UTILIZATION AND IMPLEMENTATION OF ATMOSPHERIC MONITORING SYSTEMS IN UNITED STATES UNDERGROUND COAL MINES AND APPLICATION OF RISK ASSESSMENT

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Abstract

Explosions of gas and dust continue to be recognized as an extreme danger in underground coal mines and still occur despite significant technological advances. Mining researchers have been attempting to accurately measure and quantify ventilation and gas properties since early mining; however basic monitoring attempts were limited by the available technologies. Recent advancements in monitoring and communication technologies enable comprehensive atmospheric monitoring to become feasible on a mine-wide scale. Atmospheric monitoring systems (AMS) allow operators to monitor conditions underground in real-time. Real-time monitoring enables operators to detect and identify developing high risk areas of the mine, as well as quickly alert mining personnel underground. Real-time monitoring also can determine whether conditions are safe for mining, to operate ventilation systems more efficiently, and to provide an additional layer of monitoring atmospheric conditions underground.

AMS utilizes numerous monitoring technologies that will allow underground coal mines to comprehensively monitor gas and ventilation parameters. AMS are utilized worldwide as well as in the United States, and can be modified to cater to specific hazards at different mines. In the United States, AMS are primarily used to monitor belt lines and electrical installations for smoke, CO, and CH_4, and to automatically alarm at set thresholds.

The research in this study investigates and analyzed AMS across the world (specifically Australia, Canada, and United States). Two case studies presented in Chapter 5 focus on the

utilization and implementation of AMS in two underground coal mines in the United States. These case studies identify challenges regarding installation, data management, and analysis of real-time atmospheric monitoring data. The second case study provides significant evidence that correlates mine ventilation fan outages and changes in barometric pressure to increases in methane from previous works. This research does not attempt to quantify data, but intends to provide engineers knowledge to utilize, design, and implement an AMS. Several incident scenarios are simulated using ventilation computer software, as well as the benefits of monitoring in past disasters are analyzed. This research does not intend to place blame, but intends to increase the understanding of utilizing and implementing AMS in underground coal mines.

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Virginia Tech and Blacksburg, Virginia, the City of Dreams- Thank you for everything. My childhood, teenage, and many young adult years were spent in this beautiful town. Your memories will always be held deep within me (Mount Vernon, Hethwood, Rangers, State Champs, FROG, 211, 4700, 609, 201, and 6600). I will always carry a piece of you with me where ever this life may lead me. I promise, I will neVer forgeT and always live for 32.

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LIST OF ABBREVIATIONS

AC – Alternating Current

ADC – Analog to Digital Converter

AMS – Atmospheric Monitoring System

ANN – Artificial Neural Network

CFD – Computational Fluid Dynamics

CFR – Code of Federal Regulations

DC – Direct Current

ELF – Extremely Low Frequency

EMI – Electromagnetic Interference

ERP – Emergency Response Plan

ERZ – Explosion Risk Zone

ESG – Engineering Seismology Group

GAG - Gorniczy Agregat Gasniczy

IP – Internet Protocol

IR - Infrared

IS – Intrinsically Safe

ISS – Integrated Seismic Systems

LAN – Local Area Network

LF – Low Frequency

LHD – Load-Haul-Dump Mining Equipment

MF – Medium Frequency

MINER Act – Mine Improvement and New Emergency Response Act of 2006

MSHA – Mine Safety and Health Administration

NERZ – Non-Explosion Risk Zone

NIOSH – National Institute for Occupational Safety and Health

PC – Personal Computer

PDM – Personal Dust Monitor

PLC – Programmable Logic Controller

RAID - Redundant Array of Independent Disks

RAM – Real-time Aerosol Monitor

RF – Radio Frequency

RFID – Radio Frequency Identification

RSSI – Received Signal Strength Indication

SOP – Standard Operating Procedures

TBS – Tube Bundle System

TID – Thermal Ionization Detector

TTE – Through-the-Earth

UBB – Upper Big Branch, Massey Energy Underground Coal Mine

UHF – Ultra High Frequency

UPS – Uninterruptible Power Supply

USBM – United States Bureau of Mines

VCCER/VT – Virginia Center for Coal and Energy Research at Virginia Tech

VHF – Very High Frequency

VLF – Very Low Frequency

VO – Ventilation Officer

VOD – Ventilation-On-Demand

WiFi – Wireless Fidelity

WIPP – Waste Isolation Pilot Plant

WMN – Wireless Mesh Network

XP – Explosion Proof

CHAPTER 1: INTRODUCTION

The progression of technology has allowed mine monitoring techniques to become more sophisticated, yet explosions in underground coal mines still occur. Explosions of gas and dust continue to be recognized as an extreme danger in underground coal mines. From 1900 to 2012, there were 421 explosions resulting in 10,419 fatalities in United States underground coal mines (MSHA, 2013). There were 118 fatal and 299 non-fatal days lost accidents due to the ignition or explosion of gas or dust from 1983 to 2011 (MSHA, 2010). Figure 1.1 shows the number of fatalities in United States underground coal mines from 1978 to 2012 (MSHA, 2012a).
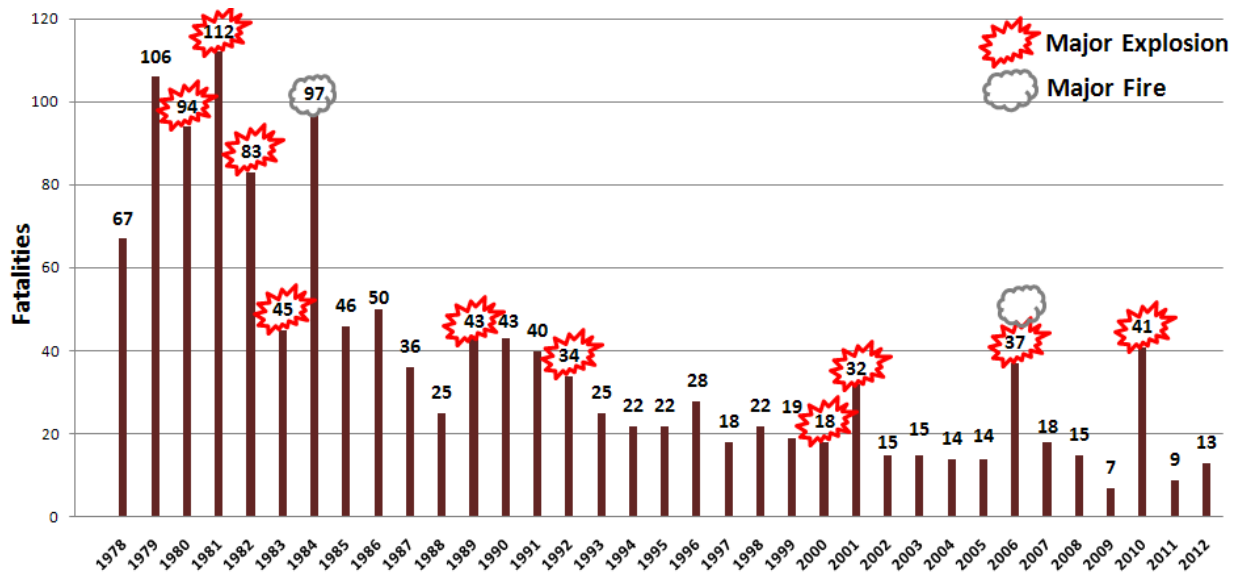
Figure 1.1: Fatalities in United States Underground Coal Mines, 1978-2012 (MSHA, 2012a)

Figure 1.1 shows a general downward trend in fatalities since 1978, but major explosions and fires still occur. Atmospheric monitoring in underground coal mines allows mine operators to analyze conditions underground in real-time. Real-time monitoring can then be used to identify whether atmospheric conditions underground are becoming problematic. Atmospheric monitoring techniques continue to be developed, but still present challenges because available technologies demonstrate issues that limit accuracy, response time, range, sensitivity, and survivability.

Explosions in underground coal mines have been a serious safety concern since the advent of mining. Most recently in the United States, on April 5, 2010 at approximately 3:02pm,

a massive methane gas and coal dust explosion occurred at the Upper Big Branch Mine-South (UBB), killing 29 miners and injuring two (MSHAa, 2011). Recent advances in atmospheric monitoring and high speed communication networks have made comprehensive mine-wide atmospheric monitoring feasible. The integration of comprehensive atmospheric monitoring systems allows the underground atmosphere to be analyzed throughout the entire mine. Real-time atmospheric monitoring in underground coal mines provides critical data to ensure the safety of underground miners as well as can be used to aid production. During the course of this work, atmospheric monitoring systems across the world (particularly Australia, Canada, and United States) were studied in order to determine the best approach to comprehensive monitoring in underground coal mines. Two cases studies are presented which examine existing MSHA-approved atmospheric monitoring technologies that have been installed in two underground coal mines in the United States.

The first objective of this project is to analyze existing AMS in underground coal mines in the United States. This objective is satisfied in Chapters 2, 3, and 4 by reviewing past literature relevant to utilizing AMS in underground coal mines, investigating AMS worldwide (specifically Australia, Canada, and United States), sensor performance and simulation of several incident scenarios, and analyzing the benefits of monitoring in past disasters. The second objective is to utilize and implement a comprehensive AMS using existing technology and make recommendations to improve that technology. This objective is satisfied in Chapter 5 with two case studies outlining the instrumentation, installation, data management, and analysis of real-time AMS data in two United States underground coal mines. The third objective is to examine the utilization of a comprehensive AMS within U.S. regulatory frame work and U.S. mining safety culture. Risk management strategies and their applications in U.S. mines are also examined, which is satisfied in Chapter 6. Finally, conclusions, recommendations for future research are presented in Chapter 7.

CHAPTER 2: ATMOSPHERIC MONITORING IN UNDERGROUND COAL MINES LITERATURE REVIEW

Ventilation systems are crucial to supplying sufficient oxygen, maintaining non-explosive and non-toxic atmospheres, and operating an efficient mine. Monitoring a mine's ventilation systems can help eliminate high risk atmospheres. Primitive techniques of monitoring a mine's atmosphere can be traced back to the use of canaries and other animals to alert miners when the atmosphere becomes toxic. Integrating ventilation monitoring systems enables a mine to intelligently make ventilation changes based on the extensive data the monitoring systems provides. Unexpected changes in the ventilation system are detected by the monitoring system, allowing immediate action to be taken. New and developing communication and tracking systems can be utilized to monitor mines more efficiently and relay the data to the surface. This literature review focuses on sensors currently implemented in United States mines, sensors implemented in other industries, United States and international mine ventilation monitoring safety standards, current state of communications in underground mines, and integrating predictive and artificial intelligence algorithms mine-wide ventilation monitoring. Sections in this chapter contain work from "A Review of Atmospheric Monitoring Systems in Underground Coal Mines: Implications for Explosion Prevention" Kenneth R. Griffin, Edmund C. Jong, Kray D. Luxbacher, Erik C. Westman. SME Annual Meeting, Denver, 2011, SME Preprint 11-127, used with permission of Tara Davis.

2.1 Sensors Currently Implemented In United States Mines

Atmospheric monitoring sensors can be used to detect a wide variety of ventilation parameters. There are sensors currently available for measurement of mine gases, psychometric properties, dust content, air velocity, and seismic events, both in the U.S. and internationally. This section outlines sensors that are currently used in mines.

2.1.1 MINE GASES

The mine atmosphere is made up of air or 78.09% nitrogen, 20.95% Oxygen, 0.03% carbon dioxide, and 0.93% argon & other rare gases by volume (Hartman, Mutmansky, Ramani,

& Wang, 1997). An underground coal mine is exposed to a wide variety of gases which increase the potential for an explosion when given the wrong mixture of gases in the mine at any given time. Other gases can create a toxic atmosphere that can be fatal for miners. Adequate ventilation ensures that the underground working environment is safe to operate in. Air tends to lose oxygen and gains other gases from strata, equipment, and other various sources. Sensors are currently available to measure methane, carbon monoxide, carbon dioxide, oxygen, nitric oxide, nitrogen dioxide, hydrogen sulfide, hydrogen, ammonia, ozone, anemometer, and chlorine. Gases are measured and detected by utilizing a wide variety of methods such as gas chromatography (GC), solid phase microextraction (SPME), infrared, pellistor, thermal conductivity, galvanic, electrochemical, and developing fiber optics. Some gas detection and measurement systems take longer than others to identify gas concentration levels. GCs are generally used in mine fires and explosions to analyze the mine atmosphere for gases produced in a fire. GCs can be difficult to maintain and do not provide real-time data because samples must be taken and later analyzed on the surface.

Methane is one of the most problematic gases experienced in underground coal, trona, potash, limestone, oil shale, and salt mines. Small amounts of methane have also been detected in copper, tungsten, iron, gypsum, marble, gold, and silver mines (Hartman et al., 1997). Methane can be contained within the coal seam or inside of fissures in the coal and surrounding strata. The amount of methane in a seam depends on temperature, pressure, degree of fracturing, and permeability of the coal and surrounding strata. Methane tends to accumulate along the roof and in high areas of the mine because it is less dense than air.

Methane emissions during mining have become more difficult to control partly because improvements in mechanized mining equipment. Faster equipment has increased face advance rates, panel size, and allowed for more extensive gate road developments (Schatzel, Karacan, Krog, Esterhuizen, & Goodman, 2008). Schatzel et al. (2008) state, "longwall mining productivity can far exceed that of room-and-pillar mining, the total methane emissions per extracted volume associated with longwall sections are generally higher than those for continuous miner or pillar removal sections." Longwall mining allows gob areas to collapse as mining advances, creating long horizontal and vertical cracks that potentially create pathways for gas migration through the gob areas. Schatzel et al. (2008) also noted, "methane that originates

and accumulates in the gob above the mined out panel is the main source of methane emissions during longwall mining." Previous studies completed by Tauziede, Pokryszka, Carrau & Saraux (1997) and Diamond, W.P., Garcia, F., Aul, G.N., & Ray, R.E. (1999), indicated that only a small portion of the overall methane emissions and gas production from a longwall is emitted from the mining face. They also reported that previous studies indicate emissions from gob strata may account for 80%– 94% of the methane emission into the ventilation system of an operating longwall. Schatzel et al. (2008) suggest that longwall face emission may account for less than 20% of face emissions and less than 6% of mine emissions. The U.S. Bureau of Mines (USBM) has done extensive research on monitoring technologies, gas sensors, and fiber optics, as discussed in Section 2.4.3.

2.1.2 PSYCHROMETRIC PROPERTIES

A mine ventilation plan can vary in operating efficiency based upon the current psychrometric properties of the air, which describe the thermodynamic behavior of the system. Air is typically considered to be moist air or "normal" air, a mixture of air and water vapor (Hartman et al., 1997). Pressure systems and inclement weather moving across the local mine area can cause pockets and building, affecting the ventilation systems' efficiency. Wet and dry bulb temperatures, air density, and barometric pressure will provide further insight into air and gas migration throughout the mine. Sensors can measure the wet and dry bulb temperatures by traditional thermometers, electrical methods, dew point hygrometers, static hygrometer, sling psychrometer, aspirated psychrometers, and psychrometers (McPherson, 2009). Mine ventilation fans typically have sensors that measure the wet and dry bulb temperatures, barometric pressure, humidity, and fan speed. Additional sensors can be placed in the mine at major ventilation nodes to better understand the thermodynamic behavior of air as it flows through the mine.

In a case study, McPherson (2009) highlighted the power of thermodynamics concerning the ventilation of the mine. The pressure across the main fan was 2.37 kPa with a pressure across the shaft bottoms of 2.5 kPa. The natural ventilating pressure at standard density was calculated to be 1.285 kPa. Natural ventilation is effected by barometric pressure, air density, humidity, and other psychrometric properties. Fan performance is dictated by the pressure at the fan and can significantly change as air properties in the mine change. Fan pressure may vary due to changes in barometric pressure, air density, humidity, and other psychrometric properties. Local weather

systems will change the barometric pressure, air density (i.e. moist or more dense air is harder to move), humidity (i.e. rain, snow, sleet), which will typically reduce the fan's operating efficiency.

Differences in pressure across geographical regions cause changes in the weather, which may impact the operating efficiency of ventilation fans. Weather constantly changes throughout the four seasons of the year and can change within a few minutes. Weather fronts carrying precipitation (low pressure systems) lower the barometric pressure on the surface. Areas of high pressure tend to move towards areas of lower pressure. Figure 2.1 shows the two types of pressure systems.
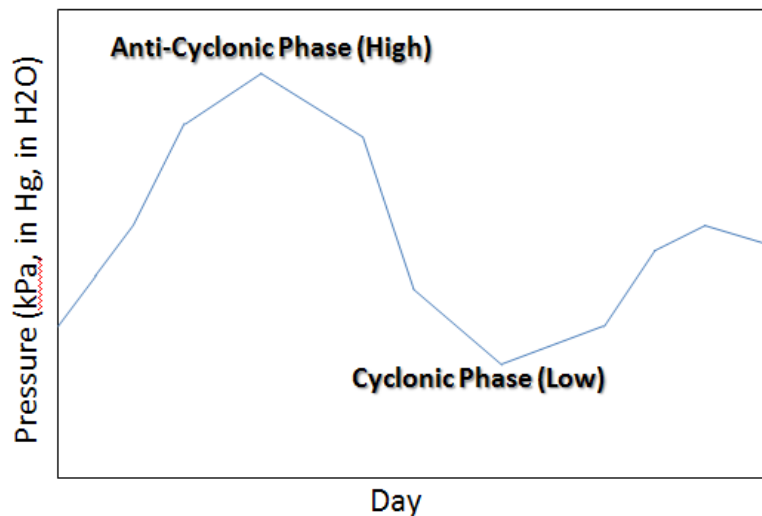
Figure 2.1: Pressure Systems

The barometric pressure and additional moisture from low pressure systems make it harder to move air in and exhaust air out of the mine. Changes in barometric pressure ultimately change the equilibrium of the coal strata and the existing mine atmosphere (Fauconnier, 1992). Figure 2.2 shows the initial barometric pressure (Pb1) and the initial gas pressure (Pg1).
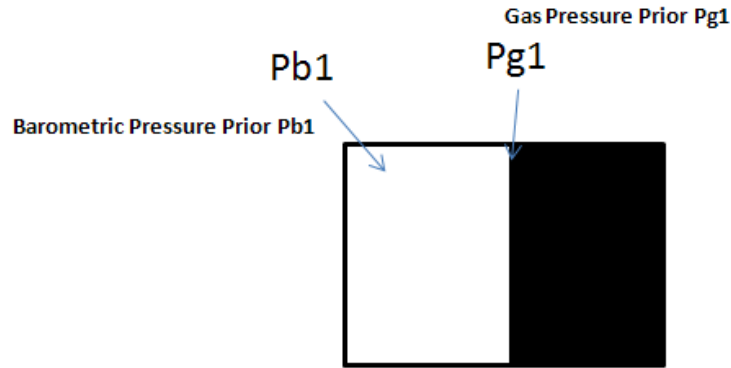
Figure 2.2: Initial Pressures

As mining progresses new coal strata is exposed with a higher gas pressure (Pg2) and causes a pressure differential as seen in Figure 2.3.
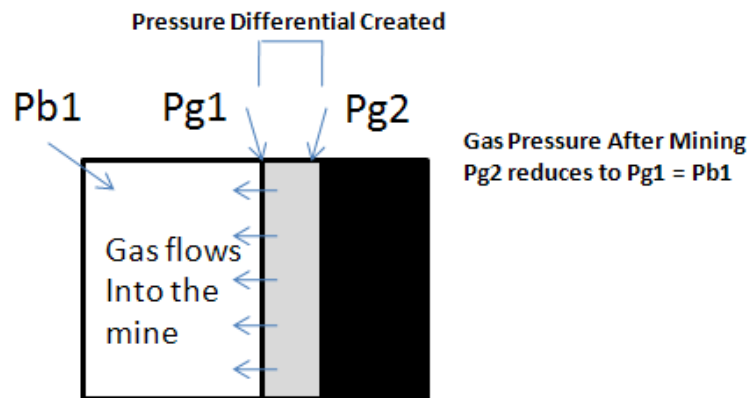
Figure 2.3: Mining Differential Pressures

The newly exposed coal strata gas pressure (Pg2) will reduce until it has reestablished equilibrium with Pb1 and Pg1. Reduction in Pg2 pressure results in gas flowing into the active mine workings.

According to Fauconnier (1992), assuming that no further excavation occurs, an anti-cyclonic high pressure system will increase the barometric pressure (Pb3) and cause gas to flow into the coal and other cracks in the strata. Figure 2.4 shows an anti-cyclonic high pressure system's influence.

Pb3 > Pg1

Barometric Pressure Increases to Pb3
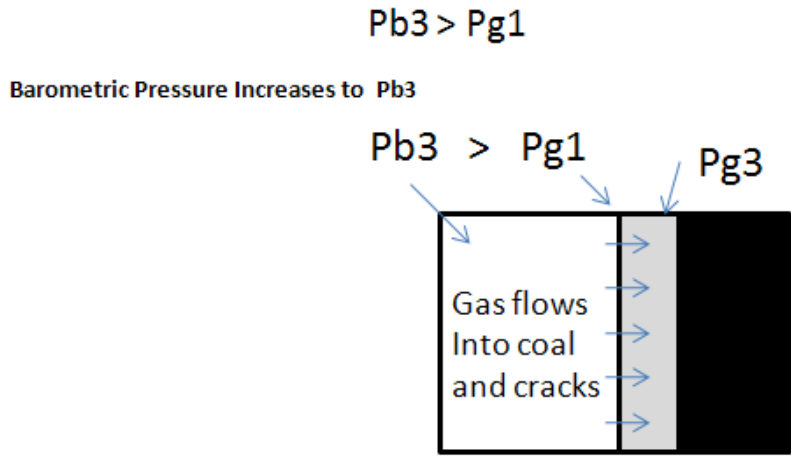
Figure 2.4: Anti-Cyclonic High Pressure System Influence

A cyclonic low pressure system will cause a decrease in barometric pressure (Pg4 < Pg3) and cause gas movement to change direction and flow into the active mine workings, as shown in Figure 2.5.

Pb4 < Pg3

Barometric Pressure decreases to Pb4
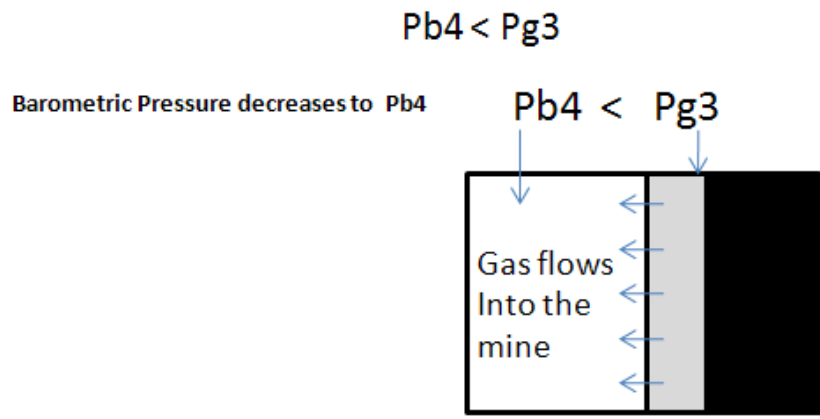
Figure 2.5: Cyclonic Low Pressure System Influence

The influence of barometric pressure pertaining to explosions in underground coal and gold mines has been widely debated, although several studies have indicated significant changes in barometric pressure can be a contributing factor. Fauconnier (1992) stated, "51 of 59 explosions in South African coal and gold mines over the time period of 1970 to 1989 were associated with a net drop in barometric pressure after an anti-cyclonic maximum, leading to a medium-term decrease in barometric pressure as a result of cyclonic weather patterns definitely contributed to risk of gas explosions."

Barometric pressure has been noted by several studies to influence mine gas emissions. Dornenburg, O'Connor & Harris (1955) noted, "Barometric pressure changes had large effects on main returns and the total mine-return-air current. Relatively small changes of barometric pressure continued over extended periods do not effect material changes in the gas content of mine air currents. Rate of change as well as the absolutely amount of change are both important factors in the case of unsealed or small areas with multiple seals." This same study also indicated that large sealed areas with a few seals, the absolute change, and duration of change in barometric pressure were important factors. A recent study completed by Yuan and Smith (2010) noted, "simulation results demonstrated that under typical bleederless ventilation conditions, the maximum temperature from the spontaneous heating in the gob was affected by the barometric pressure changes, although not significantly." The effects of barometric pressure increased as the gob permeability increased, where the changes in barometric pressure resulted in decreased oxygen concentrations at the headgate.

Most recently, MSHA (2012d) issued a winter safety alert stating, "A falling barometer often results in higher concentrations of methane at the working face. Methane and other gasses are liberated from gobs and from behind seals into the active areas of the mine as the barometer falls. Seals will begin to "out-gas" at a greater rate. A falling barometer usually indicates an approaching storm front. A rising barometer is an indication of rising atmospheric pressure. A higher barometer tends to reduce methane face liberation, but could cause seals to "in-gas" and create an explosive mixture of methane and oxygen." MSHA recommended that mines control coal dust with heavy applications of rock dust, as well as actively monitor the barometric pressure to alert miners to take more frequent methane checks.

Evidence suggests that fluctuations in barometric pressure influence the risk of gas explosions has continually accumulated over time, but has not been concluded to be the primary cause of most gas explosions.

2.1.3 AIR VELOCITY

The measurement of air velocity in underground coal mines has been accomplished by various methods ranging from observing the velocity of visible dust or smoke particles suspended in the air during the nineteenth century to developing sophisticated electronic

equipment which continuously monitor air velocity. MSHA requires that electrical equipment used at the face and in return airways are permissible, which is defined in 30 CFR § 75.506. The rotating vane anemometer is the most commonly used instrument to measure air velocity in underground coal mines. The rotating vane anemometer is a windmill-type instrument that is used with a stopwatch and indicates the air velocity by the number of windmill revolutions over a given period of time. This instrument must follow a strict operational procedure and is sensitive to measurement technique, proximity to observer, application of correction factors, its inability to measure low airflows, and are not capable of continuous measurements for monitoring (Martikainen, Dougherty, Taylor, & Mazzella, 2010). Figure 2.6 shows a rotating vane anemometer. The rotating vane anemometer's typical measuring range is 200 to 3,000 feet per minute (fpm) but is available with ranges of 50 to 5,000 fpm and 200 to 10,000 fpm (MSHA, 2006a).

Figure 2.6: Rotating Vane Anemometer (MSHA, 2006a)

Air velocity measurements are not limited to rotating vane anemometers and can also be accurately measured using a wide variety of techniques and instruments such as averaged spot measurements, anemometer traverses, ultrasonic measurements, hotwire anemometers, tracer gases, velometers, vortex shedding anemometers, smoke tubes, tracer gases, thermal mass flow, and velocity pressure measurements using a pitot tube (Prosser & Loomis, 2004).

Devices with moving parts may be problematic for remote continuous monitoring. Airflows in an underground mine are subject to considerable variation due to movement of equipment, changes in resistance in the workings, and opening of ventilation doors. Air velocities are generally limited to below 20 m/s (3940 fpm) in ventilation shafts and as low as

0.3 m/s (60 fpm) at working faces. Remote areas, such as bleeders, can exhibit extremely low velocities, which are a challenge to accurately quantify. Remote monitoring of air velocity in underground mines is difficult because of the wide range of velocities, the interference of moisture and dust with sensors, and the appropriate location of sensors so that a reasonable average flow across the cross sectional area of an entry is measured. An alternative to velocity monitoring is monitoring pressure differential, particularly in areas with high pressure differentials such as regulators. An extensive review of instruments used to measure air velocity may be found in McPherson (2009).

Newly developing continuous air velocity sensors for underground mines utilize ultrasonic, thermal mass flow, and vortex shedding technologies. While the MSHA certification status of continuous air velocity sensors varies, these continuous monitoring technologies have already been used extensively in meteorology and other fields of research (Martikainen et al., 2010). NIOSH continues to research various air velocity sensing methods to determine which best fits for use in underground coal mines.

Ultrasonic Anemometer

An ultrasonic anemometer calculates air velocity by measuring the difference in air-pulse transit times between a sound transmitter and receiver (Hall, Taylor & Chilton, 2007). The ultrasonic anemometer relies on the principle that the speed of a sound pressure wave varies with local air speed. Taylor, Chilton, McWilliams & Senk (2004) noted that ultrasonic anemometers have a, "linear response and an absolute calibration that depends only on sensor spacing and transit time measurement accuracy." Ultrasonic anemometers require no correction for air density, provide an air velocity directional sign, have no moving parts, have no start-up friction and have no inertial problems when air velocity rapidly changes (Martikainen, Taylor & Mazzella, 2012). The two main types of ultrasonic anemometers are fixed single-point and variable distance (Casten, Mousset-Jones & Calizaya, 1995). Variable distance ultrasonic anemometers consist of a fixed sound transmitter and a receiver that can measure air velocity over a known area. Variable distance ultrasonic anemometers have recently been developed in Canada (Accutron Instruments, 2010; Synergy Controls Corporation, 2010). Fixed single point anemometers are typically one-, two-, or three-axes that transmit ultrasonic pulses between

probes on each axis to calculate air velocity. Figure 2.7 illustrates the three most common types of fixed single point ultrasonic anemometers (Hall et al., 2007).
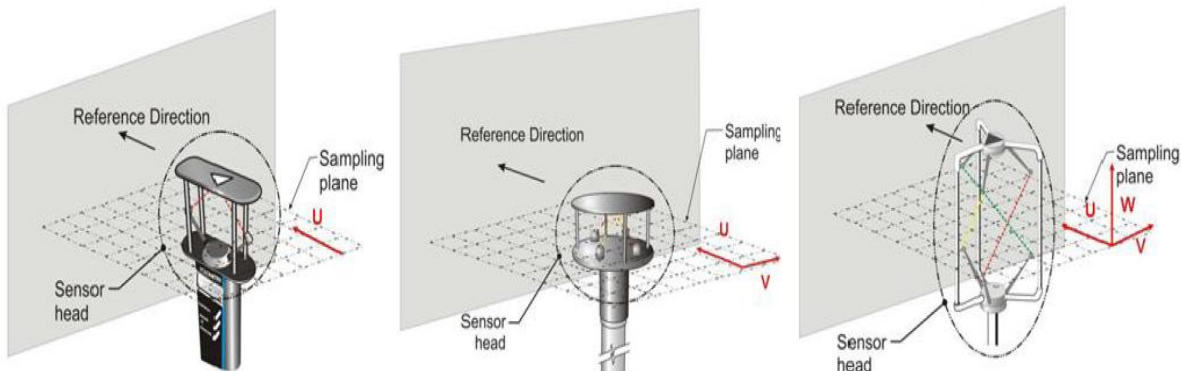
Figure 2.7: One-, Two-, and Three-axes Ultrasonic Anemometers (Hall et al., 2007)

Hall et al. (2007) found that one-, two-, and three-axis ultrasonic and vane anemometers can take accurate airflow readings when the airflow direction is known (i.e. behind ventilation curtains). Two- or three-axes anemometers must be used to take airflow measurements at the mouth of the curtain. One-axis anemometers have the same limitations as the current vane anemometers because they must be precisely aligned with the airflow direction. Martikainen et al. (2012) found in order to achieve 95% and 98% confidence in the results, for stable airflow only a few measurements are needed in an ideal area and 15 data samples or 15 seconds (one sample per second) in a less than ideal area. However, in a very turbulent airflow 1,180 samples, or almost 20 minutes, would be required. A typical rate of one sample per second was deemed adequate.

Dust can affect the measurement accuracy of all devices that are used to quantify air velocity. Dust in underground coal mines is primarily comprised of either coal or rock dust. The Code of Federal Regulations 30 §75.2 states that rock dust:

> Pulverized limestone, dolomite, gypsum, anhydrite, shale, adobe, or other inert material, preferably light colored, 100 percent of which will pass through a sieve having 20 meshes per linear inch and 70 percent or more of which will pass through a sieve having 200 meshes per linear inch; the particles of which when wetted and dried will not cohere to form a cake which will not be dispersed into separate particles by a light blast of air; and which does not contain more than 5 percent combustible matter or more than a total of 4 percent free and combined silica (SiO_2), or, where the Secretary finds that such silica concentrations are not available, which does not contain more than 5 percent of free and combined silica (MSHA, 2011b).

Ultrasonic anemometer accuracy can be affected by exposure to dust. Martikainen et al. (2010) noted, "dust exposure testing showed that coal dust rarely affected the ultrasonic anemometer and was easy to clean off the instruments. Rock dust however, tended to stock and cake on the instruments. Cleaning was required to avoid signal loss with heavy build-up of dust."

Thermal Mass Flow

A thermal mass air flow sensor typically uses a hot wire/films or heated thermocouples to determine air velocity by measuring the cooling effect of the gas flowing over a heated sensing element. Air velocity over the sensor is proportional to the electrical current required to maintain the hot wire or electrical film at a constant (Heldman, 2003). Thermal mass flow sensors measure the flow rate of methane, compressed air, natural gas, and other gases. An example of an air velocity sensor utilizing thermal mass flow is the Rel-Tek Corporation AirBoss 200W (Rel-Tek Corporation, 2010).

Vortex Shedding

Vortex shedding is a technique to measure air velocity by relying on the detection of vortices created by air or fluid flowing around an obstacle (bluff object). Theodore von Karman discovered vortex shedding in 1911. Vortices are shed from each side of the obstacle in an alternating pattern (Giosan, 2008). Figure 2.8 shows an example of vortices being created by fluid flowing around an obstacle.
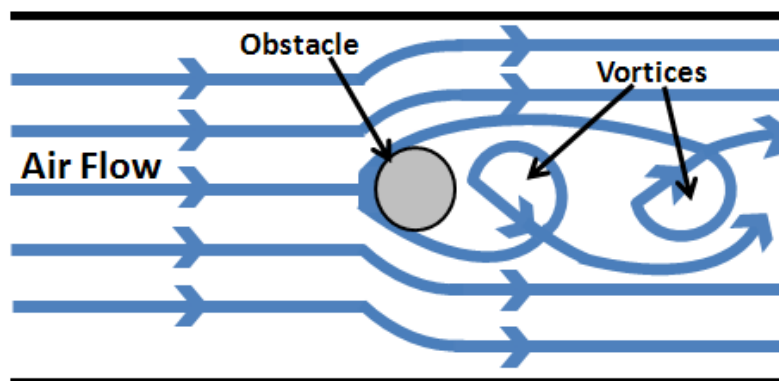
Figure 2.8: Vortex Shedding Example (Adapted from Federal Highway Administration, 2010)

Mattar and Vignos, 2010, noted that "for a large class of obstacles, as the velocity increased the number of vortices shed in a given time, or frequency of vortex shedding, increased in direct proportion to the velocity." The vortex shedding frequency, f (Hz), is equal to the dimensionless

Strouhal number, or *Sr*, multiplied by flow velocity, *U* (m/s), divided by the obstacle diameter, *d* (m), as expressed in equation 1.

Equation 2.1: $$f = Sr * U / d$$

In a pipe or an area of confined flow, the volumetric flow rate, *Q* (m³/s), is equal to the cross sectional area of the vortex orifice, *A* (m²), multiplied by the vortex shedding frequency, *f* divided by the friction factor, *K*, as expressed in equation 2.

Equation 2.2: $$Q = A * f / K$$

Mattar and Vignos, 2010, state, "When shedding is present both the pressure and velocity fields in the vicinity of the shedder will oscillate at the vortex shedding frequency. Pressure or velocity sensors transform the oscillating fields to an electrical signal, current or voltage." A device utilizing the vortex shedding technique should be located in a place where vibration and electrical inference levels are low. Hennessy (2005) noted, "vortex shedding airflow sensors are commonly used in air velocities in the range of 350 to 6000 feet per minute." A disadvantage of a vortex shedding anemometer is that the sensor must be calibrated to each specific fixed location underground when being used for monitoring purposes (McPherson, 2009). Electronic damping may be required to eliminate variations in signal caused by the passing of various mining equipment.

Air velocity is currently difficult to continuously monitor, but developing technologies should enable operators to monitor air velocity in real-time. Newly developing ultrasonic, thermal mass flow, and vortex shedding air velocity sensors can provide adequate solutions in the future to air velocity monitoring. Air velocity monitoring in underground coal mines is currently limited to measurements taken by handheld instruments, primarily vane anemometers.

Waste Isolation Pilot Plant Monitoring

The Waste Isolation Pilot Plant (WIPP) is a facility in Carlsbad, New Mexico designed to dispose of transuranic waste generated by the United States Department of Defense (U.S. Department of Energy, 2010). The WIPP facility as shown in Figure 2.9 has an underground waste disposal site contained within a deep-geological salt deposit (EPA, 2006).
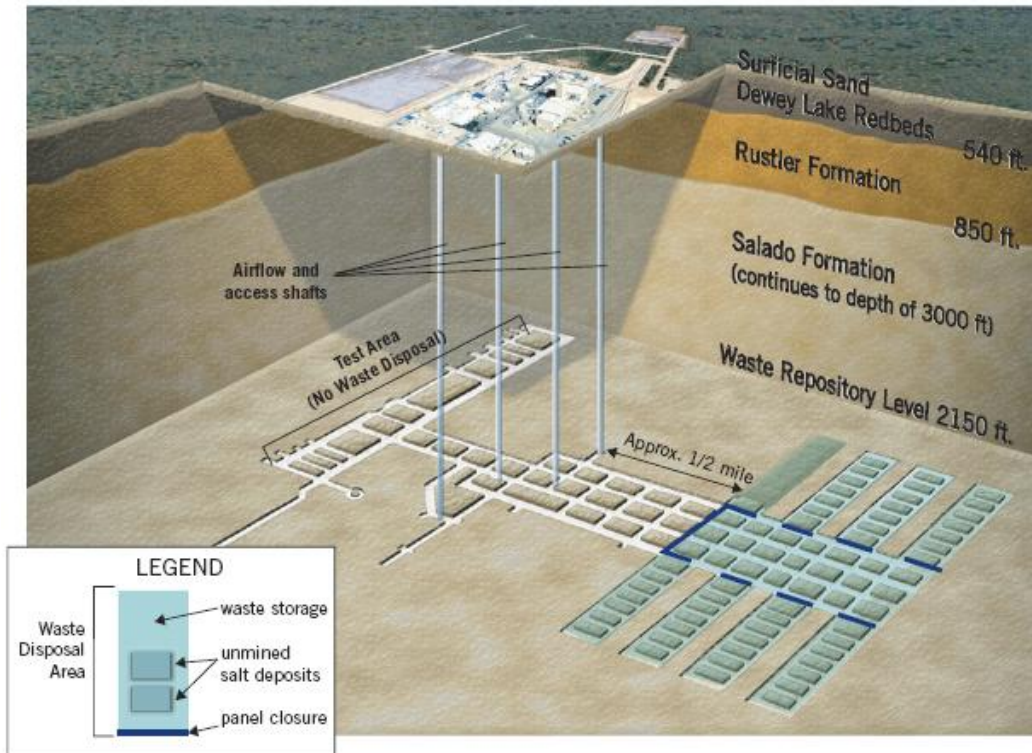
Figure 2.9: Waste Isolation Pilot Plant (EPA, 2006)

The ventilation system in the WIPP is designed to minimize the amount of radioactive contamination to the environment in the event of an accident (McDaniel, Duckworth, & Prosser, 1999). In 1994, the ventilation monitoring and control system consisted of fifteen air velocity sensors, eight differential pressure stations, and automated control features on regulators and psychrometric stations. McDaniel et al. (1999) noted that the air monitoring component of the system had always been a problem and the FloSonic, ultrasonic-type device and Rel-tek's Airboss*200W thermal mass flow unit were tested to determine which unit should replace the existing problematic air monitoring devices. McDaniel et al. (1999) study concluded that the FloSonic unit was typically more accurate, once the diagonal distance parameter was determined, than the AirBoss*200W unit. Overall, the study concluded that the FloSonic unit was the superior sensor to be used in the WIPP. The study also noted that calibration was often difficult, accuracy of velocity sensors can vary, underground installation can be less difficult based upon the design of the sensor, and the impact of dust was minimal, or required periodic cleaning.

The WIPP operation presented various challenges in an unfriendly environment that is not typically seen in underground mines. Large chain-link fences were used underground which

tended to collect salt which resulted in large salt buildups along the chain-link fences. The salt buildups did not allow sufficient air to pass through them, making it extremely difficult to measure air velocity correctly.

2.1.4 DUST CONTENT

Current dust sampling methods include cyclone samplers, gravimetric dust samplers (stationary and mobile sampling), real-time aerosol monitors (RAM), and personal dust monitor (PDM). These sampling methods are limited to personal dust monitoring devices that can be placed on equipment and miners or set to monitor a point. Dust content is difficult to measure without a high maintenance sensor or device. It is also hard to distinguish between coal and other rock material without extensive laboratory analysis, which would make it difficult to incorporate dust content sensors into a real-time monitoring system. For example, it would be difficult to differentiate between diesel particulate matter, coal, silica, rock dust, and quantify particle size with the technology currently available.

2.1.5 SEISMIC SENSING

Seismic and microseismic research has been ongoing since the late 1930's in mining. L. Obert and W.I. Duvall determined in a deep hard rock mine that a stressed pillar would emit micro-level sounds which were later verified in the laboratory (Hardy, 1981). It was also noted that mining companies and government research agencies use microseismic equipment to better understand seismic and microseismic influence on the underground mining environment. Seismic monitoring has been commonly used for locating ore deposits, locating fractures in rock formations, and identifying velocities to determine stress within rock formations (Chang, Liu, Wang & Gao, 2000). Seismic monitoring systems can be active and passive. Active seismic monitoring systems utilize seismic waves that are sent out from devices, while passive seismic systems monitor or listen for seismic waves generated by movement within the rock mass. Monitoring seismic events in underground coal mines has utilized localized measurements of the roof in the past to predict the geological behavior and stress over sections of the mine (Luxbacher, 2005). Sensors, such as geophones and accelerometers allow the velocity tomography to be analyzed in the area to predict the stress and behavior of the local geology more accurately. Velocity tomography studies the velocities and behavior of seismic energy as it

propagates through a rock mass. Identifying arrival times of the seismic waves allow problematic areas of the mine to be further investigated by locating areas with differing velocity profiles which indicate changing densities within the rock mass, whereas in the past those sections were generalized in large sections of area throughout the mine. Luxbacher (2005), states, "the wave propagation through a rock mass is dependent on many characteristics of the rock mass including rock type, fracture, anisotropy, porosity, stress, and boundary conditions." Further studies were performed by Luxbacher and others (Luxbacher, Westman & Swanson, 2007; Luxbacher, Westman, Swanson & Karfakis, 2008) reviewing recent developments utilizing tomography in underground coal mines.

