Methane-air explosion hazard within coal mine gobs

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Abstract

This paper analyzes the explosion hazard resulting from the formation of methane-air mixtures in the mined-out gobs of underground longwall coal mines. Although direct examinations of the gob atmosphere are difficult due to the inaccessibility of these gobs, evidence from methane drainage practices and investigations of 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. Most recently, this was demonstrated in the explosion of the Upper Big Branch Mine in West Virginia, where 29 miners lost their lives. 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.

Key words: Longwall, Gob, Methane, EGZ, Explosive gas zones, Underground, Coal, Explosion, Fire, Health and safety

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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 either within the gob or after expanding into the active areas of the mine. In many cases, these explosions and fires caused severe and fatal injuries to miners. The most recent and tragic such explosion happened in 2010 at the Upper Big Branch (UBB) Mine, where 29 miners were killed.

Figure 1 shows a frame from a visualization published by the U.S. Mine Safety and Health Administration (MSHA, 2011) on their website to illustrate the conditions leading to the UBB explosion.

In its investigation report of the UBB explosion (Page et al., 2011), MSHA suggests 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:

- Fundamentals of longwall ventilation with bleeder systems or bleederless, sealed gobs.
- A review of recent mine fires and explosions caused by explosive gas zones (EGZs) in longwall gobs, based on official investigation reports.
- Known and unknown factors about the formation, location and size of EGZs in longwall gobs.
- The influence of mine ventilation systems and nitrogen injection on size and location of EGZs.
- Ongoing research about EGZs.
- 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).

A concise definition of the terms "bleeder" and "gob" is given by Urosek et al. (2006):

> Bleeder systems are that part of the mine ventilation network used to ventilate pillared areas in underground coal mines. Pillared areas are those in which pillars have been wholly or partially removed, including the areas where coal has been extracted by longwall mining. Bleeder systems protect miners from the hazards associated with methane and other gases, dusts and fumes, and oxygen deficiency that may occur in these mined-out areas. Effective bleeder systems control the air passing through the area and continuously dilute and move any 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 bleeder system includes the pillared area (including the internal airflow paths), bleeder entries, bleeder connections, and all associated ventilation control devices that control the air passing through the pillared area. Bleeder entries are special air courses designed

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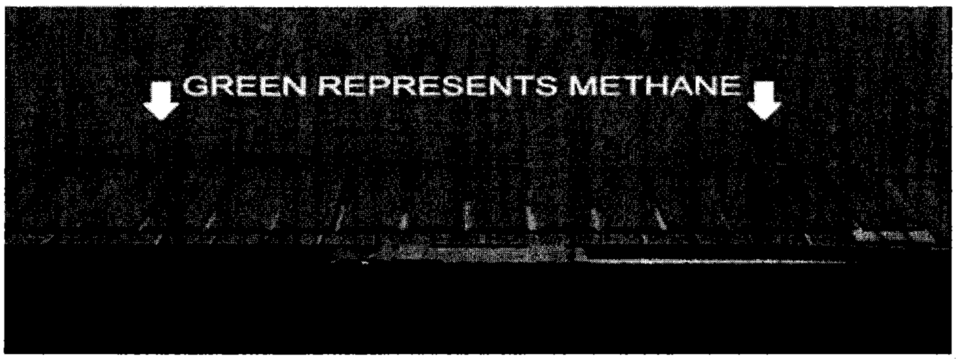

Figure 1 — Depiction of methane explosive fringe in the longwall gob behind the shields at the Upper Big Branch Mine. Not to scale. Source: MSHA (2011).

and maintained as part of the mine ventilation system. It should be noted that a mined-out longwall panel is considered a "pillared area" in the context of this definition.

Figure 2 shows a typical longwall ventilation scheme with bleeder ventilation. Longwall panels in the eastern United States are typically developed using three, or in some cases four, parallel gate entries to either side of the longwall panel. Gate entries are started from a set of main entries (mains) and connected at the far end (left side in Fig. 2) by a set of three or four parallel entries. The entries surrounding the gob are referred to as bleeders and marked in red in Fig. 2. Note that the return entries to both sides of the mains are also marked in red but not referred to as bleeders.

The set of entries containing the conveyor belt (blue) and supply track (yellow) is referred to as the headgate (top in Fig. 2); the opposite gate is the tailgate. After the longwall panel has been mined out, the current headgate becomes the tailgate for the next panel. Typical longwall panels are 300 to 360 m (1,000 to 1,200 ft) wide and 3,000 to 3,600 m (10,000 to 12,000 ft) long and contain 2.7-4.5 Mt (3-5 million st) of coal. A highly productive operation will mine such a panel in five to six months.

In a three-entry longwall development, as shown in Fig. 2, fresh air is coursed to the face from the mains through the isolated intake airways (green), as well as from the track entry (yellow). The belt air (blue) is normally coursed away from the face. Return and bleeder airways are shown in red. The tailgate is also ventilated with a small quantity of fresh air (green) to provide a secondary escape route from the face. At the tailgate junction, the air stream coming down the longwall face merges with the tailgate air and is then coursed into the bleeder system. Generally, a high-pressure bleeder fan located near the back end of the first longwall panel in each district serves to exhaust the return air from the bleeder system to the surface by creating a pressure sink that causes a general flow of air within the gob and the bleeders directed toward the bottom left, indicated by the dashed-line arrows in Fig. 2. It is important that the general pressure gradient in the gob is directed away from the production face so that contaminated air (CH_4, CO_2) from the gob does not circulate back into the active mining areas.

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 >80% methane, while some reach close to 100% (Moore et al., 1976). Typically, methane concentrations

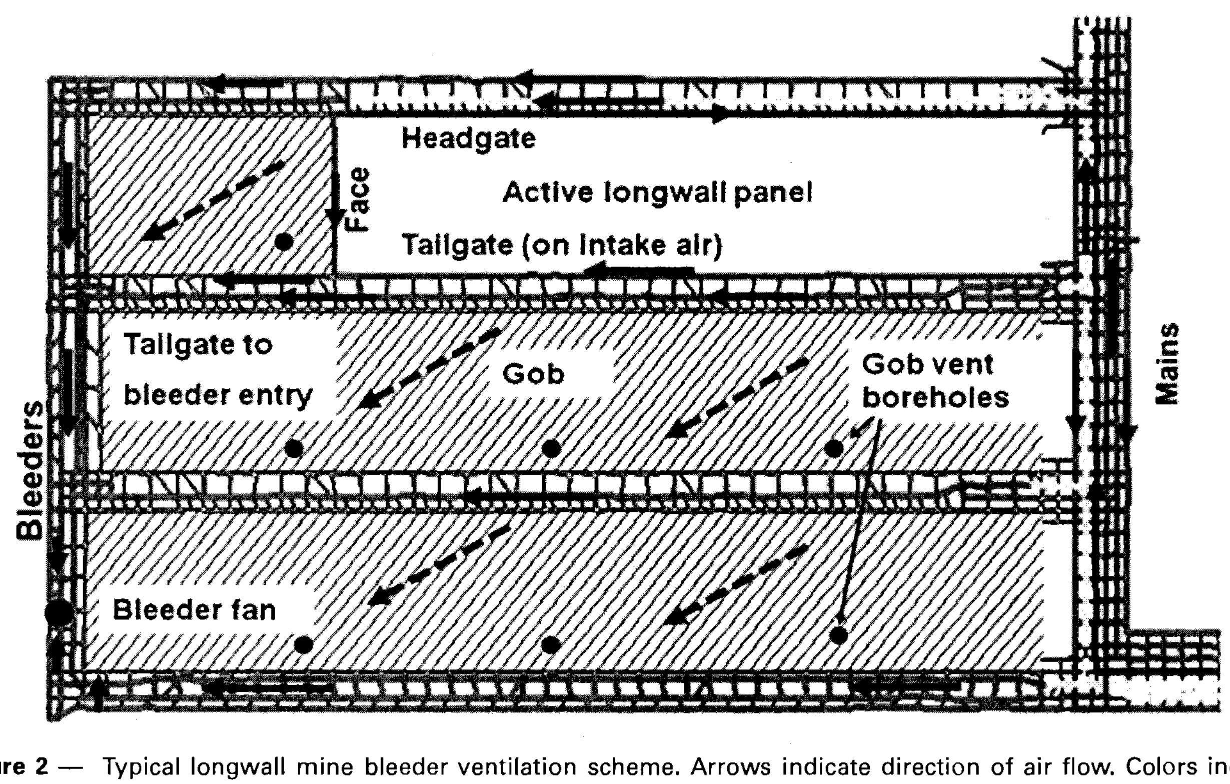

Figure 2 — Typical longwall mine bleeder ventilation scheme. Arrows indicate direction of air flow. Colors indicate fresh air (intake): green; track: yellow; belt: blue; return or bleeder air: red. Black dashed arrows indicate general air flow tendencies in the gob. After Brune et al. (1999); not to scale.

