MONITORING SYSTEMS FOR COAL MINES UTILIZING BOOSTER FANS

by

Vasu Gangrade

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STATEMENT OF THESIS APPROVAL

The thesis of **Vasu Gangrade**

has been approved by the following supervisory committee members:

Felipe Calizaya , Chair **05/14/2014**
Date Approved

Michael G. Nelson , Member **05/14/2014**
Date Approved

Kevin Perry , Member **05/14/2014**
Date Approved

and by **Michael G. Nelson** , Chair/Dean of

the Department/College/School of **Mining Engineering**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

A booster fan is an underground ventilation device installed in series with a main surface fan and is used to boost the pressure of air of the current passing through it. Currently, federal regulations in the U.S. do not permit the use of booster fans in underground bituminous and lignite coal mines. Considering that a booster fan is an active device with moving parts, it is imperative to install it with an efficient and reliable monitoring and control system. The important aspects of booster fans and monitoring systems that are discussed in this thesis are environmental monitoring, condition monitoring, design and installation principles, guidelines for safe operation of booster fans, fan interlocking, and risk assessment.

The environmental status of underground mining operations with large booster fans is critical to the health and safety of the miners. Mining operations, especially in large deep coal mines, rely greatly upon the monitoring systems to create safe and healthy work conditions by monitoring carbon monoxide, methane, carbon dioxide, oxygen, nitrogen oxides, and smoke.

Condition monitoring is the process of measuring the fan operating factors to evaluate and predict the health of mining machinery. In coal mine ventilation, condition monitoring includes the measurement and evaluation of the following factors: vibration, barometric pressure, noise, input power, motor and bearing temperatures, differential pressures, and air flow rate.

The monitoring system network in a mine could become extremely complex if the monitors are not located at the right place. Recommendations are given for calculating the appropriate siting and spacing of monitors.

Booster fans are assembled and installed to operate under harsh conditions; they are subject to wear and tear and malfunction. Installation principles are discussed in detail and recommendations are made for the safe operation of booster fans. Interlocking is one method of preventing the occurrence of unsafe conditions due to electrical or mechanical failures. It is described in detail, and the best practices used in other coal mining countries are summarized. To ensure the safe operation of booster fans and monitoring systems underground, a risk assessment was done, critical hazards were identified, and mitigation controls are outlined.

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CHAPTER 1

INTRODUCTION

Mine ventilation is essentially the application of the principles of fluid dynamics to the flow of air in mine openings. In underground coal mines, the purpose of ventilation is to supply enough air to work areas for human comfort and product needs. A good ventilation system controls both the physical and chemical quality of air. Clean, fresh air is supplied to remove air contaminants such as mine gas, dust, heat, and moisture from the underground workings. A small quantity of air may flow through mine workings naturally, but this would be insufficient and uncontrolled and therefore, it is necessary to provide a mechanical means of ventilating the mine using main surface and underground booster fans. According to U.S. regulations, to accomplish this objective, at least two connections between the surface and coal seam are required. Large surface fans are used to create the required pressure differences to overcome friction and shock losses. These fans are primarily of exhaust type, which creates negative pressure to direct the air into the mine from the surface via intake shafts, ramps, and roadways to the working areas and back to the surface through the exhaust shafts. The roadways underground are divided into two groups, one carries fresh air into the workings (intake airways) and the other carries the used air back (return airways). The belt entry is usually kept neutral. Regulations require that air used to ventilate one working location cannot be used to ventilate another (parallel ventilation). This mining practice requires a number of separate circuits off the main roadways known as ventilation splits.

In order to ensure adequate flow to all parts of the mine, a number of control devices such as stoppings, overcasts, airlocks, and regulators are used; these are arranged so that fresh air is directed to workings in the desired manner and in the desired quantities. However, in many cases high-pressure surface fans are inefficient in delivering the required quantity of air to the workings.

The use of underground booster fans is one method of increasing the effectiveness of a ventilation system. Booster fans can reduce ventilation costs and increase the system efficiency by reducing the required main fan pressure and by decreasing system leakage. Booster fan systems are used commonly in underground coal mines in the United Kingdom, Australia, and other coal producing countries where these systems are considered safe, reliable, and essential. Though booster fans are used regularly in other countries, they are prohibited in most underground coal mines in the United States (Federal Register 2010). The regulations relevant to booster fans are discussed in detail in the next section.

As described above, for deep and extensive mines with multiple workings and numerous flow control devices, the ventilation system can become a large and complex network. Therefore, monitoring of key environmental parameters becomes an essential component of the mining process to provide first-hand knowledge of what is happening in the mine. The state of the mine ventilation is monitored to ensure that the required quantity of air is supplied consistently and that the air contaminant levels are maintained below their threshold limit values.

1.1 Problem Statements

As an underground mine goes deeper and deeper, ventilation system becomes more complex, and the ventilation loads are difficult to manage without adequate planning. With progression of mining and stringent regulations, fan and atmospheric monitoring is of utmost importance. Booster fans are one method of increasing the effectiveness of the ventilation system, and an efficient and reliable monitoring system is essential for their use.

1.1.1 Blowing or Exhaust Ventilation System

The primary means of producing and controlling the airflow are main fans, either single or in combination. Main fans handle all the air that passes through the mine. Because of the hazards of gases and dust that may both be explosive, legislation governing the ventilation of coal mines is stricter than for most other underground facilities. Because booster fans are not allowed in underground coal mines in the U.S., a surface fan becomes the most important entity of a mine ventilation system. This must provide the required quantity of air to all the underground workings. As an underground mine goes deeper, the mine resistance increases considerably. The increase in mine resistance leads to a requirement of high-pressure surface fans that can range in excess of 5500 Pa (22 in.w.g.). This is the highest pressure fan that is currently manufactured in the U.S. A practical problem with using high-pressure fans is that they have to be custom built; therefore, the spare parts are hard to procure and maintenance is difficult. Another problem with use of high-pressure surface fans is that they lead to very high air leakages between intake and return airways. In order to decrease the air leakage, high duty stoppings and airlock doors are required. Often, these are expensive to install and maintain. To monitor the air leakage, efficient and reliable monitoring system is required.

1.1.2 Push-Pull Ventilation System

A push-pull ventilation system is a combination of both blowing and exhausting systems. It is comprised of a blowing fan at the intake shaft pushing the air in the mine and an exhausting fan at the return shaft pulling the air out of the mine. Whenever there is a question of using a booster fan to assist the main exhaust fan, there is always an argument to use a blowing fan on the surface rather than a booster fan underground. However, there are number of issues associated with push-pull ventilation systems. One major issue is the air leakage between intake and return, especially in a U-tube ventilation system, which is the most common type of ventilation system used in the U.S. Since coal mines are large in size, the distance between the surface connections and the workings can be as long as 6 to 7 km. Therefore, the chances of formation of neutral zones with no airflow near the workings are very high. The probability of formation of a neutral zone is highest near the working areas as they are generally farthest from the ventilation shafts, where it is most essential to have good quantity and quality of air. Another problem is that using a fan at the intake will call for an additional mine entry (ramp, etc.) for the miners and machinery to enter and exit the mine. To reduce recirculation, this entry must be equipped with multiple heavy-duty airlock doors. This increases the initial cost of development and maintenance.

1.1.3 Booster Fan Ventilation System

One of the main problems associated with the utilization of booster fans is uncontrolled recirculation. It occurs when the fan is not properly sized or sited. This causes the pressure in the return airway to be higher than the pressure in the intake airway, causing the return air to leak from the return to the intake or back to the working areas. In systems with multiple booster fans, the possibility of uncontrolled recirculation is quite high.

In underground coal mines utilizing booster fans, fan monitoring becomes an important component for the safety and overall efficiency of the mine ventilation system. Furthermore, they are usually much less accessible than a surface fan in case of an emergency condition. Therefore, a booster fan should be subjected to continuous monitoring and suitable fan interlocking. The fan needs to be equipped with reliable monitors capable of transmitting information in a near-continuous manner to the surface where the data can be analyzed, processed, and recorded for further use. Since booster fans are mostly used in return airways, it is important to protect the motor and other electrical installations by either ventilating or enclosing in flameproof housings. These safety practices are very common in Australia and the U.K.

1.1.4 Environmental and Conditional Monitoring

Atmospheric monitoring techniques continue to develop but still present challenges because available technologies demonstrate issues that limit accuracy, response time, range, sensitivity, and survivability. The monitoring sensors are limited by the sensing technology used to detect the parameters of interest. Most commercially available gas sensors have response times averaging between 10 and 30 seconds. Catalytic gas sensors range from 10 to 15 seconds, and IR sensors range from 15 to 30 seconds (Griffin 2012). These times may not be adequate to de-energize equipment in rapidly changing atmospheres and may allow for movement of equipment when it must be de-energized.

The other problem associated with monitoring sensors is the sensitivity of the sensor. It is typically based on the sensing technology and cross-sensitivity to other gases. One of the primary sensors used in underground coal mines is a catalytic or pellistor methane sensor. These are limited to detecting methane concentrations from 0 to 5% (Valoski 2010) and may experience interference from organosulfur or organophosphorus compounds, alkyl lead derivatives, higher hydrocarbons, ethane, propane, hydrogen, and other flammable gases (Eggins 2002). The deployment of carbon monoxide (CO) sensors in a mine entry to achieve early and reliable fire detection is important for miner safety. Each type of sensing technology ultimately has strengths and weaknesses because each detection method is limited by the sensing technology itself.

Air velocity and pressure are among the most important ventilation parameters. Placing these monitors at strategic locations can quickly alert operators to a malfunction of the ventilation system. The most commonly used velocity measurement methods are vortex shredding or ultrasonic anemometers, pitot tubes, pressure transducers, and thermal mass flow. However, devices with moving parts are problematic for remote continuous monitoring. Other problems arise due to interference of moisture and dust with sensors and the appropriate location of sensors where an average flow can be accurately measured.

1.2 Thesis Objectives and Scope of Work

Although progression of technology has allowed mine monitoring techniques to become more sophisticated, there are a number of gaps in the application of these systems that needs to be filled. The objective of this thesis is to fill these gaps by developing guidelines for the practical design of the monitoring systems for coal mines utilizing booster fans in the U.S. First, specific practices, design principles, and regulations related to the use of booster fans and monitoring systems in the United Kingdom, Australia, and the United States are identified and discussed. This is followed by defining the inherent issues associated with existing atmospheric monitoring systems. Next, the condition and environmental monitoring and fan interlocking systems are discussed. This is followed by recommendations for design of underground monitoring systems. Lastly, a risk assessment of booster fan installations and monitoring systems is done, and critical hazards are identified, and control and recovery measures are recommended for mitigation.

The major areas of concern that are included in this study are (1) development of guidelines for environmental and conditional monitoring of booster fans, (2) design and installation principles for booster fans, (3) development of guidelines for design of monitoring systems with special emphasis on location and spacing of monitors, and (4) risk assessment of booster fan installation and operation.

This thesis covers the topics mentioned in the scope of work and provides solutions to the major problems stated above. Critical review of condition and environmental monitoring, design recommendations for monitoring systems, and booster fan installations are discussed in atmospheric monitoring systems. Recommendations for fan monitoring, fan interlocking systems, development of guidelines for safe operation of booster fans, and risk assessment are described in booster fan monitoring systems.

CHAPTER 2

BOOSTER FAN SYSTEMS

2.1 History of Booster Fans in the U.S.

Booster fans are not new to mining; they have been in use for over 100 years in different countries around the world. These fans were used in the U.S. coal mines in the early 1900s. However, as a result of several fires, accidents, and explosions related to their use in underground coal mines, the initial regulations in the 1920s were influenced with safety concerns. For many years, research was done to formulate recommendations for the safe use of booster and auxiliary fans. The Mine Safety Board was the first organization to take a step in this direction. In 1928, they recommended that auxiliary fans or blowers should not be used as an alternate regular and continuous coursing of the air to every face. Later in 1937, the use of booster fans was recommended only in mines where sinking a new shaft was uneconomical and the operating pressure of the main fan was so high that the ventilation doors could not function properly. This recommendation was based on the investigations of recirculation of mine air in underground coal mines. A year later the booster fans were regulated in the Federal Register in 1938. These regulations stated, in part, that “Booster and auxiliary fans may be used underground only with the written permission of the district mining supervisor under specified conditions" (Martikainen 2010). It is important to understand that booster fans were still being used in coal mines. Even in The Federal Coal Mine and Safety Act of 1969, better known as the Coal Mine Act, booster fans were not specifically prohibited. In 1989, a new proposal for coal mine ventilation rules was published by the U.S. Mine Safety and Health Administration (MSHA) that did not support the use of booster fans. Later in 1992 the final rule came, which is still applicable. It does not permit the use of booster fans in underground bituminous and lignite coal mines (Martikainen 2010). Reasons cited by MSHA include existing approval criteria, established industry practice, and several safety concerns associated with issues such as recirculation, fires, fan control, noise, and dust. Specifically, section 30 CFR § 75.302 states, "Each coal mine shall be ventilated by one or more main mine fans. Booster fans shall not be installed underground to assist main mine fans except in anthracite mines." This section prohibits the use of underground fans in coal mines in the United States.

2.2 Basic Requirements

A booster fan is an underground ventilation device installed in series with a main surface fan and used to boost the pressure of air of the current passing through it (McPherson 1993). The first and foremost basic requirement of any booster fan installation is a thorough evaluation of the existing mine ventilation system. If the ventilation requirement can be fulfilled economically by upgrading the main fan, decreasing the airway resistances, or repairing bulkheads, then these options should be given priority over booster fan installations. The evaluation comprises of extensive ventilation surveys, prediction of future airflow requirements, and simulations by means of numerical simulators such as VnetPC, VUMA, and Ventsim. The simulation results are checked against practical constrains such as the need of driving bypass drifts, slashing existing drifts, and installing airlock doors. Figure 2.1 shows a schematic of a booster fan installation in a drift.

Following simulation exercises and fan selection, the next task is site preparation and fan installation. The installation begins with construction of concrete foundations, followed with the installations of an overhead monorail, fan housing, bulkheads, airlock doors and a prefabricated fixture between the diffuser and the bulkhead. Before commissioning, the fan must be tested at no-load and full load conditions. During each test, parameters such as vibration, bearing temperature, blade tip clearance, and power consumption should be measured and compared against allowable limits defined by regulations. The fan is commissioned only when the measured values are consistently lower than the allowable limits.

2.3 Fan Monitoring and Control System

Monitoring and control systems have been used in the U.S. mining industry for the last 4 decades. They have become more sophisticated over the years, and continuous monitoring and control of underground machinery from the surface is a common practice.

It is a system that performs three functions: sensing, data transmission, and data processing (recording, analyzing, and displaying). In the case of monitoring and control systems the “control” represents a fourth and separate function. A monitoring system consists of a series of transducers and sensors installed at different places and mounted on machines in the underground. They are further connected to the outstations and intelligent stations through a programmable logical controller, fiber optic cable, or other mode of transmission. The data are further transmitted to the surface for processing and displaying on the computer screen in the control room. A schematic of atmospheric monitoring is shown in Figure 2.2.

The control policies for any piece of machinery, including mine fans, are based on existing regulations and industry best practices around the world. The control policy basically defines the normal operating conditions and what actions need to be taken when there is a deviation from normal conditions. In addition, the monitoring system includes audio-visual alert and alarm devices that are activated automatically when abnormal conditions are reported.

Mine operators continue to realize the benefits of improved fire detection capabilities of the monitoring systems as the number of mines using the systems as well as the percentage of mines continues to increase. One reason for the increase in utilization is the cost effectiveness of atmospheric monitoring systems (AMS). Recent cost analyses have shown that the initial cost of AMS is in some cases less than the traditional fire detection systems (point-type heat sensors) used to comply with 30 CFR § 75.1103.

Continuous monitoring systems play a very important role in control of booster fans. The monitors underground can be primarily divided into two categories; environmental monitors and fan operation monitors. The major parameters monitored by environmental monitors are airflow velocity (0 to 23 m s^{-1}), air pressure (0 to 6 kPa), carbon monoxide (0 to 50 ppm), methane (0–5%), and barometric pressure (0 to 103 kPa). The parameters monitored by condition monitors include vibration (0–5 mm s^{-1}), bearing temperature (0 to 250°C), motor voltage (0 to 600 VAC), motor current (0 to 400 Amps), and air flow direction indicator, on/off, and emergency off control devices (Calizaya 1989).

Another important aspect of the booster fan monitoring is the fan interlock and control system. It prevents any mishap in case of failure of the main or booster fans, failure of airlock doors, fire prevention units, etc. This system mainly works on three control routines, viz. hardware control, process evaluation, and redundant control. The hardware control routine is predominantly used to check the status of main and booster fans and operating conditions of the monitoring system. The process evaluation routine is used to check the correctness of the collected data, in which the data evaluation is performed on a transducer-by-transducer basis. The redundant control routine is independent of the other two routines. It helps in re-examining the monitoring system data in case of unexpected events such as electrical and/or mechanical failure to fans, monitors, and control devices. The control system should be capable of activating/deactivating all audio-visual alarms and shutting of the main or booster fans.

2.4 Advantages and Disadvantages

In coal mines, the installation of larger surface fans and sinking new shafts is given preference over booster fan installations in the underground. This is mainly due to the operational problems and economic considerations associated with booster fans. The various advantages and disadvantages of these fans are discussed briefly in this section.

2.4.1 Advantages

There are several ways of gaining advantage from the use of a booster fan. Even if booster fans are not suitable for every situation, they are capable of providing improvements in various underground environments when properly sized and located (Calizaya et al. 1989; McPherson 1993). Some of the possible advantages of booster fans are

1. The airflow distribution in the mine is enhanced, especially in the difficult-to-ventilate areas.
2. The pressure differentials from intake to return are reduced, hence reducing leakage and need for airlocks.
3. The surface fan pressures are reduced, therefore allowing existing installations to remain in place.
4. It can be used as a method to boost single panel(s) rather than the whole mine to minimize use of regulators and hence mine resistance. A booster fan reduces the effective resistance of a section.
5. The overall development costs are much less as compared to installation of large surface fans or sinking a new shaft.
6. The operating electric power costs for booster fans is low as they augment main fan power and less energy is lost because regulators are required.

2.4.2 Disadvantages

The major disadvantages of booster fans are

1. Most coal mines have multiple parallel intake and return airways; therefore, if

booster fans are used in return airways, all the air should be directed to a single return airway, requiring heavy duty stoppings and airlock doors.

2. All coal mines are gassy; therefore, the fan must be designed with anti-sparking characteristics. This calls for use of stainless steel rotor and blades compared to normally used aluminum for axial fans.
3. It is required to have a flameproof housing for booster fan installations or the motor needs to be placed in intake air; therefore, an extended drive shaft is required.
4. Shut off of either the main or booster fan requires evacuation of the mine as a safety measure. Electric interlocking is required between the two fans to prevent uncontrolled recirculation.
5. A fire or explosion can make it impossible to control the booster fan in order to adjust ventilation in specific areas of the mine.

In coal mines, the advantages of booster fans outweigh its disadvantages. It is this reason that booster fans are widely used in many coal mining countries like the U.K., Australia, India, South Africa, etc.

2.5 Recirculation

Recirculation of air in underground coal mines is a practice that has been historically discouraged in mines across the world, particularly in U.S. Coal mines. The background to such legislation is the fear that recirculation will cause concentrations of pollutants to rise to dangerous levels. Recirculation has been defined as the movement of air past the same point more than once (Hartman 1997).

Recirculation of air contaminants is the main issue associated with the utilization of booster fans. It occurs when the pressure in the return airway is higher than the pressure in the intake airway, causing the return air to leak from the return to the intake or back to the working areas. In systems with multiple fans when the booster fans are not sited or sized properly, the possibility of recirculation is quite high. There are two types of recirculation: controlled flow recirculation and uncontrolled flow recirculation.

2.5.1 Controlled Recirculation

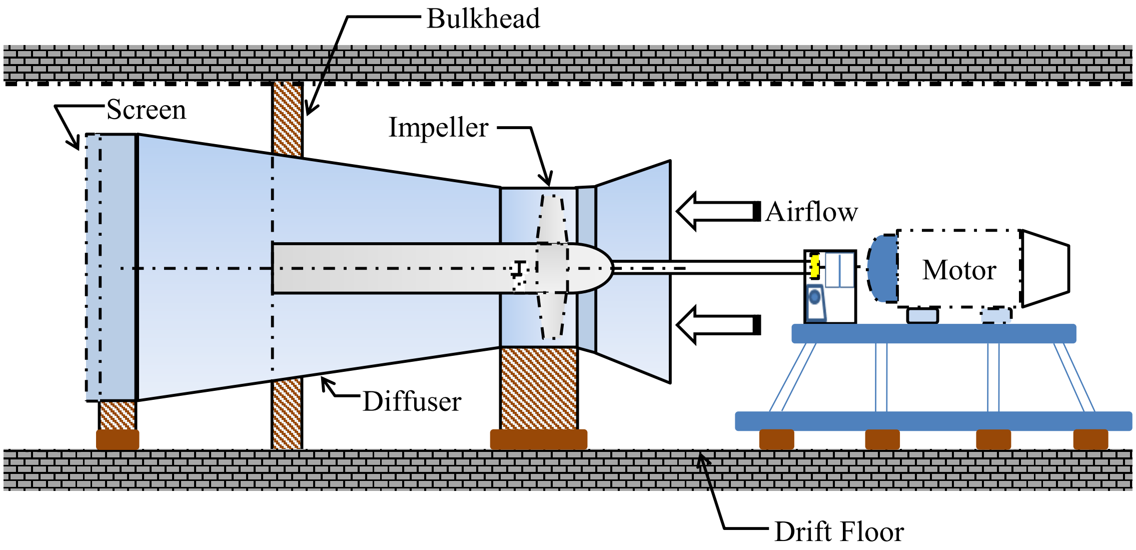
Controlled recirculation is a ventilation practice in which a specific fraction of the air returning from a work area is passed back into the intake in a controlled fashion in order to provide additional air quantity without adversely affecting other ventilation variables. When properly designed, this practice can result in increased airflow quantity at the workings, leading to overall lower general gas concentrations. The velocity of air increases at the face, which results in better turbulent mixing of air and methane at the point of release. Therefore, with controlled recirculation, the tendency of methane layering, accumulation of explosive methane-air mixtures, and gas build-up is decreased.

Depending upon the position of the booster fan in relation to the workings, there are three types of controlled recirculation: (1) cross-cut recirculation, (2) in-line recirculation, and (3) combined recirculation (as shown in Figure 2.3).

Controlled recirculation is used in deep mines to increase the face air velocity, to control the concentration of air contaminants, and to reduce ventilation costs (Calizaya 2009). Although this technology is prohibited in U.S. underground coal mines, it is used in metal and nonmetal mines.

2.5.2 Uncontrolled Recirculation

Uncontrolled recirculation occurs when air is leaked from the return airway to the intake airway, but the leakage is not expected and the recirculating air is not managed, so there is the potential for the buildup of air contaminants. It is often the result of poor maintenance of stoppings and doors. Uncontrolled recirculation can take place if stoppings are not sealed properly or if airlock doors are not able to withstand the pressure. It is extremely dangerous for mine ventilation and is one of the biggest fears associated with booster fan use in underground mines.



Section View

Figure 2.1: Schematic showing booster fan installation

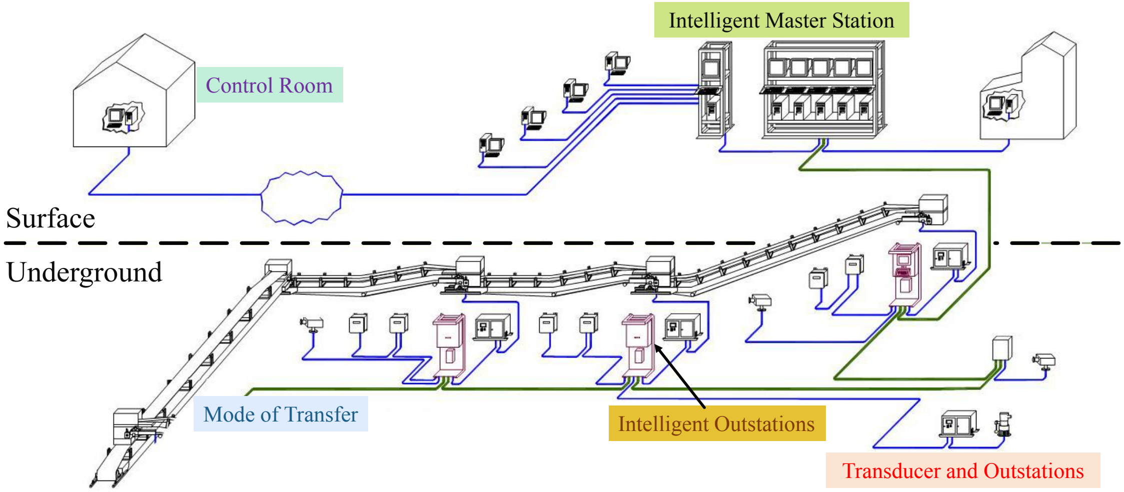


Figure 2.2: Schematic of an atmospheric monitoring system (AMS) installation

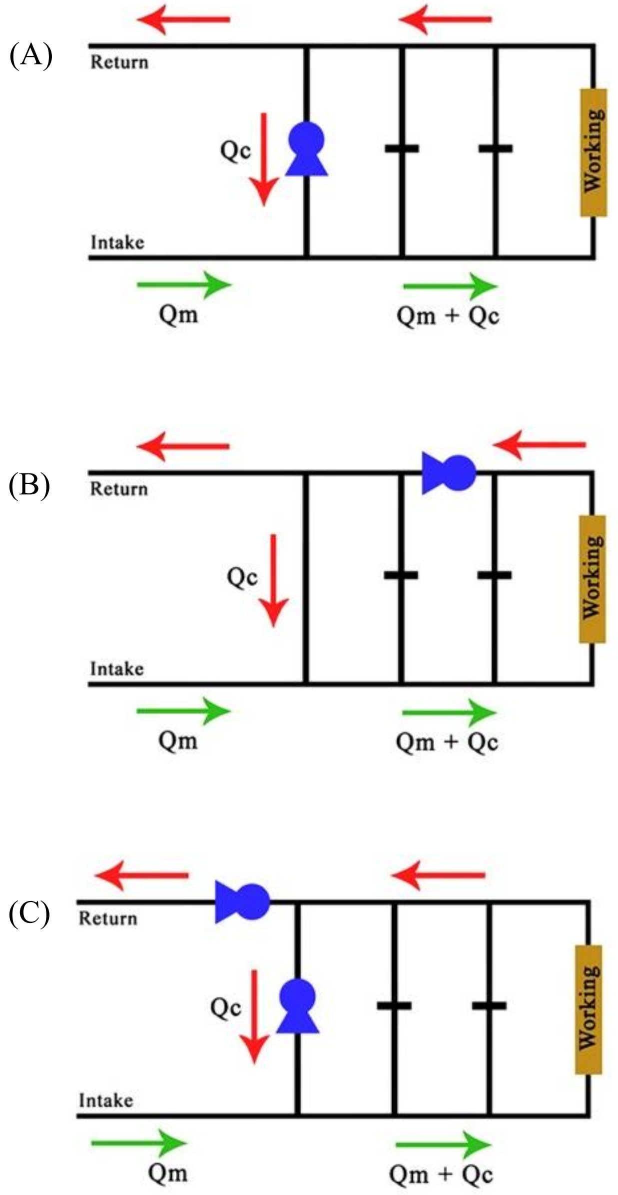


Figure 2.3: Types of controlled recirculation: (A) cross-cut recirculation, (B) in-line recirculation, and (C) combined recirculation

CHAPTER 3

MINE VENTILATION FORMULAE

In mine ventilation, the airflow is an example of a steady fluid flow process. It means that none of the variables of flow changes with time, transitions, losses in energy. The descriptions of different theories of fluid flow applicable to underground mining are found in mine ventilation textbooks (Hall 1981; McPherson 1993; Hartman et al. 1997). The basic principles and assumptions used in subsurface ventilation are summarized in this chapter.

