Utilization of Booster Fans in Underground Coal Mines

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Abstract

This study presents the principles and basic requirements for the installation and operation of booster fans in coal mines. The booster fan must be designed and installed to assist the main surface fan, not to take its place. In addition, the fan must be installed in a permanent bulkhead and equipped with airlock doors, an environmental monitoring system, and electrical interlocking devices to stop the fan and open the doors in the event of main surface fan failure. The study also presents the results of fan surveys and inspections in coal mines where booster fans are used regularly. Six underground coal mines were visited: three in Australia and three in the United Kingdom. In both countries, the regulations allow mine operators to used booster fans to overcome adverse ventilation conditions provided that certain requirements are met. One of these requirements is that the mine operator must develop a ventilation plan justifying the use of the booster fan. Another requirement is that the booster fan must be equipped with airlock doors, fan monitors, and other devices to reverse the ventilation to a flow-through system in the event of fan failure.

The University of Utah coal mine ventilation model was upgraded to include two fans (main and booster), four stoppings, and a gas injection system. This system was used to investigate the air-gas flow distribution in the model for different fan and regulator settings. Various tests were conducted by changing the fan speeds and regulator resistances. This study summarized the results of these tests and the conditions under which flow recirculation can be avoided.
The Missouri University of Science and Technology's experimental mine was upgraded to include two 12-kW booster fans. The fans were installed in steel bulkheads equipped with man-doors. Various tests were conducted to investigate the fan performances, pressure differences across the bulkheads, and volume flow rates at different blade settings and fan speeds. Additional tests were conducted to determine leakage across the stoppings. This study also summarizes the results of these tests.

One major task of this study was to develop a computer program to produce recirculation-free ventilation designs. A fan selection program based on genetic algorithms, GVENT, was developed to solve ventilation network problems. This is a modular program that combines the features of a set of genetic algorithms (GAs) developed by MIT, and a ventilation simulator developed by Mine Ventilation Services, Inc. For a given ventilation network problem with a fixed number of flow requirements and fan locations, the program generates an output file showing the fan pressures and regulator resistances that satisfies the practical constraints and minimizes the power consumption. The details of this program are presented in this report.
To prevent the recirculation of air contaminants and ensure the normal operation of the booster fan, a monitoring system is a basic requirement. This system should include: (1) fan condition sensors, and (2) environmental sensors. Types and locations of these sensors in relation to the

fans, and the interfacing of these sensors with the mine monitoring system are described in this report.

Identification of hazards and risks associated with the utilization of booster fans are part of the ventilation planning process in most coal mining countries. In the U.S., the regulations of the Mine Safety and Health Administration (MSHA) require mine operators to apply general hazard awareness and control in all operations, but do not require a comprehensive risk management program. This report presents a summary of potential hazards and risks associated with the usage of booster fans, and control measures to mitigate the risks to acceptable levels.

Finally, this report presents guidelines for the safe operation of booster fans in underground coal mines. These include a summary of standards and regulations adopted by two coal mining countries, the requirements for the fail-safe operation of the fan system, the applicable standards for use in the U.S., the system design principles to avoid flow recirculation, and the rules of safe practices developed in coal mining where booster fans are used regularly.

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1. Introduction

A booster fan is an underground ventilation device installed in the main airstream (intake or return) to handle the quantity of air circulated by one or more working districts (McPherson 1993). It is installed to operate in conjunction with the main fan and boost the air pressure of the ventilation air passing through it. To accomplish this objective, the fan is installed in a permanent bulkhead and equipped with airlock doors, electrical interlocking devices between main and booster fans, and a fan monitoring system to continuously assess the operating conditions of the fan.

Booster fans are generally installed in return airways in series with the main surface fan and sized to pressurize the air circulated through a working section of a mine. Although the booster fan is installed in series with a main surface fan, the quantity of air passing through it is usually less than the quantity of air passing through the main fan. Its operating pressure can be significantly high, but it is kept less than the operating pressure of the main surface fan to prevent recirculation.

The use of booster fans in coal mines began in the early years of the last century. Indeed, its early application in English collieries was traced back to 1906 (Saxton 1986). Since then, the use of these fans has gained an acceptance not only in England but also in coal mines of many other countries including West Germany, Australia, Canada, South Africa, and Japan (Brake 2006). In deep coal mines, booster fans can be used to overcome conditions under which surface fans are incapable of providing the airflow demands, or when these requirements can be fulfilled only at extremely high pressures, which cause excessive air leakage and may lead to unsafe conditions (Ogle 2011).

In 1986, Jim Walter Resources Inc. submitted to MSHA a proposal to operate an underground booster fan at its No. 7 mine. The plan specified a Jeffrey fan equipped with a 750-kW direct drive motor located in the main intake. The projected fan capacity was 331 m^3/s at 2 kPa (700,000 cfm at 8.0 in. w.g.). The proposal was rejected mainly due to the potential for flow recirculation through the fan. The proposal was revised to eliminate the danger of flow recirculation. The fan capacity was decreased to154 m^3/s at 1.08 kPa 4 (300 kW), provision was made to install gas detectors. The proposal was resubmitted to MSHA in 1987 (Sartain 1989), but was rejected two years later, mainly because of the lack of expertise in the mining industry to evaluate the performance of these fans (Martikainen 2010). Currently, the U.S. Mine Safety and Health Administration does not allow coal mine operators to use booster fans.

Although improved ventilation efficiency and reduced leakage may result from the utilization of underground booster fans, the possibility of uncontrolled recirculation in an inadequate design still exists. However, with the advent of smart monitoring systems the benefits offered by booster fans can be realized in a safe manner.

1.1. Objectives of this Study

The objectives of this study are to investigate the conditions under which booster fans can be used safely in underground coal mines, especially in deep mines with difficult conditions. Specifically, the study is directed at (1) developing a booster fan selection method to assist the ventilation engineer at the design stage, (2) identifying the critical hazards and risks associated with the utilization of booster fans in coal mines, and (3) developing a process control system to evaluate the fan safety during its operation. The fan selection method, based on genetic algorithms and a network solver, is used to determine the best combination of main and booster fan pressures that reduces leakage and minimizes the power consumption. The process control system includes the use of an atmospheric monitoring system equipped with smart sensors to detect abnormal conditions and allow system adjustments so that booster fans can be used to enhance the health and safety conditions in underground coal mines. Specifically, this study has the following objectives:

1. To conduct ventilation surveys in two deep or large U.S. coal mines, and determine the fan duties, airway resistances, and the airflow distribution in each mine.
2. To perform fan tests in coal mine where booster fans are used regularly. The initial plan included booster fan inspections in U.K. and Australian underground coal mines.
3. To install a booster fan system at the Missouri University of Science and Technology (MS & T)'s experimental mine and conduct ventilation surveys under various main and booster fan conditions.
4. To upgrade the University of Utah coal mine ventilation model to include a booster fan and to conduct air pressure/quantity surveys. The upgrade includes the installation of a gas injection system to study the effect of the booster fan on gas flow recirculation.
5. To develop CFD-based ventilation models to determine air flow patterns and shock losses near and around the main and booster fans.
6. To develop an efficient fan selection algorithm for underground coal mines.
7. To train six M.S. or Ph.D. graduate students to the level of advanced mine ventilation.

Main findings including the results of booster fan inspections in U.K. and Australian mines and booster fan tests conducted at the University of Utah laboratory model and at MS & T's experimental mine, and the procedure used to develop a fan selection algorithm, are described in this report.

1.2. Booster Fans in Coal Mines – Basic Requirements

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 safe and 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 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.

Once the decision is made to use a booster fan system, a detailed plan must be developed. This plan must specify the size and type of the fan(s); the number, type, and strength of airlock doors; fan condition and environmental monitors; and the electrical interlocking system to prevent flow recirculation in the event of main fan failure.

Figure 1.1 shows a schematic of a booster fan system in a return airway. The fan, with its motor in a flame-proof enclosure, is installed in a concrete bulkhead. The system is equipped with a set of airlock doors to avoid flow recirculation, and a set of condition and environmental monitors to evaluate the health of the fan continuously. The factors to be monitored include (1) methane concentration, upstream and downstream from the fan, (2) carbon monoxide concentration, downstream, (3) air velocity, upstream, (4) differential pressure across the fan and door bulkheads, and (5) bearing temperatures.

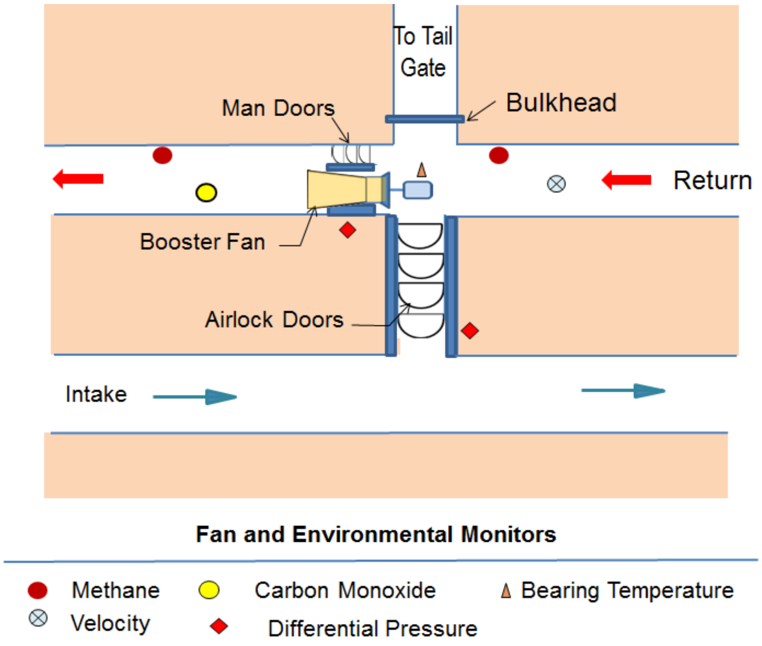

Figure 1.1. Sample booster fan installation in a return airway

When the fan is switched on, the pressure on the delivery side is higher than on the intake side. The difference is the effective fan pressure added to the air stream. This pressure is used to increase the airflow rate in a working section. However, this requires airtight doors and bulkheads. Cracks in the bulkheads or poorly maintained airlock doors will allow leakage and recirculation, thus reducing the capacity of the fan. To overcome this problem, bulkheads should be sealed from the high pressure side and the doors affixed with rubber seals. The doors should be designed in such a way that they are always kept closed when the fan is running and open when the fan is down**.**

1.3. Advantages and Disadvantages

The various advantages and disadvantages of booster fans are summarized below.

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 and 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, reducing leakage and the need for airlock doors.
3. The surface fan pressures are reduced, allowing existing installations to remain in place.
4. The booster fan can be used to boost air flow to single panel(s) rather than the whole mine, to minimize required regulation and mine resistance.
5. The overall development costs are much less than those for installation of large surface fans and sinking a new shaft.
6. The total electric power cost of a system with booster fans is lower than that of a system with surface fans only, because booster fans augment main fan power by reducing the regulator resistances.

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 the main return airways all the air should be directed to the entries where the fans are located, thus requiring heavy duty stoppings and airlock doors.

2. All coal mines are gassy, so the booster fan must be designed with anti-sparking characteristics, which calls for use of a stainless steel rotor, blades, and other fan parts.
3. The booster fan must be installed in a flameproof housing, or the motor must 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, so that its control system cannot be used to adjust ventilation in specific areas of the mine.

The authors believe that, in underground coal mines, the advantages of booster fans outweigh their disadvantages. This is why booster fans are widely used in many coal mining countries, including the U.K., Australia, Poland, Japan, and South Africa.

1.4. What Can Go Wrong with Booster Fans?

Potential hazards of increased likelihood of mine fires and recirculation of contaminants are introduced when a booster fan is not selected or installed properly. In the history of utilization of booster fans two major incidents that claimed lives have been reported, the Auchengeich Colliery fire in Scotland (1959), and the Sunshine Mine fire in Idaho (1972). In the first case, the belt drive on the booster fan caught fire. The fire spread to the roadway timbers and claimed the lives of 43 workers. The workers died from carbon monoxide poisoning. Since then, the use of vee-belt drives underground has been severely restricted (Robinson 1989). In the second case, the mine was ventilated by four booster fans installed in series. According to the U.S. Bureau of Mines, the probable cause of the fire was spontaneous combustion of scrap timber used to backfill worked out stopes. By the time the fire was detected, the smoke had already filled the main haulageway (3700 level) and the intake raises and active stopes located on lower (4000–5200) levels. The fans contributed to the rapid propagation of smoke into the workings inby the fire. Other factors contributing to this incident were failure to provide the fans with remote control, failure to monitor the mine atmosphere for carbon monoxide, and delay in starting the evacuation of personnel. As a result, 91 men died of carbon monoxide poisoning (Jarrett 1972). In both cases, new lessons were learned, contributing factors identified, and existing standards modified so that mistakes such as those illustrated in these examples would not be repeated.

1.5. Summary

This study includes the results of ventilation surveys that were conducted in underground U.S coal mines with large air flow requirements, and booster fan inspections carried out in U.K and Australian coal mines. It also includes the results of laboratory tests on leakage and flow recirculation conducted at the University of Utah, and leakage flow and fan condition monitoring tests at the MS & T's experimental mine. Finally, it includes the details of a fan selection program that was developed to determine the optimum combination of main and booster fans.

The ventilation surveys were carried out in three extensive coal mines. The collected data were evaluated and used to develop numerical models to predict future ventilation requirements. These data were also used to test the goodness of the newly developed fan selection program, GVENT.

The booster fan surveys and inspections took place in six underground coal mines, three in Australia and three in the United Kingdom. In these mines, booster fans are used regularly to overcome adverse conditions created by higher airway resistances and increased airflow requirements. In both countries, the regulations allow coal mine operators to use booster fans provided that certain conditions are met. Three of the key conditions are that the mine operator must develop a comprehensive plan justifying the use of the booster fan, that the critical hazards must be identified the risks evaluated, and that adequate control measures are in place. Another condition is that the booster fan must be sized and sited to assist the main fans and equipped with airlock doors, and condition monitors, to evaluate the status of the fan continuously.

The booster fan tests were carried out at the University of Utah's coal mine ventilation model and the MS & T's experimental mine. The laboratory model was used to study the airflow through simulated mine openings for different fan and regulator settings and determine the conditions under which flow recirculation can be avoided. The ventilation system at MS & T's experimental mine was upgraded by installing two booster fans and ventilation surveys for different main and booster fan settings were conducted. These tests were designed to determine the effects of the booster fans on the ventilation conditions in the mine.

A fan selection program was developed to assist ventilation engineers in determining the best combination of fans for a ventilation network. This is a modular program that combines the features of a set of genetic algorithms (GAs) developed by MIT, and a ventilation simulator developed by Mine Ventilation Services, Inc. The program solves a network problem subject to an objective function (total airpower) and a set of practical constrains. It requires a ventilation network, a set of airways with fixed flow quantities (working areas), fan locations, an objective function, and practical constraints. For a given network problem, the program generates an output file showing the fan pressures and regulator resistances that reduce leakage and minimizes the total power requirement. The program was tested using real mine examples successfully.