Stress is constantly redistributed as mining progresses because as ore is removed the other rock strata must compensate for the void that mining has created. Rock mechanics, tomography, and fracture mechanics may be combined in order to accurately describe the current and possibly even future behavior of the roof, ribs, and floor due to mining activities. It is possible that the redistribution of stresses within the rock mass and surrounding strata can alter fissures and nature pathways which can dictate the flow of gases into the mine but has yet to be proven for specific gas quantities.

The most commonly used types of seismic sensors are geophones and accelerometers. Geophone and accelerometers may be placed on the surface and underground to create a full picture of the rock mass the mine is within. Kerr (2011) provides an extensive overview of seismic monitoring in deep hard rock mines. Surface and underground sensors will provide details on how the rock is behaving locally and impacting the rest of the rock mass. Underground coal mines provide unique challenges in which no direct correlations of seismic activity and gas emissions have yet to be proven for specific quantitative quantities. The Engineering Seismology Group (ESG) and Integrated Seismic Systems (ISS) are companies that produce seismic monitoring systems.

2.2 Sensors Implemented In Other Industries

There are a wide variety of sensors implemented in other industries that could potentially transfer to the underground coal mine environment, although there are numerous MSHA-approved sensors available to monitor a wide variety of properties in coal mines. The MSHA

approval process for sensors typically takes 9 months to 2 years in order deems a device permissible. MSHA defines permissible equipment under 30 CFR §18.2, "a completely assembled electrical machine or accessory for which a formal approval has been issued, as authorized by the Administrator, Mining Enforcement and Safety Administration under the Federal Coal Mine Health and Safety Act of 1969 (Pub. L. 91-173, 30 U.S.C. 801 or, after March 9, 1978, by the Assistant Secretary under the Federal Mine Safety and Health Act of 1977 (Pub. L. 91-173, as amended by Pub. L. 95-164, 30 U.S.C. 801)." MSHA, 2008a defines intrinsically safe active voltage and current limit circuit as " a circuit that utilizes non-passive components such as transistors or other solid state devices that either shunt overvoltage or overcurrent conditions or limit the output of the power source fast enough to prevent an ignition of a methane-air atmosphere." Several international standards BS/EN 50020[10], BS 5501, IEC 60079-11 outline specifications for intrinsically safe and associated apparatuses as well but MSHA does not recognize those international standards as equivalent. Devices that are I.S. but not permissible are not permitted in the return air courses of underground coal mines.

2.3 United States and International Mine Ventilation Monitoring Safety Standards

It is necessary to examine international mine ventilation monitoring safety standards and regulations in order to compare and contrast the existing ventilation monitoring technologies available for mines in the United States and other countries.

2.3.1 UNITED STATES CODE OF FEDERAL REGULATIONS

The United States Code of Federal Regulations provides guidance on the installation of AMS systems in underground coal mines in 30 CFR § 75.351. Primarily, AMS systems are installed for monitoring belt lines and electrical installations in the U.S. for smoke, CO, and CH_4, and to automatically alarm at set thresholds (30 CFR §75.340, §75.350, §75.351). Some mines may also utilize real-time monitoring of returns or tube bundle monitoring of sealed areas or gob as part of an approved ventilation plan, but regulation does not specifically require either. Current regulations under CFR 30 §75.362, On-shift examinations, prescribes an alert at 1.0%

methane and alarm at 1.5% methane. 30 CFR §75.323, Actions for excessive methane state that "except intrinsically safe atmospheric monitoring systems (AMS), electrically powered equipment in the affected area shall be de-energized; other mechanized equipment shall be shut off." CFR 30 §75.351 prescribes an alert at 5ppm carbon monoxide above the ambient level and alarm at 10ppm carbon monoxide above the ambient level for underground electrical installations and belt air course ventilation. A smoke optical density of 0.022 per meter may be used for smoke alarms. The full Code of Federal Regulations 30 §75.351 AMS section can be found in Appendix A. Figure 2.10 shows a generalized schematic of the required atmospheric monitoring in the United States. Each individual mine's monitoring scheme will vary based on the mine's design and site specific circumstances.
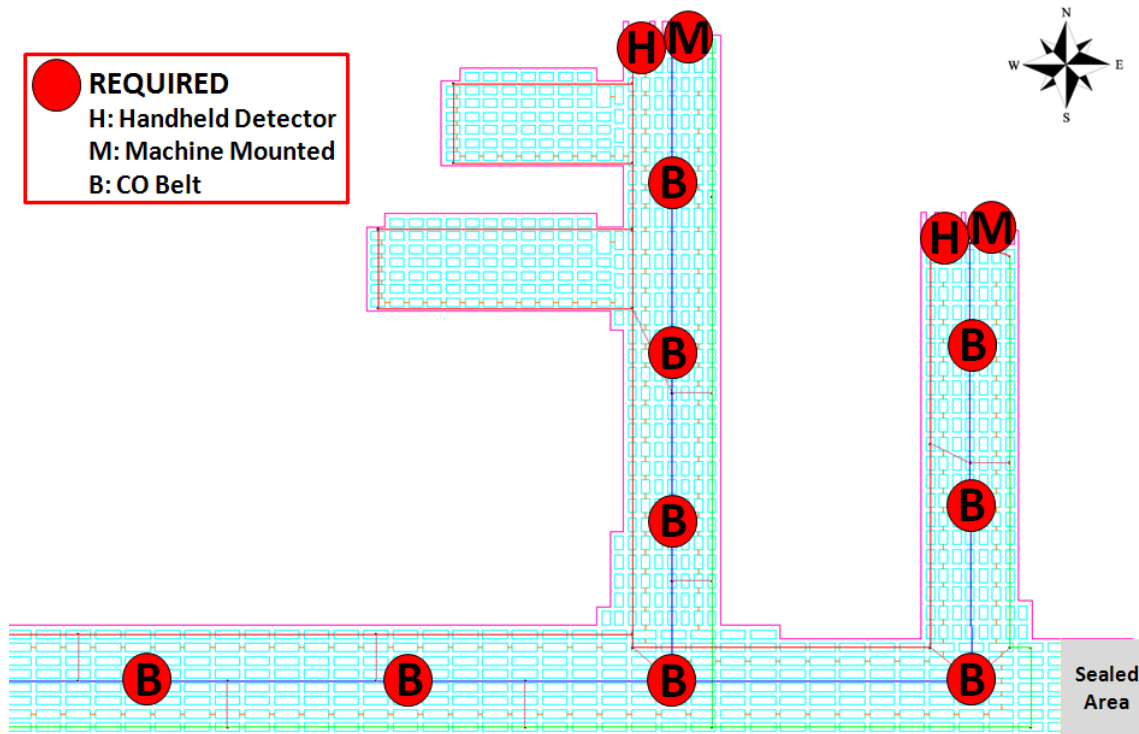
Figure 2.10: Generalized Schematic of Required Atmospheric Monitoring in the United States

The first minimum ventilation requirements were mandated in 1891. Since 1891, ventilation requirements in underground coal mines have steadily increased in response to major accidents. The Upper Big Branch (UBB) explosion on April 5, 2010 spawned several attempts to pass further regulations to increase health and safety in underground coal mines. There were numerous reports of investigation in response to the UBB explosion (State of West Virginia, West Virginia Governor's Panel, MSHA, MSHA report of the MSHA investigation, NIOSH

panel report on MSHA, United Mine Workers Association report, and the Massey Energy report). Robert C. Byrd (Democrat, West Virginia) and Jay Rockefeller (Democrat, West Virginia) proposed new disclosure regulations on May 6, 2010 to the United States Senate. Miller (Democrat, California) proposed the Robert C. Byrd Safety and Health Act of 2010, HR5663 (House of Representatives, 2010; Kittredge & Miller, 2010) which had 55 co-sponsors on July 1, 2010 to the United States House. Capito (Democrat, West Virginia) proposed a mine safety and health act (HR 5788) to the House on July 20, 2010. Dodd-Frank Wall Street Reform and Consumer Protection Act was signed by President Barack Obama on July 21, 2010 which requires the Securities and Exchange Commission (SEC) to report on mine safety. Rockefeller (Democrat, West Virginia) introduced the Robert C. Byrd Mine and Workplace Safety and Health Act of 2010 (S 3671) on July 29, 2010 to the United States Senate. Miller (Democrat, California) proposed the Robert C. Byrd Mine Safety Protection Acts of 2010 (HR 6495) on December 3, 2010 to the United States House. The Robert C. Byrd Mine Safety Protection Act of 2010 failed under a suspended vote (Yes-214, No-193) on December 8, 2010 in the United States House. Rockefeller (Democrat, West Virginia) introduced the Robert C. Byrd Mine and Workplace Safety and Health Act of 2011 (S 153) to the senate committee of the United States Senate. Miller (Democrat, California) introduced the Robert C. Byrd Mine Safety Protection Act of 2011 (HR 1579) on April 15, 2011 to the United States Senate. Capito (Democrat, West Virginia) introduced the Mine Safety Accountability and Improved Protection Act of 2011 (HR 3697) to the United States Senate on December 16, 2011. Since January 1, 2012 there have been additional draft legislation developments but all have failed to succeed.

2.3.2 AUSTRALIAN COAL MINING SAFETY AND HEALTH REGULATIONS

Queensland

Australian operators are charged with providing a safe work place and determining how to operate safely at each mine. The Government of Queensland regulations may be found in Appendix B. Australian mines are regulated by each state and regulations are not overly prescriptively written. For example, in Queensland the belt and intake air courses are kept separate but they are not always in New South Wales. Australian laws are vague and require the

mines to write a safe working procedure unique to its operation. The mine plan that each mine designs is then regulated by inspectors. Mines create Standard Operating Procedures (SOP) and Management Operating Procedures that formalize risk, communication, training, and leave it ultimately up to the operator to operate safely. Queensland regulations require a Ventilation Officer (VO) to be dedicated to each mining operation's ventilation. The VO is a statutory position that has lengthy requirements of the exact VO duties.

Queensland requires Explosion Risk Zones (ERZ) to designate areas where there is a high risk for an explosion. These ERZ zones cannot have methane concentrations above 0.5%. Different levels of Non-Explosion Risk Zones (NERZ) areas are designated where gas concentrations are still problematic. The NERZ 1 level is used for methane concentrations 0.5-2.0% which requires drilling and draining. NERZ 0 level is any area above 2% methane and access is not allowed. If there is above 2.5% methane, then the area/mine must be withdrawn from. NERZ barriers are setup to trip power outby when gas concentrations reach a predetermined level to reduce the risk for an explosion. It was said to be uncommon to have false trips, but the most common cause is an electrician not transferring the system into maintenance/bypass mode correctly.

New South Wales

New South Wales mines are not regulated by the same standards as Queensland. For example, Queensland requires belt and intake air to be separated but New South Wales does not. New South Wales requires its mines to have a continuous gas monitoring system, but does not specify which gases must be measured. The tube bundle system is continual and not continuous. Continuous monitoring has to be tied to a system. Continual monitoring can be fulfilled by handheld detectors and bag samples. Tube bundle systems are typically used to monitor goaves while real-time monitoring systems are used to monitor other parts of the mine. Bag samples are used for confirmation of real-time monitoring systems. Australian mine regulations are more vague than United States mine regulations and require Australian mines to write their own plan and that becomes the standards the mine is held to.

2.3.3 SELECT INTERNATIONAL ATMOSPHERIC MONITORING REGULATIONS

Mining regulations and standards across the world differ in many different ways depending on the specific country. Most countries provide prescriptive regulations and guidelines (e.g. United States) for mines to follow or the regulating body places the burden on the operator (e.g. Australia) to evaluate risks, create plans to reduce risks, and mitigate risks given problematic circumstances.

Germany, Poland, and Czech Republic

Germany, Poland, and the Czech Republic take similar approaches to utilizing atmospheric monitoring systems in order to actively monitor underground coal mines. Mines use stationary measurement and analysis units in their main ventilation entries (mains, declines, drifts, shafts, and return airways) and combine atmospheric measurements (barometric air pressure, humidity, and sometimes air quality) at surface stations. Mine foremen and engineers manually take direct ventilation measurements for methane and air velocity. Mobile underground testing laboratories were developed and proven to detect developing fires and increasing gas concentrations for both short-term and long-term use. Gorniczy Agregat Gasniczy (GAG), the Polish developed jet engine, is an example of a mobile laboratory that has been used in several case studies across the world that examined the inertisation of high priority underground fire locations (Gillies & Wu, 2006). Gorniczy Agregat Gasniczy loosely translates to Mine Fire Extinguisher.

China

In China, regulations have begun to take a more comprehensive approach to monitoring mine emissions. All underground coal mines are required to monitor gas at the working face. As of now, any mine classified as gassy or outburst prone is also required to monitor gas in the immediate return. Problematic mines must automatically de-energize power and provide an automatic alarm at a predetermined threshold (Burnley, 2007).

2.4 Current State of Communications

2.4.1 OVERVIEW

Hardwired communication systems have been used in underground coal mines for decades and consist of devices physically connected to both ends of the communication medium. There are many communication mediums for hardwired communication, but most commonly copper twisted pair, coaxial cable, Ethernet, and fiber optics are found in underground coal mines (Griffin, 2009). The MINER Act in 2006 spawned the rapid development of wireless technologies for use in underground coal mines. Hardwired and wireless communication systems provide data network infrastructures, which can be used to communicate and transmit data from underground locations to the surface. State-of-the-art communication and monitoring systems typically utilize both hardwired and wireless technologies to overcome each technology's disadvantages. Typical disadvantages associated with hardwired systems include a requirement to be physically connected to the communication and provide a source of failure if the cable is compromised. Typical disadvantages associated with wireless systems are propagation distance, some require line of sight, lower bandwidth than hardwired systems, and may experience electromagnetic interferences (Griffin, 2009).

2.4.2 CURRENT STATE OF WIRELESS COMMUNICATIONS

In 2006, the underground communication technologies available to the mining industry had inherent problems that limited communication capabilities. Underground communication technologies in are limited by line of sight, power and safety concerns, and the overall quality of the systems due to the harsh underground coal mine environment that significantly reduces the signal propagation range. Underground coal mines are exposed to a wide variety of interferences and harmful gases. NIOSH (2007) stated, "the propagation of radio waves is affected by limited open space for the wave to propagate, natural and man-made interferences, the electrical properties of the coal and surrounding strata, water and humidity, and many other factors."

Recent communications and tracking developments have involved leaky feeders, extremely/very-low frequency, medium frequency, Radio Frequency Identification (RFID), and wireless mesh technologies. Figure 2.11 shows an illustration of the communications radio

spectrum (Griffin, 2009). The approximate operating frequency of Extremely Low Frequency/Low Frequency (ELF/LF), Medium Frequency (MF), Very High Frequency/Ultra High Frequency (VHF/UHF), and Wireless Mesh Networks (WMN) can be seen in Figure 2.11.
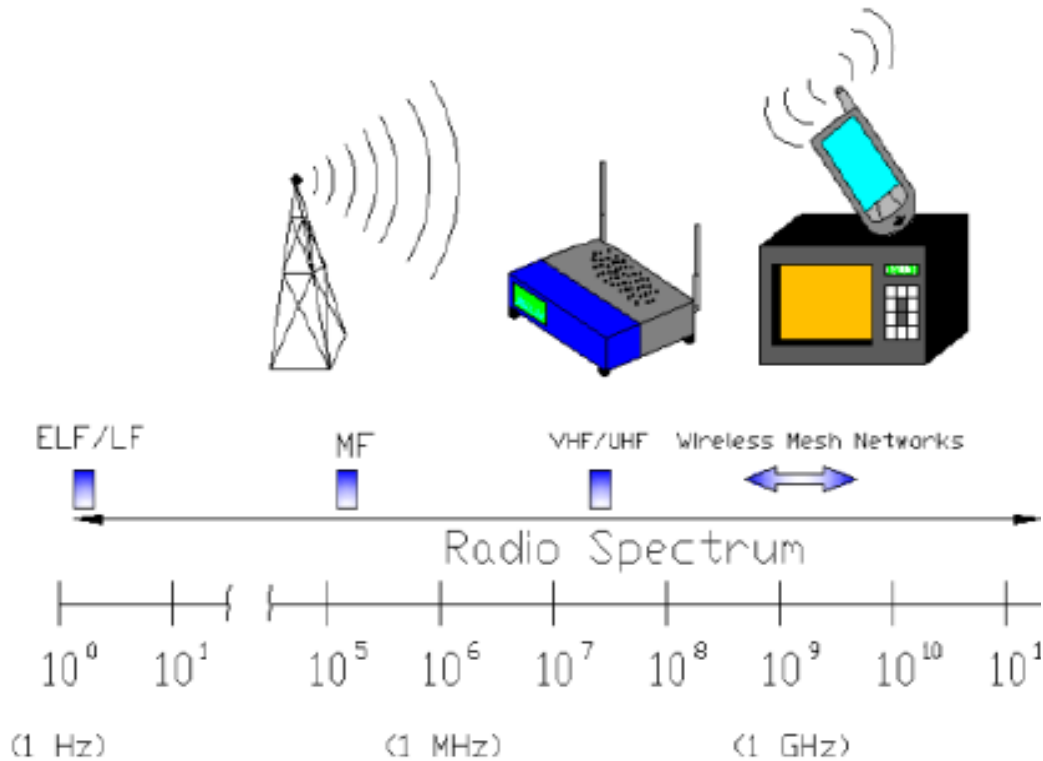
Figure 2.11: Communications Radio Spectrum (Griffin, 2009)

Leaky feeder systems typically consist of a coaxial type cable that runs down the primary and secondary escape ways. The leaky feeder gets its name because the signal tends to "leak" out of the cable, thus giving a wireless range to communicate away from the cable. The number of leaky feeder systems in underground mines has rapidly increased since the 1960's. According to Updyke, Muhler & Turnage (1980), "leaky feeder systems were quickly adopted as means of primitive communication because of their low cost and ease of installation." Recent developments in leaky feeder allowed these systems to operate at a higher frequency, increasing communication range and capabilities.

Extremely/very-low frequency systems are known as "through-the-earth" communications, communication takes place through the earth at an extremely low or very low frequency. Through-the-earth (TTE) communications are limited in application by known and unknown interferences, can only transmit text-based messages, and require large loop antennas

(Pittman, Church & McLendon, 1985). TTE applications exist for surface to underground communication, but additional research is needed for underground to surface communication.

Medium frequency technologies must utilize waveguides such as pre-existing wires or pipes in order to propagate the signal. Medium frequency technologies are limited by the continuous waveguide, which typically must be physically tapped into in order to extract the electromagnetic signal (Stolarczyk, 1983). If waveguides are intact and utilized correctly, then medium frequencies can propagate along waveguides for long distances.

Wireless mesh systems have become popular because of their redundant, self-healing network abilities. The self-healing capabilities of a wireless mesh system will reroute the signal if one pathway becomes blocked or communication is lost between communicating fixed nodes. Wireless mesh systems are typically comprised of fixed mesh nodes, or broadcast devices, and handsets. The fixed mesh nodes form a "mesh," facilitating communication between multiple fixed mesh nodes at any point in time.

Radio Frequency Identification (RFID) systems consist of readers and tags. Whether the tags are placed in the hardhats of miners or in a mine structure (such as a pillar), the reader reads the tags as they come into range and relays the information to an overview system where it is recorded. RFID does not provide a means of voice or text communication but is useful for tracking.

Operating frequency dictates the wave's propagation range and directly dictates the available bandwidth and power requirements. Typically the higher the operating frequency, the higher the bandwidth rating, but the result is greater power requirements. Mesh network communication systems require greater power requirements than medium frequency systems. Voice communication requires a higher bandwidth rating than what is required for text communication. Thus, there is a significant difference in power requirements for voice communication and text communication. Figure 2.12 shows the relationships between frequency, power requirements, and the type of communication possible based upon the frequency.
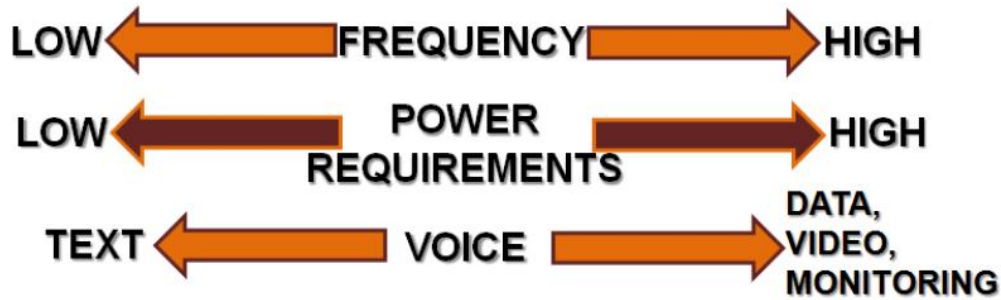
Figure 2.12: Frequency Trades

Ultimately, there are tradeoffs with using different operating frequencies because power requirements and the bandwidth provided by different frequencies are proportional to the operating frequency. No single system for communication is optimal in every set of circumstances; optimal communication solutions may be mine-specific.

2.4.3 FIBER OPTICS

The recent integration of wireless communication systems in underground coal mines significantly increased the utilization of fiber optics underground. Fiber optics provide an intelligent communications solution that has high bandwidth speeds, relatively low cost, operates in severe environmental conditions, electrical and extreme temperature and pressure immunity, low weight, small size, and can be ruggedized for underground applications (Taylor & Reid, 2008). Taylor and Reid (2008) noted the following Figure 2.13 when comparing coaxial cable to fiber optics. Figure 2.13 was used under fair use, 2013, from Taylor, C., & Reid, W. (2008), *Improved Mining Safety, Communications and Productivity Through the Use of Fiber Optics*.

Cable Comparisons Coax vs. Fiber			
Fiber advantages over Copper			
	Coaxial Cable	Fiber Optic Cable (MM)	Fiber Optic Cable (SM)
Representative Distance Bandwidth Products	100 MHz km	500 MHz km	100,000+ MHz km
Attenuation/km @ 1 GHz	>45 dB *	1 dB	0.2 dB
Cable cost ($/m)	$$$	$	$
Cable diameter (in.)	1	1/8	1/8
Data Security	Low	Excellent	Excellent
EMI Immunity	OK	Excellent	Excellent

* Andrew HFC 860 Series

Figure 2.13: Coaxial Versus Fiber Cable Comparison (Taylor & Reid, 2008)

Fiber optics' high bandwidth speeds allow safety, environmental, equipment, and other production sensors to be deployed throughout the mine to provide real-time measurements. Sensors placed throughout the mine allow operators to monitor for changing conditions even when personnel are not in that area of the mine. Newly developed fiber communication networks allow emergency communication systems, gas monitoring, video cameras, environmental monitoring, longwall systems, conveyor belt systems, automation of remote systems, fire detection systems, laser analysis, and many other data intensive processes to be controlled underground or on the surface.

U.S. Bureau of Mines Fiber Optics Explosibility Testing

In 1995, the U.S. Bureau of Mines (USBM) completed a field test of a prototype monitoring system that used light to power and communicate with several toxic gas sensors (Dubaniewicz & Chilton, 1995). The USBM noted that fiber optics provided a reliable long-distance telemetry that did not experience electromagnetic inference (EMI) that wire-based telemetry systems encounter due to fiber optics utilizing a light source to transmit data.

Extensive research established the explosibility of methane-air and coal dust clouds in the United States, Australia, United Kingdom, and Germany. This is important when integrating new devices and sensors into the mine to ensure that they do not cause an explosion. Sensors commonly use lasers with fiber optics to optically analyze atmospheric samples to determine gas concentrations and the explosibility of the underground environment. The figures 2.14 and 2.15 are ignition charts that show the relationship of laser power versus beam diameter (NIOSH, 2009).
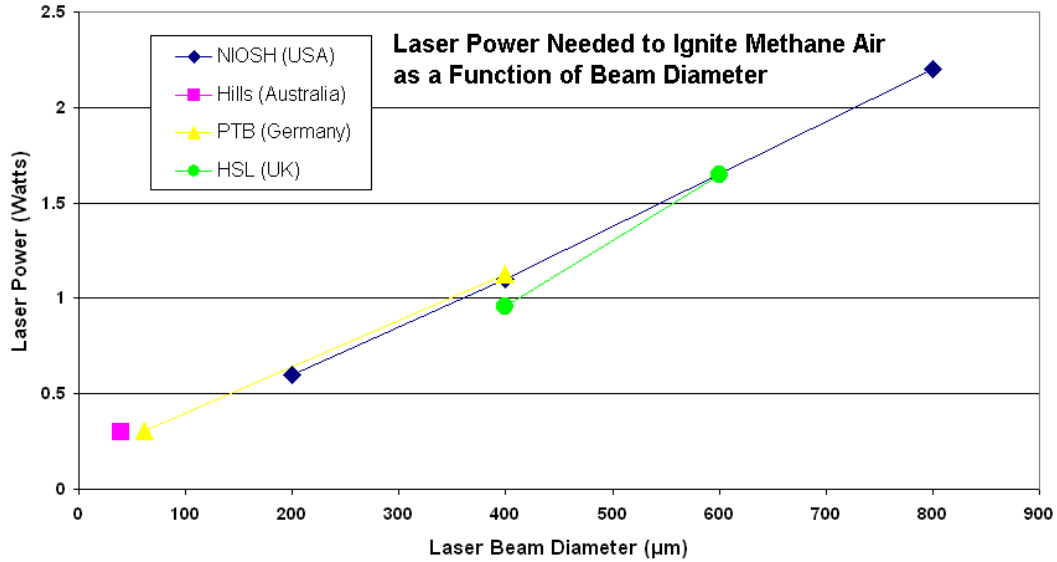
Figure 2.14: Methane-Air Laser Ignition Chart (NIOSH, 2009)
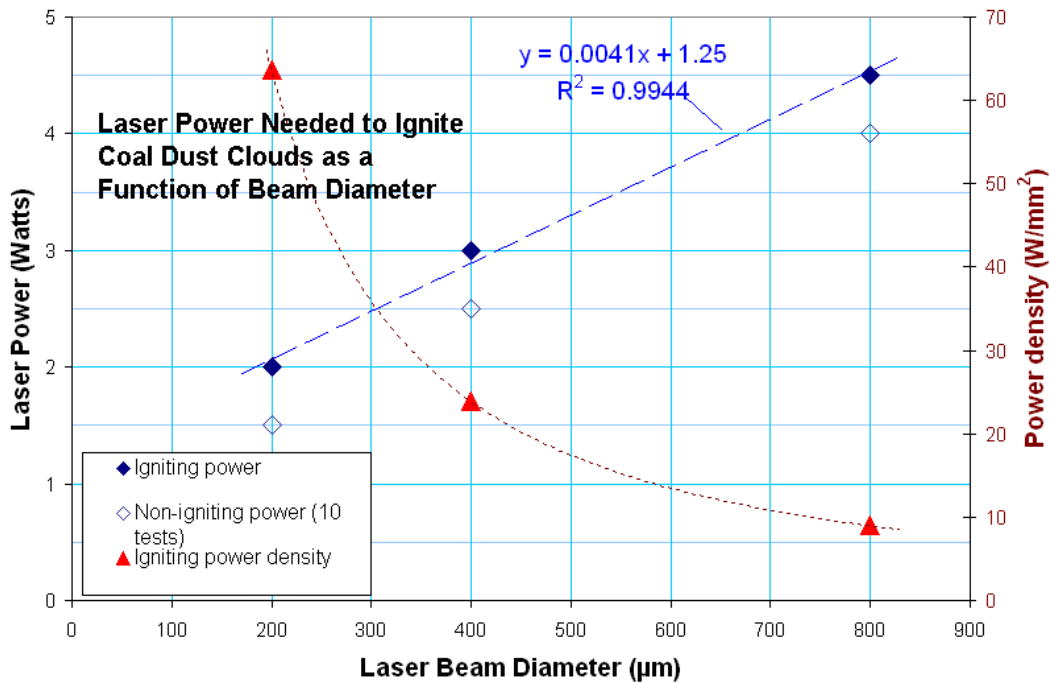
Figure 2.15: Coal Dust Clouds Laser Ignition Chart (NIOSH, 2009)

According to Taylor and Reid (2008), "These experiments confirmed that more power is needed to ignite coal dust clouds than is needed to ignite methane-air. Researchers also observed that the amount of laser power needed to create explosions was proportional to the laser beam diameter for the coal dust clouds, as well as for methane-air."

Shandong Academy of Science Fiber Optics Testing

The Shandong Academy, utilizes a fiber optics system to monitor strain/displacement of roof conditions, water pressure, gas concentrations, seismic, and ultrasonic (Liu et al., 2009). The Shandong Academy claims the fiber optics system will monitor every part of the mine and has been tested in underground coal mines in China. The primary advantage of fiber optics is that the technology is I.S. and can be deployed in explosive environments while monitoring for multiple parameters.

2.4.4 MSHA APPROVAL PROCESS

The evaluation of communication systems is found under the existing guidelines for Telephones and Signaling Devices, found under Title 30 Code of Federal Regulations Part 23. These regulations are intended for audible and visual communication devices. Communication system devices must be I.S. or in an enclosure that is MSHA certified to be explosion-proof (XP) and flame-resistant, or is in a hose conduit (interconnecting cables) that is flame-resistant and MSHA-approved. System devices are required to either be permissible, IS or XP in case there is a loss of ventilation in the mine. All devices (including tracking tags, which are considered portable apparatuses) are subjected to regulatory drop tests.

2.4.5 WIRELESS COMMUNICATION SYSTEMS INCORPORATING SENSING TECHNOLOGY

The integration of wireless communication systems in underground coal mines has enabled mining companies the flexibility to utilize these communication systems for other applications such as remote monitoring. Sensors can be integrated into a communication and tracking system in order to monitor and measure mine gases, psychometric properties, dust content, air velocity, and seismic events.

Monitoring capabilities of different communications systems are limited based upon the communication system's operating frequency, power requirements, and available bandwidth. Systems currently in mines may have the capabilities to add sensors to measure nearly all parameters necessary to monitor the mine's ventilation system in real-time. Although the number of companies utilizing their communication systems to monitor gases is generally low, there are

currently several active mines monitoring gas concentrations, pressures, velocities, and other various ventilation properties. Communication systems capable of real-time ventilation monitoring tend to be leaky feeder, wireless mesh networks, hard-wired, and fiber optic based systems.

2.5 Integrating Predictive and Artificial Intelligence Algorithms

The progression of technology has allowed mine monitoring techniques to become more sophisticated, by implementing faster, more advanced mechanized equipment. However, advanced technology has made it more difficult to control methane emissions during mining. Faster equipment has increased face advance rates, increased panel size, and allowed for more extensive gate road developments (Schatzel et al., 2010). Reasons to monitor mine atmospheres include, but are not limited to a rise in safety standards, higher production demands, equipment speed increases, variability in mining conditions, and weather fluctuations affecting the mine atmosphere. Ventilation requirements are constantly changing because mining is continuously advancing which will cause variations in the amount of methane and other gases into the active mine workings (Karacan, 2008a). The growing complexity of maintaining a mine's atmospheric conditions requires mine ventilation to be examined using highly sophisticated computer methods, such as Artificial Neural Network (ANN), expert based rule systems, fuzzy logic, and other computer control methods that are used in ventilation engineering and mineral processing.

Neural networks have limitless applications including computing, medicine, engineering, sales forecasting, industrial process control, data validation, risk management, and target marketing (Palade, Neagu, & Patton, 2001; Dagli & Lee, 1997). ANN recent developments related to mining include real-time control of mineral processing plants (Hodouin, Thibault & Flament, 1991), longwall stability prediction (Park, Deb, Jiang & Sanford, 1995), tunnel design (Lee & Sterling 1992), ore-reserve estimation (Wu & Zhou 1993), and geologic roof classification (Cardon & Hoogstraten 1995).

ANN recent developments in underground coal mining ventilation consist of the application of neural networks to underground methane prediction (Dixon, Özveren, Sapulek, & Tuck, 1995), neural network approach to automatic control of mining ventilation (Puchkov, Temkin & Mesentsev, 1996), mine fire source discrimination using fire sensors and neural network analysis (Edwards, Friel, Franks, Lazzara & Opferman, 2000), real-time neural network application to mine fire – nuisance emissions discrimination (Edwards, Franks, Friel, Lazzara & Opferman, 2005), neural network application to mine-fire diesel-exhaust discrimination (Friel & Edwards, 2008), advances in grid-based numerical modeling techniques for improving gas management in coal mines (Karacan, Ren & Balusu, 2008), development and application of reservoir models and artificial neural networks for optimizing ventilation air requirements in development mining of coal seams (Karacan, 2008a), modeling and prediction of methane emissions from longwalls (Karacan, 2008b), artificial neural networks to determine ventilation emissions and optimum degasification strategies for longwall mines (Karacan & Goodman, 2008), and forecasting gob gas venthole methane production from longwalls (Karacan, 2009).

Real-time atmospheric monitoring enables ANNs to analyze and predict future gas concentrations and trends. Predicting future gas concentrations allows future problematic high gas levels to be sufficiently planned for to prevent potential explosions. Statistical modeling, grid based numerical modeling, computational fluid dynamics (CFD), ANNs, and atmospheric monitoring can be used jointly to understand a specific mine's ventilation. Understanding a mine's ventilation completely will allow an operator to ventilate the mine safe, efficient, and reduce ventilation expenses.

ANN, Expert Based, Fuzzy logic, and other control systems can evaluate monitoring system's data in order to predict when conditions are favorable for an explosion. This is powerful because it allows monitoring to be evaluated in real-time for explosion prevention. Mine atmospheric conditions are constantly changing which enables operators to utilize predictive and artificial intelligence algorithms to establish mine baselines, determine parameter trending tolerances and determining when parameter combinations are becoming problematic.

CHAPTER 3: ATMOSPHERIC MONITORING OVERVIEW IN UNDERGROUND MINES

Mining researchers have been trying to accurately measure and quantify ventilation and gas properties since the advent of mining. Early attempts were limited by the technologies available and the progression of technology has allowed mine monitoring techniques to become more sophisticated. Underground base metal mines utilize gas, environmental, ventilation, production, and other types of monitoring. Base metal mines do not typically experience problems with production emissions of methane like underground coal mines do. Ventilation-On-Demand (VOD), booster fans, and auxiliary fans are used in underground metal mines to enhance efficiency and decrease operating costs. Methane emissions in underground coal mines present the risk of an explosion at any given time; equipment must be approved by MSHA, which does not allow many of the sophisticated metal-mine techniques to be used. NIOSH has completed various studies that quantify the emissions of methane in underground mines and can be confirmed by real-time atmospheric monitoring. This section highlights recent successful and unsuccessful strategies and attempts at mine-wide ventilation monitoring.

3.1 United States Underground Salt Mine

3.1.1 BACKGROUND

The mine uses an undercut, drill, and blast method. They drill horizontally above the undercut, shoot approximately 25 feet, and then bench the floor by vertical drill and blast to approximately 55 feet. Salt is mucked, hauled by LHD to a belt dump, and conveyed to skips. They produce about 1,000,000 tons/year by skip with capacity of 17 tons, on 3 shifts. The fan exhausts 400,000 cfm. There are two active ventilation shafts, #3 and #4, #1 and #2 are inactive. The inactive shafts were purchased by the federal government for the strategic petroleum reserve, and were currently flooded. The mine is located on an inter-coastal waterway, but does not typically experience problems, such as flooding underground from hurricanes; most problems are associated with damage to surface facilities. The product is chemical and

agricultural grade, and the only processing required is screening and sizing. The tunnels creep approximately 1 inch per year.

3.1.2 METHANE OUTBURSTS AND MONITORING

The operation does not experience emissions from the salt in comparison to most coal mines experience continuous emission from the seam, and rarely see any outburst in inactive areas. Typically, outbursts occur only in the active face immediately after blasting. Figure 3.1 displays a cavity formed by previous outburst. This feature was approximately 40 feet above and difficult to see, but width was estimated at 10 to 15 feet.

Figure 3.1: Location of Previous Outburst

The amount of time needed to dilute the methane varies, with the longest incident requiring approximately a week. Like many large opening mines, this operation moves a large quantity air at low pressure, which can result in long dilution times. There are no estimates on volume of methane released during an outburst. All face equipment, vertical drills, horizontal drills, and undercutters are equipped with methane sensors that flash a warning at 0.5% and shut down the equipment at 1.0%, in the same way that coal mining equipment does. Figure 3.2 displays an undercutter (right, top view) with the methane sensor (left, side view) mounted on it.

Figure 3.2: Joy Undercutter (Right, Top View) with Methane Sensor (Left, Side View)

Nearby underground salt operations are believed to also monitor for methane outbursts. Other operations have been known to move the active mining area if methane is encountered instead of continuously monitoring. The methane monitoring system at the operation is manufactured by Pyott-Boone with Rel-tek sensors. Pyott-Boone Electronics (2010) provides more information about Pyott-Boone methane monitoring systems. Currently, a warning light and siren activate when concentrations of 0.25% are reached, and the mine is deenergized at 0.50%. Evacuation lights are mounted on mine phones and it usually takes about 30 to 45 minutes to evacuate all miners.

Methane sensors are strategically placed near active mining areas and inby of any non-permissible equipment, such as power centers. A sensor mounted near the roof outby active mining is shown in Figure 3.3. There are 14 sensors currently active, and the mine is operating on several different depth levels. The current monitoring system was projected to be replaced in less than a year and will include outstations underground to reduce better sampling times, and also tie into the existing fiber optics system. Electrical barriers at the outstation caused the sampling rate to decrease approximately 4,000 to 5,000 feet from the outstation. The current sampling rate is 80 samples/second, and the new system will sample at about 300 samples/second.

Figure 3.3: Methane Sensor Mounted Near Roof Outby Active Mining

There are no major complaints from contacts at the operation, but indicated high air pressure changes from blasting could affect the sensor's accuracy Management considered trying to implement automatic calibration; the wheatstone bridge would be remotely heated to different levels and the readings adjusted remotely. Of course, some manual calibration would still be required. The miner that primarily maintained the system stated regular calibration and troubleshooting are straight forward.

The system has several different operating modes. For example, in routine mode, the system will wait 1 minute before deenergizing the mine after 0.5% is sensed, but when in blasting mode the mine is deenergized immediately when 0.5% is sensed. The company wants to modify the system so that they can deenergize only certain sections of the mine affected by methane inundation, rather than deenergizing the entire mine.

The software to view output from the system was written by a local company, and everyone indicated it is user friendly, and displays a running average and real-time reading at each sensor. The output from the system is dedicated in a room near the lamphouse. Output screens are shown in Figure 3.4. Most miners, with the exception of new hires, are fairly familiar with it and can be seen checking output screens regularly prior to starting the shift; this office is the only place where the data are viewed, but they could easily be monitored elsewhere.
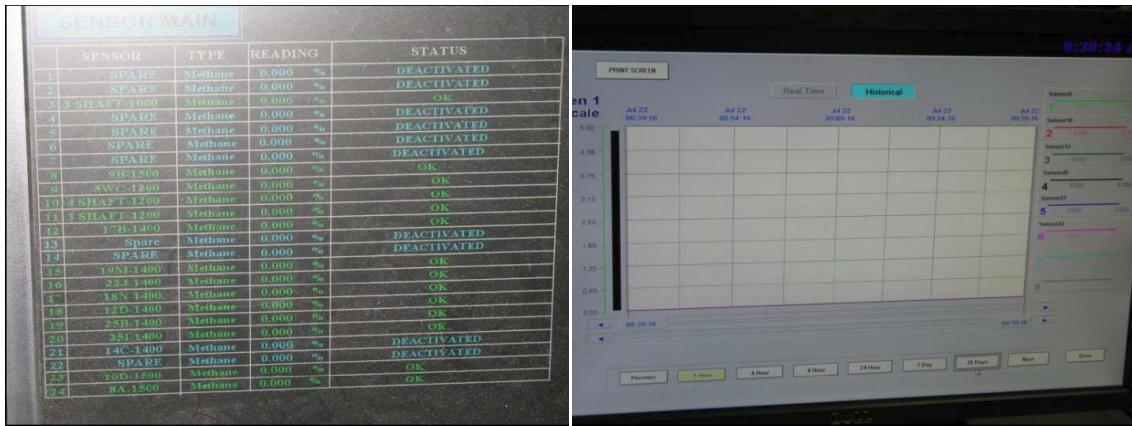
Figure 3.4: Methane Monitoring Sensor Status Screens

3.2 United States Underground Coal Mine Tube Bundle Systems

Tube bundle systems are installed in several United States underground coal mines. Tube bundle systems are a popular form of gas monitoring, commonly used in Australia. This section details the two tube bundle systems in the United States that were visited.

3.2.1 TUBE BUNDLE SYSTEM I UTILIZATION

An underground coal mine in the United States is using a tube bundle gas monitoring system to monitor for CH_4, CO, CO_2, and hydrogen sulfide at strategic points. This mine is one of the only bleederless underground coal mines in the country. The advantage of the bleederless system is that O_2 is not introduced into the gob, which is prone to spontaneous combustion. Nitrogen is injected into the areas when certain gas concentrations are reached to neutralize the influx of gases. The system utilizes a gas chromatograph on the surface to analyze the air samples. The company's extensive background in international mining operations allowed them to successfully implement the tube bundle system technology in the United States. Further discussion of this tube bundle system can be found in Bessinger, Abrahamse, Bahe, McCluskey & Palm, 2005.