3.1. Fluid Flow Principles

The air is composed of different gases and water vapor and is compressible in nature. However, it is considered as an ideal, incompressible gas if the mass density is nearly constant. This condition exists in most mine ventilation situations. An exception to this is when the mine is located at great depths where heating and cooling of air is required and where the vertical movement of air is more than 500 m (1,640 ft). In these situations, thermodynamics laws must also be considered. Since the heat energy is neglected, the total energy at any section in a moving fluid (in this case air) consists of the sum of static ($p\gamma^{-1}$), velocity ($V^2(2g)^{-1}$), and potential (h) energies. For most calculations in subsurface ventilation, the well-known Bernoulli equation for incompressible gases is used:

$$\left(\frac{p_1}{\gamma}\right) + \left(\frac{V_1^2}{2g}\right) + h_1 = \left(\frac{p_2}{\gamma}\right) + \left(\frac{V_2^2}{2g}\right) + h_2 + h_f \tag{3.1}$$

Where

p = absolute air pressure (Pa)

V = air velocity (ms^{-1})

γ = specific weight of the air ($kg\ m^{-3}$)

h = measuring point elevation (m)

h_f = head loss (m)

The subscripts 1 and 2 denote any two individual measurement locations. In practice, it is convenient to make all head measurements on a gage-pressure basis:

$$H_s = {}^{p}/_{\gamma} \tag{3.2}$$

$$H_v = {}^{H_v}/_{2g} \tag{3.3}$$

Where

H_s = static head (m)

H_v = velocity head (m)

In general, changes in p and h are almost reciprocal. When this is done, the measuring point elevations (h_{st}) are omitted, and Equation 3.1 can be written as

$$H_{s1} + H_{v1} = H_{s2} + H_{v2} + H_L \tag{3.4}$$

This is called the modified energy equation. At any point in the system, the total head H_t (m) is the sum of velocity and static head. In this equation, each term is expressed in terms of gage pressure:

$$H_t = H_s + H_v \tag{3.5}$$

Pressure (Pa) measurements are obtained by multiplying the head values in Equation 3.5 by the specific weight of air, giving

$$p_t = p_s + p_v \tag{3.6}$$

In mine ventilation, the modified energy equation is preferred over the steady state energy equation.

3.1.1 State of Airflow

In our everyday world, we can observe many examples of the fact that there are two basic kinds of fluid flow. A stream of oil poured out of a can on a slope flows smoothly and in a controlled manner while water, poured out at the same rate, would break up into cascading rivulets and droplets. This example suggests that the type of flow seems to depend on the fluid type and its flow rate. In fluid mechanics, two distinct states of fluid flow are defined: laminar and turbulent. The criterion used in establishing boundaries for each state is the dimensionless Reynolds Number N_R. Laminar flow exists where $N_R < 2000$ and turbulent flow where $N_R > 4000$. The region between is known as the transition range. For any fluid flow conditions, N_R can be determined from measurements and fluid properties:

$$N_R = \frac{\rho D V}{\mu} = \frac{DV}{v} \tag{3.7}$$

Where

N_R = Reynolds Number (dimensionless)

ρ = density of the fluid (kg m^{-3})

V = velocity of the fluid (m s^{-1})

D = diameter of conduit (m)

μ = dynamic viscosity (Pa·s)

v = kinematic viscosity (m^2 s^{-1})

In subsurface ventilation engineering, the characteristic length is normally taken to be the hydraulic mean diameter of an airway, d, and the characteristic velocity is usually the mean velocity of the airflow. In most mine airways, it is important that turbulent flow always prevails to provide sufficient dispersion and removal of contaminants (Kennedy 1996). Using typical dimensions of mine openings and air velocities in Equation 3.7, it is evident that turbulent flow will nearly always prevail in any mine airway. Exceptions to this include laminar flow in caved areas and "air-tight" stoppings (Hartman et al. 1997). The state of airflow in a mine can also be perceived in terms of resistance to airflow.

3.2 Airflow Resistance

The concept of airway resistance is of major importance in mine ventilation. The cost of passing any given airflow through an airway varies directly with the resistance of that airway. This is made up by friction and shock losses. The friction losses typically constitute 70 to 90% of the total losses (Hartman et al. 1997). Friction losses are caused by the drag forces between the walls and the air streams, which depend primarily on the roughness of the individual wall surfaces. For example, moving air through a smooth duct requires less power than moving air through the same size duct with rough walls. Thus, rough walls have higher frictional resistance to flow.

In 1854, J. J. Atkinson published an equation that was originally derived from the Chezy-Darcy fluid flow equation. Atkinson's Equation is applicable to incompressible fluid flow that is turbulent in nature. As such, it is perhaps the most widely used equation in mine ventilation:

$$\Delta p = \left(\frac{k.L.Per.V^2}{A}\right) \tag{3.8}$$

Where

Δp = differential pressure (Pa)

k = friction coefficient (kg m^{-3}, a function of density)

L = length (m)

Per = perimeter of the mine entry (m)

V = average velocity (m s^{-1})

A = cross-sectional area (m^2)

The parameters in Equation 3.8 are average values and/or differential measurements between two locations. In mines, airflow quantities are calculated from measurements of velocity and cross-sectional area of an airway:

$$Q = V \cdot A \tag{3.9}$$

Where

Q = airflow quantity (m^3 s^{-1})

Velocity, V, can be replaced with Q/A in Equation 3.8 and rewritten as:

$$\Delta p = \left(\frac{k.L.Per}{A^3}\right) * Q^2 \tag{3.10}$$

The friction factor k in mine ventilation corresponds to the coefficient of friction in general fluid flow. It is assumed to be constant for a given airway, regardless of the Reynolds number. It only changes with the density of air.

Whenever the airflow changes direction, additional vortices are formed. The propagation of these large-scale eddies consumes mechanical energy (shock losses) and hence, the resistance of the airway may increase significantly. This occurs at bends, junctions, changes in cross-section, obstructions, regulators, and at points of entry or exit from the system. The effects of shock losses remain the most uncertain of all the factors that affect airway resistance. This is because fairly minor modifications in geometry can cause significant changes in the generation of vortices and, hence, the airway resistance. In general, the shock loss is calculated by multiplying the shock loss factor and velocity head. The shock loss factor depends on a number of parameters such as geometry of the airway, angle of bend, change of area, etc.

$$P_x = X \times P_v \tag{3.11}$$

Where

P_x = Shock loss

X = Shock loss factor

P_v = Velocity head

Shock loss plays an important role in designing the fan houses, etc. They can range as high as 30% loss of pressure.

3.3 Leakage Flow

Leakage of air is one of the major problem in mine ventilation systems. In coal and metal mines, leakage is the most common cause of inefficient distribution of air. While leakage in coal mine ventilation systems averages 50% of total volume of air circulated, in metal mines, it averages about only 25%. Leakage flow is defined as any quantity of air that is not usefully employed somewhere in the mine. This quantity can be determined indirectly:

$$Q_L = Q_T - \sum Q_E \tag{3.12}$$

Where

Q_L = leakage quantity ($m^3\ s^{-1}$)

Q_T = total air quantity at the fan ($m^3\ s^{-1}$)

Q_E = air quantity reaching a working area ($m^3\ s^{-1}$)

A working area in a coal mine is any location in the mine that requires a minimum fixed quantity of air. It includes longwall (LW) and continuous miner (CM) sections, underground shops, charging stations, bleeder monitoring points, gob seals, and pumping stations.

The total percent leakage in the system is the ratio of the quantity of air that is short-circuited before reaching the working areas to the total quantity circulated by the fan. It is calculated as follows:

$$L_T = (100) \times (Q_T - \sum Q_E)/Q_T \tag{3.13}$$

Where

L_T = total leakage (%)

Another important aspect related to leakage flow is volumetric efficiency. The volumetric efficiency of the mine is defined as

$$\text{Volumetric Efficiency} = \frac{\text{Useful Airflow}}{\text{Total Airflow through main fan(s)}} \times 100\% \tag{3.14}$$

The useful airflow can be defined as the sum of the airflows reaching working faces and important parts of the mine such as electrical gear, pumps, charging stations, etc. (McPherson 1993). The volumetric efficiency of mines may vary from 10–75%.

3.4 Fan Pressure

In ventilation planning, the pressure gradient is one of the most important graphs to be drawn. Gradients are particularly helpful in visualizing the relation between mine resistance and fan pressure. It can represent the blower or exhaust fan and can include the booster fan. A pressure gradient graph was developed for the lab model at the University of Utah. It consists of a combination of a blowing type centrifugal main fan and booster fan. The pressure (static and total) are plotted against distance from the fan. The fan creates a pressure difference between the inlet and outlet that is consumed in overcoming flow energy losses. Figure 3.1 shows a large initial pressure increase induced by the fan followed by a gradual reduction in pressure and rise again due to a booster fan.

The mine static head, mine H_s, includes all of the pressure head losses that occur along the airstream between the inlet and outlet. These head losses are made up of two components, frictional loss H_f caused by the resistance of the walls on the airstream, and shock loss H_x, caused by abrupt changes in the airstream velocity:

$$\text{Mine } H_s = \Sigma H_L = \Sigma\,(H_f + H_x) \qquad (3.15)$$

Notice that the inlet velocity head is negative. This occurs because a suction condition must exist here in order for air to flow into the system. Similarly, the discharge velocity head is positive because the air is in motion when it leaves the system and is lost to the system in the form of kinetic energy. The loss of velocity head at the discharge is minimized by converting some of it to static head through the use of a diffuser duct or evasé discharge, a standard practice in mine ventilation.

3.5 Recirculation

Recirculation of contaminated air in underground coal mines is an unsafe practice that has been discouraged historically across the world, particularly in U.S. coal mines. The main reason is that recirculation may cause concentrations of pollutants to rise to dangerous levels. Recirculation has been defined as the movement of air past the same point more than once.

Recirculation of air contaminants is the main hazard associated with the utilization of booster fans. It occurs when the pressure in the return airway is higher than the pressure in the intake airway, causing the return air to leak from the return to the intake. In systems with multiple fans when the booster fans are not sited or sized properly, the risk of recirculation might be quite high.

The recirculation of air and recirculation fraction (C_R) can be better understood with the two mine ventilation diagrams shown in Figure 3.2. In Figure 3.2(A), a section or mining district is ventilated by a quantity of air Q_i that contains a decimal proportion of the contaminant C_i. At the working face, a quantity of contaminant Q_g is introduced into the air-stream and increases the level of contamination. As a result of this set of conditions, the following ventilation parameters are found in the mine:

$$C_R = \frac{Q_i C_i + Q_g}{Q_i + Q_g} \qquad (3.16)$$

Where

C_R = recirculation fraction

In order to increase the air at the working face without increasing the amount of intake air, a recirculation circuit is set up by developing a recirculation crosscut as shown in Figure 3.2(B). A fixed quantity of air Q_r is deliberately recirculated through the recirculation crosscut and therefore increasing the total flow through the working face to a quantity level of ($Q_i + Q_r$). In a recirculation circuit, the proportion or fraction of the air that is returned through the recirculation crosscut is termed the recirculation factor RF (McPherson 1993). It is defined as

$$\mathrm{RF} = \frac{Q_r}{Q_i + Q_r} \tag{3.17}$$

Where

RF = recirculation factor

Controlled recirculation is a ventilation practice in which a specific fraction of the air returning from a work area is passed back into the intake in a controlled fashion in order to provide additional quantity of air without adversely affecting other ventilation variables. When properly designed, this practice can result in increased airflow quantity at the workings, leading to overall lower general body gas concentrations. The velocity of air increases at the face, which results in better turbulent mixing of air and methane at the point of release. Therefore, with controlled recirculation the tendency of methane layering, accumulation of explosive methane-air mixtures and gas build up is decreased.

3.6 Methane Layering

The gases emanating from the ore body or surrounding strata is one of the most common and serious gas problems found in the underground. Of particular concern is the accumulation of strata gas such as methane and carbon dioxide, which can lead to explosive atmospheres and oxygen-deficiency. A dangerous effect called layering has been observed in coal mines with methane. The buoyancy of methane with respect to air (specific gravity 0.554) produces a tendency for concentrated methane to collect in roof cavities and to layer along the roofs of airways or working faces.

There are two main hazards associated with methane layers. First, they extend greatly in poorly ventilated areas to form layers of gas that can ignite. Secondly, when such an ignition has taken place, a methane layer acts very effectively as a fuse along which the flame can propagate rapidly—perhaps leading to much larger accumulations in roof cavities or gob areas that can cause explosions (McPherson 1993).

To foreworn of the likely occurrence of methane layering, Leach and Thompson developed an empirical indicator, layering number N_l, which can be calculated from this relationship:

$$N_l = \frac{V_u}{1.8}\left(\frac{b}{Q_g}\right)^{1/3} \tag{3.18}$$

Where

V_u = air velocity in the upper half of the airway (m s^{-1})

Q_g = methane inflow (m^3 s^{-1})

b = airway width

The empirical results have defined that layering can be controlled if the air velocity is sufficient to maintain N_l at values ≥ 5 in a horizontal airway, 5 in an airway with uphill flow (8 if steep), and 3 in an airway with downhill flow (5 if steep). Irrespective of airway slope, a safe approximate value of N_l to use on normal grades is thus 5. In a typical coal mine, openings with moderate gas inflows and high air velocities (≥ 1 m/s) may be required to counteract the layering effect.

In the case of products of combustion, dispersion and diffusion also play a very important role. The rate of diffusion of a gas into air is inversely proportional to the square root of specific gravity of the gas. In other words, a gas lighter than air will diffuse faster than one heavier than air. Diffusion is also aided by turbulence and temperature.

When a plume of combustion products rises towards the mine roof due to the thermally induced density differences between the hot products-of-combustion (POC) and the ambient air, the POC will also be convected with the bulk air flow downwind from the fire source. The POC will be dispersed by the dilutive mixing with the fresh air over the entry cross-section downwind from the source fire. This dispersion process is enhanced by the thermal equilibration of the POC with the ambient air. It is therefore important to know the expected distribution of CO near the mine roof in smoldering and flaming coal fire to control the fire hazard (Edwards 2006).

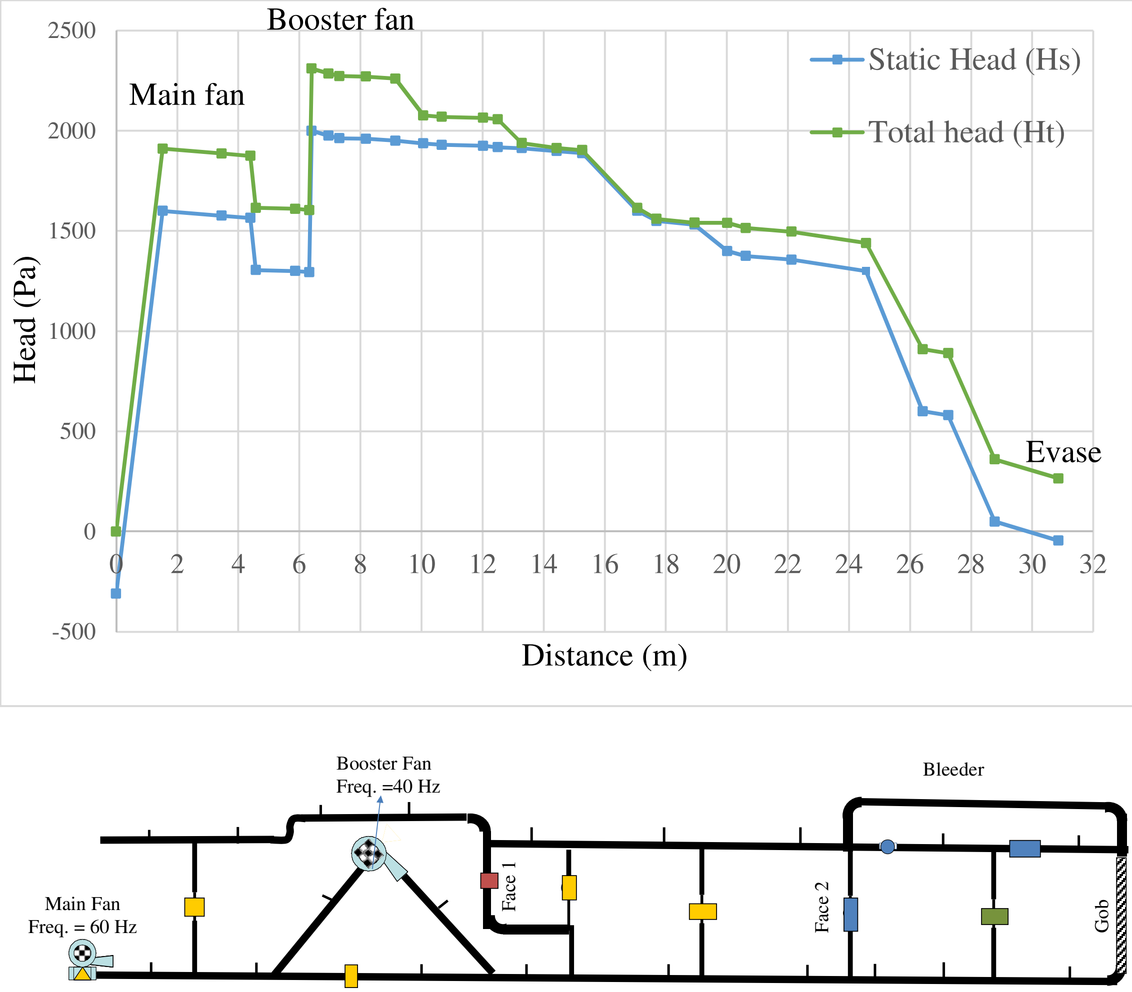


Figure 3.1: Example of ventilation system to demonstrate pressure losses in a mine

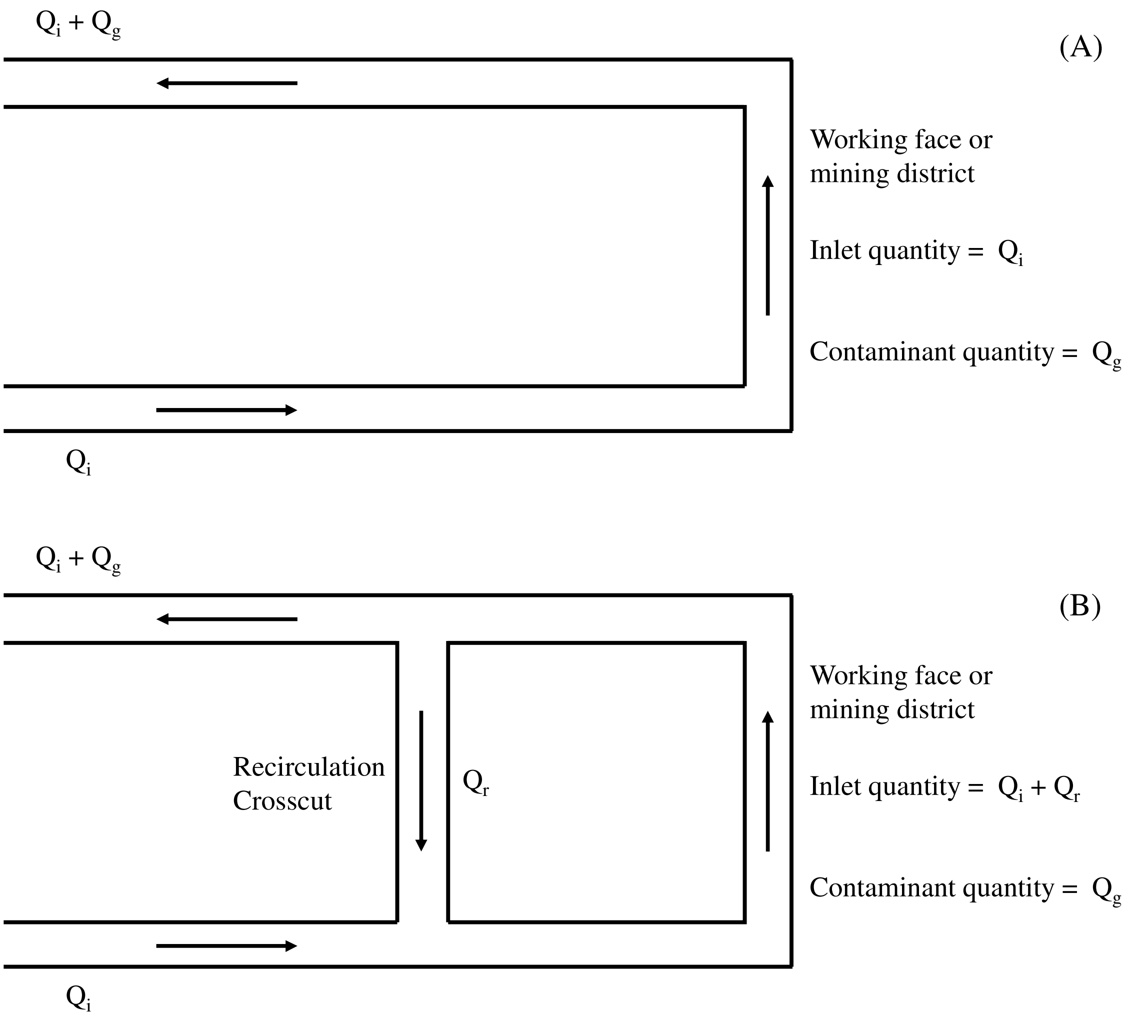


Figure 3.2: Basic layout of face or district ventilation flow quantities: (A) without recirculation; (B) with recirculation

CHAPTER 4

ATMOSPHERIC MONITORING SYSTEMS

Atmospheric monitoring systems (AMS) are used as a means to measure and evaluate the air quality and quantity in the mine and to develop strategies to control potential fire hazards. The application of these systems in coal mines has increased rapidly in the last 20 years (Francart 2005). One reason for this increase is the cost effectiveness of the system. Recent cost analyses have shown that the initial cost of an AMS is often less than the cost of traditional fire detection systems. While maintenance costs increase the overall cost of the AMS, effective early fire detection can save the mine operator many times its initial investment by preventing losses in production and recovery of fire areas.

The major manufacturers of the AMS are Pyott-Boone, AMR, CONSPEC, MSA, and Rel-Tek. These companies are the market leaders in the United States. Around 90% of the systems installed in coal mines are used for belt conveyors, and more than half of them are used to monitor ventilation parameters including main fan duties. AMS can easily be interfaced with booster fan monitoring systems. It provides the AMS operator booster fan monitoring data along with the AMS data.

4.1 Terminology

- Monitoring: The word monitoring originates in Latin where it means one who warns or admonishes. In reference to mining, monitoring means measuring certain parameters of mining, transmitting data for processing and then using the data as input for decision-making. Monitoring is used for protection from a safety hazard such as fires or explosions or for protection from a health hazard such as a toxic gas.
- Transducer: It is a device that is a component of a monitoring and control system. It is actuated by a one-transmission subsystem and supplies related waves to a receiver. In another sense a transducer is a device that measures certain parameters of a system such as pressure, current, and voltage and converts them into related or proportional units. It converts a signal in one form of energy to another form of energy. Energy types include (but are not limited to) electrical, mechanical, electromagnetic, chemical, acoustic, and thermal energy. In this sense a transducer is used as a synonym for a sensor.
- Sensor: A sensor is a converter that measures a physical quantity and converts it into a signal that can be read by an observer or by an electronic instrument that is a part of a monitoring and control system."
- Outstation: Outstations or field data stations represent a point of aggregation in a hierarchical structure of data flow. They serve as an economical compromise by allowing access to the communication trunk by a number of sensors. The major function of an outstation is to provide a communication interface between a sensor and the trunk connected to the central station computer.
- Monitoring System: It is a system that performs three functions: sensing, data

transmission, and data processing (recording, analyzing, and displaying). In the case of monitoring and control systems, the –control” represents a fourth and separate function. This system is called a –monitoring and control system.”