In addition, this project allowed two mining schools to join expertise and laboratory facilities to train M.S. and Ph.D. graduate students in advanced mine ventilation. The group included one Ph.D. and three M.S. students at the University of Utah, and three M.S. students at the Missouri University of Science and Technology.

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2. Literature Review

A total of 225 articles were collected for the literature review. The articles were organized into six categories: (1) coal mine ventilation, (2) seals and leakage, (3) use of booster fans in coal mines, (4) fan optimization methods, (5) condition and environmental monitoring, and (6) controlled recirculation. A hard copy of each article is stored in a three-ring binder. Digital copies of all articles are kept in PDF format, organized in files by category. Articles that could not be located digitally were digitized using a desktop scanner. A listing of all articles is stored in Microsoft Excel, so the articles can be easily sorted out by main author, year of publication, title, publication, and category. A summary of each category is presented below.

2.1. Coal Mine Ventilation

These articles focus primarily on meeting MSHA face ventilation requirements. The prohibition of booster fans presents a challenge to coal mine operators in the U.S., especially when a mine is very deep or extensive. For example, the Aberdeen mine, located in central Utah, has reserves at depths of up to 790 m (2,600 ft). The mine has used several surface fans to ventilate workings, with two intake and return shafts, in a push-pull fan arrangement (Richardson et al. 1997). The mine is gassy and liberates about 0.31 million m^3 of methane per day, along with H_2S and CO_2. The SUFCO mine, also in Utah, is one of the largest underground mines in the U.S. In this mine, the methane liberation from coal is extremely low; however, the coal is classified as highly susceptible to spontaneous combustion (Kenzy 2013). The mine uses a wrap-around bleeder system to ventilate the working areas, which are located tens of miles from access portals. At SUFCO, more than 50% of the total quantity of air handled by the surface fan is "lost" through old workings. In both mines, the use of booster fans could make a difference.

2.2. Stoppings and Seals

A number of recent coal mine disasters involving mine seals prompted the Mine Safety and Heath Administration's Final Rule on mine seals (30 CFR § 75.335), which became effective on October 20, 2008 (MSHA, 2014). Among other things, the Final Rule states that, seals must withstand:

- 345 MPa (50 psi) if the sealed area is monitored and maintained inert
- 827 MPa (120 psi) if the sealed area is not monitored
- Greater than 827 MPa (120 psi) if the area is not monitored and certain conditions exist that might lead to higher explosion pressure.

Based on an analysis of possible explosion pressures, Zipf et al. (2007) recommend that mine seals be structurally designed to withstand a 4.4 MPa (640 psi) detonation wave if the sealed area atmosphere is not monitored and if it is unknown whether a flammable gas-air mixture exists behind the seals.

Many seal designs have been approved by MSHA and constructed by the mining industry. Much of the literature describes the design and testing methods used, and retrofit techniques for in situ strengthening of thousands of existing138-MPa (20-psi) seals to meet the new standard (Weiss and Harteis 2008) The most common structural materials used in the approved seal designs are concrete or reinforced concrete and lightweight, cementitious materials like pumpable Tekseal®. The new seal design requirements have resulted in a drastic increase in the unit cost of mine seals. For this reason other low-cost alternatives, such as using blasted gob material, have been proposed.

At the 2010 SME annual meeting, MSHA addressed a number of key issues that have arisen since the Final Rule took effect. Several such issues discussed include the directional, design-load criteria required by MSHA, the presence of fireclay in the surrounding strata where a seal is to be built, and the measurement of convergence of the mine opening in which a seal has been constructed. A number of publications suggest methods to help control the problem of leakage, not only through seals, but other stopping structures as well.

2.3. Use of Booster Fans in Coal Mines

The use of booster fans in underground coal mines started in the United Kingdom in the early 1900s. In 1905, Alfred Tonge reported that three underground Sirocco fans were used to ventilate the workings of the Hulton Colliery (Saxton 1986). In 1911, the U.K. passed its Coal Mine Act. This act allowed British coal mines to use booster fans provided that there was a main fan on surface. Since then, the use of these fans has gained acceptance not only in England but also in the coal mining industries of many other mining countries including Germany, Poland, Australia, India, and Japan.

A review of the current literature in mine ventilation shows numerous examples of the utilization of booster fans. The Wearmouth colliery is typical. In this mine, coal was extracted from two levels, the 1570 level and the 1850 level (The level number indicated depth in feet.) All the workings were under the North Sea at distances of more than 7 miles from the access shafts. The ventilation system consisted of two main intake slopes and one return shaft. The air was directed through the mine openings by means of one surface fan and three booster fans. The surface fan had a capacity of 236 m^3/s at 1.75 kPa of pressure. The booster fans were situated 3 miles inby the shafts, one on the 1570 level and two on the 1850 level. The fans on the 1850 level were installed to operate in parallel with a combined capacity of 100 m^3/s at 5 kPa of pressure (Robinson 1989).

In the U.K., booster fans are regularly used in coal mines. However, the Coal and Other Mines Regulations of 1956 imposed a number of requirements and constraints on owners for installing and operating booster fans. One regulation states that before installing a booster fan, an extensive survey must carried out and a detailed report submitted to Mines Inspectorate. Another regulation states that the booster fan must be inspected at 30-minute intervals and the results recorded every two hours. However, the Mines Inspectorate has the power to grant exemption from any aspect of law (Leeming 2012).

In Australia, booster fans are used in two coal mining states, New South Wales and Queensland. The practice of using underground boosters is quite common in Australian metal mines but their use in modern collieries has been very limited. One primary example of the use of these fans was the North Goonyella colliery's booster fan system in the Bowen Basin, Queensland. The system, equipped with twin centrifugal fans, was placed in two main return entries with one bypass door installed in the center entry. The drive shafts were run through the bulkheads in the crosscuts next to the fans so that the motors could be installed in areas of intake air. Each fan had a capacity of 150 m^3/s at 2 kPa total pressure. The fans were equipped with environmental monitors operated from the surface. The main objective for choosing this system was to increase the air pressure inby the booster fans and reduce the air leakage (Burnett and Mitchell 1988).

The second major application of this technology took place at the West Cliff colliery in Wollongong, New South Wales. In this mine, the ventilation system included two 750-kW centrifugal surface fans with a combined capacity of 175 m^3/s at 3.3 kPa total pressure. In addition, the mine operated four centrifugal booster fans located in the main return airways. Each fan had a capacity of 150 m^3/s at 3 kPa total pressure. The fans were equipped with airlock doors and a monitoring system controlled from the surface. Rigorous risk analyses were completed prior to their design and installation (Benson 2002).

The third example is the Tahmoor Colliery's booster fan system. This is a single centrifugal fan, installed in the main return and equipped with a set of airlock doors and a monitoring system. It is designed and installed to assist the main surface fan to ventilate the longwall panels and reduce leakage. The motor room and fan sites are fully monitored for methane, carbon monoxide, vibration, and bearing temperature. The fan, equipped with a 675-kW motor, has a capacity of 125 m^3/s at 3.9 kPa of pressure. The position of the doors is monitored such that the fan will turn off if the doors do not close immediately after fan start (Ogle, 2011).

2.4. Fan Optimization Methods

In mine ventilation, finding the optimal combination of fan pressures for a ventilation network may be a complex problem. It involves selecting the best combination of main and booster fans pressures that minimizes the airpower while satisfying the airflow requirements in the mine. Fan optimization methods can be categorized into two groups:

a) **Traditional Methods**. Traditional methods are based on empirical relationships established between fan pressures and regulator resistances. Calizaya et al. (1987) proposed an algorithm to determine the best combination of main and booster fan pressures for a ventilation network with a fixed number of working areas. In this study, a sample network was investigated in two stages, a single fan system and a two fan system. In each stage, a set of feasible solutions was generated. The solutions consisted of fan pressures and an added resistance for each working area where a fixed quantity of air was required. Pressure-added resistance relationships for fans were plotted and the resulting graphs evaluated for the optimum fan pressure. The same procedure was repeated for different booster fan pressures to determine the best combination of two fan pressures. This algorithm requires a ventilation simulator and skills to interpret the results graphically. The approach can be time consuming and tedious, particularly for large or complex networks.

b) **Advanced Methods**: Advanced methods are based on the application of genetic algorithms into ventilation networks. Yang et al. (1998a) used a modular program that combined the features of genetic algorithm optimization techniques with a ventilation simulator. The program was based on binary strings, used to represent the network variables, and a ventilation simulator to determine the fitness of the solution strings. The fitness of a solution string is measured in terms of total power required by the fans. This program was applied successfully, first to determine the best combination of main and booster fan pressures for a sample network and then for a large U.K. coal mine (Yang et al. 2000). Years later, the approach was used to solve multi-level metal mine ventilation problem (Lowndes et al. 2004 and 2005).

Recently, genetic algorithms have been used to solve many ventilation network problems with increasing levels of confidence, and have been tested using sample ventilation networks. However, when considering tools for global optimization, it must be acknowledged that genetic algorithms are only search routines. The solution space comprises many data points generated by a ventilation solver. These data points are combined by means of cross-over and mutation processes to generate offspring for the next generation. The process is repeated until the stopping criterion or fitness function is reached and an optimal solution found. Genetic algorithms have been applied to both semi-controlled and free splitting ventilation networks to determine the best combination of main and booster fan pressure (Acuña et al. 2010).

2.5. Condition and Environmental Monitoring

A monitoring system is an integral part of a good booster fan installation. It includes atmospheric monitoring and fan condition monitoring

a) **Atmospheric Monitoring.** A real time monitoring system can be used to determine whether a mine ventilation system is functioning properly. Proper operation of the ventilation system directly impacts daily health and safety of workers as well as the mine's efficiency. However, the real time monitoring is limited by the sensing technology used to detect the parameters of interest, locations of sensors, and sensor response time and sensitivity. Most commercially available gas sensors have response times of 10 to 30 seconds. Catalytic gas sensor response times range from 10 to 15 seconds and IR sensors from 15 to 30 seconds (Luxbacher 2012). These times may not be adequate to satisfactorily de-energize equipment in rapidly changing atmospheres, and may allow for movement of equipment some distance into an explosive atmosphere.

The other problem associated with real time atmospheric monitoring sensors is the sensitivity of the sensors used, which is typically based on the sensing technology and cross-sensitivity of each sensor 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 zero to 5% (Valoski 2010), and may experience interference from organosulfur or organophosphorus compounds, ethane, propane, higher hydrocarbons, and other flammable gases (Eggins 2002). For proper operation, a catalytic methane sensor requires oxygen concentrations in excess of 12% (Valoski 2010). In addition, as methane concentration exceeds 9 to 10%, lower oxygen concentrations will reduce the function of the sensor and give a false reading.

b) **Fan Condition Monitoring.** In mine ventilation, fan condition monitoring includes the measurement and evaluation of parameters such as vibration, barometric pressure, input power, motor and bearing temperatures, differential pressures, and air quantity. A few of these parameters are discussed briefly here.

- Vibration. Vibration analysis is a powerful tool for assessing the performance of main and booster fans. Variation in normal operating conditions of mine fans produces significant changes in vibration level, and causes wear or deterioration of the fan. A review of the current literature on vibration monitoring, found that at least six velocity-type vibration monitors are required, 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 monitors is somewhat limited in predicting potential failures. Acceleration-type vibration monitors are recommended for this purpose (Howden Fan Engineering 1999 and Sandwell 2012).

- Air Pressure and Quantity. Main fans are the most important pieces of equipment for any underground mine, so it is essential to continuously monitor their duties, which are indicated by pressures and flow rates. Commonly, fan pressures are measured using manometers and flow rates are calculated by measuring the linear air velocity and the cross-sectional area of the airway. Fan static pressures are monitored using differential pressure transducers that are easily interfaced with a mine-wide monitoring system. Air velocities are monitored by using Pitot tubes and manometers, ultra-sonic anemometers, and vortex-shedding anemometers. Commonly, velocity transducers are located near the roof, so they collect point velocities. Then these are corrected (calibrated) using hand held instruments.

- Bearing Temperature. Bearings are the most critical components of main fans. Along with vibration, 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 imbalance of the rotor assembly. They must also be able to operate at the intended speed without overheating. Normally, the bearings should be maintained at temperatures of less than 85°C.

c) **Mine Monitoring Systems**. Presently, there are three types of mine monitoring systems: programmable logic controllers, fiber optics and telemetering system. A brief description of some of the components used in these systems follows. These components may be used in various combinations, depending on the needs of a given mine.

- Programmable Logic Controllers. Programmable logic controllers (PLCs) are used widely for automation and control of electro-mechanical systems. These systems first came into use in underground mining in the seventies, using mini- computers on the surface. The remote outstations were not intelligent, being wholly dependent on remote mini-computers to collect information, process the data, make logical decisions, and instruct the outstations of any logic changes to be made (Smallwood et al. 1993). While PLC-based atmospheric monitoring systems were originally designed to provide continuous monitoring of CO and other toxic and combustible gases, current systems allow the user to continuously monitor and control all other processes for underground mining operations. For example, in many systems monitors are placed along the belt lines to detect any rise in CO or combustible gases, providing an early warning of potential hazards. The collected information is immediately transmitted to the surface, so the AMS operator can locate the problem area, determine the existing conditions, shut down processes in that section, and restart when conditions permit.

- Fiber-optic Systems. A fiber-optic monitoring system transmits information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. Over the last several years there has been much research in the area of fiber-optic sensing, though little of this work has impacted the mining industry. This is partly because of the small return on investment possible in the limited mining market, but perhaps a bigger reason is the perception that optical fiber is unable to withstand the hostile mine environment. Compared to wired systems, fiber-optic systems can be installed over greater distances in large mines and communicate at higher speeds. The systems require no electrical power within the mine and should operate safely under emergency conditions (Dubaniewicz 1992). Fiber-optic sensing technology has the potential to revolutionize the way mines are monitored and controlled. The drawbacks with fiber optics system is their high initial cost, high maintenance costs, and downtime costs occasioned in the repair or replacement of broken optical fibers.

- Telemetry. Telemetry is used in automated communication systems, so that data can be collected at remote points and transmitted to receiving equipment for monitoring and control. Since telemetry is merely a form of electronic data transmission, it requires the use of communication channels in much the same way as the mine telephone system. A telemetry system also has remote outstations and an inelegant master station on surface. Conventional AMS installations for measuring CO, CH_4, O_2, and air velocity throughout underground mines are usually relegated to a modest 3- to 5-mile extent. To communicate farther and faster has always been a problem, because data reliability degenerates with excessive distances and high speeds. Because of this, very large mines often resort to costly fiber optic media, using expensive cables and repeaters to obtain the necessary coverage. Recent innovations in telemetry systems present a low-cost alternative to fiber optics and PLCs, that is easier to install and far easier to maintain.
- Wireless Monitoring System. In a wireless monitoring system, a network of wireless sensors gathers environmental data and real-time status information from different mining operations. These sensors enable the remote monitoring and control of critical pieces of equipment, while providing data to enable more informed decision-making, better control, and increased revenue opportunities. The

mines of the future will see a number of instruments with the highest level of reliability at the lowest possible cost.