3.2.2 TUBE BUNDLE SYSTEM II BACKGROUND

The mine employs a continuous miner unit and one longwall unit. In December, 2009 at the beginning of the first panel, caving did not commence immediately. The initial cave resulted in a windblast that fatally injured one miner. The resulting investigation idled the panel and rising CO concentrations were observed. This mine is prone to spontaneous combustion and the operator requested technical assistance from NIOSH. The mine experiences little to no CH_4 emissions. The mine agreed to install a tube bundle system in the spring of 2010, and converted to a bleederless ventilation scheme after installation.

3.2.3 TUBE BUNDLE SYSTEM II UTILIZATION

The tube bundle system was obtained from the Safety and in Mines Testing and Research Station (Simtars) in Brisbane, Queensland, Australia (Department of Mines and Energy, 2010). The tube bundle system utilizes the SIMTARS/SafeGas software; the control system is housed in a trailer on the surface. The tube bundle trailer was pre-constructed and shipped to the mine. The trailer houses s Sick Maihak infrared (IR) gas analyzer, air sampling pumps, gas tanks for calibration, a system of valves for moving various samples to the analyzer and drawing bag samples, a PC, an uninterruptable power supply (UPS), and work space.

Plastic tubing runs from the trailer on the surface, down a borehole next to the trailer, and into the mine. The tubes are individually connected to five gallon air tanks that are used as water traps. From the five gallon water traps, the tubes are then run to each sampling location in the mine. The sampling tubes have automobile air filters placed on the ends of the tubes to ensure that dust or other particulate matter from the underground mine atmosphere does not enter the tubes. Figure 3.5 shows a basic diagram of the tube bundle system. Figures 3.6 and 3.7 show the exterior and interior of the trailer.
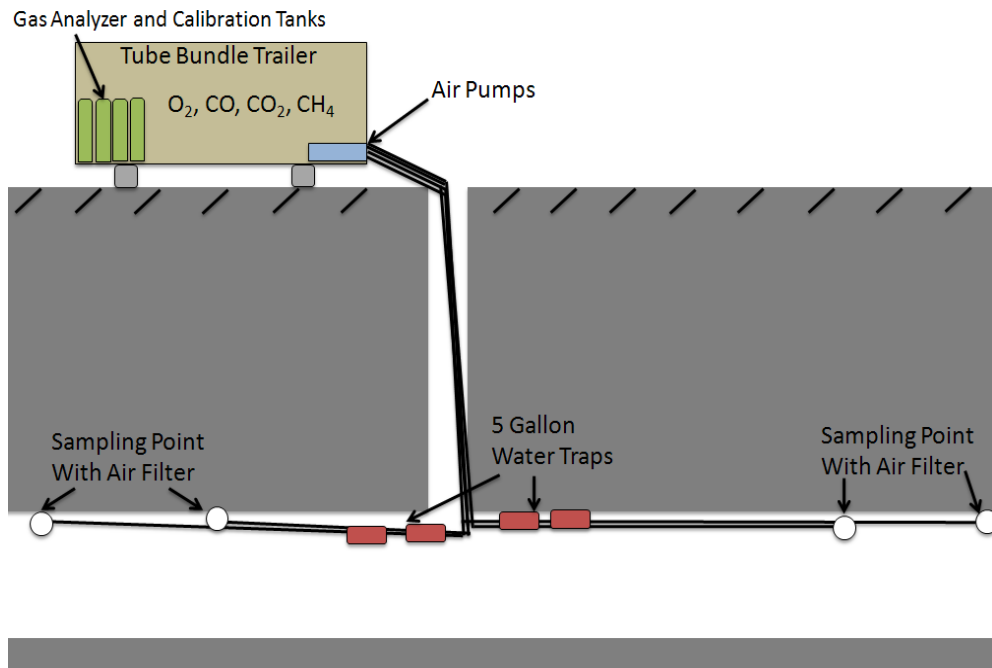
Figure 3.5: Basic Tube Bundle Diagram

Figure 3.6: Tubes Entering Back of Trailer (Left), Back of Trailer (Right)

Figure 3.7: Analysis Unit Mounted on the Back Interior of the Trailer (Left) and Full View of Interior of Trailer (Right)

The mine monitored 10 points on the first longwall panel, with 4 inactive points in the summer of 2010. The borehole distance to the furthest location is about 17,500 feet, and the lag on sample collection and analysis is about 20 minutes, and may eventually approach 65 minutes. Zipf, Marchewka, Mohamed, Addis & Karnack (2013) stated, "for a system with 30 sample points, about 45 minutes are required to cycle through all sample points."

The mine was fairly wet, primarily from ground water, over knee deep in many active places, but little water was found in the water traps, presumably because of the relatively dry air. The system maintenance and calibration display contains a flow diagram with corresponding pressures at the air compressors on the surface and the gas concentrations for each sampling point underground. Alarm and alert thresholds are operator controlled, and set to notify the dispatcher at low O_2 or high CO. The main monitoring station is in the dispatcher's office. Users can view a mine map with current levels at each location or look at historical concentrations for individual stations. Batch data can also be downloaded.

Mine personnel were pleased with the system and indicated that there is system maintenance, but it provides an extensive amount of information. The operation collected two bag samples per day and analyzed them for fire gases off site by GC. The infrared analyzer measures CO, CH_4, O_2, and CO_2.

The long tubing is susceptible to damage resulting in sample contamination. A hole, caused by a falling rock, equipment, or personnel, allows an influx of air into the tube, thus

diluting gas concentrations. In order to determine if there is a hole in the tubing, one end of the tube must be capped and the other end pressurized. The tubing is also susceptible to ice forming inside the tubing, particularly the tubing inside of boreholes. The mine also has a Conspec belt monitoring system installed, like many other underground coal mines in the United States. Conspec Controls Inc. (2010) provides additional information regarding Conspec's fixed gas detection systems.

The installation of the tube bundle system was quoted by Zipf et al. (2013) to require a four person crew several days to run the tubing but later manpower requirements for maintenance were quoted as little as two man-days per month. Zipf et al. (2013) noted that the tube bundle initially cost $350,000 which included the gas analyzer, purge pumps, sample pump, solenoid valves, power supplies, PLC, server and client computers, licenses for Safegas and Seagas and a 9.8 meter long (32 feet) office storage trailer to house the components. Zipf et al. (2013) also noted that an installation of eight sample lines may cost US$10,000 plus another US$5,000 for connector fittings, for a total cost of US$400,000 at the time of installation.

3.3 Australian State-of-the-Art Monitoring

Australian mines are not federally regulated, but are regulated by the state that the mine is in. Each state has written regulations that must be interpreted by the mines. Australian mines are then required to assess risk at the operation and develop a plan to mitigate that risk. This plan will then be considered law. Australians require that best practice should be used to monitor and to ensure operations are producing safely. After the Mora No. 4 explosions in 1994, caused by spontaneous combustion in a gob area that ignited a methane explosion, Queensland, Australia mandated the installation of atmospheric monitoring systems in every underground coal mine.

Tube bundle systems allow a mine operator to monitor a mine atmosphere by remotely pulling air samples and analyzing them at the surface. Tube bundle systems utilize a series of tubes that are run from the surface, where a pump is constantly pumping air into the outside surface atmosphere, causing the tubing in the mine to have a negative pressure, thus constantly drawing air samples. The Queensland Parliamentary Counsel Coal Mining Safety and Health Regulations are discussed in Section 2.3.2.1.

3.3.1 QUEENSLAND, AUSTRALIA UNDERGROUND COAL MINE

Background

The mine employs one longwall unit and two continuous miner units. The coal extracted is a high grade metallurgical coal. The seam is approximately 6 m (19.7 ft) thick, 0.5 m (1.6 ft) are left in the floor, with about 2 m (6.6 ft) left in the roof. The mine has high in situ gas content, and is prone to spontaneous combustion and outburst. Degasification is accomplished prior to mining via in-mine horizontal holes and surface vertical to horizontal single and double lateral wells. Methane captured in the mine is moved immediately to a riser hole where it is flared or emitted. Because of spontaneous combustion risk, the gob is inertized with nitrogen using an Air Liquide system, acquired in December. Prior to this system, a Thomlinson boiler was utilized, and generated inert combustion gases, but the unit had extensive maintenance problems. The boiler will still be used in conjunction with nitrogen for district inertization and panel sealing. As the longwall advances, the gob is sealed and tube bundle monitoring is utilized through the seals.

Monitoring Systems

Extensive monitoring systems are utilized at the mine, and five levels of monitoring were identified:

1. Personal Gas Detection (handheld methane/CO detection)
2. Fixed methane and CO detection (machine mounted and fixed outby points)
3. Tube bundle system (sealed areas and select return nodes)
4. Continuous fixed real-time monitoring (CO, CO_2, CH_4, O_2) and velocity in select areas
5. Bag sampling with onsite gas chromatography (GC) analysis for fire gases

Personal Gas Detection

Personal units are carried by equipment operators, people working in supervisory roles, traveling alone, or inspecting areas, and using units similar to the personal detectors carried in the United States. A limited number of units will read over 5% methane. Use of these units is limited to emergency situations or special zones, such as gobs where high concentrations of methane can reasonably be expected.

Fixed CH$_4$/CO Detection

Fixed CH$_4$ and CO detection is fairly standard and utilized along belt lines, similar to US practice. The belt power is deenergized at a given threshold of CO. The primary difference in Queensland versus the United States is that Explosion Risk Zones (ERZ) are defined. The ERZ is specified as follows and is listed in ascending probability of the presence of an explosive mixture:

- NERZ: No Explosion Risk (outby areas)
- ERZ1: Explosion Risk 1 (active mining areas)
- ERZ0: Explosion Risk 2 (gob)

If one of the fixed detectors rises above a certain concentration all power in that zone and inby zones is deenergized. In the United States, the belt can be automatically deenergized if CO rises above a certain concentration threshold and miners inby are notified of an alarm, but power to areas inby is not generally deenergized automatically.

Tube Bundle Monitoring

The mine has been conducting tube bundle monitoring since the 1990's and was using the Sick Maihak infrared gas analyzer system with Simtars SafeGas software (same general system as found in the United States underground coal mine II, Section 2.3.5). The mine has 37 active monitoring points and three points idle. The majority of monitoring points are at the longwall gate-road seals, although select return points, where continuous monitoring is not required, are also monitored. Sampling times take from 10 minutes to over an hour. The time to sample a specific point is dependent on two variables: first, the distance from the sample point to the sampling trailer, and second, the wait for the infrared (IR) analyzer. The IR analyzer produces sample results in approximately 3 minutes. If there are 40 points, it will take at least 2 hours to sample through all of the points. It is likely that there will be points that represent a higher risk area that the ventilation officer will want to those tubes sampled more frequently. The system can be programmed to analyze specific sample tubes as often as necessary, such as, every 30 minutes, which will further extend the wait for other samples. This system is more of a method for analyzing trends, but not a replacement for a real-time system.

Data is collected by the SafeGas software, but the mine also uses independent software for all data output in the control room. Data is extracted from the SafeGas software and viewed in the independent software. This allows for integration of the tube bundle and real-time monitoring systems.

A series of Trigger Action Response Plans (TARP) are developed for the most possible atmospheric scenarios; these indicate the plan of action for specified gas levels. The control room operator will contact a responsible person if these gas levels approach action levels as described in the TARP. This representative is expected to follow the appropriate TARP plan, which can escalate to evacuation of the mine. If a mine emergency, such as a fire, occurs, the government has a mine rescue trailer that will hook directly into the mine's tube bundle system.

Maintenance includes moving the sampling points, and testing the lines for integrity on a monthly basis. Line testing is generally performed with compressed air, by hooking an airline to the underground end, and checking to see if pressure is maintained at the surface end. Often lines will have several leaks and water is used to identify the leaks. This process can be fairly time consuming. The air tubing for the tube bundle system, at the time of the mine visit, costs approximately AU$1.25/m (US$0.37/ft).

Real-Time Monitoring

Real-time monitoring of CO_2, CO, O_2, and CH_4 is accomplished at major return nodes and is required under Queensland regulation. Additionally, the mine has attempted to monitor velocity at these nodes. The mine has used a vortex shedding air velocity sensor, similar to those available in the US, but has had little success; management found it is sensitive to dust and moisture. The air velocity sensor was being used as an indicator for velocity change, because velocity values were not reliable. The air velocity sensor no longer gave a reliable change either.

The gas sensing technology is similar to what is available in the United States. Communication with the monitoring system is accomplished using a Dupline system which is relatively older, but very robust. The Dupline system is be used to move analog and digital data, and the mine has incorporated PLC for power switching.

Maintenance of the sensors includes monthly calibration, occasional malfunction and associated troubleshooting, re-hanging sensors when they are knocked down. Additionally, real-time sensors must be sent for external laboratory calibration every six months.

Bag Sampling

Bag sampling of high risk seals is conducted daily and the samples are tested for fire gases, including CO. These CO levels are used to verify the analysis from the tube bundle system. No other system monitors for a full complement of fire gases. The mine maintains a rapid GC with thermal ionization detector (TID) for bag sampling analysis, and control room operators, ventilation officers, and other designated employees are trained on GC.

Monitoring Systems

Real-time and fixed monitoring can control much of the mine power and automatically deenergize areas that are deemed dangerous. The tube bundle system does not control power. However, all of the systems output data to a control room and activate yellow or red alarms to the screen, depending upon severity. The control room operator is required to acknowledge the system that he has seen the alarm and the system logs his acknowledgement.

It is important to note that there are many layers of detection at the mine which makes this system redundant. At some locations there may be two fixed methane detectors for real-time monitoring. Tube bundle monitoring is constantly verified with bag sampling. The mine models their ventilation system every month and verifies the model underground with a ventilation survey. The tube bundle system, although used in active areas, is primarily for monitoring sealed areas. There is also a very specific set of triggered responses outlined for almost every atmospheric scenario.

Finally, the role of the ventilation officer in this system cannot be understated. A ventilation officer is a position in underground coal mines in Australia that is mandated by regulation and they are heavily involved in utilizing, planning, and maintaining these systems.

3.3.2 NEW SOUTH WALES, AUSTRALIA UNDERGROUND COAL MINE

Background

      The mine produces about 5.5 million tons of thermal coal annually and is overlain and underlain by other operations. The mine is not outburst prone and there is no pre-drainage of methane. However, the operation is prone to spontaneous combustion. In situ gas content is 8 m^3/ton (283 ft^3/ton), including methane and carbon dioxide. Approximately 30% of adsorbed gas is carbon dioxide. This mine was acquired in 2006 and several major ventilation related upgrades were required, including design and installation of new mine fans to satisfy air requirements. Previously, the mine contracted the role of ventilation officer, and now has an in-house ventilation officer, which is viewed as a major improvement.

Monitoring Systems

     The five tiers of monitoring found at the underground coal mine in Queensland can also be identified at this mine in New South Wales, but the monitoring systems were still in the process of being upgraded. The five tiers of monitoring include:

1. Personal Gas Detection (handheld methane/CO detection) - EXISTING
2. Fixed methane and CO detection (machine mounted and fixed outby points) - EXISTING
3. Tube bundle system (sealed areas and select return nodes) - EXISTING
4. Continuous fixed real-time monitoring (CO, CO_2, CH_4, O_2) and velocity in select areas – INSTALLATION UNDERWAY
5. Bag sampling with onsite gas chromatography (GC) analysis for fire gases – EXISTING

     The systems at the mine in New South Wales are largely similar to the systems at the Queensland mine, and will not be reiterated in detail, although installation of real-time monitoring was started and appeared to be progressing well. The mine uses an older tube bundle system. Although, it operates in much of the same way, the layout of the equipment in the trailer makes it more difficult to maintain, and the mine intends to install a new tube bundle system in the next year.

The mine does have a large flat screen TV mounted in the lamphouse that displays all the data from the various gas monitoring systems, in addition to operational data, including which underground conveyor belts are running.

Summary

Many of the points noted in Queensland's underground coal mine are also true in New South Wales, including multiple layers of monitoring. Generally, New South Wales and Queensland have many common practices. For example, rather than specifying explosion risk zones (ERZ) as Queensland does, New South Wales specifies hazardous and non-hazardous zones. New South Wales regulation appears to be more prescriptive; however, both Queensland and New South Wales regulations are less prescriptive than the United States. Ultimately, the burden is on the mine to evaluate risk and design plans that will mitigate that risk, and submit these plans to regulators. A mine manager indicated that if a serious accident occurs, the mine is either negligent for not mitigating the risk or incompetent for not recognizing the risk in the first place. There appears to be a great deal of personal liability for individuals in supervisory roles, but also more autonomy in dealing with risk.

3.4 Canadian Underground Deep Hard Rock Metal Mine

3.4.1 BACKGROUND

The Canadian underground metal mine uses the mining method of sublevel stopping/sublevel caving for mining of copper and nickel. The mine depths exceed 6,000 feet. The mine is regulated by Ontario authorities, as Canadian mines are regulated by the province or territory in which the mine resides. Regulations are not written prescriptively, but instead mandate that companies use best practice and monitor the atmosphere of the mine based upon each mine's specific issues.

This mine does not typically experience gas problems, with the most problematic gas in the mine being carbon monoxide that is generated from blasting and diesel equipment. Methane is encountered when drilling, but due to methane detectors on the drilling equipment, explosive ranges are never encountered. If the drill detects methane, the machine will turn off and the drill hole is then ventilated until methane levels have dissipated.

Additionally, the mine also monitors for NO_2 and SO_2, also caused by blasting. Fixed Dragër CO monitors are placed along ramps and Dragër X-AM 5000 handheld gas monitors are used to monitor for CO and other gases in other areas (O_2, CH_4, and CO_2). The mine uses Accutron velocity sensors and does not experience the dust buildup on the sensors that underground coal mines are likely to. The mine has observed issues with ultrasonic velocity sensors in areas (such as fans) where the cross sectional area is not big enough to accurately calculate air velocity. The mine was investigating installation of SynEnergy velocity and gas sensors. Ventilation-On-Demand (VOD) is in the process of being implemented at the mine and auxiliary and booster fans are placed strategically throughout the mine where additional ventilation is needed.

The mine has a control room with 15 LCD monitors (19 inches) and five big screen televisions (approximately 50 inches) that allow the control room operator to actively monitor seismicity, gases, pumps, muck bins, belts, sumps, air flow, and many other parts of the mine. The seismic monitoring system runs the Engineering Seismology Group Inc. (ESG) software (ESG, 2010) and the overall system utilizes the RS-View software. Both of the software packages visually display the data in a manner easy for the operators to monitor and react to problems found by the systems. RS-View software has a button to send warnings to all the radios in case of an emergency. The software also has a list of miners that are working alone that day. The software records the last time each radio is used by solo miners and if that miner has not used their radio in at least two hours (each time the radio is used, the timer is reset to zero), then the miner is marked as missing and further action must be taken.

The mine utilizes the ESG Paladin seismic monitoring system to detect location and time of micro and macro seismic events. Seismic events enable operators to understand the behavior of the rock mass and are vital at a mining depth of approximately 7,900 feet. Each Paladin (or separate computer node) has six channels, which allows multiple devices to be connected to the same node.

Accelerometers are used to detect seismic activity. ESG's software contains the mine map that shows seismic events and displays events as dots (varying in size based upon the magnitude) on the mine map. Seismic events have to be recognized by several sensors in order to

trigger an alarm. Problematic seismic events are displayed on an LED screen that is located next to the elevator shaft so that miners will be aware of the events and which areas are restricted.

A seismic event of magnitude 2.6 was recorded around 2PM during March 2009 on the 7400 level. The event is thought to have been triggered by blasting that occurred before the event. Stresses migrated and caused a seismic event of magnitude 2.9 later that same day around 8PM. Tomography/seismic/velocity monitoring enables areas to be highlighted that require additional roof support. Boreholes have been drilled at the bottom level and triaxial stress sensors have been placed in the underlying rock. Tri-axial stress sensors below the bottom level of mining help with future mine planning as well as additional insight on how the rock body is behaving.

Sensors connected to copper cabling have been placed on several different types of bolts (Yield Lock, Rock Bolt, MCB, DB) to measure displacement, stress and other parameters in problematic areas. Typically this is placed around pillars that have been predicted to yield in order to provide additional insight on how the pillar is behaving. A handheld YieldPoint monitor (MIU v. 5.0) can be plugged into the ends of the copper cabling (connectors on the end) in order to collect the current data readings.

3.4.2 SUMMARY

The mine utilizes a seismic monitoring system for safety and production. The seismic monitoring system allows management to be confident after production blasts occur that it is safe for miners to re-enter the mine. A deep metal mine utilizes a sublevel caving method which also provides a unique advantage to using a seismic system because seismic events can help provide useful insight on the progression of caving in production areas.

3.5 Monitoring Summary

There are numerous monitoring techniques that allow underground coal mines to comprehensively monitor gas and ventilation parameters. Atmospheric monitoring systems are used in countries around the world. The number of monitoring solutions available to the United States is limited in comparison to the rest of the world due to United States monitoring systems must be approved specifically by MSHA. Monitoring systems can be modified in order to cater

to specific issues at different mines. Monitoring underground coal mines comprehensively is feasible and the technologies required are currently available. Systems cost is commonly the driving factor for the mine. Further developments in longwall gob monitoring to allow the areas within the gob to be monitored would provide information needed to develop a model of the air flow over the entire mine area.

CHAPTER 4: ANALYSIS OF ATMOSPHERIC MONITORING SYSTEMS PERFORMANCE AND SENSOR PLACEMENT

An underground coal mine emits a wide variety of gases, several of which are potentially explosive, toxic, or indicators of undesirable events. It is critical to monitor for methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) in underground coal mines and may be necessary to monitor for additional gases that pose hazards at specific mines. The US Code of Federal Regulations provides guidance on the installation of AMS systems in underground coal mines. Primarily, AMS systems are installed for monitoring belt lines and electrical installations in the U.S. for smoke, CO, and CH_4, and automatically alarm at set thresholds (30 CFR §75.340, §75.350, §75.351). Some mines may also utilize real-time monitoring of returns or tube bundle monitoring of sealed areas or gob as part of an approved ventilation plan, but the regulation does not specifically require either. The ventilation plan for each mine is approved by MSHA, and this plan, tailored for the particular mine, then becomes part of the regulations that the mine must comply with. Sections 4.1, 4.2, and 4.3 contain work from "Comprehensive ventilation simulation of atmospheric monitoring sensors in underground coal mines" K.R. Griffin, K.D. Luxbacher, S.J. Schafrik, M.E. Karmis, 14th U.S./North American Mine Ventilation Symposium, Salt Lake City, 2012, used with permission from Felipe Calizaya.

4.1 Analysis of Conventional Monitoring System Sensors

Atmospheric monitoring techniques continue to develop, but still present challenges because available technologies demonstrate issues that limit accuracy, response time, range, sensitivity, and survivability. Real-time monitoring in underground coal mines assists operators to determine whether or not conditions are safe for mining and allows them to operate ventilation systems more efficiently. The placement of atmospheric monitoring sensors depends on the mine geometry, mine ventilation system design, in situ conditions, power sources and other mine specific parameters. These limitations, such as contamination, interference from dust, and limited detection range must be considered during emergencies and rescue efforts, as sensors exposed to extreme atmospheres may not continue to provide accurate information.

It is nearly impossible to predict the psychological processes going on inside a miner's brain during a mine emergency, although careful and frequent training can better prepare miners for emergency situations. Additionally, it is possible to monitor the mine atmosphere and plan a rescue operation or better direct an evacuation according to real-time data assessed on the surface. Atmospheric monitoring and communication systems in the United States have been designed to specific regulatory standards, but survivability is difficult to assess due to the massive forces that systems could be subject to during a mine disaster. This is why it is important to design intelligent systems that can "heal" their communication's backbone with surviving equipment or install networks that can be quickly restored post-accident in order to be able to monitor and communicate. Mobile standalone atmospheric monitoring and communication systems may also be utilized in emergencies to quickly start monitoring and communicating with personnel trapped underground.

4.1.1 REAL-TIME MONITORING

There are numerous real-time monitoring techniques that allow underground coal mines to globally monitor gas and ventilation parameters. Real-time monitoring can be used to determine if a mine's ventilation system is functioning properly which directly impacts daily health and safety, as well as production and efficiency. Atmospheric monitoring can be used to detect incidents that have occurred, such as an explosion behind seals, an ignition at the face, an outburst of gas, and a belt fire. Real-time atmospheric monitoring sensors may be limited by the sensing technology used to detect the parameters of interest, with limitations including sensor response time and sensitivity.

Gas sensor response time can often be an issue. Most commercially available gas sensors approved for use in underground coal mines have T90 response times averaging between 10 and 30 seconds. A T90 response time is defined as the time required for a sensor to achieve 90 percent of the final reading (Honeywell Analytics, 2013). Catalytic gas sensors' response times range from 10 to 15 seconds, with infrared sensors' response time even longer, ranging from 15 to 30 seconds, due to the diffusion of gas into the optical chamber where the gas is quantified. These times may not be adequate to de-energize equipment in rapidly changing atmospheres, and may allow for movement of equipment well into an explosive atmosphere. For example, a massive methane gas inundation would require an immediate response time, but may not be

immediately detected because of the diffusion of gas into the sensor's gas chamber. If a methane gas inundation occurs, then an immediate response time would be ideal but the response time of current sensors may not be capable of detecting the inundation until at least 10 seconds after the contaminated ventilation stream reaches the sensor. Other incidents may not be detected by a sensor in a timely matter due to the sensitivity of the sensor being unable to detect small amounts of increasing gas concentrations.

The ability to respond to rapidly changing conditions is also a function of the frequency with which data are collected. The frequency with which a gas sensor polls data impacts the battery life of a sensor. Additionally, if a sensor is polled too often it can cause more data traffic over the network resulting in high latency on the data network that may impact other devices utilizing the network as well. It may be necessary to poll a sensor every second in high risk areas and every minute in low risk areas of the mine.

Currently available real-time atmospheric monitoring sensors are often limited by the sensitivity of the sensor. Sensitivity limitations are typically based on the sensing technology the sensor utilizes and cross-sensitivity to other gases. The three main types of handheld gas detecting instruments operate using catalytic beads, electrochemical, and infrared sensing. One of the primary sensors used in underground coal mines is a catalytic or pellistor methane sensor. A pellistor methane sensor utilizes a platinum wire resistance thermometer/heating wire that is embedded in a ceramic or catalytic bead (Eggins, 2002). Pellistor type sensors utilizing catalytic beads are limited to detecting methane concentrations from 0 to 5% (Valoski, 2010), and may experience interference from organosulfur or organophosphorus compounds, alkyllead derivatives, higher hydrocarbons, ethane, propane, hydrogen, and other flammable gases (Eggins, 2002; Hartman, et al, 1997). McPherson (2009) noted that given a one percent concentration individually of methane, carbon monoxide, hydrogen, ethane, and propane, that a pellistor methanometer can read values differently based upon the specific gas. One percent of methane produced a one percent methanometer reading; one percent of carbon monoxide produced a 0.39 percent methanometer reading, one percent of hydrogen produced a 1.24 percent methanometer reading, one percent of ethane produced a 1.61 percent methanometer reading, and one percent propane produced a 1.96 percent methanometer reading. Pellistor methane sensors rely upon the oxidation process and availability of oxygen. In order for a catalytic

methane sensor to operate properly, it generally requires oxygen concentrations to exceed 12% (Valoski, 2010). McPherson (2009) noted that as methane exceeds 9 or 10 percent, lower oxygen concentrations will reduce the function of the sensor and give a false reading.

Electrochemical gas sensors in underground coal mines typically are used to detect carbon monoxide, oxygen, and hydrogen, and require a range of oxygen levels to operate properly. Electrochemical sensors can measure carbon monoxide in the range of 0 to 9,999 ppm, oxygen 0 to 30%, and hydrogen 0 to 1000 ppm (Valoski, 2010). Carbon monoxide electrochemical sensors experience cross sensitivity to hydrogen and hydrogen sulfide, oxygen sensors experience cross sensitivity to carbon monoxide, and hydrogen sensors experience cross sensitivity to carbon monoxide and hydrogen sulfide.

Infrared sensors can measure methane concentrations from 0 to 100% CH_4 but response times are higher than for catalytic bead detection because the mine atmosphere must diffuse through a filter before analysis in the optical chamber. Also, infrared gas sensors experience cross sensitivity from moisture (Valoski, 2010). However, infrared sensors can operate in oxygen depleted atmospheres unlike catalytic and electrochemical sensors which require sufficient amounts of oxygen in the atmosphere to operate properly.

4.1.2 VELOCITY MONITORING

Monitoring of air velocity and quantity at strategic locations can quickly alert operators to malfunction of the ventilation system, especially if substantial volumes of air are suddenly lost. The most commonly used velocity measurement methods in underground coal mines are anemometers, pitot tubes, tracer gases, pressure transducers, ultrasonic velocity, vortex shedding, and thermal mass flow. Devices with moving parts may be problematic for remote continuous monitoring. Airflows in an underground mine are subject to considerable variation due to movement of equipment, changes in resistance in the workings, and opening of ventilation doors. Air velocities are generally limited to below 20 m/s (3940 fpm) in ventilation shafts and as low as 0.3 m/s (60 fpm) at working faces, and remote areas, such as bleeders, can exhibit extremely low velocities which are a challenge to accurately quantify. Remote monitoring of air velocity in underground mines is difficult because of the wide range of velocities, the interference of moisture and dust with sensors, and the appropriate location of sensors so that a reasonable

average flow across the cross sectional area of an entry is measured. An alternative to velocity monitoring is monitoring of pressure differential, particularly in areas with high pressure differentials such as regulators.

4.1.3 TUBE BUNDLE ATMOSPHERIC MONITORING

Tube bundle systems are widely used in underground coal mines in Australia. These systems utilize a series of tubes that are run from the surface and allow for direct access of an air sample at the surface, with only tubing maintained underground. Tube bundle systems are completely passive in the underground environment which allows them to be used in the return airways, bleeders, gob, and other high risk areas in the mine. Tube bundle systems can be used in post-accident monitoring but are subjected to a delay in sampling because samples are continually being drawn through the tubes underground to the surface, with each point being monitored by separate tubes. While samples from all monitoring points may be drawn continuously, only one sample is typically analyzed at a time. A tube bundle system represents a continual form of monitoring rather than a continuous monitoring system.

Real-time monitoring allows operators to designate specific areas that should be de-energized to eliminate ignition sources when certain thresholds are met with delays of less than one minute. It allows greater flexibility to respond to an incident immediately because real-time sensors will detect changing conditions within a minute of the atmosphere reaching the sensor.

4.2 VnetPC PRO Simulation Scenarios: Sensor Placement

Three different accident scenarios were chosen to examine whether currently available atmospheric monitoring sensors are capable of providing adequate information to the surface to determine what conditions are present underground. This exercise examines atmospheric monitoring sensor technologies and sensor locations. Sensor limitations can provide misleading information that can place mine emergency personnel in danger and hamper evacuation and rescue efforts. The three different accident scenarios that were chosen are an explosion behind seals, an ignition at the face, and an outburst of gas. A massive explosion behind a sealed area would more than likely cause damage or complete failure of the immediate seals and release a large amount of methane and carbon monoxide. Smaller amounts of carbon monoxide and

methane would be detected if there was an ignition at the active mining face. An outburst of gas is typically when a medium to large amount of methane is instantaneously released from the active mining face or floor. Each of the three scenarios will present challenges to correctly quantify mine gases because of issues with response time, range, sensitivity, and survivability.

4.2.1 MINE MODEL

A medium size mine model was created to simulate accident scenarios using network simulation in order to develop guidelines for sensor placement. Dangerous atmospheric conditions were simulated in locations of the mine that each accident scenario could occur to determine whether the atmospheric monitoring sensor locations would correctly assess the severity of the incident. The mine layout was loosely based on the Sago mine because of the publically available map with limited amounts of ventilation data, methane quantities, and other parameters (MSHAa, 2007). The main development entries within the model consisted of five to nine 5.5-meter-wide (18 ft) parallel entries, with main entries on approximately 23.8- to 32.9-meter centers (78- to 108-ft). Crosscuts were on 14.6- to 20.7-meter centers (48- to 68-ft). An average roof height of 1.8 meters (6 ft) was assumed for the entire mine. The entries are numbered left to right facing inby. Figure 4.1 shows a map of the mine.
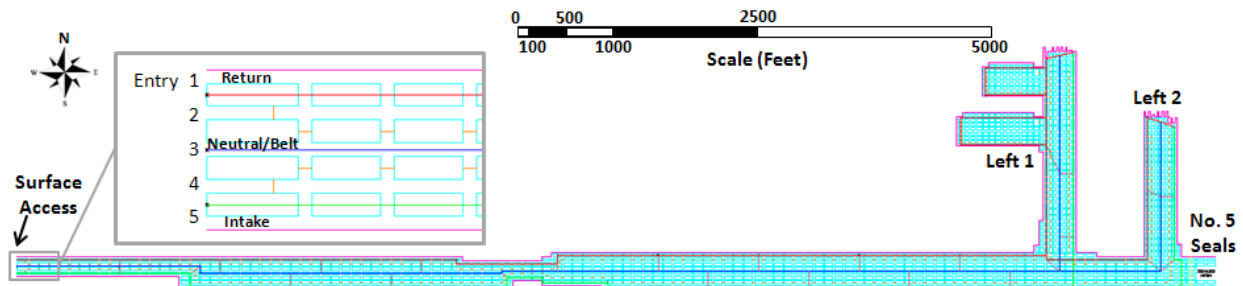
Figure 4.1: Mine Map

The mine ventilation is a single-split system where entries are numbered from left to right facing inby. Entries 1 and 2 are return airways, 4 and 5 are intake entries, and entry 3 is a neutral airway with flow maintained in the outby direction. Surface access to the mine is through five main entry drifts. The main mine fan is a Joy Axivane mine fan model M120-65-590 configured in a blower system, intaking air into the No. 5 drift opening. Return air is primarily exhausted from No. 1 drift opening and neutral through the No. 3 drift opening. The No. 5 Seals are located

on the east side of the mine. The first two panels to the left (Left 1 and Left 2, respectively) are working sections.

The mine ventilation was reduced to a ventilation network so that Mine Ventilation Services' VnetPC PRO, an accelerated form of the Hardy Cross iterative network solver, could be used to analyze the ventilation network under the different accident scenarios discussed previously. Table 4.1 contains the mine model input parameters for VnetPC PRO.

Table 4.1: VnetPC PRO Mine Model Input Parameters

Parameter	Value (English)	Value (SI)
Main Development Entries Pillar Size	30 x 90 ft	9.1 x 27.4m
Crosscut Entries Pillar Size	30 x 50 ft	9.1 x 15.2m
Opening Size (Constant)	18 x 6 ft	5.5m Wide, 1.8m High
Opening Cross-Sectional Area (Constant)	108 ft^2	10.0 m^2
Opening Perimeter (Constant)	48 ft	14.6 m
Friction Factor (K) – Intake, Clean Conditions	$49 \text{ lb·min}^2/\text{ft}^4 \times 10^{-10}$	0.009 kg/m^3
Friction Factor (K) – Returns, Some Irregularities	$54 \text{ lb·min}^2/\text{ft}^4 \times 10^{-10}$	0.010 kg/m^3
Friction Factor (K) – Belt Entries	$27 \text{ lb·min}^2/\text{ft}^4 \times 10^{-10}$	0.005 kg/m^3
Friction Factor (K) – Post Explosion	$250 \text{ lb·min}^2/\text{ft}^4 \times 10^{-10}$	0.046 kg/m^3
Leakage Resistance (R) - Average	4200 P.U.	$4690 \text{ Ns}^2/\text{m}^8$
Main Fan Operating Pressure	3.68 in. w.g.	0.92kPa
Main Fan Operating Quantity	193 kcfm	$91.1 \text{ m}^3/\text{sec}$

The main pillar size and panel pillar size are 9.1 meters by 27.4 meters (30 ft by 90 ft) and 9.14 meters by 15.2 meters (30 ft by 50 ft), respectively. The opening sizes of the mine entries are assumed to be 5.5 meters (18 ft) wide and 1.8 meters (6 ft) high, with a cross-sectional area and perimeter of openings of 10.0 meters^2 (108 ft^2) and 14.6 meters (48 ft) respectively. The friction factors (K) for intake, returns, and belt entries were 0.009 kg/m^3, 0.010 kg/m^3, and 0.005 kg/m^3 (49, 54, and 27 lb·min^2/ft^4 x 10^{-10}), respectively (McPherson, 2009). The leakage resistance (R) for a single stopping was chosen to be 4690 Ns^2/m^8 (4200 P.U.) for average conditions (Oswald, Prosser & Ruckman, 2008). Leakage resistance was converted into Practical Units (PU) (milli-inch·wg/kcfm) for the simulation. It was assumed that damage to the ribs, roof, and floor would

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occur in the immediate vicinity of the explosion and behave similarly to the airflow through a heavily cribbed area, so a friction factor of 0.046 kg/m^3 (250 lb·min^2/ft^4 x 10^{-10}) was used. The main fan operating pressure and quantity under average conditions was 0.92 kPa (3 in. w.g.) and 91.1 m^3/sec (193 kcfm). VnetPC PRO is limited to steady state flow evaluation. In order to evaluate gas concentrations due to a one-time release of methane, such as an outburst, it is necessary to set the contaminant emission level to the maximum concentration expected. Generally, sensors may not be sensitive enough or have an adequate response time to suitably resolve the change in gas concentration in the temporal domain, so for this preliminary work this assumption is appropriate.

The minimum time for gas to reach the sensor is calculated separately based on velocity in each branch and compared to sensor response time. Calculated times were first calculated by neglecting forces associated with an ignition, explosion, and an inundation that may propel the gases through immediate low velocity zones created by fixed air quantities in the model. Alternatively, short circuiting due to damage to ventilation controls may cause much slower travel times. Calculated times were separately calculated for each scenario by assuming the forces associated with an explosion would propel gases through low velocity zones (approximately 406 ft) in the immediate vicinity and inundation forces would momentarily (2 minutes) disrupt the ventilation. Murray (2009) noted that stopping debris can be thrown 300 ft, which indicates that gases could be propelled much further.

4.2.2 INCIDENTS SCENARIOS

The explosion in a sealed area, working face methane inundation, and working face ignition scenarios were simulated in VnetPC PRO by introducing methane as a contaminant at the accident site and making reasonable assumptions about damage to ventilation controls. Figure 4.2 contains a schematic of incident locations (circles) and monitoring locations (stars). Incident location number 1 is the explosion in the sealed area, incident location number 2 is the working face methane inundation, and incident location number 3 is the ignition at the working face.
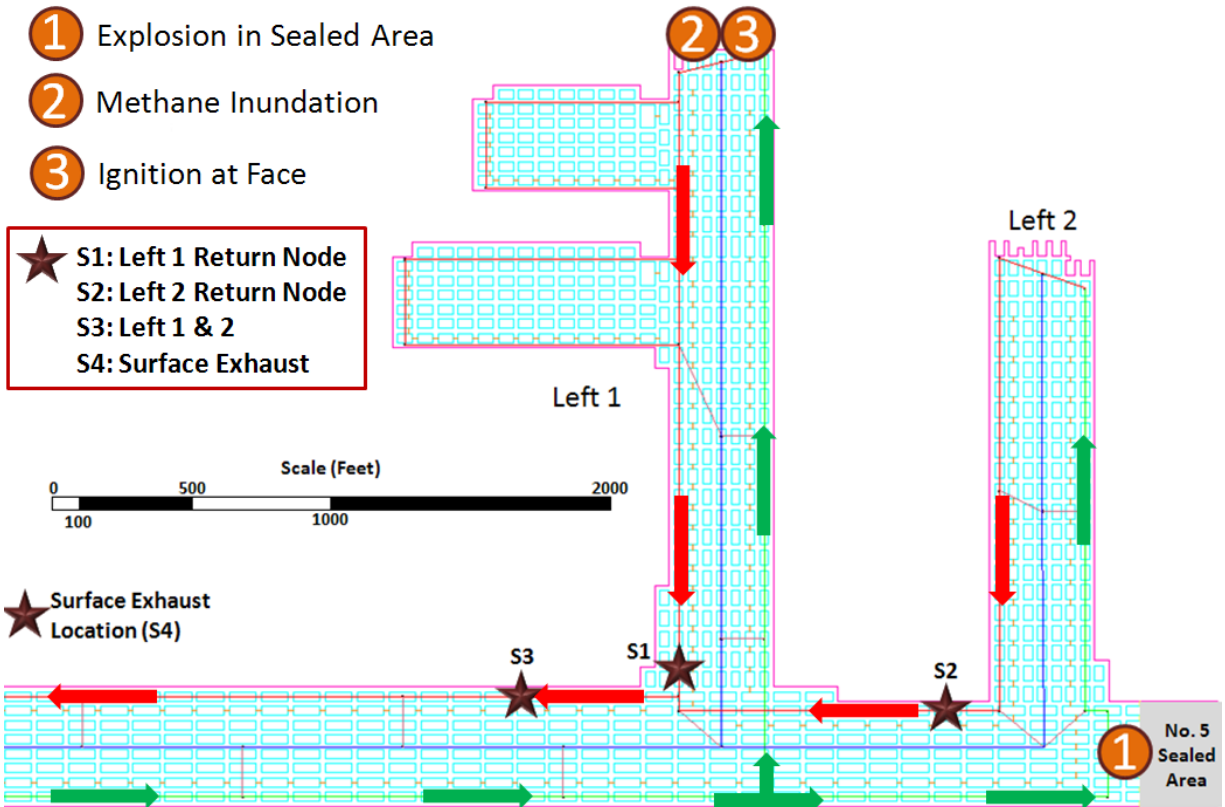
Figure 4.2: Mine Schematic, Incident Locations (Circles) and Monitoring Locations (Stars)

Monitoring locations were chosen as major return nodes and at the exhaust point on the surface to represent a bare minimum monitoring strategy. These locations were chosen as they represent global monitoring of the mine, allowing the gases leaving each panel to be quantified, and they may be viewed as long term monitoring locations. Major return nodes are typically where belt drives that require power centers nearby. Long term monitoring locations are also chosen due to proximity to mine power centers in order to minimize the length of cable runs.

