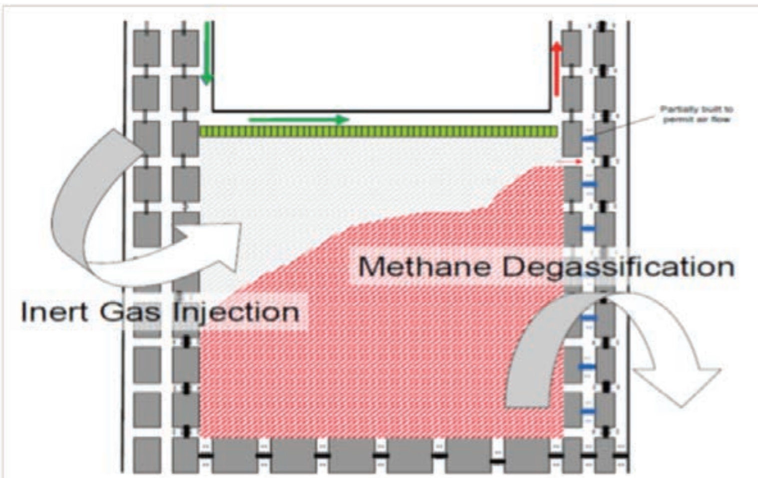


Figure 6

Rendering of the gob atmosphere non-explosive by injecting nitrogen (MSHA, 2007, not to scale).



The investigation report (McKinney et al., 2001) includes a noteworthy description of the function of a bleeder system, stating that:

In highly gassy mines, methane emanates from caved material and surrounding strata, or rubble zone, in concentrations close to 100 percent. Dilution of the methane must occur. The methane begins to dilute as it flows from the rubble into the primary airflow paths in the gob. Further dilution occurs as the methane-air mixture moves into the bleeder entries and out of the mine.

This description is illustrated by the depiction in Fig. 3. McKinney et al. imply that dilution must occur as part of the designated function of a bleeder system because the law requires the methane content in bleeder entries to remain below 2 percent (30 CFR §75.323 (e)). However, as this dilution occurs, the methane air mixture must pass through the explosive range. Therefore, EGZs must exist in bleeder ventilated gobs.

The mine operator brought a case before the U.S. Federal Mine Safety and Health Review Commission (FMSHRC) disputing certain violations that MSHA wrote. FMSHRC (2006) stated:

"This is a case in which MSHA had little evidence that the ventilation system was malfunctioning, yet the mine experienced an explosion and fire. Prior to the first explosion, air [flow] volumes [at relevant evaluation points] were above design levels and all measuring points were within expected ranges. The explosion itself was caused by a very small amount of methane 1.4 m^3 (50 cu ft) of pure methane diluted to 23 m^3 (800 cu ft), a volume that would not be unexpected at the fringe of the rubble zone."

This statement is noteworthy for two reasons:

- First, a cloud of 23 m^3 (800 cu ft) of explosive methane air mixture should not be considered "very small." Because the flame volume expands by a factor of approximately five (Nagy 1981), a 110-m^3 (4,000-cu ft) fireball would clearly be able to penetrate the shield line and reach the active face if it was close enough to the shields.
- Second, the FMSHRC noted "little evidence that the ventilation system was malfunctioning," and it is noted that a volume of 1.4 m^3 (50 cu ft) of methane "would not be unexpected at the fringe of the rubble zone." This is an indication that investigators considered the bleeder system in proper working order and, despite this, that an EGZ forming close to the mine workings was nothing unusual.

Buchanan Mine explosions and fires, 2005 and 2007. The first of two suspicious explosion events occurred without serious injuries at the Buchanan Mine in Virginia in 2005. According to the MSHA investigation report (Carico et al., 2005), the breaking of a thick sandstone bed overlying the coal seam caused a rush of gob air containing methane into the longwall face. A few seconds later flames were visible at the tailgate, described as "red in color" and extending about 2.5 m (8 ft). This example produces strong evidence that an EGZ existed in this bleeder ventilated longwall gob. The EGZ was likely close to the face and was pushed into the active face area by the caving in the gob.