2.6. Controlled Recirculation

Recirculation is generally classified into two categories, controlled recirculation, where a limited and known quantity of air is deliberately passed from the return airways to the intake airways, and uncontrolled recirculation, where a quantity of air is leaked from the return airways to the intake airways unintentionally. The use of controlled recirculation of air in mines is not a new concept. The first deliberate use of controlled recirculation in British collieries dates back to the early 1930s where it was used to improve comfort level in hot workings (Lawton 1933). Although the fundamental principles were established over thirty years ago (Bakke et al. 1964, Leach 1969) and the first large-scale controlled recirculation system was applied in a coal mine around that time (Robinson 1972), extensive research and field applications did not get started until the late 1970s and early 1980s.

Several parameters were identified as being important in characterizing the effects of flow recirculation (Jones 1987). These are:

- Recirculation fan position
- Recirculation fan pressure
- Presence of out-by booster fans
- Effect of any leakage paths within or outside the recirculation zone
- Size of the recirculation circuit.

Properly planned and operated controlled recirculation can reduce the maximum general body gas concentration in a ventilation system (McPherson 1988). The use of booster fans may lead to the development of uncontrolled recirculation, especially when the fans are not sited or sized properly. To reduce or eliminate the risk, a synchronized operation of booster fans, airlock doors, and environmental monitor is required. The fans and doors should be designed to allow an acceptable level of recirculation (±10%), and the monitors to detect combustion products and to allow the mine operator to stop recirculation and to return the area to one ventilated by through flow ventilation system (Middleton 1985).

Calizaya et al. (1990) proposed two algorithms to detect flow recirculation, the maximum flow algorithm, and the cut-and-search algorithm. The first algorithm is based on finding the maximum flow for each path from a source to a sink. Nodes with residual capacities show the recirculation path and also show the quantity of recirculation. The second algorithm is based on deletion of source and sink nodes while traversing a network. The remaining nodes, left after the deletion process, constitute the recirculation path(s). The two algorithms were tested in small networks to demonstrate their capabilities and limitations. Both were able to find the recirculation loops, but the first algorithm was faster than the second.

Acuña et al. (2012) presented a new algorithm to detect multiple recirculation. Based on this algorithm a new auxiliary graph is generated, initially with no nodes. A node of the ventilation network is added and identified as source, sink, or saddle. All the source and sink nodes are deleted. The resultant graph is then evaluated starting from any node following a path to create a cycle. This cycle is then appended to the original auxiliary graph. If the cycle has super nodes, then these are merged with the auxiliary graph. In the original network, the cycle is collapsed into a single super node by deleting the internal nodes and branches of the cycle. This algorithm has the capacity to identify the strongly connected nodes, thus allowing the user to determine recirculation loops.

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3. Ventilation Surveys in U.S. Coal Mines

Ventilation surveys were conducted at three U.S. underground coal mines: one room-and-pillar mine (Highland 9), and two longwall mines (SUFCO and Twentymile). In each case, pressure-quantity surveys were carried out, mine resistances calculated, and fan duties determined. These data were used to update mine ventilation networks, and to estimate future ventilation needs. For each mine, two ventilation scenarios were considered, using main fans only, and using main and booster fans.

3.1. The Highland 9 Coal Mine

Patriot Coal's Highland 9 mine is located in western Kentucky. This is an extensive, but shallow, room-and-pillar mine with five isolated working districts and several mined-out areas. Pressure-quantity surveys were conducted at Highland 9 mine in May 2010. Based on the collected data, an expanded mine ventilation model was developed and the flow requirements estimated. The model was solved for fan duties and regulator resistances to satisfy the flow ventilation needs.

Currently, the mine is ventilated using an intake shaft, an intake slope, and a single return shaft with an exhaust fan. There are five working sections in the mine, each with a flow requirement of 9.4 m^3/s. The three areas of the mine that are ventilated but not active working faces require a total of 4.7 m^3/s of air flow. The main surface fan mine exhausts 220 m^3/s of air at 1.95 kPa of static pressure, with a total power requirement of 420 kW.

Based on the collected data, a ventilation schematic for the Highland 9 mine was generated, then expanded to reflect a 5-year mining production plan. The schematic is shown in Figure 3.1, on the next page. The mine's future ventilation needs estimated using two scenarios, one with only a surface fan and one with a surface fan and a booster fan.

<u>Singe Surface Fan System</u>. In this scenario the updated model was solved using a ventilation simulator, VnetPC. After a few trials, the ventilation simulator yielded the following results:

Main fan duty:	200 m^3/s at 2.24 kPa
Total airpower:	440 kW

Under these conditions, all the flow requirements were met and the input power minimized.

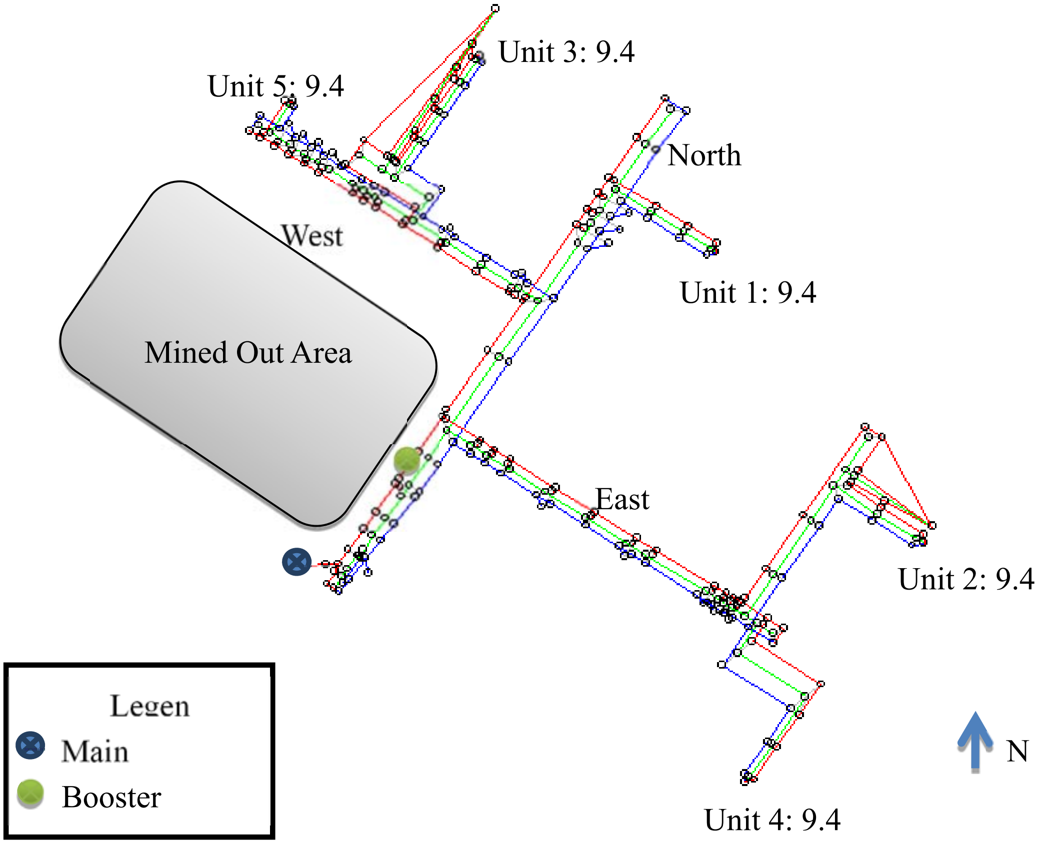

Figure 3.1. Proposed mine ventilation network for expansion of Highland 9 mine

<u>Two Fan System</u>. For this scenario, a single booster fan was added to the ventilation system. The booster fan is located in line with the surface fan (See Figure 3.1). The fan is positioned to assist the main fan in ventilating the working areas. Again, the problem was solved for fan duties using the VnetPC software, and the following results were obtained:

Main fan duty:	180 m^3/s at 1.37 kPa
Booster fan duty:	150 m^3/s at 0.57 kPa
Total airpower:	330 kW

Adding a booster fan to the system reduced the main fan pressure from 2.24 to 1.37 kPa and the total power requirement by 110 kW.

Table 3.1 shows a summary of results for the two ventilation scenarios. A comparison of the results shows that the system with one main fain and one booster fan is the preferred alternative for the proposed 5-year ventilation plan of this mine.

Table 3.1. Comparison of ventilation systems for the Highland 9 mine

	Quantity, m^3/s	Pressure, kPa	Air Power, kW
Single Fan System			
Main Fan (Expanded)	200.0	2.24	448.0
Two Fan System			
Main Fan	180.0	1.37	246.6
Booster Fan	150.0	0.57	85.5
Total			332.1

3.2. The SUFCO Coal Mine

The SUFCO mine is located in Sevier County, Utah. At the time of the visit, the mine was owned by Arch Coal, Inc., but has since been purchased by Bowie Resources, Ltd. SUFCO produces 6 million st of coal annually using one longwall and three development sections with continuous miners. This mine is one of the largest underground mines in the United States with an overburden depth of more than 600 m The longwall face is located at about 18 km from the mine portal. The coal is classified as highly susceptible to spontaneous combustion.

<u>Current Ventilation System</u>. The mine uses a wrap-around bleeder system equipped with three exhaust fans on the surface. The capacity of the main exhaust fan is 318 m^3/s at 1.8 kPa of static pressure. Of the total quantity provided, only 40 % reaches the working areas. The mine currently operates four working sections and one bleeder system. The flow requirements in this configuration are:

Longwall face (LW):	35.4 m^3/s
Set-up section (SET-UP):	11.8 m^3/s
Continuous miner, CM-A:	26.0 m^3/s
Continuous miner, CM-B:	26.0 m^3/s
Bleeder entry:	8.50 m^3/s

<u>Future Ventilation System</u>. To simulate large potential resistances, the mining sections were located in the far reaches of the mine with a third continuous miner (CM-C) added to keep up with the development work. Upon completion of mining the old areas were assumed to be sealed. Sealed areas were ventilated with 14.17 m^3/s of fresh air. For clarity in modeling, branches representing the mined out areas were deleted and replaced with a single fixed quantity branch. Based on this ventilation network, and the above flow requirements, the problem was to determine the best combination of fan operating points that minimize the power requirement and avoid unwanted recirculation. The problem was

solved using VnetPC.

Single Fan System**.** In this case, the ventilation network is the same as the current system but configured so that the system is used to ventilate working faces located at remote, and opposite ends. The system is equipped with a single surface fan. The ventilation simulator generated the following results:

Main fan duty:	349 m^3/s at 2.74 kPa
Total airpower:	956 kW

Under these conditions, all the flow requirements were met and the input power minimized.

Two Fan System. In this case, the network configuration shown in Figure 3.2 was used, with a booster fan installed near the confluence of the main returns serving both sides of the expanded network. The problem was solved using the VnetPC for the best combination of fan pressures. The resulting fan duties were:

Main fan duty: flow rate: 317.6 m^3/s at 1.74 kPa
Booster fan duty: flow rate: 81.5 m^3/s at 0.75 kPa
Total airpower: 613 kW

The resulting flow rates were evaluated for recirculation, and none was found.

Table 3.2 shows a summary of results for the two ventilation scenarios. A comparison of these results shows that the system with one main fain and one booster fan appears to be the preferred alternative for the proposed 5-year ventilation plan of this mine.

Table 3.2. Comparison of ventilation systems for the SUFCO mine

	Quantity, m^3/s	Pressure, kPa	Air Power, kW
Single Fan System			
Main Fan (Expanded)	348.9	2.74	956.0
Two Fan System			
Main Fan	317.6	1.74	553.0
Booster Fan	81.5	0.75	61.0
Total			613.0

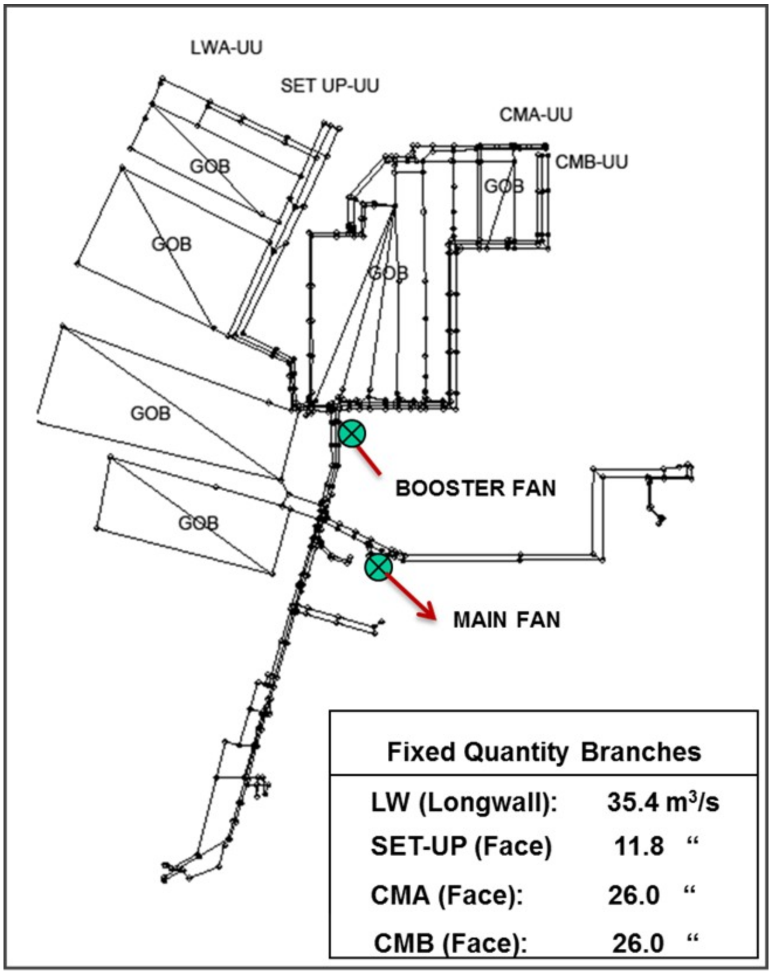

Figure 3.2. Expanded SUFCO mine ventilation model using two fans

A comparison of results of the single fan and two fan systems shows that the use of the booster fan reduces the main fan pressure, decreases the leakage flow rate (as shown by the difference in main fan quantities), and results in a net savings of 343 kW (956– 613 kW). This is a 36% reduction in air power compared to the expanded single fan system.

3.3. The Twentymile Coal Mine

Peabody Energy's Twentymile coal mine, located near Steamboat Springs in northern Colorado, operates two continuous miner sections and a longwall panel. Mine ventilation surveys were conducted in January 2012.

The mine is ventilated by an exhaust system. There are three exhaust fans in this mine, one main surface fan and two bleeder fans. At the time of the visit, the main fan was exhausting 373 m^3/s air at 4.0 kPa of static pressure. The rated power for the fan motor was 2,250 kW. There are three intake airways: the intake shaft, No. 5 Portal, and the bleeder shaft.

The flow requirements in the mine are:

Continuous Miner, section 1	33.0 m^3/s
Continuous Miner, section 2	23.6 m^3/s
Longwall face (LW)	17.4 m^3/s
Bleeder system	14.1 m^3/s
Old workings (near Portal 5)	66.1 m^3/s

Figure 3.3 shows the ventilation network for this mine. Based on this network and the above flow requirements, the problem was to determine the best fan operating points that fulfills the flow requirements and minimize the total power consumption.