Reasonable methane concentrations for the three accident scenarios were determined based on reported values in the literature. Conditions can vary significantly based on a number of parameters including the size of the sealed area, lapsed time since sealing, seam and surrounding strata characteristics, and other mine specific parameters. Therefore, methane concentrations within the given ranges contained in literature were used to simulate the accident scenarios. Each incident scenario simulation is not intended to simulate every aspect and byproducts of each incident, but rather use ideal conditions for an incident to determine how sensors would evaluate gas concentrations throughout the mine.

4.2.3 EXPLOSION IN SEALED AREA

MSHA's final report on the Sago mine explosion estimated the total methane in the sealed area at the time of the explosion (9,830 m^3, 347,000 ft^3 CH$_4$), the methane consumed in the explosion (4,020 m^3, 142,000 ft^3 CH$_4$), and the remaining methane after the explosion behind the seals (5,800 m^3, 205,000 ft^3 CH$_4$), which were used as base line values to simulate an explosion in a sealed area (MSHA, 2006c). This simulation is not intended to replicate the Sago mine explosion, but was chosen because of the publically available data regarding methane content behind a sealed area.

In order to simulate the estimated 5,805 m^3 (205,000 ft^3) of methane that remained in the sealed area after an explosion entering the mine atmosphere it was assumed that the entry associated with the No. 5 sealed area had a fixed quantity of 0.472 m^3/s (1 kcfm). The location of the sealed area is shown above at location 1 on Figure 4.2. A fixed quantity of 0.47 m^3/s (1 kcfm) simulates the release of a large volume of highly concentrated methane gas in the sealed area where ventilation controls have been heavily damaged. A fixed quantity of 0.47 m^3/s (1 kcfm) simulates a methane concentration of 90.91 percent which corresponds with a 4.72 m^3/s (10 kcfm) contaminant emission rate. Byproducts of the explosion were not taken into consideration.

4.2.4 METHANE FACE INUNDATION

Morris (1974) reported methane emissions from floor outbursts could be 140,000 m^3 (~4,900,000 ft^3) and over 8×10^6 m^3 (~280,000,000 ft^3) from sudden roof emissions. A methane floor inundation was simulated similarly to an explosion in a sealed area because VnetPC PRO is limited to steady state flow evaluation. A methane floor inundation was simulated at location 2 in Figure 4.2. A fixed quantity of 0.47 m^3/s (1 kcfm) was assumed for the entry at location 2 which simulated 90.91 percent methane with a corresponding contaminant emission rate of 4.72 m^3/s (10 kcfm).

4.2.5 IGNITION AT THE WORKING FACE

Murray (2009) noted that a methane-gas mixture of 267-283 m^3 (8,000-10,000 ft^3) with a localized volume of 9.5% methane (27 m^3, 950 ft^3 CH$_4$) would represent a moderate-sized methane explosion that could occur at the working face. An ignition model assumed that the

initial ignition was caused by a short term increase in methane emissions. While some this methane would be consumed by the initial ignition, complete combustion of the methane was not assumed so a sensible increase in methane concentration would be realized. An ignition at the working face was simulated in as a contaminant with a concentration of 9.49 percent (methane) at location 3 in Figure 4.2.

4.2.6 EXPLOSION IN SEALED AREA RESULTS

It is assumed the explosion did not completely consume methane in the No. 5 sealed area and released a large volume of sealed area gases which were simulated as a contaminant with a concentration of 90.91 percent methane. The entry associated with the No. 5 sealed area was solved under normal operating conditions to have an air quantity of 32.29 m^3/s (68.41 kcfm). The entry associated with the No. 5 sealed area must have a fixed quantity of 0.47 m^3/s (1 kcfm) in order to simulate a methane concentration of 90.91 percent which corresponds with a contaminant emission rate of 4.72 m^3/s (10 kcfm). It was also assumed that the stoppings in the immediate vicinity of the No. 5 sealed area would be heavily damaged and were assigned a resistance similar to that of a heavily cribbed entry. The leakage friction factor post explosion can be found in Table 4.1. Air quantities in the immediate area were also significantly reduced and air reversal was observed in the belt airways on the Left 2 Section. The explosion in the No. 5 sealed area produced methane concentrations over 91 percent in the Left 2 Section.

Methane concentrations at sensor locations range from 11 percent (on the surface) to 21 percent (exhaust branch for Left 2 Section). Sensor S1, located on the return airway of the Left 1 Section is unaffected (0 percent methane) in this scenario. Table 4.2 contains the methane concentrations observed at sensor locations.

Table 4.2: Summary of Incident Simulation Results

Incident	Map Incident Number	Methane Concentration (%) at Sensor Location					Main Fan	
		S1 (Left 1)	S2 (Left 2)	S3 (L1 & L2)	S4 (Surface)	Incident Branch	Operating Pressure (in. w.g.)	Operating Quantity (kcfm)
Explosion in Sealed Area	1	0	21.1	13.40	10.75	90.91	3.64	193.89
Face Inundation	2	79.55	0	14.45	11.10	90.91	3.69	192.49
Ignition at Working Face	3	9.35	0	5.04	3.95	9.5	3.68	192.87
Normal	-	-	-	-	-	-	3.68	192.87

The explosion in a sealed area simulation also showed the air velocities in the immediate vicinity were significantly reduced and that entries experience air flow reversal in several areas. Decreased air velocities are a result of a fixed air quantity placed on the sealed area entry to simulate a large volume of methane. This same behavior could be expected due to damage to ventilation controls and the forces exerted by the incident itself. The estimated arrival time of gas at each sensor location was calculated using the air velocities and distances to each sensor from the location of the incident which can be found in Table 4.3.

Table 4.3: Estimated Gas Arrival Times at Sensor Locations

Incident	Map Incident Number	Estimated Gas Arrival Time (minutes) at Sensor Location			
		S1 (Left 1)	S2 (Left 2)	S3 (L1 & L2)	S4 (Surface)
Explosion in Sealed Area (no blast force)	1	-	241	245	278
Explosion in Sealed Area (with blast force)	1	-	12.5	15.8	46
Face Inundation (total disruption)	3	323	-	326	358
Face Inundation (momentary disruption)	3	15	-	18.5	28
Ignition at Working Face	2	13	-	16.5	25.75

The high range of methane concentrations indicate that a pellistor sensor would be unlikely to give a meaningful reading, although irregular readings would alert the surface to a disturbance. If a velocity sensor were still properly aligned and intact in the vicinity of the seals at S2, which is highly unlikely, it would show a significant change. Additionally, survival of a velocity sensor at S3 is more likely, and it would likely show a small detectable change in air velocity. Assuming that communication with the sensor network is maintained; problems underground would be noticed by anyone monitoring data on the surface. However, the extent of those problems would be more difficult to ascertain. If pellistor-type methane sensors were used the concentration data would not be meaningful. In addition, if infrared methane sensors were used response times could be extremely slow due to the dust raised by the explosion and the diffusion of the mine atmosphere through the filter into the optical chamber. These monitoring locations and technologies would not be ideal under this scenario.

4.2.7 METHANE FACE INUNDATION RESULTS

A methane inundation at the working face was simulated in as a contaminant with a concentration of 90.91 percent (methane). The entry at the working was solved under normal

operating conditions to have an air quantity of 15.23 m³/s (32.26 kcfm). After the inundation it was assumed the ventilation system was momentarily disrupted and the entry at the working face had a fixed quantity of 0.47 m³/s (1 kcfm) of fresh air and a contaminant emission rate of 4.72 m³/s (10 kcfm). This corresponds to a methane concentration of 90.91 percent. The inundation at the working face produced methane concentrations in the return airways ranging from approximately 90.91 percent (at the working face where the inundation occurred) to 11.1 percent (at the exhaust on the surface). Table 4.2 which can be found in above, shows the summary of results from the inundation at the working face simulation. Methane concentrations in this scenario are above 79 percent on the working section (S2) and 11 percent at the exhaust on the surface (S1), which would not be accurately read by a pellistor type sensor. An operator on the surface might observe fully saturated readings for both a massive face inundation and an ignition at the working face even though these two events differ significantly in reality.

The inundation at the working face simulation showed air velocities significantly decreased on Left 1 Section. Decreased air velocities on Left 1 Section are a result of the fixed air quantity used to simulate a large volume of methane gas being released quickly at the working face. A massive methane inundation can exert forces that displace machinery and disrupt the auxiliary ventilation, such as line curtain or ducting on that section. The estimated arrival time of gas at each sensor location can be found above in Table 4.3.

4.2.8 IGNITION AT THE WORKING FACE RESULTS

An ignition at the working face was simulated as a contaminant with a concentration of 9.49 percent (methane). Under normal operating conditions the mine network model showed the working face entry airflow had an air quantity of 15.23 m³/s (32.26 kcfm) with a corresponding methane emission rate of 1.6 m³/s (3.39 kcfm). The ignition at the working face produced methane concentrations in the return airways ranging from approximately 9.5 percent (at the working face where the ignition occurred to the main entries) to 3.95 percent (at the exhaust on the surface). Methane concentrations above 4.5 percent may produce fully saturated readings (methane may already be present in return airways from mining) if pellistor type methane sensors are placed at locations S1, S3, and S4 (S2 is unaffected by this incident). If sensor readings are fully saturated at 5 percent methane, then the operator on the surface cannot distinguish the difference between 9.5 percent and 25 percent methane. Methane concentrations

above 5 percent may also cause pellistor type methane sensors to become inoperable. Table 4.2 shows the methane concentrations at each sensor location as well as the branch where the incident occurred. There were no changes in air velocities on Left 1 Section in the ignition at the working face simulation. Additionally, it is possible an ignition would be associated with an isolated increase of methane, resulting in no observed change at methane sensors because all the methane would be consumed.

4.2.9 SUMMARY OF INCIDENT SIMULATION RESULTS

Table 4.3 which can be found above, shows the summary of results from the incident scenarios. This table estimates the time after the initial event that it will take gas concentrations to be detected at each sensor location.

After an explosion in the sealed area (neglecting blast forces), the first gas arrival time recorded at sensor S2 on Left 2 section with an estimated arrival time of 241 minutes. An additional sensor would be required to determine whether an incident occurred near the sealed area or on the Left 2 section. Alternatively, if blast forces are considered after an explosion in the sealed area, the first gas arrival time was at sensor S2 with an estimated arrival time of 12.5 minutes.

After a methane inundation (assuming total ventilation disruption), the first gas arrival time was at sensor S1 on Left 1 section with an estimated arrival time of 323 minutes. The delay for sensor S1 may be increased due to the fixed quantity placed on the entry associated with the working face. Zero percent methane at sensor S2 indicates the incident occurred outby of Left 2 section.

After a methane inundation (assuming only momentary ventilation disruption of 2 minutes), the first gas arrival time was at sensor S1 with an estimated arrival time of 15 minutes.

The first gas arrival time for the ignition at the working face was at sensor S1, 13 minutes after the initial incident. A zero percent methane reading at sensor S2 indicates that the incident occurred outby of Left 2 section.

Real-time atmospheric monitoring data provides continuous measurements of gases, air velocity, barometric pressure, temperature, and relative humidity, and can reveal areas

experiencing near instantaneous changes in gas levels and air velocity. Real-time monitoring allows operators to designate specific areas to deenergized when certain gas concentrations are met. Monitoring data can be used to create algorithms and pin point combinations of parameters that influence gas emissions and could potentially become problematic. However, both sensor technology and placement are key in atmospheric monitoring. This study highlights the importance of both. In two of the three scenarios pellistor sensors would be saturated by high methane concentrations and time for the contaminant to reach the sensor could be excessive. At best, the atmospheric monitoring system assessed here would only communicate a problem to the operator, but the nature of the problem would be less clear.

4.2.10 VNETPC PRO SIMULATION CONCLUSIONS

Current atmospheric monitoring sensors are limited by inherent operating issues, such as response time, sensitivity, survivability, accuracy, and range. Most commercially available gas sensors approved for use in underground coal mines have response times averaging between 10 and 30 seconds. Catalytic, electrochemical, and infrared real-time gas monitoring sensors will experience cross sensitivity from other gases and moisture. Each type of sensing technology ultimately has strengths and weaknesses because each detection method is limited by the sensing technology itself. The scope of this section is real-time continuous monitoring underground, which allows operators to designate specific areas that should be de-energized to eliminate ignition sources when certain gas concentration is met. Real-time monitoring allows greater flexibility to respond to an incident immediately because sensors detect trending conditions within one minute of being emitted into the immediate mine atmosphere.

The three simulated scenarios show that current atmospheric monitoring sensors given the bare minimum global monitoring strategy cannot always distinguish between two different simulated incidents. Additional sensors are required to distinguish between an explosion behind the seals and a methane inundation at the working face. Sensors mounted on mining equipment could provide valuable real-time data if each piece of equipment is connected to the monitoring network, which may be feasible with advances in underground wireless communication. It is recommended for atmospheric monitoring sensors to be placed in active return airways at every major return node in order to determine which section is experiencing adverse conditions. Additional sensors should be installed inby major return nodes and immediately outby the active

working section to ensure that the mine ventilation is functioning properly and to detect incidents rapidly. Mine specific risk assessment plans should be created to determine areas where additional sensors should be installed. It is anticipated that nearby incidents can cause damage to sensors, but the opportunity to have increased knowledge at more locations would prove to exceed the value of the initial capital investment of additional sensors. Additional sensors would reduce estimated gas travel times associated due to anticipated damage to ventilation controls in the immediate vicinity of an incident. The wide ranges of estimated gas arrival times at sensors demonstrate the importance of sensor location and sensor density. While general guidelines such as locating sensors at major return nodes are useful in AMS design, site specific risk assessment is critical. The nature of each incident (forces) would likely cause methane to reach gas sensors at varying times because each specific incident ultimately provides different circumstances.

The underlying issue with all atmospheric monitoring systems as they relate to emergency management is ultimately the survivability of the system. Survivability will always be a hurdle that must be overcome given any incident. There is room for technology advancements in order to help make the survivability gap smaller. In recent disasters it has taken a significant period of time to ascertain the nature and extent of the incident and atmospheric monitoring systems can help pin point the severity of the incident while allowing for more coordinated and educated emergency response. Network simulation of individual mines under different scenarios can be utilized to demonstrate the need to improve atmospheric monitoring sensors and monitoring schemes. Future work will cover simulation of a belt fire, developing sensor technology, and improved communication during emergencies (i.e. wireless).

4.3 Analysis of the Benefits from Monitoring in Past Disasters

Analyzing past disasters in underground coal mines allows researchers to develop monitoring schemes that will help to prevent similar disasters from occurring in the future. Monitoring systems have typically not been required in underground coal mines or were limited to specific areas of the mine. Monitoring systems allow operators to predict when explosions are more likely to occur and detect problematic areas of the mine. From 1900 through 2008 there have been 420 explosions resulting in 10,390 fatalities in underground coal mines (Brnich &

Kowalski-Trakofker, 2010). This section reviews the causes of recent disasters in underground coal mines and provides insight on what type of monitoring could have been beneficial to preventing the disaster as well as aiding rescue teams during the rescue operation. This summary table included at the end of each accident assumes AMS is correctly installed, maintained, and that operators continuous observe and react to data. The intent of this section is to provide insight on how monitoring can be utilized to prevent future disasters and provide a more informed response during post disaster scenarios. This section in no way is meant to criticize or place blame.

4.3.1 PLATEAU MINING CORPORATION WILLOW CREEK MINE

Background

On July 31, 2000 at approximately 11:48pm an initial explosion occurred in the worked-out area of the D-3 longwall panel gob at the Willow Creek underground coal mine in Carbon County, Utah. The initial explosion was believed to be caused by a roof fall in the worked-out area of the D-3 longwall panel gob that ignited methane gas and other gaseous hydrocarbons (MSHA, 2001). The initial explosion caused a fire in the longwall panel gob. The longwall personnel believed that a roof fall occurred, so they stayed on the D-3 longwall section to extinguish a fire near the base of the shields on the headgate side of the longwall. MSHA (2001) states, "Two closely spaced explosions occurred at approximately 11:55pm. A fourth explosion occurred at 12:17am on August 1, 2000. Two fatalities occurred as a result of the second and third explosions." A total of two people were fatally injured and eight others were injured throughout the four explosions. Figure 4.3 shows a map of the Willow Creek mine with the blue line indicating the area immediately affected by the explosions.
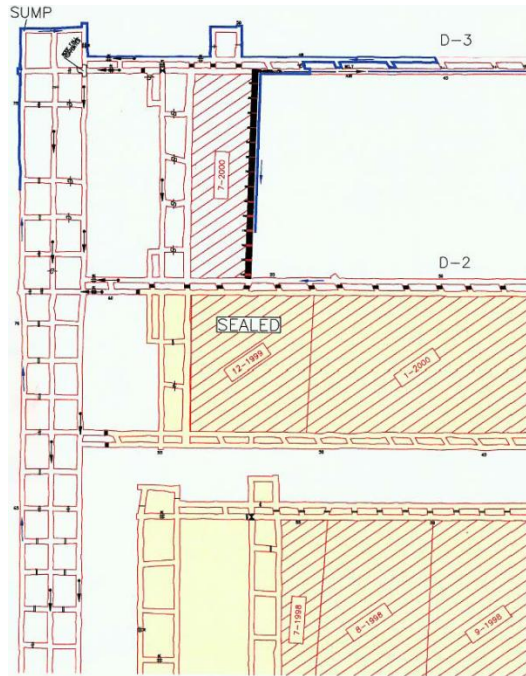
Figure 4.3: Plateau Mining Corporation Willow Creek Mine Map (MSHA, 2001)

A mine rescue operation was conducted and completed by 4am on August 1, 2000 which allowed rescuers to recover the injured miners and the two bodies of the fatally injured miners. The mine surface openings were sealed at approximately 10:30am on August 1, 2000.

Fan pressure recordings showed three distinct pressure spikes that were consistent with explosion forces. MSHA (2001) states, "due to the sampling and recording intervals, the Allen-Bradley monitoring system did not record the first explosion pressure spike. The magnitude of the fan pressures recorded by the Allen-Bradley monitoring system differed with those recorded by the Bristol recorder. Decreases following the pressure spikes were likely the result of damage to underground ventilation controls." It appears that natural ventilation pressure did influence the fan operating pressure at the Willow Creek mine, but did not have a significant impact to be considered as a contributing factor of the accident. Changes in barometric pressure were concluded to not have a significant impact on conditions within the D-3 panel.

Benefits of Monitoring

The Willow Creek mine utilized diesel discriminating sensors (DDS) for CO and nitric oxide (NO) in the two-entry longwall development panels (MSHA, 2001). CO/NO sensors were used along beltlines instead of point-type heat sensors. Ambient CO levels in the approved mine

ventilation plan were set to 2ppm. Diesel discriminating sensor alert and alarm levels in the longwall retreat areas were set to 8ppm and 12ppm, respectively. The range of the CO sensors was from 0 to 50ppm (MSHA, 2001). The ventilation plan amendment approved July 7, 2000 required AMS sensors at: MPL #1 (tailgate intake to the longwall), MPL #5 (headgate No. 2 entry bleeder connector regulator), MPL #6 (headgate No. 1 entry bleeder connector regulator), MPL #7 (tailgate No. 2 entry bleeder connector), MPL #8 (tailgate No. 1 entry bleeder connector regulator), and MPL B1 (D-1 tailgate No. 1 entry near the D Northeast Mains). Methane, oxygen, CO, and velocity sensors were installed at MPL #5, MPL #6, MPL #7, and MPL #8. Methane, oxygen, and CO sensors were installed at MPL #1. Methane and CO sensors were installed at MPL B1. AMS attendants were instructed to immediately notify and stop production if methane concentration reached 4 percent at any of the longwall headgate or tailgate bleeder connectors (MPL #5, MPL #6, MPL #7, or MPL #8), reached 1.95 percent at MPL B1, or reached 0.9 percent in the longwall tailgate intake (MSHA, 2001). Production could resume when methane concentrations at those locations decreased to 3.7 percent, 1.75 percent, and 0.7 percent, respectively. If methane concentrations reached 4.5 percent at any of the headgate or tailgate bleeder connectors (MPL #5, MPL #6, MPL #7, or MPL #8) or reached 2.5 percent at MPL B1. The longwall section and shift foremen were to be notified if methane concentration in the longwall tailgate intake was 1.0 percent or greater (MSHA, 2001).

Methane concentrations and decreased air velocities played a major role in the problematic circumstances the mining crew encountered. MSHA (2001) states, "The AMS data for the period July 16 through August 1, 2000 indicated that the overall trend of methane concentrations at MPL B1 had been increasing. In the days immediately preceding the accident, the trend was accelerated." The methane concentration at MPL B1 exceeded the operator's 1.95 percent action level twice (once at 2:48am for 11 minutes and second at 3:33am for 40 minutes) on July 31. Airflow velocities showed a decreasing trend after July 26, 2000 which indicated a decrease of airflow ventilating the longwall face. Later it was determined that the air velocity sensors positioned at MPL #5, MPL #6, and MPL #7 did not appear to accurately represent the airflow at those locations, although the velocity sensor at MPL #8 appeared to be accurate and indicated that the airflow at the location decreased July 27 through 31, 2000.

The first explosion likely ignited methane and hydrocarbon vapors resulting in a fire around and behind the headgate shields. Part of the initial fire was inaccessible and an adequate supply of fire-extinguishing agent was not available which allowed the fire to continue to spread and eventually gave an ignition source for the other three explosions. Liquid hydrocarbons were suspected of being ignited in the second, third and fourth explosions. The explosibility is significantly increased when hydrocarbons are present. According to MSHA (2001), "In 1998 Data Chem. Laboratories established the explosive range of hydrocarbon gases to be between 1.03% and 5.36%. Methane, also a hydrocarbon, has a lower explosive limit of 5%. However, the combination of these gases would cause the lower explosive limit of the mixture to be less than 5.0%. Due to the volume of methane being liberated, methane was the more significant fuel source in the D-3 gob for the explosions of July 31 and August 1, 2000."

The placement of AMS gas and air velocity sensors prescribed in the mine ventilation plan would have been capable of detecting when the chances of danger were increasing. AMS data from July 16 through August 1, 2000, indicated that the overall trend of methane concentrations at MPL B1 had been increasing and the trend was accelerated in the days immediately preceding the accident (MSHA, 2001). Methane concentrations exceeded the operator's 1.95% action level twice on July 31 which indicates that the bleeder system was near its capacity. The limitations of methane sensors used would not have been able to accurately quantify the explosibility of the methane-air-hydrocarbon mixture the mine experienced. The ventilation plan required air quantities to be increased by 10% above approved quantities when hydrocarbons were present. The presence of hydrocarbons were not uniform throughout the mine, however, interviews of miners indicated that hydrocarbons were present on the longwall face prior to and on July 31, 2000 (MSHA, 2001). The Willow Creek Mine ventilation plan did not correctly utilize the AMS with presence of hydrocarbons. Methane sensors are susceptible to cross-contamination from hydrocarbons and methane becomes explosive at significantly lower concentrations with hydrocarbons present. Action levels to stop production at 4% methane, at the headgate/tailgate bleeders, were not adequate when hydrocarbons are prevalent. Observed reduced air velocities by remote sensing and handheld devices along the longwall face in the days preceding the accident in combination with increasing methane and hydrocarbon concentrations indicated that high risk atmospheres were developing, but these signs were ultimately missed or ignored.

The initial explosion was attributed to a roof fall that ignited a small pocket of methane or other gaseous hydrocarbons. This accident reinforces the need to correctly utilize an AMS and understand the constraints and weaknesses of the system because there were various indicators that high risk conditions were not properly mitigated. High methane concentrations, the presence of hydrocarbons, and decreased air velocities are indicators that a high risk atmosphere is developing. Table 4.4 provides a summary of the roles that monitoring had in the Plateau Mining Willow Creek Mine disaster. Prevention in Table 4.4 refers to the prevention of the initial incident responsible for fatalities, while escape refers to the safety and successful escape of surviving personnel, and rescue refers to the successful rescue of surviving personnel and safety of the mine rescue personnel. Low priority indicates a category that would have helped very little, medium priority indicates a category that would have helped moderately, and high priority indicates a category that would have helped substantially. Question marks (?) in the table indicate a category that the level of priority indicated is debatable due to specific circumstances during the accident.

Table 4.4: Plateau Mining Willow Creek Mine Disaster Summary

Detection/Sensing/Monitoring		Plateau Mining Willow Creek Mine		
		Roof Fall/Gob Ignition, Fire, Additional Explosions		
		Prevention	Escape	Rescue
Existing Handheld Monitoring	(CO, O_2, CH_4)	Low	High	High
Existing Belt Monitoring	(CO)	Low	High	High
Methane Monitoring of Returns	(CH_4)	? High ?	High	High
Multigas Monitoring of Returns	(CO, O_2, CH_4)	? High ?	High	High
Air Velocity Monitoring of Returns	(Velocity)	? High ?	High	High
Seals Monitoring (inby and outby)	(CO, O_2, CH_4)	Low	Medium	High
Seismic Monitoring (Large Scale)	(Frequency, Location, Magnitude)	Medium	Low	Low
Lightning Detection		Low	Low	Low
System Survivability		Low	Medium	High

4.3.2 JIM WALTER RESOURCES NO. 5 MINE

Background

On September 23, 2001 two separate explosions resulted in 13 fatalities at the Jim Walter Resources No. 5 Mine. MSHA (2002) stated, "A roof fall occurred at the intersection near the scoop battery charging station, releasing methane and damaging a scoop battery. A methane explosion occurred within minutes after the roof fall when an explosive methane-air mixture was ignited by arcing of the damaged battery". The explosion damaged critical ventilation controls causing airflow to be disrupted and methane to accumulate in 4 Section, including the face areas and in the No. 2 Entry where the first explosion occurred. The four miners working on the No. 2 Entry of 4 Section at the time of the first explosion were all injured and the miners moved

towards exiting 4 Section. One of the miners could not be moved from the section due to the severity of his injuries.

Miners de-energized the high-voltage electrical circuit for 4 Section shortly after the first explosion; however the track haulage block light system that extended into 4 Section remained energized. Three other miners entered 4 Section to rescue the injured miner on 4 Section and additional miners from other areas of the mine traveled towards 4 Section to provide assistance. MSHA (2002) states, "The miners who entered 4 Section traveled in the track entry through debris from damaged ventilation controls and encountered reserved airflow outby the end of the track. No handheld gas detectors were found near the miners in 4 Section".

A second explosion occurred when methane in No. 2 Entry accumulated when the stoppings were destroyed by the first explosion, and was ignited by the block light system causing the methane explosion to propagate towards the faces of 4 Section. The second explosion strengthened from methane and coal dust near the intersection of the last open crosscut and the No. 3 and No. 4 entries. The second explosion continued into 6 Section, the Shaft 5-9 area, and 3 East which resulted in at least 12 fatalities. Mine rescue teams recovered a severely injured miner and transported him to the surface, but the miner passed away on September 24th. A total of 13 miners lost their lives from the second explosion. On September 24th it was concluded that the missing miners could not have survived the effects of the explosion and it was necessary to abandon the rescue due to a fire and other unsafe conditions. Figure 4.4 shows a diagram of the areas affected by the mine explosion; the red outline indicates flame propagation (MSHA, 2002).
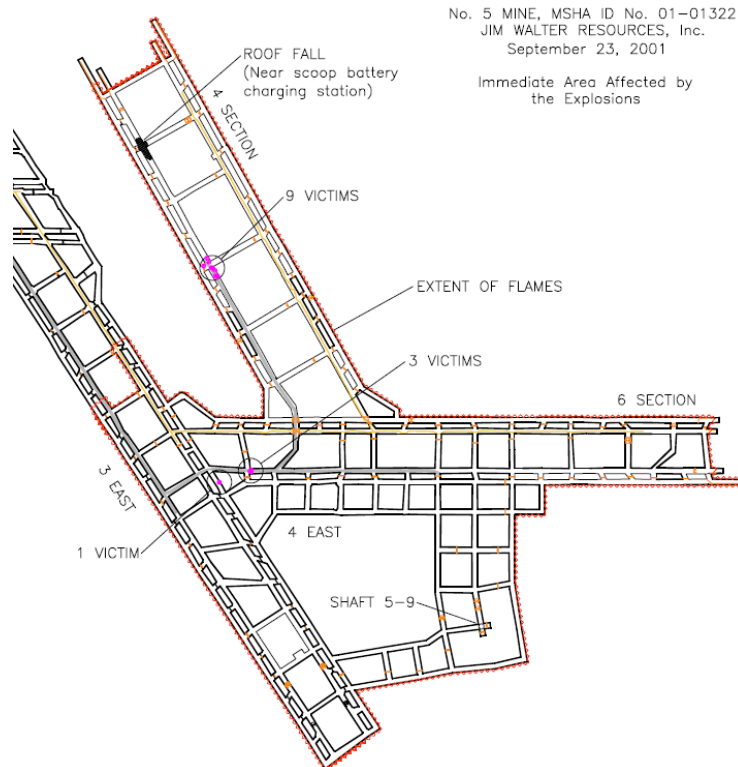
Figure 4.4: Jim Walter Resources No. 5 Mine Explosion Diagram (MSHA, 2002)

Benefits of Monitoring

It does not appear that atmospheric monitoring systems were installed in the affected areas of the mine. Atmospheric monitoring would not have prevented the initial roof fall, but it would have determined developing explosive conditions and given the miners advance notice to exit the working section. Atmospheric monitoring systems would have alerted mine operators to automatically cut power to underground areas, thus deenergizing the block light system. Atmospheric monitoring would have also prevented the second explosion from fatally injuring 13 miners because it would have been determined it was unsafe for them to enter 4 section and forced a full evacuation. Although, the MSHA investigative report noted that the miners were ordered to leave the mine, but disobeyed the order, refusing to leave the missing miners behind, which an AMS would not have been able to prevent. Even if the AMS did not survive the first explosion in 4 Section, it is likely that the system would have survived in outby areas which could have yielded key information about methane levels and airflow. Damages to the ventilation controls in 4 Section would most likely cause changes in airflow quantities outby of 4 Section.

Table 4.5 provides a summary of the roles monitoring could have had in the Jim Walter Resources No. 5 Mine disaster.

Table 4.5: Jim Walter Resources No. 5 Mine Disaster Summary

Detection/Sensing/Monitoring		Jim Walter Resources No. 5 Mine		
		Roof Fall, Explosion, Explosion		
		Prevention	Escape	Rescue
Existing Handheld Monitoring	(CO, O$_2$, CH$_4$)	Low	High	High
Existing Belt Monitoring	(CO)	Low	High	High
Methane Monitoring of Returns	(CH$_4$)	? High ?	High	High
Multigas Monitoring of Returns	(CO, O$_2$, CH$_4$)	? High ?	High	High
Air Velocity Monitoring of Returns	(Velocity)	Low	High	High
Seals Monitoring (inby and outby)	(CO, O$_2$, CH$_4$)	Low	Medium	High
Seismic Monitoring (Large Scale)	(Frequency, Location, Magnitude)	Medium	Low	Low
Lightning Detection		Low	Low	Low
System Survivability		Low	Medium	High

4.3.3 INTERNATIONAL COAL GROUP SAGO MINE

Background

A methane ignition in a recently sealed area of the mine triggered a larger explosion on January 2, 2006 at 6:26am at International Coal Group's Sago mine. The explosion pulverized all ten of the omega seals inby of the 2 North Mains seals (MSHA, 2007a). The explosion sent smoke, dust, debris, carbon monoxide, and methane into the working sections of the mine. One miner died of carbon monoxide poisoning shortly after the explosion. Sixteen miners working in the One Left section were able to escape, but the twelve miners working in the Two Left section

were unable to escape and retreated to await rescue behind a curtain at the working face. Figure 4.5 shows a diagram of the Sago mine (MSHA, 2007a).
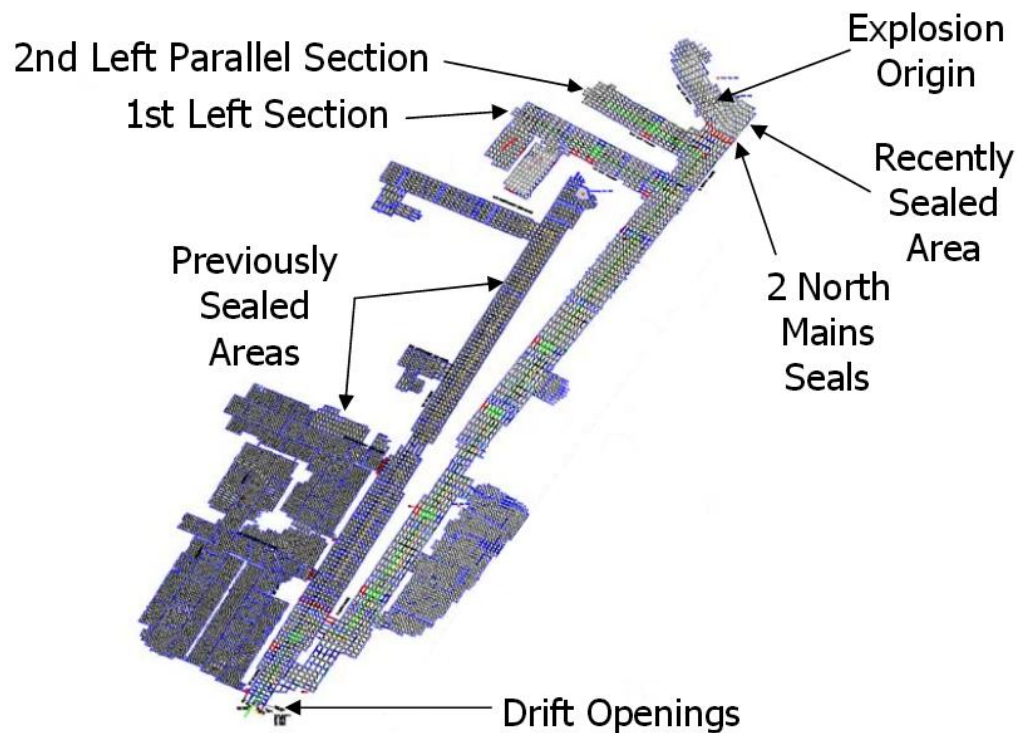
Figure 4.5: Sago Mine Diagram (MSHA, 2007a)

Mine rescuers attempted to restore the ventilation damaged by the explosion, but were unable to using temporary ventilation controls. They had to initially evacuate the mine because rescuers were unable clear the smoke and gases. Elevated CO and methane levels further delayed mine rescue teams from entering the mine. MSHA (2006c) states "Initial instrument readings (handheld detectors) at the mine portals indicated that 500ppm of carbon monoxide and 1.5% concentration of methane were exiting the mine via the ventilation current. Carbon monoxide is an indicator of a possible fire and methane is an explosive gas. Safe entry into the mine could not be accomplished until trending of carbon monoxide and methane gases indicated an active fire was not present." After gas concentrations stabilized, rescuers entered the mine and found the first victim near the Two Left section track switch on January 3. On the evening of January 3, mine rescue teams were able to advance into the Two Left section where 12 miners had barricaded themselves near the working face. Approximately 41 hours after the explosion, one miner was found alive but the other 11 miners had passed away due to carbon monoxide poisoning.

The dispatcher monitored an atmospheric monitoring system that consisted of sensors placed throughout the mine that relayed a continuous readout of CO levels at each sensor located along each belt conveyor entry, belt startup, belt shutdown and mine power status (MSHA, 2007a). An alarm recorded CO levels of 51ppm at 57 Crosscut, No. 4 Belt at approximately 6:26:35AM. The AMS system was equipped with a battery backup that maintained power until the mine rescue teams discovered the system energized during exploration. At 8:40am two foremen used handheld gas detectors and instruments measured the air quality was 47ppm CO, 0.0% methane, and 20.4% at the No. 1 Drift Opening of the return air. Air quantity was measured at 93,204 cfm. Air quality and quantity were repeatedly measured as time progressed at the No. 1-4 Drift opening return airways. The first gas chromatograph (CONSOL) arrived on site and was operational by 3:00PM. MSHA's Ventilation and Physical and Toxic Agents personnel arrived at approximately 5:15PM and began to setup atmospheric sampling equipment, consisting of infrared and electrochemical instantaneous monitoring equipment, a gas chromatograph, and all associated equipment.

Benefits of Monitoring

Atmospheric monitoring behind sealed areas would allow operators to estimate a reasonable time range of when sealed areas will be passing through the explosive range of methane (5%-15% by volume). Operators may choose not to work in the immediate surrounding areas when the sealed area is passing through the explosive range. Atmospheric monitoring systems in the mine would have been beneficial to rescue teams and allowed them to monitor the atmosphere post-accident to determine the best time to rescue trapped miners. It would have been beneficial to have remote monitoring of the 2 Left Section immediately after the explosion. Although the exhaust at the drift was monitored regularly, damage to ventilation controls on the mains outby and inby of 2 Left Section made it difficult to determine what the atmospheric conditions were in the sections, and slowed rescue efforts. Atmospheric monitoring sensors on 2 Left Section would have survived the explosion, but it is impossible to determine whether or not the data connection to the sensors would have been destroyed or blocked. It is possible that a wireless type system would have been capable of communicating through a roof fall. Table 4.6 provides a summary of the roles monitoring had in the International Coal Group Sago Mine disaster.

Table 4.6: International Coal Group Sago Mine Disaster Summary

Detection/Sensing/Monitoring		International Coal Group Sago Mine		
		Explosion from Lightning, Seals Breached		
		Prevention	Escape	Rescue
Existing Handheld Monitoring	(CO, O_2, CH_4)	Low	High	High
Existing Belt Monitoring	(CO)	Low	High	High
Methane Monitoring of Returns	(CH_4)	Low	High	High
Multigas Monitoring of Returns	(CO, O_2, CH_4)	Low	High	High
Air Velocity Monitoring of Returns	(Velocity)	Low	High	High
Seals Monitoring (inby and outby)	(CO, O_2, CH_4)	Medium	High	High
Seismic Monitoring (Large Scale)	(Frequency, Location, Magnitude)	Low	Low	Low
Lightning Detection		Medium	Low	Low
System Survivability		Low	High	High

4.3.4 MASSEY ENERGY ARACOMA ALMA NO. 1 MINE

Background

A fire started at the 9 Headgate longwall belt takeup storage unit of the Aracoma Alma No. 1 mine at approximately 5:14pm on January 19, 2006 (MSHA 2007b). Miners attempted to initially put out the fire, but failed and observed that smoke from the fire was traveling inby via the 2 Section intake air course. There were 29 miners working underground on the shift and the miners in the affected areas were not immediately notified or withdrawn from the mine when the AMS alarms detected high levels of carbon monoxide at 5:14pm.

After the 2 Section foreman was informed that smoke was traveling towards 2 Section in the intake air course, he gathered the other 11 miners on the section and headed outby on the main roadway. It was later determined that there was smoke in the intake air because there was

no separation between the primary escapeway and belt air course. MSHA (2007b) states, "Approximately 28 minutes elapsed between the time of the first CO alarm and the time evacuation of the miners on 2 Section was initiated." The group of 12 miners eventually encountered heavy smoke, donned their SCSRs and moved through a personnel man door to clear air in the belt entry. After entering into the belt entry the miners noticed two miners did not make it through the personnel man door. Three miners returned to the smoke filled intake air course to search for the two missing miners but could not find them and returned back to the clear air belt entry. The ten miners continued the evacuation along the alternate escapeway to a safe area outby of the fire.

Mine management personnel and later mine rescue teams traveled underground in attempt to find the missing miners and extinguish the fire, but were all unsuccessful. The fire continued to burn and forced a full evacuation of the mine. On January 21, the bodies of the two missing miners were discovered in the North East Mains and the fire was fully extinguished on January 24. Figure 4.6 shows a map of the North East Mains of the Aracoma Alma No. 1 Mine after the fire (MSHA, 2007b). Key locations in the Aracoma Alma No. 1 mine fire are labeled but roof falls are not shown.
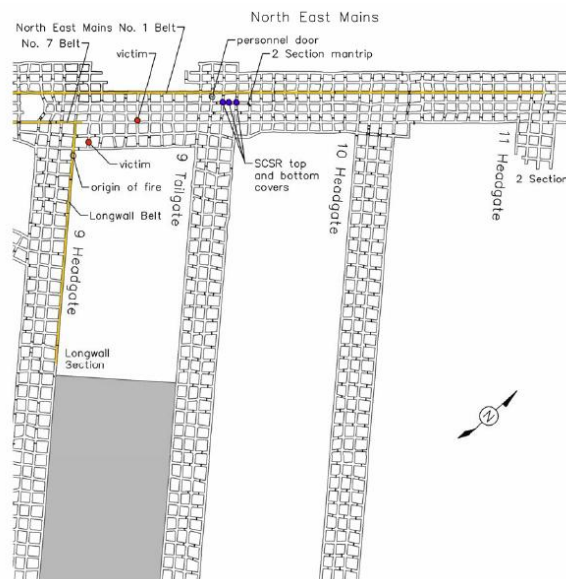
Figure 4.6: North East Mains of the Aracoma Alma No. 1 Mine after the Fire (MSHA, 2007b)

The MSHA Investigative Report identified the source of the fire as a frictional heating when the longwall belt drop-off carriage assembly did not properly disengage causing the belt to become

misaligned in the 9 Headgate longwall belt takeup storage unit (MSHA, 2007b). The initial frictional heating ignited accumulations of combustible materials. The required fire suppression system was not installed, firehose couplings were not compatible with fire valve outlets, and there was no water in the line to fight the fire. The MSHA Investigative Report noted, "Airflow carried the smoke from the fire to the No. 7 Belt entry and then into the primary escapeway for 2 Section because stoppings that were required to maintain separation between the belt entry and the primary escapeway for 2 Section had previously been removed" (MSHA, 2007b). Examinations of the mine were not sufficient and did not identify the lack of separation between the primary escapeway and belt air course.