- Data Acquisition System: Data acquisition is the process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer. Data acquisition systems typically convert analog waveforms into digital values for processing.
- Threshold Limit Values (TLV): It refers to those concentrations within which personnel may be exposed without known adverse effects to their health or safety.
- Time-Weighted Average (TWA): It is the average concentration to which nearly all workers may be exposed over an 8-hour shift and a 40-hour work week without known adverse effects.
- Short-Term Exposure Limit (STEL): It is a time-weighted average exposure for duration of 15 minutes that cannot be repeated more than 4 times per day with at least 60 minutes between exposure periods.
- Ceiling Limit (TLC-C): It is the concentration that should not be exceeded at any time. It is mostly relevant for the most toxic substances or those that produce an immediate irritant effect.

A schematic of an AMS installation in a mine is shown in Figure 4.1

4.2 Transmission of Data

Conventional AMS installations for monitoring CO, Smoke, CH_4, O_2, and fan parameters throughout underground mines are usually relegated to a modest 3–5 mile extent and with data communication speeds confined to a ponderous 1–5K baud range (Ketler 2008). New MSHA and state regulations require fast reporting of unsafe conditions, and the old 20–30 minute updates are no longer acceptable. To communicate farther and faster has always been a problem because data reliability degenerates with excessive distances and high speeds. Presently, there are four major types of data transmission modes based on the principles of wireless communication, programmable logic controllers, fiber optics, and telemetering system.

In wireless monitoring, a network of wireless sensors gathers environmental data and real-time status information from different mining operations. The mines of the future will see a number of instruments with the highest level of reliability at the lowest possible cost. One of the key areas of the next generation instrumentation is wireless monitoring systems in underground coal mines. Emerging wireless networking technologies are opening up opportunities for new systems, achieving significant cost savings in equipment design and maintenance as well as significant reductions in time-lost incidents due to injuries in mining operations (Smutny 2003).

A Programmable Logic Controller (PLC) is a digital computer-based system used in underground mines for automation and control. The initial systems utilized mini computers on the surface as the intelligence of the system. The remote outstations were not intelligent, being wholly dependent on the remote mini computers to collect information from and then to process the data to make logical decisions. Therefore, all logic decisions were made by the microcomputer on the surface based on scanned input data (Smallwood et al. 1993). Currently, monitors are placed along the belt lines and are linked to the host computer in the control room through a PLC network. The monitors can detect a rise in carbon monoxide or concentrations of other combustible gases, which helps by giving out an early warning of potential hazards. The collected information is immediately transmitted to the surface, so the operator can clearly locate the problem area, determine the existing conditions, shut down processes in that section, and restart when conditions permit (Conspec 2014).

A fiber-optic monitoring system uses a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The fiber-optic systems are much more efficient than the PLC based systems as they can be laid out to much further distances in large mines and are faster in communication speed. The optical fiber technology offers an intrinsically safe, rapid, reliable, and accurate method of sensing and monitoring. The drawback with fiber optics system is that they have high initial cost as well as high maintenance costs and downtime costs to repair or replace broken optical fibers (CRC mining 2013).

Telemetry is the highly automated communication system by which measurements are made and other data collected at remote or inaccessible points and transmitted to receiving equipment for monitoring and control. The telemetry monitoring systems have intelligent outstations along with an intelligent master station on the surface. Telemetry systems provide an inexpensive alternative to expensive fiber optic systems by using a communication data highway, which uses inexpensive twisted-pair telemetry cables, which can communicate well into the 20-mile extent of the largest mines (Ketler 2008).

4.3 Implementation of AMS in the U.S.

AMS have evolved rapidly since the 1970s, an area that the Bureau of Mines and the Mine Safety and Health Administration (MSHA) foresaw as having huge potential for safety improvements. Mine operators continue to realize the benefits of improved fire detection capabilities as the number of mines using the systems continues to increase.

Fire detection data and new technology implemented in underground coal mines have been reviewed as well as the regulatory compliance, diesel exhaust emissions, and hydrogen interference in carbon monoxide detection. Compliance with federal regulations or petitions for modification (PFM) of federal regulations is the major cause for installation of AMS in many mines (Francart 2005).

MSHA has conducted multiple surveys over the last 3 decades to monitor the implementation of AMS in the United States. This survey was first completed in 1984 and has been periodically updated with the latest survey data released in 2003. In 1984, only 38 mines used AMS in monitoring for mine fires. In 2003, the survey indicates that the number of mines using AMS had increased to 146. The number is believed to be much higher now. The increase in the number of installations is more dramatic when the number of mine closures is considered. In 1992, 115 mines used AMS. Of this number, 79 have been removed from the survey, mostly due to mine closure. This yields an increase of 110 new AMS installations in underground coal mines in the past 10 years.

The increased implementation of AMS technology can be attributed to two main factors. First, carbon monoxide (CO) detection technology is far superior to the heat sensor technology used in mines for decades. The detection of reportable fires by atmospheric monitoring systems using carbon monoxide sensors in belt entries has been flawless since 1984. Second, the initial cost of an AMS system is competitive with traditional heat sensor systems. For mines monitoring beltlines only, the initial capital cost for an AMS can be less than heat sensors when more than 2,750 m (9,000 ft) of belt are monitored. While maintenance and operating costs will cause the overall costs to be greater for the AMS, there is no doubt that many mine operators have decided the cost benefit of early detection of belt fires is justification for the AMS installation.

Many AMS installations monitor a variety of mine functions in addition to providing fire detection in the belt entry. It is reported that almost 90% of mines monitor the belt operations. Fan stoppage is monitored in 42% of the mines as the second most monitored function. Twenty-two percent of mines monitor for methane using AMS. Table 4.1 shows the functions monitored as a percentage of AMS installations (Francart 2005).

4.4 Environmental Monitoring

Industrial and commercial application of computerized mine monitoring systems started in the early 1970s. Since then, the systems have been developed and improved significantly. The modern systems can monitor the mine environment, equipment performance, and work force. Monitoring systems are used in almost all the mines in the United States, and the other operators are considering future installation of these systems. Mining operations, especially in large coal mines, rely upon monitoring systems to provide safe and healthy work conditions to workers. Presently, various monitoring systems are in industrial use in coal mines; several new systems are being developed, and others are waiting to be approved for specific mining and geological conditions. The various methods for monitoring gases underground are discussed in this section and in further detail in Appendix A.

4.4.1 Gas Sensing Methods

The primary purpose of environmental monitoring is to ensure that the atmosphere in the mine is free from toxic or flammable airborne pollutants. The parameters that are essential for designing an environmental monitoring system for a mine are (1) air contaminant, (2) type of sensor, and (3) location, spacing, and frequency of these sensors.

4.4.1.1 Performance Indicators and Gas Sensor's Stability

To evaluate the performance of gas sensing methods, several factors should be considered:

1. Sensitivity: the minimum value of target gas concentration
2. Selectivity: the ability of gas sensors to identify a specific gas among a gas mixture.
3. Response time: the period from the time when gas concentration reaches a specific value to that when sensor generates a warning signal.
4. Reversibility: whether the sensor could return to its original state after detection.
5. The principle and performance of different gas sensing methods based on the above performance indicators are described in Appendix A.

4.4.2 Classification and Monitoring of Mine Gases

When air enters a mine atmosphere it has a volume composition of approximately 78% nitrogen, 21% oxygen, and 1% other gases on a moisture free basis. However, this composition changes as air moves through different airways of the mine. This happens because of two reasons. First, mining allows strata gases such as carbon dioxide and methane to enter the ventilating air. These gases are produced over geological time and are entrapped in the strata. Secondly, a number of chemical reactions take place in the ventilating air, which changes its composition. Oxidation reduces the percentage of oxygen and often causes evolution of carbon dioxide or sulfur dioxide. Incomplete oxidation leads to an increase in carbon monoxide in air. A primary requirement of a mine ventilation system is to dilute and remove airborne pollutants, including dust and toxic gases. Therefore, an environmental monitoring system is of utmost importance for an efficient and safe mine ventilation system (McPherson 1993).

The gases that are most commonly encountered in underground are discussed in further detail in this section and are summarized in Table 4.2.

4.4.2.1 Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless, and tasteless gas that is slightly less dense than air. The high toxicity of carbon monoxide coupled with its lack of smell, taste, or color make this one of the most dangerous and insidious of mine gases. Most fatalities that have occurred during fires and explosions in mines have been a result of carbon monoxide poisoning. The hemoglobin present in the blood has a very high affinity for carbon monoxide.

The high toxicity of CO makes it very important to have a good monitoring system for continuous monitoring. Since CO is one of the first products of combustion, it also acts as a parameter for early detection of fire underground. CO detectors are designed to measure CO levels over time and sound an alarm before dangerous levels of CO accumulate in an environment, giving people adequate warning to safely ventilate the area or evacuate. The common sensors that are used for detection of CO are based on catalytic oxidation, electrochemical reaction, semiconductors, and infrared absorption principles. The time weighted average (TWA) value is .005% (50 ppm), and the short term exposure limit (STEL) value is .04% (400 ppm) for carbon monoxide.

4.4.2.2 Methane

Methane is one of the most common strata gases. It is produced by bacterial and chemical action on organic material during the formation of coal. Methane is not particularly toxic but it is flammable and can form explosive mixtures with air. This has resulted in the fatalities of many thousands of miners. Methane is retained within fractures, voids, and pores in the rock either as a compressed gas or adsorbed on mineral surfaces. When the strata is pierced by boreholes or mined openings, then the gas pressure gradient that is created induces migration of the methane towards those openings through natural or mining-induced fracture patterns. Methane has a density that is a little over half that of air. This gives rise to a dangerous behavior pattern in which methane forms pools or layers along the roofs of underground openings. Any ignition of the gas can then propagate along those layers to emission sources. The buoyancy of methane can also create problems in inclined workings. In an abundant supply of air, methane burns to produce water vapor and carbon dioxide.

The explosive range for methane is normally quoted as 5 to 15% by volume in air. It is considered to be most explosive at around 9.8% by volume in air. According to legislation, 30 CFR § 75.342 directs that MSHA approved methane monitors shall be installed on all face cutting machines, continuous miners, longwall face equipment, loading machines, and other mechanized equipment used to extract or load coal within the working place. The sensing device for methane monitors on longwall shearing machines shall be installed at the return air end of the longwall face. It is recommended that when the methane concentration at any methane monitor reaches 1% the monitor shall give a warning signal and automatically de-energize electric equipment or shut down diesel-powered equipment when the methane concentration at any methane monitor reaches 2%. Mine personnel should also be removed from the mine when the concentration of methane reaches 2%.

The common sensors that are used in monitoring of methane are based on the principles of catalytic oxidation, thermal conductivity, and flame safety lamps.

4.4.2.3 Smoke

Smoke is an aerosol that is formed by incomplete combustion and ordinarily consists of particles 0.01–1.0 micrometers in size. Smoke particles are usually visible and distinguished from fumes by the fact that they do not result from condensation processes. Smoke is one of the products of combustion and acts as a good indicator of a fire underground. Smoke sensors can be classified into two types based upon their operational principle: ionization and optical.

Ionization smoke sensors use a radioisotope such as americium-241 to produce ionization in air. The oppositely charged ions form a current between two charged electrodes. Diffusion of smoke particulates into the path of the ion current reduces the ion current. This process increases the ion's probability of recombination. The ion current reduction is amplified as a measurable signal.

Optical smoke sensors operate on the principle of scattering or absorption of light over an optical path through which the smoke particles migrate. For optical scattering, the sensor is located to the side of the optical path to measure the amount of light scattered by a smoke particle. In the case of optical absorption, the reduction of transmitted light due to absorption and scattering is measured.

In summary, ionization sensors are more sensitive to the smaller smoke particles associated with flaming combustion, whereas optical sensors are more sensitive to larger smoke particles associated with smoldering combustion (Edwards 2006).

4.4.2.4 Oxygen

Oxygen is an important part of the mine atmosphere as it is used in respiration. In mines, the oxygen concentration is maintained at levels between 18.5 and 23% (as per 30 CFR § 7.506). The concentration should be on the higher side, close to 21.5% in the fresh air. There are several techniques that are available for monitoring the oxygen concentration. One common method for mine sensors is a simple battery type electrochemical cell. The air is allowed to diffuse through a membrane to a cathode where oxygen is reduced to hydroxyl ions. The anode is oxidized producing a current proportional to the oxygen concentration. A membrane diffuser barrier is used to set the rate of oxygen transport to the cathode to be proportional to the oxygen concentration. The cell is operated in the current limiting region where all the oxygen reaching the electrode is consumed.

As air flows through an underground facility, it is probable that its oxygen content will decrease. This occurs not only because of respiration but, more importantly, from the oxidation of minerals (particularly coal and sulfide ores) and imported materials. The burning of fuels within internal combustion engines and open fires also consume oxygen. The oxygen concentration can easily drop below 19% in poorly ventilated areas such as old workings, bleeders, etc. Oxygen deficiency implies an increased concentration of one or more other gases.

4.4.2.5 Carbon Dioxide

Carbon dioxide appears in a mine from a variety of sources such as strata emissions, oxidation of carbonaceous materials, internal combustion engines, blasting, fires, explosions, and respiration. The specific gravity of CO_2 to dry air is 1.5 and will, therefore, tend to collect on the floors of mine workings. It is common to find emanations of CO_2 from the bottoms of seals behind which are abandoned workings, particularly during a period of falling barometric pressure. The concentration of CO_2 in air is normally 0.037%, but when it increases to 2%, the lung ventilation increases by 50% leading to intolerable panting, severe headache, and collapse as exposure increases over time.

4.4.3 Thermal Sensors

Thermal sensors respond to environmental changes produced by the presence of a fire. Thermal sensors are not reliable for detecting fires in underground mines; they have been phased out in the last few years. Thermal sensors work on a simple principle of detecting an increase in air temperature and actuate an alarm that signals the presence of a fire condition. Commonly used thermal sensors are primarily based on thermocouples. A thermocouple is a bimetallic junction that generates an electromotive force when heated. They are fairly rugged and suffer no adverse effects from humidity or convection cooling owing to the ventilation flow. Another widely used thermal sensor is a thermoresistive type. These sensors change their resistance as the temperature increases. However, these devices should be maintained at a fairly constant humidity and should not be subjected to excessive changes in the ventilation flow. These factors can adversely affect the sensitivity and, hence, the reliability of the sensor. Other types of thermal sensors include line-type heat sensors, fixed-temperature sensors, rate-of-temperature rise sensors, and pressurized heat-sensitive plastic tubes.

In general, thermal sensors work fine, but the time response can be quite long (several minutes). If a fire occurred immediately adjacent to a thermal sensor, it would respond rapidly, but if a fire occurred far away from a thermal sensor, the ventilation flow would be required to carry the warm air to the sensor. Along the way, the air would cool, and the time response could be too long to initiate any corrective action (Litton 1979).

4.5 Condition Monitoring

A well-maintained and low cost mining operation requires the use of condition monitoring techniques. Condition monitoring is the process of measuring environmental and fan operating factors to evaluate and predict the health and safety conditions of the mine fans. An adequate and reliable condition monitoring system is quintessential for a mine using a booster fan ventilation system. This includes the measurement and evaluation of the following variables: vibration, barometric pressure, noise, power, bearing temperature, differential pressure, and quantity of airflow.

4.5.1 Vibration

In its simplest form, vibration can be considered to be the oscillation or repetitive motion of an object around an equilibrium position. The equilibrium position is the position the object will attain when the force acting on it is zero. Vibration in a system is a factor that can cause machinery distress. Identifying the vibration level that is due to the changed operational parameters can prevent potential damage. Vibration analysis is a powerful tool to assess the performance of mine fans. Variations in normal operating conditions in mine fans produce significant changes in vibration level. It also causes wear or deterioration of the fan’s condition. The cause of fan vibrations can be either internal or external. The internal sources of vibration are defects in manufacturing or machine problems such as being out of balance, misalignment, or looseness. External factors responsible for producing vibration in the system include the operation of the fan in the stall region, changes in the equivalent orifice of the ventilation system, and changes in the rpm of the fan (Mukhopadhyay 1998). Fans often exhibit excessive vibration due to aerodynamic forces and flow turbulence. When excessive vibration at the aerodynamic frequency (i.e., at the blade frequency) is encountered, a common cause is the resonance of some part of the fan. It may also be due to obstructions that disturb the smooth flow of air through the fan.

There are two types of vibrations: forced and free. An elastic body will vibrate freely at one or more of its natural frequencies if an external force momentarily disturbs its equilibrium. The motion will gradually die down because of damping. If an external force is applied repeatedly, an elastic body will vibrate at the frequency of the external excitation, whether this coincides with a natural frequency or not. The modes of vibration are classified according to their numerical order and the direction of vibration relative to the principal axis of the part or member. The direction of oscillation may be longitudinal, lateral, or angular. Longitudinal vibrations are seldom serious in fan parts. Lateral vibrations cause bending. Angular vibrations lead to torsion. The first bending mode may have a higher or lower frequency than the first torsional mode, depending on the geometry and material of the part (Jorgenson 1999).

After reviewing the current technology and industry practice of vibration monitoring, it is recommended to have at least six vibration monitors (velocity type): two for the fan fixed bearing, one for fan floating bearing, two for the motor nondrive end, and one for the motor drive end. Although these monitors are extremely useful and necessary for minimizing fan system damage, they are somewhat limited in predicting potential failure. To that end, further vibration monitoring (acceleration type) is recommended. This technique allows frequency analysis of the vibration to be undertaken and is therefore more useful in predicting potential failure.

4.5.1.1 Vibration Measurement

To measure the vibration entity, a vibration transducer commonly known as a Vibrometer is used. It produces an electric signal that is a replica, or analog, of the vibratory motion it is subjected to. A Pruftechnik's Vibscanner instrument was used for measurement in the laboratory as shown in Figure 4.2. This instrument works on the piezo-electric principle. In mine fans, vibration is monitored at more than one place on the fan. Therefore, the sensors are placed at critical points on the fan and motor installation. These sensors are then connected to the Vibrometer and the information is transmitted real-time to the data acquisition system of the condition monitoring system. The different modes for measuring vibration are discussed as follows.

- **Velocity**: Velocity of vibration is measured in peak units such as inches per second (ips) or millimeters per second (mm s^{-1}). Another way of looking at velocity is distance per time or how much is the machine moving every second in three important directions at all main bearing points (axial, vertical, and horizontal). Velocity measurements and monitoring of vibration are the most common units to identify various problems or acceptability such as unbalance, misalignment, looseness (machinery structural, foundations, or bearings), harmonics, and many other issues in the machinery frequency range and many multiples of actual speed. Velocity measurements (if using a single axis sensor/probe and hand-held meter) are recorded in three directions: axial, horizontal, and vertical at all main bearing blocks or motor frame end bells.
- **Acceleration**: Acceleration is measured in units of G. Simplified = millimeters per second/second (mm s^{-2}). Acceleration is very important bearing fault data in the

high frequency ranges. Acceleration is also a sudden change in velocity. Acceleration data are relevant in the rotational axis only. Some vibration meters have earphone output to allow the analyst to listen to the noise inside bearings while recording G. Listening to bearings using earphones such as an electronic stethoscope is very useful for defect identification (Sandwell 2012).

- **Displacement**: Displacement is measured in peak-to-peak units of mils (1 mil = .001”) or mm (1 mm = .0025”). Displacement measurements are recorded in the three directions as velocity (axial, horizontal, and vertical). Displacement is not used or recommended for recording or monitoring because severity or acceptability is speed dependent. For example 1 mil at 1800 rpm is excellent, but 1 mil at 30,000 rpm is dangerous. Displacement is used to identify problems in the lower frequency ranges. Displacement can be used for measuring reference values for walls, floors, beams, pads, frames, and for very slow moving or stationary objects (Sandwell 2012).

It is always a question whether to use the displacement, velocity, or acceleration amplitude unit for monitoring the fan vibration. Here is a rule of thumb based on the frequency. Displacement is a good measure at lower frequencies especially less than 5 Hz. The failure mode is generally the ―stress” due to the displacement. Velocity measures how often the displacement is being applied in a given time period. It is related to the fatigue mode of failure. Velocity amplitude unit is a good measure in the range of 5–2000 Hz frequency. Even at small displacement amplitudes, the repeated motion can cause fatigue failure. Above 2000 Hz, the failure is normally force related. Acceleration is a measure of the likelihood of force being the mode of failure. The proper selection of the amplitude unit will depend upon the application under study. Note that frequency, displacement, velocity, and acceleration are related. Knowing any two quantities allows other variables to be easily calculated.

4.5.1.2 Vibration Severity Chart

In order to come up with a specific recommendation or guideline for machine vibration for mine fans, a number of regulations and industry best practices from different countries like South Africa, the United States, and the United Kingdom were reviewed. Also, the vibration severity chart for rotating equipment machinery from the International Standards Organization (ISO 2014) was reviewed. The chart depicts the findings and is recommended as reference to study the fan vibration (as shown in Figure 4.3).

4.5.2 Fan Noise

Noise is sound that is unwanted or disturbing. The sound emitted by a fan is an inevitable by-product of the energy-transfer process. Because most fan sound is unwanted, it is classified as noise. Noise control can be accomplished by reducing the amount of noise generated, by altering the characteristics of the acoustical path, or by protecting the receiver. Both the quantity and quality of noise are important in determining the undesirability of sound. It is necessary to understand these physical properties and how they are measured before numerical values can be assigned to generated sound, acceptable sound, and the reduction required in a particular situation

(Jorgenson 1999).

Noise is an important factor and is discussed in detail in the Code of Federal Regulations (CFR). A number of protective devices are commonly used in mines to protect the workers from excessive noise. Some of the common ones, as mentioned in the CFR, are earplugs and earmuffs. It is essential to use these when working near the mine fans, both at the surface and underground.

4.5.2.1 Sources of Noise

There are different sources of noise in a fan. These include mechanical as well as aerodynamical sources of noise. If the mechanical noise predominates, this usually implies a mechanical deficiency. For instance, excessive bearing noise suggests that these components are either overloaded or failing and that immediate corrective measures should be undertaken. Similarly, the forces due to rotating unbalance tend to produce vibrations that can be transmitted mechanically and will, ultimately, produce noise. Excessive unbalance should be corrected immediately, and any mechanical-transmission paths should be interrupted with flexible connections and resilient mounts, as appropriate.

The other form of noise created by mine fans is aerodynamic noise. It consists of a series of discreet tones superimposed on a broadband background. The series of tones can be traced to the energy transfer that also leads to the development of head. One way to solve the problem is isolation. The fan can be installed in the return way and isolated by means of stoppings and doors. The return airway is not used by miners for walking or as a road for trucks or other mining equipment unless it is an emergency situation.

Even in emergency situations, the booster fan is always turned off; therefore, fan noise is not a major problem in return airways. Another way to control noise is by using the fans at optimum frequency. For example, large diameter fans should be used at low rpm (600–800 rpm). If the large fans are used at higher frequencies, it generates a lot of noise and fan vibration (Calizaya 2000).

4.5.3 Barometric Pressure

Barometric pressure is the force per unit area exerted on a surface by the weight of air above that surface in the atmosphere of Earth. In most circumstances barometric pressure is closely approximated by the hydrostatic pressure caused by the weight of air above the measurement point. It is of common knowledge that barometric pressures vary. It is also well known that these variations in barometric pressure can affect conditions in mines. As per popular belief and studies over the years, it is believed that there are only two situations in which variations in barometric pressure affect conditions in mines. The first is their effect on gas emissions from the strata, the gas concerned usually, but not always, being methane. Secondly, variations in barometric pressure result in leakage into and out of sealed areas or areas such as the gob in longwall coal mining that have not been sealed effectively. These leakages can result in either the emission of undesirable gases into the mine workings or the addition of air to an area where it is not desired. In some cases, both effects are of importance (Hemp 1994). The tests conducted during the course of this study suggest that there is a third situation: the barometric pressure also affects the operating point of mine fans in underground mines. While this is well known in a qualitative sense, little work has been aimed at providing a quantitative understanding of the situation. Such an understanding is essential for the complete design of ventilation systems and also for the formulation of any warning system and for the design of mine fans according to the place where the mine is located. The tests conducted at the University of Utah show that there is a certain relation between the barometric pressure and the fan's operating point. It can be seen in Figure 4.4 that the fan pressure has a direct relation with barometric pressure or natural ventilation pressure.

Natural heating and cooling of the atmosphere is responsible for localized changes in barometric pressure, known as diurnal pressure changes. Under certain conditions, these changes may be more significant than the general barometric pressure trend. By accounting for both the general and diurnal pressure changes, the mine operator may be able to adjust to the effects of these changes. To study these effects, the barometric pressure data were recorded every 20 seconds using a Druck DPI 740 Precision Pressure Barometer in Salt Lake City, Utah (altitude ~1500 m). The differential pressure is higher for near sea level altitudes and it also varies from season to season. A 250 Pa drop in barometric pressure in 2 hrs time can cause sudden emission of gas from the sealed gob into the active mine ventilation system. During the course of this project, a number of deep mines were visited in the U.K., the changes in barometric pressure at these mines had a significant impact on the ventilation system with the natural ventilation pressure accounting for approximately 500 Pa. Mines in the U.K. are generally deep and hot, with depth in the order of 1000 m and temperatures in the order of 35°C.

Another important aspect associated with variation of barometric pressure is storm fronts. Storm fronts are normally predicted by the National Weather Service (NWS). They are associated with decreasing barometric pressures as they approach, followed by an increasing barometric pressure after they pass. Hurricanes and some strong tropical storms have the potential for rapid pressure change rates for short periods of time. Even a powerful line of thunderstorms has been capable of short-term rate of change as high as 60 Pa min^{-1} (Chalmers 2010).

4.5.4 Airflow and Pressure Measurement

One of the main differences between a mine ventilation system and ductwork in a building is that the mine is a dynamic entity, changing continuously due to modifications of the structure of the network and resistances of individual branches. Fans are the most important entities of the mine ventilation system. It is, therefore, important to continuously monitor the airflow and pressure at the main and booster fans. The volume of air passing any fixed point in an airway every second, Q, is normally determined as the product of mean velocity of the air, v, and the cross-sectional area of the airway, A:

$$\mathrm{Q} = \mathrm{v} \times \mathrm{A} \tag{4.1}$$

Most of the techniques of measuring airflow are, therefore, combinations of the methods available for measuring mean velocity and the cross-sectional area. The different techniques and industry best practices from mining and related fields are reviewed and discussed in this section.