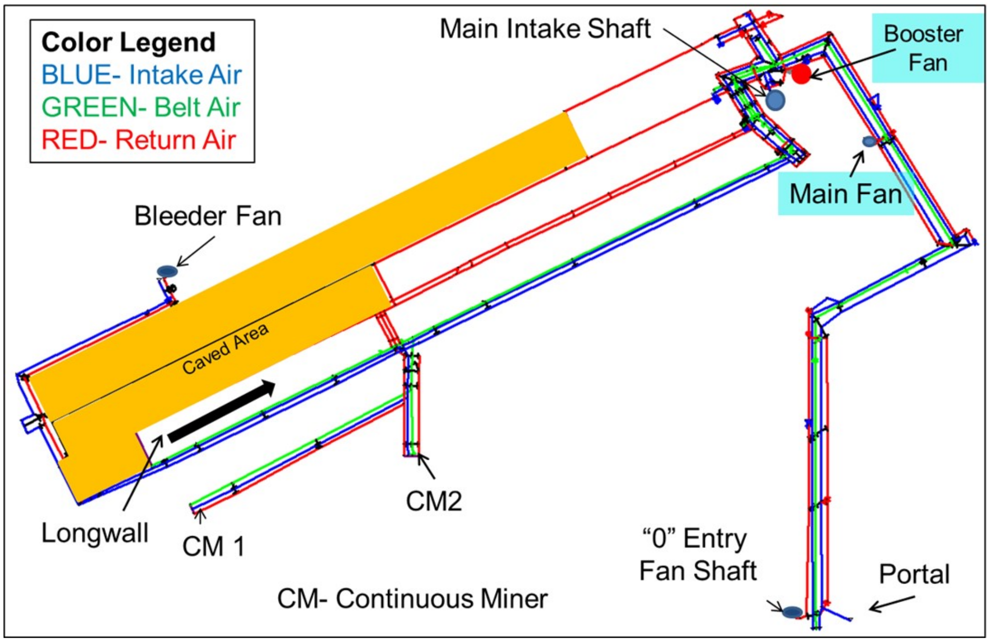

Figure 3.3. Mine ventilation network

To demonstrate the potential effectiveness of booster fans, the model of the Twentymile coal mine ventilation system was calibrated with the survey data and modified to include the flow requirements of an extended scenario. The mine ventilation network was simulated using VnetPC for three scenarios, a single surface fan system, a two fan system with main and booster fans, and a modified mine ventilation system. For each scenario, a set of feasible solutions was generated and the best fan combination chosen as the one that minimized the total power requirement.

<u>Single Fan System</u>. With this system, the mine was ventilated with the main surface fan only. The fan is located on top of the exhaust shaft. The problem was to determine the optimal pressure for this fan. It was found that when the fan pressure was greater than the optimum, all sections with fixed flow rates were regulated and some of the fan power was

wasted. When the fan pressure was inadequate, the solution to the problem could not be found except by adding booster fans. The problem was solved by using VnetPC software. Table 3.3 shows the solution to this problem.

Two-Fan System. In this case the ventilation system allowed the use of two fans: one on the surface and other in underground. The booster fan was located in a return branch (121-115 in Figure 3.4) that would best serve the network, and the problem was to determine the optimum combination of two fan pressures. The problem was approached by applying a procedure similar to that used for the single fan system, but including two fan pressures and evaluating the vent system for unwanted recirculation. Table 3.3 also shows the solution to this problem.

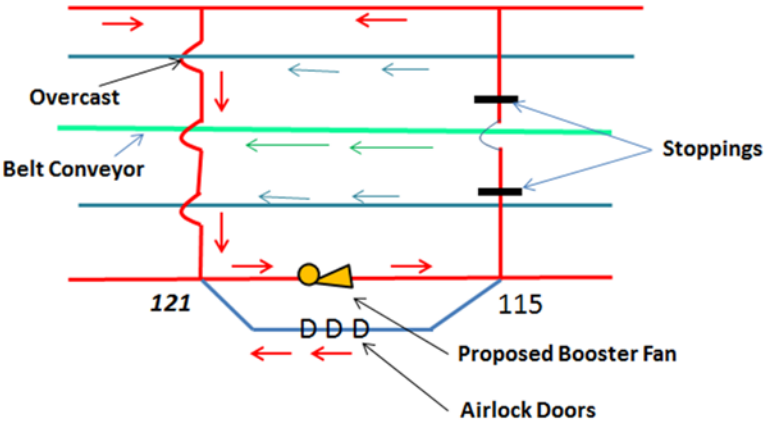

Figure 3.4. Proposed location of booster fan

A comparison of results of the two scenarios shows that the use of booster fans reduces the main fan pressures, decreases the leakage flow rate (shown by the difference of main fan flow rates) and results in a net saving of 120 kW (9% reduction.)

Table 3.3. Comparison of ventilation systems for the Twentymile mine

Fan Location	Quantity, m^3/s	Pressure, kPa	Air Power, kW
Single Fan System			
Main Fan (Expanded)	373.2	3.69	1377.0
Two Fan System			
Main Fan	352.4	2.89	1018.4
Booster Fan	190.9	1.25	238.6
Total			1257.0

Modified mine ventilation system. For this scenario, the network problem was modified by increasing the air requirement in the longwall section. Considering an increased methane emission rate from the prospective longwall panels, the air quantity at the face was increased from 14.4 to 47.2 m^3/s. The flow requirements at other sections including the old workings were kept constant.

As in the previous case, the problem was investigated for two conditions, one using the main fan only, and the other with the combination of a main fan and a booster fan. The booster fan was again installed at branch 121–115 and the airlock doors in the bypass drift. Table 3.4 shows the solutions to the problem for these two cases. A comparative evaluation of these results shows that the utilization of booster fan could reduce the main fan pressure from 5.75 to 4.05 kPa (30% reduction), and the air power from 2,707 to 2,583 kW (4.5% reduction).

Table 3.4. Comparison of expanded ventilation systems for the Twentymile mine

Fan Location	Quantity, m^3/s	Pressure, kPa	Air Power, kW
Single Fan System			
Main Fan (Expanded)	470.0	5.76	2707.2
Two Fan System			
Main Fan	433.6	4.05	1756.2
Booster Fan	270.2	3.06	826.8
Total			2583.0

A further evaluation of the previous results shows that in the single fan scenario, the flow requirements can only be met by increasing the main fan pressure to 5.76 kPa. A fan head of 5.76 kPa is quite high for mining applications. A system of this type will require several sets of airlock doors. If these doors are not installed or operated correctly, they will induce local flow recirculation and represent a safety hazard for all workers. In the two fan scenario, the system requires two fans where the main fan pressure dropped to 4.05 kPa. Reducing the main fan pressure by 30% is indeed a substantial contribution of the booster fan to the mine safety.

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4. Use of Booster Fans in Two Prominent Coal Mining Countries

Personnel of the University of Utah and the Missouri University of Science and Technology conducted booster fan surveys and inspections in six underground coal mines, three in Australia and three in the United Kingdom. In these mines, booster fans are used regularly to overcome adverse conditions created by higher airway resistances and increased airflow requirements. In both countries, booster fans are installed and commissioned after a period of review by the mines inspectorate, and their uses are justified through studies, and there is no other practical and economic way of ventilating planned production sections.

In Australia, booster fans are used in the two underground coal mining states of New South Wales and Queensland. In both states, the installation of booster fans requires a thorough evaluation and risk analysis and a management plan demonstrating adoption of best practice that must be submitted to the state inspectorate for approvals. Before the use of any booster fan is considered, alternate options should be evaluated.

In the United Kingdom, the 1956 Coal and Other Mines Regulations place a number of requirements on owners and managers both before these fans can be installed in a coal mine. One of these requirements is a detailed report on the intended use of the booster fan, specifying its effects on all parts of the mine. Another requirement is that the fan must be equipped with a monitoring system, and its operating conditions inspected every half hour. Although, this period is typically extended by the Mine Inspectorate to eight hours provided that certain requirements are met.

4.1. Booster Fan Inspections

Prior to inspection by the research group, a common survey form was developed to facilitate the systematic collection of relevant information on each company’s ventilation system, main and booster fan details, and the operator’s perspective on the use of booster fans. This form was reviewed by a group of experts.

The survey form contained four sections.

- Section A requested general information on the mining method, depth of overburden, distance from the surface to active workings, major air contaminants, and types of equipment used.
- Section B sought information on the company’s current ventilation system, fan duties, and type and size of surface fans. This section also sought information on details of any monitoring equipment used with the ventilation system.

- Section C sought technical information on the reasons for installing booster fans in their mines, advantages and disadvantages of booster fans, and their importance in the overall ventilation system.
- Section D requested the mine operator's perspective on the use of booster fans.

The form was sent to each mine manager prior to the mine visit and completed at the mine site in consultation with the mine ventilation engineer, an electrical engineer, and at least one additional senior technical person. For some sites, there were follow up calls to ensure the accuracy of the collected information. The collected information was then examined and evaluated against the adopted standards in each country. A summary of this evaluation is presented in this report.

a) Surveys in Australian Mines

The mines visited in Australia are identified here as A, B, and C. Detailed information for each mine is given in Table 4.1. A summary of the collected information is as follows:

Mine A is one of the deepest mines with workings located at about 500 m below surface and over 9 km from the access shafts. It produces 2 million tons of coal per year from one longwall and two development sections. The two major air contaminants are carbon dioxide and diesel products. The mine is ventilated by an exhaust system equipped with two 800-kW centrifugal fans with a combined capacity of 500 m^3/s at 7 kPa pressure. In addition, the mine operates one 600-kW centrifugal booster fan to exhaust 160 m^3/s at 3 kPa pressure. The booster fan is located in the main return airway and used to ventilate two working districts. The fan is installed in a 150-mm-thick concrete wall and equipped with environmental and fan monitors.

Mine B is the deepest mine, with workings located at about 550 m below surface and over 10 km from the main intake shaft. It produces 3.5 million tons of coal from one longwall and two development sections. The three major air contaminants are methane, carbon monoxide, and diesel products. The ventilation system includes a slope entry and shaft intake and an upcast haulage shaft all near the mine bottom. The surface fan house is equipped with two 750-kW centrifugal fans with a combined capacity of 350 m^3/s at 3.3 kPa total pressure. In addition, the mine operates four centrifugal booster fans located in main return airways. Each fan has a capacity of 150 m^3/s at around 3.5 kPa pressure. The fans are equipped with environmental and fan monitors, and are controlled from the surface.

Table 4.1. Use of booster fans in Australian coal mines—analysis of results

Scope of Survey	Mine A	Mine B	Mine C
Section A – General Information			
Mining method	Longwall (LW)	Longwall	Longwall
Production rate, tpy	2 million	3.5 million	3.2 million
Active sections: LW or Dev	1 LW + 2 Dev	1 LW + 2 Dev	1 LW + 2 Dev
Max overburden	500 m	550 m	320 m
Distance from surface to working	9 km	10 km	9.2 km
No. of employees	350	350	400
Equipment: E=electrical; D=diesel	1 E + 3D	1 E + 3D	1 E + 3D
Configuration: I=intake; R=return	2 I + 2 R + bleeder	3 I + 2 R + bleeder	3 I + 2 R + bleeder
Main contaminants	Diesel, methane	CO, CH_4, diesel	CO, CH_4, diesel, heat, sponcom
Vent system	Exhaust	Exhaust	Exhaust
Face ventilation	Auxiliary fans	Auxiliary fans	Auxiliary fans
Coal transportation	Conveyor	Conveyor	Conveyor
Additional information	Min Q(face) 25 m^3/s		
Section B – Ventilation System			
No. of main fans, type, diameter	2 centrifugal, 1.8 m	2 centrifugal, 2.5 m	2 centrifugal, 2.3 m
Motor size	2 x 1.8 MW/ea	2 x 750 kW/ea	2 x 770 kW/ea
Quantity, m3/s	250	175	320
Pressure, kPa	7.0	3.3	2.3
Atmospheric monitoring system	Yes + fan monitoring	Yes + fan monitoring	Yes + fan monitoring
Factors monitored	CO, CH_4, CO_2, fan, temp, tube bundle	CO, CH_4, CO_2, fan, temp, tube bundle	CO, CH_4, CO_2, fan, temp, tube bundle
AMS used for fan monitoring	Yes	Yes	Yes
Belt air used for intake ventilation	Yes	Yes	Yes
Section C – Utilization of Booster Fans			
No. of booster fans, type	1, centrifugal	4, centrifugal	2, centrifugal
Fan duty: quantity, m^3/s	170	150 ea	150 – 160 ea
Pressure, kPa	3.0	3.0	2.0
Impeller diameter, m	N/A	3 m	N/A
AMS for booster fan monitoring: factors	Q, P, Vibration B temp., CO	P, CH_4 B temp., CO	Q, P, Vibration, CH_4, B temp., CO
Additional information	Pit with insufficient flow capacity	Pit with insufficient flow capacity	Booster fan decommissioned
Location & reasons for site selection	Return, avoidance of travel route, min recirc.	Return, avoidance of travel route, min recirc.	Return, avoidance of travel route, min recirc.
Other reasons for site selection	Distance from surface High resistance return Leakage control	Distance from surface High resistance return Leakage control	Distance from surface Minimize recirculation Sponcom potential
Design Evaluation	Reviewed by experts	Risk assessment	Reviewed by experts
Electrical Interlocking	Main & booster fans Interlocked	Main & booster fans Interlocked	Main & booster fans Interlocked
Life of Fan	4- 5 yrs (shaft sinking)	8 yrs (rest of mine life)	Removed after 6 yrs.
Section D – Questions for Coal Mines			
Inspectorate Questions on booster fans:			
a) If permitted, would you use it again?	Yes	Yes	Y & N
b) Were inspectorate discussions unduly onerous?	Yes	Yes	Not trivial
Which factor contributed most to your desire to use a booster fan?	Distance from surface High resistance circuit	Distance from surface High resistance circuit	Distance from surface High resistance circuit
Advantages of using booster fans	Increased flow in high resistance circuits.	Mine could not operate without	Minimize leakage. Mine could not operate without
Disadvantages of using a booster fans	Risk of uncontrolled recirculation & fire	Risk of uncontrolled recirculation & fire	Risk of uncontrolled recirculation & fire

Mine C is a relatively shallow mine with workings located at about 320 m below surface and over 9 km from the access shafts. It produces 3.2 million tons of coal from one longwall and two development sections. The major air contaminants are methane, carbon monoxide, diesel products, and heat. In addition, the coal in the mine is highly prone to spontaneous combustion. The mine is ventilated by an exhaust system equipped by 2 centrifugal, fans with a combined capacity of 320 m^3/s at 2.3 kPa of total pressure. Until recently, the mine operated two 400-kW centrifugal booster fans to ventilate the working areas. Each fan had a capacity of around 150 m^3/s at 2 kPa total pressure. The fans operated without any problem. During the site visit, the booster fans were in the process of being decommissioned as they were no longer needed (Calizaya and Nelson 2014).

b) Surveys in British Mines

During the inspection period, three of the five significant coal mines using booster fans were visited. All three mines are located near Rotherham, in South Yorkshire. The mines are identified here as D, E, and F. Detailed information of each mine is given in Table 4.2. A summary of the collected information is as follows:

Mine D is one of the largest coal mines in the United Kingdom with an annual production in excess of 2.5 million tons. This production is achieved with a single longwall face located 850 m below the surface and around 8 km distant from the shafts. The retreat longwall is supported by two development sections. The panels, 2,500 m long and 350 m wide, are developed using single entries that are 5.5 m high and 6 m wide. Isolation pillars from 90 to 180 m wide are left between adjacent panels for roof support and to manage the risk of spontaneous combustion. The mine is ventilated by an exhaust system equipped with two surface fans and two sets of twin booster fans. The surface fans, of centrifugal type, are installed on top of the exhaust shaft. Each is capable of extracting 170 m^3/s at 2.8 kPa total pressure. Only one is operated at a given time. The two booster fans are double-stage axial fans, each with a capacity of 120 m^3/s at 3.5 kPa pressure. The fans are installed in a concrete bulkhead and above the coal seam to prevent spontaneous combustion. If no booster fans were used, the main fan pressure would have to be about 13 kPa.