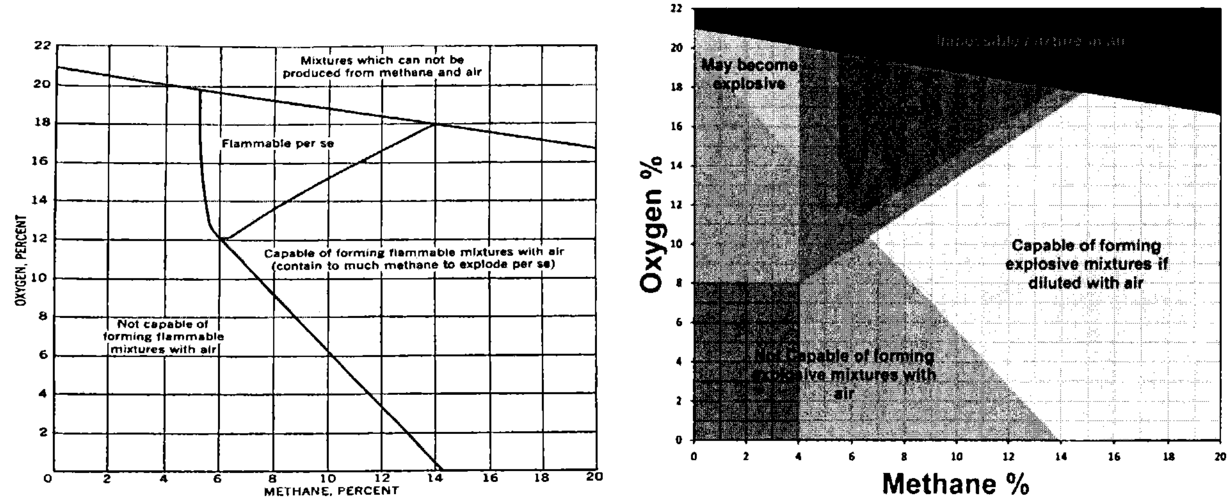

Figure 3 — Methane explosibility diagram by Coward and Jones (1952), along with the color coding scheme used to characterize EGZs. The orange area surrounding the red, explosive zone is an arbitrary buffer zone indicating a gas mixture close to explosive. The blue area may become explosive if methane is added. The yellow area may become explosive if the mixture is diluted with oxygen. Green areas are inert.

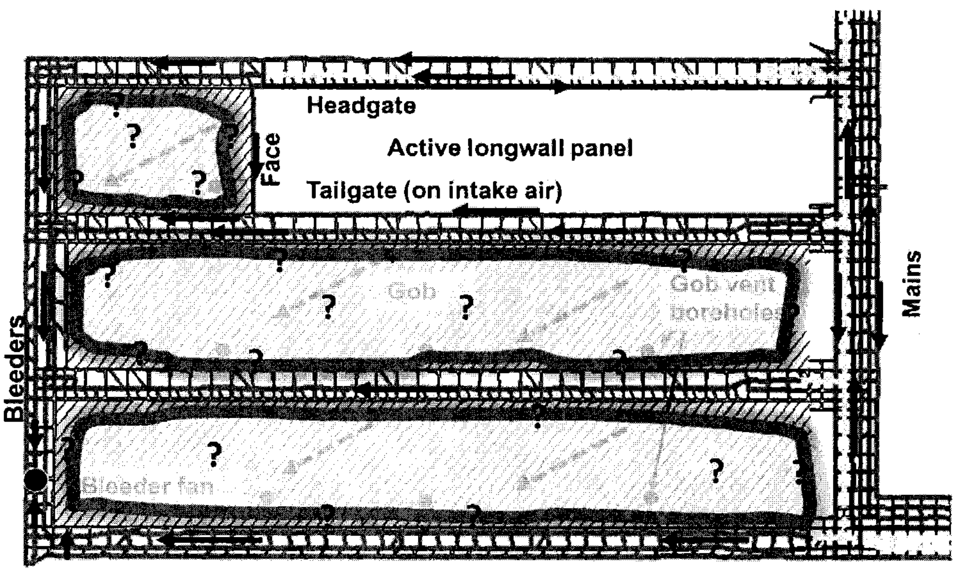

Figure 4 — Presumed location of zones of explosive gas areas (EGZs) within the longwall gob. The EGZs in the gob contain methane mixed with air at explosive concentrations between 5 and 14% and are shown in red (note the colors of the gob areas are not to be confused with those of the mine entries). The "?" indicate that the exact location of the zones is not known. The yellow shading indicates fuel-rich zones of methane-air mixture between 14 and 100% methane content. Gob fringe areas outside the orange perimeters are between 0 and 5%, i.e., fuel-lean inert. Figure not to scale.

in operating GVBs are maintained above 50%. Below 50%, the methane concentration becomes insufficient to operate the exhaust pumps, but some GVBs continue to produce free-flowing methane gas at lower concentrations (Mucho et al., 2000).

The GVBs are designed to extract methane from the upper, fractured zones of the gob, and fresh air dilution from the active mining areas is to be avoided. Still, the gases in the longwall gob and those in the GVBs communicate with the gases in the active face areas and in the bleeder entries. Tracer gas studies by Mucho et al. (2000) have documented this communication between the active face and the GVBs.

The active production area, the longwall face, is ventilated with fresh air such that the methane content in the air is diluted to 1% or less and oxygen is maintained above 19.5%, as required by 30 CFR §75.321. Bleeder entries surrounding the gob may carry up to 2% methane (30 CFR §75.323(e)).

If the methane concentration near the GVBs is above the explosive range of methane (~5 - ~15%), while in the surrounding airways it is below 2%, it follows that explosive gas zones (EGZs) must exist inside the gob area, between the fringes and the locations of the GVBs. EGZs are zones within the gob where the methane and oxygen concentrations lie within the explosive range, as shown in Fig. 3. If the oxygen level drops below 12%, methane will no longer explode.

Figure 4 illustrates the EGZs that likely exist within a longwall gob. In the face and bleeder entries, by statute, the methane concentration must be kept below 1 and 2%, respectively. Toward the center of the gob, there likely exists a methane-rich region (shaded in yellow) where the methane concentration is above 15%, beyond the explosive range, as demonstrated by the output methane levels from the GVBs.

Somewhere in between these inert areas, EGZs (marked in red in Fig. 4) must, therefore, exist where the methane concentrations are in the explosive range. The exact locations of these zones have not been measured directly, and their size and extent is not well-understood from theoretical calculations. Near the active mine airways, the ventilation pressure gradient may keep the explosive zone some distance into the longwall gob away from the active workings. Near the bleeder entries, that gradient may move the zone closer to the bleeder entries.

Beiter (2007) identified zones of lighter compaction and higher airflow permeability along the edges of longwall gobs, as shown in Fig. 5. The location of these zones agrees with studies conducted by Esterhuizen and Karacan (2007) and Wachel

(2012). Beiter's image delineates this fringe with red shading in the gob and adjacent, partially collapsed bleeder entries. Computational fluid dynamics (CFD) modeling studies (see also "Specific hazards for mine workers") show that these zones of lighter compaction will allow ventilation air to enter the gob and dilute methane, potentially creating explosive mixtures.

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 (spon com). If the coal is susceptible to spon com, 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 or immediately after 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 U.S. with bleederless, sealed gobs.

Figure 6 (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. As Fig. 6 shows, on the headgate side, new seals are installed in each crosscut inby the face. The tailgate is already fully sealed, as the tailgate seals had been installed during mining of the previous panel. The arrangement of seals around the gob ensures that the inflow of fresh air (= oxygen) into the gob is minimized to prevent spon com.

Figure 6 also shows the locations of atmospheric monitoring stations (AMS, blue stars) in the headgate, face and tailgate areas and gas chromatograph (GC) sampling points (red triangles) on the inside of each seal, where gas samples from the gob can be drawn through sampling lines that penetrate the seals. These monitors typically detect methane and carbon monoxide, while GC sampling also includes oxygen, nitrogen and carbon dioxide.

As indicated in Fig. 6, the goal of sealing the gob is to render the atmosphere in the active gob as well as in the previous gobs fuel-rich inert (marked "CH_4 Non-explosive"). This can be attained by either maintaining the CH_4 content above 15% or by reducing the oxygen content to below 12% 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. 7 and clearly demonstrate that there are potentially explosive conditions in the gob. These contours were deduced by representing the gob as a mesh of discrete ventilation entries, then modeling the methane distribution and calibrating the model with gas concentration readings at the

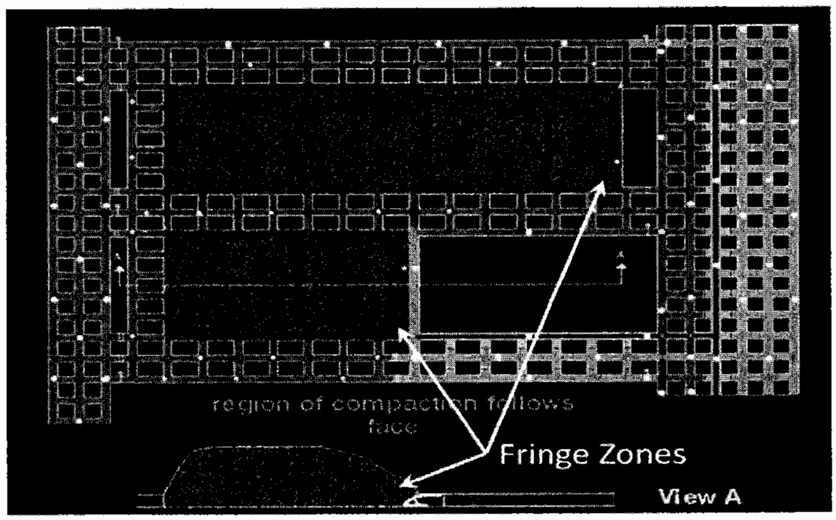

Figure 5 — Fringes of lighter compaction around the edges of the longwall gobs, modified from Beiter (2007), not to scale.