4.5.4.1 Vane Anemometer

Anemometers are the most common instruments used around the world to measure air velocity. When held in a moving airstream, the air passing through the instrument exerts a force on the angled vanes, causing them to rotate with an angular velocity that is closely proportional to the airspeed. A gearing mechanism and clutch arrangement couple the vanes either to a pointer that rotates against a circular dial calibrated in meters (or feet) or to a digital counter. The instrument is used in conjunction with a stopwatch and actually indicates the number of "meters of air" that have passed through the anemometer during a given time period. The quantity of air is found by multiplying the average velocity measured by the anemometer to the area of cross-section where the measurement is taken. Considering that the mine fans require continuous monitoring, they do not fulfill the required standards of the modern day mining industry and, therefore, are not recommended for recording the quantity of air flowing through a fan.

4.5.4.2 Pitot Tube

A pitot-static tube is used to measure static, velocity, and total pressures of a moving stream of air. This device consists essentially of two concentric tubes. When held facing directly into an airflow, the inner tube is subjected to the total pressure of the moving airstream, P_T. The outer tube is perforated by a ring of small holes drilled at right angles to the shorter stem of the instrument and, hence, perpendicular to the direction of air movement. This tube is, therefore, not influenced by the kinetic energy of the airstream and registers the static pressure only, P_S. A manometer connected across the two taps will indicate the difference between the total and static pressure (i.e., the velocity pressure, P_V):

$$V = \sqrt{\frac{2P_V}{\rho}} \tag{4.2}$$

Where

V = Velocity of air, m/s

P_V = Velocity pressure, pa

ρ = Density of air, kg/m^3

Pitot-static tubes vary widely in overall dimensions. Modern pitot-static tubes reflect the total, static, and velocity pressures of the airflow to an excellent degree of accuracy. The precision of the measurement depends also upon the manometer connected to the taps. It is used to measure high velocities (> 5 ms^{-1}).

Though pitot tubes are very effective and easy to use for calculating the velocity of air, they do not always give the accurate readings required for reliable condition monitoring. The flow near the fan is extremely turbulent and therefore, the pitot tubes show different readings at different points and also fluctuating readings at the same point of measurement. Therefore, they require frequent calibration.

Pitot tubes are very handy for measuring the quantity of air flowing through a booster fan underground. The airflow is measured at the inlet side of the fan, as the flow of air is less turbulent on this side. They are seldom used in underground mines.

4.5.4.3 Vortex Shedding Anemometer

Vortex shedding anemometers are widely used for continuous monitoring systems, especially in fluids. They are better than the rotating vane and swinging vane instruments as they have no moving parts. In this instrument, a bluff object is placed in a stream of fluid, which forms a series of oscillating vortices downstream by boundary layer breakaway, first from one side of the body then the other. The propagation of the vortices is known as a Kármán street and can often be observed downstream from projecting boulders in a river. The rate of vortex production depends upon the fluid velocity. In the vortex-shedding anemometer, the vortices may be sensed by the pulsations of pressure or variations in air density that they produce, which can be used to find the velocity of the air. There is one apparent disadvantage with this anemometer: it requires calibration for each specific location they are placed in for measurement.

It has been experimentally proven by many researchers that the repetitive shedding of vortices in a Karman Vortex Sheet conforms to a constant frequency. This frequency is predicted by using the known relationship between the dimensionless parameters, known as the Strouhal number (S_t) and Reynolds number (N_R).

$$S_t = \frac{f \times d}{U} \tag{4.3}$$

Where

f = frequency

d = cylinder diameter

U = free stream velocity

The Strouhal Number attains a constant value, 0.21, when the Reynolds Number is in excess of 1000. The Reynolds Number found in mine air flows is typically much greater than 1000. Therefore, the relationship between the frequency and the free stream velocity is

$$U = \frac{f \times d}{0.21} \tag{4.5}$$

Vortex shedding anemometers are fairly reliable and also rugged to some degree. They are used in underground mines considering they do not have any moving parts and are easy to install and maintain.

4.5.4.4 Ultrasonic Anemometer

Ultrasonic anemometers use ultrasonic sound waves to measure air velocity. They measure air velocity based on the time of flight of sonic pulses between pairs of transducers. Measurements from pairs of transducers can be combined to yield a measurement of velocity in 1-, 2-, or 3-dimensional flow. Modern ultrasonic sensors measure accurate values of air velocity, volumetric flow, temperature, and flow direction. These sensors are generally not affected by temperature, humidity, or dust. They are connected to the central conditional monitoring system and the real-time values of the above-mentioned parameters can be displayed remotely on the computer linked to the monitoring system. In a mine, two ultrasonic sensors are placed diagonally across the fan inlet duct in which airflow is measured (as shown in Figure 4.5). Each of these sensors is capable of sending and receiving ultrasonic pulses. In order to measure the velocity of air, the time of transit of a pulse is measured from transmitter sensor to the receiving sensor. The transit time of a second pulse is then taken in the opposite direction. The difference in the transit time is proportional to the velocity of air. Airflow is measured in both directions. One direction is represented as positive measurement, the other as a negative measurement. It is to be noted that although these sensors are very accurate in measuring velocities, they actually measure velocity in only one plane in which they are placed (as shown in Figure 4.6). Therefore, the overall airflow through the duct is still questionable. One way to increase the accuracy of the reading is by adjusting the sensor read out by a calibration factor.

4.5.4.5 Differential Pressure

The estimation of booster fan operating pressure is done by measuring the pressure differential (or gage pressure) across the bulkhead. It is common for ventilation textbooks to show that the static pressure taken across a booster fan mounted in a duct system is equal to the total pressure generated by the fan. This simple method is based on the assumption that the ducting and fan have the same shape and diameter; therefore, the velocity pressure remains constant and hence no shock loss. Therefore, the standard equation for fan total pressure is

$$\mathrm{H_T = H_{T_O} - H_{T_I} = \left(H_{V_O} + H_{S_O}\right) - (H_{V_I} + H_{S_I})} \tag{4.6}$$

However, in common practice as per assumption, $\mathrm{H_{V_O}} = \mathrm{H_{V_I}}$; therefore the equation reduces to

$$\mathrm{H_T = H_{T_O} - H_{T_I} = H_{S_O} - H_{S_I}} \tag{4.6}$$

However, in real mining conditions, booster fans mounted in bulkheads with a large aspect ratio in cross-sectional area and free discharge can have very high shock losses that drastically reduce the overall efficiency of the fan assemblage (Krog 2002). In spite of this phenomenon, the fan pressure is measured across the bulkhead because it gives an approximate reading effortlessly and is easy to measure without any additional installation of expensive instruments. In some cases, when measuring the pressure differential across the bulkhead is not possible, it should be measured at the nearest airlock door for an approximate reading.

4.5.5 Bearing Temperature

Bearings are one of the most critical components in the operation of a fan and careful consideration must be given for proper monitoring of the bearings. One of the most reliable indicators of the status of bearing condition is the bearing temperature. Fan bearings are an important part of the fan assembly because they have to withstand the loads due to the dead weight, thrust, and unbalance of the rotor assembly. They must also be able to operate at the intended speed without overheating. Various methods are used to estimate the temperature rise in the sleeve and antifriction bearings. When enough heat is not dissipated by natural convection from the pillow block or other type of bearing housing, some form of forced cooling is necessary. Small fan wheels, called heat slingers, mounted on the shaft between a hot fan casing and the bearing promote cooling by increasing the circulation of air over the bearing and by providing an extended heat-dissipation surface for the shaft. Pillow blocks and some bearing liners can be provided with internal passages through which cooling water or even cooling air can be circulated. Lubricating oil can also be circulated through an external cooler.

Motor stator temperature monitoring is used to locate hot spots or high operating temperatures. Each 10°C increase in operating temperature shortens motor life by 50%. Bearing temperature monitoring can indicate problems related to fluid-film bearings, including overload bearing fatigue or insufficient lubrication.

The permissible operating temperature for track runner bearings is mainly limited by the dimensional stability of the bearing rings and rolling elements, cage, seals, and the lubricant. The bearing temperature should be maintained below 85°C for better dimensional stability.

4.6 Design of AMS

Atmospheric Monitoring Systems (AMS) are used as means to measure and evaluate the air quality and quantity in a mine and to develop strategies to control potential fire hazards. It performs three functions: sensing, data transmission, and data processing (recording, analyzing, and displaying). The AMS network in a mine could become extremely complex if the monitors are not located in the right places. For efficient and reliable working of the AMS, it is critical to place sensors at a certain minimum spacing in intake, belt, and return airways. In this section, the regulations related to location and spacing of monitors are discussed followed by procedure-based guidelines to calculate the appropriate spacing of sensors in the intake, belt, and return airways.

4.6.1 Regulations

Title 30 Code of Federal Regulations discusses the operation of AMS in more than one section. The details can be found in sections § 75.323, 75.340, 75.350, 75.351, and 75.362. The locations of sensors are directed for the belt entries, primary escapeways, and return air splits. Regulations are in a greater detail for the belt entries than for intake or return. The federal regulations are briefly described in Appendix B.

4.6.2 Location and Spacing of Monitors

The design of AMS in coal mines is based on a number of factors. These factors include size of the mine, background gas concentrations, methane emission, diesel particulate matter concentration, number of entries, velocity of air, etc. In the intake, the monitors are primarily located near the bottom of the shaft, at places where the air splits, at point-feed regulators, and near the working sections. The main purpose of monitors in the intake is to measure the quality and quantity of the fresh air. In case of return airways, the monitors are located near the working section for measuring the CO, smoke, and methane concentrations. It also provides some data on the emissions from the working area. In belt entries, the regulations for the spacing and location of monitors are defined in 30 CFR § 75.351, where the maximum spacing ranges from 350 ft to 1000 ft between monitors. The spacing of monitors is primarily dependent on the velocity of air in the airway, which in turn is dependent on the dust in the mine. Although booster fans are currently not being used in U.S. coal mines, several papers were reviewed to understand the types of monitors required near the fan installation. The three major environmental parameters monitored are CO, smoke, and CH_4. It is interesting to note that the CH_4 monitors are located both before and after the fan installation, whereas the CO and smoke monitors are located after the fan. This configuration is desirable because if there is a fire in the fan installation, it will be recorded only after the fan by the three monitors and not before the fan. In case there is a fire in the working sections, it will be picked up both before and after the fan. The three parameters used for condition monitoring are differential pressure, vibration, and temperature.

For an AMS to provide a specified level of protection for an underground mine, few guidelines for sensor distribution exist. This section discusses briefly the relationships that exist between the fire, products of combustion that are liberated, sensitivity of the detectors, velocity of air, size of the drift, federal regulations, and how these factors can be utilized to determine the optimum distribution of candidate sensors. A number of reports by different agencies including the Bureau of Mines (Litton 1983), NIOSH (Edwards 2006), and MSHA (Stricklin 2013) were reviewed. A couple of AMS manufacturing companies, namely CONSPEC and AMR, were also contacted via email. The information obtained from this review is used to form guidelines for spacing of sensors in a drift. The guidelines are described for lateral, vertical, and siting placement in a drift.

4.6.2.1 Lateral Placement

An AMS uses different monitors for different parameters. In general, AMS are used mainly to detect and monitor products of combustion in entries. The point of origin of a fire is quite unpredictable. It may occur along the floor, ribs, or roof of an entry. In order to provide optimum protection, it is recommended that the sensors be located within 0.7 m of the approximate midpoint of the entry. Another important factor that should be taken into account is the height of the largest vehicle that is used in the drift. In case the vehicle or machine is too big and does not give much vertical clearance in the center, the monitor should be placed on either side of the drift. For entries in which the point of origin of the fire can be better estimated (such as a belt entry), the sensors should be located in such a manner that they provide for the estimated best coverage of that entry. As an example, in a belt entry where the conveyor is on one side of the entry, it would be judicious to locate the sensors above the centerline of the belt conveyor rather than to locate them in the middle of the entry (as shown in Figure 4.7), One thing that needs to be addressed in this case is that the monitor should be reachable, and if there is a problem with a monitor, it can be fixed without stopping the conveyor.

4.6.2.2 Vertical Placement

The vertical placement of a monitor in an airway depends on multiple factors such as the type of gases present, size of the entry, height of the largest vehicle, and most importantly the dispersion and diffusion of gases in the entry. Again, as most common monitors are designed to detect and monitor the products of combustion such as smoke, CO, CO_2, and methane the location should be based on them. The hot gases from a fire will rise owing to buoyancy forces. As a result, combustion products will initially be stratified near the roof of an entry. As this stratified gas layer moves away from the fire, the resultant cooling and dilution will eventually produce a well-mixed flow of combustion products. Data from full stratification can exist at distances of hundreds of feet from the source of the fire. Because of this effect, POC fire sensors should be located at a vertical distance from the entry height. For example, in an entry with a height of 2 m, the maximum distance from the roof is 0.3–0.5 m. In case the height of the entry is 2 m and say the height of largest vehicle is 1.8 m, then the monitor should be placed on either side of the entry with a vertical spacing of 0.3–0.5 m.

4.6.2.3 Spacing

The most complicated part in the design of an AMS for a mine is to determine the spacing of monitors. The regulations for spacing and location of monitors are defined in

30 CFR § 75.351. Guidelines for improving the rationale for spacing of monitors in underground mine are presented in Appendix C.

4.7 AMS Operator Training

In the event of a mine emergency, one of the most important people to respond to the emergency is the AMS operator. AMS operators must have the background, experience, training, and authority to assure that proper actions are taken in response to AMS signals, including alerts, alarms, and malfunctions. AMS operators should be experienced miners and certified foremen who have been given all the tools they need, including the mine map, computers, video, two-way communications, and access to the technicians to assure that the system operates correctly. The AMS operators do far more than just monitor the AMS. AMS operators receive calls on a number of issues that are unrelated to the operation and monitoring of the AMS. They also have to monitor the operation of the fans at the mines and receive calls on the mine pager phone with people traveling to and from different areas of the mines. The AMS operator monitors the CO sensors and relays any messages to the proper people. A mine needs a responsible person whose sole job is to monitor the AMS to ensure the health and safety of each and every person in the mine and who is trained and certified to do so. This action would result in a reduction of miners' exposure to smoke or gas in the mines in the event of a fire or an explosion. Also, the withdrawal time would be less, and the probability of someone surviving these events would be greater (MSHA AMS Training Guide 2014).

One of the important aspects during an emergency situation in a mine are the critical actions (or nonactions) of the AMS operator. Mine operators may assign the AMS operator to be the ―Responsible Person" required to take charge during mine emergencies under 30 CFR § 75.1501—Emergency evacuations. AMS operators involved in emergencies may or may not have sufficient training to unequivocally handle mine emergencies. Therefore, it is imperative that the AMS operator have the background, experience, training, and authority to ensure that proper actions are taken in response to all AMS signals, including alerts, alarms, and malfunctions to provide the utmost assurance of safety of all affected miners. In an emergency situation, decision-making involves the following steps: detection of the problem, definition/diagnosis, consideration of options, choosing from options, and execution of the decision. This process is impacted by miners' skills, knowledge and attitude, uncertainty, stress, and the complexity of the situation. Therefore, there should be special training for dealing with emergencies, which should include routine functioning of the system, diagnosing nonroutine situations, giving and receiving emergency warnings, and the impact of stress during and after emergencies.

AMS operator duties and responsibilities are contained in 30 CFR § 75.351—Atmospheric monitoring systems and 30 CFR § 75.352—Actions in response to AMS malfunction, alert, or alarm signals.

Booster fans are one of the most important entities of any mine ventilation system. It is, therefore, very important to have an efficient and reliable monitoring system for it. The present day technology of atmospheric monitoring systems, as was discussed in this chapter, is good enough to accommodate booster fan monitoring. There is no additional need of a new technology to monitor a booster fan if it is added in an underground mine. AMS installation similar to the one used for monitoring main surface fan duties can easily handle the booster fan's conditional and environmental monitoring in an underground mine.

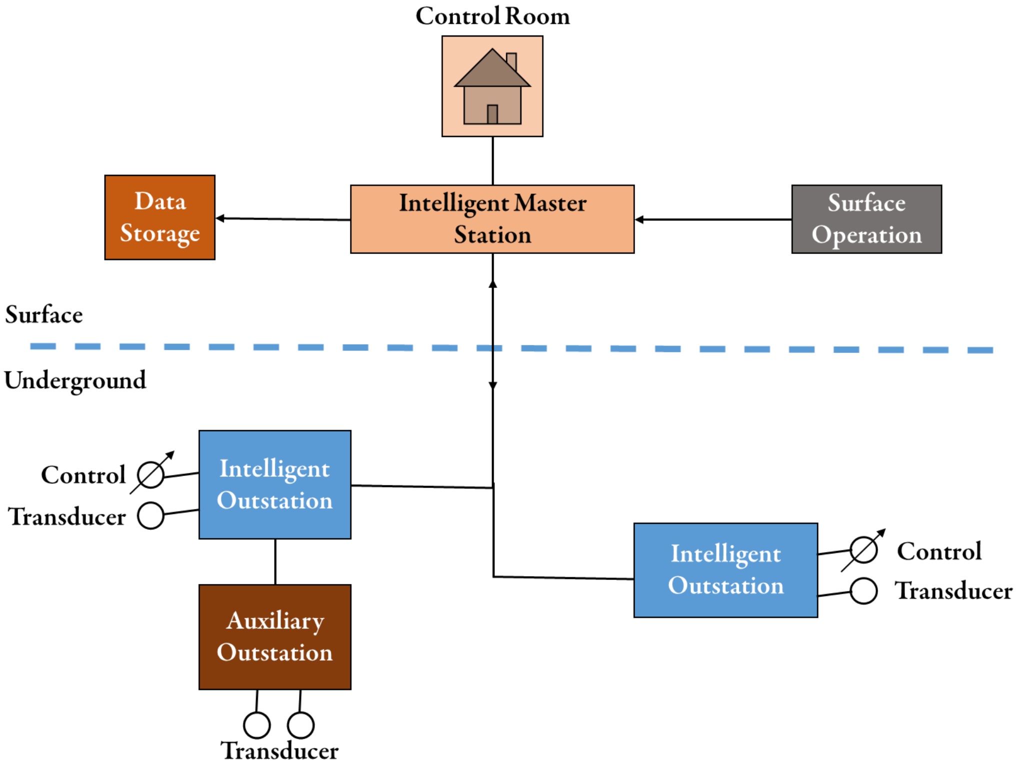


Figure 4.1: Schematic of an AMS installation in mine

Table 4.1: Parameters monitored by AMS (adapted from Francart 2005)

Parameter	Percent of mines
Belt operations	90
Fan stoppage	42
Fan pressure	32
Electrical installations	32
Motor amperage	32
Pumps	29
Water level	29
Methane	22
Coal storage	15
Other ventilation parameters	15
Battery charging stations	14
Other	10

Table 4.2: Classification of mine gases

Name	Hazards	Guideline TLVs	Methods of detection	Flammability Limits
Carbon Monoxide, CO	Highly toxic and explosive	TWA=50 ppm STEL=400 ppm	Electrochemical, catalytic oxidation, semiconductor, infra-red	12.5 to 74.2%
Methane, CH_4	Explosive; layering	1%: de-energize equipment 2%: remove personnel	Catalytic oxidation, thermal conductivity, optical, acoustic, flame safety lamp	5 to 15%
Oxygen, O_2	Oxygen deficiency; may cause explosive mixtures with reactive gases	>19.5%	Electrochemical, paramagnetic, flame safety lamp	Supports combustion; itself not flammable
Carbon Dioxide, CO_2	Promotes increased rate of respiration	TWA=0.5% STEL=3%	Optical and infrared	Does not supports combustion