Miners monitored gas concentrations in the airflow exhausting from the mine on the surface during the rescue operation. Initial CO concentration levels at the Ethel fan were reported of 865ppm at 10:00pm. CO levels in air exhausting from the mine through a borehole located inby the fire in the North East Mains were 1,300ppm at 11:28pm and reached 1,700ppm during the initial exploration stages. Light to heavy smoke was encountered at the furthest point of advance in 4 Right. CO concentrations as high as 500ppm were detected in locations in the 4 Right entries, but later it was determined that some handheld detectors had a maximum range of 500ppm. Gas concentrations measured 500ppm CO, 20.4 percent oxygen, and 0.0 percent methane in the 9 Headgate entries.

Benefits of Monitoring

The Pyott-Boone AMS, Model 9500 was installed at the mine to measure CO concentrations along the belt system. It is common practice in the United States to only monitor along beltlines, but monitoring in other areas, such as returns would provide valuable information about the development of unsafe conditions and can allow for a more direct evacuation. CO alert or warning levels were set to 5ppm and alarm levels were set to 10ppm. Figure 4.7 contains an image of a carbon monoxide sensor (MSHA, 2007b).

Figure 4.7: Pyott-Boone Carbon Monoxide Sensor (MSHA, 2007b)

Required responses to alerts/warnings, alarm, and malfunction were specified in Section 75.352, which required the dispatcher to contact mine foremen, supervisors, electricians, belt examiners, and/or beltmen to investigate the cause of the signals. The mine did not properly use the AMS to alert personnel underground when CO alarm indicated possible danger. If personnel were properly alerted when the initial CO alarm sounded at 5:14pm, miners could have started to move outby and to safer areas of the mine. A full evacuation may not have been necessary due to one alarm sounding (possible false alarm), but more than one sensor alarming would have indicated miners should move to safer areas of the mine while the severity of the situation was investigated.

The MSHA investigation found inconsistencies in CO sensor spacing, sensor calibration records, and responses to alarms by the surface and underground personnel. MSHA (2007b) shows an extensive ten page description of the various ways the mine did not satisfy or comply with AMS requirements. Weaknesses in current AMS give mine operators and personnel a false sense of security and often keep personnel from responding quickly to alarms even though it is required by law. Current AMS sensors are often limited to only being able to measure the lower explosive level of methane or some other low range (500ppm CO). Additional gas monitoring sensors strategically placed underground throughout the mine would have also allowed mine rescue teams to determine the location of the fire faster. AMS could have been used to quickly determine that there was a lack of separation between the two air courses. AMS could have also detected rising toxic gas concentrations or the presence of a fire. Table 4.7 provides a summary of the roles monitoring could have had in the Massey Energy Aracoma Alma No. 1 Mine Fire.

Table 4.7: Massey Energy Aracoma Alma No. 1 Mine Fire Summary

Detection/Sensing/Monitoring		Massey Energy Aracoma Alma Mine No. 1		
		Belt Fire		
		Prevention	Escape	Rescue
Existing Handheld Monitoring	(CO, O_2, CH_4)	Low	High	High
Existing Belt Monitoring	(CO)	Medium	High	High
Methane Monitoring of Returns	(CH_4)	Low	High	High
Multigas Monitoring of Returns	(CO, O_2, CH_4)	Low	High	High
Air Velocity Monitoring of Returns	(Velocity)	Low	High	High
Seals Monitoring (inby and outby)	(CO, O_2, CH_4)	Low	Low	High
Seismic Monitoring (Large Scale)	(Frequency, Location, Magnitude)	Low	Low	Low
Lightning Detection		Low	Low	Low
System Survivability		Low	Medium	Medium

4.3.5 *JERICOL MINING INC. (OPERATED BY KENTUCKY DARBY LLC) DARBY NO. 1 MINE*

Background

An explosion occurred at approximately 1:00am in the sealed A Left Section of the Kentucky Darby, LLC, Darby No. 1 Mine on May 20, 2006. The explosion fatally injured five miners and injured one miner. The MSHA Investigative Report (2007c) states, "A methane explosion occurred behind the seals at A Left, which was caused by the cutting of a metal roof strap that passed through the No. 3 Seal. The forces from the explosion resulted in fatal injuries to two miners and complete destruction of the seals. Forces from the explosion also damaged conveyor belt structure, roof supports, and ventilation controls". An acetylene torch was determined to be the cause of the explosion. The four miners who were working in the B Left

Section attempted to evacuate, but encountered thick smoke. The four miners donned their SCSRs, but two of the miners intermittently removed their mouthpieces to communicate and eventually became separated from each other. It appeared that none of the four miners had a detector capable of detecting carbon monoxide. The MSHA Investigative Report (2007c) states, "One miner survived and three died due to carbon monoxide poisoning with smoke and soot inhalation. Mine Management failed to ensure that proper seal construction procedures were utilized in the building of the seals at A Left Section. Mine management failed to ensure that safe work procedures were used while employees attempted to make corrections to an improperly constructed seal." Figure 4.8 shows a map with key locations of the Darby No. 1 Mine (MSHA, 2007c).
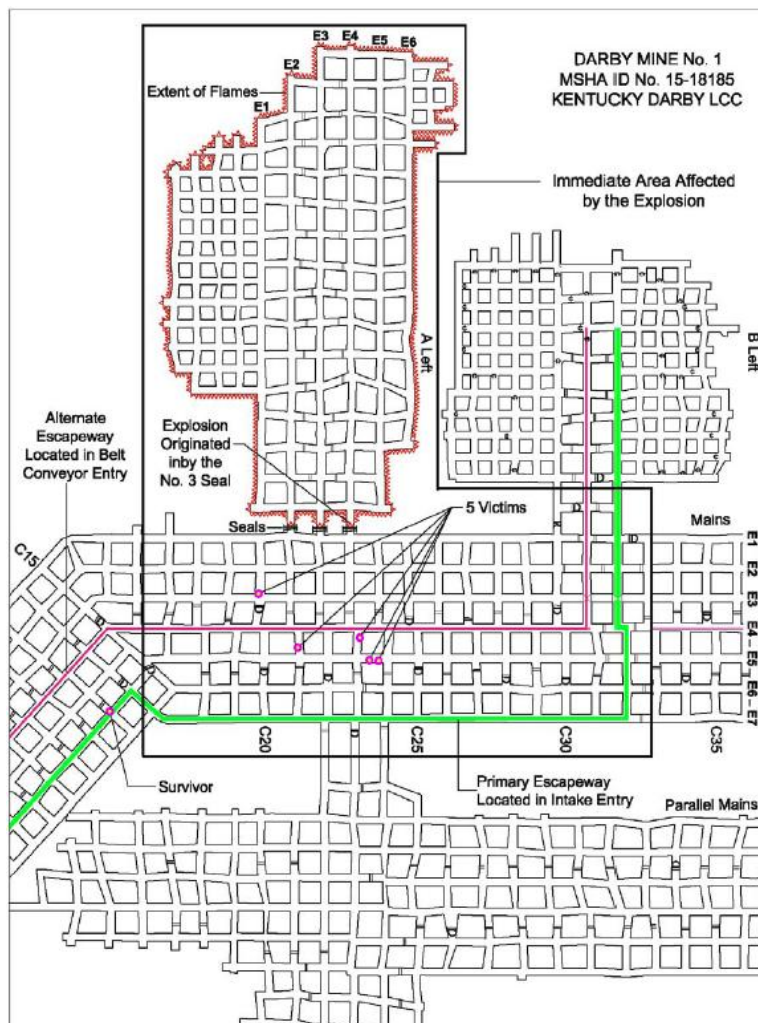
Figure 4.8: Darby No. 1 Mine Map with Key Locations (MSHA, 2007c)

One fatally injured miner was found after the explosion with an operational methane detector in his pocket. The use of an acetylene cutting torch was not in compliance with federal law. When the miner's body was found that was using the acetylene cutting torch, the handheld methane detector was sounding an alarm from the miner's pocket. This indicated that the explosion most likely occurred within the sealed area.

The fan was operating when an MSHA inspector arrived at the property and verbally issued a 103(k) order at 1:54am. The MSHA inspector detected 2.6 percent methane and over 500 ppm carbon monoxide at the fan using a MSA Solaris multiple gas detector. The MSHA inspector took an air sample at 2:01am that later found to contain 0.23 percent methane, 19.26 percent oxygen, and 6,162ppm carbon monoxide. An unorthodox decision was made by the rescuers present to enter the mine barefaced and preceded until their multiple gas detectors detected 50ppm carbon monoxide, low oxygen, or an explosive atmosphere. Later mine rescue teams arrived at the mine and assisted in the rescue operation. MSHA (2007c) notes that the barometric pressure started decreasing near the time of the accident and "a decreasing barometric pressure would cause the atmosphere behind the seals to expand in accordance with Boyle's Law, which states that the volume of gas varies inversely with the absolute pressure. The gas expansion would have caused the atmosphere in the sealed area to mitigate (sic) towards the seals and into the active workings through any opening."

Benefits of Monitoring

An atmospheric monitoring system with sensors behind sealed areas would have been beneficial to determine the explosibility of the atmosphere in the sealed area. The ultimate problem was that the seal's improper construction and the clear violation of using an acetylene cutting torch to cut into the sealed area. CO and methane sensors placed throughout the mains would have most likely survived the explosion and provided rescue teams with valuable information about the mine atmosphere during the rescue operation. Table 4.8 provides a summary of the roles monitoring had in the Jericol Mining Inc. Darby No. 1 Mine explosion.

Table 4.8: Jericol Mining Inc. Darby No. 1 Mine Explosion Summary

Detection/Sensing/Monitoring		Jericol Darby No. 1 Mine		
		Explosion Near Seals		
		Prevention	Escape	Rescue
Existing Handheld Monitoring	(CO, O_2, CH_4)	? Medium ?	Low	High
Existing Belt Monitoring	(CO)	Low	Low	High
Methane Monitoring of Returns	(CH_4)	Low	Low	High
Multigas Monitoring of Returns	(CO, O_2, CH_4)	Low	Low	High
Air Velocity Monitoring of Returns	(Velocity)	Low	Low	High
Seals Monitoring (inby and outby)	(CO, O_2, CH_4)	High	Low	High
Seismic Monitoring (Large Scale)	(Frequency, Location, Magnitude)	Low	Low	Low
Lightning Detection		Low	Low	Low
System Survivability		Low	Low	High

4.3.6 MURRAY ENERGY CORPORATION (OPERATED BY GENWAL RESOURCES INC.) CRANDALL CANYON MINE

Background

A catastrophic coal outburst accident occurred during a pillar recovery in the South Barrier section while the section crew was retreat mining the barrier pillar near crosscut 139. The outburst occurred at approximately 2:48 AM on August 6, 2007. The failure of overstressed pillars throughout the South Barrier section over a distance of approximately ½ mile expelled coal into the mine openings on the section and likely caused fatal injuries to six miners. The MSHA Investigative Report (2008b) states, "The barrier pillars to the north and south of the South Barrier section also failed, inundating the section with legally oxygen-deficient air from the adjacent sealed area(s), which may have contributed to the death of the miners. The resulting

magnitude 3.9 seismic event shook the mine office three miles away and destroyed the telephone communication to the section." Genwal Resources Inc. started a rescue plan (approved by MSHA) on August 8, to use the continuous mining machine to load burst debris from the South Barrier section No. 1 at crosscut 120. Figure 4.9 shows a map of the Crandall Canyon Mine with the two accidents labeled in red (MSHA, 2008b).
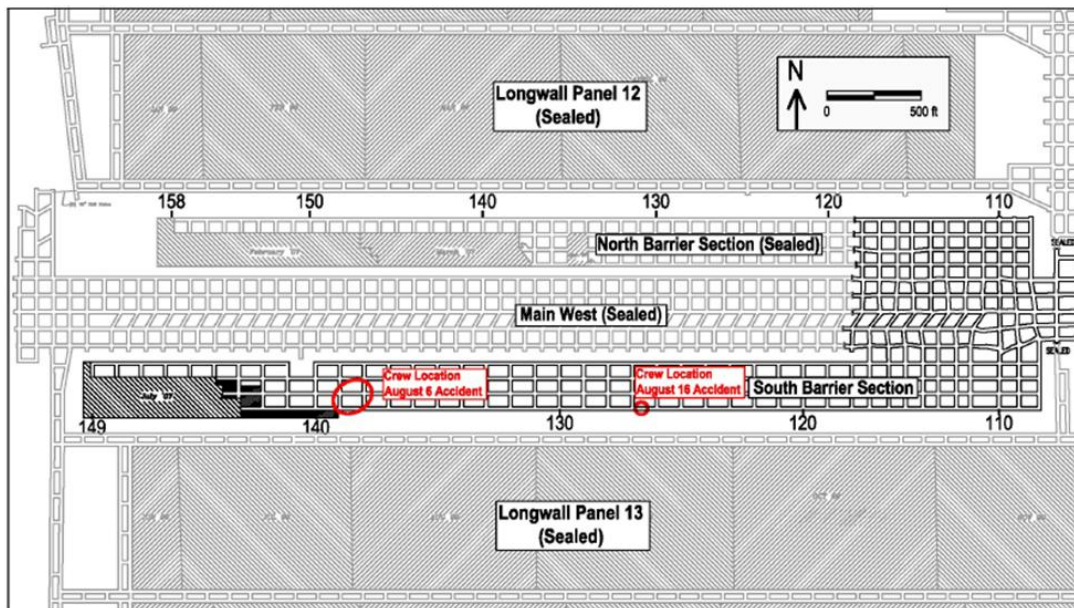
Figure 4.9: Crandall Canyon Mine Map with Accident Locations in Red (MSHA, 2008b)

A second coal outburst occurred at 6:38 PM from the pillar between No. 1 and No. 2 entries on August 16, 2007. Rescue workers were completing the installation of ground support behind the continuous mining machine when coal was ejected from the pillar. The second outburst fatally injured two mine employees and one MSHA inspector. The second outburst forced rescuers to suspend the rescue operation through the mine openings and continued the rescue operation by drilling boreholes from the surface. A total of seven holes were drilled but none identified the location of the trapped miners. MSHA (2008b) stated, "Ultimately, it was learned that the area where the miners were believed to have last been working sustained extensive pillar damage and had levels of oxygen that would not have sustained life."

The Analysis of Retreat Mining Pillar Stability (ARMPS), finite element analysis, and boundary element analysis methods were used and all three methods confirmed that the mine design factor of safety for ground stability was inadequate.

Benefits of Monitoring

It is possible that seismic monitoring could have enabled operators to determine that the mine was becoming unstable before the collapse. Modeling of the mine plan should have indicated poor stability before the design was approved, the strength of coal was estimated incorrectly by an outside contracting company. AMS sensors throughout the mine could have provided valuable information about the mine atmosphere if the sensors survived the first collapse. It is possible AMS sensors would have indicated that the mine atmosphere throughout the mine would not have supported life and the rescue efforts would have been suspended before the second collapse fatally injured three rescue workers. Table 4.9 provides a summary of the roles monitoring had in the Murray Energy Corporation Crandall Canyon Mine collapse.

Table 4.9: Murray Energy Corporation Crandall Canyon Mine Collapse Summary

Detection/Sensing/Monitoring		Murray Energy Crandall Canyon Mine		
		Massive Roof Failure, Failure During Rescue		
		Prevention	Escape	Rescue
Existing Handheld Monitoring	(CO, O_2, CH_4)	Low	Low	Low
Existing Belt Monitoring	(CO)	Low	Low	Low
Methane Monitoring of Returns	(CH_4)	Low	Low	Low
Multigas Monitoring of Returns	(CO, O_2, CH_4)	Low	Low	Low
Air Velocity Monitoring of Returns	(Velocity)	Low	High	High
Seals Monitoring (inby and outby)	(CO, O_2, CH_4)	Low	Low	Low
Seismic Monitoring (Large Scale)	(Frequency, Location, Magnitude)	? High ?	Low	High
Lightning Detection		Low	Low	Low
System Survivability		Low	High	High

4.3.7 ANALYSIS OF PAST DISASTERS CONCLUSIONS AND RECOMMENDATIONS

Accidents and disasters in underground coal mines are comprised of a combination of unforeseen circumstances. Accident reports attempt to summarize the events that caused an accident, but have the distinct advantage of hindsight. Decisions during rescue situations are often made in a chaotic environment that is emotionally charged with little data available. Monitoring systems in underground coal mines allow operators and miners to gain an advantage by allowing for immediate collection of data. Monitoring systems may help determine when the underground atmosphere, stress concentrations and other various conditions that can be monitored are becoming problematic. Monitoring systems can be utilized in order to aid mine operators in daily operation, and rescue teams in the event of an emergency.

Monitoring systems should be reliable, give information about the entire mine ventilation system, and allow for early detection of unsafe conditions to aid in preventing accidents. In the event of a severe incident, monitoring systems should be redundant in order to give the system the best chance of survival to continue to relay data during rescue operations. Monitoring systems should be able to measure data over the full range (i.e. above the lower explosive range, zero to 100 percent of gas concentrations) to quickly inform rescue efforts in a manner that protects rescuers and gives victims the best chance of survival. There is no evidence that mines have monitored for quantity (or velocity) data; which can provide valuable post-accident information about the state of ventilation controls.

In summary, the Plateau Mining Corporation Willow Creek mine explosion would have benefited from the real-time AMS being correctly utilized with the frequent presence of hydrocarbons. Hydrocarbons often can cause inaccurate readings regarding the explosibility of the atmosphere, as well as, the mine did not follow the ventilation plan to increase air quantities when hydrocarbons were present. The Jim Walter Resources Brookwood mine explosion may have benefitted from local seismic monitoring that would have indicated unstable roof conditions, but management had already realized the intersection needed additional support. An AMS that survived likely would have discouraged miners from attempting a rescue operation and instead encouraged an immediate evacuation or further reinforced to the miners that disobeyed evacuation orders that danger was imminent. The International Coal Group Sago mine explosion could have benefitted from an AMS system with sensors behind the seals to indicate

that the atmosphere was in the explosive range and that caution should be used or not to operate in the immediate area. An AMS would have allowed immediate knowledge of the atmospheric conditions on the 2 Left Section to better inform rescue efforts. The knowledge provided by an AMS would have relieved to the miners trapped on 2 Left Section that equipped with SCSRs it was potentially possible to reach fresh air. The Massey Energy Aracoma mine fire would have benefitted from a mine-wide AMS to have better informed evacuation efforts and CO sensors throughout the mine would have also been helpful. An AMS would have provided additional information yielding that action should have been taken immediately. The Jericol Mining Inc. Darby mine explosion occurred from the improper use of an acetylene cutting torch and construction of the seal. AMS sensors within the sealed area may have deterred the miner from taking the risk of using a cutting torch on the seal, given the concentrations behind the seal were known. The Murray Energy Crandall Canyon mine collapse may have benefitted from seismic monitoring but seismic monitoring is not currently a well-defined monitoring technique. A failure may be preceded by an increased number of seismic events, but it is tough to accurately quantify the significance of the observed increased number of events. If an AMS system survived the first collapse it may have deterred the second rescue effort. Crandall Canyon mine collapse is an example of non-ventilation related major accident and was analyzed due to the potential benefits of utilizing seismic systems.

It is recommended that continuous atmospheric monitoring be installed throughout the mine, on active working sections, and in sealed areas. Sensors strategically placed throughout the mine could provide a global understanding and provide redundancy in the event of an emergency. The integration of global monitoring systems in underground coal mines may prove in the future to benefit the miners and mine operators.

4.4 Sensor Placement and Recommended Best Practices

The United States Code of Federal Regulations provides guidance on the installation of Atmospheric Monitoring Systems (AMS) systems in underground coal mines. Primarily, AMS systems are installed for monitoring belt lines and electrical installations in the U.S. for smoke, CO, and CH_4, and automatically alarm at set thresholds (30 CFR §75.340, §75.350, §75.351). The Code of Federal Regulations does not specifically mandate where a comprehensive AMS sensors must be placed. Cauda (2012) provides an overview on the location that sensors should

be placed in a poorly ventilated mine entry. Sensor placement within an entry is determined by the gas' density relative to the densities of other gases that are found in underground coal mines. It is nearly impossible to predict the psychological processes going on inside a miner's brain during a mine emergency, although careful and frequent training can better prepare miners for emergency situations.

Atmospheric monitoring and communication systems in the United States have been designed to specific regulatory standards, but survivability is difficult to assess due to the massive forces that systems could be subjected to during a mine disaster. This is why it is important to design intelligent systems that can "heal" their communication's backbone with surviving equipment or install networks that can be quickly restored post-accident in order to be able to monitor and communicate. Mobile standalone atmospheric monitoring and communication systems may also be utilized in emergencies to quickly start monitoring and communicating with personnel trapped underground.

Mine specific risk assessment plans should be created in order to determine the areas where additional sensors should be installed. It is anticipated that nearby incidents can cause damage to sensors but the opportunity to have increased knowledge at more locations would prove to exceed the value of the initial capital investment of additional sensors. Additional sensors would reduce estimated gas travel times associated due to anticipated damage to ventilation controls in the immediate vicinity of an incident. While general guidelines such as locating sensors at major return nodes are useful in AMS design, site specific risk assessment is critical. The nature of each incident (forces) would likely cause methane to reach gas sensors at varying times because each specific incident ultimately provides different circumstances.

Historical mining disasters and explosions have been pin pointed to the tail end of the longwall, longwall gob, belt drives, sealed areas, battery charging stations, and several other key locations as discussed in Section 3.2. Historical mining disasters source locations suggest that these areas are the most problematic and should be watched closely to ensure history does not repeat itself. Remote areas (e.g. Bleeders) are often difficult to monitor because these areas are not easily accessible to place sensors on data links for real-time monitoring. Future developments with wireless communications will make remote areas more accessible for monitoring applications. Initial deployment of comprehensive AMS sensors should be placed at major return

nodes is a practical approach to monitoring and maintaining the AMS system but may not necessarily be the "most dangerous location" in the mine. Although, the benefit of sensors placed at all major return nodes is that it makes it easier to quickly isolate the source location of an incident. This is why it is necessary to evaluate a mine using risk assessment and management strategies in order to reduce the severity of the incident.

The underlying issue with all atmospheric monitoring systems as they relate to emergency management is ultimately the survivability of the system. Survivability will always be a hurdle that must be overcome given any incident. There is room for technology to advance in order to help make the survivability gap smaller. In recent disasters it has taken a significant period of time to ascertain the nature and extent of the incident and atmospheric monitoring systems can help pin point the severity of the incident and allow for more coordinated and educated emergency response. Network simulation of individual mines under different scenarios can be utilized to demonstrate the need to improve atmospheric monitoring sensors and monitoring schemes. Ventilation network simulation of several different mine emergency scenarios is further discussed in Griffin, et al, 2012.

CHAPTER 5: ATMOSPHERIC MONITORING IN UNITED STATES UNDERGROUND COAL MINES CASE STUDIES

Atmospheric monitoring systems are covered in the United States Code of Federal Regulations, Part 30 §75.351. Atmospheric monitoring systems are primarily installed to monitor belt lines and electrical installations for smoke, CO, and CH_4 with set prescriptive alert and alarm threshold levels (30 CFR §75.340, §75.350, §75.351). This chapter outlines two case studies utilizing atmospheric monitoring systems. The systems used in the case studies were primarily research orientated and were installed in two underground coal mines in the United States. The focus of this research study was to evaluate the feasibility of utilizing mine-wide monitoring systems and make recommendations for comprehensively monitoring atmospheric conditions in underground coal mines.

5.1 AMS General Guidelines

Comprehensive mine-wide atmospheric monitoring will provide important information that can be used to mitigate high risk circumstances. The aim of an atmospheric monitoring system should be to prevent ignitions and explosions in underground coal mines by intelligently making decisions based upon the gas concentrations measured by an AMS. Current regulations do not outline comprehensive mine-wide atmospheric monitoring (CFR 30 §75.351). Atmospheric monitoring can be achieved by combining independent devices to make up a complete system, which can be comprised of instrumentation (i.e. devices, sensors, PLCs), data networking technologies (i.e. twisted copper pair, Ethernet, fiber optics), surface computer with data acquisition software, and a main centralized data server with backup.

5.1.1 INSTRUMENTATION

The instrumentation installed in underground coal mines widely varies based on the manufacturer of the sensors or system. Furthermore, instrumentation differs between off the shelf devices to proprietary devices developed by an individual company. Proprietary instrumentation is often difficult or impossible to integrate into other existing systems that may already been installed in the mine. Data acquisition will vary based on the device and how the software

interacts. Several companies provide services to integrate proprietary devices into software monitoring packages to ensure the system comprised of multiple brands can function properly.

An underground coal mine presents a unique challenge when utilizing AMS as power requirements are dictated by the ventilation air course each section of the AMS resides within. It is critical that installation of AMS is carefully planned out to account for future expansions of the monitoring system as the mine develops.

The risk for an explosion in an intake air course is typically minimal and devices are not required to be permissible, therefore most non-permissible devices can be used in fresh air or intake ventilation air courses. Permissible devices are the only devices allowed to be used in the return airway of an underground coal mine, and must meet specific requirements that limit voltage, current, and potential interaction with the surrounding atmosphere. Permissible AMS devices are typically limited to lower voltages (<24 volts) than non-permissible devices to ensure that electrical interaction does not inadvertently cause an ignition. Permissible power limitations restrict the number of devices that can be powered from a single 24 volt DC power source, as many of these devices require relatively higher voltages.

Real-time atmospheric monitoring sensors are most commonly powered through a variation of copper twisted pair, which contain both positive and negative power wires, as well as data send and receive wires. Atmospheric monitoring sensors are often connected to an outstation located underground that contains a Programmable Logic Controller (PLC) or a similar routing and data gathering device, an analog-to-digital converter (ADC), a power supply and several other necessary electrical components housed in an explosion proof (XP) box. Outstations are generally placed in intake airways and have optional battery backup capability. A PLC is a personal computer (PC) that has been reduced to a micro-sized package which has been industrialized to allow the computer to operate in a wide variety of temperature ranges and electrical noise characteristics (Hooper, 2006). PLCs are used extensively to control devices in the case studies presented in this work to collect, route, and transmit data to other devices located on the mine intranet that will then archive data as it is received. The specific setup of the data acquisition system will vary based on the mine's power and data infrastructures. This work has simplified the data acquisition process of measuring an analog signal and converting it to a digital database. Smith (2003) provides an overview of digital signal processing. Figure 5.1 is a

simplified diagram of sensors connected to an outstation that contains a PLC. Sensors placed inside a return airway require a barrier device to be placed between sensors and the outstation.
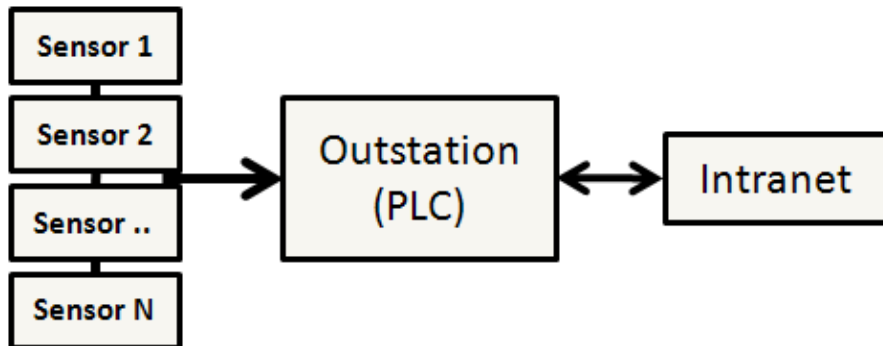
Figure 5.1: Simplified Intake Airway Sensors and Outstation Data Flow Diagram

The number of sensors each outstation can handle depends on the sensor power requirements, cabling distance to each sensor, and other factors. Sensors placed inside a return airway require a barrier device to be placed between sensors and the outstation. The barrier device decreases the voltage from approximately 120 volts AC to 24 volts DC and ensures, the sensors will not provide feedback beyond the barrier device in the event of an explosion. Figure 5.2 shows a simplified diagram of sensors connected to an outstation through a barrier device in a return airway.
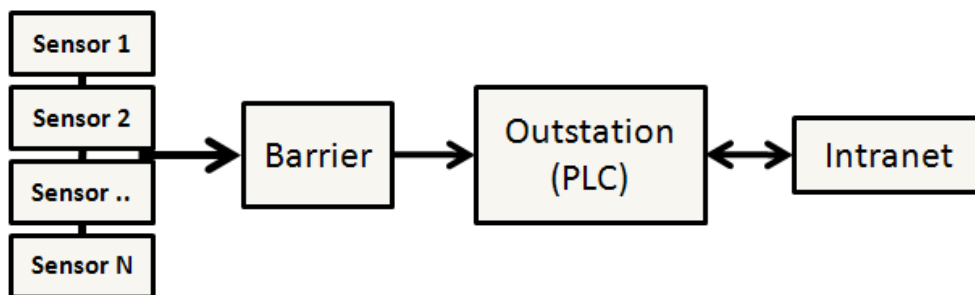
Figure 5.2: Simplified Return Airway Sensors, Barrier, and Outstation Data Flow Diagram

An outstation can be used to aggregate data from multiple sensors. Data measured by the sensors must be tagged by the outstation's PLC in order to ensure data from each sensor is kept separate. An outstation's communication module allows data network(s) to be utilized to alleviate power issues by providing data connections between outstations or other devices underground, while providing power closer to the outstation. Reinforced mine grade fiber optics are the most commonly used high speed data communication medium to most efficiently alleviate AMS

power requirements. The data network plays an important role in ensuring AMS components have connectivity as a mine develops since a mine is a dynamic operation and power requirements are constantly changing as ventilation air courses are modified.

In this study analog sensors were used to measure voltages in given ranges. A PLC can be programmed to interrogate a sensor at a predetermined time interval and the sensor will return the measured voltage at that specific time. Figure 5.3 shows the inside of an outstation which contains a power supply, PLC, integrated circuit board, and communication module.
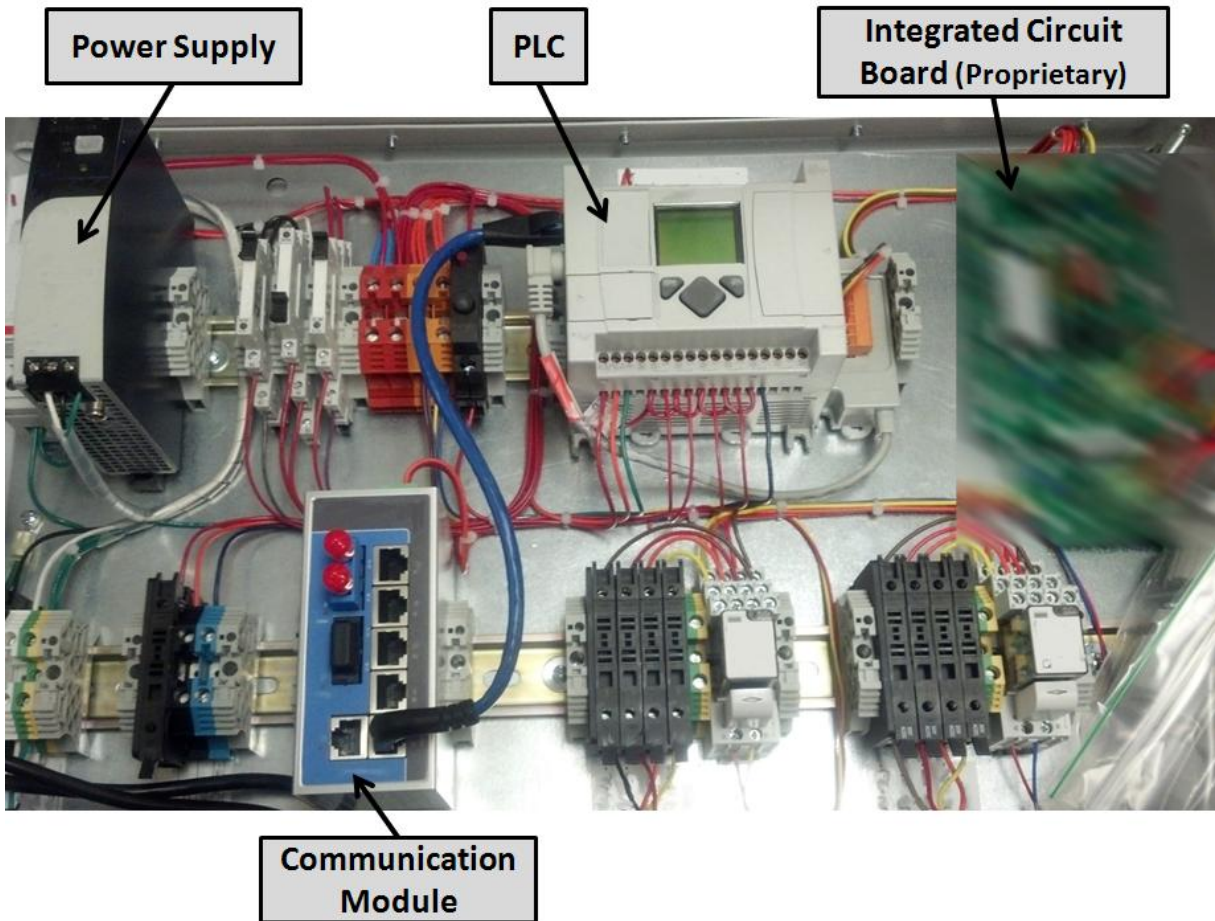
Figure 5.3: Inside of an Outstation

The sensor's measured analog signal (voltage) is translated by an Analog-to-Digital Converter (ADC) into a digital signal to the PLC. The ADC has a bit rating that directly impacts the accuracy and precision of the sensor. Fraden (2010) provides an extensive overview of modern sensors. The PLC will then retransmit measurements from sensors, through the intranet, where a dedicated computer and data acquisition software is used to record and display data in real-time.

Figure 5.4 shows data flow for a simplified AMS diagram with sensors located in a permissible area.
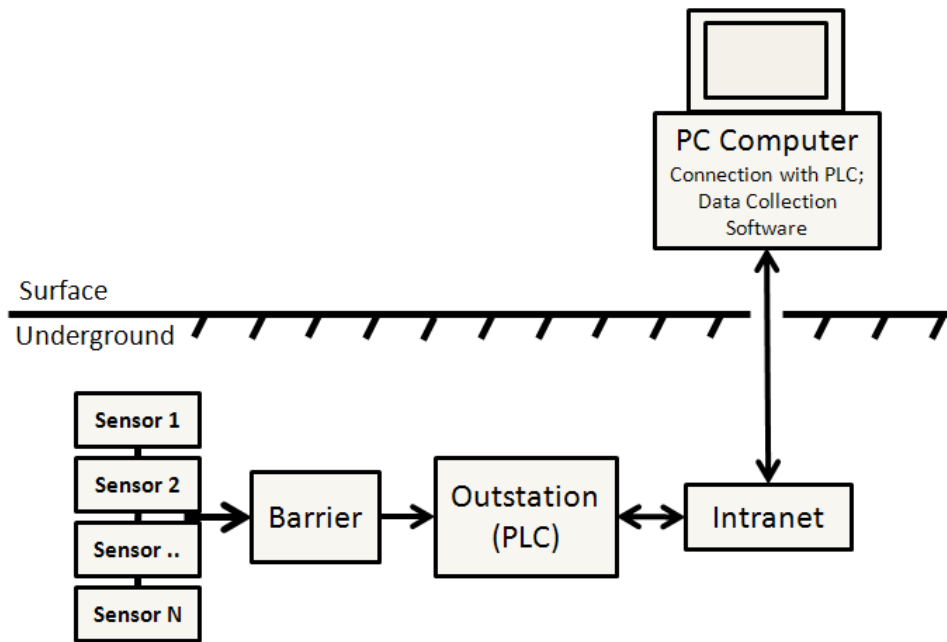
Figure 5.4: Simplified AMS Data Flow Diagram with Sensors Located in Return Airway

The data acquisition software on the surface computer can be customized in an infinite number of ways depending on how users want to handle the data. The overall goal of monitoring is to collect incoming data, display in real-time, archive the data, and warn appropriate individuals when alert and alarm conditions have been met. Alert and alarm conditions may be found in CFR 30 §75.351 for specific atmospheric monitoring parameters.

5.1.2 INSTALLATION

The design of an AMS will vary based on the monitoring areas, ease of access between the surface and desired monitoring areas, available power sources, how the data is handled, available communication mediums, preexisting systems, and other challenges unique to each operation. The required installation time will vary based on the same factors that impact the design of an AMS. Installation of the system consists of placing and correctly orienting each sensor and connecting communication cabling and power infrastructures to sensors and support devices, as shown in Figure 5.4 above. The installation of a mine-wide comprehensive AMS is

comparable to the installation of a communication and tracking system of similar infrastructure size.

Power requirements will become the biggest issue with installation-and maintaining an AMS over time. Since power is generally limited to specific locations in an underground coal mine, particularly near power centers and belt drives. Sensors may require standalone power, while other sensors utilize a power and data combination cable. Power will always be required to outstation devices and barrier boxes. It is best to connect outstations with data networking cabling instead of power and data combination cabling. Power degradation is based on Ohm's law and may be calculated given the cabling's specific power loss per unit length and the number of devices desired to operate at a given point. Shafts also present a unique challenge when installing AMS since guide wires and heavily reinforced cabling are necessary to ensure data network cabling does not experience failure under the cable's own weight.

5.1.3 DATA MANAGEMENT

Data management of an AMS is crucial to ensure that the integrity of historical data is maintained and the system is actually utilized for improving safety. Under current AMS regulations (CFR 30 §75.351), data archiving is not required. The regulation states that the following records must be kept for one year at a surface location at the mine made for inspection by miners and authorized representatives of the Secretary (CFR 30 §75.351 (o) Recordkeeping):

> *(o) Recordkeeping. (1) When an AMS is used to comply with § § 75.323(d)(1)(ii), 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), 75.350(d), or 75.362(f), individuals designated by the operator must make the following records by the end of the shift in which the following event(s) occur:*
>
> *(i) If an alert or alarm signal occurs, a record of the date, time, location and type of sensor, and the cause for the activation.*
>
> *(ii) If an AMS malfunctions, a record of the date, the extent and cause of the malfunction, and the corrective action taken to return the system to proper operation.*
>
> *(iii) A record of the seven-day tests of alert and alarm signals; calibrations; and maintenance of the AMS must be made by the person(s) performing these actions.*
>
> *(2) The person entering the record must include their name, date, and signature in the record.*

The required records are limited to alert or alarm signals, malfunctions, system tests, and calibration. Figure 5.4 above shows a simple form of data management in which the data is read by the sensors, collected and retransmitted through the outstation, and then collected and archived by a computer on the surface. An atmospheric monitoring station may be defined as a section of the overall AMS, designated by an outstation or PLC device and sensors. Each monitoring station can communicate via the intranet or internet to a client utilizing PLC software to collect and archive data. Figure 5.5 shows a simplified diagram of monitoring stations communicating through the intranet and internet to clients where data is archived.
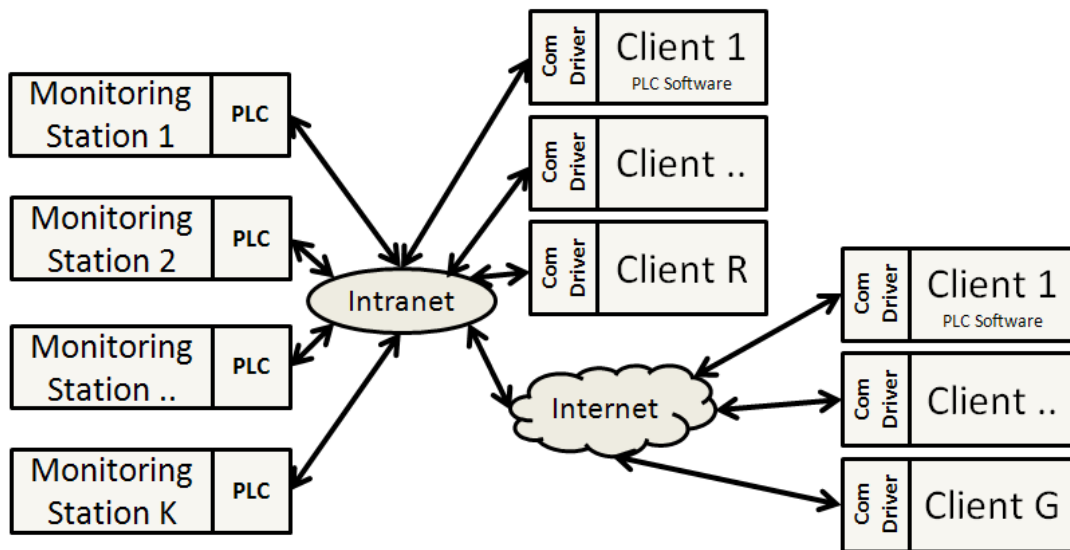
Figure 5.5: Simplified Data Flow of Monitoring Stations Communicating with Clients

A company ideally should set up a centralized server to collect data from each mine's AMS. The centralized server should be connected to a file backup system or redundant array of independent disks (RAID). These centralized servers may also be used to store data from mining operations and processing plants. Figure 5.6 shows a generalized schematic, where several AMS, mining operations, and processing plants sync via the internet to the centralized server.
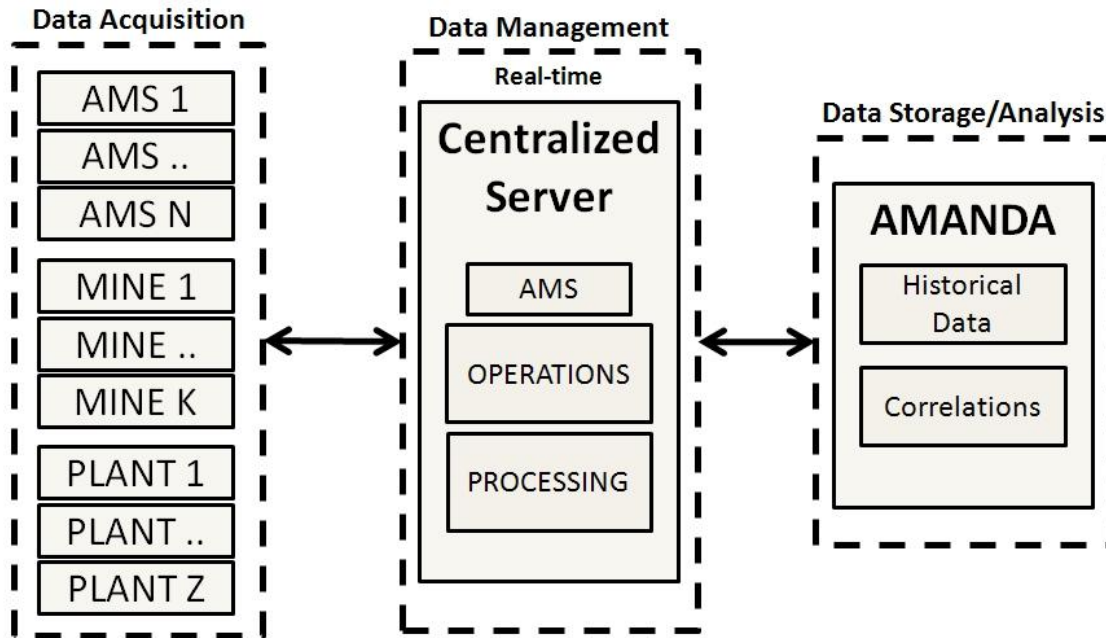
Figure 5.6: Generalized Schematic of Company-Wide Data Flow with Centralized Server

Network security at the mines and the centralized server will need to be addressed and proper measures must be taken to ensure the system or data is not compromised.