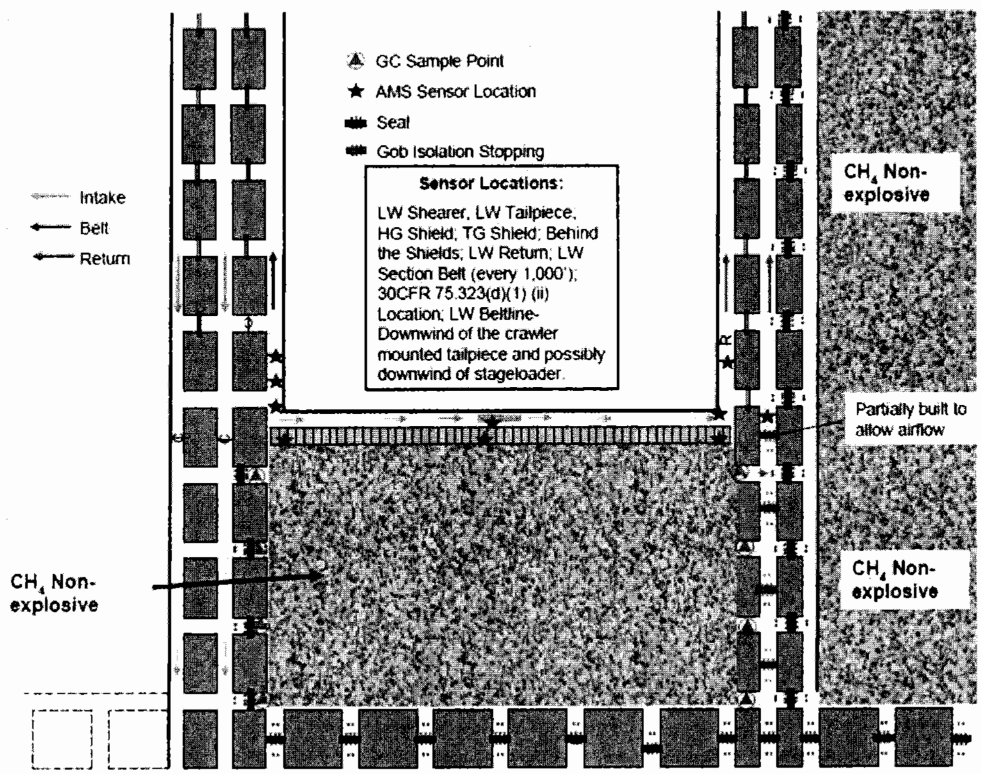

Figure 6—Schematic of a bleederless longwall ventilation system (MSHA, 2007, not to scale). It should be noted that the characterization "CH_4 nonexplosive" is one made by MSHA and has not been scientifically documented. It is believed that, if the gas in this zone is diluted with oxygen, it may become explosive.

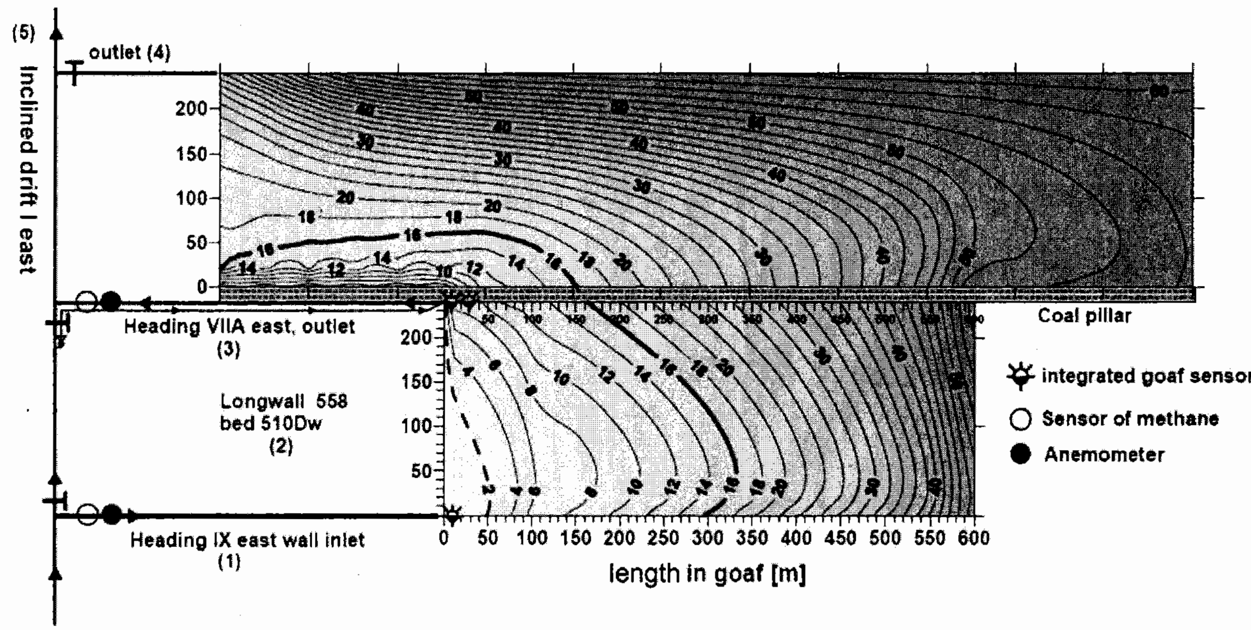

Figure 7 — Methane percentages in a bleederless longwall gob (Dziurzynski and Wasilewski, 2012, dimensions as indicated).

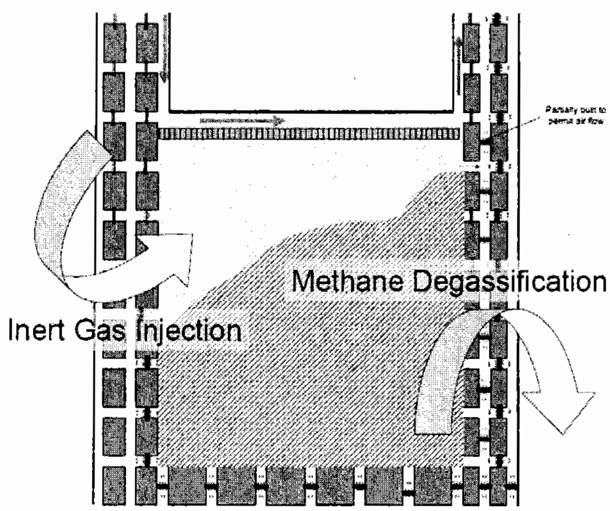

Figure 8 — Rendering the gob atmosphere nonexplosive by injecting nitrogen (MSHA, 2007, not to scale).

seals and other accessible locations.

The highlighted contour of 16% delineates the methane-rich, inert zone deep in the gob, primarily along the fringe of the tailgate and in the active gob immediately inby the face. The authors considered 16% as the upper explosive limit. Along the tailgate side, Dziurzyński and Wasilewski show a contour of 2% (dashed blue line) that represents the methane concentration in and near the active face. It appears that EGZs are formed close to the active areas of the longwall where oxygen (fresh air) can migrate into the gob through the longwall shields and through seal leakage.

To reduce the oxygen content in the gob and render it inert, it is common in bleederless longwalls to inject nitrogen through the seals, primarily immediately inby the headgate and tailgate. Figure 8 (MSHA, 2007) depicts schematically what happens during the inertization process.

Nitrogen is injected through the seals at some distance inby the face on the headgate and tailgate sides. The effect of nitrogen injection is depicted with gray shading in Fig. 8 and is aimed to reduce the oxygen content below 12% in the areas where methane may range between 5 and 15%. The red shaded area indicates the zone where the methane concentration is above 15% and the atmosphere is fuel-rich inert.

Summary. 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.

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

In this section, we will review 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. We suggest factors that may have caused the EGZ to move into the mine workings prior to or during the explosion. We discuss unknowns about the EGZ such as how to properly control its location and extent, and how to detect the hazard should it move to close to active mine workings. Finally, we discuss needed modeling and measurement efforts to better understand the EGZ hazard.

There is frequent anecdotal reference from miners hearing or feeling "pops" (perhaps explosion concussions) and seeing