Figure 4.2: Measuring vibration using a vibrometer

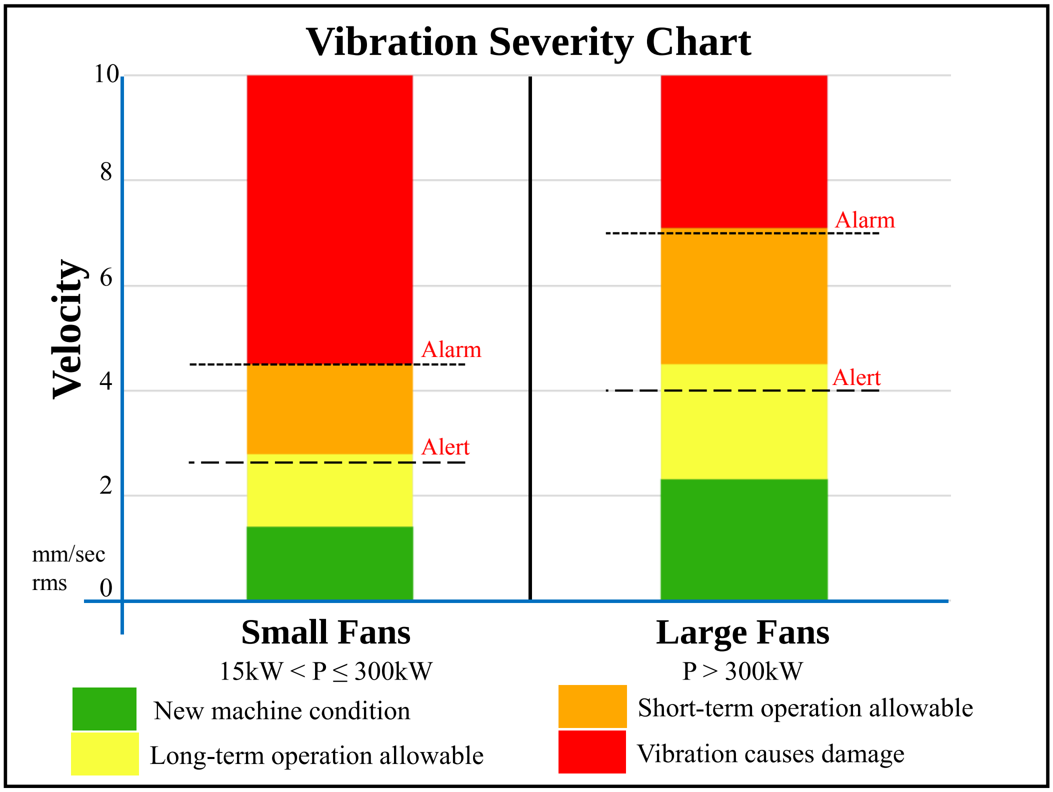


Figure 4.3: Vibration severity chart

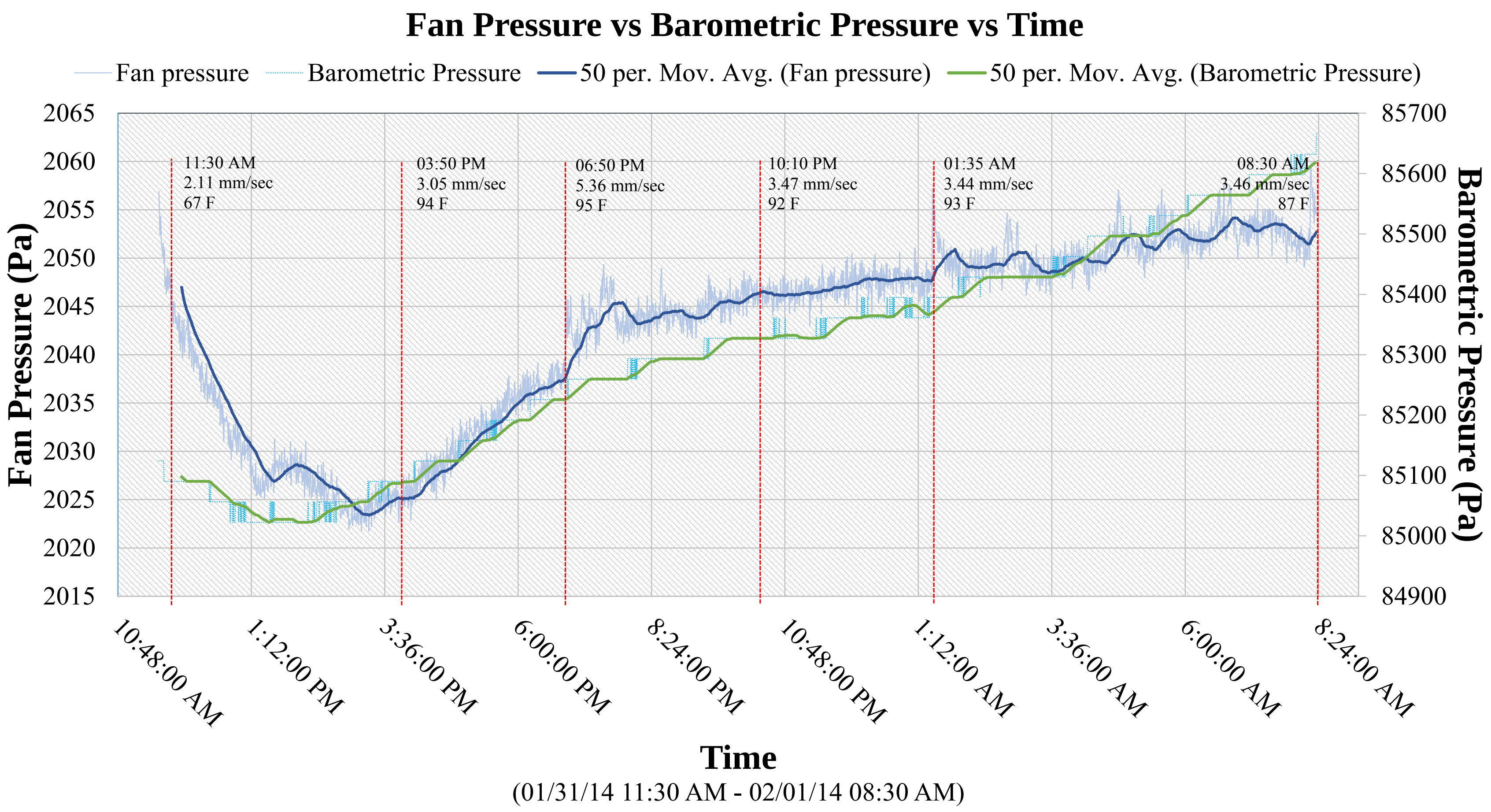


Figure 4.4: Fan pressure vs. barometric pressure measured in Salt Lake City

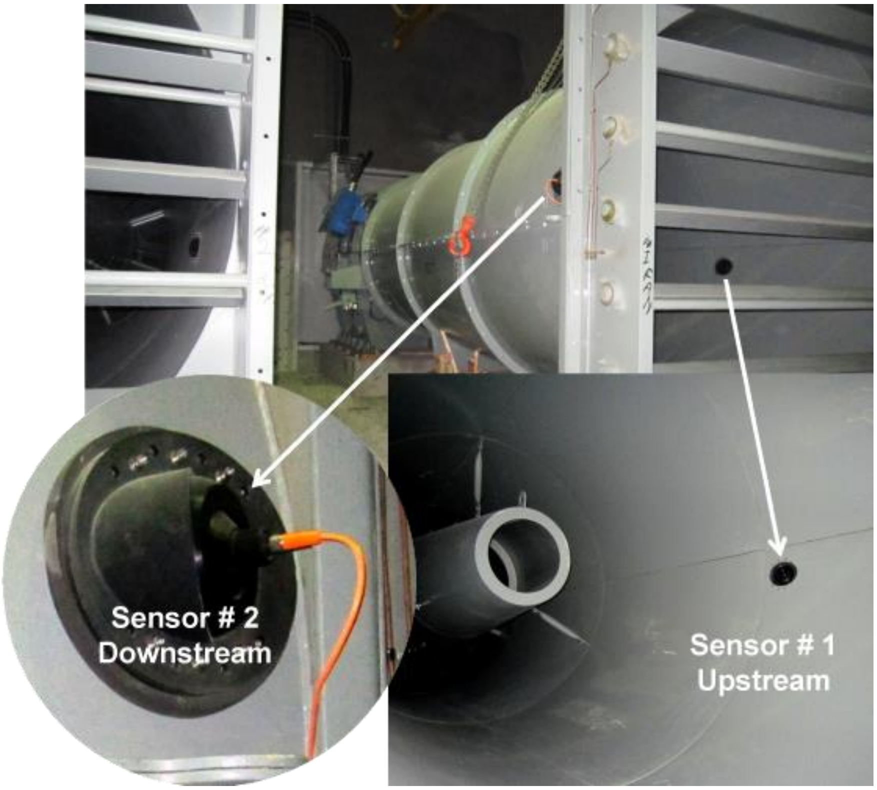


Figure 4.5: Measure of velocity at an underground booster fan

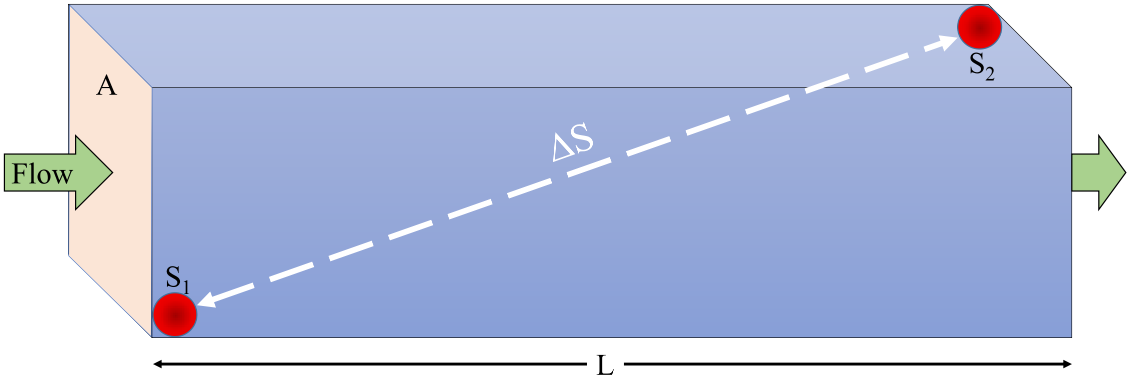


Figure 4.6: Schematic showing the operating principle of an ultrasonic anemometer. ΔS: Sensor face-to-face distance, A: Drift cross-sectional area perpendicular to air flow stream, and L: Distance from Sensor #1 (S1) to Sensor #2 (S2) parallel to the airflow stream

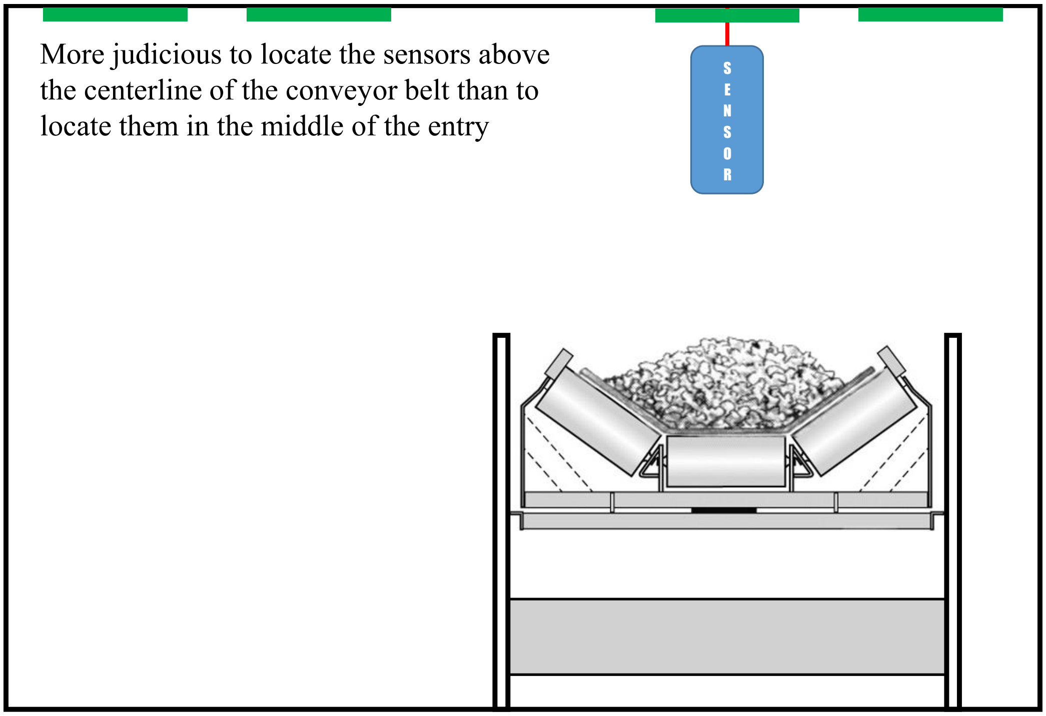


Figure 4.7: Lateral placement of sensor in belt entry

CHAPTER 5

BOOSTER FAN MONITORING SYSTEMS

As underground mines go deeper and deeper, ventilation conditions may deteriorate due to the difficulties found in attempting to meet the required airflows. This problem is even more difficult when the mine is ventilated solely by means of surface fans. At greater depths coal mining has encountered several problems, including increased gas emission and heat flow rates, requiring larger quantities of fresh air. Currently, high-pressure fans are being used to supply these quantities. High-pressure fans often induce substantial losses of fresh air in the form of leakage. In addition, they require a number of airlock doors. Booster fans can be used to overcome this problem. The operation of these units must meet a certain number of requirements including fan condition and environmental monitoring. In fact, in all coal mining countries, an AMS is an integral part of the booster fan ventilation system. It is of utmost importance to understand that booster fans cannot be used in place of main fans at any point.

In this chapter, the experiences of booster fan use in the U.K. and Australia are discussed followed by design and installation principles of the booster fans. Next, fan electrical interlocking systems and the importance of uninterruptible power supplies are discussed in brief detail. The environmental and condition monitoring guidelines are laid out. Finally, risk assessment has been conducted to study the issues associated with booster fan use, and the subsequent control measures are laid out. Special emphasis was given to risk assessment because it is one of the most integral parts of designing booster fan ventilation systems in the U.K. and Australia.

5.1 Introduction

A booster fan is an important component of a mine ventilation system. In practice, this term is generally used to describe a fan that gives boost to the air current passing through it. The fan is installed in a permanent bulkhead and equipped with airlock doors, stoppings, electrical interlocking devices with the main fan, and an atmospheric monitoring and control system. Considering that the fan is an active device with moving parts, it is imperative to install it with an efficient continuous monitoring and control system. This task is accomplished by a modern day monitoring and control system that can not only monitor and collect data but also control numerous parameters from a computer terminal at the control room on surface. The parameters monitored at or near a booster fan may include environmental parameters such as CH_4, CO, smoke, barometric pressure, air velocity and pressure, and conditional parameters such as fan speed, vibration, motor and impeller bearing temperatures, and electric power.

5.1.1 Sample Installations

In order to understand the principle and design of booster fan installations, six underground coal mines were visited, three in Australia and three in the United

Kingdom, during the course of the project. In these mines, booster fans are used regularly to overcome adverse conditions created by higher airway resistances and increased airflow requirements. In each case, booster fans are installed in the return airway to assist the main fans in delivering the required quantities of air to workings that are located at great depths, with large CH_4 emission rates and under environmentally sensitive areas. In both countries, booster fans are seen as integral parts of the mine ventilation design (Calizaya 2014). The installation principles learnt from these inspections are summarized in two sample installations.

5.1.1.1 Sample Installation I

This installation represents a typical booster fan system in an Australian underground coal mine. The working areas are approximately 500 m below the surface. As mentioned above, the fans are installed in the return airways. The system primarily consists of two double-inlet centrifugal fans installed in concrete bulkheads. The system is designed to deliver 300 m^3s^{-1} at 3.0 kPa pressure, with the surface fans delivering 320 m^3s^{-1} at 3.2 kPa. The fans are equipped with heavy-duty airlock doors and an independent fan conditioning and environmental monitoring system (as shown in Figure 5.1). One of the interesting things to see in Australian installations is that, because of regulatory restrictions, the fan motor is required to be ventilated by fresh air all the time (Benson 2002). As a result, the fan motor must be located in a specially designed, fire resistant chamber, which is ventilated with fresh air by two separately routed, 30-cm-diameter pipes. The heavy-duty airlock doors are used in series; sometimes an installation can have more than two airlock doors in series. These doors are capable of withstanding high pressure differentials and are used to allow machine access to the fan site and to minimize recirculation. The booster fan system is equipped with condition monitors and environmental monitors located upstream and downstream of the booster fan and in the motor chamber. The factors that are monitored include differential pressure, air flow rate, smoke sensors, and CH_4 and CO concentrations. From a safety point of view, the system is equipped with an independent power supply routed from the surface through a borehole. A site specific operating procedure is used to start and stop the fans and to avoid the onset of unwanted flow recirculation. The fact of that the surface fan capacities are larger than those of the booster fans reduces the possibility of flow recirculation.

5.1.1.2 Sample Installation II

Figure 5.2 shows a schematic of a booster fan installation in a British underground coal mine with significant flow requirements. In this mine, the workings are located at about 1000 m below the surface, where the rock temperature may be as high as 42ºC. In addition, the mine uses a substantial amount of water to control dust and to cool the mining machinery. The booster fan system consists of a single 1500-kW axial fan installed in the main return airway, near the neutral point. The motor, also located in the return airway, is protected by a fireproof enclosure. The fan is equipped with a set of heavy duty airlock doors to reduce flow recirculation and a system that monitors the operating condition of the fan. Because of high pressure differentials across the stoppings, four heavy duty airlock doors are used to isolate the fan from the intake entries. The factors that are monitored include differential pressure, flow rate, motor and bearing temperatures, vibration, and CH_4 and CO concentrations. The fan system is designed to deliver 160 m^3s^{-1} at 7.0 kPa pressure with the surface fans delivering 280 m^3s^{-1} at 5.5 kPa. A site specific safe operating procedure is used to start and stop the fans and the mining machinery near the fan. Although series ventilation is discouraged because of the high pressure differentials across the stoppings, some recirculation (< 10%) is allowed (Leeming 2012). In this mine, booster fans are viewed as an essential component of the ventilation system. Other alternatives such as sinking a new shaft and upgrading the main fans have been considered, but all were rejected because they were not as effective or economic as the booster fans in providing adequate air volume to the workings.

A comparative analysis of use of booster fans in UK and Australian coal mines is presented in Table 5.1.

5.2 Design and Installation Principles

Booster fan installation may require development of a bypass drift, widening of an existing drift, installation of stoppings, and miscellaneous civil constructions. The drifts should be widened as recommended by the fan manufacturer. They should provide ample space to house the fan assembly, an overhead monorail, man doors, and fan condition monitoring components. In coal mines, booster fans are generally located in the return way in the straight section of a drift or a bypass drift and are equipped with airlock doors and stoppings. When multiple fans in parallel are used, each fan must be equipped with self-closing doors. Bulkheads and doors should be designed to reduce leakage and to withstand high pressure differences.

The concept of bypass drift can also be utilized to control the problem of spontaneous combustion near the fan. Figure 5.3 shows an installation of a booster fan in a bypass drift developed in the overlying strata. This is generally made up of sandstone or shale, which minimizes the chances of spontaneous combustion, increases the stability, and provides a route for the machinery to move across the fan if there is a problem.

Another simpler but less effective method to deal with the problem of spontaneous combustion near the fan installation is to grout the roof, walls, and floor around the installation (Figure 5.4). This is generally done for 30 m upstream and downstream of the fan. It helps in controlling the spontaneous combustion up to a certain level. It should also be noted that the fan motor should be enclosed in a flameproof enclosure. If something goes wrong with the motor such as sparks or fire, it should be contained within the enclosure. This is mostly required when axial fans are used.

Another important aspect of booster fan installation is the selection of the right type of fan, preferably custom made. The type of installation is dependent on the type of fan. Generally, axial fans operate at lower pressures and deliver higher quantities of air, whereas the centrifugal fans operate at higher pressures and deliver lower quantity. Booster fans are used underground to overcome the high resistance of the mine by assisting the main fan in delivering the required quantity of fresh air at the working areas. It is therefore recommended to use centrifugal fans as booster fans. Another reason why centrifugal fans should be preferred over axial fans is that the motor does not need to be in-line with the fan as in the case of axial fans. In centrifugal fan installations, the motor is placed in a chamber next to the fan; this chamber is ventilated by fresh air at all times. The fresh air ventilates the chamber through ~30-cm steel ducts connected to the intake airway (Figure 5.1). This reduces the chances of fire or other major problems in the underground (Benson 2002). As booster fans are installed in return airways, centrifugal fans are the better option. If axial fans are used, the motor and all electrical components need to be enclosed in a flameproof housing. Flameproof is a theoretical term since from a practical point of view, nothing is flameproof. It can withstand the pressure up to a certain level. Even after flameproof enclosure, an explosion or fire could take place near the fan installation.

A few more recommendations are also made related to installation of booster fans underground. Most mine pillars are square or rectangular in shape, which leads to higher shock losses near booster fans in return airways. In general, booster fans are permanently installed in one or two return airways, and the air from other entries is directed to them. It is, therefore, recommended to have special designs such as trapezoidal shaped pillars with a 45-degree crosscut angle to minimize the shock loss (Figure 5.5). It will also be worthwhile to have longer pillars and wider drifts where booster fans are to be installed. This will help in streamlining the flow and reducing shock losses but will also lower the air leakage through crosscuts. Most leakage takes place through the 10–12 crosscuts near the fan (Miles 2010). Hence, increasing the pillar size would lower the amount of air leakage and uncontrolled recirculation.

5.3 Basic Monitoring Requirements in Coal Mines

Monitoring is the process of measuring environmental and fan operating factors to evaluate and predict the health and safety conditions in the mine. When booster fans are used in coal mines, a mine monitoring system is a basic requirement, not only to determine the operating status of booster fans but also to ensure that it is being used safely and efficiently. Monitoring systems have been used in the mining industry for almost 4 decades. The use of these units in U.S. coal mines began in 1976 when, for the first time, belt entry was used to ventilate the face with fresh air. This section is subdivided into two major subparts: condition monitoring and environmental monitoring.

5.3.1 Condition Monitoring

A well-maintained and low-cost mining operation requires the use of condition monitoring techniques. Condition monitoring is the process of measuring fan operating factors to evaluate and predict the health and safety conditions of the mine fans. An adequate and reliable condition monitoring system is quintessential for a mine using a booster fan ventilation system. This includes the measurement and evaluation of the following variables at booster fans: vibration, noise, power, bearing temperature, differential pressure, and quantity. They are used to diagnose the health of the fan. These parameters are briefly discussed in this section and are discussed in greater detail in Chapter 4.

5.3.1.1 Vibration

Vibration analysis is a powerful tool to assess the performance of main and booster fans. Variations in normal operating conditions of mine fans produce significant changes in vibration levels and causes wear or deterioration of the fan. After reviewing the current literature on vibration monitoring, it is recommended to have at least six vibration monitors (velocity type): two for the fan fixed bearing, one for fan floating bearing, two for the motor non drive end, and one for the motor drive end. The application of this type of monitoring is somewhat limited in predicting potential failures. Acceleration-type vibration monitors are recommended for this purpose (Jorgenson 1999).

5.3.1.2 Bearing Temperature

Bearings are the most critical components of main fans. Bearing temperature is one of the most reliable indicators of the status of the fan. Bearings are important parts of the fan assembly because they must withstand the loads due to the dead weight, thrust, and unbalance of the rotor assembly. They must also be able to operate at the intended speed without overheating. Each 10°C increase in operating temperature shortens the motor life by 50%. High bearing temperatures indicate problems related to fluid-film, including overload bearing fatigue, and insufficient lubrication. Under normal conditions, the bearings should be maintained at temperatures of less than 85°C (Snaith 1998).

5.3.1.3 Air Pressure and Quantity

Booster fans are one of the most important entities of a mine; therefore, it is essential to continuously monitor their duties, that is, fan pressure and flow rate.

Commonly, fan pressures are measured by means of manometers and the flow rates by measuring the air velocity and the cross-sectional area of the airway. Fan static pressures are monitored by means of differential pressure transducers that are easily interfaced with a mine-wide monitoring system. The differential pressure is monitored across the bulkhead and airlock doors. Air velocities are monitored by means of a Pitot tube and manometer, ultrasonic anemometer, or a vortex shedding anemometer. The pros and cons of the application of these instruments were discussed in greater detail in Chapter 4. The main problem here is the location of the monitor in the airway to record an average velocity. Commonly, velocity transducers are located near the roof, thus collecting point velocities. Then these are corrected (calibrated) using hand-held instruments. Other types of sensors are seldom used in coal mines. Another important aspect of measuring the air flow near the underground booster fan is the location of the monitor relative to the fan. It is recommended to place the monitor at a distance equivalent to 2–4 diameters on the intake side and 6–10 diameters distance on the exhaust side of the fan as shown in Figure 5.6. Results are expressed as flow rate.

5.3.1.4 Booster Fan Noise

Noise is sound that is unwanted or disturbing. The sound emitted by a fan is an inevitable by-product of the energy-transfer process. Because most fan sound is unwanted, it is classified as noise. Fan noise increases with both flow rate and specific output. However, selecting the fan operating point properly so that the fan operates at its quieter points of rating will minimize noise. Noise is an important factor and is discussed in detail in the Code of Federal Regulations (CFR). It is recommended to continuously monitor noise near the booster fans. The noise pattern along with vibration patterns is a good sign to know if there is something wrong with the fan.

5.3.2 Environmental Monitoring

Monitoring of environmental parameters near the booster fans in underground is critical to the health and safety of the miners particularly in a large mine. The multitude of interacting parameters that can favorably or adversely affect the environmental status makes the manpower requirement of the routine checking of specific areas and conditions a formidable one. Mining operations around the world, especially in large deep coal mines using booster fans, rely upon monitoring systems to provide miner safety by monitoring CO, CH_4, smoke, and several other parameters. From the inspection in Australian and British coal mines, as discussed in sample installations, a number of principles were learnt for optimal design of monitoring system. The location of monitors and monitor parameters is explained with the help of Figure 5.1 and 5.2. More details on the type of monitors and their pros and cons are discussed in Chapter 4 and Appendix A.

5.3.2.1 Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless, and tasteless gas that is slightly less dense than air. The high toxicity of CO coupled with its lack of smell, taste, or color make this one of the most dangerous and insidious of mine gases. The high toxicity of CO makes it very important to have a good monitoring system for continuous monitoring. Since CO is one of the first products of combustion, it also acts as a parameter for early detection of fire underground. CO detectors are designed to measure the gas levels over time and sound an alarm before dangerous levels of poisonous gases accumulate in an environment, giving people adequate warning to safely ventilate the area or evacuate. The common sensors that are used for detection of CO are based on catalytic oxidation, electrochemical reaction, and infrared absorption principles. After carefully reviewing all the sensing principles, it is recommended to use the monitors based on the infrared absorption principle near the fan as the primary monitor for CO. The monitor should be placed approximately 4–6 diameter lengths away from the fan on the exhaust side. It is placed after the fan so that if there is a fire in the fan installation, it can be detected early by this monitor. Monitors based on the optical methods are highly sensitive, selective, and stable. Although they are expensive, they have a long lifetime that would call for fewer inspections and troubleshooting. As for a redundant monitor, it is recommended to have a monitor based on electrochemical principles used traditionally in mines. One of the major disadvantages of electrochemical analyzers is that they can become temporarily saturated when exposed to high concentrations of gas. The recovery period may be several minutes. However, as a redundant monitor they are a good choice because they can indicate the concentration of CO if infrared monitors do not work in case of a large fire. They must be calibrated regularly.

5.3.2.2 Smoke

Smoke is an aerosol that is formed by incomplete combustion and ordinarily consists of particles 0.01–1.0 micrometers in size. Smoke particles are usually visible and distinguished from fumes by the fact that they do not result from the condensation processes. Using smoke sensors for environmental monitoring is mentioned in the CFR. Smoke is one of the products of combustion and acts as a good indicator of a fire underground.

Smoke sensors can be more sensitive to the early detection of mine fires than the CO sensors currently used in most AMS systems (Edwards 2003). Smoke sensors can be classified into two types based upon their operational principle: ionization and optical. Ionization sensors are more sensitive to the smaller smoke particles associated with flaming combustion, whereas optical sensors are more sensitive to larger smoke particles associated with smoldering combustion. The advantages of smoke sensors over CO sensors for early warning is partly due to the origins/mode of the conveyor belt heating/fire and the materials involved (e.g., producing significant smoke but little CO). It is obvious that multiple sensor types, used in combination, could provide earlier and more reliable detection. Multiple sensors (CO and Smoke) should be used near the booster fan. In the case of a conveyor fire, the smoke sensor should go off before the CO sensor, which is a good indication that there may be conveyor fire and not fire in the fan installation.

5.3.2.3 Methane

Methane is one of the most common strata gases. It is produced by bacterial and chemical action on organic material during the formation of coal. Methane is not particularly toxic but it is flammable and can form explosive mixtures with air. This has resulted in the fatalities of many thousands of miners. As shown in Figure 5.1 and 5.2, CH_4 is monitored upstream and downstream of the fan. This enables the AMS operator to know if the fire is in the fan installation or in other parts of the mine. The common sensors that are used in monitoring methane are based on the principles of catalytic oxidation and thermal conductivity. The details of these monitors can be found in Appendix C. When the methane concentration at any methane monitor reaches 1% the monitor shall give a warning signal. As learnt from experience from the mines in the U.K., it is recommended to permit the operation of booster fans up to 1.25% methane. At levels above this the fans must be shut off. At 1.8% methane development should be halted and at 2% methane all personnel should be withdrawn from the mine. According to 30 CFR § 75.342, when the methane concentration at any methane monitor reaches 1.0% the monitor shall give a warning signal. The warning signal device of the methane monitor shall be visible to a person who can de-energize electric equipment or shut down diesel-powered equipment on which the monitor is mounted. This shall be done automatically if the methane concentration at any methane monitor reaches 2.0% or if the monitor is not working properly.

5.4 Number, Location, and Type of Monitors

The key to an efficient and reliable monitoring system is selecting the right type and number of monitors and placing them at optimum locations. There is no absolute rule for the type or number of monitors for booster fan installations; it depends on the specific installation and conditions of the mine. Some recommendations are made in section 4.6.2 for optimum placement and spacing of monitors. Monitoring of fan and environmental parameters near a booster fan installation underground is critical for the health and safety of the miners.

For condition monitoring, the parameters that need to be monitored are vibration, noise, differential pressure, airflow, electrical power, and motor and bearing temperatures. For monitoring vibration, six vibration monitors are required (velocity type); two for the fan fixed bearing, one for fan floating bearing, two for the motor non drive end, and one for the motor drive end. This recommendation is valid for both axial and centrifugal fans. Noise should be monitored near the fan at all times; fluctuations in noise are a good indication of a malfunction in the fan. Also, proper hearing protectors should be used if somebody had to go near the fan as booster fans create a lot of noise. Dosimeters are used for monitoring noise. The differential pressure is measured across the bulkhead, nearest airlock doors, and across the intake and return airway at the nearest stopping. Airflow is probably the most important parameter that needs to be monitored continuously underground. It is recommended to place the monitor at a distance of 6–10 drift diameter lengths away on the exhaust side of the fan or 2–4 diameter lengths away on the intake side (Daly 1992). The airflow readings on the intake side of the fan are more reliable because the flow is less turbulent compared to that on the exhaust side of the fan. Electrical power is another important parameter that needs to be monitored really well. Booster fans have an independent power supply separate from the other equipment in the mine. Monitoring power gives a good indication of the efficiency of the fan. Motor and bearing temperatures should be monitored continuously; they are a good indicator of any malfunction in the fan installation. Booster fan installation should have four temperature probes on the bearings; two on motor and two on fan along with amperage monitoring of the motor.