Atmospheric monitoring data should be assigned to a mine ventilation engineer or a team of individuals that have extensive knowledge of the operation, the mine ventilation, engineering, and management to ensure the group has a complete understanding of the operation and typical gas emissions. Qualified individuals should be responsible for daily, weekly, and monthly oversight on problematic areas of the mine and potential trends that may be developing.

One way in which data can be managed from an AMS is through the use of the application Atmospheric Monitoring Analysis aNd Database mAnagement (AMANDA), which was developed by Zach Agioutantis. AMANDA utilizes a relational database to analyze and manage atmospheric monitoring data. Relational database models were first introduced by Edgar F. Codd in 1970 (Codd, 1970). The relational database model's major advantages over hierarchical and network databases models are its flexibility and minimal redundancy. As noted by Taylor (2007), "it is much easier to restructure a relational database than it is to restructure either a hierarchical or network database." AMANDA allows data from any number of sensors located on the surface or underground to be managed and analyzed. AMANDA stores data in a database instead of individual files. It is an application based on the Firebird database engine,

which practically has no limit on table size. Firebird (2013) provides an extensive overview of the Firebird database, its capabilities and limitations.

AMANDA utilizes a collection of tag groups and tags. A single measured value or one stored value corresponds to a single tag (e.g. each sensor will be identified by a tag; measured concentrations or other data through this sensor are tagged accordingly for easy retrieval). Projects may be setup within AMANDA to separate different mines or installations within the same mine. AMANDA was designed to interface with Rockwell Automation's RSView32 software data formats (Rockwell, 2013), but can easily be amended to support other data formats. Data can be automatically imported from ".dat" and ".dbf" files typically produced by RSView32 installations once tags are setup. In addition, data available from other sources (i.e. weather stations) can be imported into AMANDA once the appropriate tag groups and tags are set. The user can then view the data or generate simple or composite plots for a number of tags for various dates or periods.

Data management can quickly become a problem given the large number of sensors that are setup in underground coal mines. In AMANDA, each data value requires a storage space of about 50 bytes. If one data value is sampled every ten seconds, there would be approximately 432,000 bytes (0.412MB) of data generated per sensor, per day. If the mine has 20 sensors, then approximately 8.2MB of data is generated daily. One year of data with only 20 sensors generates approximately 3.0 GB of data. Large mining operations and processing plants may incorporate hundreds to thousands of sensors throughout the operation to control and monitor devices. If a large mining operation deployed 300 sensors and its processing plant utilizes 400 sensors, with a sampling frequency of 10 seconds, those sensors would generate approximately 288MB daily and 105GB each year. If the data sampling frequency was increased to 5 seconds, those 700 sensors would generate approximately 210GB each year. High risk areas may benefit from a higher sampling frequency of every second, which would further increase the amount of data generated each year. If a company owned several large mining operations and processing plants, the amount of data generated could quickly become problematic to maintain, store, review, analyze, and interpret. The massive undertaking of maintaining, storing, reviewing, analyzing, and interpreting large amounts of data generated daily makes it necessary to properly place sensors at the locations which will yield the most information.

5.1.4 MAINTENANCE

Maintenance is a critical and costly part of any comprehensive system installed in a mine, and AMS are no exception. Maintenance is crucial to ensure the system will function properly in an emergency scenario, and more importantly, in the prevention of emergencies. While 30 CFR §75.351 outlines the expected maintenance for an AMS, regulations are not specifically written for a comprehensive AMS, but a comprehensive AMS would likely be maintained in a similar method as existing AMS for belt installations. CFR 30 §75.351 states the following regarding examination, testing, calibration:

> *(n)* Examination, testing, and calibration. *(1) At least once each shift when belts are operated as part of a production shift, sensors used to detect carbon monoxide or smoke in accordance with § § 75.350(b), and 75.350(d), and alarms installed in accordance with § 75.350(b) must be visually examined.*
>
> *(2) At least once every seven days, alarms for AMS installed in accordance with § § 75.350(b), and 75.350(d) must be functionally tested for proper operation.*
>
> *(3) At intervals not to exceed 31 days—*
>
> *(i) Each carbon monoxide sensor installed in accordance with § § 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), or 75.350(d) must be calibrated in accordance with the manufacturer's calibration specifications. Calibration must be done with a known concentration of carbon monoxide in air sufficient to activate the alarm;*
>
> *(ii) Each smoke sensor installed in accordance with § § 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), or 75.350(d) must be functionally tested in accordance with the manufacturer's calibration specifications;*
>
> *(iii) Each methane sensor installed in accordance with § §75.323(d)(1)(ii) or 75.362(f) must be calibrated in accordance with the manufacturer's calibration specifications. Calibration must be done with a known concentration of methane in air sufficient to activate an alarm.*
>
> *(iv)If the alert or alarm signals will be activated during calibration of sensors, the AMS operator must be notified prior to and upon completion of calibration. The AMS operator must notify miners on affected working sections, areas where mechanized mining equipment is being installed or removed, or other areas designated in the approved emergency evacuation and firefighting program of instruction (§75.1502) when calibration will activate alarms and when calibration is completed.*
>
> *(4) Gases used for the testing and calibration of AMS sensors must be traceable to the National Institute of Standards and Technology reference standard for the specific gas. When these reference standards are not available for a specific gas, calibration gases must be traceable to an analytical standard which is prepared using a method traceable to the National Institute of Standards and Technology. Calibration gases must be within 2.0 percent of the indicated gas concentration.*

The components and wiring of the AMS must be routinely inspected to ensure the system is functioning correctly. Federal and state laws will dictate the frequency and portion of the system that must be inspected. Alarming functions must also be inspected on a routine basis (weekly). The employee performing the inspection must be certified with a federal electrical card. Required man hours for maintenance will vary based upon the performance of the system, if

there are faulty sensors and problematic areas where current sensors may experience contamination from outside sources (i.e. diesel for carbon monoxide sensors).

Mine power system reliability can directly impact the requirements for maintenance if not properly addressed. Frequent power outages, brownouts, power surges, and other electrical issues will negatively affect the behavior of an AMS. Battery backup power is recommended to ensure that power will be supplied to the system during power outages and brownouts. Battery backups alleviate additional maintenance requirements associated with restarting outstations underground and optimize the functionality of an AMS. Non I.S. systems must be deenergized during extended mine fan outages or mine power outages. Systems that utilize battery backup are required to follow non-permissible electrical equipment regulations to deenergize during specific circumstances (i.e. greater than 1.0% methane, extended fan outage). If outstations do not utilize battery backup and power to the outstations has been lost, there will be more individual components that must be reset after an outage. The more components that need to be reset, the more difficult the system is to utilize. Battery backup can alleviate these power issues by providing power to outstations during minor outages. Whether battery backup is utilized or not, it is extremely important to avoid having power restored to uninspected permissible/return areas. Each area must be inspected by a certified fireboss before work can be performed in any areas of the mine after a power outage or before a shift. Specific firebossing standards may be found in 30 CFR §75.

Atmospheric monitoring sensors require frequent calibration to ensure each sensor performs correctly. Calibration is required every 31 days (monthly) for CO belt monitoring systems, as prescribed in, 30 CFR §75.351. Calibrations for the two systems used in the case studies below utilize a zero and scale gas of known concentrations. The carbon monoxide sensors were calibrated using oxygen (O_2, 20.9%) as the zero gas and carbon monoxide (CO, 25ppm) as the scale gas. The methane sensors were calibrated with oxygen (O_2, 20.9%) as the zero gas, and methane (CH_4, 2.5%) as the scale gas. The oxygen sensors were calibrated with nitrogen (N_2, 99-100%) as the zero gas and oxygen (O_2, 20.9%) as the scale gas. Figure 5.7 shows an example of a calibration spike starting at 18:13:16 (6:13pm, 16 seconds) is when the CO sensor was calibrated underground using a calibration concentration of 25ppm CO.
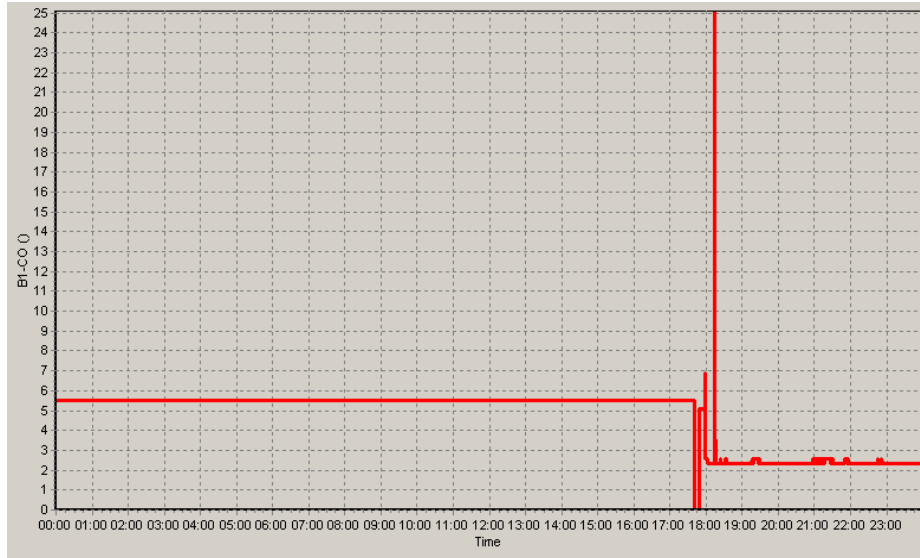
Figure 5.7: Graphical Calibration Confirmation of Carbon Monoxide Sensor

The calibration can be confirmed numerically within the raw data. The raw data shows the spike starting at 18:13:16 (6:13pm, 16 seconds) with an initial CO concentration of 2.3ppm, rising steadily to 25.0ppm CO at 18:14:26 (6:14pm, 26 seconds). From here it levels off at 18:15:46 (6:15pm, 46 seconds), with a CO concentration of 2.5ppm. The field survey data confirms the calibration of the sensor was performed between 5:55pm to 6:15pm.

5.1.5 REGULATORY IMPLICATIONS

The wide spread integration of AMS in the United States has the potential to increase safety and ventilation standards in underground coal mines, and there are many regulatory implications. While United States mine safety regulations are prescriptively written and typically provide little to no incentive for operators to integrate additional safety systems beyond compliance, there are notable examples of operators who have done so. Prescriptive regulations allow operators to comply with minimum safety requirements and often force compliance or increased regulatory oversight. Yang (2012) stated, "This type of highly prescriptive regulation prevents companies from developing a risk management model. On the one hand, compliance consumes the resources that companies could use to adopt the model; on the other hand, such regulation creates a compliance mentality that is not compatible with the idea of risk management, which expects operators to proactively identify, analyze, and control hazards." Recent mine safety legislation (i.e. Mine Improvement and New Emergency Response, MINER

Act) as well as recent draft legislation (i.e. Robert C. Byrd Mine Safety Protection Acts of 2010) have primarily been focused on emergency response. The MINER Act's major changes include development of emergency response plans, standards for post-accident communications, post-accident tracking, post-accident breathable air, post-accident lifelines, training, changes in requirements for mine rescue teams, increased civil and criminal penalties, increased standards for sealed areas, and penalties for failure to notify MSHA (i.e. within 15 minutes) of an accident that may result in a fatality or entrapment (MSHA, 2006b). The changes enacted by the MINER Act focused on emergency response and dealing with catastrophes and disasters rather than accident prevention (i.e. monitoring of sealed areas).

The National Research Council (2013) stated, "The current technology regulatory and approval process in the United States appears to be a deterrent to rapid technological innovation and access to global markets, which hampers the commercial viability of innovation." The National Research Council (2013) recommended that NIOSH and MSHA should re-examine the technology approval and certification processes to ensure they are not deterring innovation in relation to self-escape technologies. The current technology approval and certification process makes it more difficult to transfer technology and practice developed outside of the United States.

5.2 United States Underground Coal Mine Case Study I

In the first case study presented in this work, a real-time AMS was installed in an underground coal mine to gain a better understanding of design, installation, data collection and analysis, daily utilization, and performance issues that a mine may experience during daily operation. The AMS' sensors were placed in four strategic areas that were each chosen to gain a better understanding of the behavior of the mine ventilation system. The areas monitored were a longwall bleeder in two parts, the return airways of section mains, and return airway of a development section. The major return node monitoring scheme was chosen to demonstrate the benefit a minimal AMS monitoring scheme could provide. The system was used to monitor gas concentrations and air velocities in real-time. The monitoring system was MSHA approved and state approved for mine location. The system is permissible, but is not I.S. The methane, oxygen,

carbon monoxide, and air velocity sensors used were pellistor, electrochemical, electrochemical, and thermal mass flow type sensors, respectively for each area described above.

5.2.1 BACKGROUND

An AMS was installed in an underground coal mine that had a longwall and two continuous miner development units. The AMS was installed to further the research and understanding of typical acceptable gas trends at this mine. Research aims to illustrate that an AMS can benefit daily production and other operational uses for future applications.

5.2.2 INSTALLATION

The four strategic areas that were monitored are noted by red stars in Figure 5.8. The purple circle located on the east side of the mine is the location of the fan shaft, where fan pressure and barometric pressure sensors are located. Sensor bank locations K1 and K2, in the north, monitored the longwall bleeders for CH_4, CO, O_2, and air velocity. Sensor bank locations G1 and G2, in the south, monitored the development section's return airways for CH_4, CO, O_2, and air velocity.
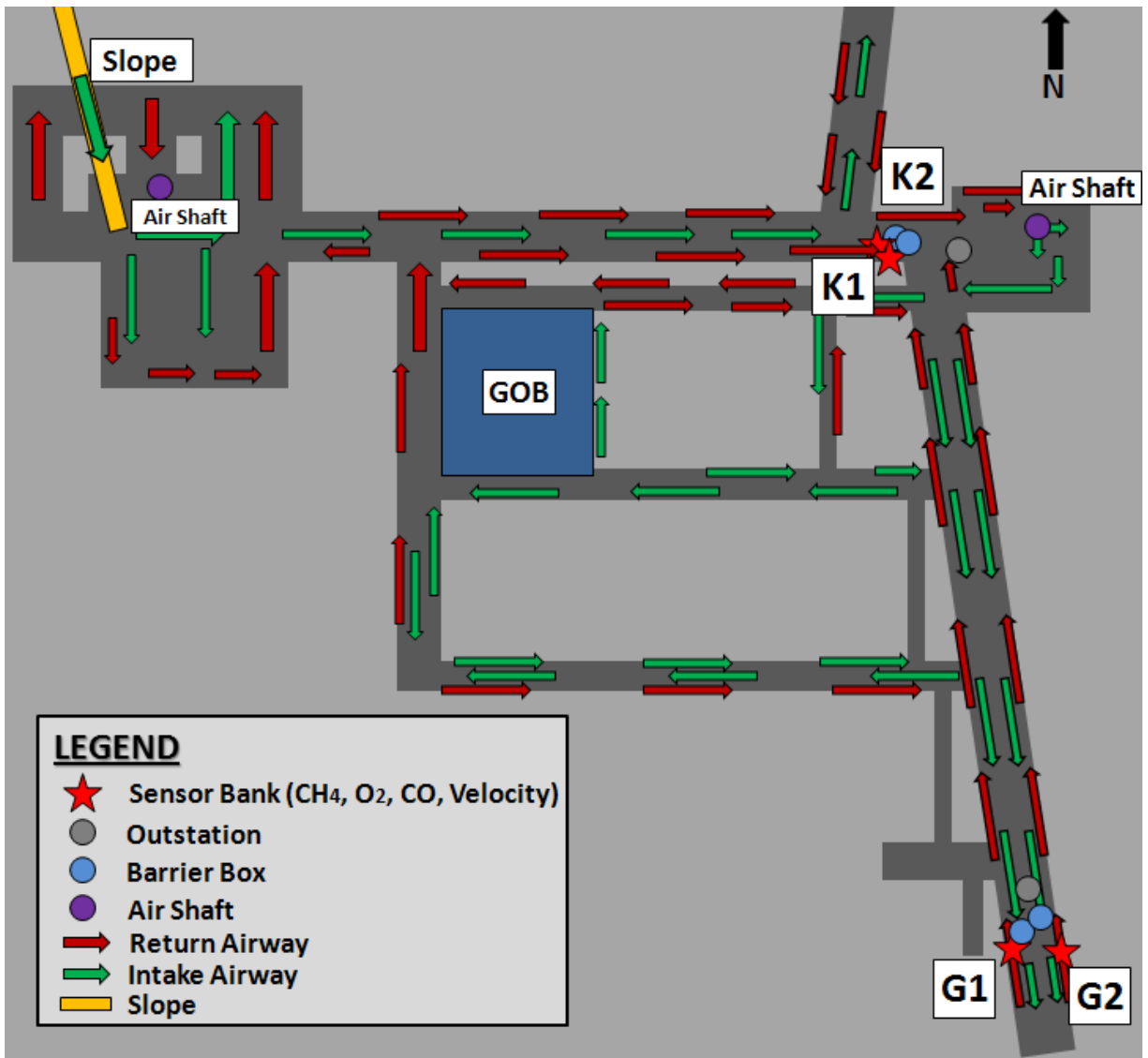
Figure 5.8: Underground Coal Mine Ventilation

Figure 5.9 shows a line diagram of the AMS. Fiber optic cabling connected the north outstation to the surface intranet. The north outstation was connected to the south outstation via fiber optic cabling. Copper cabling, used for data and power, connected the barrier boxes and the atmospheric sensors. Figure 5.9 is a zoomed-in area to showing device and cabling connections.
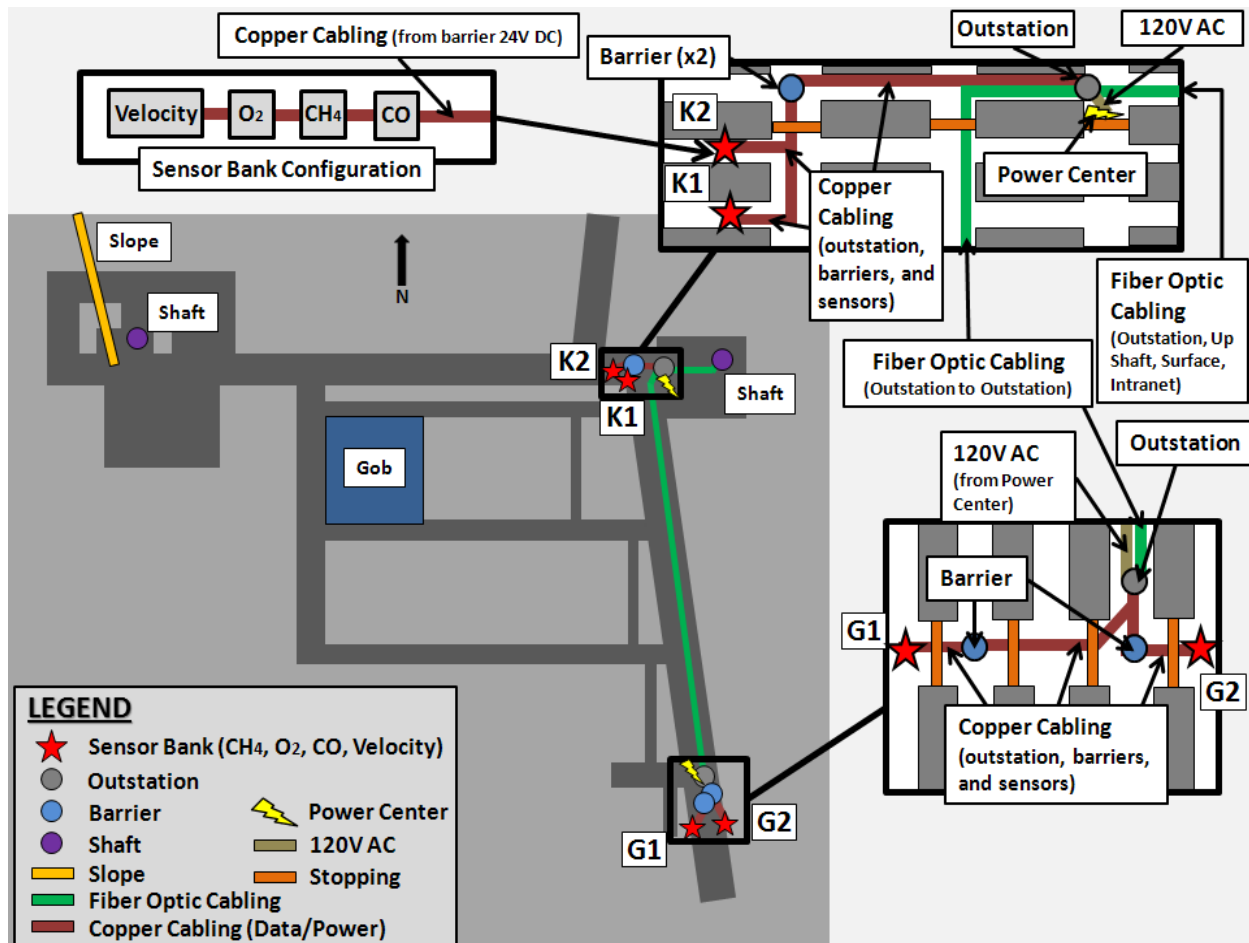
Figure 5.9: Atmospheric Monitoring System Line Diagram

The following conditions should be noted regarding the conditions of this study. The AMS installation for monitoring both longwall bleeders and the mains development is considered to be a reasonably small monitoring system installation. The outstations used in this case study did not utilize battery backup. Figure 5.10 contains the system data flow, beginning when a sensor measured a value, the signal flowed through the barrier, outstation, onto the intranet, where the data was collected by a PC. The barometric pressure sensor was placed on the surface adjacent to the mine fan shaft housing, where the sensor connected to the PLC that controlled the fan. Post processing, data storage, and analysis was performed using AMANDA.
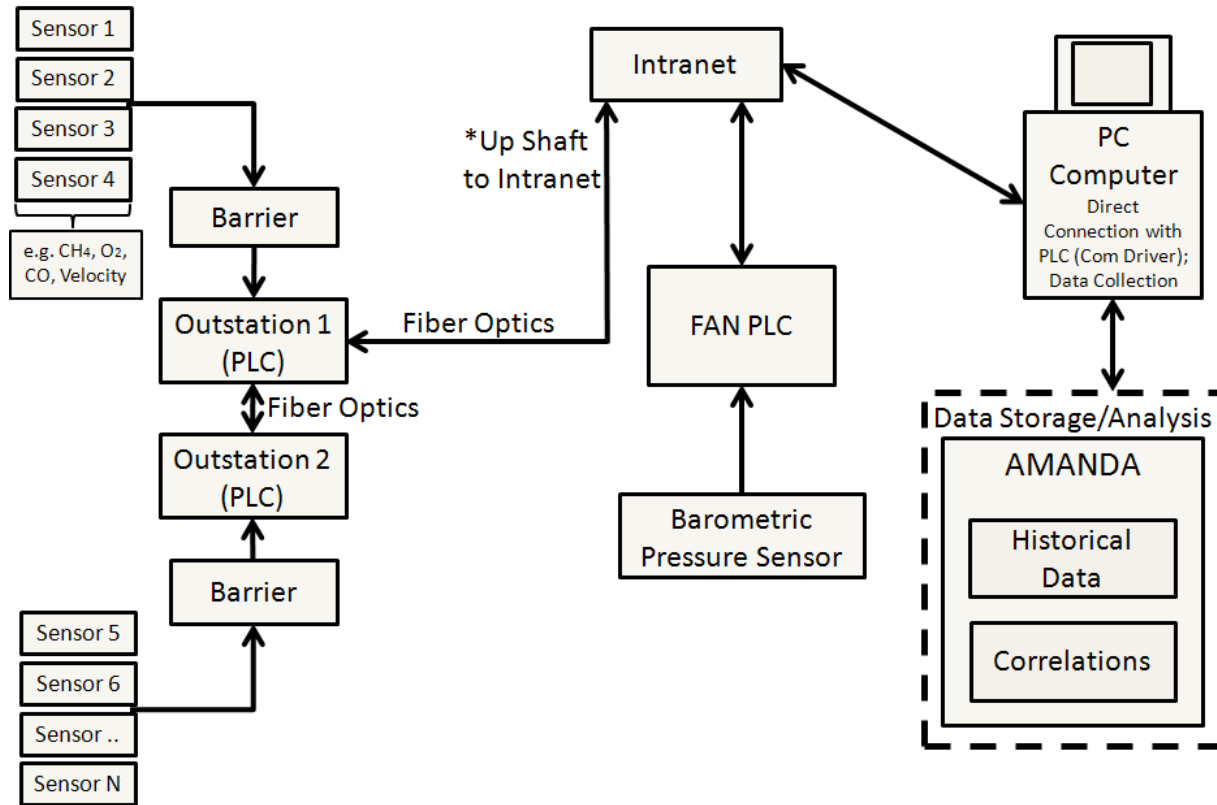
Figure 5.10: System Data Flow

A mine utilizing AMS is provided with additional alarming, safety, and data that can provide valuable insight on the behavior of the mine ventilation. The major return node monitoring scheme, commonly used in Australia, was chosen because it is viewed as the best value per monitoring coverage area. The major return node monitoring scheme allows operators to isolate areas that are experiencing abnormal conditions, develop plans to mitigate those risks, and monitor the situation appropriately. Monitoring schemes that include regular spacing and a large number of monitoring stations require additional capital costs, maintenance, data management and analysis. The additional requirements for an increased monitoring scheme were determined to not be feasible for a research oriented AMS.

5.2.3 MAINTENANCE

An extensive overview of the regulations regarding the maintenance and specific calibration of an AMS is discussed above in Section 5.1.4. The AMS CH_4, CO, and O_2, sensors used in this study were calibrated monthly with the prescribed calibration gases discussed in Section 5.1.4. The air velocity sensors used did not require routine calibration and only required

the sensor air tube to be cleaned. Maintenance lasted approximately 25 minutes for each sensor bank that included a CH_4, CO, O_2, and air velocity sensor. There were no observed effects of moisture on sensors or AMS components.

The AMS installed in this case study did not utilize battery backup. Following a power outage, each outstation and barrier device required mine personnel to reset each individual device at its location. This was done to ensure that power was not restored to an area that had not yet been inspected and deemed safe by a fireboss. The mine experienced frequent power outages to different areas. It was observed that when the PC on the surface lost connectivity with the outstation underground for an extended period of time, the PC's data collection software stopped performing correctly. The PC required the operating system and data collection software to be restarted before data collection resumed properly. Table 5.1 shows the system connectivity based on available power which directly impacts the entire system's connectivity. The system connectivity in Table 5.1 is broken down into four scenarios. The letters 'Y' and 'N' denote yes and no, respectively, whether the part of the AMS in the far left has system connectivity based on available power.

Table 5.1: System Connectivity Based on Available Power

	Power on Surface/ Power Underground	Power on Surface/ No Power Underground/ With Underground UPS	Power on Surface/ No Power Underground/ No Underground UPS	No Surface Power/ No Backup Generator
Surface Computer	Y	Y	Y	N
Network	Y	Y	N	N
Outstation (PLC)	Y	Y	N	N
Sensor	Y	Y	N	N
Data	Continuous	Continuous	Null/No Data/Preset Values	Null/ No Data/Preset Values

The availability of power directly impacts the data network between monitoring sensors and the PC on the surface that collected the data. When power is available on the surface, but there is no power underground without UPS/battery backup power, then the data collected is typically null or no data and required mine personnel to frequently restore power to each AMS component.

Battery backup eliminates the requirement for mine personnel to restart each AMS component proceeding a power failure, provided the mine fan is operating properly or an outage does not exceed 15 minutes which requires actions for main mine fan stoppage with persons underground outlined in 30 CFR §75.313.

Table 5.2 below shows the system connectivity with failure codes. The letters 'Y' and 'N' denote yes and no, respectively, whether the part of the AMS system has connectivity or not. The operational status of the AMS is noted on the right with the action to be taken if necessary. The operational status 'normal' is when the surface PC, network, outstation, and sensors have connectivity. The operational status 'null/no data' indicates when none of the AMS had no connectivity. The entire system should be inspected, starting at the surface PC and proceeding underground.

Table 5.2: System Connectivity with Failure Codes

Surface PC	Network	Outstation (PLC)	Sensors	Operational Status	Action
Y	Y	Y	Y	Normal	N/A
N	N	N	N	Null/No Data	Inspect Entire System, Start at PC
Y	N	-	-	Code 1, Com. Failure, Cannot Ping Outstation from PC	Inspect Cabling from PC to Outstation, Ensure PC and Outstation are functioning properly
Y	Y	N	-	Code 2, Outstation Failure, Can Ping Outstation from PC	Inspect Outstation to ensure properly setup, then inspect from outstation to sensors
Y	Y	Y	N	Code 3, Sensor Failure	Inspect Outstation to ensure properly setup, then inspect from outstation to sensors
			FAN FAILURE	Code 4, Fan Failure	Inspect Mine Fan, Inspect Cabling Between PC/Network and Fan

The operational status 'code 1' indicates when the surface PC does not have connectivity with the outstation underground. Network layer connectivity can be tested end to end using the UNIX network 'ping' command (Cisco Systems, 2002). Network layer connectivity can also be tested utilizing other commands for Modbus or other non-IP based systems. If the ping command determines no connectivity from the surface PC to any destination(s), cabling from the surface

PC to the network should be inspected. If the ping command determines no connectivity between the surface PC and the outstation only, the cabling and components from the surface PC to the outstation should be inspected to ensure devices are operating properly and cabling connections are intact. The operational status 'code 2' indicates when the surface PC can ping the outstation underground requiring the outstation, cabling between outstation and sensors, and sensors should be inspected to ensure all devices are functioning properly. The operational status 'code 3' indicates sensor failure requiring the outstation should be inspected to ensure all cabling is connected properly. Each sensor should be inspected to ensure it is operational and proper connections have been made. The operational status 'code 4' indicates fan failure requiring the mine fan, sensors, and cabling should be inspected to ensure it is functioning properly. Additional proper procedures can be established based upon mine specific conditions.

Power requirements will become the biggest issue and since power is generally limited to specific locations in an underground coal mine, particularly near power centers and belt drives. Monitoring stations should use the closest available power source to avoid excessive cable runs. Future power requirements will change as the mine expands, which also should be implemented into the electrical and network designs of an AMS. Power cabling is best suited for short distances. Outstations should be powered from the closest available power source. Network cabling should be utilized to provide connectivity between outstations, as well as, provide access to surface intranet.

5.2.4 DATA MANAGEMENT AND ANALYSIS

Data redundancy is an important issue that should be addressed to ensure the protection of monitoring data. Data management for a small AMS installation was considered to be feasible given the proper setup. The surface PC was a single point source for failure since data redundancy was not utilized in the system. Data files acquired by the surface PC were transferred to another PC where data analysis was performed. Daily data files were 6.5MB in size. Data management and analysis was performed using AMANDA.

5.2.5 PRELIMINARY ANALYSIS

This case study's preliminary analysis highlights numerous operational and system design issues. The mine's frequent power outages and the underground outstations not utilizing battery backup yielded various types of system failures. Figure 5.11 shows a sample of the mine data with common system failures. The figure highlights the need for careful design of data acquisition and communication systems.
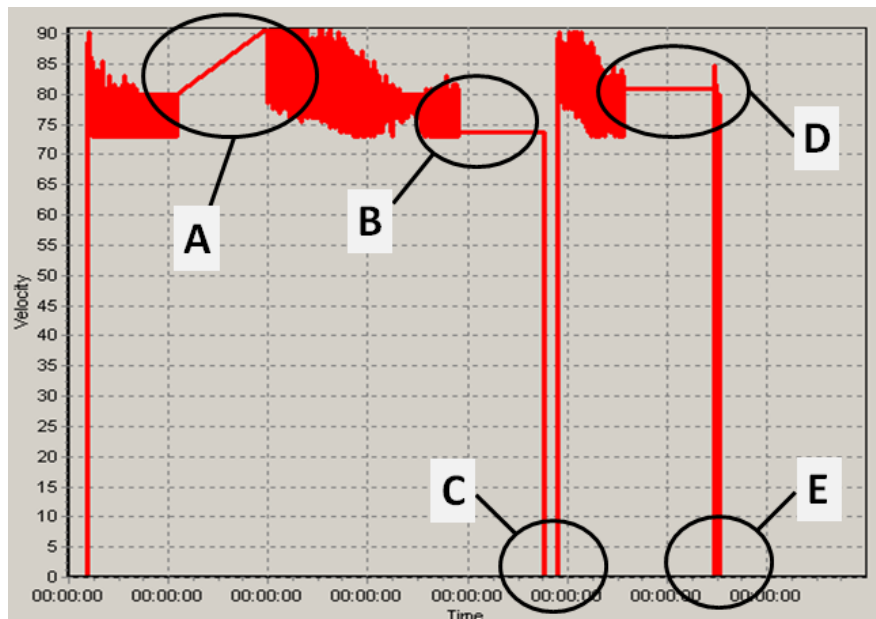
Figure 5.11: Mine Data Sample, Highlighting Common System Failures

Points A, B, and D are examples of communication loss/failure in Figure 5.10. Communication loss occurs when the sensor and the system lose connectivity for differing reasons. Communication loss can occur when the trending/data logging software quit gathering data for an unknown reason or communication across the data link fails. If the data logging software quits, the data is often connected from the last known point to the current value. Data from communication loss/failure should be programmed in the system to be flagged as a static value in order to eliminate these trends from occurring. A static value that should never occur should be chosen to represent communication loss/failure. Points C and E are examples of when power failed and was resorted.

The AMS was compared to other MSHA approved handheld devices commonly used to measure gas and air velocity in underground coal mines' return airways. Table 5.3 contains the

measured values for the personal handheld gas detector and the AMS taken in early 2013. The location of the AMS sensor banks were surveyed to show the variance in commonly used devices. The measured values were recorded from the LCD screens of the handheld gas detector and atmospheric monitoring sensors. The values contained in the "Before Cal" columns are measured from both devices before calibration was performed on the AMS (e.g. 'Before' time in table). Calibration was performed according to the manufacturer's specifications. The handheld device was calibrated on the surface, in compliance with state and federal laws, prior to the gas survey conducted underground. The values contained in the "After Cal" columns are values measured from both devices after calibration was performed on the AMS (e.g. 'After' time in table).

Table 5.3: Gas Survey at AMS Sensor Bank Locations

Location	Parameter	Handheld Detector		AMS	
Time	Gas	Before Cal	After Cal	Before Cal	After Cal
Sensor Bank 1	CH_4 (%)	0.4	0.45	0.32	0.34
Before Cal: 9:31 am	CO (ppm)	0	0	002	002
After Cal: 9:56 am	O_2 (%)	20.8	20.8	20.7	20.5
Sensor Bank 2	CH_4 (%)	0.45	0.5	0.43	0.4
Before Cal: 10:00 am	CO (ppm)	0	0	002	002
After Cal: 10:24 am	O_2 (%)	20.8	20.8	20.7	20.7
Sensor Bank 3	CH_4 (%)	0.35	0.25	0.15	0.18
Before Cal: 11:02 am	CO (ppm)	0	0	002	001
After Cal: 11:25am	O_2 (%)	20.8	20.8	21.7	20.9
Sensor Bank 4	CH_4 (%)	0.2	0.19	0.18 *	0.18 *
Before Cal: 11:47am	CO (ppm)	0	0	001	001
After Cal: 12:08pm	O_2 (%)	20.8	20.8	21.9	20.9

The survey shows there is variance in commonly used and accepted devices used to measure gas concentrations in underground coal mines. Sensor bank 4's methane sensor, denoted by *, was not calibrated because it was newly installed and the manufacturer calibration had not expired.

5.2.6 DISCUSSION

The AMS performed correctly when there was available power. Outstations not utilizing battery backup were found to be the most common source of failure for the system. The system design, which featured network cabling connecting outstations, provided the best system design. Lengthy cabling runs for power and data combination cabling yielded system low power issues. Several instances in the field have shown that power less than approximately 13 volts DC can become unreliable for the devices used in this case study. Extensive power and data combination cabling runs yielding low power were noted to cause unreliable data acquisition, permanent sensor failure, and other various connectivity problems.

Installation a reasonably small AMS installation could be estimated to take a crew of several miners approximately four to six shifts to set up, provided the installation went smoothly from a logistics standpoint. Maintenance of a reasonably small AMS could be expected to take a crew of two miners one shift to calibrate a small number of sensors. Troubleshooting and other maintenance is highly variable based upon the problems being experienced. The required man hours beyond installation can easily exceed the initial capital cost of the AMS. AMS components vary significantly, but one can expect sensors can cost approximately US$1,000 - $2,000 each. Larger outby components such as outstation and barriers cost upwards of US$12,000, and cabling/fiber optics are highly variable dependent on mine geometry. System components and cabling requirements will also change if the system advances with mining.

Data acquisition and management plays an important role when selecting a monitoring scheme, since the amount of data generated daily is a direct function of the number of sensors in a system. A large number of sensors, regularly placed, may provide what appears to be an extensive amount of data, but if it cannot be quickly analyzed, the only added benefit of the sensors are for alarming purposes. Data management and analysis should take place daily while mining is occurring to ensure that problematic circumstances are not developing. Data management and analysis techniques were developed in this case study to utilize real-time AMS data.

The gas survey at each AMS sensor bank concluded that there is variance in commonly accepted handheld gas detector and AMS gas sensors. The AMS' gas sensors and handheld gas

detector were properly placed and oriented within the mine entry. Further gas surveys, comparisons to bag sampling with gas chromatograph analysis, and a method for determining the reliability of different devices needs to be established. Integrating a wide range of detection and monitoring devices could quickly confuse mine management and personnel. The confusion caused by different detection and monitoring devices could even misconstrue judgments made in response to differing concentration measurements from different devices.

The air velocity sensors used in the study showed variance from commonly used handheld rotating vane anemometers. The Code of Federal Regulations does not specify an orientation or mounting method for air velocity sensors. Air velocity sensors should be affixed by manufactured mounts to roof bolts or another similar mounting style and extend down from the roof to orient the sensor's measurement point in the middle of the entry. Sensor mounts must be created to work in a variety of different circumstances depending upon the application. Air velocity surveys should be conducted to compare air velocity measurement devices to determine which device should be accepted over other devices.

The AMS has shown potential at improving daily tasks by integrating AMS with existing data systems in the mine. Integrating production into the design of the system provides additional information regarding one of the most abundant gas generation sources in the mining operation. Production can be measured from power drawn from continuous miners/longwall, the amps from belt motors, belt scales, real-time communication from cutting equipment, and a wide range of other production parameters that can help provide additional information on gas emissions.

The AMS should be redesigned to have outstations that utilize battery backup. Battery backup eliminates minor power outages and the AMS can be programmed to deengerize given an extended fan outage or other circumstances requiring I.S. equipment. An AMS utilized in hazardous areas, where power issues are present in the mining operation, makes it difficult when a remote system is easily restarted. Careful planning should ensure that the system will not have power restored unless that area of the mine has been inspected. An electronic device may perform variably given intermittent and frequent power losses which make it necessary to utilize battery backup. The system should be evaluated to ensure battery backup would completely eliminate intermittent power issues by confirming each device will be provided with auxiliary power.

5.3 United States Underground Coal Mine Case Study II

A real-time AMS was installed in an underground coal mine to comply with Federal regulations. AMS sensors were placed in strategic areas as well as regularly spaced in some areas. The mine was adjacent to previous mining that is isolated from active works. The monitoring scheme was primarily installed to serve as alarming devices, given a specific threshold has been achieved. The system was used to monitor gas concentrations (CH_4, CO, O_2), fan pressure and electrical current drawn by the mine fan's motor. The monitoring system was MSHA approved and state approved for the mine location. The system was permissible, but was not I.S. The methane sensors were pellistor type and the carbon monoxide and oxygen were electrochemical type sensors. The system utilized battery backup for outstation auxiliary power.

5.3.1 BACKGROUND

An AMS was installed in an underground coal mine that utilizes two continuous miner development sections. The AMS was used as an alarming system, while data was collected from several strategic locations throughout the mine for further research. This research aimed to illustrate whether AMS can benefit daily production and other operational uses for future applications.