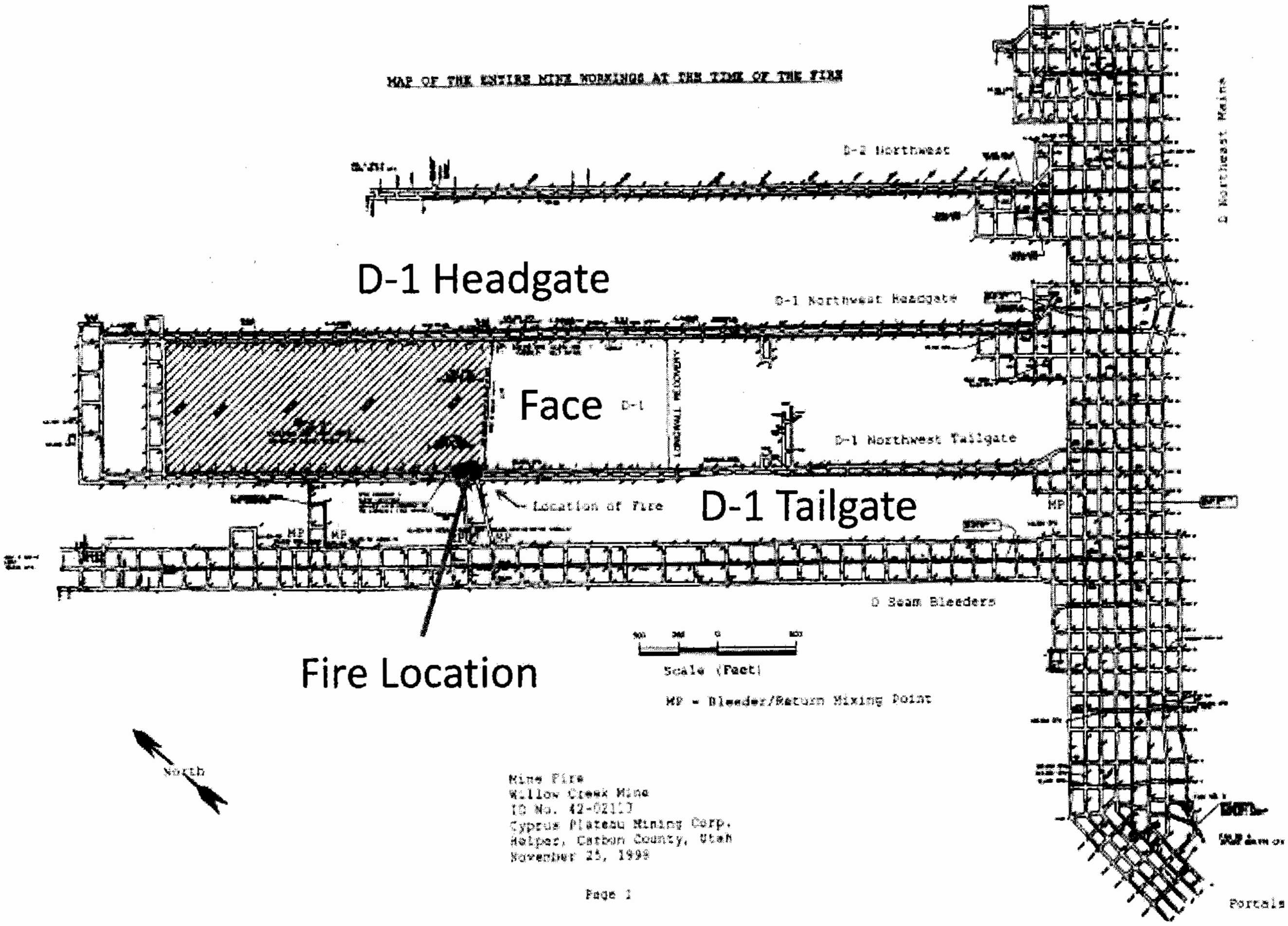

Figure 9 — Map showing the location of the 1998 Willow Creek explosion and fire (Elkins, 2001).

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 is felt by the miners, this may often be interpreted as a consequence of a major roof fall or gob cave-in rather than a methane explosion. Increased concentrations of carbon monoxide (CO) in the exhaust air of coal mines are routinely investigated, but often point at occurrences of spontaneous combustion. If there was a small explosion of a methane gas cloud, this would not likely be noticed, since the amount of CO in the exhaust ventilation air would not change significantly and the "spike" in the readings would be of short duration and possibly missed by mine examiners. Brief CO spikes recorded by the atmospheric monitoring system often do not raise concerns because examiners primarily look for slow, steady rises of CO concentration that are a sign of a fire or spon com.

Investigation records of several sentinel events indicate that explosions of methane gas have occurred in longwall gob areas, some resulting in mine fires and causing fatal or serious injuries. The following subsections summarize these events.

Willow Creek Mine explosion and fire, 1998. 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). One miner was thrown a distance of 3 m (10 ft). A longwall shield operator reported that he felt heat from the airblast, clearly indicating an explosion rather than an airblast from a roof fall. Figure 9 shows a map of the Willow Creek Mine, indicating the location of the fire on the tailgate of the first longwall panel, just inby the face.

After the explosion, the face air flow returned to its normal direction and then, briefly, reversed again, suspending dust and reducing visibility. Dust-laden air was also observed pulsating in and out between the shields. The miners observed an orange colored flame in the gob behind the shields that appeared to move towards the face and then back into the gob.

It appears that an EGZ existed in the gob that was either close enough to migrate into the active face or was pushed close to the face area by a roof fall in the gob.

According to the investigation report, the orange glow was pulsing back and forth along the tailgate entry from about 4.5 - 30 m (15 - 100 ft) inby the shields ("inby" indicating the direction into the gob as viewed from the face). This pulsing motion may indicate a diffusion flame burning a methane-air near the fuel-rich side (>15%). The flame advanced as long as oxygen became available and, then, retreated as the oxygen was consumed. This pulsating effect has also been observed at the NIOSH Lake Lynn Experimental Mine (LLEM) in an unpublished explosion test (No. 488), where a 12-m- (40-ft-) long zone of 20% methane-air (approximately 140 m^3 or 5,000 cu ft of mixture) was ignited and deflagrated in a diffusion flame that burned for a period of about 90 seconds.

Elkins et al. (2001) noted that, besides methane, there were other hydrocarbons in significant quantities also present in the mine. The mine would routinely pump out 4,500 L (1,200

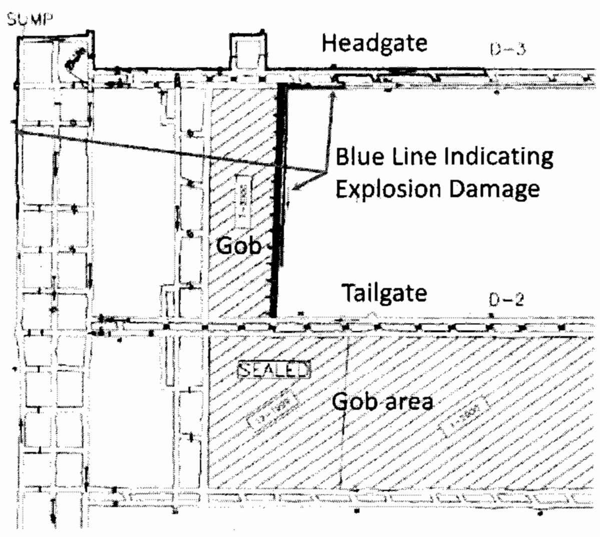

Figure 10 — Map of the Willow Creek Mine 2000 explosion after McKinney et al., 2001, no scale indicated).

gal) per day of mixed liquid hydrocarbons (characterized as containing approximately 15% gasoline, 35% diesel fuel and 50% motor oil) with a flash point of 36° C (97° F). These hydrocarbons may have significantly lowered the ignition threshold for the gassy atmosphere and may have contributed to the fire. Also, the mine excavated only the upper half of the 6-m- (20-ft-) thick coal seam, leaving the bottom half in the gob. This may have caused significant methane and other gaseous hydrocarbon emissions in the gob.

After detecting the fire, the mine was immediately evacuated, and the portals and shafts were sealed to extinguish the fire. Carbon dioxide (CO_2) was injected into the suspected fire area on the longwall tailgate for inertization. The longwall equipment was recovered beginning in December 1998 and the affected longwall panel was permanently sealed. Development production for a new longwall panel resumed in May 1999, six months after the incident. Still, the operator was unable to control the fire in the sealed panel and additional sealing commenced in November 1999 before normal longwall production could be resumed.

MSHA learned from interviews with the longwall crew that an ignition had not been seen in the longwall face. Also, none of the miners received burn injuries, indicating a high likelihood that the fire was ignited deeper within the gob and did not reach the face before the miners had evacuated the area. MSHA inspectors found signs of fire damage on several shields and along the tailgate entry where wooden roof support cribs were charred.

The shearer was idle at the time the airblast was felt, ruling out a frictional ignition from cutting sandstone. Electrical inspections did not find evidence that defective or overheated face equipment might have caused the ignition. No lightning strikes were observed in the area of the mine during the time of the ignition, and the coal did not have a history of spontaneous combustion. Regular fireboss inspections and gas measurements had indicated that the amount of hydrocarbons present in the face area had been higher than usual during the days before the fire, but a bleeder inspection by a fireboss just two hours before the ignition did not indicate any problems or unusual conditions.

The MSHA report states that a massive roof fall was highly likely to have caused the ignition. Miners had observed that the cave line of the overlying sandstone lagged as much as 40 m (120 ft) behind the shields in the tailgate area. According to the maps included in the MSHA report, the tailgate had been lagging about 30 m (100 ft) behind the headgate. Only shallow caving of the immediate roof had occurred in other areas of the longwall. According to the investigation, the two major airblasts reported by the miners are indicators of a concussion from an explosion.

Based on the fact that the miners' eardrums did not burst, MSHA estimated the explosion pressure at the face to be about 34 kPa (5 psi) or below and classified it as a "low magnitude explosion." The MSHA reports states that geophones installed at the mine did not indicate a large-scale explosion.

Willow Creek Mine explosions and fire, 2000. A series of four explosions occurred in 2000 at the Willow Creek Mine, killing two miners and injuring eight more, with some of them severely burned.

The first explosion, shortly before midnight on July 31, was followed by two closely spaced explosions about seven minutes later. The fourth explosion occurred approximately 30 minutes later on Aug. 1. 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." The ignition source was most likely friction from falling rock in the gob "causing either a piezoelectric spark or a spark against a metal object" (McKinney et al., 2001). Again, this strongly suggests that an EGZ existed in the gob and was ignited.

Figure 10 shows an excerpt from the mine map depicting the area affected by the explosion as a blue line beginning on the face near the tailgate, wrapping around the headgate and extending into the bleeder system.

McKinney et al. concluded that the explosion pressures would have been around 34 kPa (5 psi) near the origin and sufficient to damage regulators and other ventilation controls. They also noted that damaging forces from the explosion could have acted over significant distances into the mine. In their report, they state that "as little as 1.4 m^3 (50 cu ft) of methane, diluted to about 6.5%, would be capable of generating this limited pressure."

Based on MSHA's back-calculated volume and estimated concentration of methane in the first explosion, the total volume of the explosive cloud would have been about 23 m^3 (800 cu ft; = 1.4 m^3 or 50 cu ft of pure methane diluted to 6.5%). This cloud was apparently large enough to cause a significant airblast that was capable of disrupting the ventilation flow.

