Comprehensive ventilation simulation of atmospheric monitoring sensors in underground coal mines

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ABSTRACT: Atmospheric monitoring in underground coal mines has become more sophisticated with advanced technology and allows mine operators to analyze atmospheric conditions underground in real-time. Real-time monitoring can be used to determine whether conditions are safe for mining and to operate ventilation systems more efficiently. Optimal placement of sensors and design of the monitoring system is dependent on the mine geometry and in situ conditions. However, ventilation network simulation can be used to evaluate placement of sensors under varying operating conditions and emergency scenarios. Network simulation of a realistic underground coal mine under different scenarios is utilized to make recommendations for optimization of comprehensive real-time atmospheric monitoring systems for underground coal mines. Additionally, technological limitations and developing technology are addressed.

1. Introduction

The progression of technology has allowed mine monitoring techniques to become more sophisticated, yet explosions in underground coal mines are still occurring. Explosions of gas and dust continue to be recognized as an extreme danger in underground coal mines. There were approximately 89 fatal and 290 non-fatal days lost accidents due to the ignition or explosion of gas or dust from 1983 to 2008 (MSHA, 2010). 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 enables operators to determine whether or not conditions are safe for mining and 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. Ventilation network simulation can be used to determine whether sensors could correctly quantify atmospheric parameters given various mine emergency scenarios.

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 will examine 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 in correctly quantifying mine gases because of issues with response time, range, sensitivity, and survivability.

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 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.
2. Atmospheric Monitoring Technology and Strategy

2.1 Current Atmospheric Monitoring

An underground coal mine is exposed to a wide variety of gases which increase the potential for an explosion given the wrong mixture of gases. It is critical to monitor for methane (CH₄), carbon monoxide (CO), carbon dioxide (CO₂), and oxygen (O₂) 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 of belt lines and electrical installations in the U.S. for smoke, CO, and CH₄, 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.

2.2 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 mines ventilation 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. A belt fire is not covered in this exercise but similar simulations can be performed to ensure fire gas sensors are properly placed. Real time atmospheric monitoring sensors can be limited by the sensing technology used to detect the parameters of interest, 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. Catalytic gas sensors response times can range from 10 to 15 seconds and infrared sensors response time is 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 sensors gas chamber. If there is a methane gas inundation 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 a gas sensor polls data will impact the battery life of a sensor if it is battery operated. 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 typically 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. Electrochemical gas sensors also require oxygen to operate properly. Electrochemical sensors can measure hydrogen 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% CH₄ 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.

2.3 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.

2.4 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. The scope of this study is real time continuous monitoring underground, so, while tube bundle systems have an important role in monitoring of underground atmospheres they are not assessed in this study.

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. Real time monitoring 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.

3. Methodology

3.1 Mine Model

A medium size mine 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 (MSHA, 2007). The main development entries within the model consist 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 are 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 1 shows a map of the mine which can be found in Appendix A.

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 airways with flow maintained in the outby direction. Surface access to the mine is through the 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 1 contains the mine model input parameters for VnetPC PRO.
Table 1. VnetPC PRO Mine Model Input Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (English)</th>
<th>Value (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Development Entries Pillar Size</td>
<td>30 x 90 ft</td>
<td>9.1 x 27.4m</td>
</tr>
<tr>
<td>Crosscut Entries Pillar Size</td>
<td>30 x 50 ft</td>
<td>9.1 x 15.2m</td>
</tr>
<tr>
<td>Opening Size (Constant)</td>
<td>18 x 6 ft</td>
<td>5.5m Wide, 1.8m High</td>
</tr>
<tr>
<td>Opening Cross-Sectional Area (Constant)</td>
<td>108 ft²</td>
<td>10.0 m²</td>
</tr>
<tr>
<td>Opening Perimeter (Constant)</td>
<td>48 ft</td>
<td>14.6 m</td>
</tr>
<tr>
<td>Friction Factor (K) – Intake, Clean Conditions</td>
<td>49 lb·min²/ft⁴ x 10⁻¹⁰</td>
<td>0.009 kg/m³</td>
</tr>
<tr>
<td>Friction Factor (K) – Returns, Some Irregularities</td>
<td>54 lb·min²/ft⁴ x 10⁻¹⁰</td>
<td>0.010 kg/m³</td>
</tr>
<tr>
<td>Friction Factor (K) – Belt Entries</td>
<td>27 lb·min²/ft² x 10⁻¹⁰</td>
<td>0.005 kg/m³</td>
</tr>
<tr>
<td>Friction Factor (K) – Post Explosion</td>
<td>250 lb·min²/ft³ x 10⁻¹⁰</td>
<td>0.046 kg/m³</td>
</tr>
<tr>
<td>Leakage Resistance (R) - Average</td>
<td>4200 P.U.</td>
<td>4690 Ns²/m⁸</td>
</tr>
<tr>
<td>Main Fan Operating Pressure</td>
<td>3.68 in. w.g.</td>
<td>0.92kPa</td>
</tr>
<tr>
<td>Main Fan Operating Quantity</td>
<td>193 kcfm</td>
<td>91.1 m³/sec</td>
</tr>
</tbody>
</table>

The main pillar size and panel pillar size 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 meters² (108 ft²) and 14.6 meters (48 ft) respectively. The friction factors (K) for intake, returns, and belt entries were 0.009 kg/m³, 0.010 kg/m³, and 0.005 kg/m³ (49, 54, and 27 lb·min²/ft⁴ x 10⁻¹⁰), respectively (McPherson 2009). The leakage resistance (R) for a single stopping was chosen to be 4690 Ns²/m³ (4200 P.U.) for average conditions (Oswald et. al, 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 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/m³ (250 lb·min²/ft³ 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 m³/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 then separately calculated for each scenario by assuming that 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.