Mine E is one of the oldest and deepest coal mines in the U.K. that is still in operation. It produces 3 million tons of coal per year from a seam located 1,000 m below surface, using a retreating longwall developed using single entries. The panel is supported by four development sections. The mine liberates about 25 m^3 of methane per ton of coal. Heat also adds another ventilation load. In the deepest areas the rock temperature is near 42°C. The mine uses an exhaust ventilation system with two intake shafts and one exhaust shaft. One of the intake shafts is used to transport men and materials, and the exhaust shaft is used to transport coal to the surface. Two identical centrifugal fans on the surface ventilate the mine. Each fan is capable of extracting 280 m^3/s of return air at 5.5 kPa total pressure. Only one fan is used at a given time. In addition to the main fan, the mine uses an axial booster fan in the main return. This position places the booster fan out of the travel route and minimizes recirculation and leakage. The booster fan is capable of extracting 138 m^3/s at 7.4 kPa pressure. Because of the high pressure difference across the stoppings some recirculation is allowed, but it is limited to less than 10%. To control the risks associated with fires, methane concentration is monitored regularly upstream and downstream of the fan.

Mine F is the largest and deepest remaining coal mine in Yorkshire. It produces 2.3 million tons of coal per year using a retreating longwall supported by four development sections. The mine has two shafts, each almost 800 m deep. The downcast shaft is used to transport men and materials and the upcast shaft to transport coal. Currently workings are in a 2.6-m-thick seam located at a depth of 780 m. The major environmental concerns are methane, heat, and dust. The mine uses two centrifugal surface fans and three booster fan installations. Each surface fan is capable of extracting 290 m^3/s at 2.5 kPa total pressure. Of the two fans, only one is used at a given time. Of the three booster fan installations, two are groups of four fans each, installed in parallel in the main returns. Each group has a combined capacity of 67 m^3/s at 2.5 kPa pressure. The third booster installation is a centrifugal fan, also installed in the main return, which has a capacity of 68 m^3/s at 7 kPa pressure. The locations of these fans were selected to minimize recirculation and leakage.

Table 4.2. Use of booster fans in British coal mines—analysis of results

Scope of Survey	Mine D	Mine E	Mine F
Section A – General Information			
Mining method	Longwall	Longwall	Longwall
Production rate, tpy	2,500,000	3,000,000 ROM; 1,000,000 Clean	2,300,000
Active Sections: LW or Dev	1 LW + 1 Dev + 1 Salvage	1 LW + 4 Dev	1 LW + 4 Dev
Max overburden, m	850	960	800
Distance from surface to working area	7,500	8,000	9,000
No. of employees	700	500	650
I = Intake; R = return; N = neutral	1 I + 1 R	1 I + 1 R	1 I + 1 R
Main contaminants	Dust, Methane	Dust, Methane, Heat	Dust, Methane, Heat
Vent system	Exhausting	Exhausting	Blowing
Face Ventilation	Auxiliary fans	Auxiliary fans	Auxiliary fans
Coal transportation	Conveyors	Conveyors, Skips	Conveyor, Skips
Section B – Ventilation System			
No. of centrifugal main fans, diameter	2 centrifugal	2 centrifugal, 5.3 m	2 centrifugal, 4.14 m
Motor Size, kW	757	2,300	2,200
Quantity, m^3/s	169	280	290
Pressure, kPa	2.8	5.5	2.5
Atmospheric monitoring system	Yes	Yes	Yes
Factors monitored	CO, Methane, Fan pressure, Fan bearing temp, Fan vibration	CO, Methane, Fan pressure, Fan bearing temp, Fan vibration, Airlock position	CO, Methane, Fan pressure, Fan bearing temp, Fan vibration, Airflow
AMS used for fan monitoring	Yes	Yes	Yes
Belt air used for ventilation	No	Yes	Yes
Section C – Utilization of Booster Fans			
No. of booster fans, type	4 axial cluster fans	1 axial	One centrifugal fan and two sets of 4 axial cluster fans
Fan Duty: Quantity, m^3/s	120	138	Centrifugal: 68 & Axial: 67
Pressure, kPa	3.5	7.4	Centrifugal: 7 & Axial: 2.5
Impeller diameter, m	2	2.05	Centrifugal:1.6 & Axial:1.2
AMS for booster fan monitoring: factors	Airflow, Pressure, Vibration, Bearing temp, Methane, CO, Alert/alarm indicator	Pressure, Vibration, Bearing temp, Methane, CO, Alert/alarm indicator	Pressure, vibration, temp, methane, CO, Alert/alarm indicators, water curtain and water curtain pressure
Location & reasons for site selection	Required to provide adequate ventilation, location chosen to minimize leakage	Required to provide adequate face ventilation, location chosen to minimize recirculation and leakage	Chosen to assist main low-pressure fan, location chosen to minimize recirculation and leakage
Design Evaluation	Full pressure-quantity survey of mine	Other alternative were considered but no other alternatives were as effective as booster fans	Full pressure-quantity survey of mine
Electrical Interlocking on Fans	No electrical interlocking	No electrical interlocking	No electrical interlocking
Life of Fan System		Planned for 8 years, actual life 3 years	More than 20 years
Section D – Questions for Coal Mines			
Inspectorate questions on booster fans:			
a) If permitted, would you use it again?	Yes	Yes	Yes
b) Were discussions unduly onerous?	No	No	No
Which factor contributed most to your desire to use booster fans?	Spontaneous combustion	Distance from surface; Cost effective; Leakage	High Resistance; Cost effective
Advantages of using booster fans	Decrease main fan pressure	Increase flow; Decrease main fan pressure	Increase flow
Disadvantages of using booster fans	Recirculation	Uncontrolled recirculation	Increased noise, and coal dust

4.2. Sample Booster Fan Installations

Figure 4.1 shows a schematic of typical booster fan system in an Australian underground coal mine where the working areas are located at about 500 m below surface. The system consists of two double-inlet centrifugal fans, installed in concrete bulkheads in the main return airways. Each fan is equipped with heavy-duty airlock doors, barrier fences, and an independent environmental monitoring system. Because of regulatory restrictions, the fan motor is located in a specially designed, fire resistant chamber, which is ventilated with fresh air by two separately routed, 30-cm-diameter pipes. Double air-lock doors, designed to stand high pressure differences, are used to allow machine access to the fan site and to minimize recirculation (Gillies 2012). The 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 methane and carbon monoxide concentrations, differential pressure, and air flow rate. The system is designed to deliver 300 m^3/s at 3.5 kPa pressure, with the surface fans delivering 350 m^3/s at 3.3 kPa. The fact that the surface fan capacities are larger than those of the booster fans reduces the possibility of flow recirculation. A site specific operating procedure is used to start and stop the fans and to avoid the onset of unwanted flow recirculation.

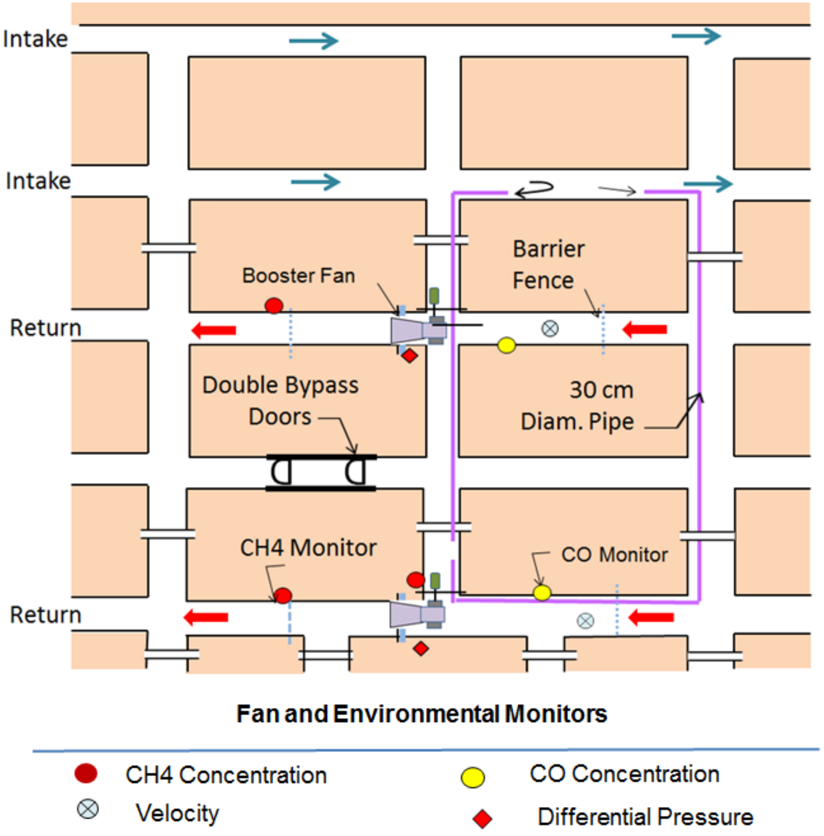

Figure 4.1. Typical booster fan installation in Australian coal mines

Figure 4.2 shows a schematic of a booster fan installation in a British coal mine with significant and airflow requirements. In this case, the workings are located at about 1,000 m below the surface, where the rock temperate reaches 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 1,500-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, air velocity, and bearing temperatures, to assess the fan operating conditions, methane concentration to limit the potential for the formation of an explosive atmosphere, and carbon monoxide monitors, to detect the early stages of combustion. In addition, this mine uses a tube bundle system to continuously sample and evaluate the mine air for methane and carbon monoxide concentrations.

The fan system is designed to deliver 160 m^3/s at 7.0 kPa pressure with the surface fans delivering 280 m^3/s at 5.5 kPa. A site specific safe operating procedure is used to start and stop the fans and the mining machinery inby the fan. Although series ventilation is discouraged because of the high pressure differentials across the stoppings, some recirculation (< 10%) is allowed (Leeming 2012).

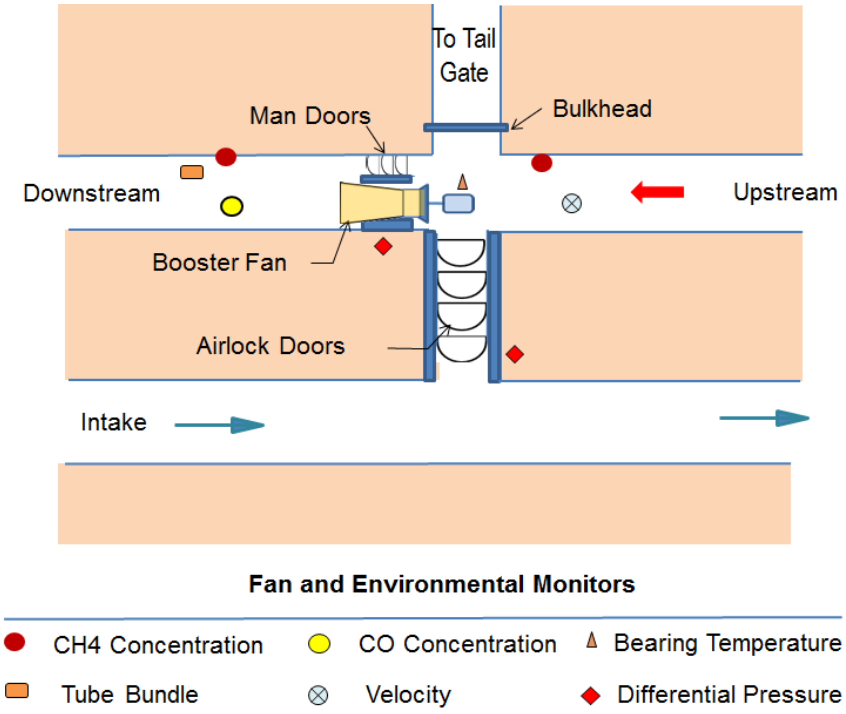

Figure 4.2. Typical booster fan installation in British coal mines

4.3. Summary of International Coal Mine Surveys

A booster fan system 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.

Table 4.3 shows a comparative evaluation of current regulations, types of fans used, and basic requirements under which booster fans are designed, installed, and operated in Australian and British coal mines. In both countries, the booster fan installation plan is justified using studies that document the risks associated with booster fan use, the control measures included in the design, and the plan approved by the mine inspectorate. In every case, booster fans are installed in the return airway, and are equipped with heavy duty airlock doors to minimize leakage and recirculation and a monitoring system to evaluate the operating conditions of the fans. Depending on the pressure differential, a booster fan requires at least two airlock doors in series. Furthermore, the fan operating conditions are evaluated by an atmospheric monitoring system. The variables being monitored included methane and carbon monoxide concentrations, air pressure and flow rate, fan vibration, and bearing temperature.

This table also shows some differences which are attributed to local conditions. One difference is that recirculation is not allowed in Australian mines, while recirculation of less than 10% is accepted in British mines. Another is that electrical interlocking between the main and booster fans is required in Australian mines, but not in British mines. In fact there was no electrical interlocking between fans at any of the mines visited in the UK. In both countries booster fans are used to assist the main fans in ventilating working areas with higher volumetric requirements and located at great depths. This table also shows some similarities in regulations, and good practices for the operation of booster fans in coal mines.

References

Calizaya, F. and Nelson, M.G. 2014. Booster Fans in Australia and British Coal Mines. *Proceedings of the 10th International Mine Ventilation Congress*. The Mine Ventilation Society of South Africa.

Gilles, A.D.S., and Calizaya, F. 2012. Use of underground booster fans in foreign prominent coal mining countries compared with the ban in the United States. *Proceedings of the 14th U.S./North American Mine Ventilation Symposium*. Edited by F. Calizaya and M.G. Nelson. Salt Lake City, UT: University of Utah, June 17-20.

Leeming, J.R., and Webb, D.J.T. 2012. Underground booster fans—Current UK practice for safe installation and management. *Proceedings of the 14th U.S./North American Mine Ventilation Symposium*. Edited by F. Calizaya and M.G. Nelson. Salt Lake City, UT: University of Utah, June 17-20.