During the hours before the initial explosion, a sudden release of methane from the gob had caused the shearer to automatically de-energize (indicating that methane content at the detector had exceeded 1.5%). It took the crew 42 minutes to clear the methane by changing ventilation curtains to increase the air flow quantity at the face. The investigators stated that interruptions similar to this had been "common" occurrences at Willow Creek.

The airblast from the initial explosion was clearly felt by the miners on the face, although they first interpreted it as an airblast from rock caving in the gob. The miners also observed temporary ventilation air flow reversal and disruption of ventilation at the face following the explosion.

The crew then observed blue flames near the toes of the headgate side shields. According to Nagy (1981), blue flames typically indicate methane burning between low (pale blue) and stoichiometric (bluish-white) concentrations. The miners tried unsuccessfully to fight the flames with fire extinguishers.

The second and third explosions had a more violent impact on the miners, fatally injuring two miners (one from direct trauma caused by the airblast, the other from CO inhalation and asphyxiation) and seriously injuring and burning eight others. The third explosion was the most powerful and may have been a continuation of the second explosion. The fourth explosion was recorded on the fan pressure chart, but there were no witnesses who could describe the effects underground.

The investigation report 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%. 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 schematic on methane concentrations shown in Fig. 4. The description implies 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% (30 CFR §75.323 (e)). However, as this dilution occurs, the methane air mixture must pass through the explosive range. Therefore, zones or clouds of explosive mixtures must exist in bleeder ventilated gobs.

The mine operator brought a case before the U.S. Federal Mine Safety and Health Review Commission (FMSHRC) in which the operator disputed the justification for certain violations that MSHA wrote following the explosion. The decision document (FMSHRC, 2006) states that

> 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 (50 cubic feet [1.4 m^3 of pure methane diluted to 800 cu ft or 23 m^3]), 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." As indicated above, a cloud of this size is easily capable of causing severe traumatic and burn injuries in addition to extensive damage of ventilation controls. 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 face if it were 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 that an EGZ close to the mine workings was not unusual.

According to explosion tests conducted at the NIOSH Lake Lynn Experimental Mine (LLEM, Weiss et al., 2002), semi-confined explosions of methane-air mixtures with volumes of only 18.7 m^3 (660 cu ft) are capable of producing pressures of up to 140 kPa (20 psi), especially if sufficient turbulence can be generated by obstacles in the explosion path, which certainly is the case in a longwall gob. A 140-kPa (20-psi) explosive airblast on a human body with a hydrodynamic reference area of 0.6 m^2 (6 ft^2) can generate a drag force of over 76 kN (17,000 lb), creating a potential for severe traumatic injury and death.

Given the evidence from the investigation of this fatal accident, it appears uncertain whether it is possible to create bleeder ventilation systems for longwall mines that are truly "effective" under all mining circumstances. This appears to be the case even if the ventilation systems are properly designed, well-maintained and considered to be functioning based on required examinations.

Buchanan Mine explosion and fire, 2005. 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, 2005), the breaking of a thick sandstone bed overlying the coal seam caused a rush of gob air containing methane into the 6 Right longwall face. This initial roof fall in the gob was recorded as a seismic event of magnitude 3.3. Four seconds later, flames were visible at the tailgate of the longwall. One miner described the flames as "red in color" and observed their extent as about 2.5 m (8 ft). He saw them for only about two seconds, until a thick cloud of dust obscured his view. This example produces strong evidence that one or possible several EGZs existed in the bleeder ventilated longwall gobs. They either were already close to the face or they got pushed into the face area from a roof collapse in the gob.

The concussion forces from the airblast felt by the miners were strong enough to almost knock them off their feet. Some of the miners reported having heard and felt up to three different blasts. One miner working in the mains reported a second pressure change that followed about 45 seconds after the initial blast. Another miner working in the mains described a doubling of the air flow in a location where the normal air flow velocity would already be about 4 m/s (800 ft/min), indicating a significant amount of ventilation energy involved.

Figure 11 (Ratliff, 2005) shows a map of the Buchanan Mine indicating the fire locations. According to Ratliff's report, the fire started at the tailgate corner of 6 Right longwall panel. The ignition flame was sustained long enough to propagate the flames through the main connections into the 3 Right headgate. The report also states that a secondary ignition caused a fire in the bleeder entries between the 4 Left and 5 Left panels.

The mine was quickly evacuated and no injuries were reported. The fire ignited roof support cribs along several thousand feet of return and bleeder airways and caused a shutdown of the mine for four months. The Pocahontas No. 3 seam mined at Buchanan produces a low volatile metallurgical coal that does not easily burn, yet is among the gassiest coalbeds in the United States. The fire was primarily driven by the continuing supply of methane from the gob and the active workings and by the burning wooden roof support materials. The miners at the longwall face reported a temporary air flow reversal and "estimated that the quantity of [reverse flowing] air was at least as great as the normal flow quantity" (Ratliff, 2005; emphasis in brackets added). The reverse flow quickly returned back to its normal direction. All electric power at the face was automatically shut off, since the methane level exceeded 1.5%.

The MSHA report notes that no permissibility defects were found on the electrical face equipment that might have ignited the methane. The report states that:

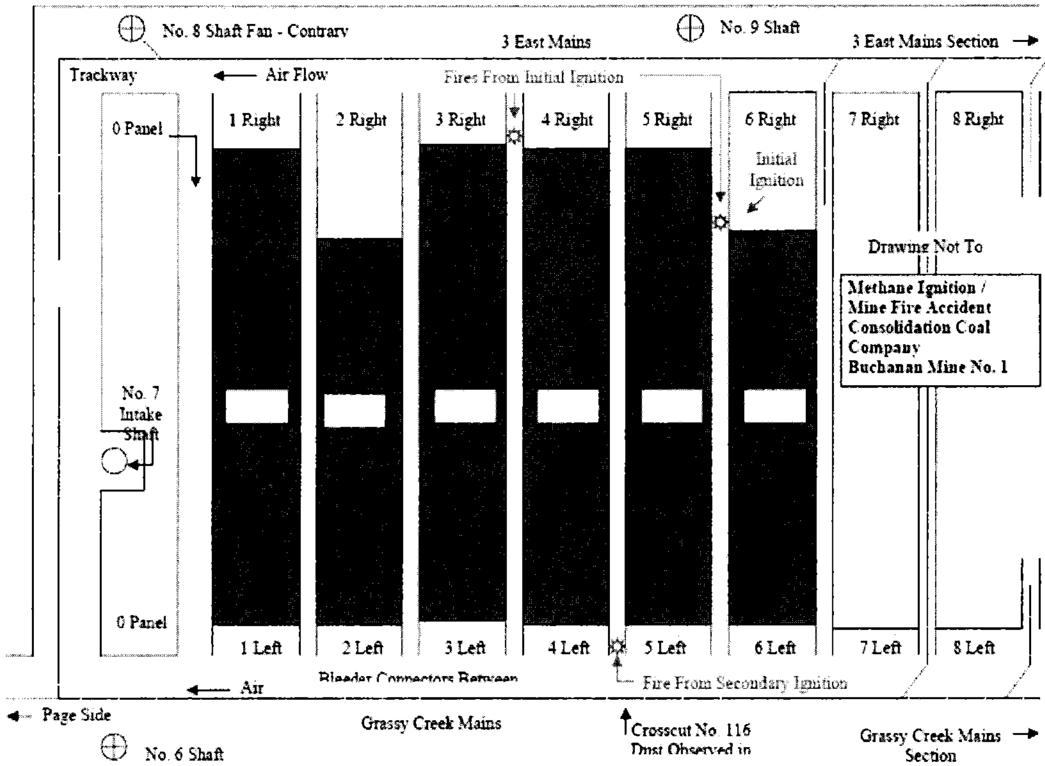

Figure 11 — Map of Buchanan Mine showing fire locations (Ratliff, 2005, not to scale).

> The most probable ignition source for the methane was frictional energy generated by the roof fall. This would imply that the methane was ignited within the gob area and that the flames traveled outby toward the face area.

The MSHA report further states (emphasis in brackets added):

> The width and location of the elevated methane/air mixture along the gob periphery [i.e., inside the gob area] 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. Where sufficient volumes of these [EGZ] mixtures are present and those volumes are sufficiently confined, the resulting explosions will be evidenced at the closest pressure relief point into adjacent open areas of the mine such as regulated gate entry gob connectors, active gate roads, or active faces.

This statement suggests that investigators were aware of the explosion hazards from methane accumulations in the gob, that these hazards exist under normal mine ventilation conditions and that they may be similar to those shown in Fig. 4. This is a significant indication that even fully functional bleeder ventilation systems may not be effective to dilute, render harmless and carry away flammable or explosive gases that could injure mine workers.

Since the Pocahontas No. 3 coalbed and overlying seams are liberating high amounts of methane gas, coal seam degasification is a profitable business segment at the Buchanan Mine. Degasification is done in advance of, during and after mining by drilling and hydrofracturing the virgin coal and through vertical degasification holes in the longwall gob, which is extensively fractured in the longwall mining process. The extracted gas is captured and marketed as high-quality natural gas.

The gob is ventilated using a bleeder system, but the gateroad entries along the perimeter of the gob typically cave in tightly since the mine is more than 450 m (1,500 ft) deep. The investigation report states that the pressure difference between the tailgate and the bleeder entry exceeded 1.5 kPa (6 in. of water gauge), indicating that the gob had a low permeability, as is typical for this mining environment. Investigators also state that there was little air flow in the older gob entries due to continuing subsidence and convergence from the thick overburden. Convergence compresses entries and gob areas become tighter with time, increasing ventilation resistance.