3.2 Incident 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 2 (Appendix A) 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. 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, the 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.
3.3 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 m³, 347,000 ft³ CH₄), the methane consumed in the explosion (4,020 m³, 142,000 ft³ CH₄), and the remaining methane after the explosion behind the seals (5,800 m³, 205,000 ft³ CH₄), which were used as base line values to simulate an explosion in a sealed area (MSHA, 2006). This simulation is not intended to replicate the Sago mine explosion but was chosen because of the publicly available data regarding methane content behind a sealed area.

In order to simulate the estimated 5,805 m³ (205,000 ft³) 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 m³/s (1 kcfm). The location of the sealed area is shown at location 1 on Figure 2. A fixed quantity of 0.47 m³/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 m³/s (1 kcfm) simulates a methane concentration of 90.91 percent which corresponds with a 4.72 m³/s (10 kcfm) contaminant emission rate. Byproducts of the explosion were not taken into consideration.

3.4 Methane Face Inundation

Morris reported methane emissions from floor outbursts could be 140,000 m³ (~4,900,000 ft³) and over 8x10⁶ m³ (~280,000,000 ft³) from sudden roof emissions (1974). 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 2. A fixed quantity of 0.47 m³/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 m³/s (10 kcfm).

3.5 Ignition at the Working Face

Murray 2009 noted that a methane-gas mixture of 267-283 m³ (8,000-10,000 ft³) with a localized volume of 9.5% methane (27 m³, 950 ft³ CH₄) would represent a moderate-sized methane explosion that could occur at the working face. An ignition was modeled assuming 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 2.

4. Results

4.1 Explosion in Sealed Area Results

The explosion in the No. 5 sealed area was simulated in 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 m³/s (68.41 kcfm). The entry associated with the No. 5 sealed area must have a fixed quantity of 0.47 m³/s (1 kcfm) in order to simulate a methane concentration of 90.91 percent which corresponds with a contaminant emission rate of 4.72 m³/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 1. Air quantities in the immediate area are also significantly reduced and air reversal is 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 2 contains the methane concentrations observed at sensor locations.

The explosion in a sealed area simulation also showed the air velocities in the immediate vicinity were significantly reduced and 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 Figure 6. The high range of methane concentrations indicate that 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 clearly 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, and in 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 technology would not be ideal under this scenario.
4.2 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 working face entry was solved under normal operating conditions to have an air quantity of 15.23 m$^3$/s (32.26 kcfm). The entry at the working face must have a fixed quantity of 0.47 m$^3$/s (1 kcfm) in order to simulate a methane concentration of 90.91. This corresponds with a contaminant emission rate of 4.72 m$^3$/s (10 kcfm). 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 2 which can be found in Appendix A, 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 measured by a solid-state 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 in Table 3 (Appendix A).

4.3 Ignition at the Working Face Results

An ignition at the working face was simulated in 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 m$^3$/s (32.26 kcfm) which has a corresponding methane emission rate of 1.6 m$^3$/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 inoperative. Table 2 (Appendix A) 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 in which case no change would be observed at methane sensors because all the methane would be consumed.

4.4 Summary of Incident Simulation Results

Table 3 which can be found in Appendix A, 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 was 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 that should be de-energized when certain gas concentrations are met. Also, monitoring data can be used to create algorithms and pinpoint 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.
5. Conclusions

Current atmospheric monitoring sensors are limited by inherent operating issues. Current sensors are limited in terms of 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 study is real time continuous monitoring underground, so, while tube bundle systems have an important role in monitoring of underground atmospheres they are not assessed in this study. Real time monitoring 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 real time sensors will detect trending conditions within a 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 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. 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 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. Future work will cover simulation of a belt fire, developing sensor technology, and improved communication during emergencies (i.e. wireless).

6. References

7. Appendix A

Figure 1. Mine Map

Figure 2. Incident Locations and Monitoring Points

Table 2. Summary of Incident Simulation Results

<table>
<thead>
<tr>
<th>Incident</th>
<th>Map Incident Number</th>
<th>Methane Concentration (%) at Sensor Location</th>
<th>Main Fan</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S1 (Left 1)</td>
<td>S2 (Left 2)</td>
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<tr>
<td>Explosion in Sealed Area</td>
<td>1</td>
<td>0</td>
<td>21.1</td>
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<td>Face Inundation</td>
<td>2</td>
<td>79.55</td>
<td>0</td>
</tr>
<tr>
<td>Ignition at Working Face</td>
<td>3</td>
<td>9.35</td>
<td>0</td>
</tr>
<tr>
<td>Normal</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3. Estimated Gas Arrival Times at Sensor Locations

<table>
<thead>
<tr>
<th>Incident</th>
<th>Map Incident Number</th>
<th>Estimated Gas Arrival Time (minutes) at Sensor Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S1 (Left 1)</td>
</tr>
<tr>
<td>Explosion in Sealed Area (no blast force)</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Explosion in Sealed Area (with blast force)</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Face Inundation (total disruption)</td>
<td>3</td>
<td>323</td>
</tr>
<tr>
<td>Face Inundation (momentary disruption)</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Ignition at Working Face</td>
<td>2</td>
<td>13</td>
</tr>
</tbody>
</table>