For environmental monitoring, the parameters that need to be monitored are carbon monoxide, smoke, and methane. Redundancy is also very important for a reliable environmental monitoring system. Since monitors are placed in harsh environments with lots of heat, humidity, and dust, a number of things can go wrong in a monitor. Therefore, it is essential to have redundant units especially near the booster fan installation. It helps the AMS operator and mine management in making decisions with a greater confidence level, in case of an emergency. The monitoring sensors are limited by the sensing technology used to detect the parameters of interest. Most commercially available gas sensors have response times averaging between 10 and 30 seconds. Catalytic gas sensors used for monitoring CO and CH_4 range from 10 to 15 seconds, and IR sensors used for monitoring CO and CO_2 range from 15 to 30 seconds (Griffin 2012). In addition to these sensing timings, additional time is required for transmitting the data to the surface and processing it, followed by making a logical decision. These times may not be adequate to de-energize booster fan and equipment downstream in rapidly changing atmospheres and may allow for movement of equipment well into an explosive atmosphere. For monitoring carbon monoxide, it is recommended to use monitors based on the infrared absorption principle near the fan as the primary monitor for CO. The monitor should be placed approximately 4–6 diameters away from the fan on the exhaust side. It is placed after the fan so that if there is a fire in the fan installation, it can be detected early by this monitor. Monitors based on the optical methods are highly sensitive, selective, and stable. As for redundant monitors, it is recommended to have a monitor based on electrochemical principles used traditionally in mines. As a redundant monitor they are a good choice because they can indicate the concentration of CO if infrared monitors do not work in case of a large fire. In addition to CO, smoke sensors should also be used near the fan installation. They can be more sensitive to the early detection of mine fires than the CO sensors. The advantages of smoke sensors over CO sensors for early warning is partly due to the origins/mode of the conveyor belt heating/fire and the materials involved, e.g., producing significant smoke but little CO. For methane, it is recommended to have monitors based catalytic oxidation principle as primary monitor because they are heavy duty and can accurately measure concentrations within the 0–5% range. As a second monitor, monitors based on thermal conductivity should be used since they are good for a range from 5–100%. This sort of arrangement both before and after the fan not only gives the indication of the fire but also provides information on the scale of the fire or explosion in greater detail. As far as lateral and vertical spacing is concerned, all the monitors should be placed in the center of the drift and at a distance of 1 to 2 ft from the roof.

All these monitors should be connected to the surface control room where all the levels are computer monitored. Preset alarm conditions should be listed on screens with an alert for the operator and visually displayed on schematics.

5.5 Fan Interlocking System

Interlocking is a method of preventing the occurrence of any unsafe condition, which in a general sense can include any electrical, electronic, or mechanical problem in the mine ventilation system. The simplest example of fan interlocking is that if the main fan shuts off due to power failure or any other problem, the booster fan and all the mining equipment should automatically switch off to prevent any kind of uncontrolled recirculation in the mine. Most mines use electrical interlocking with the AMS so that if high concentrations of gas are detected, electrical equipment downstream is de-energized and the booster fans are disabled to allow flow through ventilation and prevent the recirculation of contaminants (Burton et al. 1986). Main and booster fans are operated as long as the workers are in an underground mine. The monitoring system measures all the relevant parameters including the concentrations of air contaminants. The booster fan is equipped with an interlocking device to cut off the power to the fan in the event of main fan failure. If a booster fan fails for any reason, the equipment nearby must be de-energized and the airlock doors must open automatically. This action is performed to prevent the build-up of air contaminants. If the main fan fails for any reason, the booster fan and all underground equipment must be de-energized. Under this condition, the whole system is down and an alarm must be generated. That alarm may be generated automatically or by a management procedure. Alternatively, a redundant main fan is used as in the U.K. Workers must be trained to understand that, in the instance of such an alarm, the mine's emergency evacuation procedure is initiated. A fan start-stop protocol is to be established to restore power after any power stoppage, including those scheduled for changing the fan duties.

In order to come up with proper recommendations for fan interlocking, practices in the U.K. and Australia were reviewed. In Australia, booster fans are used in two coal mining states: New South Wales (NSW) and Queensland (QLD). In both the states, fan interlocking is part of the regulations. The underground mines in Australia are shallower (~500 m) compared to mines in the U.K. Therefore, it is not difficult to have a fan interlocking in place. It is a common practice in Australia to have ventilation boreholes. These boreholes are also used for providing an independent power line for the booster fan. Most Australian mines have centrifugal fans over axial fans, mainly because of their high pressure requirements. Recirculation is not permitted in the Australian mines; therefore, to prevent any uncontrolled recirculation or gas build up, fan interlocking is used. The airlock doors are opened if the booster fan turns off due to any problem. In case the main fan shuts off, the booster fans are switched off automatically (Coal Mine Health and Safety Regulation 2006).

In the United Kingdom, electrical interlocking between the main and booster fan is not required (The Coal and Other Mines (Ventilation) Order 1956). The coal mines in the U.K. are very deep (In the order of 800–1000 m). Therefore, it is difficult to have an interlocking system. Booster fans are accepted as a necessary tool for adequate mine ventilation. In several mines in the U.K., booster fans are recognized as the only feasible option for providing adequate air velocity and quantity to the active work areas. In order to prevent any uncontrolled recirculation or gas build up in the underground because of failure of the main surface fan, mines in the U.K. have a redundant surface fan. The two fans have different power supplies so that if the primary fan fails, the redundant back up fan can be switched on. The redundant fan may not have the same capacity and may or may not provide the equal amount of air as provided by the primary surface fan, but it still serves the purpose of buying time for miners to take shelter in a rescue chamber and move mine equipment to a safe place if possible. Meanwhile, the problem in the primary fan can be resolved. The booster fan cannot be controlled from the surface directly; it has to be manually switched off or on by a competent person in the underground. When the booster fan is switched off, the airlock doors are opened. Booster fans can be installed in a ventilation system without any special application to the Mine Inspectorate, but a person must monitor them every half hour. In order to extend the fan inspection time to 8 hours, the mine must use a robust environmental and fan monitoring system and apply to the Inspectorate for an exemption.

The recommended design of the fan interlocking system can be seen in Figure 5.7. Different equipment, fans, airlock doors, and AMS are connected to a central electric interlocking system. This system not only provides an interlock between the main fan and booster fan, but also includes other mine equipment, airlock doors, and AMS. Firstly, on the surface, it is recommended to have two main fans. The two fans may or may not be of the same capacity. These fans should have independent power supplies from each other. One is used as a primary and the other is always used as a redundant fan. As shown in the figure, if the primary fan fails due to some reason, it sends a signal to the electric interlocking system that in turn sends a signal to the redundant fan and switches it on. The redundant fan may or may not provide the same quantity of air as delivered by the primary fan. Secondly, the booster fan can both send and receive a signal from the electric interlocking system. If the primary fan fails, the booster fan should be turned off immediately, and the airlock doors should be opened automatically to prevent any kind of uncontrolled recirculation or gas build-up. When the redundant fan is switched on, the booster fan may or may not be used depending on the ventilation conditions and fan duty of the redundant fan. Thirdly, the electric interlocking system is also connected to the AMS so that if high concentrations of gases are detected, the booster fans can be turned off accordingly to prevent any disaster from happening. In all the cases, the mining equipment and machinery nearby (longwall, continuous miners, shuttle cars, etc.) shall be de-energized automatically. This pattern of electric interlocking can prevent most of the problems in the mines related to the use of booster fans in underground.

5.6 Uninterruptible Power Supply

An uninterruptible power supply, UPS, is an electrical apparatus in a mine that provides emergency power to mine fans and other electrical equipment when the input power source, typically main power, fails. A UPS differs from an auxiliary or emergency power system or standby generator in a way that it will provide near-instantaneous protection from input power interruptions by supplying energy stored in batteries or a flywheel. The on-battery runtime of most uninterruptible power sources is relatively short (only a few minutes) but sufficient to start a standby power source or properly shut down the protected equipment. A UPS is typically used to protect hardware such as monitoring systems, data centers, communication equipment, mine fans, or other important electrical equipment in the mine where an unexpected power disruption could cause injuries, fatalities, serious business disruption, or data loss.

The primary role of any UPS is to provide short-term power when the main power source fails. However, most UPS units are also capable in varying degrees of correcting common utility power problems like voltage spikes or sustained overvoltage, momentary or sustained reduction in input voltage, noise, defined as a high frequency transient or oscillation, usually injected into the line by nearby equipment, instability of the mains frequency, etc. It is very important to have UPS as an integral part of the booster fan ventilation system because power failure can lead to disastrous conditions such as uncontrolled recirculation or gas build up along with monitoring systems down for a few minutes.

5.7 Risk Assessment of Monitoring Systems

Risk assessment is the process by which the outcomes of risk analysis are compared against the risk acceptance criteria established for this purpose and understood by all parties. If requirements are not met, changes to the system should be made and the process is repeated until the requirements are met. Risk assessment has many powerful tools that can identify hazards associated with the operation and maintenance of booster fans and the AMS in the mine. It analyzes the accompanying risks and recommends control measures to reduce those risks to acceptable levels. The hazards associated with the operation of monitoring systems were identified, the risks analyzed, and the response to each failure mode was established.

Although mine monitoring systems are assembled and installed to operate under harsh conditions, they are subject to wear and tear and malfunction. The system components should be maintained regularly, and the sensors must be calibrated against primary standards. Furthermore, the system must be equipped with redundant units. If the system provides erroneous readings, fan conditions cannot be predicted and the failure modes cannot be avoided. Gas sensors, pressure transducers and other devices used with a monitoring system are subject to wear and malfunction. Using faulty units can result in unsafe and unhealthy conditions. To overcome the problem, transducers should be calibrated frequently. Redundant units and uninterruptable power supplies should be provided for critical monitors. The same is true for condition monitoring parameters such as motor and bearing temperatures. The fan motor and bearings may fail under high load beyond their rated power. The motor and bearing temperatures are key indicators of the fan health. When the fan is installed properly, with the right alignment, these temperatures should never exceed the alarm level, which is typically 85ºC. However, these temperatures may vary with weather conditions.

5.7.1 Risk Matrix

The risk matrix is an evaluation tool used to rank the risk of a potential hazard in terms of the likelihood (L) and consequence (C) of the undesired events. It increases the visibility of the risk and assists the management in making timely, informed decisions (Chapanis 1986; Grayson 2001). Table 5.2 shows the risk matrix used in this study.

Work Place Risk Assessment and Control (WRAC) is a qualitative risk ranking method (as shown in Table 5.3). It breaks down the work into steps in a process map and evaluates each unwanted event using a risk matrix. A WRAC analysis was performed for the installation and use of booster fans and its monitoring system (Calizaya 2014).

5.7.2 Bow-Tie Analysis for Booster Fan Ventilation Systems

Risk assessment of the booster fan ventilation systems was conducted using bow-tie analysis. The analysis was conducted as a part of a process designed to ensure that the hazards relating to booster fan system safety are being managed appropriately in order to render the associated risks to an acceptable level to all workers, management, and stakeholders.

Bow-tie analysis is an extremely powerful tool for assessing and managing the risks associated with operations in mining, machinery use, etc. It is simple to use and can be used for a wide variety of risks. It can be used to assess work-place conditions and workers' behavior. It produces a clear picture of cause-consequence relationships and helps producing risk registries. Unlike traditional risk evaluation tools, the bow-tie method makes the link between risk controls and the health safety and management systems. However, it is difficult to link this analysis to other quantitative techniques.

The analysis began with the scoping process, which basically means assessing the risks associated with booster fan ventilation systems. The objectives, scope, and breadth of the risk assessment were defined in this step. Identifying the different threats to the system and consequences associated with them that would lead to malfunction of the booster fan ventilation systems followed this.

The threats related to the operation of the booster fans were identified with the aim of establishing appropriate control measures and in turn booster fan operation protocol. The different threats identified are loss of mine power, failure of the main fan, failure of the booster fan, failure of airlock doors, failure of monitoring system, and spontaneous combustion. The control measures to each of the threats identified were developed through a process defining operating conditions existing prior to the threat and the safe operating conditions subsequent to the threat. The control measures are summarized for each of the threats respectively (as shown in Figure 5.8).

The consequences are identified based on previous experiences and experience of other mines utilizing the booster fans ventilation systems. Recovery measures corresponding to every consequence can be seen in the bow-tie analysis chart (Figure 5.8). The major consequences are build-up of air contaminants, uncontrolled recirculation, fire in fan housing, reduction of total quantity of air delivered, and unavailability of monitoring data. Some of the control and recovery measures to deal with the threats are removing power from booster fans, opening by-pass doors, de-energizing equipment, redirecting air, adjusting regulators, etc.

Under current regulations, booster fan research in the U.S. is challenging due to nonexistent options for field studies. Computer simulations, laboratory studies, and comparison to metal and nonmetal mines are the only available tools for research. Research, experiences, and regulations of other countries present important comparisons for the potential use of boosters in the US. The use of booster fans can facilitate continued operation of a mine that is being considered for closure. Booster fans when installed with proper bulkheads, an efficient and reliable monitoring system, and sizing and position work normally just like any other fan in a mine.

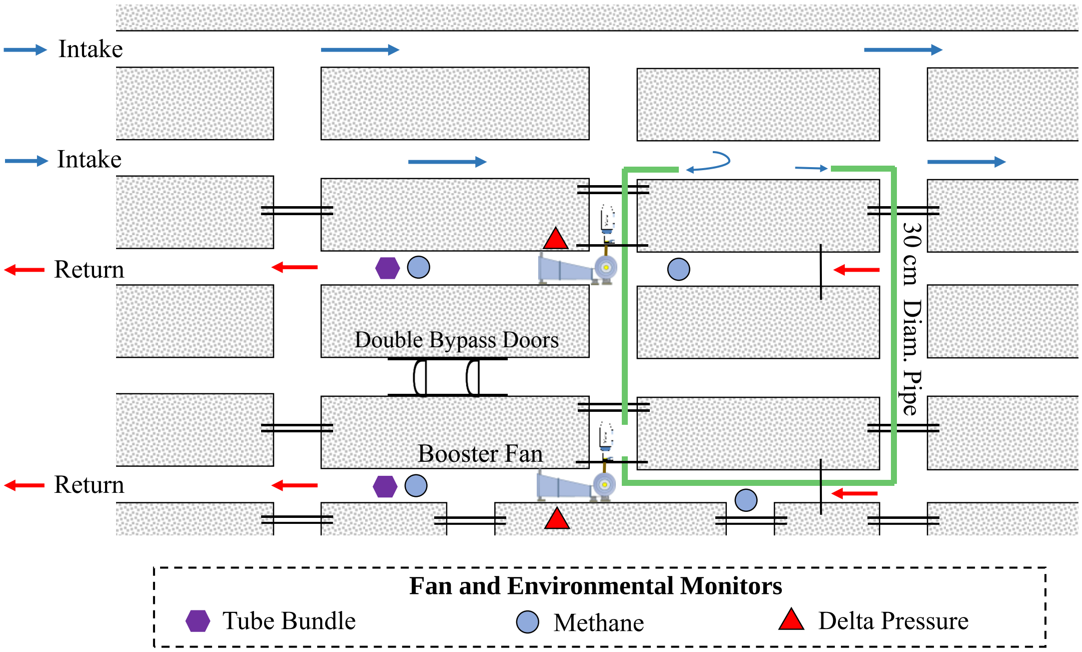


Figure 5.1: Installation of booster fans in Australian coal mines

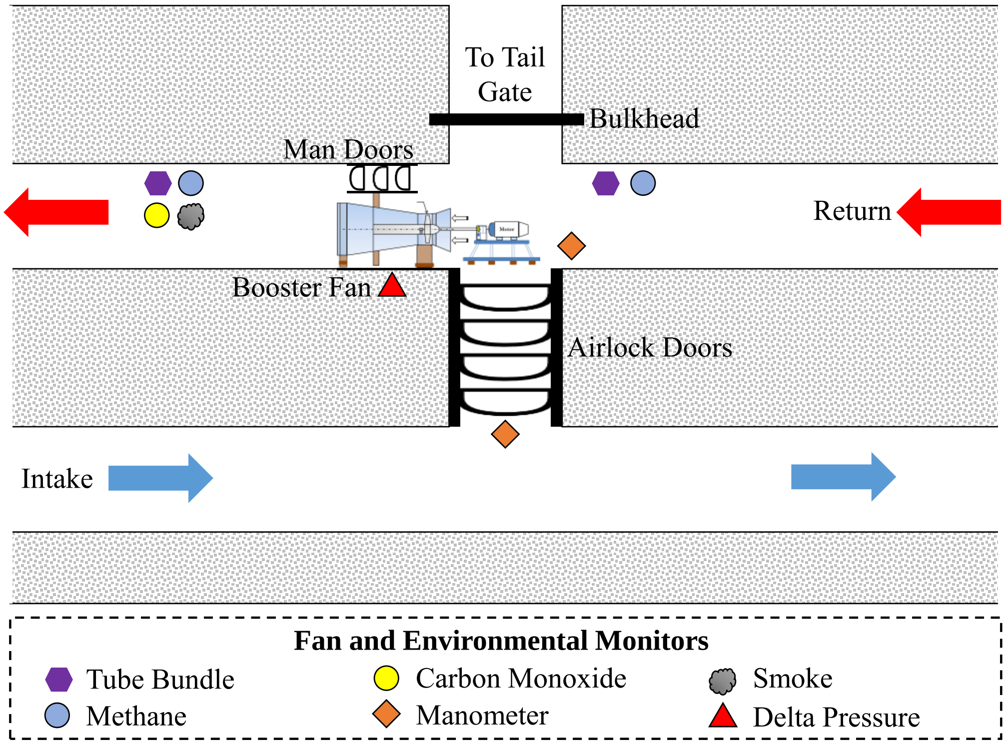


Figure 5.2: Installation of booster fan in U.K. coal mines

Table 5.1: Use of booster fan in U.K. and Australian coal mines—comparative analysis

Description	Australia	United Kingdom
1. Regulations	Coal mine operators are allowed to use booster fans to assist main fans in Australian mines	Booster fans are accepted as safe and effective ventilation control devices in underground coal mines
2. Reasons for using booster fans	Because of mine depths (± 500 m), remoteness of workings, and economic reasons	Because of mine depths (> 800 m) and increased resistance, to decrease effective mine resistance, and economic reasons
3. Basic Requirements	• Fan installation plan approved by Mine Inspectorate • Installed in concrete bulkhead • Multiple airlock doors • Set of fan controls and monitors • Safe operating procedure (SOP) for each fan • Maintenance every four months	• Need demonstrated through studies to mine inspector and results included in the ventilation plan • Installed in concrete bulkhead and equipped with airlock doors • Fan condition and environmental monitoring system • Fan examination every 30 min*

Table 5.1 continued

4. Number and type of booster fans	Single or double inlet centrifugal fans	Centrifugal and axial fans; if multiple axial fans used, each must be equipped with antireversal doors at discharge
5. Fan and motor locations	Booster fan in return airway motor in a chamber ventilated with fresh air taken from an intake drift	Booster fan and motor both located in return way. Motor enclosed in fireproof housing
6. Recirculation	Return air from one production district cannot be used in another production district	Recirculation and series ventilation not prohibited; heavy duty airlock doors provided to reduce recirculation.
7. Fire Prevention	Possibility of fire is major design parameter; booster fans are equipped with CO sensors and alarms activated when TLVs are exceed.	Fan site (20 m upstream and 30 m down-stream) maintained free from risk of fire; area equipped with CO and smoke sensors and fire suppression systems
8. Electrical Interlocking	Electrical interlocking between main and booster fans required	Electrical interlocking between main and booster fans not required

Table 5.1 continued

9. Risk Analysis	Each mine must develop and implement appropriate H&S management system, to ensure that risks are assessed and controls are in place at all times	No fan (not being an auxiliary fan) shall be installed at any place below ground unless the manager is satisfied that it is necessary to install it at that place for proper ventilation of the mine

*: Mine inspector has the power of exemption for all aspects of mining law.

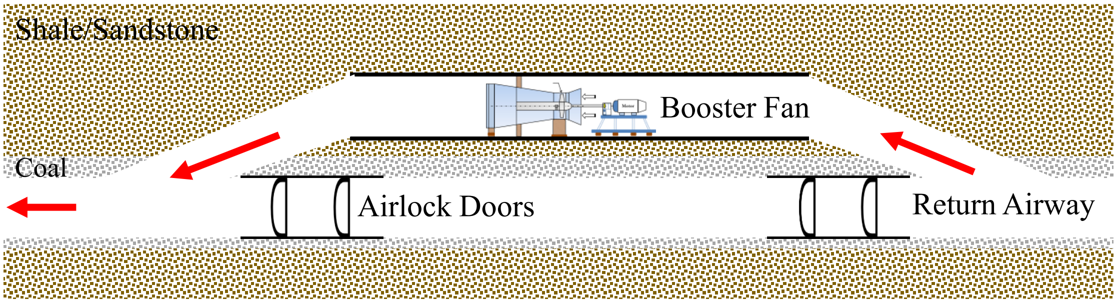


Figure 5.3: Booster fan installation in the roof (section view)