5.3.2 INSTALLATION

The AMS was installed in a similar method as the AMS in Case Study I, Section 5.2. The AMS contains sensor banks of CH_4, CO, O_2 sensors that are placed throughout the mine. Some sensor banks were installed in a regularly spaced pattern, while others were placed to monitor specific circumstances the mine may experience. Figure 5.12 shows a generalized diagram of the mine ventilation at this location. The mine utilizes a blower style ventilation scheme and maintains the belt/neutral airways in an outby direction.
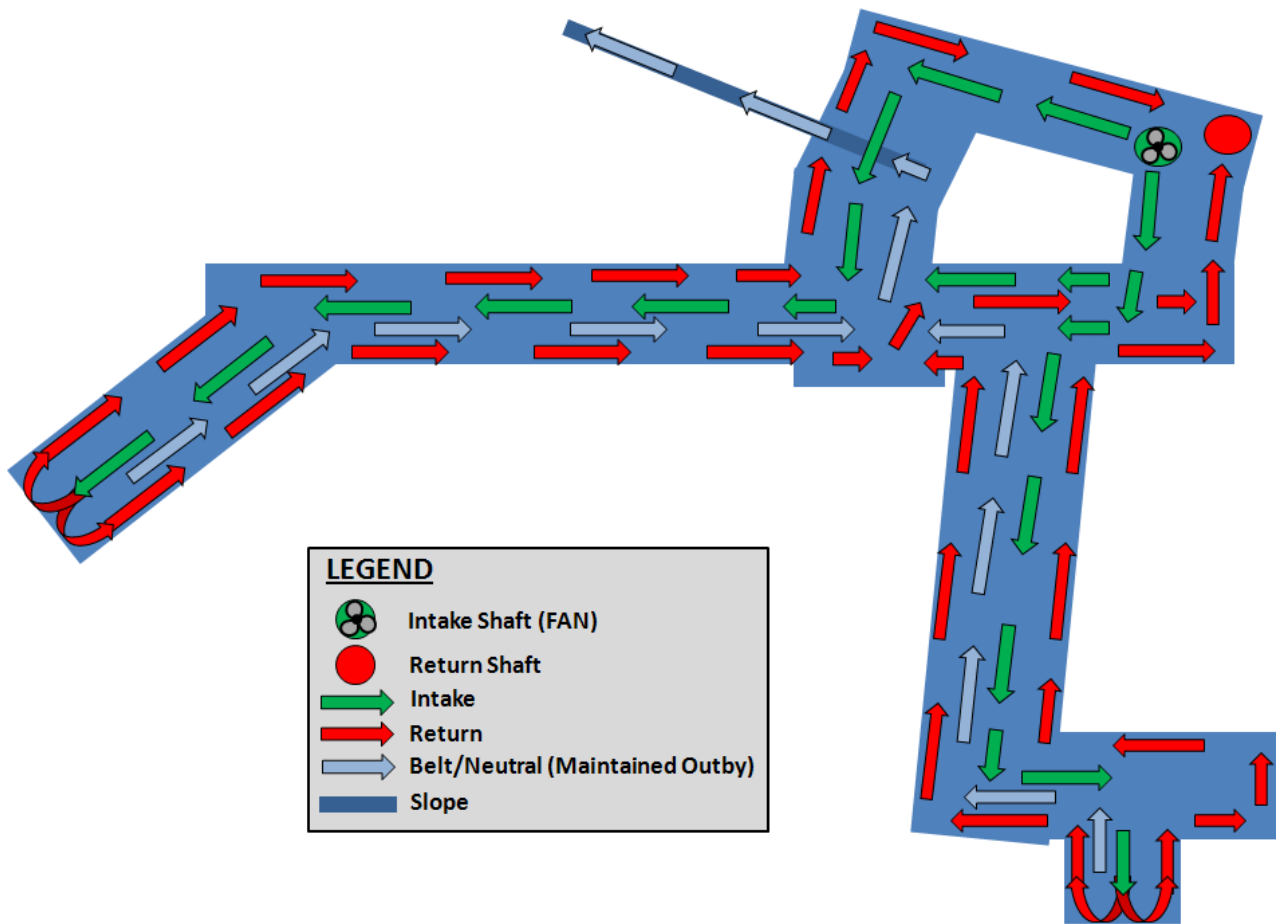
Figure 5.12: Generalized Mine Ventilation Diagram

Figure 5.13 shows a generalized schematic of the sensor placement of the AMS. Triangles represent methane sensors, and squares represent carbon monoxide sensors. Red sensors are located in return airways while green sensors located in intake airways.
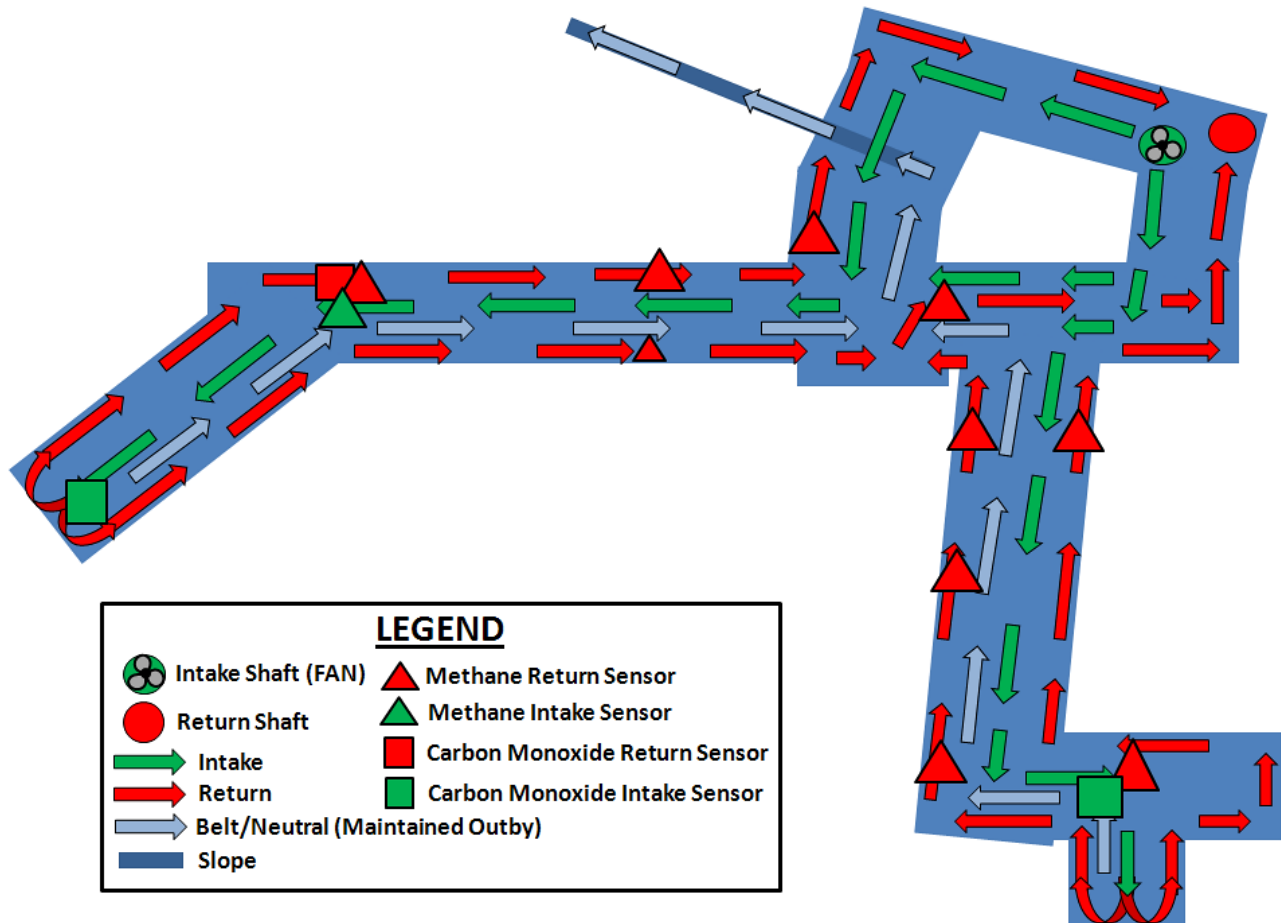
Figure 5.13: Generalized Sensor Placement Schematic

5.3.3 MAINTENANCE

The AMS requires a dedicated technician to maintain and perform regular system maintenance. Atmospheric sensors are calibrated in compliance with CFR 30 §75.351(n). The system in this case study did not experience intermittent power issues as with, the system in Case Study I since it, utilized battery backup powered outstations. The system was deenergized when I.S. equipment was required.

5.3.4 DATA MANAGEMENT AND ANALYSIS

Data management for a medium to large AMS installation proved to be more challenging than a small installation. The system utilizing battery backup allowed continuous data collection by the surface PC. Data files generated by the surface PC were transferred to another PC where

data analysis was performed. Data redundancy was not utilized in the system, which was a single point source for failure at the surface PC. Data redundancy is an important issue that should be addressed to ensure the protection of monitoring data. Data files varied in size from 4.2MB to upwards of 25MB, based upon the time period, data format, number of numerical digits recorded, system connectivity, number of operational sensors, and other various factors. Data files should be designed where the time stamp is only written once for the many sensor readings. Data management and analysis was performed using AMANDA.

5.3.5 PRELIMINARY ANALYSIS

The preliminary analysis of data collected in this case study showed several instances that an AMS provides an additional layer of safety to miners underground. The data collected from the sensors located throughout the mine create a comprehensive understanding of the mine atmosphere. Each sensor located throughout the mine provides information about current conditions, as well as the overall flow of gas emissions. Multiple evident trends correlate fan outages and changes in barometric pressure to increasing gas emissions.

Fan outages can generally be identified when the mine fan's motor amps are less than or equal to zero. This is an indication that the fan motor is not running, assuming the system monitoring the fan's motor is functioning properly. There is evidence to show that in result of a fan outage, that methane concentrations can increase. Figure 5.14 and Figure 5.15 shows examples of fan outages with corresponding increases in methane concentrations read at several sensor locations in the return airways. The fan motor amps are shown in red, corresponding to the left vertical axis, and three various return airways methane sensors in green, blue and black, which correspond with the right vertical axis.
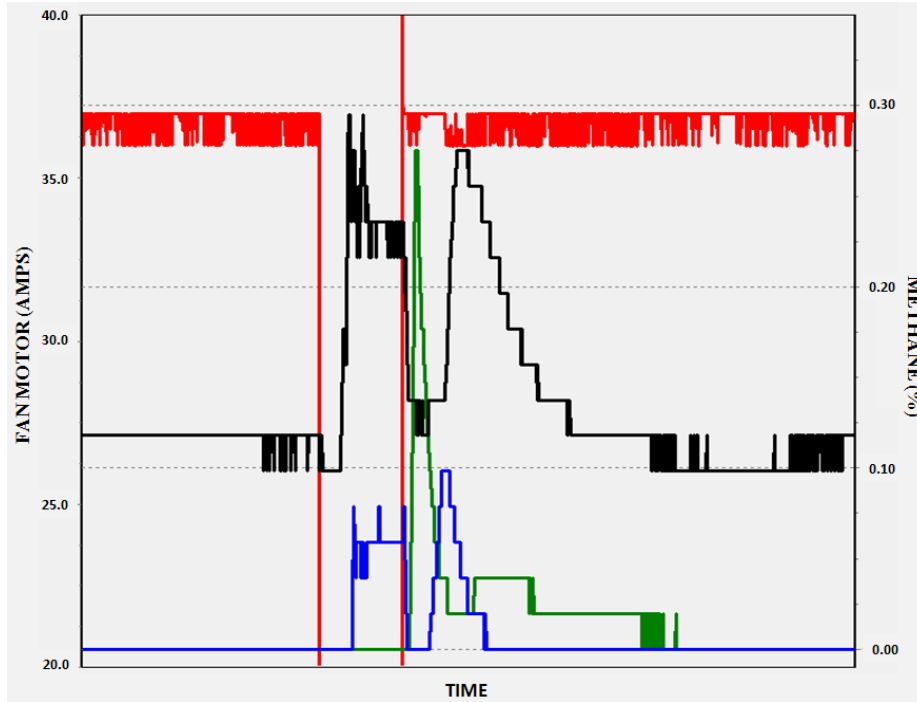
Figure 5.14: Fan Outage Example I Showing Increasing Methane
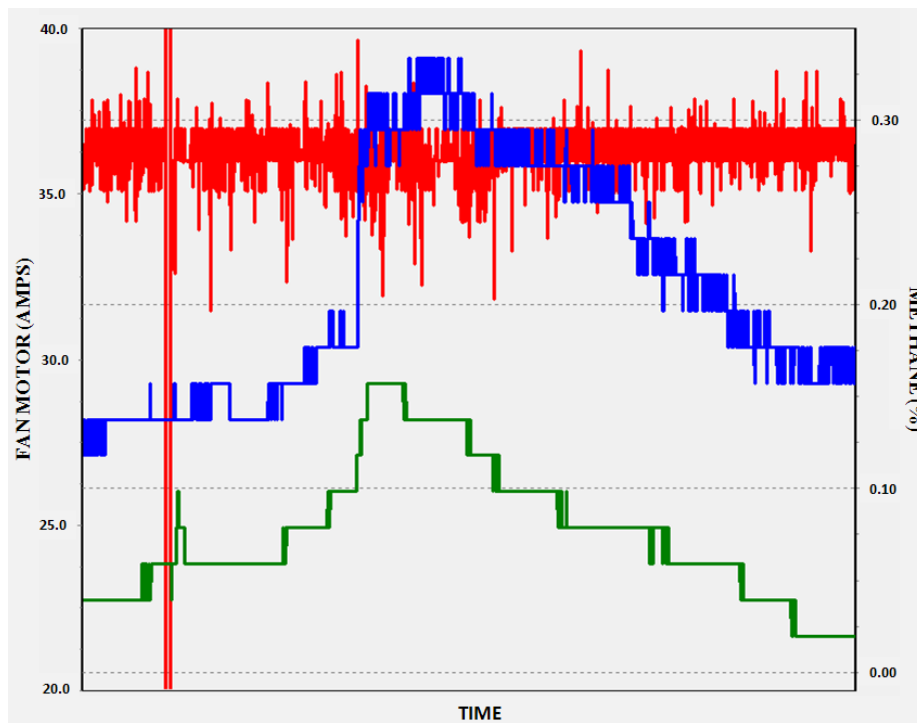
Figure 5.15: Fan Outage Example II Showing Increasing Methane

The two fan outage examples show methane increasing immediately and shortly after a fan outage occurs. The locations of the sensors with increasing methane concentrations were not adjacent to the working face. The increase in methane does not reach an abnormal concentration

for a return airway of an underground coal mine, but further illustrates how an operator can utilize and benefit from an AMS. Figure 5.16 shows an example of a methane increase after a ventilation air change. The fan motor amps are illustrated in red and a return airway methane sensor in green.
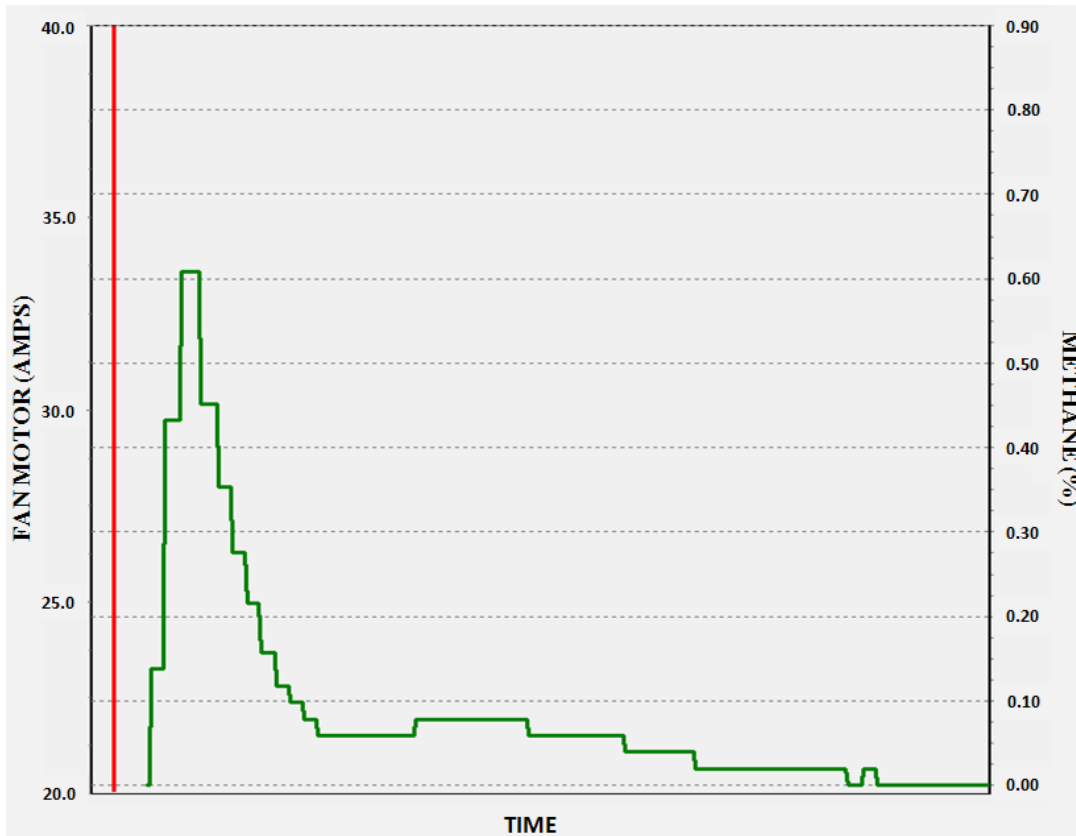
Figure 5.16: Methane Increase after Ventilation Air Change

The influence of barometric pressure has been widely debated, as discussed in Section 2.1.2. Figure 5.17 shows an example of decreasing barometric pressure (red) with corresponding rises in return airway methane concentrations (blue and green).
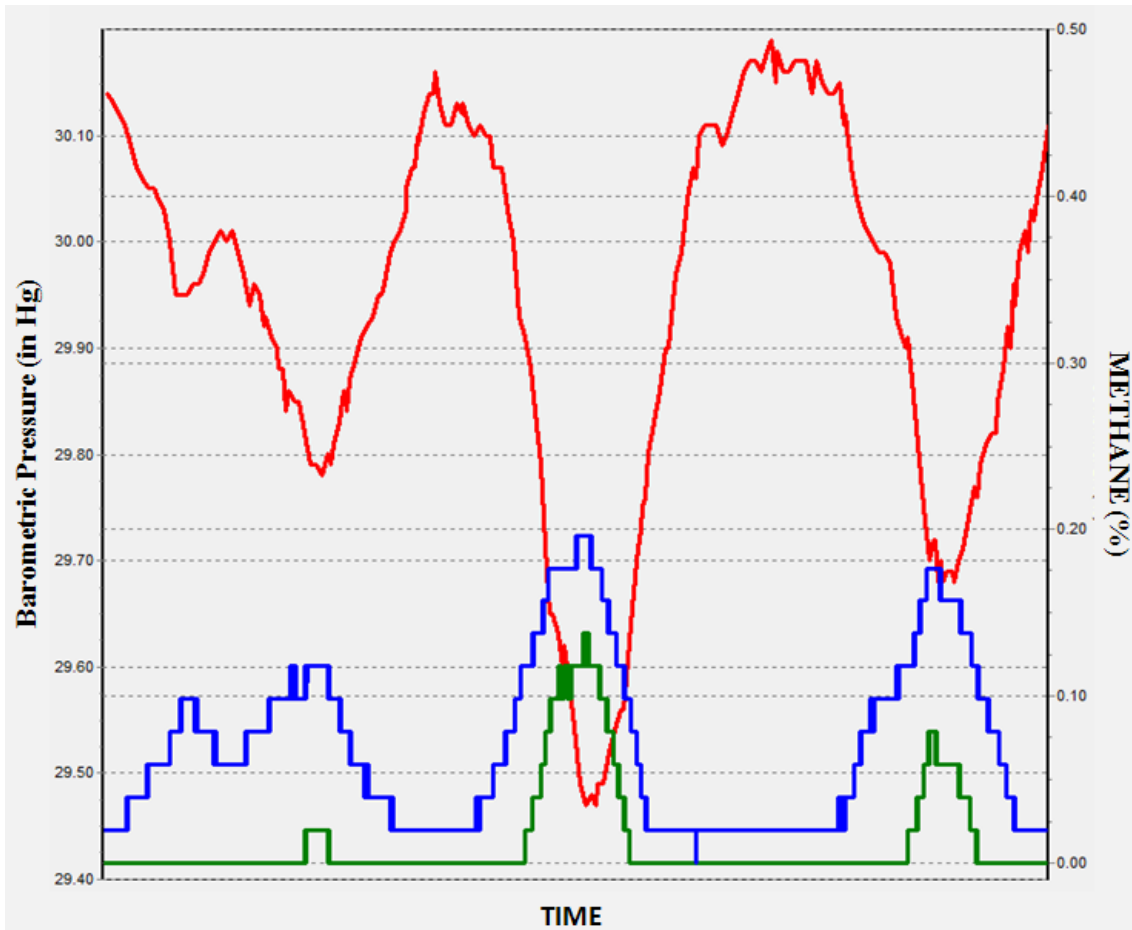
Figure 5.17: Decreasing Barometric Pressure with Increasing Methane

Figure 5.18 shows another example with decreasing barometric pressure (red) with increasing concentrations of methane (blue, green, and black).
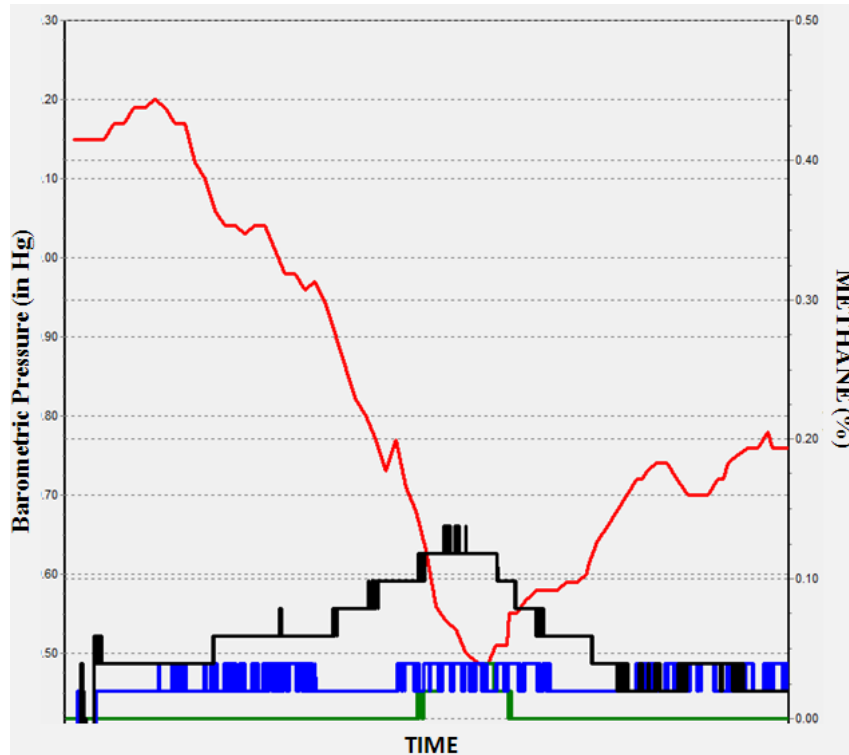
Figure 5.18: Increasing Methane with Decreasing Barometric Pressure

5.3.6 DISCUSSION

The AMS in Case Study II was used extensively for alarming and alerting miners underground throughout daily production. The AMS provided an additional level of safety for miners and a tool for management to troubleshoot the ventilation in different areas of the mine. There is evidence to show that fan outages, as well as significant changes in barometric pressure, can cause gas emissions to increase in specific areas of the mine. Further research should be conducted to quantify gas emissions due to fan outages and significant changes in barometric pressure, as well as, integrate production to determine root causes of gas emissions.

5.4 Further Improving Atmospheric Monitoring

The integration of every aspect of the mining operation into a master system has the potential to increase the quantitative understanding of each individual mining operation. The mine ventilation is impacted by every aspect of the mine and more information is often required to further determine the root causes of gas emissions measured in different areas of the mine.

The integration of ventilation monitoring, production, processing and other aspects of the mine will allow management to make more educated decisions based upon quantitative data.

5.5 Monitoring Discussion

The two case studies in this chapter reinforce that an AMS can benefit daily production, safety, and research. AMS provides an additional safety system that can pinpoint and monitor high risk areas of the mine. Several examples in this chapter provide evidence that fan outages and changes in barometric pressure can cause communication with previous works. Battery backups must be utilized on underground outstations in order to maintain alarming and warning systems, continuous data, and to avoid increasing required AMS maintenance. AMS requires improvements to its sensors and systems to increase accuracy, precision, and functionality for daily operational use. Complete I.S. systems are required to monitor atmospheric conditions for extended fan outages; commercially available real-time systems for use in United States mines have not been identified. There appear to be few resources for the coal industry regarding data acquisition and management. It appears most data acquisition and management work is required to be completed within each mining company in order to customize the AMS to perform in accordance with each operation's needs.

AMS are primarily used in the United States for their alarming rather than their prediction and trending features, which is the powerful added benefit of utilizing AMS. Further work is required to evaluate the accuracy of different brands of gas and air velocity sensors. Overall, AMS has been found to benefit a mining operation in many ways and it is recommended that every United States underground coal mine utilize AMS beyond the current regulations. AMS gives miners information on the mine atmosphere routinely so that an understanding of typical mine behavior is developed more readily, immediately identify problems in ventilation including improper utilization of ventilation controls and controls requiring maintenance especially in areas that contribute to leakage, engineering design and planning can be improved including more accurate simulation, immediate identification of developing high risk atmospheres, provide history and possibly real-time data in emergency-type situations, and provide additional information to miners responsible for inspecting areas to ensure the areas are safe.

CHAPTER 6: UTILIZATION OF ATMOSPHERIC MONITORING SYSTEMS FOR RISK MANAGEMENT AND ASSESSMENT

Atmospheric conditions underground are constantly changing and from a safety perspective, it is critical to identify when conditions are trending abnormally. Atmospheric monitoring in underground coal mines allows mine operators to analyze atmospheric conditions underground in real-time. Real-time monitoring can then be used to identify whether atmospheric conditions underground have become problematic. The implementation of a risk assessment and management process allows operators to then use a risk-informed decision making to identify comprehensive site specific ventilation parameters. Establishing risk informed ventilation parameters and tracking conditions relative to these parameters, management can modify ventilation plans as mine conditions develop to manage evolving risks. Ventilation risk assessment and management allows developing atmospheric monitoring technologies to be fully utilized in order to increase safety standards in the United States. This chapter reviews general risk assessment approaches, state-of-the-art ventilation based risk assessment, and the risk assessment and management application within the United States regulatory framework. This chapter contains work from "Ventilation Risk Management in Underground Coal Mines: Atmospheric Monitoring in the United States" Kenneth R. Griffin, Robert M. Liebe, Kray D. Luxbacher, M.E. Karmis, Barry C. Ezell, Robin L. Dillion-Merrill. SME Annual Meeting, Denver, 2013. SME Preprint 13-118, used with permission of Tara Davis.

6.1 Introduction

The implementation of atmospheric monitoring technologies has allowed operators to actively monitor atmospheric conditions underground in real-time. In the United States, atmospheric monitoring systems are primarily installed to monitor belt lines and electrical installations for smoke, CO, and CH_4 with set prescriptive alert and alarm threshold levels (30 CFR §75.340, §75.350, §75.351). Atmospheric monitoring technologies continue to develop to minimize and eliminate issues with cross-sensitivity and range (Griffin et. al, 2012). There were

approximately 118 fatal and 299 non-fatal days lost accidents due to the ignition or explosion of gas or dust from 1983 to 2011 (MSHAa, 2012). There were approximately 159,070 (23.04% yearly average) violations for underground coal mines in the United States, pertaining to the accumulation of combustible materials (30 CFR §75.400), mine ventilation plan; submission and approval (30 CFR §75.370), and permissible electric face equipment; maintenance (30 CFR §75.503) from 2001-2011 (MSHAa, 2012). While fatalities, injuries, and violations continue, there has also been an increasing focus and awareness on the coal mining industry to decrease accidents, injuries, and violations, and this can be accomplished with an increased focus on risk assessment and management. Much of the pioneering work in risk assessment and management came from the nuclear industry (Rasmussen, 1975) because society demanded proof that nuclear technology was safe. Since this groundbreaking work, risk assessment and management have been widely adopted in the chemical, nuclear, medical, military, financial, international mining, and many other industries, and in the nuclear industry, for example, regulation has adopted a risk-informed approach which requires an assessment of the safety significance or relative risk when considering the regulatory burden. Risk assessment and management tools have been considered by the coal mining industry for some time, but with better atmospheric monitoring sensors and other monitoring systems, the opportunity now exists to use risk-informed decision making to have a significant impact in further reducing fatalities, injuries, and violations. MSHA (2003) developed a system safety evaluation program which utilizes several risk assessment and management techniques but this program never was implemented.

The coal mining industry faces a changing environment in which stakeholder expectations of business' environmental and social performance have an increasing impact on the business' social license to operate (Yang, 2012). Yang (2012) provides an extensive evaluation of the regulatory governance and policy standpoints of the United States coal mining industry. A company's reputation has become easier to impact and evaluate because social media and marketing is more readily available to the public. A company's reputation can be damaged or tainted by an accident and the damage may be irreparable which can have significant financial impacts. MSHA estimates that annual accident costs range from approximately $910,000 per occupational death, $28,000 per lost workday cases, and $7,000 per reportable case without lost work days (MSHAb, 2012). These figures do not include the estimated overall impact of

accidents on profits and sales which can be unrecoverable. Settlements from disasters related to explosions in underground coal mines have reached upwards of 210 million dollars.

The Mine Safety and Health Administration (MSHA, 2012c) released on August 6, 2012 in the final rule, "Examination of Work Areas in Underground Coal Mines for Violations of Mandatory Health or Safety Standards" that it is now requiring, "mine operators to identify and correct hazardous conditions and violations of mine health and safety standards that pose the greatest risk to miners, including the kinds of conditions that led to the deadly explosion at the Upper Big Branch Mine in April 2010." The abundance of violations, fatalities, and injuries indicate that coal mining companies should internally implement assessment and management techniques used in risk management because companies that fail to identify and correct hazardous conditions and violations will be held accountable to the increased standard from August 6, 2012 (MSHAc, 2012). Risk management and assessment can directly impact health and safety, a company's reputation, cost, efficiency, work force morale, and environmental impacts. Risk management allows mining companies to further investigate, plan, and prevent minor to major accidents from occurring.

6.2 Risk Assessment and Management

A risk can be defined as the chance of something happening that will have an impact, whether it may be positive or negative. Risk can also be defined mathematically as the product of the probability and consequence of a specific event occurring. Simple definitions of risk rarely survive contact with a real organizational challenge, however, because organizations attempting to assess and manage risk must clarify how they will address (i.e., measure) uncertainty and outcomes, and how they will make decisions regarding actions to reduce their exposure to these outcomes.

In risk assessment, the goal is to answer the following three questions about the risks for the situation being considered (Kaplan & Garrick, 1981): What can go wrong? What is the likelihood that it would go wrong? And, what are the consequences? Answers to these questions help decision makers to identify, measure, quantify, and evaluate risks and the associated consequences. Risk management builds on the risk assessment process by seeking answers to a second set of three questions (Haimes, 1991): What can be done? What options are available and

what are the associated trade-offs in terms of all costs, benefits, and risks? And what are the impacts of current management decisions on future options?

The International Organization for Standardization created the ISO 31000, which is the family of standards relating to risk management. Most recently the ISO 31000:2009 was created to provide principles and generic guidelines on risk management to be used across a wide range of industries. ISO 31000 defines risk as "the effect of uncertainty on objectives." Risk assessment and management is a continuous process where context is established, risks are identified, analyzed, assessed and prioritized, treated, and monitored and reviewed in order to ensure the process of risk management is correctly functioning. There are many different tools to support risk assessment and management such as event tree analysis (ETA), failure mode and effect analysis (FMEA), failure mode and effect criticality analysis (FMECA), fault tree analysis (FTA), and probabilistic risk analysis (PRA). Choosing the right approach for an organization is highly dependent on the context of the decision making: the nature of the decision, the skills of the decision maker, the time available to assess risk, the availability of mitigations, the cost of mitigation alternatives, and the availability of time and resources to commit to risk mitigation. The Australian Government Department of Resources Energy and Tourism (2008) provides an extensive overview of risk assessment and management application to Australian mines.

To demonstrate the use of risk assessment and management a simple fault tree analysis is used to examine the risk of a methane gas explosion in a coal mine, an event whose consequences are frequently the loss of life and reduced profitability. Methane naturally occurs in coal, but the gas becomes explosive when it makes up 5 percent to 15 percent of the volume of air. Therefore, explosive mixtures of methane will naturally occur, and the goal of risk assessment and management is to first prevent an explosive mixture from forming and secondly to prevent an explosive mixture from igniting. A gas explosion can be deconstructed into two precipitating events to better understand the likelihood of a gas explosion. Figure 6.1, contains a simple fault tree analysis that shows a flammable gas concentration and an ignition source are required for a gas explosion. This simple tree structure, allows probabilities to be assigned to the required events occurring in order to assess the probability of a gas explosion. A gas explosion is often comprised of varying parameters and events where probabilities may not be able to be determined easily.

However, the mining industry demands more than an academic exercise to predict the likelihood of an explosion; the industry requires decisions and actions to reduce the likelihood of the two initiating conditions and reducing the severity of outcomes should an explosion occur. By modeling the risks in terms of initiating events, risk management strategies can be planned to minimize gas accumulations, minimize potential sources of ignition, and to maximize the distance between potential gas accumulations and ignition sources. Atmospheric monitoring systems can be used to detect gas accumulations so that additional management efforts can be taken to reduce gas accumulations before they combine with an ignition source. Atmospheric monitoring systems can potentially provide advance notice when gas accumulations are trending towards becoming problematic which allows mine operators to introduce additional controls to reduce or eliminate the impact of an explosion.
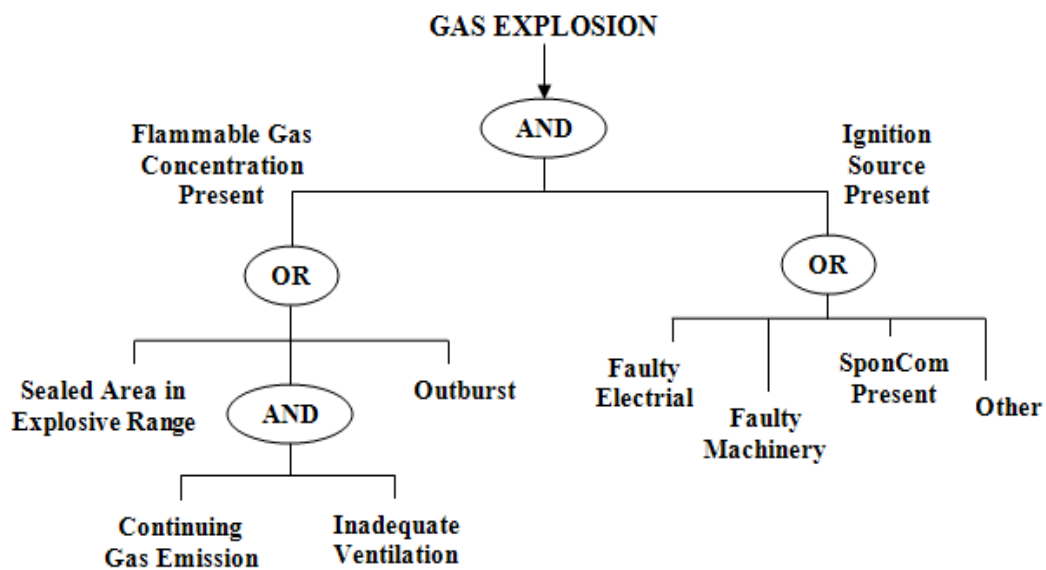
Figure 6.1: Simple Fault Tree of Methane Gas Explosions (adapted NSW Department of Primary Industries, 1997)

Atmospheric monitoring systems can be used to help reduce or eliminate the ignition or explosion of gas or dust, but mine operators are likely to wonder how many sensors are "sufficient" and if there are other more cost-effective mitigations to reduce the likelihood and/or consequence of an explosion. Policies can control incidences of employees performing actions that can likely result in negative consequences (i.e. welding under dangerous conditions) but these types of accidents continue to occur. Proper procedures must be established to first assess risks and identify mitigation techniques, as well as enhance the effectiveness of the mitigation

techniques used to ensure those procedures achieve the full potential of reducing the incidences and outcomes.

6.3 Behavior-Based Safety

Behavior-based Safety (BBS) is commonly used in the United States mining industry and has shown in several cases that it can be used to significantly reduce accident incident rates (MSHA, 1998; MSHA, 2011c). BBS is based on the application of safety procedures and the behaviors of employees in work situations (McSween, 2003). Geller (2005) states, "BBS focuses on what people do, analyzes why they do it, and then applies a research-supported intervention technique to improve behavioral processes. BBS provides tools and procedures workers can use to take personal control of occupational risk." BBS research studies have shown that typically 80 to 90 percent of today's incidents are a result of unsafe acts rather than unsafe conditions (McSween, 2003). A behavior-based safety system is comprised of several teams that work together in order to ensure the system is functioning properly to ultimately improve health and safety. MSHA (1998) noted that several teams which have been successfully used by many companies are the safety steering team, observation and feedback team, ergonomics team, incident analysis team, celebration team, incentives/rewards team, and preventative action team.

All levels of management must believe and reinforce the safety system in order for the system to successfully reduce accidents and injuries. The organizers of safety systems must draft a mission statement and a plan of action to gain the focus and support of management and employees. The United States mining industry typically uses BBS systems to help reduce accidents and injuries. The major advantage of BBS is that based off observational experiences of employees, where risks can be identified and reduce minor or moderate injury sources that can occur from completing routine daily tasks. BBS is a significantly reduced and simplified version of risk management that does not tend to evaluate the overall plans such as engineering and mine design where large scale risks are exposed (i.e. explosions and roof falls).

6.4 A Comparison: Risk Management and Behavior Based Safety

There is an increasing emphasis on reducing the number of accidents and injuries each year in mining. In 2010, there were 41 fatalities in underground coal mines which was the worst year in the United States since 1990 when there were 43 fatalities. There has been a yearly average for underground coal mines of approximately 63 fatalities during the 1980's, 27 fatalities during the 1990's, and 18 fatalities during the 2000's. Figure 1.1, in Chapter 1 shows the number of fatalities in underground coal mines from 1978 to 2011. There is an overall general downward trend with a reduction of 2.3 fatalities per year since 1978.

There has been significant progress towards reducing the overall number of fatalities in underground coal mines but with the most recent decade average of 18 fatalities per year, most would agree that there is still a level of unacceptable risk being assumed. Restated, most would agree that the mining community can and should reduce the probability of events that lead to loss of life, and most would agree that there are ways to reduce the loss of life should such an event occur. The mining industry has an overall goal of zero accidents which further supports additional implementation of management strategies as well as new and developing technologies to increase health and safety. Management strategies play a major role in the decrease of yearly fatalities, as well as an increasing national emphasis on continuing to develop safer mining practices.

Mining companies must assess and manage risks to safety and risks to profitability. The mining industry must create an environment that both reduces and eliminates the tensions between risks to life and profitability to create an environment that is both safe and profitable. There are unique benefits to using risk management and behavioral based safety approaches together. Risk assessment and management allows a company to identify the critical risks at a mine and to further investigate problematic occurrences from a mine planning and organizational standpoint. Risk assessment and management requires a company to create detailed plans that examine the specific risks and possible outcomes to the mine and its facilities as they develop. Risk management also tends to rely on procedural and technical approaches to risk that

encompass every facet of the operation and can require significant resources in order to properly function.

Behavior based safety systems can be used in conjunction with risk management in order to increase the overall performance and scope of the safety system. Behavior based safety systems enable operators to identify the day to day outcomes that may result in minor to moderate injuries. Protecting miners from minor to moderate injuries is extremely important because the company's most precious resource is their workforce. BBS is often broadly based, focusing on ensuring that employees modify their behavior to focus on safety. BBS relies on the fact that once employees have modified their daily routines to constantly think about safety, it will then become second nature. But research has shown that cognitive responses to prior "near miss" incidents can influence future risk taking and that taking risks that do not result in events with salient bad outcomes can encourage more future risk taking (Tinsley, Dillon & Madsen, 2011). BBS does not necessarily provide employees with the tools necessary to identify, assess, and manage risks, and to overcome the cognitive biases they may adopt from past experience with taking risks and getting away with it. Instead, BBS creates a culture that creates sensitivity to risk and an adherence to risk management plans. In combination, BBS, risk assessment and risk management practices enable a mining company to systematically and comprehensively address uncertainties and outcomes of concern and enact daily attitudes and procedures to reduce risk.

Health and safety management systems rely on all levels of management from the top down fully believing in the system being implemented and reinforcing the system with incentives and goals for employees to work towards. Problems arise when different levels of management prioritize and reinforce conflicting goals and emphasize productivity over completing jobs according to the safety system. Both risk assessment and management processes and behavior-based safety systems will be overridden if the company culture does not value safety in the mine.

6.5 Atmospheric Monitoring in the United States

To continue the example of a gas explosion, it would not be hard to imagine a mining company that had policies that required compliance with regulations to conduct atmospheric

monitoring, but also knew that its sensors were occasionally unreliable. Under the circumstances of bare minimum compliance with regulations and no recent adverse outcomes, what is the risk? Why consider doing anything more? What more can be done to achieve zero fatalities? A BBS-driven culture with appreciation for risk assessment and risk management techniques would address these questions in earnest to understand how improved systems and/or processes might continue to reduce risk.