Table 4.3. Use of booster fans in U.K. and Australian coal mines

Description	Australia	United Kingdom
Regulations	Coal mine operators are allowed to use booster fans to assist main fans in Australian mines (a)	Booster fans are accepted as safe and effective ventilation control devices in underground coal mines (b)
Reasons for using booster fans	Because of mine depths (± 500 m), remoteness of workings, and economic and environmental reasons	Because of mine depths (> 800 m) and increased resistance, to decrease effective mine resistance, and economic reasons
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*
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 anti-reversal doors at discharge
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 airway. Motor enclosed in fireproof housing
Recirculation	Return air from one production district cannot be used in another production district and recirculation is not an accepted practice. Booster fans are generally located so that the return pressure outby the booster fan remains lower than the adjacent intake roadway.	Recirculation and series ventilation not prohibited; heavy duty airlock doors provided to reduce recirculation.
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
Electrical Interlocking	Electrical interlocking between main and booster fans required	Electrical interlocking between main and booster fans not required
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.

(a) Queensland: http://www.legislation.qld.gov.au/LEGISLTN/CURRENT/C/CoalMinSHR01.pdf
New South Wales:
http://www.legislation.nsw.gov.au/maintop/view/inforce/subordleg+783+2006+cd+0+N

(b) United Kingdom: http://www.legislation.gov.uk/uksi/1956/1764/made

5. The University of Utah Coal Mine Ventilation Model

The University of Utah coal mine ventilation model was upgraded to include two fans (main and booster), four stoppings, and a gas injection system. Figure 5.1 shows a line diagram of this model. The model consists of 0.15-m (6-in.) diameter ductwork configured in a common U-shaped ventilation system. The intake and return airways are joined by five crosscuts. Four of them (A, V3, B, and C) are kept blocked by perforated gate valves that form leakage paths, and the last crosscut represents the working area, where a fixed quantity of air is required. The system is powered by two fans, a 3.75-kW main fan and a 2.25-kW booster fan. The booster fan is installed in a bypass duct between the first and second crosscuts. Two gate valves, one in the straight section (V2) and another in the bypass (V1), are used to simulate leakage paths of variable resistances. Each fan is equipped with a variable-frequency drive motor (30–60 Hz), which allows each fan to operate at different speeds and to develop different pressures to meet specific flow requirements.

Pressurized carbon dioxide is used to simulate mine gas emissions. The gas was injected at two stations under controlled conditions.

This system was used to investigate the air-gas flow distribution in the model for different fan and regulator settings. The main objective of this investigation was to determine the critical factors that affect the pressure-quantity distribution in the simulated gob area.

Figure 5.2 shows photos of various views of the University of Utah ventilation model.

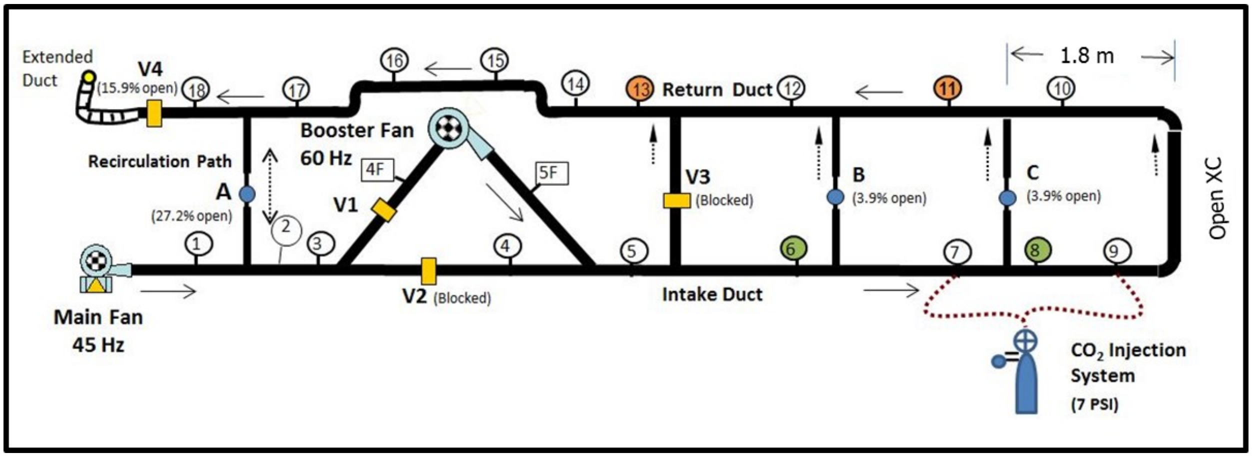

Figure 5.1. Schematic of the University of Utah coal mine ventilation model

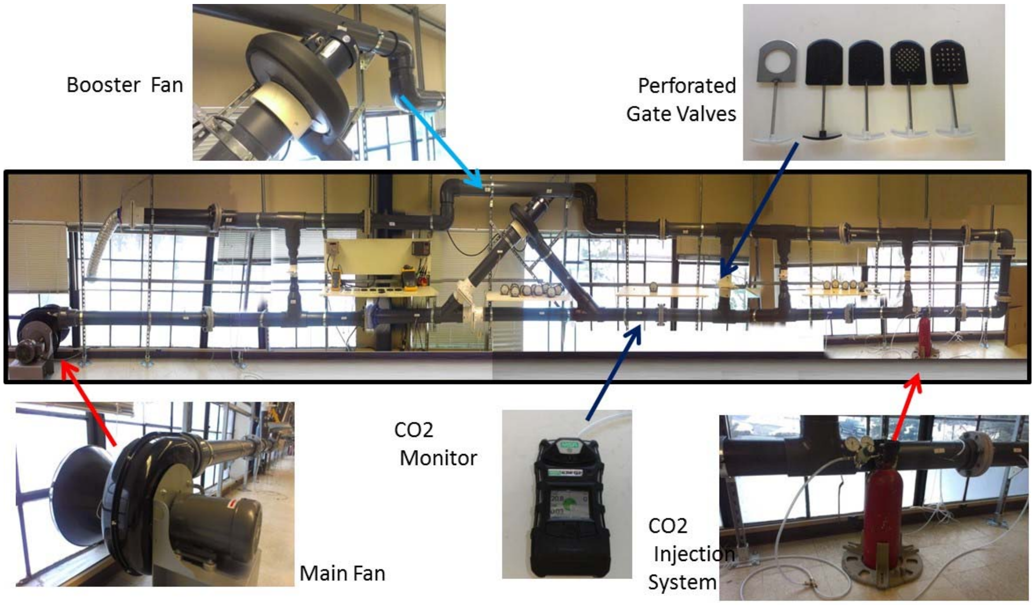

Figure 5.2. Side view of the University of Utah's coal mine ventilation model

5.1. Laboratory Experiments

Several experiments evaluating the air quantity-pressure distributions in the model were completed. The model conditions and results of three of these experiments are presented below.

<u>Near-zero local recirculation</u>. This experiment was conducted with the main fan set at 2.0 kPa (60 Hz), and the booster fan at 1.2 kPa (50 Hz). Crosscut valves A, V2, V3, B, and C were completely closed, and the bypass valve V1 was wide open.

After the main fan had run for approximately 1 minute to allow the system to achieve a dynamic equilibrium, the booster fan was turned on, and pressure-quantity surveys were carried out. Velocity pressures were monitored at stations 2, 3, 4f, 5, and 8. The pressures measured at stations 2 and 4f were used to determine the capacity of the fans, while the pressures monitored at stations 3, 5 and 8 were used to determine the flow recirculation around the fan and the quantity of air directed to the workings (last open crosscut). In addition, static pressures were measured throughout the system. During this experiment the air temperature was 21^{0}C and the barometric pressure was 86 kPa. Under these conditions, no local recirculation around the booster fan was detected. Figure 5.3 shows the pressure gradients for this experiment. Two significant pressure changes can be seen in these graphs: a sudden increase in pressure around 6.5 m from the origin due to the booster fan, and a large pressure drop at about 15 m from the origin due to shock losses caused by the two 90°-elbows near the simulated working areas (last open crosscut).

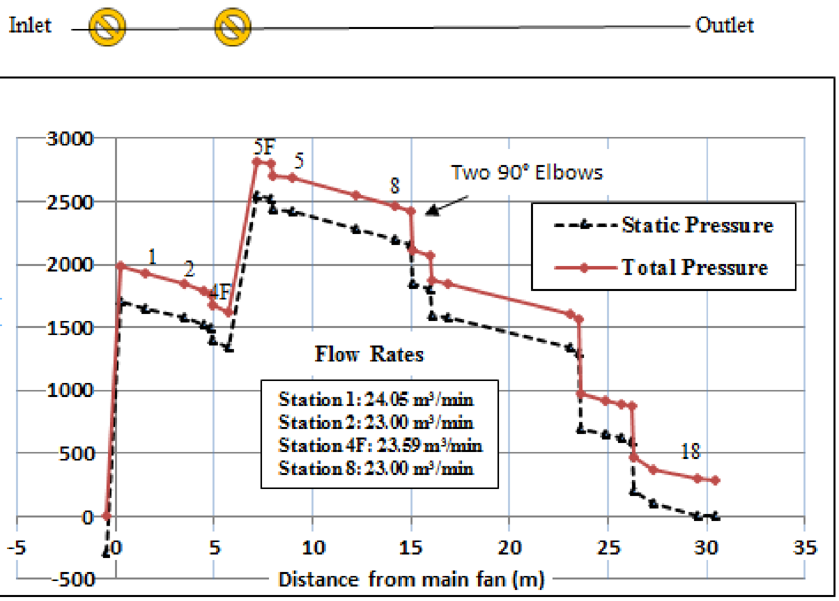

Figure 5.3. Pressure profiles with near zero local recirculation.

Based on the pressure profiles shown in Figure 5. 3, the following fan operating points and flow rates were recorded:

Main fan: 24.05 m^3/min at 1.9 kPa
Booster fan: 23.59 m^3/min at 1.2 kPa
Quantity directed to the face (open cross-cut): 23.00 m^3/min
Backflow through valve V2: 0.59 m^3/min.

Of the total quantity handled by the booster fan (23.59 m^3/min), 23.00 m^3/min reached the simulated face, and 0.59 m^3/min recirculated through valve V2. The local recirculation was estimated at 2.5%.

<u>18.5% local recirculation</u>. For this experiment, the bypass valve V1 was completely open and valve V2 replaced by a regulator that had 28% of its cross-sectional area open, (representing damaged airlock doors). All the intermediate crosscuts except the last one were completely closed. An experiment was conducted with the main fan operating at 60 Hz and the booster fan operating at 50 Hz. As in the previous case, the velocity pressures were measured at stations 2, 3, 4F, 5, and 8. These were collected to determine the airflow rates in the model and to estimate the local recirculation through the damaged airlock doors (V2). In addition, static pressures were measures at each pressure tap. These were then used to plot pressure gradients for the system. Because valves V3, B, and C were completely blocked the leakage flow in this system was restricted to that of crosscut A. For the stated conditions, the quantity of air circulated by the main was 23.25 m^3/min and the quantity directed to the face was 22.00 m^3/min.

Figure 5.4 shows the pressure gradients generated during this experiment. The upper graph represents the total pressure, an the lower graph, the static pressure. The velocity pressure is the area between the two graphs. Based on these graphs, the following fan operating points and flow rates were estimated:

Main fan: 23.25 m^3/min at 2.05 kPa
Booater fan: 27.01 m^3/min at 0.97 kPa
Quantity directed to the face: 22.00 m^3/min
Backflow through valve V2: 5.01 m^3/min.\

For these values, the local recirculation was estimated at 18.5%.

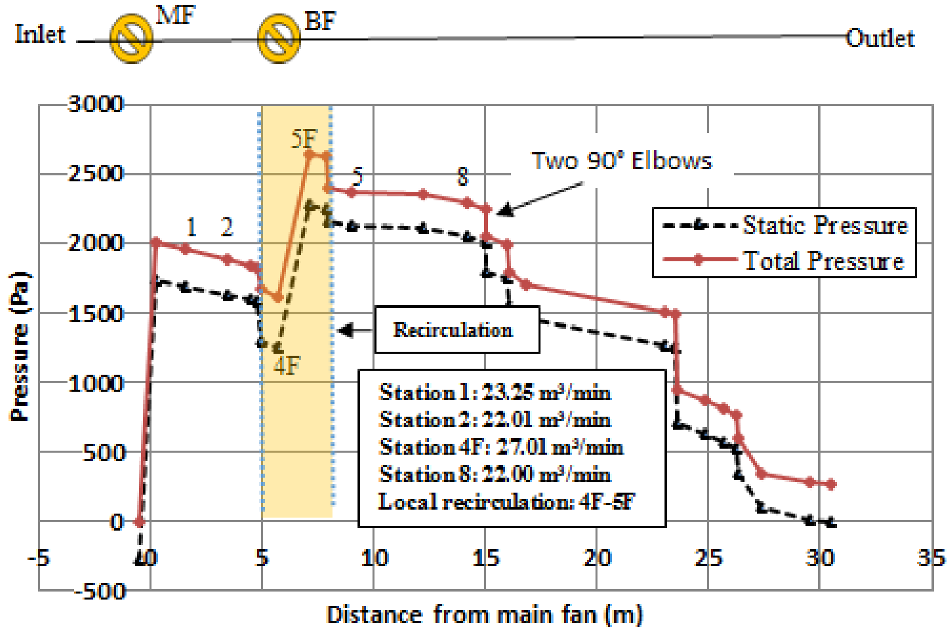

Figure 5.4. Pressure profile with 18.5% local recirculation

5.2. 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 working, leading to overall lower general body gas concentrations (McPherson, 1993).

Percent Recirculation (%R). Based on the measuring stations of Figure 5.1, this parameter is calculated by:

$$\%L = \frac{Q_2 - Q_1}{Q_8} 100 \qquad (1)$$

Where: $Q_2 - Q_1$ = fraction of return quantity passed back into the intake, m^3/s
Q_8 = quantity of air used effectively at the workings, m^3/s.

The objective of this experiment was to demonstrate the general air-gas flow behavior under controlled recirculation and to observe the variations of gas concentration with changes of fan pressure. To this purpose, the University of Utah coal mine model was modified to include a regulator at the discharge end to intentionally induce return-air recirculation while the gas injection rate is kept constant. A pressurized CO_2 container connected to the inlet duct near the open crosscut was used to simulate the gas emissions from the coal (Figure 5.5). In addition, the model was equipped with two MSA ALTAIR 5 multi-gas detectors to monitor CO_2 concentrations. Several recirculation tests were carried out to determine the carbon dioxide increase in the simulated working area when a booster fan was used to induce controlled recirculation (Shriwas 2014).

Figure 5.5. CO_2 Gas injection system

Sample Experiment. This experiment was carried out for two fan conditions: (1) using main fan only and (2) using two fans: one main fan and one booster fan. Prior to this experiment, to allow some flow recirculation, two changes were made to the model. The control valve in crosscut A was purposely replaced with a perforated plate, and the control valve V4, was partially blocked (72% of its area) to create high resistance in the return airway. All other crosscuts were kept blocked to reduce leakage flow through them. Valve V2 was replaced by a solid plate to prevent local recirculation and valve V1 was fully opened to establish a flow-through path. During the experiment, the main fan was operated at its lowest speed (30 Hz), the booster fan at its highest speed (60 Hz), and the CO_2 gas injected at station 9 at a gage pressure of 35 kPa (5 psi).