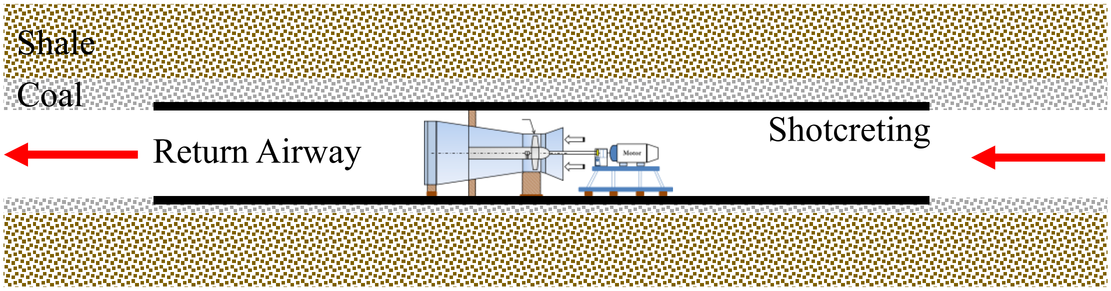


Figure 5.4: Shotcreting near the booster fan installation

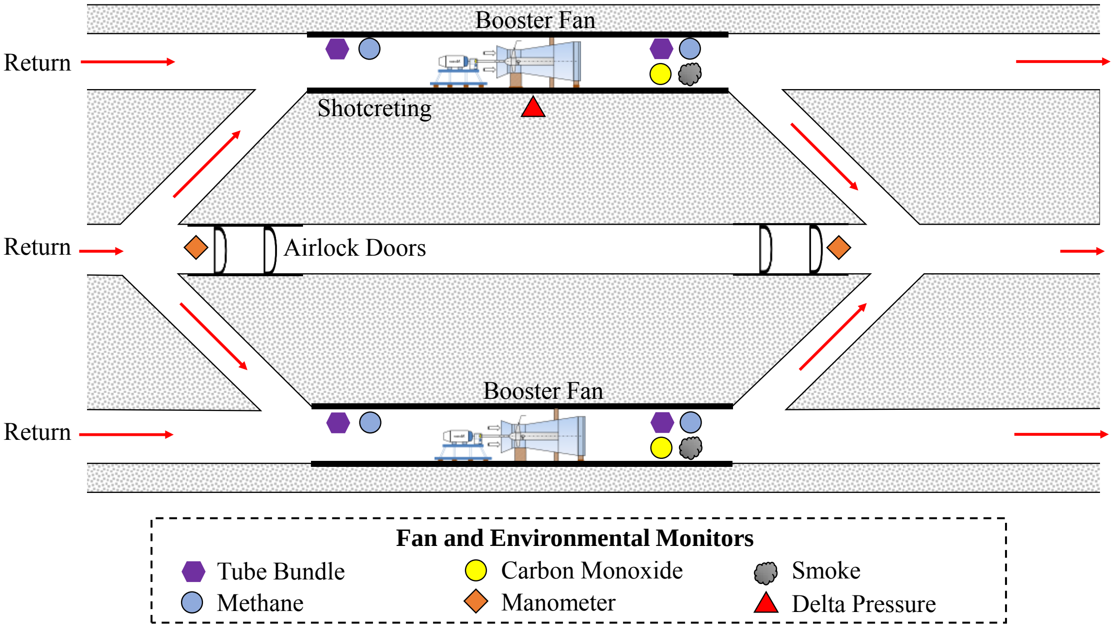


Figure 5.5: Conceptual design of booster fan installation and monitoring system

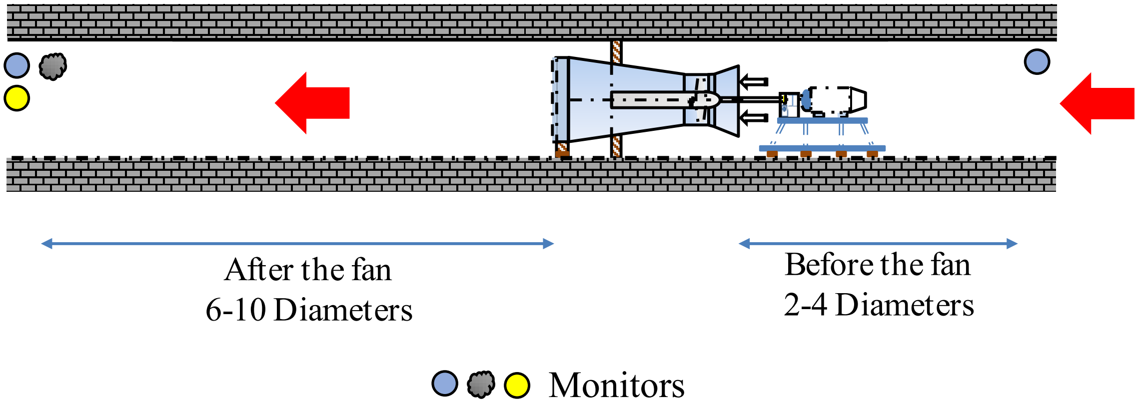


Figure 5.6: Location of monitor for air flow measurement

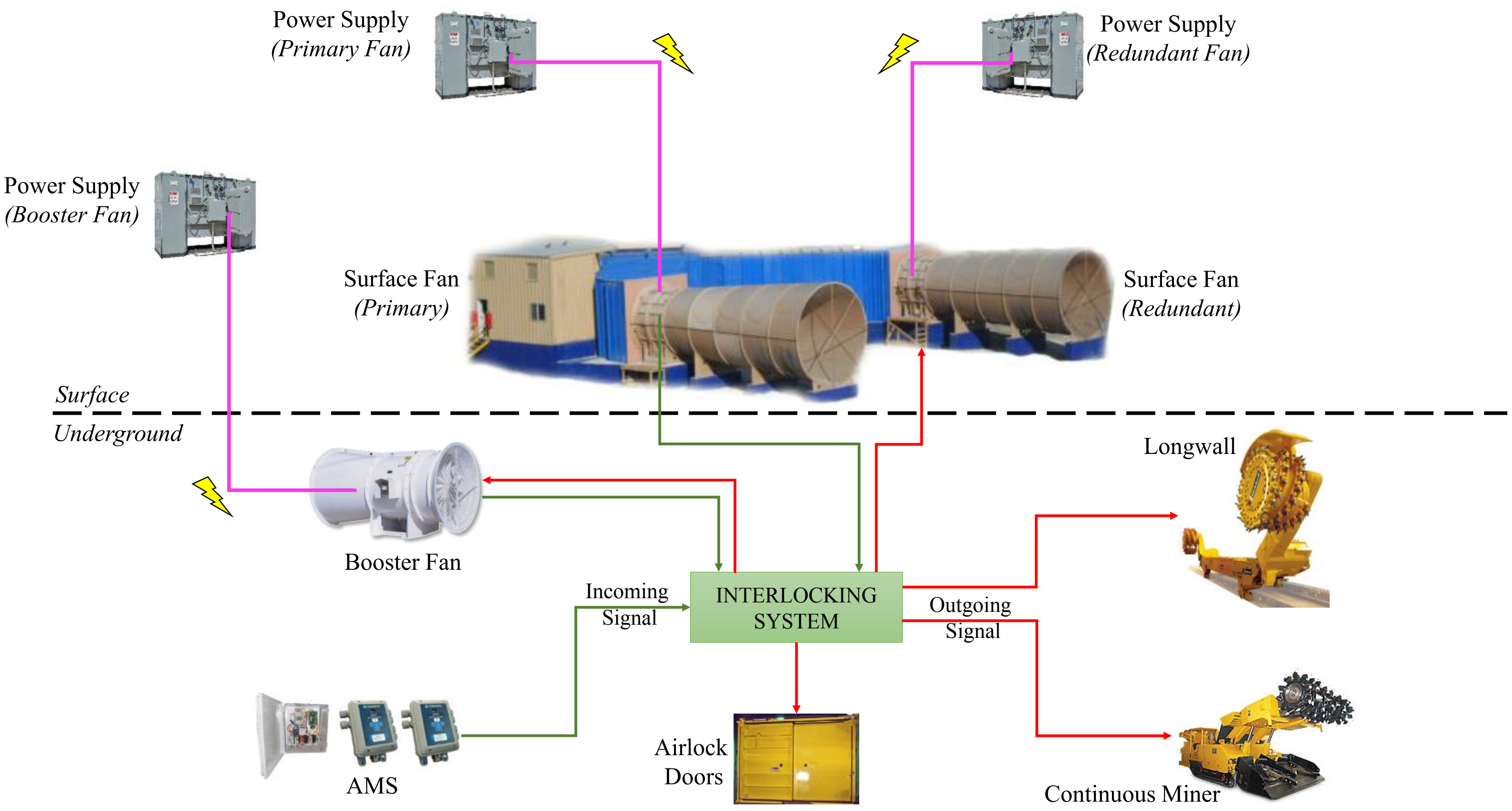


Figure 5.7 Schematic of interlocking system

Table 5.2: Risk matrix

Severity	Insignificant (1)	Minor (2)	Moderate (3)	Major (4)	Catastrophic (5)
Likelihood	**Risk Rating**				
Most Certain (5)	**5**	**10**	**15**	**20**	**25**
Likely (4)	**4**	**8**	**12**	**16**	**20**
Poosible (3)	**3**	**6**	**9**	**12**	**15**
Unlikely (2)	**2**	**4**	**6**	**8**	**10**
Rare (1)	**1**	**2**	**3**	**4**	**5**
Risk Rating	**Guidelines for Risk Matrix**				
15 to 25	Eliminate or Avoid and Implement Action Plan				
9 to 12	Proactive Manage				
4 to 8	Actively Manage				
1 to 3	Monitor & Manage				
Categories of harm severity			**Categories of harm likelihood**		
Catastrophic	Multiple deaths		Most Certain	Occurs once or twice in a year	
Critical	Death or multiple severe injuries		Likely	Occurs less than once in a year	
Moderate	1-3 severe injuries		Possible	Occur or may re-occur in 10 years	
Minor	Severy injury or multiple minor injuries		Unlikely	Can happen in 20 years	
Insignificant	Minor injury		Rare	Has never occurred before	

Table 5.3: WRAC analysis and outcomes

Steps in process	Unwanted Event	Current Controls	L	C	R	Recommendation
Failure to design monitoring system	Undetected fire and recirculation	Use hand held units to monitor CO	3	4	12	Follow the good practices as adopted in other country
Failure to design airlock doors and bulkhead	Airlock doors fails to open, or close	Test airlock doors for stability	2	4	8	Follow the good practice as adopted in other country.
Failure to measure vibration and temperature	Damage to motor and fan parts	Fan monitoring system	2	4	8	Check manually, redundant sensors.
Mechanical or Electrical fault	Failure of electrical interlocks	Fans installed in same circuit	1	5	5	Independent power sources for main and booster fans
	Failure of monitoring system	Check air quality manually	2	4	8	Install redundant monitoring
	Failure of motor	Regular maintenance	2	4	8	Keep spare motor and fan parts

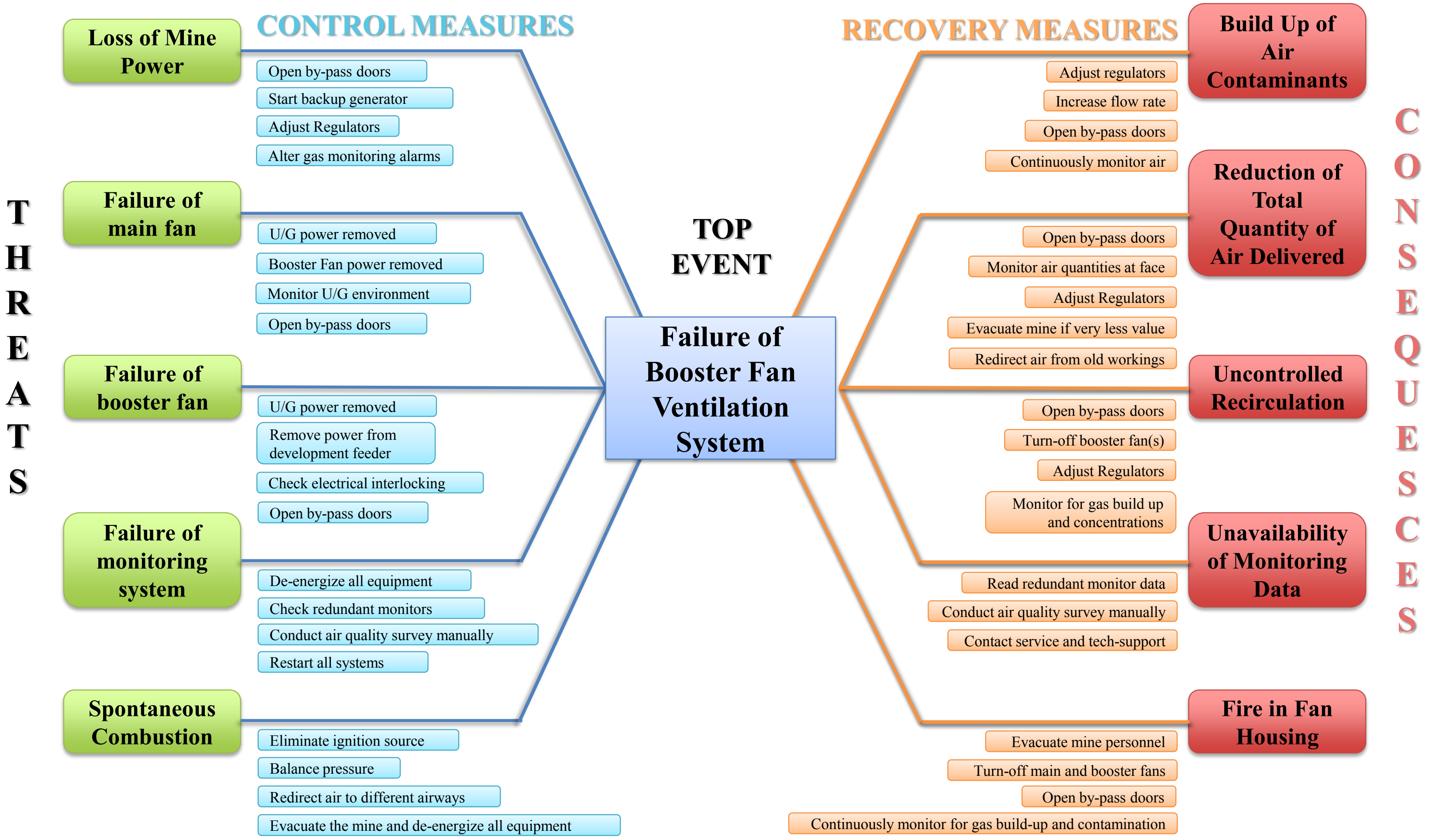


Figure 5.8: Bow-tie analysis chart

CHAPTER 6

CONCLUSIONS AND DISCUSSIONS

6.1 Conclusions

As underground mines go deeper and deeper, ventilation conditions may deteriorate in the mine due to the difficulties found in attempting to meet the required airflows. The resistance of active mines increases due to more extensive development, heat and mine gases, and as adequate mine ventilation becomes difficult. In these mines, the volumetric efficiency of the ventilation system is often low, and high pressure main fans with high volumetric flow capacity are necessary to achieve adequate airflow. The use of booster fans is one method of increasing the efficiency of ventilation systems, reducing the required main fan pressure and reducing the total flow rate by reducing leakage. In the United States, booster fans are permitted in metal and nonmetal mining as well as in anthracite coal mines. However, booster fans are not allowed in the U.S. bituminous and lignite coal mining operations at the present time due to safety concerns. Installing booster fans is the only alternative to building more surface connections when the usual ways to increase ventilation, such as adding intake and return entries or installing larger main fans or widening shafts, are considered impractical or uneconomical. A booster fan is typically installed to overcome mine environmental conditions in which the surface fan is physically incapable of meeting the airflow requirements or when these requirements can only be fulfilled at extremely high pressures, which can cause excessive air leakage. The attempts to install booster fans in U.S. coal mines are effectively blocked by MSHA, and proposals by companies like Jim Walter Resources and others have been rejected in the past.

There are several requirements that accompany the use of booster fans in underground mines. A booster fan installation may require the development of a bypass drift or widening of an existing drift. It may also require construction of concrete foundations and installation of an overhead monorail, fan housing, bulkheads, airlock doors, and a prefabricated fixture between the diffuser and the bulkhead. There are several ways of gaining advantage from the use of a booster fan. Even if booster fans are not suitable for every situation, they are capable of providing improvements in various underground environments when properly sized and located. The operating electric power costs for booster fans are relatively low as compared to that of augmenting the main fan pressure, and less energy is lost because of few airlock doors. The overall development costs are much less as compared to installation of large surface fans or sinking a new shaft. If a booster fan is added to the system, the required operating pressure of the surface will be less, which allows the existing installation to remain in place. The airflow distribution in the mine is enhanced, especially in the difficult-to-ventilate areas. However, there are several concerns associated with the use of booster fans in underground mines. Recirculation of air contaminants is the main issue associated with the utilization of booster fans. It occurs when the pressure in the return airway is higher than the pressure in the intake airway, causing the return air to leak from the return to the intake. One of the simplest ways to decrease or eliminate recirculation is by choosing a booster fan that has a lower operating pressure than the main fan. Although this does not ensure elimination of recirculation, it is a good starting point for designing and optimizing the ventilation system. Most coal mines have multiple parallel intake and return entries. Therefore, if a booster fan is used in a return airway all the air should be directed to a single return airway. Another example is that a fire or explosion can make it difficult to control the booster fan in order to adjust ventilation in specific areas of the mine.

Considering that booster fans are active devices with moving parts, it is imperative to install them with an efficient atmospheric monitoring and control system. Monitoring systems are used as a means to measure and evaluate the air quality and quantity in the mine and to develop strategies to control potential fire hazards. The important aspects of monitoring systems involve environmental and condition monitoring. The environmental status of underground mining operations with large booster fans is critical to the health and safety of the miners. Mining operations, especially in large deep coal mines, rely solely upon the monitoring systems to provide for miner safety by monitoring carbon monoxide, methane, carbon dioxide, oxygen, nitrogen oxides, and smoke. In coal mines, condition monitoring includes the measurement and evaluation of the following factors: vibration, barometric pressure, noise, input power, motor and bearing temperatures, differential pressures, and air quantity.

A booster fan is a large fan running on electrical power in the underground. Therefore, it is very important to have an efficient fan electrical interlocking system in place. The simplest example of fan interlocking is that if the main fan shuts off due to a power failure or any other problem, the booster fan and all the mining equipment should automatically switch off to prevent any kind of uncontrolled recirculation in the mine. A good interlocking system not only provides an interlock between the main fan and booster fan, but also includes other mine equipment, airlock doors, and the AMS. If the primary or booster fan fails or if the AMS detects high concentrations of gases, the mining equipment and machinery inby (longwall, continuous miners, shuttle cars, etc.) should be de-energized automatically.

6.2 Discussions

Booster fans, when sized and sited properly, assist the surface fans in balancing pressure drops and reducing airflow leakage, thereby decreasing the total airpower requirement in the mine. They are not intended to replace main surface fans. The restriction on booster fan use reduces flexibility in mine system design and operation. As depths to coal seams increase, or as panels become larger and wider, the difficulty of designing coal mine ventilation systems with fans located only on the surface must surely increase. Without approval of booster fans in underground mines on an experimental basis, data and experience in U.S. coal mines will not be developed. It can be said that deep cover seams may not be mined without using booster fans in ventilation systems. One of the reasons why booster fans are still not used in the U.S. is the fear among the lawmakers and lack of expertise. Booster fans are still not considered as safe devices to use underground. The main problem that is always discussed in the use of booster fans is the possibility of uncontrolled recirculation in an inadequately designed system. However, with good planning and the use of reliable monitoring systems, booster fans can be operated safely and economically. When a monitoring design is used to evaluate and control the operating conditions of booster fans, sufficient redundancy should be built into the system, such that abnormal alarm conditions could be detected and corrective actions undertaken based on reliable data.

The booster fan installation principles and practices vary from country to country. In the U.K., multiple booster fans are used in clusters. Mines have several active booster fan sites with few additional sites generally available. Each booster fan site consists of multiple fans in clusters; all of them may or may not be active simultaneously. Booster fans are mostly of axial type with a few exceptions of centrifugal fans. One of the important parameters that should be taken into account while designing the installation is the spacing between the fans. If the fans are closely placed, there will be a loss of energy and higher turbulence. Incorrect spacing can also lead to uncontrolled local recirculation. These fans also require self-closing doors.

A push-pull system is often considered as an alternative of having a booster fan. A push-pull ventilation system is a combination of both blowing and exhausting systems. It is comprised of a blowing fan at the intake shaft pushing the air in the mine and an exhausting fan at the return shaft pulling the air out of the mine. Whenever there is a question of using a booster fan to assist the main exhaust fan, there is always an argument to use a blowing fan on the surface rather than a booster fan underground. However, there are a number of issues associated with push-pull ventilation systems. One major issue is that it is very hard to balance the ventilation system, which results in neutral zones in the mine. Since coal mines are large in size, the distance between the intake shaft and return shaft can be on the order of 3 to 4 miles. Therefore, the chances of formation of the neutral zones with no airflow are very high. The probability of formation of a neutral zone is highest near the working areas, especially when a U-tube ventilation system is used. The working areas are generally farthest from the two shafts where it is most essential to have good quantity and quality of airflow. Another alternative that is considered is to increase the size of the main surface fans. A surface fan has to provide the air for the workings underground by overcoming the resistance of the mine. As the underground mines goes deeper and deeper, the mine resistance increases considerably. The increase in mine resistance leads to a requirement of high-pressure surface fans that ranges in order of 5500 pa (22 in.w.g.). This is the highest pressure fan that is currently manufactured in the U.S. A practical problem with using high pressure fans is that they have to be custom built. Therefore, the spare parts are hard to procure and maintenance is difficult. The main technical problem with use of high pressure surface fans is that it leads to very high air leakages between intake and return airways. In order to decrease the air leakage, multiple, heavy-duty airlock doors are required. For fan pressures ranging in order of ~5000 pa (~20 in.w.g.), more than two heavy-duty airlock doors are required, which are expensive to build and maintain.

A few recommendations are also made related to installation of booster fans underground. Most mine pillars are square or rectangular in shape, which leads to higher shock losses near booster fans in return airways. In general, booster fans are permanently installed in one of the return airways, and the air from other entries is directed to it. It is, therefore, recommended to have large trapezoidal shaped pillars with 45-degree crosscut angles to minimize the shock loss. It will also be worthwhile to have longer pillars and wider drifts where booster fans are installed. This will help in streamlining the flow and shock losses but will also lower the air leakage through crosscuts. Most leakage takes place through the 10–12 crosscuts near the fan. Hence, increasing the pillar size will lower the amount of air leakage and uncontrolled recirculation.

It should always be kept in mind that no matter how objective, systematic, and comprehensive a monitoring system is, it only provides an early detection of a problem. For example, a fire can be detected early, but the smoke and carbon monoxide from the fire will still contaminate the mine, with or without a monitoring system. The mine operator and miners still have to find the fire, bring it under control, and evacuate everybody who is in the mine. The monitoring system does prevent fires from occurring and does not result in controlling combustible materials or sources of ignition or products of combustion being conveyed to face. In summary, booster fans are very efficient tools that buy us time by early detection to stop a disaster from occurring and save expensive machinery and lives of the miners working underground. In addition to electronic gas monitoring systems, a tube bundle system should also be used to sample mine gases underground.

Finally, an important aspect of having an efficient monitoring system is its maintenance and calibration. Qualified people are needed to operate and maintain the monitoring system. Most mines have difficulty in maintaining their monitoring system the way manufacturers would like to see them maintained. The best monitoring system in the world is useless and will not benefit the miners unless it is properly installed, operated, and maintained.

A booster fan system is a proven technology used in most coal mining countries, including those described in this thesis report, the United Kingdom and Australia. It is used to reduce pressure differentials between intakes and returns, reduce the surface fan pressure, and boost the flow rate in single panels rather than the whole mine. Both types of fans, axial and centrifugal, are used as booster fans in these countries. In the United States, specific guidelines for the safe and effective use of booster fans in underground coal mine ventilation systems need to be defined. It should include methods for identifying and controlling risks associated with booster fans at every stage, such as planning and design, installation and commissioning, and fan operation. Workplace risk assessment and control (WRAC) analysis can be used to identify critical hazards during all the stages of booster fan use. The failure mode effect and criticality analysis (FMECA) can be used to evaluate the effects of potential failure modes of subsystems, assembly components, or functions. The guidelines should also include recommendations for an extensive and robust monitoring system, effective protocols for fan electrical interlocking systems, guidelines for installation and maintenance, and other requirements for practical use of booster fans in underground coal mines in the United States.

APPENDIX A

GAS SENSING METHODS

A.1 Gas Sensing Methods

The primary purpose of environmental monitoring is to ensure that the atmosphere in the mine is free from toxic or flammable airborne pollutants. There are three main points that are essential for designing an environmental monitoring system for a mine: threshold limit value for each pollutant, type of sensor, and the location, spacing, and frequency of these sensors. The operating principles, advantages, and shortcomings of commonly used gas sensors are discussed briefly in this section.

A.2 Filament and Catalytic Oxidation (Pellistor) Detectors

A pellistor is a solid-state device used to detect gases that are either combustible or that have a significant difference in thermal conductivity to that of air. The word "pellistor" is a combination of pellet and resistor. The filament type detector has a thermal conductivity (TC) pellistor that works by measuring the change in heat loss (and hence temperature/resistance) of the detecting element in the presence of the target gas. The catalytic oxidation detector uses a catalytic bead sensor for gas detection that works by burning the target gas, the heat generated producing a change in the resistance of the detecting element of the sensor proportional to the gas concentration. This filament and bead sensor acts as one arm of a Wheatstone bridge circuit; its change in resistance can be sensed as a change in voltage drop or current that is proportional to the concentration of the combustible gas. This principle is primarily used for the measurement of methane and other gases that will burn in air such as carbon monoxide and hydrogen. Pellistor detectors have shown a high degree of reliability; they operate satisfactorily and continuously over a period of time. However, there are still some disadvantages that should be taken in account. First, they rely on the oxidation process and, hence, the availability of oxygen. A good quality, heavy duty, pellistor will indicate increasing concentrations of methane up to 9 or 10%. These sensors are limited to detecting methane concentrations from 0 to 5% (McPherson 2009). Second, pellistors are subject to poisoning by some other gases and vapors. Vaporized products of silicon compounds or phosphate esters will produce permanent poisoning of pellistors, while halogens from refrigerants or heated plastics can give a temporary reduction of the instrument output. Third, pellistor transducers react to any combination of combustible gases that pass through absorbent filter. It may experience interference from organosulfur compounds, alkyl lead derivatives, ethane, hydrogen, and other flammable gases (Eggins 2002).

A.3 Gas Detectors Based on Thermal Conductivity

Thermal conductivity detectors are used in high range methanometers. The principle behind this detector is the difference in thermal conductivity of methane and air at the same temperature. For example, at 20°C and at normal atmospheric pressures, the thermal conductivity of methane is 0.0328 Wm^{-1}°C compared with 0.0257 Wm^{-1}°C for air. Based on this principle, the detector consists of two heated sensors, one exposed to the gas sample and the other retainer as a reference within a sealed, air-filled chamber. A sample of the ambient air is drawn through the instrument at a constant rate. The sample sensor cools at a greater rate due to the higher thermal conductivity of the methane. The change in resistance of the sample sensor is detected within an electrical bridge to give a deflection on the meter. Typical ranges for a thermal conductivity methanometer are 2 or 5% to 100%. To reduce interference from other gases, suitable filters should be employed. For use in mining, a soda lime filter is advisable.

A.4 Gas Chromatograph

Gas chromatographs (GC) are used widely for the laboratory analysis of sampled mixtures of gases. GC is a common method for gas sensing. It is a typical laboratory analytical technique that has excellent separation performance, high sensitivity, and selectivity. An inert carrier gas is pumped continuously through one or more columns that contain gas adsorbents. A small pulse of the sample gas mixture is injected into the line upstream from the columns. The column material that eventually gives very accurate concentrations of different gases present in the air sample initially adsorbs the constituent gases. However, the cost of GC is high, and its miniaturization for portable application needs more technological breakthroughs. Therefore, GC does not quite satisfy the device and material constraints for unattended operation (McPherson 2009).

A.5 Electrochemical Methods

Small concentrations of many gases can be detected by their influence on the output from an electrochemical cell. This method is based upon oxidation or reduction of the gas within a galvanic cell. The cell has at least two electrodes and an intervening electrolyte. The gas sample is supplied to the interface between the electrolyte and one of the electrodes (the "sensing electrode”). The electrochemical reaction at the electrode/electrolyte interface changes the rate at which free electrons are released to flow through the electrolyte and be collected by the "receiving electrode." The resulting change in electrical current is proportional to the concentration of gas in the sample. One of the major disadvantages of electrochemical analyzers is that they can become temporarily saturated when exposed to high concentrations of gas. The recovery period may be several minutes.

APPENDIX B

SUMMARY OF FEDERAL REGULATIONS

B.1 Federal Regulations

Title 30 Code of Federal Regulations discusses the operation of AMS in more than one section. The details can be found in sections § 75.323, 75.340, 75.350, 75.351, and 75.362. The locations of sensors are directed for the belt entries, primary escapeways, and return air splits. Regulations are in a greater detail for the belt entries than for intake or return. The regulations are briefly described in this section.

B.2 Belt Entries

The sensors are installed in accordance with the locations specified in the Ventilation Plan, PFM, and §§ 75.351(e) and 75.1103-4.

For a mine using air from the belt entry to ventilate the section, 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. This mixing point is not considered a pointfeed. For automatic fire sensor and warning device systems that use carbon monoxide sensors to provide identification of fire along belt conveyors, a sensor is required not more than 100 feet downwind of each section loading point. Upwind, a distance no greater than 50 feet from the point where the belt air course is combined with another air course or splits into multiple air courses (as shown in Figure B.1).

For a mine not using air from the belt entry to ventilate the working section, the sensor must be located at intervals not to exceed 1,000 feet along each belt entry. The air velocity must be maintained at 50 fpm or higher. In areas along each belt entry where air velocities are less than 50 feet per minute, the sensor spacing must not exceed

350 feet (as shown in Figure B.2)

For a mine using air from a belt entry to ventilate a working section, the sensor must be located at intervals not to exceed 1,000 feet along each belt entry. The air velocities must be maintained at 100 fpm or higher. For air velocity between 50 and 100 fpm, sensor spacing must not exceed 500 feet. In areas along each belt entry where air velocities are approved to be less than 50 fpm, the sensor spacing must not exceed 350 feet (as shown in Figure B.3)

The sensor must be located in the intake entry at a location 50 feet upwind of the point-feed regulator. If the air through the point-feed regulator enters a belt air course that is used to ventilate a working section, a second sensor must be located 1,000 feet upwind of the point-feed regulator (as shown in Figure B.4). In the belt entry, sensor must be located within 50 feet of mixing point where air flowing through the point-feed regulator mixes with the belt air (as shown in Figure B.4).

As far as the lateral and vertical spacing of sensors is concerned, the CO sensors and cables should be installed in the upper third of the entry (height), near the center of the entry (width). The sensor must be placed in such a manner that it is protected from roof falls and the moving belt. It should not be located in abnormally high areas or in other locations where the airflow patterns do not permit products of combustion to be carried to the sensors.