In MSHA's investigation report, section "Root cause analysis," Carico (2005) notes:

> Causal Factor: The massive sandstone roof strata inby the longwall face failed and initiated a methane ignition/explosion in the gob inby the longwall face. The ignition/explosion eventually propagated around a large portion of the longwall gob and resulted in fires and concussive damages to ventilation controls. The mine design and methods of mining did not control the sandstone roof in a manner that would have prevented the ignition.

As a corrective action, the investigators proposed to avoid mining in areas with massive sandstone in the roof. Notably, the report proposed no corrective action to improve the ventilation of the gob or address problems with the ventilation system, although investigators had established and documented the EGZs in the gob.

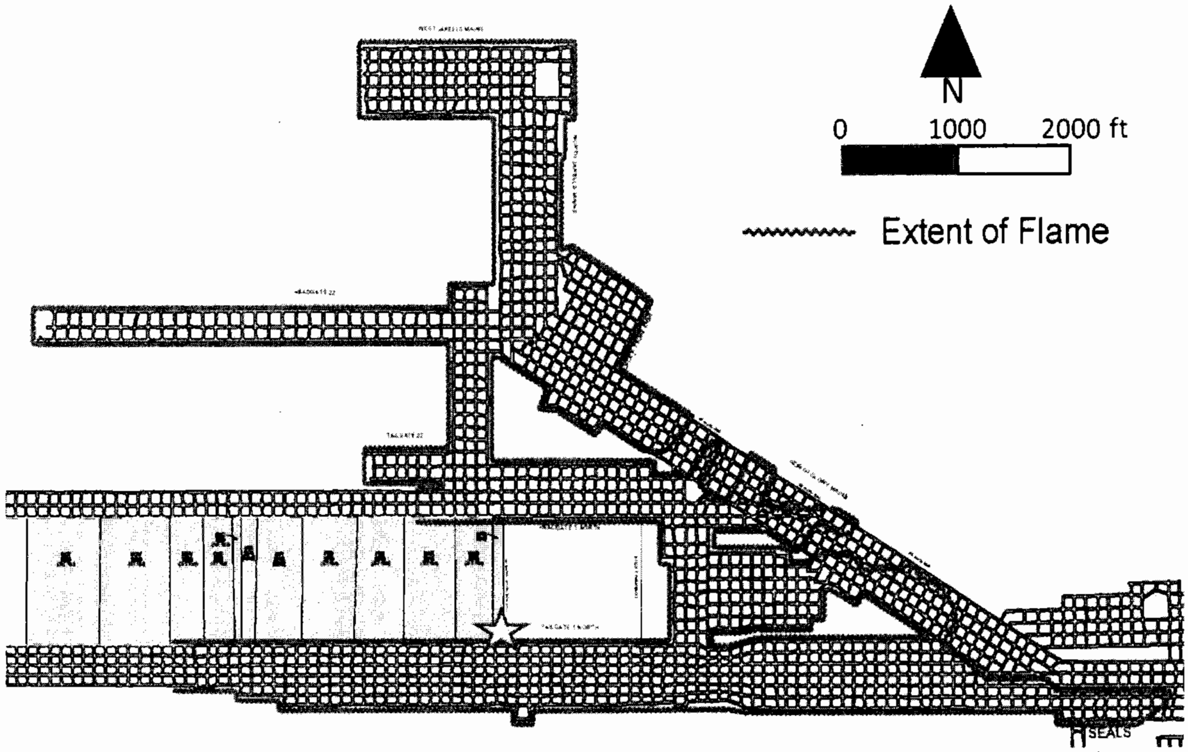

Figure 12 — Extent of the flame zone of the Upper Big Branch Mine explosion. The star indicates the origin of the explosion on the tailgate side of the longwall face. Modified after Page et al. (2011).

Buchanan Mine explosion and fire, 2007. The 2007 event at the same (Buchanan) mine was investigated by MSHA (Woodward and Sheffield, 2007) and was found to have similar causes as the 2005 incident. As in 2005, the 2007 ignition was again triggered by a violent cave-in of the sandstone overlying the coal bed. Two separate seismic events were initially registered having magnitudes of 2.9 and 3.4. A third event was recorded about 50 minutes later at a magnitude of 3.4. The report states that the initial roof fall "ignited methane within the gob," as no other probable causes such as defective electrical equipment on the face could be identified. Again, this is clear evidence that an EGZ existed in the gob. The explosion damaged ventilation controls and caused short-circuiting of air, as evidenced by the fan pressure dropping significantly in each of the fan shafts. Elevated levels of carbon monoxide (CO) were detected in the mine following the explosion.

The MSHA report makes reference to another suspicious event: While two foremen were investigating the incident, one detected 10 ppm of CO on his handheld multigas detector while traveling up 8 Right toward the tail of the 9 Right Longwall. The CO level rose to 25 ppm immediately prior to a pressure wave knocking the foremen to their knees. It is of note that investigators found no record of seismic activity within two hours of this occurrence. The absence of a seismic record combined with the spike in CO readings likely points to a methane explosion, with the observations similar to those made by the Willow Creek miners in 1998. The MSHA investigation report does not indicate a time, suspected location or additional detail for this event.

Upper Big Branch Explosion, 2010. The most recent explosion happened at the Upper Big Branch Mine in West Virginia. On April 5, 2010, a major coal dust explosion ripped through the Upper Big Branch (UBB) Mine near Montcoal, WV. The explosion killed 29 miners, making it the worst mining disaster in the United States in nearly 40 years. The miners died from physical and burn trauma as well as CO poisoning.

The explosion was caused by a methane ignition near the tailgate of the longwall face, which created a subsequent, major coal dust explosion. The methane is believed to have come from the gob and was likely ignited by the shearer. The MSHA investigation (Page et al., 2011) identified as contributing factors a deficient ventilation system (it did not sufficiently dilute the methane accumulation) and insufficient amounts of rock dust having been placed in the mine entries to inertize the coal dust and prevent a dust explosion.

In a video presented by MSHA (2011) that simulated the likely scenario of the UBB explosion, MSHA showed an accumulation of methane along the fringe of the gob behind the longwall shields. Figure 1 shows a screen shot from this video, with the green shading representing the explosive methane fringe zone.

MSHA's investigation report and the video both present clear evidence that explosive methane was present in the gob. It remains somewhat unclear how the EGZ was pushed out onto the tailgate, but it is clearly documented that the EGZ existed prior to the explosion. Based on MSHA's investigation, the explosive cloud of methane-air mixture migrated to the tailgate, where it was ignited as the shearer cut the sandstone roof. Several water sprays on the cutting drum were missing, reducing the effectiveness of dust and ignition control. Investigators concluded that the initial EGZ only encompassed about 85 m^3 (3,000 cu ft) of methane-air mixture. The impact from an explosion of this size would have been limited to the immediate tailgate area. However, the methane explosion suspended coal dust in air, creating a massive coal dust explosion that expanded into a flame volume of 880,000 m^3 (31 million cu ft) and spread through 66 km (42 mi) of mine entries, as shown in Fig. 12. The mine operator was cited for insufficient placement of rock dust in the mine, which otherwise would have stopped the coal dust explosion.

A report by the state of West Virginia investigators (Phillips, 2012) indicates that the ventilation system of the mine may have been compromised by accumulation of water in the longwall tailgate entries inby the face. This water may have reduced the amount of air flowing across the longwall face and contributed to the accumulation of methane that led to this initial explosion.

Endeavour Colliery Mine explosion, Australia, 1995. Anderson et al. (1997) reported a methane explosion in a longwall gob where a bleeder system had not been established, unlike in other longwall panels at this mine where bleeder systems were in place. A roof fall pushed an explosive methane gas cloud out of the gob into the headgate entries, where it was ignited, most likely by a defective coupling in a shuttle car electric cable. Again, we find evidence that an EGZ existed in the gob. All 30 miners were safely evacuated and no fatalities or injuries resulted.

The investigators determined the extent of the flame and the magnitude and direction of explosion forces. The report states that approximately 5.7 m^3 (200 cu ft) of methane diluted to between 6 and 7% (about 85 m^3 or 3,000 cu ft of explosive gas mixture) could have resulted in the flame spread and blast forces observed. Explosion pressures were estimated in the range between 3.4 to 28 kPa (0.5 and 4 psi). The airblast was felt by the miners but none suffered severe physical trauma. Investigators also noted that a drop in barometric pressure had occurred prior to the explosion and may have contributed to an expansion of gob gases causing methane to migrate from the gob into the active mine workings. Finally, investigators noted that a mine foreman stated that he could detect 3-4% methane behind a brattice curtain in the gob.

Gob explosions at the Camphausen Mine (1986) in Germany. Hinderfeld and Stamer (1995) report a series of methane explosions in the gob near the longwall face at the Camphausen Mine in the German Saar region in 1986 that caused seven fatalities and injured 19 miners. Clearly, an EGZ must have existed in the gob. The initial explosion damaged ventilation controls, leading to a disruption in the ventilation flow that caused a second, more severe explosion. It is assumed that the seven fatally injured miners survived the initial blast but died from the second explosion. Four miners died of heat and direct pressure trauma and three from asphyxiation due to CO and combustion products in the atmosphere. An official report is not currently available due to legal confidentiality restrictions. Hermülheim (2009) indicated that the second explosion developed a pressure of 100 kPa (15 psi), which would be sufficient to cause fatal injuries and extensive damage to ventilation controls.