Pressure-Quantity Surveys. The static pressures were measured at 18 different stations along the ductwork, and the velocity pressures at four stations (1, 2, 5f, and 8). These measurements were used to determine the airflow rates and to plot pressure gradients. Table 5.1 shows a summary of average velocity pressures and airflow quantities for two fan conditions. The velocity pressures were used to calculate the air flow rates and determine the leakage rates (from intake to return) for the single fan system, and the recirculation rates (from return to intake) for the two fan system. For the latter, applying equation 1, the recirculation fraction was estimated at 17.2%.

Table 5.1. Sample experiment—velocity pressures and calculated flow rates

Description	Stations	Ps kPa	Pv kPa	V* m/min	Q m^3/min	Leakage Q, m^3/min
Main fan only	1	0.590	0.017	348	5.92	+ 0.39
	2	0.568	0.015	327	5.56	
	8	0.500	0.015	324	5.51	
Main fan and booster fan	1	0.420	0.085	772	13.13	− 2.72
	2	0.335	0.105	932	15.85	
	5f	1.580	0.116	932	15.85	
	8	1.400	0.103	932	15.85	

*Calculated for air density, ρ =1.01 kg/m^3 and A = 0.017 m^2

Figure 5.6 shows the pressure gradients for this experiment. The effect of the booster fan is represented by a sudden jump in static pressure at about 5.6 m from the fan inlet.

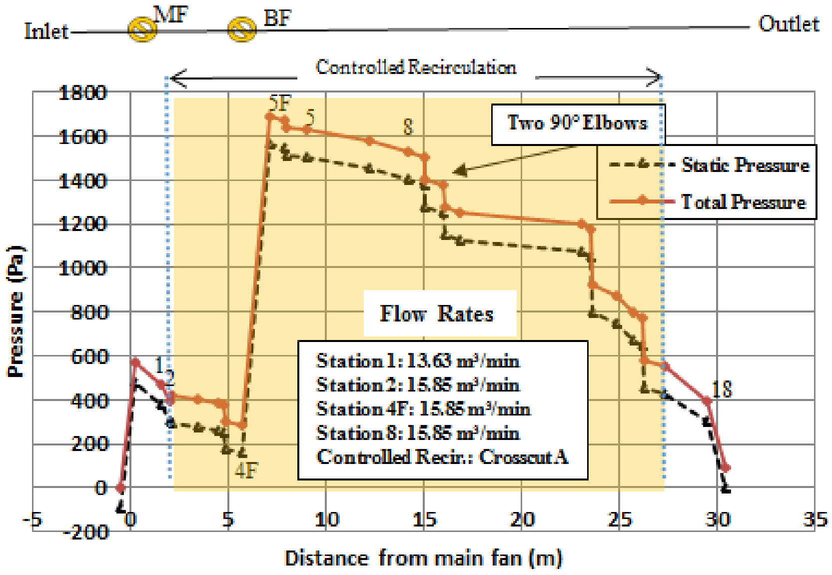

Figure 5.6. Pressure gradients from main fan inlet to outlet (17% recirculation)

Carbon Dioxide Concentrations. CO_2 monitors were connected to stations 10 and 18 and operated to collect the CO_2 concentrations in the model for two gas flow conditions: (1) with no gas injection to determine the ambient CO_2 concentration, and (2) when the CO_2 injection system was switched on and the gage pressure set at 35 kPa.

When the main fan was switched on to operate at its lowest speed, the gas monitors recorded the background concentration of the gas. This reached a steady state condition rapidly (point B in Figure 5.7). Five minutes after the start, the CO_2 gas was released from its source and injected into the system. For the same airflow rate, this caused a sudden increase in gas concentration at stations 10 and 18 (from point B to C).

Ten minutes after the start, the booster fan was switched on and operated for 5 minutes. This increased the airflow rate at the simulated working face, causing a sudden drop in gas concentration (point C). The increased flow rate was partly caused by an increase in flow through ventilation, and partly by partial recirculation of return air. Fifteen minutes after the start, the booster fan was switched off while the main fan was still running. Again, there was a rise in gas concentration in the return air (point D), because of the smaller flow rate circulated by the main fan. Twenty minutes after the start, the gas injection into the system was stopped (point E), causing a fall in gas concentration in both the intake and return airways.

This experiment showed that the operation of the booster fan increased the capacity of the ventilation system, thus increasing the air velocity at the face. In a coal mine, an increased air velocity reduces the tendency of methane layering due to better mixing with air. Recirculation, a condition associated with the use of booster fans, can be controlled by adequately sizing and positioning the fan. In this experiment, return air recirculation reduced the gas concentration at the face by about 55%.

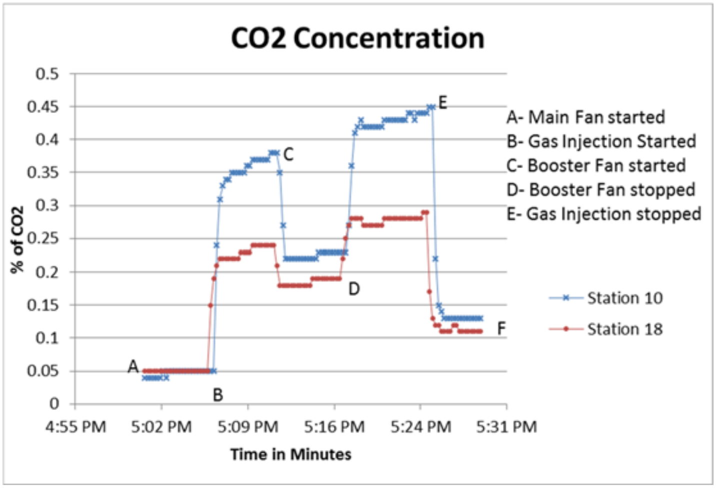

Figure 5.7. Variation of CO_2 concentrations with time

5.3. Main Findings and Discussion

Recirculation is the major concern associated with the use of booster fans. In controlled recirculation, a portion of the return air is purposely mixed with the intake air and the mixture is directed towards a working district, while the air quantity and gas concentrations in the air are closely monitored and managed (Burnett 1988 and Wempen 2012).

Several experiments were conducted in a laboratory model to determine the effect of controlled recirculation on the quality of air circulated through the working faces. Preliminary results showed that controlled recirculation can be beneficial to ventilation planning because it reduces the build-up of air contaminants at the working faces and reduces the overall power consumptions.

The laboratory experiments demonstrated that the size of the booster fan relative to that of the main fan is an important consideration. If the booster fan operates at a pressure as large as or larger than the main fan pressure, there is significant potential for recirculation. In addition, the location of a booster fan in a ventilation system has a significant impact on recirculation. The closer the booster fan is to the development or production sections, the greater the likelihood of recirculation regardless of the booster fan pressure

Recirculation can be controlled by adequately sizing and positioning the fan. Recently developed technology, such as wireless communication, automatic monitoring systems, and improved power system control, can contribute to the correct and safe operation of booster fans (Gangrade 2013).

5.4. Computational Fluid Dynamics (CFD) Modeling

The primary purpose of the physical lab model was to obtain measurements that could be used to calibrate a computer model so that more extensive and complicated configurations could be examined. In this case, the CFD numerical modeling was done using the software package FLUENT, provided by ANSYS. The application of this software in mine ventilation is not in modelling the overall mine system, but rather in analyzing detailed fluid flow at specific locations such as the working face, fan installation, or leakage through stoppings (Stephens 2011).

Using this software package, a 3-D simulated laboratory model was drawn at 1:1 scale and meshed using the integrated ANSYS Workbench modules. The model includes one inlet, one working face, one return, and four crosscuts. It is powered by a 1.5 kW fan. All crosscuts, except the last one are blocked by stoppings. In FLUENT, the stopping gates were modeled as porous jumps which are defined by face permeability (2.7×10^{-8} m^2), a pressure jump coefficient (1000 m^{-1}), and the gate thickness (0.003175 m). The permeability and pressure jump coefficients were derived from the pressure and velocity measurements. The input parameters (boundary conditions) were defined by inlet pressure (430 Pa), inlet velocity (14.2 m/s), and outlet pressure (0 Pa).

The CFD model was calibrated to the laboratory model, with the main fan pressure at 430 Pa. Table 5.2 shows the laboratory measurements and the CFD average velocities for five critical stations. All the CFD velocities were within ±5% of the lab measurements.

Table 5.2. Laboratory and CFD model correlation using average velocity (m/s)

Model	Station				
	1	5	6	7	8
Lab	14.20	11.98	10.68	9.59	8.55
CFD	13.75	11.93	10.58	9.37	8.51
% Difference	3.2	0.4	0.9	2.3	0.5

Figure 5.8 shows the CFD model geometry (a), velocity contour lines (b), and static pressure contour lines (c). A closer look at Figure 5.8b shows a decrease in velocity as the air moves towards the face due to leakage through the simulated stoppings. This figure also shows the velocity variation through the crosscut due to the changes in duct diameter. Figure 5.8c shows the pressure variation along the ductwork, which decreases from about 400 Pa at the fan to almost zero at the system discharge.

In general, the results of the laboratory model and the CFD model are all similar. However, there is one observation worth mentioning. The general trend of the leakage through stoppings is the same, a decay function. In all cases, the majority of the leakage occurs through the stopping closest to the fan. In the sample case, 35% of the leakage occurs through the first leakage path.

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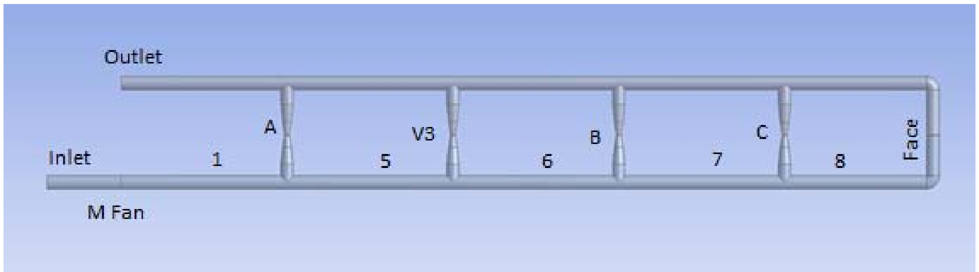
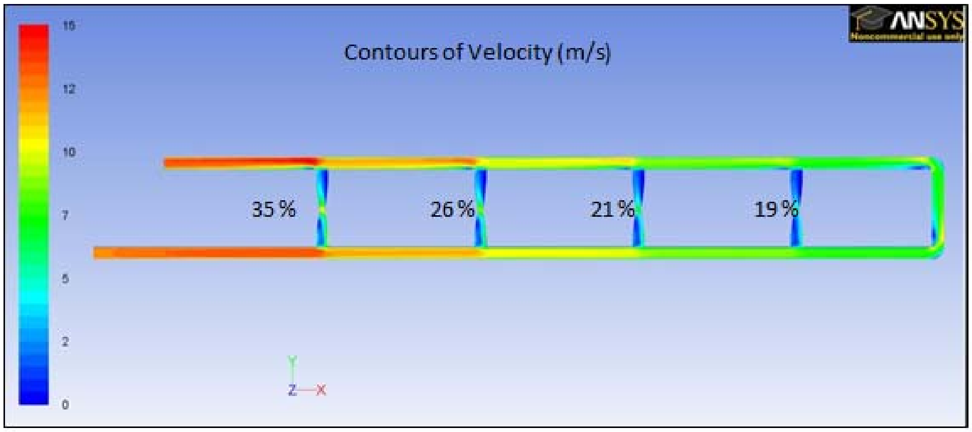
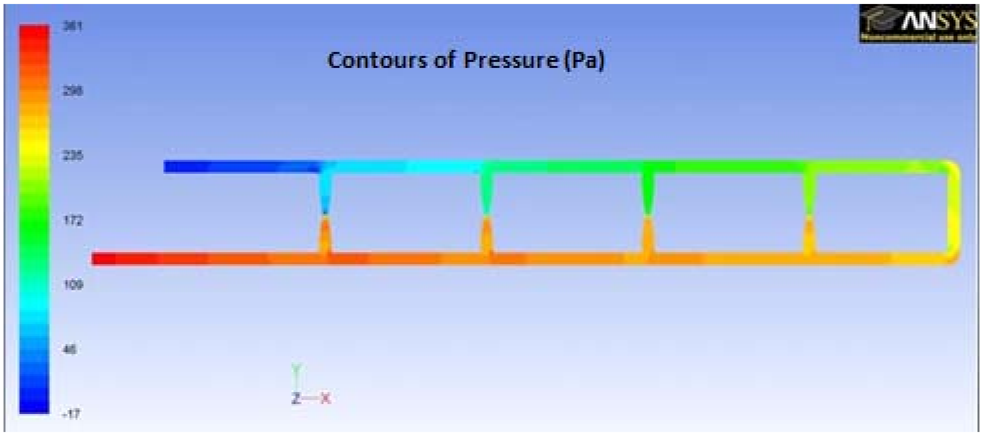


a) CFD model geometry



b) Velocity Contours (m/s)



c) Static pressure Contours (Pa)

Figure 5.8. Fluent output showing CFD model geometry (a), velocity contour lines (b), and static pressure contour lines (c)

6. Booster Fan Installation at MS & T's Experimental Mine

The experimental mine at the Missouri University of Science and Technology (MS & T) is an underground limestone mine located in Rolla, Missouri. The mine is accessed by two adits (Wheeler and Kennedy). It has three raises to the surface and a primary ventilation shaft. The mine portals both have ventilation doors. The mine is ventilated by a 22.5-kW (30-hp) blower fan located on surface, near the top of an intake shaft. The shaft is about 1.5 m in diameter and 12 m long. The fan is connected to the shaft through a 1-m-diameter duct and a 90º elbow. There are two working areas in this mine, one on the west and the other on the east side of the mine. Of these two, only one is active at a given time. The required quantity of air per working was estimated at 16.5 m^3/s. Bulkheads, doors, and regulators are used to direct the air to the workings. Most of the contaminated air is exhausted through the Wheeler Portal.

Two 12-kW (16-hp) booster fans (West and East) were installed in steel bulkheads in a flexible manner so locations can be varied during the project. Figure 6.1 shows the ventilation map of the mine, including the locations of main and booster fans, the flow directions, and the locations of doors, regulators, and simulated working areas (Habibi, 2012).

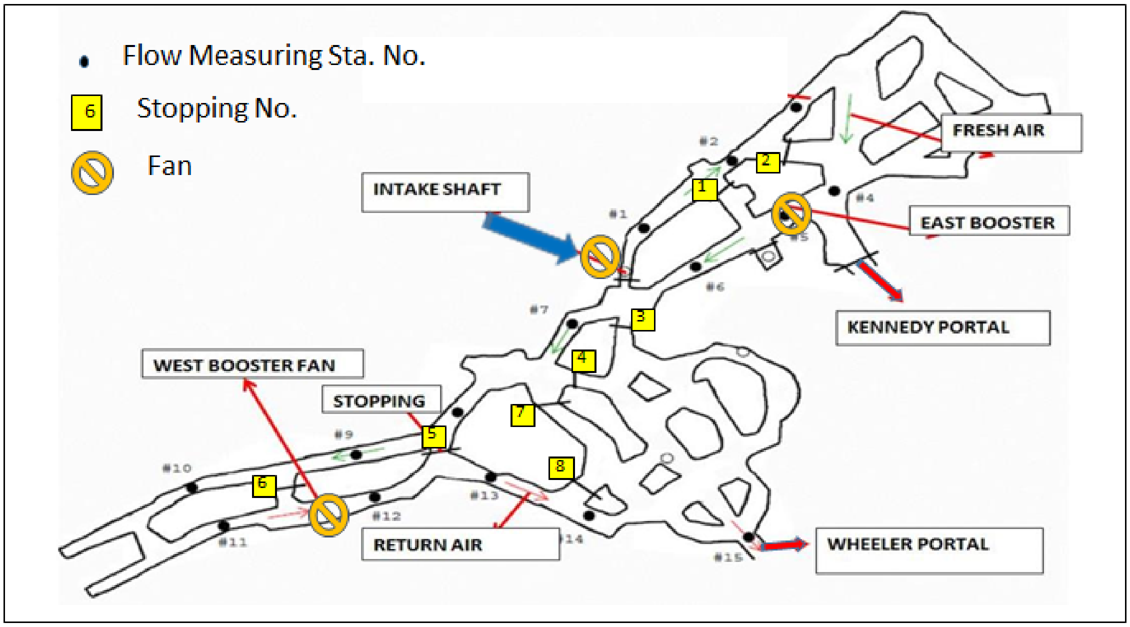


Figure 6.1. The MS & T experimental mine map.