Atmospheric monitoring technologies continue to develop which help to eliminate or reduce the effects of cross-sensitivity. Newly developing fiber optics gas sensors at Virginia Tech will help eliminate cross-sensitivity as well as they are completely passive at the sensor head. Atmospheric monitoring sensors currently have inherent limitations based upon the technology used to sense the specific parameter. Griffin et al, 2011 provides an extensive review of the available atmospheric monitoring systems. Atmospheric monitoring in underground coal mines in the United States could potentially cause wide spread issues between operators and regulators. Inherent limitations of sensors make it necessary for regulators to work with operators in order to achieve the overall goal of the reduction of injuries pertaining to the ignition or explosion of gas or dust, instead of using atmospheric monitoring systems to be violation watchdogs.

The implementation of sophisticated atmospheric monitoring systems should initially be used to determine typical operating and ambient gas concentration and other ventilation parameters that are specific to each mine. Ventilation parameters, baselines and ambient gas concentrations will trend throughout the year as the mine and atmosphere change. Government regulators should consider providing reasonable leeway to companies who are initially implementing sophisticated AMS in order to ensure that false readings and other issues are not occurring with the AMS. Operators and regulators should work together to establish reasonable and safe ventilation parameters, while continuously improving the overall safety at each mine. Cooperative learning is important because AMS technologies have not been routinely used in the United States and typical ventilation baselines have not been established at each mine.

Atmospheric monitoring systems potentially can provide unique advantages such as identifying when ventilation parameters are becoming problematic, de-energizing mining and electrical equipment when gas concentrations become too high, and increasing the overall

awareness of ventilation from a health and safety standpoint. Current regulations set specific action response plans when certain gas concentrations are met; according to 30 CFR §75.342, methane monitors are set to automatically de-energize electric equipment or shut down diesel-powered equipment which it was mounted on if the methane concentration reaches 2.0 percent or the monitor is not operating properly.

The selection of an AMS for an underground coal mine should be based upon baseline ventilation parameters for each mine. Coal mines mining in low gas content seams should be required to have a less comprehensive AMS than a mine located in a seam with high gas content. The current gas monitoring schemes in the United States may be sufficient to monitor low gas seams with handheld, beltway, and machine mounted monitors whereas in high as seams it may be more beneficial to install AMS at major return nodes or a more sophisticated monitoring scheme. Griffin et al., 2012, reviews the placement and simulation of atmospheric monitoring sensors in underground coal mines. The placement of AMS sensors throughout the mine will directly dictate the data available for evaluation of the mine's ventilation system. Risk assessment plans of the mine may find it advantageous to place additional sensors to increase survivability. There is evidence to show that AMS and communication cabling can be damaged at 2 PSI of blast pressure and electronics components can be damaged at 10 PSI (Murray, 2009). Survivability can be increased by calculating a "safe distance outby," which is a function of the blast pressure from a given source (i.e. explosion at the working face). The "safe distance outby" is calculated by determining the magnitude of blast pressure, the distance required for the blast pressure to degrade enough to prevent damage of electronics cabling and components, and whether or not it is necessary to offset the sensor into a crosscut from the main return entry. Figure 6.2 shows a schematic of atmospheric monitoring sensor placement given three different monitoring schemes. The red circles indicate currently required atmospheric monitoring sensor locations (handheld gas detectors at the working face, machine mounted detectors, and CO beltway sensors). The maroon stars indicate sensor placement given a major return node monitoring scheme and yellow triangles indicate sensor placement for comprehensive atmospheric monitoring where a sensor can be placed a safe distance outby.
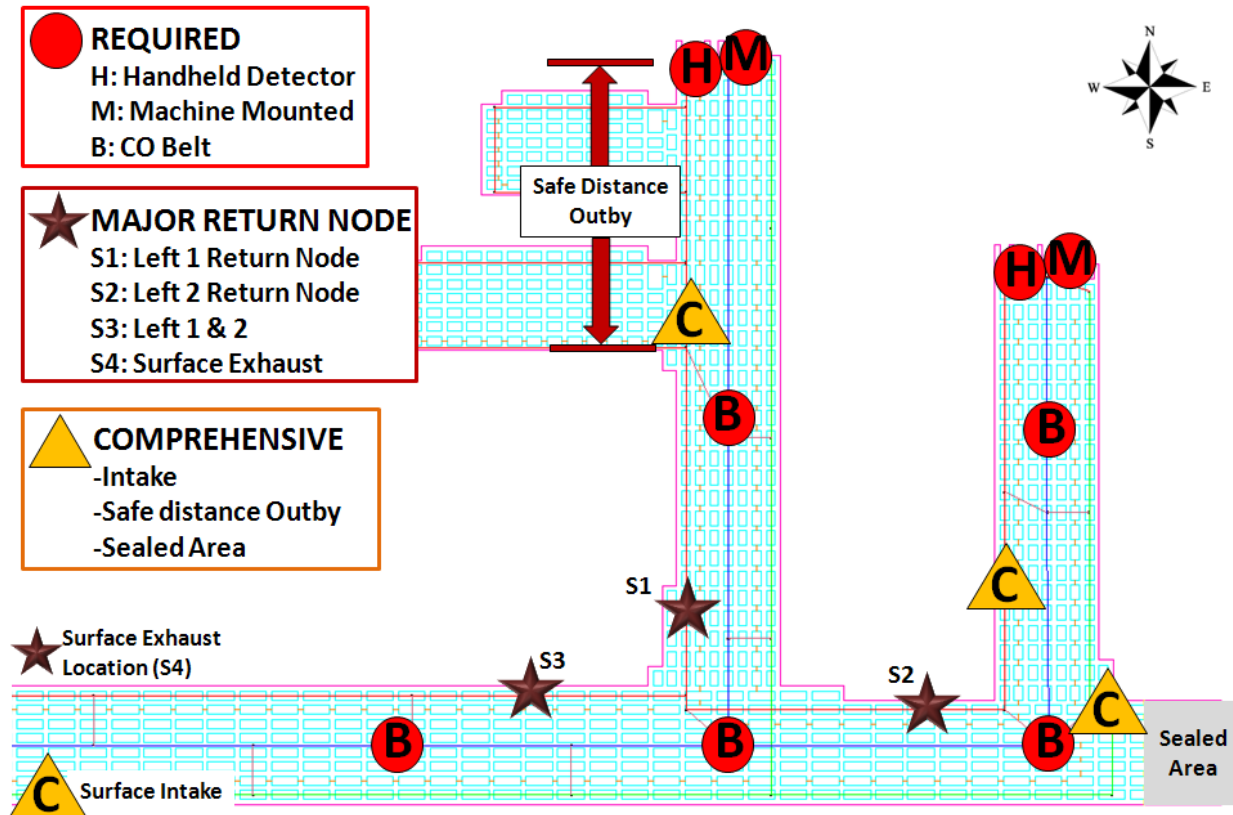
Figure 6.2: Atmospheric Monitoring Sensor Placement Schematic (Griffin, et. al, 2013)

A BBS-driven culture motivates a mining company to push beyond compliance with regulations by use of "good enough" sensors and to explore the opportunities to reduce risk with new technologies. Risk assessment methods should be used to dictate the level of atmospheric monitoring required at each mine, and the assessment would explicitly address the effects of varying levels on impacts to safety and profitability. Comprehensive atmospheric monitoring can provide early warnings and potentially prevent explosions in underground coal mines, and risk assessment techniques can help quantify the impact in a systematic, repeatable manner. Risk assessment techniques will ultimately dictate the spacing frequency and placement of atmospheric monitoring sensors.

6.6 Conclusions

The prevention of the ignition or explosion of gas or dust in underground coal mines provides context for the discussion of the integration of risk assessment, risk management, BBS, and comprehensive atmospheric monitoring systems. Prescriptive regulations typically provide little to no incentive for operators to integrate additional safety systems unless it is required by

law. Prescriptive regulations allow operators to comply with the minimum safety regulations and often force compliance or increased regulatory oversight. Compliance suggests that the existing level of atmospheric monitoring are sufficient, but recent losses suggest otherwise. The implementation of atmospheric monitoring technologies has allowed operators to actively monitor atmospheric conditions underground in real-time which can be used to increase health and safety. There are inherent issues with current atmospheric monitoring sensors which make it necessary to develop more reliable sensors. Atmospheric monitoring systems can still be used to determine if atmospheric conditions underground are trending towards becoming problematic. Risk management and behavior-based safety systems can be used to further reduce accidents and injuries. Risk management can be used to examine and identify risks that can be planned for accordingly and mitigated. Risk management and assessment also can be used to determine the level of atmospheric monitoring required to ensure a mine is safe. Joseph Main, the Assistant Secretary of Labor of MSHA (Main, 2012) noted in response to the Upper Big Branch disaster that "more needs to be done to improve health and safety and instill a culture of prevention in the mining industry that reflects the values of those who give so much of themselves to provide for their families, and enrich their communities." Atmospheric monitoring, risk management, and increasing the levels of behavior based safety systems will increase the level of prevention and awareness within the industry necessary in order to help prevent future accidents and motivate future industry profitability.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

A mine is a dynamic operation influenced by geology, mining conditions, and unforeseen circumstances that yield a unique working environment. Since every mining operation's ventilation is different and constantly changing as the mine develops, it is necessary to actively monitor, analyze, and mitigate high risk circumstances. It is important to ensure the technologies deployed into a mining operation can accurately provide critical information to management, as well as warn miners underground when high risk circumstances are developing. An AMS can be utilized to monitor and analyze ventilation parameters underground in real-time.

7.1 Conclusions

Chapter 2 demonstrated there are currently sensors available to monitor a wide variety of mine gases, psychrometric properties, air velocity, and seismic activity. Sensors must be MSHA approved in order to be implemented into United States underground coal mines. In the United States, atmospheric monitoring systems are primarily installed to monitor belt lines and electrical installations for smoke, CO, and CH_4 with set prescriptive alert and alarm threshold levels. Some mines may also utilize real-time monitoring of returns or tube bundle monitoring of sealed areas or gob as part of an approved ventilation plan, but regulation does not specifically require either. It is possible to create algorithms and computer intelligence to determine when high risk atmospheres are more likely.

Chapter 3 outlines mines are located throughout the world and within the United States utilizing real-time atmospheric and seismic monitoring. Australia leads the world in state-of-the-art atmospheric monitoring with several layers of monitoring. Tube bundle systems provide a continual form of monitoring with delays in sampling time proportional to the length of the sampling tube, and associated with the number of samples. International regulations typically place the burden on the operator to identify risks, create plans to mitigate those risks, and submit plans to regulators. The plan submitted to regulators then becomes the standards the mine is held to.

Chapter 4 provides a critical analysis of the implementation of conventional monitoring systems. VnetPC PRO simulations of several accident-type scenarios determined the major return node monitoring scheme, commonly used in Australia, could provide a bare minimum sensor placement scheme. The major return node monitoring scheme may not provide crucial information rapidly enough, thus requiring an increased level of monitoring to more quickly detect incidents and isolate areas where the accidents may have occurred. Sensors placed a "safe distance outby" would be beneficial to continue to measure gas concentrations after an incident. The "safe distance outby" can be calculated as a function of the degradation of the pressure wave created by an explosion. Methane pellistor-type sensors limited detection range (0-5%) was shown to be fully saturated in most areas during the three simulated incidents. Infrared methane sensors would have provided more information regarding the severity of the incident. There was qualitative evidence when analyzing the benefits of monitoring in past disasters, which suggests that given AMS is used correctly, that it would have aided in the prevention, escape, and rescue efforts of the disasters. The limited simulations and major accidents presented illustrate it is important that operators utilizing AMS understand the advantages, disadvantages, and constraints of utilizing such monitoring systems, which are highly site specific. All the possible explosive constituents in a mine atmosphere must be investigated to design an AMS that accurately quantifies explosion risk. The simulations indicate a comprehensive AMS may have sensors placed at major return nodes, a safe distance outby, inby of major return nodes, immediately outby of active working sections, remote bleeders, intakes, exhausts, and other problematic areas of the mine. Mine-specific risk assessment plans should be used to determine where additional sensors should be placed throughout the mine and survivability will always be an issue.

Chapter 5 outlines two case studies of United States underground coal mines utilizing real-time AMS. This research does not attempt to quantify data, but instead intends to provide engineers knowledge to utilize and implement an AMS. The first case study found the major return node monitoring scheme provides critical information beneficial to every mine operator. Battery backups on outstations must be utilized to maintain continuous data, as well as alleviate additional maintenance from short-term power outages. The case studies provide information regarding typical instrumentation, system installation, maintenance, data management and analysis, and expected initial capital costs. The second case study provided significant evidence

which indicate fan outages and changes in barometric pressure can result in increases in methane verifying mechanisms described in previous works. It is necessary for complete I.S. systems to be developed in order to monitor during extended fan outages and other circumstances. Virginia Tech is currently developing a fiber optics gas monitoring system that will fulfill I.S. requirements. There are differences in readings between AMS utilized in the case studies and commonly used handheld devices, while fairly minor, still warrant further investigation. Unless specifically required in the mine ventilation plan, mines are not currently required to archive AMS data. Historical behavior could be useful to understand normal operating conditions and identifying abnormal and high risk atmospheres.

Chapter 6 reviews that formal safety systems, technology, advances in mine research, improved equipment, and mine legislation have aided in reducing the number of fatalities from 1969 to present. Increasing the complexity of current safety systems is unlikely to result in further reduction of accidents and fatalities; however, improved sensing technology used in concert with risk assessment and management could allow for significant improvement. There are fundamental differences between risk management and commonly used safety systems in the United States, such as behavior-based safety. Government regulators should provide reasonable consideration to companies who are initially implementing sophisticated AMS in order to ensure false readings and other issues are not occurring with the AMS. Proper development of comprehensive AMS in the United States should be implemented in phases to ensure these systems are utilized correctly and allow more accurate sensors to be developed.

7.2 Recommendations for Future Work

The research presented provides insight to increase the understanding and benefits associated with the implementation and utilization of AMS in United States underground coal mines. This study provided significant evidence, via simulated scenarios and examination of past major accidents, which indicate more should be done to monitor ventilation parameters to aid in the prevention of ignitions and explosions related to gas and dust in the United States. Real-time monitoring of ventilation parameters can be used to aid in the prevention of ignitions and explosions related to gas and dust, which has been a reoccurring problem throughout the history of coal mining across the world. Table 7.1 contains recommended levels of monitoring, which

are based on the gas emissions that each mine experiences. Levels of monitoring include non-gassy, moderate, gassy, multiple seam mining, and sealed area or extensive gobs.

Table 7.1: Recommended Levels of Monitoring

Mine Gas Emissions	Ventilation Related Risk Level	Recommended Level of Monitoring
Non-Gassy	Low	Low
Moderate	Medium	Medium
Gassy	High	High
Multiple Seam Mining	High	Regular Spacing in Impact Zone and Buffer
Sealed Area/ Extensive Gob(s)	High	Sealed Area/ Extensive Gob(s)

The levels of mine gas emissions in Table 7.1 above cannot cite a specific source for the expected quantities of gas that determine which level of gas emissions a mine would fall under. Currently, mine gas emission ratings vary based on federal and state law, which does not present a common strategy for rating underground coal mine emissions. Further research should be conducted to determine quantitative rankings which correspond to non-gassy, moderate, and gassy.

Table 7.2 contains the descriptions for each of the recommended levels of monitoring in Table 7.1. This study recommends that a bare minimum monitoring scheme of low level monitoring where sensors placed at exhaust(s) and a "safe" distance outby of mining should be implemented in every United States underground coal mine. The 'medium' level of recommended monitoring consists of exhaust(s), "safe" distance outby, and major return nodes sensors. Major return node sensors allow operators to quickly determine which section is experiencing adverse conditions, as discussed in previous chapters. A 'high' level of monitoring consists of exhaust(s), "safe" distance outby, major return nodes, and comprehensive sensors which consist of monitoring other problematic areas of the mine (i.e., sealed areas). Sensors are installed inby of major return nodes and immediately outby the active working section (i.e., "safe" distance outby) in return airways to ensure that the mine ventilation is functioning properly and to detect incidents more rapidly. A 'high' level of monitoring should provide flexibility because the number of sensors to maintain can quickly become unmanageable.

Operators should carefully monitor when and where sensors are moved as mining develops to continue to have sensors in high risk areas of the mine.

Table 7.2: Recommended Levels of Monitoring Descriptions

Level of Monitoring	Recommended Level of Monitoring Description
Low	- Exhaust Sensor(s), CH_4, CO, O_2, CO_2 "Safe" Distance Outby
Medium	- Exhaust Sensor(s), CH_4, CO, O_2, CO_2 "Safe" Distance Outby - Major Return Node, CH_4, CO, O_2, CO_2, Air Velocity
High	- Exhaust Sensor(s), CH_4, CO, O_2, CO_2 "Safe" Distance Outby - Major Return Node, CH_4, CO, O_2, CO_2, Air Velocity - Comprehensive
Regular Spacing in Impacted Area and Buffer	Regularly Spaced, "X" distance, Inside Impacted Areas (under/over old workings) with "Buffer" sensors placed "Y" distance from Impacted Area, CH_4, CO, O_2 Spacing distance based on range of expected air velocities inside impacted area. "X" distance is equal to diffusion distance of gases at given range of air velocities. "Y" distance is based on diffusion distance. Calculated sensor spacing distance should be different for operations under old workings, compared to operations over old workings. Operations over old workings may be subject to interaction between the active and old workings due to complete extraction/caving/subsidence. Further studies should address sensor spacing when active workings may be subjected to interaction by old workings.
Sealed Area/ Extensive Gob	- Inside Sealed Area – I.S. Sensors Placed before Sealing - Outside Sealed Area – "Buffer" sensors placed "Z" distance away from sealed area. "Z" distance is based on diffusion distance.

Multiple seam mining operations are subject to potential communication from isolated previous workings via cracks and fissures that provide pathways to active mining workings. Additional scenarios may prove to require regular sensor spacing in the impacted areas that are not addressed in this study. Regular spacing in impacted areas and buffers consist of regularly spaced "X" distance sensors inside the impacted areas (i.e. over/under old mine workings) with

"buffer" sensors placed "Y" distance from impacted areas. Sensor spacing distances should be calculated based on the expected air velocities inside the impacted areas. Sensor spacing "X" and "Y" distances can be calculated based on gas diffusion for expected air velocities in those areas. The gas diffusion distance is equal to the calculated distance required for a given gas concentration to dilute. Further studies should be conducted to address sensor spacing when active workings may be subjected to interaction by old workings.

Sealed areas and extensive gobs can be monitored to better predict the impact these areas have on the active mine workings. I.S. sensors can be placed in sealed areas or gobs before sealing or caving commences. Outside the sealed area or in bleeder areas "buffer" sensors should be placed "Z" distance away from these areas. Sensor spacing "Z" distance is based upon the gas diffusion distance.

Further research should be conducted to determine the mechanisms which cause increases in methane concentrations corresponding to changes in barometric pressure. It is possible that barometric pressure will have a more significant impact on out- and in-gassing from previous mined areas that are isolated from active mine workings than areas within the active mine workings.

The integration of AMS into United States underground coal mines should be implemented in phases to allow for improved technologies to develop and the reliability of each system to be determined. The integration of AMS in phases is important to ensure that monitoring systems are evaluated across the United States and inherent issues with current monitoring technologies can be addressed appropriately. There are several necessary steps to be completed before AMS should be implemented into United States underground coal mines:

- The accuracy of available AMS sensors must be established, which will require significant laboratory and in-mine testing. The minimum detection limits, accuracy, and tolerances (±) of each sensor must be established in order to ensure operators and regulators understand the benefits and limitations of each sensor and system. Acceptable tolerances must be established in order to ensure confidence in the data being measured by AMS. AMS sensors performance compared to other commonly used handheld detection methods for gas and air velocity should be addressed. It is necessary to

establish the reliability of all detection devices that are approved for use in United States underground coal mines. The calibration process of sensors should be established over a given scale. Current calibration consists of a zero gas point and a given concentration point specific to which gas the sensor is detecting. Utilizing a calibration process over a given scale can establish the accuracy of each sensor over a range of given concentrations.

- Methods should be established for processing, managing, and interpreting real-time atmospheric monitoring data. Actions required to be taken when managing real-time data should be standardized using a risk and operation based approach. Complete I.S. systems must be developed in order to be beneficial in emergencies and extended fan outages.

- Development of a standardized methodology for rating a mine's gas emissions. Currently, federal and state regulations differ on the definition of "gassy" and "non-gassy" underground coal mines. This standardized methodology must account for unique and variable factors at each mine, and can then inform initial design of each AMS.

Ultimately, comprehensive real-time AMS has great potential to improve health and safety in United States underground coal mines, but careful implementation is critical to optimal utilization and maximum benefit to stakeholders.

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APPENDIX A: UNITED STATES ATMOSPHERIC MONITORING REGULATIONS 30 CFR § 75.351

United States Atmospheric Monitoring
30 CFR § 75.351
Atmospheric monitoring system (AMS)

(a) *AMS operation*. Whenever personnel are underground and an AMS is used to fulfill the requirements of § § 75.323(d)(1)(ii), 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), 75.350(d), or 75.362(f), the AMS must be operating and a designated AMS operator must be on duty at a location on the surface of the mine where audible and visual signals from the AMS must be seen or heard and the AMS operator can promptly respond to these signals.

(b) *Designated surface location and AMS operator*. When an AMS is used to comply with § § 75.323(d)(1)(ii), 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), 75.350(d), or 75.362(f), the following requirements apply:

(1) The mine operator must designate a surface location at the mine where signals from the AMS will be received and two-way voice communication is maintained with each working section, with areas where mechanized mining equipment is being installed or removed, and with other areas designated in the approved emergency evacuation and firefighting program of instruction (§ 75.1502).

(2) The mine operator must designate an AMS operator to monitor and promptly respond to all AMS signals. The AMS operator must have as a primary duty the responsibility to monitor the malfunction, alert and alarm signals of the AMS, and to notify appropriate personnel of these signals. In the event of an emergency, the sole responsibility of the AMS operator shall be to respond to the emergency.

(3) A map or schematic must be provided at the designated surface location that shows the locations and type of AMS sensor at each location, and the intended air flow direction at these locations. This map or schematic must be updated within 24 hours of any change in this information.

(4) The names of the designated AMS operators and other appropriate personnel, including the designated person responsible for initiating an emergency mine evacuation under § 75.1501, and the method to contact these persons, must be provided at the designated surface location.

(c) *Minimum operating requirements*. AMSs used to comply with § § 75.323(d)(1)(ii), 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), 75.350(d), or 75.362(f) must:

(1) Automatically provide visual and audible signals at the designated surface location for any interruption of circuit continuity and any electrical malfunction of the system. These signals must be of sufficient magnitude to be seen or heard by the AMS operator.

(2) Automatically provide visual and audible signals at the designated surface location when the carbon monoxide concentration or methane concentration at any sensor reaches the alert level as specified in § 75.351(i). These signals must be of sufficient magnitude to be seen or heard by the AMS operator.

(3) Automatically provide visual and audible signals at the designated surface location distinguishable from alert signals when the carbon monoxide, smoke, or methane concentration at any sensor reaches the alarm level as specified in § 75.351(i). These signals must be of sufficient magnitude to be seen or heard by the AMS operator.

(4) Automatically provide visual and audible signals at all affected working sections and at all affected areas where mechanized mining equipment is being installed or removed when the carbon monoxide, smoke, or methane concentration at any sensor reaches the alarm level as specified in § 75.351(i). These signals must be of sufficient

magnitude to be seen or heard by miners working at these locations. Methane signals must be distinguishable from other signals.

(5) Automatically provide visual and audible signals at other locations as specified in Mine Emergency Evacuation and Firefighting Program of Instruction (§ 75.1502) when the carbon monoxide, smoke, or methane concentration at any sensor reaches the alarm level as specified in § 75.351(i). These signals must be seen or heard by miners working at these locations. Methane alarms must be distinguishable from other signals.

(6) Identify at the designated surface location the operational status of all sensors.

(7) Automatically provide visual and audible alarm signals at the designated surface location, at all affected working sections, and at all affected areas where mechanized mining equipment is being installed or removed when the carbon monoxide level at any two consecutive sensors alert at the same time. These signals must be seen or heard by the AMS operator and miners working at these locations.

(d) *Location and installation of AMS sensors*. (1) All AMS sensors, as specified in § § 75.351(e) through 75.351(h), must be located such that measurements are representative of the mine atmosphere in these locations.

(2) Carbon monoxide or smoke sensors must be installed near the center in the upper third of the entry, in a location that does not expose personnel working on the system to unsafe conditions. Sensors must not be located in abnormally high areas or in other locations where air flow patterns do not permit products of combustion to be carried to the sensors.

(3) Methane sensors must be installed near the center of the entry, at least 12 inches from the roof, ribs, and floor, in a location that would not expose personnel working on the system to unsafe conditions.

(e) Location of sensors-belt air course.

(1) In addition to the requirements of paragraph (d) of this section, any AMS used to monitor belt air courses under Sec. 75.350(b) must have approved sensors to monitor for carbon monoxide at the following locations:

(i) At or near the working section belt tailpiece in the air stream ventilating the belt entry. In longwall mining systems the sensor must be located upwind in the belt entry at a distance no greater than 150 feet from the mixing point where intake air is mixed with the belt air at or near the tailpiece;

(ii) No more than 50 feet upwind from the point where the belt air course is combined with another air course or splits into multiple air courses;

(iii) At intervals not to exceed 1,000 feet along each belt entry. However, in areas along each belt entry where air velocities are between 50 and 100 feet per minute, spacing of sensors must not exceed 500 feet. In areas along each belt entry where air velocities are less than 50 feet per minute, the sensor spacing must not exceed 350 feet;

(iv) Not more than 100 feet downwind of each belt drive unit, each tailpiece, transfer point, and each belt take-up. If the belt drive, tailpiece, and/or take-up for a single transfer point are installed together in the same air course, and the distance between the units is less than 100 feet, they may be monitored with one sensor downwind of the last component. If the distance between the units exceeds 100 feet, additional sensors are required downwind of each belt drive unit, each tailpiece, transfer point, and each belt take-up; and

(v) At other locations in any entry that is part of the belt air course as required and specified in the mine ventilation plan.

(2) Smoke sensors must be installed to monitor the belt entry under Sec. 75.350(b) at the following locations:

(i) At or near the working section belt tailpiece in the air stream ventilating the belt entry. In longwall mining systems the sensor must be located upwind in the belt entry at a distance no greater than 150 feet from the mixing point where intake air is mixed with the belt air at or near the tailpiece;

(ii) Not more than 100 feet downwind of each belt drive unit, each tailpiece transfer point, and each belt take-up. If the belt drive, tailpiece, and/or take-up for a single transfer point are installed together in the same air course, and the distance between the units is less than 100 feet, they may be monitored with one sensor downwind of the last component. If the distance between the units exceeds 100 feet, additional sensors are required downwind of each belt drive unit, each tailpiece, transfer point, and each belt take-up; and

(iii) At intervals not to exceed 3,000 feet along each belt entry.

(iv) This provision shall be effective one year after the Secretary has determined that a smoke sensor is available to reliably detect fire in underground coal mines.

(f) *Locations of sensors--the primary escapeway*. When used to monitor the primary escapeway under § 75.350(b)(4), carbon monoxide or smoke sensors must be located in the primary escapeway within 500 feet of the working section and areas where mechanized mining equipment is being installed or removed. In addition, another sensor must be located within 500 feet inby the beginning of the panel. The point-feed sensor required by § 75.350(d)(1) may be used as the sensor at the beginning of the panel if it is located within 500 feet inby the beginning of the panel.

(g) *Location of sensors--return air splits*. (1) If used to monitor return air splits under § 75.362(f), a methane sensor must be installed in the return air split between the last working place, longwall or shortwall face ventilated by that air split, and the junction of the return air split with another air split, seal, or worked out area.

(2) If used to monitor a return air split under § 75.323(d)(1)(ii), the methane sensors must be installed at the following locations:

(i) In the return air course opposite the section loading point, or, if exhausting auxiliary fan(s) are used, in the return air course no closer than 300 feet downwind from the fan exhaust and at a point opposite or immediately outby the section loading point; and

(ii) Immediately upwind from the location where the return air split meets another air split or immediately upwind of the location where an air split is used to ventilate seals or worked-out areas.

(h) *Location of sensors--electrical installations*. When monitoring the intake air ventilating underground transformer stations, battery charging stations, substations, rectifiers, or water pumps under § 75.340(a)(1)(ii) or § 75.340(a)(2)(ii), at least one sensor must be installed to monitor the mine atmosphere for carbon monoxide or smoke, located downwind and not greater than 50 feet from the electrical installation being monitored.

(i) *Establishing alert and alarm levels*. An AMS installed in accordance with the following paragraphs must initiate alert and alarm signals at the specified levels, as indicated:

(1) For § 75.323(d)(1)(ii) alarm at 1.5% methane.

(2) For § § 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), and 75.350(d), alert at 5 ppm carbon monoxide above the ambient level and alarm at 10 ppm carbon monoxide above the ambient level when carbon monoxide sensors are used; and alarm at a smoke optical density of 0.022 per meter when smoke sensors are used. Reduced alert and alarm settings approved by the district manager may be required for carbon monoxide sensors identified in the mine ventilation plan, § 75.371(nn).

(3) For § 75.362(f), alert at 1.0% methane and alarm at 1.5% methane.

(j) *Establishing carbon monoxide ambient levels*. Carbon monoxide ambient levels and the means to determine these levels must be approved in the mine ventilation plan (§ 75.371(hh)) for monitors installed in accordance with § § 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), and 75.350(d).

(k) *Installation and maintenance*. An AMS installed in accordance with § § 75.323(d)(1)(ii), 75.340(a)(1)(ii),

75.340(a)(2)(ii), 75.350(b), 75.350(d), or 75.362(f) must be installed and maintained by personnel trained in the installation and maintenance of the system. The system must be maintained in proper operating condition.

(l) *Sensors*. Sensors used to monitor for carbon monoxide, methane, and smoke must be either of a type listed and installed in accordance with the recommendations of a nationally recognized testing laboratory approved by the Secretary; or these sensors must be of a type, and installed in a manner, approved by the Secretary.

(m) *Time delays*. When a demonstrated need exists, time delays may be incorporated into the AMS. These time delays must only be used to account for non-fire related carbon monoxide alert and alarm sensor signals. These time delays are limited to no more than three minutes. The use and length of any time delays, or other techniques or methods which eliminate or reduce the need for time delays, must be specified and approved in the mine ventilation plan.

(n) *Examination, testing, and calibration*. (1) At least once each shift when belts are operated as part of a production shift, sensors used to detect carbon monoxide or smoke in accordance with § § 75.350(b), and 75.350(d), and alarms installed in accordance with § 75.350(b) must be visually examined.

(2) At least once every seven days, alarms for AMS installed in accordance with § § 75.350(b), and 75.350(d) must be functionally tested for proper operation.

(3) At intervals not to exceed 31 days--

(i) Each carbon monoxide sensor installed in accordance with § § 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), or 75.350(d) must be calibrated in accordance with the manufacturer's calibration specifications. Calibration must be done with a known concentration of carbon monoxide in air sufficient to activate the alarm;

(ii) Each smoke sensor installed in accordance with § § 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), or 75.350(d) must be functionally tested in accordance with the manufacturer's calibration specifications;

(iii) Each methane sensor installed in accordance with § § 75.323(d)(1)(ii) or 75.362(f) must be calibrated in accordance with the manufacturer's calibration specifications. Calibration must be done with a known concentration of methane in air sufficient to activate an alarm.

(iv) If the alert or alarm signals will be activated during calibration of sensors, the AMS operator must be notified prior to and upon completion of calibration. The AMS operator must notify miners on affected working sections, areas where mechanized mining equipment is being installed or removed, or other areas designated in the approved emergency evacuation and firefighting program of instruction (§ 75.1502) when calibration will activate alarms and when calibration is completed.

(4) Gases used for the testing and calibration of AMS sensors must be traceable to the National Institute of Standards and Technology reference standard for the specific gas. When these reference standards are not available for a specific gas, calibration gases must be traceable to an analytical standard which is prepared using a method traceable to the National Institute of Standards and Technology. Calibration gases must be within 2.0 percent of the indicated gas concentration.

(o) *Recordkeeping*. (1) When an AMS is used to comply with § § 75.323(d)(1)(ii), 75.340(a)(1)(ii), 75.340(a)(2)(ii), 75.350(b), 75.350(d), or 75.362(f), individuals designated by the operator must make the following records by the end of the shift in which the following event(s) occur:

(i) If an alert or alarm signal occurs, a record of the date, time, location and type of sensor, and the cause for the activation.

(ii) If an AMS malfunctions, a record of the date, the extent and cause of the malfunction, and the corrective action taken to return the system to proper operation.

(iii) A record of the seven-day tests of alert and alarm signals; calibrations; and maintenance of the AMS must be

made by the person(s) performing these actions.

(2) The person entering the record must include their name, date, and signature in the record.

(3) The records required by this section must be kept either in a secure book that is not susceptible to alteration, or electronically in a computer system that is secure and not susceptible to alteration. These records must be maintained separately from other records and identifiable by a title, such as the `AMS log.'

(p) *Retention period*. Records must be retained for at least one year at a surface location at the mine and made available for inspection by miners and authorized representatives of the Secretary.

(q) Training.

(1) All AMS operators must be trained annually in the proper operation of the AMS. This training must include the following subjects:

(i) Familiarity with underground mining systems;

(ii) Basic atmospheric monitoring system requirements;

(iii) The mine emergency evacuation and firefighting program of instruction;

(iv) The mine ventilation system including planned air directions;

(v) Appropriate response to alert, alarm and malfunction signals;

(vi) Use of mine communication systems including emergency notification procedures; and

(vii) AMS recordkeeping requirements.

(2) At least once every six months, all AMS operators must travel to all working sections.

(3) A record of the content of training, the person conducting the training, and the date the training was conducted, must be maintained at the mine for at least one year by the mine operator.

(r) *Communications*. When an AMS is used to comply with § 75.350(b), a two-way voice communication system required by § 75.1600 must be installed in an entry that is separate from the entry in which the AMS is installed no later than August 2, 2004. The two-way voice communication system may be installed in the entry where the intake sensors required by § § 75.350(b)(4) or 75.350(d)(1) are installed.

APPENDIX B: OFFICE OF QUEENSLAND PARLIAMENTARY COUNSEL AUSTRALIA 2010, GAS MONITORING

Part 7   Gas monitoring

Division 1   Safety and health management system

221A   Application of div 1
This division does not apply to a drift or shaft being driven
from the surface in material other than coal.

222   Gas monitoring system
(1) An underground mine's safety and health management system
must provide for a gas monitoring system complying with this section.

(2) The gas monitoring system must provide for the following—
      (a) continuous monitoring of the mine atmosphere at the places mentioned in section
      223(1), to detect methane, carbon monoxide, carbon dioxide and oxygen;
      (b) automatically detecting or calculating the values and trends of the following—
            (i) gas concentrations;
            (ii) the ratio of carbon monoxide and oxygen deficiency;[11]
            (iii) the ratio of carbon monoxide and carbon dioxide;
            (iv) gas explosibility;
      (c) automatically activating an alarm if a gas alarm level is exceeded;
      (d) recording the values and trends mentioned in paragraph (b) and displaying the
      record—
            (i) at the surface of the mine where the record can be easily accessed by coal
            mine workers; and
            (ii) in a way that the record can be easily read by the workers;
      (e) keeping the information on which the values and trends mentioned in paragraph (d)
      were based at the mine in a way that enables the information to be easily accessed and
      inspected.
(3) The gas monitoring system must also provide for—
      (a) an alternative electricity supply to ensure the system continues to function if the
      normal electricity supply fails; and
      (b) electrical equipment installed and operated underground for the system to have the
      following explosion protection category—
            (i) for equipment other than a gas detector head—Exia;
            (ii) for a gas detector head—Ex ia or Ex s.

223   Monitoring and sampling mine atmosphere

(1) An underground mine's safety and health management system must provide for continuous monitoring of the mine atmosphere, using the mine's gas monitoring system, at the return airway of each ventilation split.

(1A) The safety and health management system must also provide for sampling of the mine atmosphere, using the mine's gas monitoring system, at each of the following places—

> (a) the return airway from each unsealed waste, idle workings and goaf area;
>
> (b) the return of each airway at the upcast shaft;
>
> (c) other places stated in the mine's principal hazard management plan for gas monitoring as places where gas monitoring must be carried out.

(1B) The safety and health management system must also provide for—

> (a) continuous monitoring, using the mine's gas monitoring system, to detect products of combustion in the mine atmosphere at the return side of each conveyor belt; and
>
> (b) when the products are detected, the automatic activation of an alarm located on the surface in a position that is generally under observation to warn persons of the products' presence.

(2) The safety and health management system must also provide for a regularly updated plan to be kept at the mine showing the location of—

> (a) the sampling point for each of the places mentioned in subsection (1); and
>
> (b) each of the mine's ventilation control devices designated under section 351(1).
>
> (3) A person must not relocate equipment used for sampling without the ventilation officer's authorisation.

224   Gas alarm levels

(1) An underground mine's principal hazard management plan for gas monitoring must state the values and ratios for gas, mentioned in section 222(2)(b), that are gas alarm levels.

(2) The mine must have a standard operating procedure for changing the gas alarm levels, including recording the following details—

> (a) the nature of, and reason for, the change;
>
> (b) the date it was made;
>
> (c) the name of the person who made it.

225   Changing gas alarm level settings

A person must not change a gas alarm level setting without the ventilation officer's authorisation.

226   Acknowledging alarms

(1) An underground mine must have a standard operating procedure for acknowledging alarms that are activated when gas alarm levels are exceeded.

(2) The procedure must provide for at least 1 person to be—

> (a) on the surface when a person is underground; and
>
> (b) authorised by the underground

Division 2   Methane and other gas detectors

Subdivision 1   General

227   Portable gas detectors
228   Providing portable gas detectors

229 Fixed methane detectors

(1) This section applies to a fixed methane detector at an underground mine that is—
    (a) fitted to equipment; or
    (b) a self-contained unit located at a particular place; or
    (c) part of the gas monitoring system.

(2) The site senior executive must ensure that if the detector malfunctions or fails it will automatically—
    (a) shut down the equipment, or part of the equipment, it is monitoring; and
    (b) give a visible alarm.

(3) Subsection (2)(a) does not apply if the equipment or part is fitted with more than 1 methane detector and 1 of the detectors remains operational.

Subdivision 3   Places where methane detectors must be located

241 Places where methane detectors must be located

The site senior executive must ensure a place mentioned in this subdivision has automatic methane detectors located at the place under this subdivision.

242   Intake airways

(1) At least 1 automatic methane detector must be located in each intake airway at the interface between—
    (a) a NERZ and ERZ1; and
    (b) 2 NERZs.
        Example of interface between 2 NERZs— the interface between subdivided parts of a
        NERZ

(2) A detector located at an interface between a NERZ and ERZ1 must—
    (a) when the general body concentration of methane detected at the interface exceeds 0.25%—automatically activate a visible alarm; and
    (b) when the general body concentration of methane detected at the interface exceeds 0.5%—automatically trip the electricity supply to non-intrinsically safe plant in—
        (i) the ERZ1 and NERZ; or
        (ii) if the NERZ has been subdivided—the ERZ1 and the subdivided part of the NERZ adjacent to the ERZ1.

(3) A detector located at the interface between a NERZ and an ERZ1 must be a self-contained unit or part of the gas monitoring system for the mine.

(4) A detector located at an interface between 2 NERZs must—
    (a) automatically activate a visible alarm when the general body concentration of methane detected at the interface exceeds 0.25%; and
    (b) if the NERZ has been subdivided—automatically trip the electricity supply to non-intrinsically safe plant in the adjacent subdivided part when the general body concentration of methane detected at the interface exceeds 0.5%.

(5) From 3 months after the commencement of this subsection, the alarm mentioned in subsections (2)(a) and (4)(a) must be visible at the interface.

243   Main return airway and return airway in a ventilation split

(1) At least 1 automatic methane detector must be located in—
    (a) each main return airway; and

(b) each return airway in a ventilation split.

(2) The detector must automatically activate a visible alarm when the general body concentration of methane detected in the return air exceeds the percentage stated in the mine's principal hazard management plan for ventilation as the percentage that must not be exceeded before the detector activates the alarm.

244   Longwall face

(1) At least 1 automatic methane detector must be located at the following places—

> (a) the intersection between the longwall face and an intake airway;
> (b) the intersection between the longwall face and the return airway.

(2) A detector located between the longwall face and an intake airway must automatically trip the electricity supply to longwall equipment in the longwall face and intake airway when the general body concentration of methane detected at the intersection exceeds 2%.

(3) A detector located between the intersection between the longwall face and the return airway must automatically trip the electricity supply to longwall equipment in the longwall face and return airway when the general body concentration of methane detected at the intersection exceeds 2%.

Division 4   Miscellaneous

252   General back-up for gas monitoring system

(1) An underground mine's principal hazard management plan for gas monitoring must provide for the use of portable gas detectors to manage risk in the event of a failure or the non-operation of the gas monitoring system.

Example of non-operation of the gas monitoring system— a non-operation caused by the repair, testing or maintenance of the system

(2) The mine must have a standard operating procedure for using the portable gas detectors in the event of the failure or non-operation.

(3) If the system fails or becomes non-operational, the underground mine manager must ensure coal mining operations are not carried out in the part of the mine affected by the failure or non-operation unless the part is continually monitored, using portable gas detectors, to achieve an acceptable level of risk.

253   Withdrawal of persons in case of danger caused by failure or non-operation of gas monitoring system

For section 273 of the Act, a part of an underground mine is taken to be dangerous if the part is affected by the failure or non-operation of the gas monitoring system and the mine does not have—

> (a) a standard operating procedure for using portable gas detectors; or
> (b) sufficient portable gas detectors to continually monitor the part to the extent necessary to achieve an acceptable level of risk.