Summary of sentinel events. All sentinel events discussed above demonstrate that EGZs can be present in longwall gobs and that they can generate fatal mine explosions and fires. These EGZs have several things in common:

- The point of ignition often lies closely behind the longwall face, and the flames are then able to penetrate the shield supports and reach the face area, creating windblast and burn hazards for the miners.
- 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 in the face. Roof collapses are also often suspected as the source of ignition.
- Sudden changes in ventilation quantities and leakage flowing into the gob can increase the explosion hazard as the gas composition in the gob moves from fuel-rich inert to explosive. This can create, move or eliminate EGZs. Hermülheim (1997) notes that such changes frequently occur when mining through fault zones.
- Another frequent ignition source is spontaneous combustion within the gob.

Hermülheim (1997) confirmed these common causes in his summarized investigation results of 11 explosions and fires in longwall gobs in German coal mines.

Specific hazards for the mine workers

The sentinel events discussed above, along with the results of numerical modeling studies, demonstrate that explosive gas zones in longwall gobs pose significant hazards for the miners working at the face and in other areas of the mines. Neither bleeders nor bleederless ventilation systems can eliminate the presence of these zones in all instances. Therefore, it must be recognized that longwall gobs can pose a potentially fatal hazard to miners.

Based on the investigation reports, the following specific hazards may result from explosive methane gas clouds within longwall gobs:

- Explosion pressure can cause traumatic injuries from windblasts. Besides knocking miners down or throwing them a great distance, air pressure can cause the alveoli to burst. Air pressure can also cause severe damage to the ear, bursting the eardrums and damaging the inner ear. While many of the observed explosions in the gob were relatively weak and did not create violent airblasts, some explosions, namely the Willow Creek 2000, Camphausen (Germany) and Upper Big Branch cases, caused multiple fatal traumatic injuries.
- Even weak explosions have caused air flow reversals and damage to mine ventilation controls. The airblast often destroys ventilation controls such as stoppings, curtains, overcasts and regulators, as these controls typically do not withstand more than about 14 to 35 kPa (2 to 5 psi; Weiss et al., 2002). Explosion pressure can also interrupt or even reverse air flow in the ventilation system. Secondary explosions can result when damaged ventilation controls cause additional accumulations of methane.
- Explosion forces can damage mining equipment and roof control devices and cause secondary damage. The airblast from an explosion can entrain coal and rock dust, severely limiting visibility and creating difficult conditions for escape and rescue. Flying debris can also cause traumatic injuries.
- If there is fine coal dust ("float dust") present in the gob or in the bleeder entries, and an airblast from a methane explosion is sufficient to entrain that dust, then the fine coal dust can ignite, causing a more violent secondary dust explosion. Coal dust can add significant amounts of fuel to the explosion and cause the explosion to

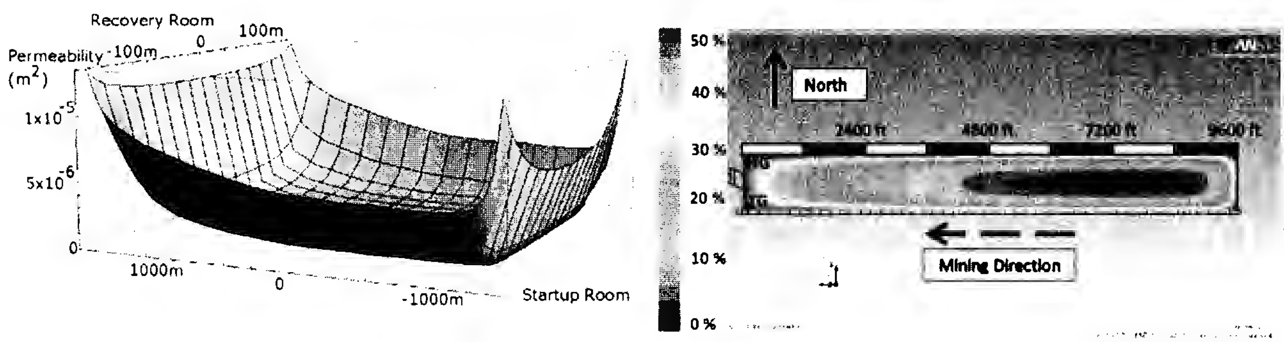

Figure 13 — Longwall gob permeability (left) and resulting porosity distribution (right), from Worrall et al. (2012).

expand along hundreds, even thousands of feet of entries. Most disastrous mine explosions with multiple fatalities involved secondary coal dust explosions. The 2010 explosion at the Upper Big Branch Mine is the most recent example for such a coal dust explosion, triggered by a methane-air explosion that originated in the longwall gob (Page et al., 2011).

- Besides explosions, witnesses also observed diffusion flames (deflagrations) that lasted for prolonged periods of time. Such flames can start severe mine fires and cause entrapment and CO poisoning hazards for the miners. In the case of the UBB explosion (Page et al., 2011), investigators suspect that a diffusion flame burned for several minutes. During this time, miners working near the shearer at the tailgate end of the longwall face were able to initiate an orderly shutdown of the shearer and proceed with their escape to about mid-face, where they were overcome by the explosion flames, pressures and/or gases. In other documented cases, flames from the explosions have propagated into the face areas and caused burn injuries to the miners. Heat can also damage ventilation controls and ignite coal, wood and other combustible materials, including wooden roof support, causing significant secondary damage. Heat can also lead to roof falls from spalling and expansion of moisture in the rock. Fires within the gob are especially difficult to control because of the lack of access to the area.
- Smoke and toxic combustion products, mainly carbon monoxide (CO), from explosions and fires are a severe respiratory hazard. Smoke also makes escape from the mine difficult. CO in large concentrations can lead to immediate death. CO exposure often surprises miners because CO is colorless and has no odor so it can only be detected with specialized instruments.

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

We have 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 EGZs likely to exist and what methods can be used to detect them?
2. How large are these EGZs?
3. What is the possible extent of an explosion of fire within the EGZs?
4. How can location, size, gas composition and flammability of the EGZs be effectively controlled, for example through changes in the ventilation system or injection of inert gases?

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. The key to successful research is obtaining accurate information on the permeability distribution inside the gob areas. It is equally important to obtain actual gas composition data along the gob boundaries and atmospheric quality and air flow data in the active, accessible mine entries to calibrate and verify the CFD models. Since the gob areas cave in and are inaccessible, some measurements must be obtained through remote sampling from boreholes and tube bundle systems.

What follows is a summary illustrating significant research accomplishments in addressing these challenges.

Permeability modeling. Esterhuizen and Karacan (2007) developed a methodology to model the compaction of longwall gobs based on geomechanical parameters of the gob strata and as a function of time. Based on their geotechnical model, they were able to estimate the permeability of the gob as a function of a three-dimensional location and provide realistic input parameters for a comprehensive gas reservoir flow model. The model has been developed primarily for the Pittsburgh coal bed in the northern Appalachian coal region. Based on this geotechnical model, Karacan et al. (2007) then conducted reservoir modeling studies to characterize gas flow in longwall gobs. Karacan et al. developed a model for an active longwall mine in southwestern Pennsylvania and conducted in-mine, gob ventilation borehole and flow and pressure measurements in dedicated observation boreholes to calibrate the model. The gob flow was modeled dynamically in several stages at different times prior to, during and after mining. Also, several parameter studies were developed to investigate the impact of gob ventilation borehole (GVB) completion depth, location, borehole diameter and time of completion with respect to the longwall mining progression.

Wachel (2012) also conducted gob compaction studies using FLAC3D, a finite difference continuum modeling program developed by Itasca, to establish longwall gob porosity for western U.S. coal mines. Unlike earlier studies, Wachel removed the coal in her model in a step-by-step process that leads to a more realistic, asymmetric distribution of gob permeability and porosity, as shown in Fig. 13.

Gas flow modeling within the gob. Balusu et al. (2005) developed CFD modeling solutions to describe the gas flows

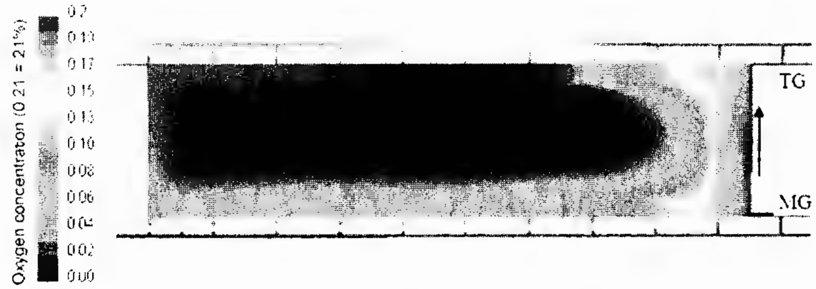

Figure 14 — CFD model of oxygen concentration in a longwall gob (Balusu et al., 2005, no scale indicated; however, the text states that the crosscut spacing is 100 m (300 ft). "MG" indicates main or headgate, and "TG" indicates tailgate).

in a sealed (bleederless) gob for nitrogen inertization purposes to prevent spon com. Figure 14 shows the distribution of oxygen in a longwall gob that is isolated from the mine with gob isolation seals in each crosscut, sealing off the gob along both gate roads. This sealing practice is effective in reducing the oxygen content deep inside the gob below 12%, rendering the atmosphere nonexplosive.

The inert zone is depicted in green and blue shades (<10% oxygen) in Fig. 14 and begins about 200 m (700 ft; approximately two crosscuts) inby the face. However, closer to the active face, oxygen concentrations would still be sufficient to support the combustion and explosion of methane.

Balusu et al. found that the extent of the oxygen-rich zone depended on the intake air flow at the longwall headgate and that the zone could extend 300 m (1,000 ft) inby the face in cases with increased air flow. This suggests that it may be possible to control the compositions of gases inside the gob by varying the inflow rates along the gob boundaries, specifically near the longwall face.