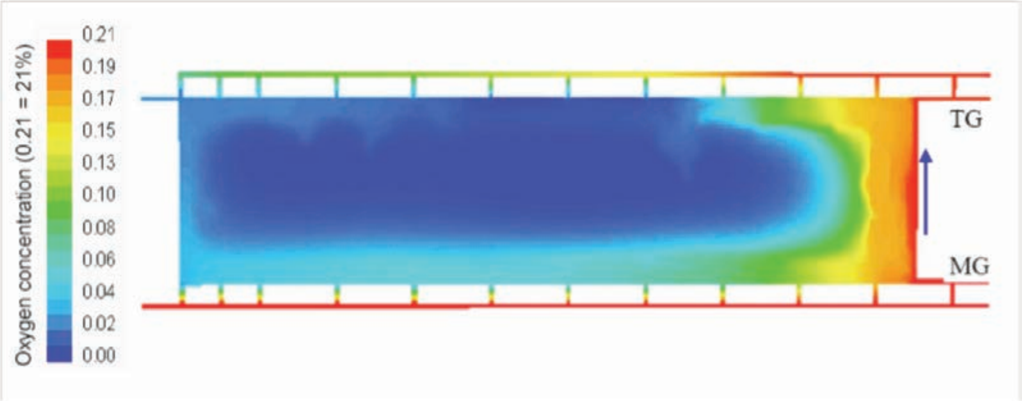
The MSHA report (Carico et al., 2005) states that the methane was likely ignited by a frictional ignition generated by a roof fall. Carico et al. (2005) further state: "The width and location of the elevated methane/air mixture along the gob periphery is variable dependent upon the permeability of the periphery and the proximity of the diluting air currents. An ignition of the methane within this zone can result in flame/explosion propagation along that periphery to other [presumably active] areas of the mine."

This statement also suggests that investigators were aware of the possibility of having EGZs in the gob, that these hazards exist under normal mine ventilation conditions and that they may be similar to those shown in Fig. 3.

In 2007, a similar explosion and fire occurred at the Buchanan Mine. It was investigated by MSHA (Woodward and Sheffield, 2007), which indicated that it had also been triggered by a violent cave-in of the sandstone overlying the coal bed. Again, this is clear evidence that an EGZ existed in the gob.

Figure 7

CFD model of oxygen concentration in a longwall gob (Balusu et al., 2005; no scale indicated).



Upper Big Branch Mine explosion, 2010. On April 5, 2010, a major coal dust explosion ripped through the Upper Big Branch (UBB) Mine near Montcoal, WV, killing 29 miners and injuring two.

MSHA investigators (Page et al., 2011) believe the methane came from the gob and was likely ignited by the shearer as it was cutting out the tailgate. A video illustration presented by MSHA (2011) shows an accumulation of methane along the fringe of the gob behind the longwall shields. Figure 1 shows a snapshot from this video, with the green shading representing the explosive methane fringe zone. MSHA's investigation report and this video each present clear evidence of an EGZ present in the gob. The initial methane explosion suspended coal dust in air, creating a massive coal dust explosion that expanded through 68 km (42 miles) of mine entries.

Summary of sentinel events. All sentinel events discussed clearly demonstrate that EGZs were present in the longwall gobs and that they can cause fatal mine explosions and fires. Additional detail is provided in Brune (2013). These EGZs have several things in common:

- If the EGZ lies closely behind the longwall face, the flames can penetrate the shield supports and reach the active face area, creating blast trauma and burn hazards.
- EGZs can be pushed around inside the gob by roof collapses and cave-ins. If they get pushed out into the face area, sudden methane inundations can result.
- Fresh air flowing into the gob can create an explosion hazard as the gas composition in the gob moves from fuel-rich inert to explosive, creating an EGZ.
- Ignition sources inside the gob can be frictional ignitions or spontaneous combustion.

State of current research and the need for future research in longwall gob ventilation

It has been established that EGZs exist in longwall mines with bleeder and bleederless ventilation systems. These EGZs create significant explosion and fire hazards and threaten miners' lives. Research is needed to determine the following:

1. Where in the gob are EGZ likely to exist and what methods can be used to detect them?
2. How large are these EGZs and what explosion or fire hazard do they constitute?
3. How can location, size and gas composition of the EGZs be effectively controlled to mitigate these hazards?