B.3 Primary Escapeways

The location of the sensors in the primary escapeway is discussed in section § 75.351(f). When air from the belt entry is used to ventilate the working section, CO sensors must be located within 500 feet of the working section and areas where mechanized equipment is being installed or removed. A sensor is required within 500 feet inby the beginning of the panel. However, the point-feed sensor may also serve at the beginning of the panel if it is within 500 feet of the beginning of the panel (as shown in Figure B.5).

B.4 Return Air Splits

If an AMS is used to monitor return air splits, a methane sensor should be installed between the last working place, longwall or shortwall face ventilated by that air split. The methane sensors should be installed in the return air course opposite the section loading point, within 300 feet downwind from the fan exhaust and immediately upwind of the location where an air split is used to ventilate seals or worked out areas.

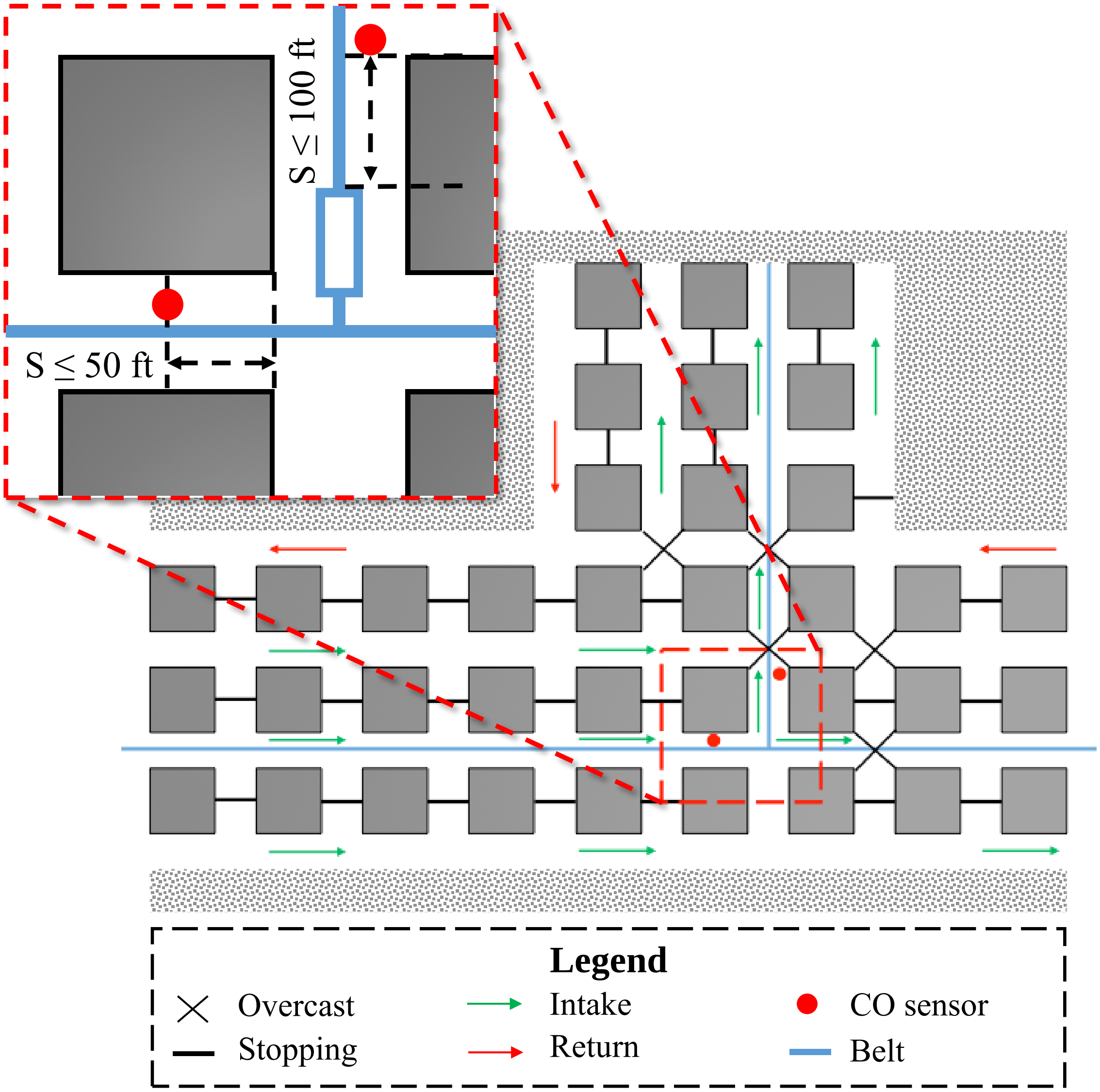
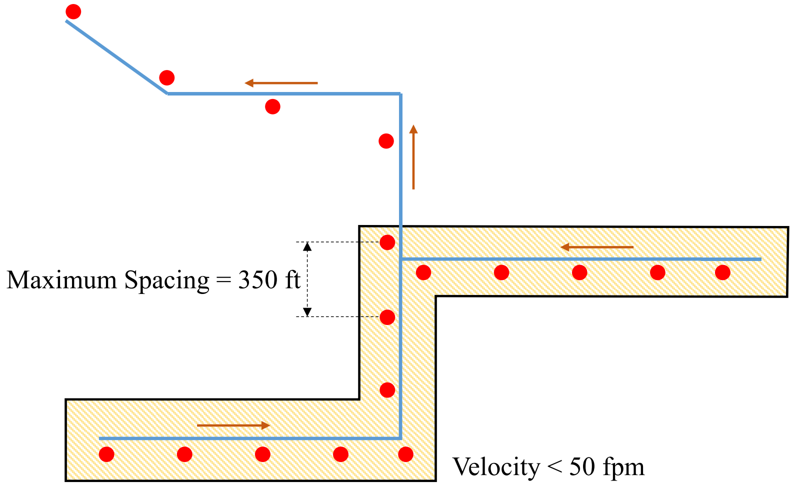
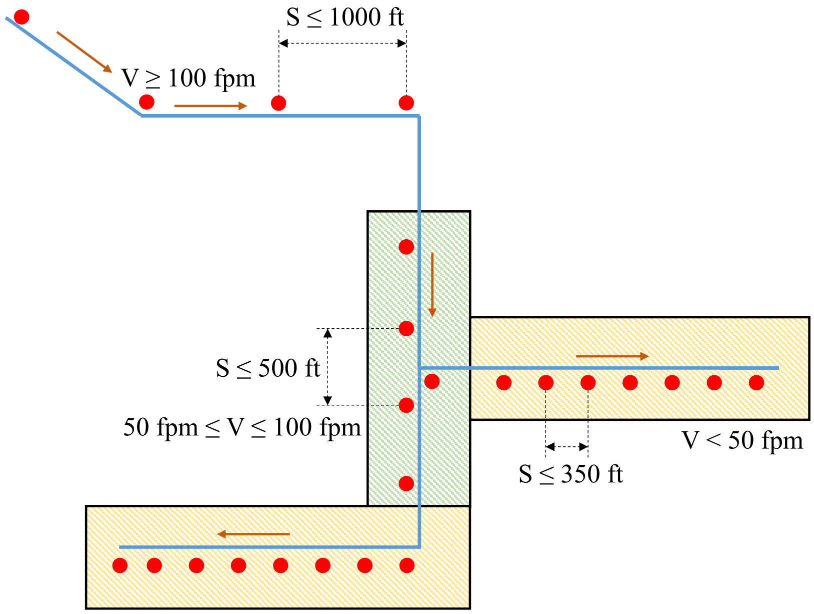


Figure B.1: Location of CO sensor where air splits



(Sensor Spacing - Belt air is NOT used for Ventilation)

Figure B.2: Sensor spacing—air from belt entry is not used to ventilate working sections



(Sensor Spacing - Belt air is used for Ventilation)

Figure B.3: Sensor spacing—air from belt entry is used to ventilate working sections

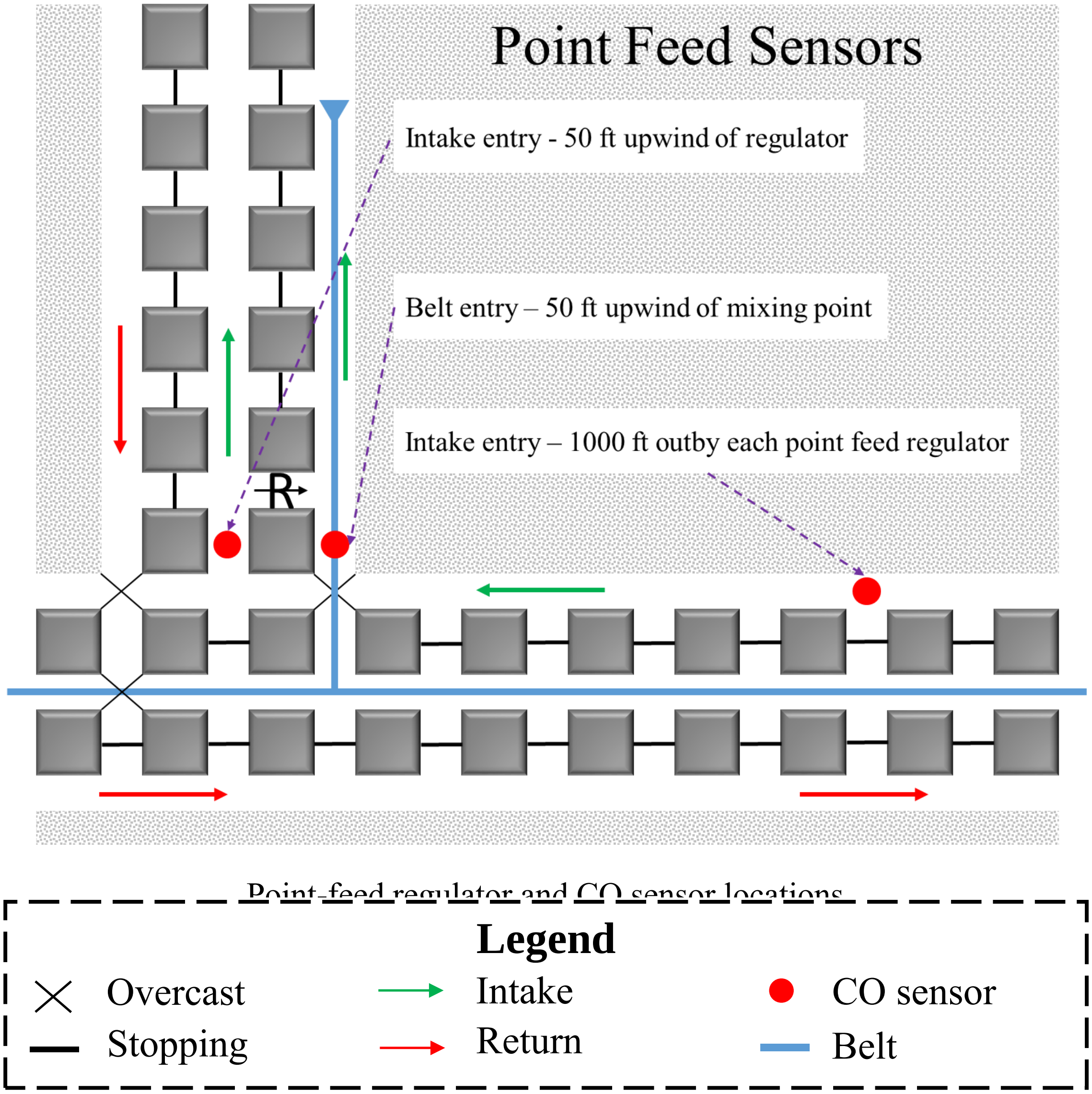


Figure B.4: Point-feed regulator and CO sensor locations

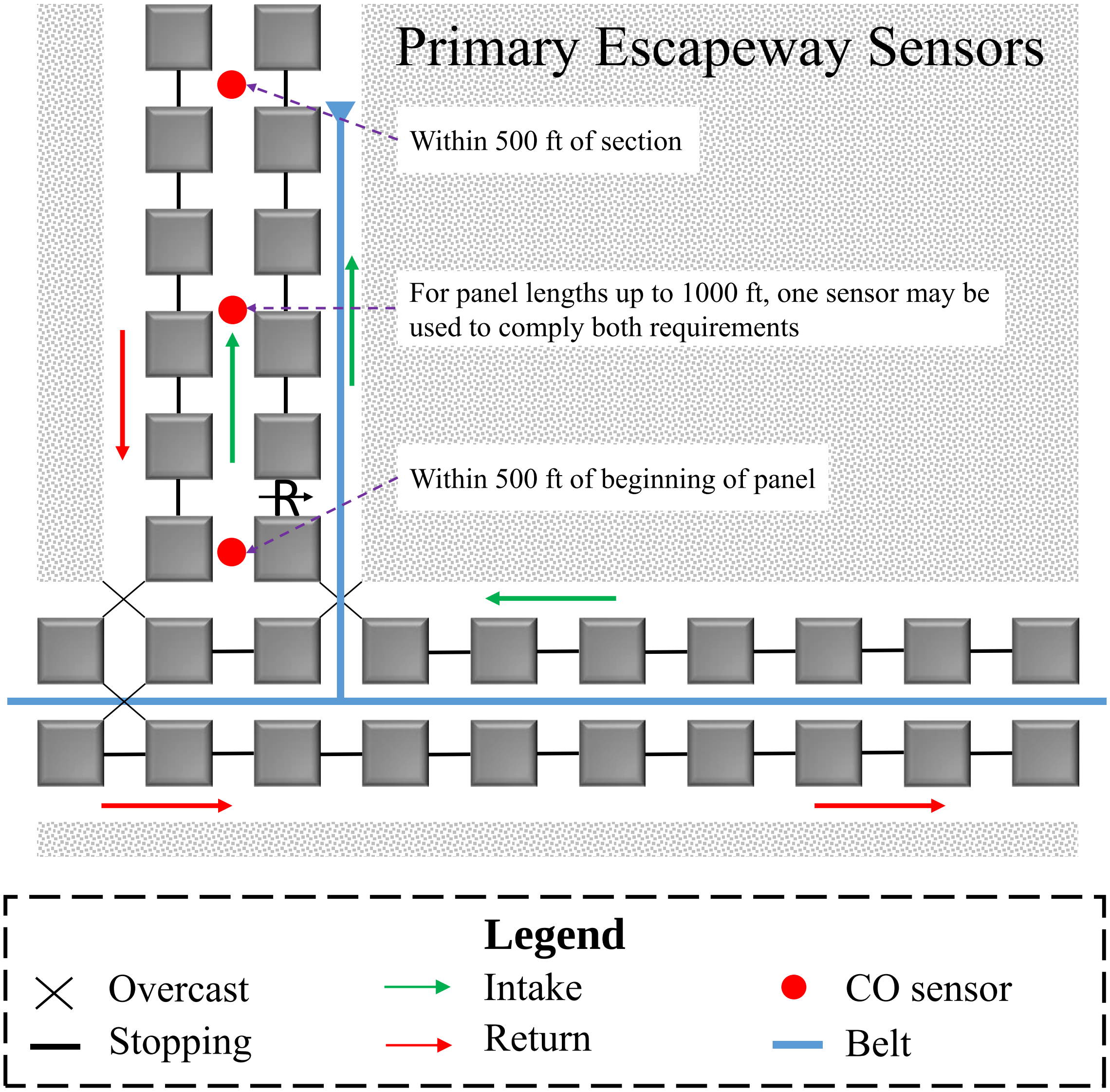


Figure B.5: Primary escapeway sensor locations—mines using air from belt entry to ventilate working sections

APPENDIX C

GUIDELINES FOR SPACING OF MONITORS

C.1 Spacing of Monitors

The most complicated part in the design of an AMS for a mine is to determine the spacing of monitors. A guideline for spacing of monitors in underground mines is presented step by step as a recommendation for an airway.

1. Determine the average entry height (H) and width (W).
2. Take the ratio of height to width (H/W) and, from Figure C.1, determine the appropriate value for the entry parameter (Υ_E).
3. Determine the type of sensor to be used (CO, CO_2, or smoke) and its alarm threshold (X_a); that is the gas concentration that will activate the sensor alarm.
4. Determine the primary combustible within the entry (either coal or wood) and, from Table C.1, select the production constant (K_X) for the gas to be detected.
5. Determine the average background level (X_o) of the gas to be detected.
6. Subtract X_o from X_a and divide the result by the appropriate K_X-value.
7. From Figure C.2, determine the value of the gas parameter (Υ_X) at the value of $(X_a - X_o)/K_X$ defined in step 6.
8. Determine the average velocity (V), in feet per minute, within the entry and, in Figure C.3, draw a vertical at this velocity parallel to the y-axis.
9. Multiply H by W to determine the average entry cross-sectional area (A) and, in Figure C.3, draw a horizontal line at this A-value parallel to the x-axis.
10. Use the point of intersection of the vertical and horizontal lines in Figure C.3 to find appropriate spacing equation for calculation of sensor spacing Z.
11. For intake and return airways, the resulting Z is recommended spacing. For belt entry, the spacing also depends on velocity in airway as per the CFR 75.351. For V

≤ 50 fpm, if $Z \leq 350$ ft, then use the value of Z else use 350 ft as appropriate spacing. Similarly, for $50 < V \leq 100$ fpm; $Z \leq 500$ ft; and for $100 < V \leq 1000$ fpm, $Z \leq 1000$ ft. If the calculated sensor spacing (Z) is less than the sensor spacing value in federal regulations, it is recommended to use the calculated spacing rather than the sensor spacing mentioned in regulations.

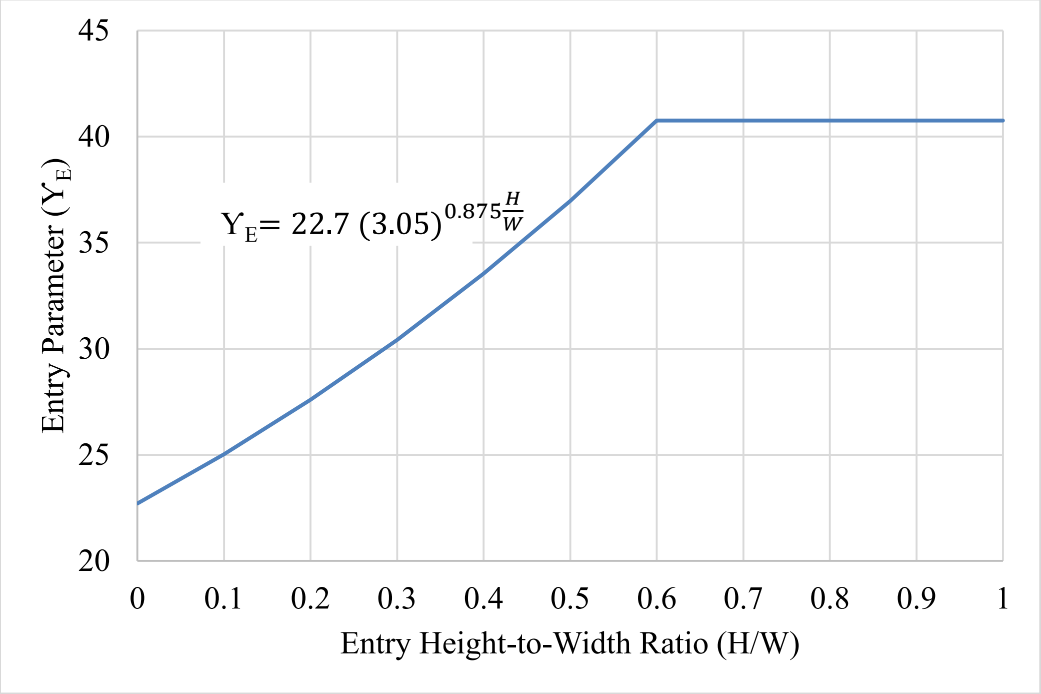


Figure C.1: Entry parameter (Y_E) as a function of the entry height-to-width ratio (H/W)

Table C.1: Production constants for coal and wood

K_X	**Gas Concentration Units**	**Coal**	**Wood**
K_{CO}	ppm	1.1	0.95
K_{CO2}	ppm	6.7	6.90
K_{Smoke}	particles per cm^3	$7.2*10^4$	$2.5*10^5$
K_{Smoke}	mg/m^3	0.45	0.3

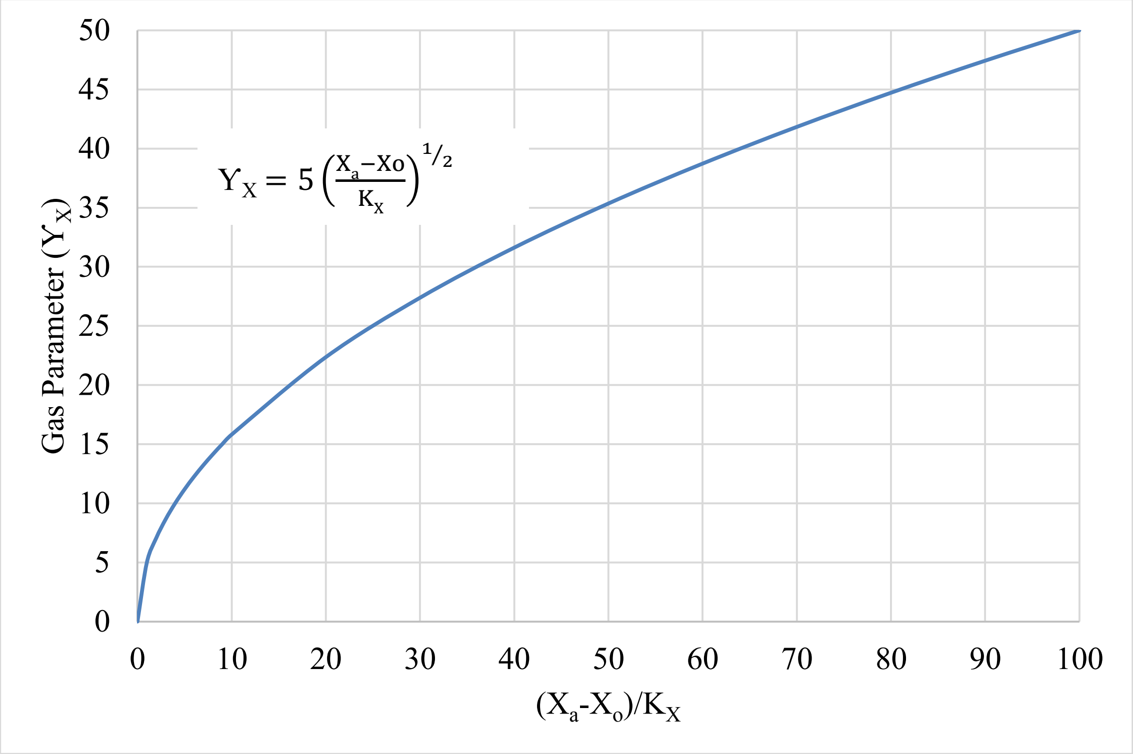


Figure C.2: Gas parameter (Y_X) as a function of the ratio of alarm threshold to production constant $(X_a - X_o)/K_X$

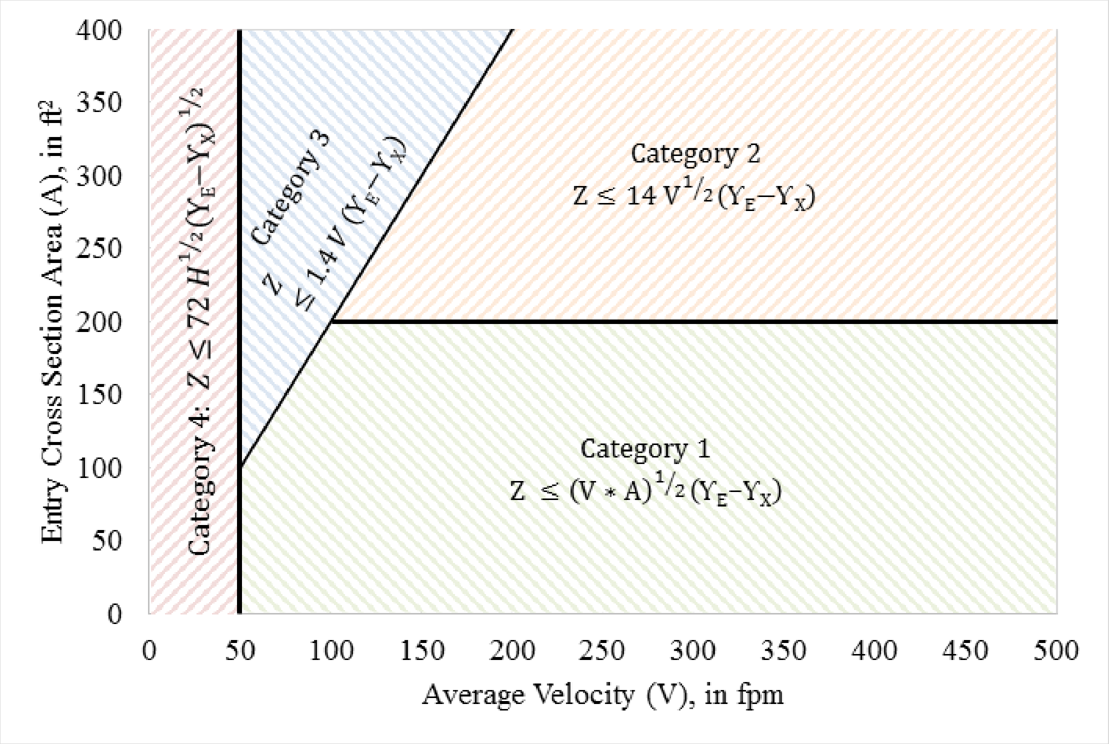


Figure C.3: Spacing categories and appropriate spacing equations for mine entries

Category 1: A ≤ 200 ft2, V > 50 fpm, and Ratio A/V ≤ 2

Category 2: A ≥ 200 ft2 and Ratio A/V ≤ 2

Category 3: Ratio A/V > 2

Category 4: V ≤ 50 fpm

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