Worrall (2012) developed an advanced CFD model of a bleederless (sealed) longwall gob, demonstrating that the concentrations of methane and oxygen could, to some extent, be controlled by injecting nitrogen into the gob on both the tailgate and headgate sides. Worrall's studies demonstrate that nitrogen injection will significantly reduce the available oxygen in the gob and, therefore, be effective in controlling spontaneous combustion as well as explosive methane-air mixtures.

Marts et al. (2013) show that it is possible to reduce the size of explosive gas zones (EGZs) in bleederless longwall gobs by injecting nitrogen inby the face. Headgate side injection is much more effective that tailgate side injection. Figure 15 shows the effect of minimizing the EGZ based on Worrall's model of a bleederless (sealed) gob (Marts et al., 2013) through increased nitrogen injection from 0.1 - 0.4 m^3/s (200 - 800 cfm) on the headgate side. Marts et al. also showed that increasing the nitrogen injection quantity would reduce oxygen penetration into the gob, as Fig. 16 demonstrates. Reduced oxygen penetration not only renders the methane mixtures inert but also helps prevent spontaneous combustion.

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 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.

Equally important is a thorough assessment of the potential for spontaneous combustion. The CFD numerical models can provide estimates of the available oxygen at a given location in the gob. Researchers at the University of Queensland have recently developed a new methodology to determine how long a given coal may be exposed to oxygen before thermal runaway occurs. This analytical test has been described by Beamish and Beamish (2011) and is similar to the R_{70} method for testing the propensity for spon com. Unlike the R_{70} method, however, Beamish and Beamish recommend testing the sample as received, without drying, and choosing a starting temperature

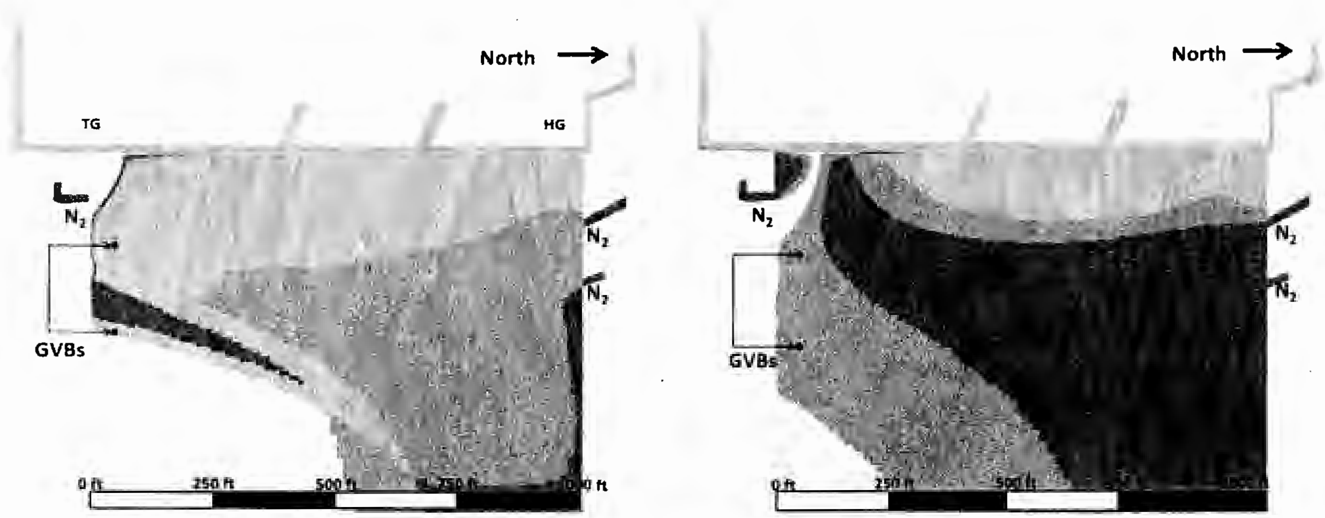

Figure 15 — Effective reduction of explosive mix zone (shown in red) in a bleederless (sealed) gob by increasing the headgate nitrogen injection rate from 200 cfm (0.1 m^3/s; left image) to 800 cfm (0.4 m^3/s; right; Marts et al., 2013). Yellow indicates fuel-rich inert atmospheres, while green and blue shades denote fuel-lean inert zones. Orange indicates a buffer zone where the gas mixture is close to explosive.

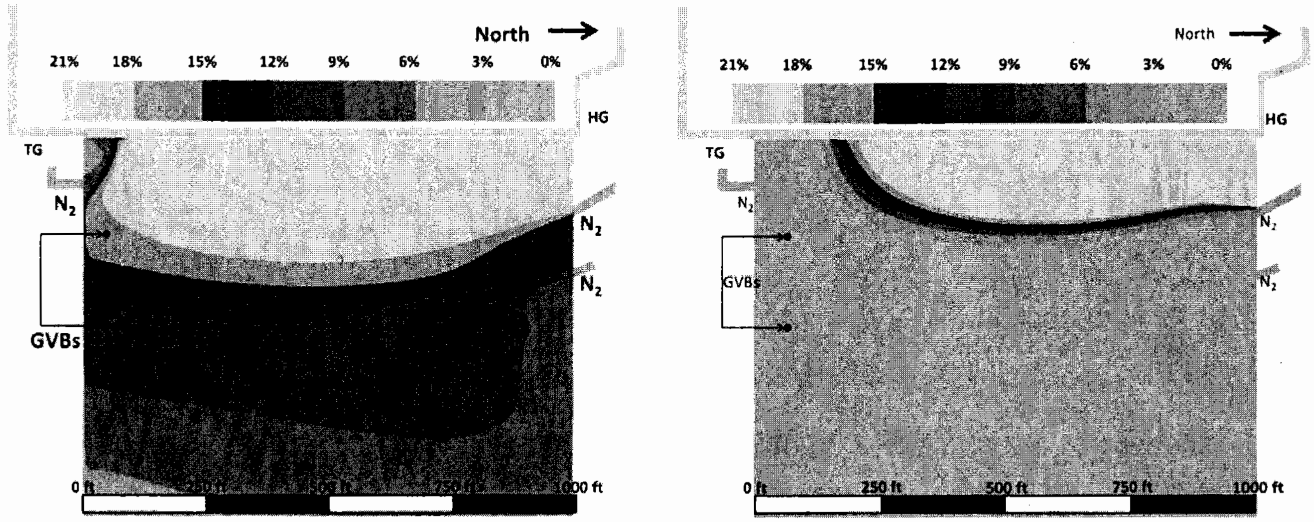

Figure 16 — Reduction of oxygen penetration into the gob by increasing nitrogen injection quantities from 0.1 (left) to 0.4 m^3/s (right) (200-800 cfm) on both headgate and tailgate sides (Marts et al., 2013).

equal to that in the mine rather than 40° C (104° F) as in the R_{70} test. As a result, Beamish and Beamish's test can determine the time during which a given coal is safe from developing thermal runaway. As an example, if this time is three days and the longwall advances 60 m (250 ft) during this interval, nitrogen inertization must be controlled such that the oxygen zone in the gob does not extend farther than 60 m (250 ft) inby the face, as shown in Fig. 16 (right).

As stated earlier, 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 gas analysis tubes extended into the gob through seals or from the bleeder entries, but also drill vertical boreholes into the gob from the surface and equip these boreholes with sampling tubes. Sampling tubes must be monitored continuously to detect the impact caused by variation of the other ventilation and inertization parameters.

Researchers need to gain a more complete understanding of the function and, perhaps, limitations of bleeder systems used to ventilate longwall gobs. Likewise, researchers must determine the advantages and disadvantages of bleederless ventilation systems so that mine operators and regulating authorities can make decisions about longwall ventilation that are supported by well-established scientific evidence. 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

Methane accumulations in explosive concentrations most likely exist in all bleeder-ventilated and bleederless longwall gobs. Under the right circumstances, if the clouds of explosive methane are large enough in size or close to the active mine workings, these clouds 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 likely 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 explosive gas zones or clouds in longwall gobs, and the factors controlling the location such as ventilation air flow rates, pressure differentials, barometric pressure changes and gob ventilation hole production rates.
2. Methods to estimate consequences of explosive gas zones in mined-out gob areas. Questions such as "Will the gas zone burn, deflagrate or, possibly, detonate? What exactly happens when it ignites? How will the rubble in the gob affect the expansion and propagation of the explosive flame? Scientific studies of this issue have not been found in the literature.
3. Engineering methods to control the location and extent of the explosive gas clouds. It appears that engineering solutions to control the clouds through better mining, ventilation, gas production, gas drainage, or inertization practices are effective, but general guidelines for mine operators have not been developed.

It should also be noted that, for bleederless longwall gobs, research is significantly more advanced. Australian and European longwall operators are fully aware of explosion hazards in their bleederless longwall gobs. They actively monitor the gas composition along the fringes and are able to effectively mitigate the hazards through active and controlled inertization. In the United States, 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 alternative longwall gob ventilation systems are needed.

Mine operators and regulators will be able to use the recommendations and guidelines developed from this research for designing better ventilation systems and methane gas drainage and production practices. Such practices would greatly decrease the risk of formation and ignition of flammable gas mixtures that exist within the mined-out area.

This research may also be used as a scientific basis for consideration of improvements to mine safety regulations pertaining to mine ventilation and gas production that would incorporate the engineering controls proposed for hazard mitigation. Specific health concerns, including respiratory and auditory hazards to miners, have been noted in the cases outlined earlier.

It is expected that this research will result in a significant reduction or elimination of the explosion hazards for mine workers that result from methane accumulations in longwall gobs. Thus, the research will greatly improve the safety of our underground coal mines.

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