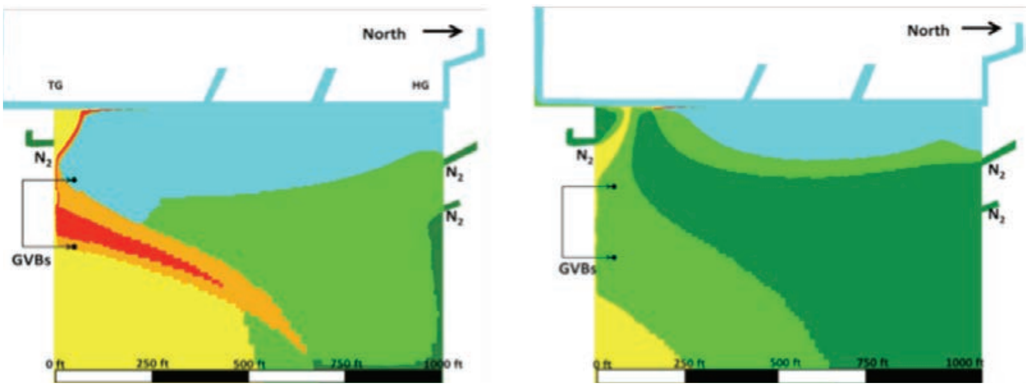
Researchers in the United States and Australia are working on a variety of projects modeling the flow of gases in longwall gobs. These models use computational fluid dynamics (CFD) software packages. To calibrate the CFD models, it is important to obtain gas composition data along the gob boundaries. Since the gob areas cave in and are inaccessible, some measurements must be obtained through remote sampling from boreholes and tube bundle systems. A summary follows that illustrates significant research accomplishments in addressing these challenges.

Gas flow modeling within the gob. Balusu et al. (2005) developed CFD modeling solutions to describe the gas flows in a sealed (bleederless) gob for nitrogen inertization purposes to prevent spontaneous combustion. Figure 7 shows the distribution of oxygen in a progressively sealed longwall gob. Sealing is effective in reducing the oxygen content deep inside the gob below 12 percent. Balusu et al. found that the extent of the oxygen-rich zone depended on the intake air flow at the longwall headgate and could extend 300 m (1,000 ft) inby the face in cases with increased air flow.

Marts et al. (2013) show that it is possible to reduce the size of EGZs in bleederless longwall gobs by injecting nitrogen inby the face. Headgate side injection is more effective than tailgate side injection. Figure 8 shows the effect of minimizing the EGZ through increased nitrogen injection from 0.1 to 0.4 m^3/s (200 cu ft to 800 cu ft/min) on the headgate side.

Figure 8

Effective reduction of explosive mix zone (shown in red) in a bleederless gob by increasing the headgate nitrogen injection rate from 200 cfm (0.1 m^3/s; left image) to 800 cfm (0.4 m^3/s; right; Marts et al., 2013). Yellow indicates fuel-rich inert atmospheres, while green and blue shades denote fuel-lean inert zones. Orange indicates a buffer zone where the gas mixture is close to explosive.



Future research needs. Researchers are only beginning to understand how explosive gas zones form in longwall gobs and how different mine ventilation systems, air flow parameters, nitrogen inertization, barometric pressure changes, gob ventilation and other methane drainage efforts impact the size and location of these EGZs. Accident investigations have clearly established that longwall gobs present a serious fire and explosion hazard so a thorough understanding of these hazards and ways to mitigate them is essential.

Successful gob and bleeder system numerical modeling requires actual mine data to calibrate and verify the models. It is desirable to not only obtain gas concentration data from sampling tubes extended into the gob through seals or from the bleeder entries, but also drill vertical sampling boreholes into the gob from the surface.

Researchers must gain a more complete understanding of the function and, perhaps, limitations of bleeder and bleederless systems used to ventilate longwall gobs. Mine operators must be able to manage mine fire and explosion risks based on solid science and data, neither of which is available today.

Summary and conclusions

EGZs most likely exist in all bleeder ventilated and bleederless longwall gobs. These EGZs pose a significant hazard to the miners working in and around longwall production faces. Since there are a variety of potential ignition sources, one must assume that, if such explosive methane zones exist, they can ignite at any time.

According to U.S. federal and state investigation reports, accumulations of methane gas in bleeder ventilated longwall gobs have caused several serious explosions and mine fires, some of them with multiple fatalities. The most devastating accident in recent history occurred at the Upper Big Branch Mine in West Virginia in April 2010, where 29 miners lost their lives in a coal dust explosion that originated from a methane accumulation in the longwall gob. Despite these well-documented sentinel events, it appears that no scientific studies have targeted this workplace hazard in U.S. underground coal mines. In undertaking such a comprehensive research study, several major unknowns would need to be addressed:

1. The location, shape and volume of the EGZs in longwall gobs, and the factors controlling their location.
2. Methods to estimate hazardous consequences of explosive gas zones in mined-out gob areas.
3. Engineering methods to control the location and extent of the EGZs and to mitigate the explosion hazards.

A targeted, comprehensive research program would determine whether longwall bleeder ventilation systems can be designed such that they are truly effective in diluting and rendering harmless accumulations of explosive methane-air mixtures, or if bleederless gobs or alternative longwall gob ventilation systems are needed. ■

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