Various experiments were conducted to investigate the fan performances, pressure drops across the bulkheads, and volume flow rates at different blade settings and fan speeds. Experiments were also conducted to determine the effect of booster fans on the overall flow distribution in the mine.

6.1. Booster Fan Installation Details

Site Preparation. The site preparation started in early February 2012 with delivery of two booster fans to Rolla by truck from Spendrup Fan Company, Grand Junction, CO. Both fans were checked and tested at Rock Mechanics and Explosives Research Center. Construction at the mine included drift widening and bulkhead construction. Each bulkhead was built on a framework of treated timbers, 150 x 150 mm. The timbers were bolted with100-cm, fully threaded, expanded bolts to the walls and roof (Figure 6.2a). The void between the timbers and the wall was sealed by applying cementitious plaster mixture on metal laths (Figure 6.2b). Additional effort was made to fully seal the void and minimize leakage through the bulkhead by applying expanded foam (Habibi 2013).

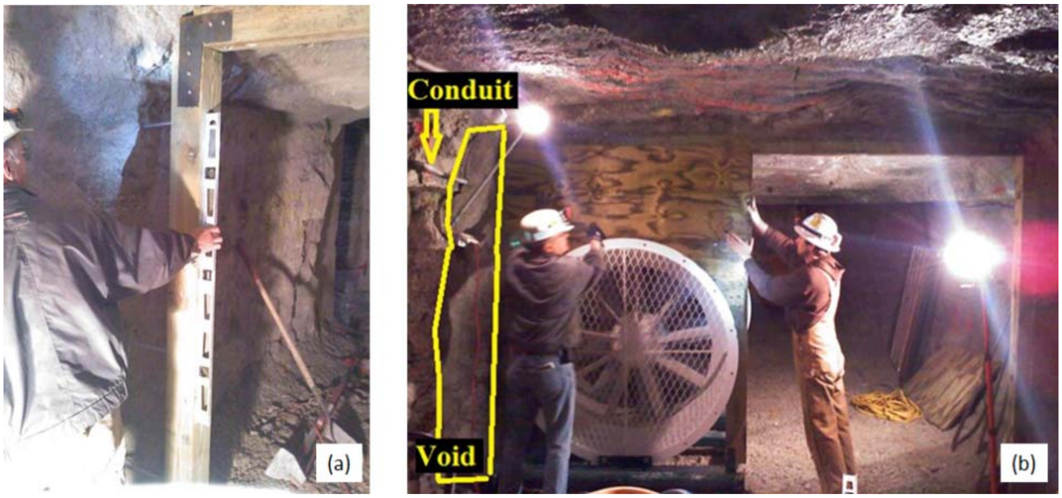


Figure 6.2. Bulkhead construction details: (a) Bulkhead frame, (b) Bulkhead before booster fan placement.

Booster Fan Installation. The process was started by installing the West booster fan. The fan was bolted on painted steel metal skids that were transported from the Rock Mechanics Center to the experimental mine. The skids were bolted to the floor to reduce the vibration caused by booster fans. A Kennedy man door and metal stoppings were installed to ensure the access around the bulkhead. Finally, the fan was attached to the frame and tested. Once the West booster fan was successfully installed, the East booster fan was hauled underground and installed in a similar fashion (Figure 6.3).

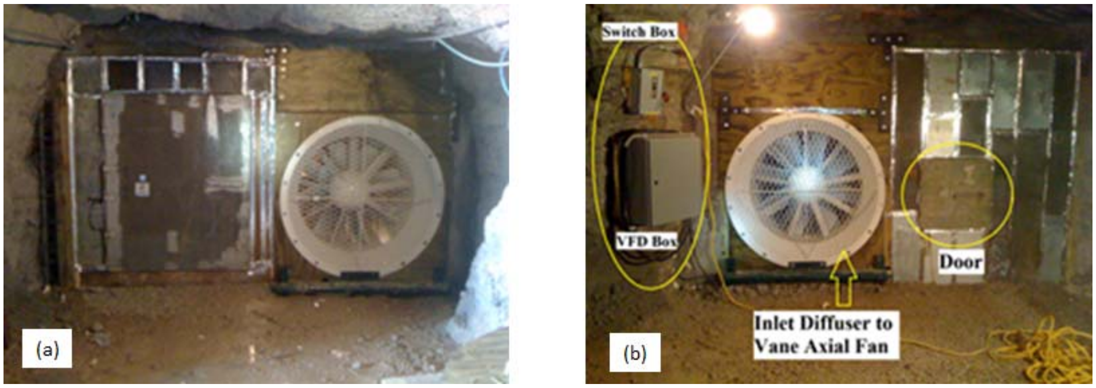


Figure 6.3. Booster fan installation details: (a) West booster fan, (b) East booster fan

<u>Electrical Work</u>. A 76-mm hole was drilled from the surface, to allow passage of the power cable for the booster fans. The hole was located next to the main pole from which power is distributed throughout the mine, as shown in Figure 6.4. A safety “kill” switch for the booster fan power was installed on the electrical pole, but is not shown in this picture. The switch will shut down both booster fans in case of emergancy. Underground wiring for the fan is 10-guage, and was strung from the mine back. A splitter box separates the fan power into two circuit, one for to each fan. The electrical components are installed next to the fan. One 15-kW, three-phase, 460-V motor is installed on each booster fan. Each will motor is rated at 20 amps. Safety equipment (circuit breakers, etc.) are sized at 50 amps, providing a 1.25 safety factor.

Figure 6.4. A 76-mm drill hole with the 50-mm conduit passing wire to underground

Mine Stoppings and Doors. Kennedy yielding steel stoppings are used throughout the mine to temporarily direct the air to where it is needed. A Kennedy stopping is a system of 300-mm wide, vertically telescoping steel panels, installed under pressure in a drift. To minimize stopping leakage, polyurethane foam was applied from the high pressure side. Figure 6.5 illustrates a stopping made of steel panels and sealed with polyurethane foam and duct tape. The doors used in the experimental mine are Kennedy steel man doors and Kennedy steel machine doors. The man doors are made with galvanized steel designed for insertion in Kennedy steel stoppings. A Kennedy stopping and Kennedy door panel arrangements are shown in Figure 6.5. The doors seal on the outside of their frames.

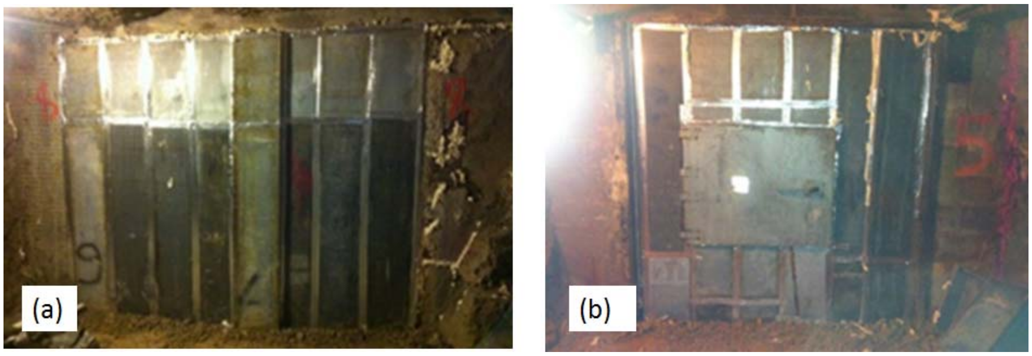


Figure 6.5. Kennedy stopings and doors: (a) Steel stopping, (b) Steel door

Fan Curve and Blade Settings. Figure 6.6 shows the Spendrup booster fan characteristic curves. The blade settings of this fan can be change from setting 1 to setting 6. These curves were used mainly for simulation purposes.

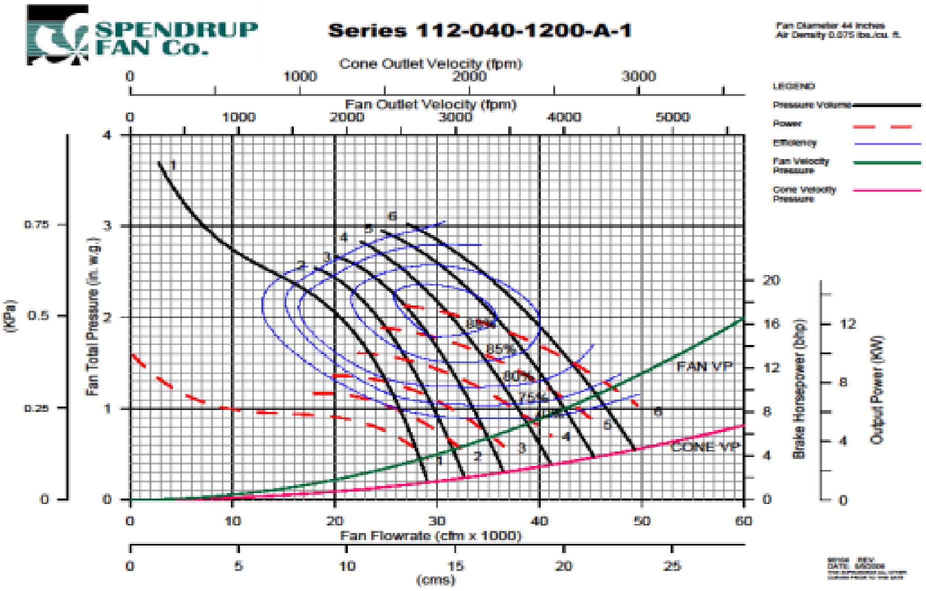


Figure 6.6. Spendrup fan characteristic curves

While not operating, the fans were inspected to determine and set the blade angles, using the manufacturer's curves. Both booster fans are set to operate on the same blade setting. Figure 6.7 shows two aspects of setting blade angles. Several ventilation scenarios were set up by changing the blade setting and the fan speed. The fan speed is manually controlled from a separate VFD control box which allows for adjustments while the fan is running.

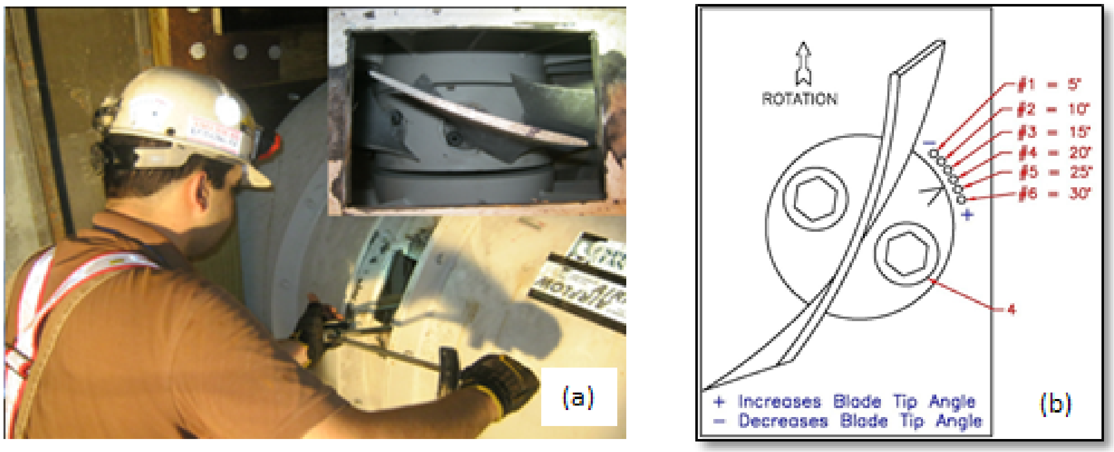


Figure 6.7. Axial fan equipped with adjustible pitch blades: (a) Changing blade setting. (b) Diagram showing possible blade settings.

6.2. Main Fan Tests

Currently, ventilation is provided by the main surface fan, which is 1.2 m in diameter. This Joy axial vane fan is equipped with a 24-kW motor and is set to deliver approximately 25 m^3/s of air at 1.1 kPa of static pressure. The fan passes the air through a 90° elbow, in which there is a substantial loss of pressure, and then into the ventilation shaft.

Tests were conducted to determine if the angle of the louvers in the main fan outlet duct had any effect on the ventilation pressure, and that relation affects the total flow rate. To do this, calibrated manometers were used to measure the pressure before and after the louvers, as shown is Figure 6.8. Two louver blade angles were tested, the original one at 60° and the new one at 0°.

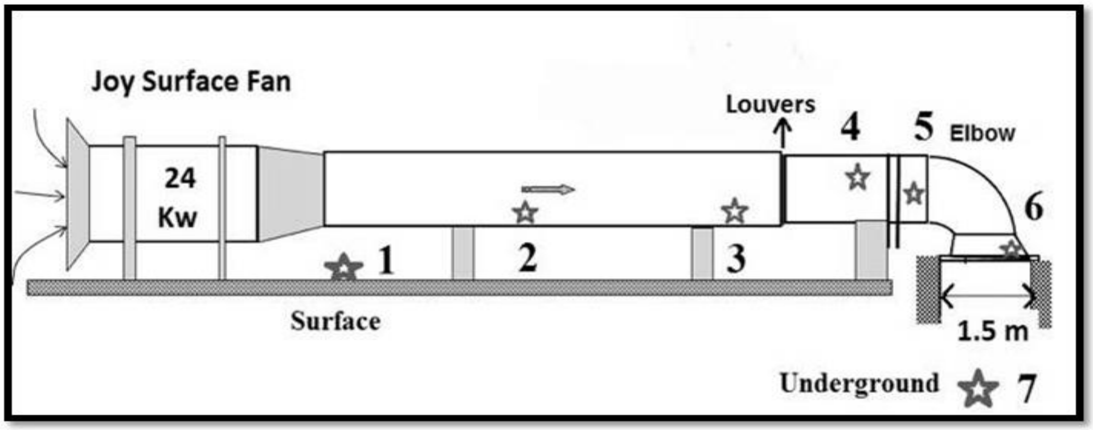


Figure 6.8. MS & T experimental mine main fan showing points of pressure measurements

In Figure 6.8, the survey points were at station 2, which is before the louvers, and station 4, which is after the louvers. The results are shown in Tables 6.1 and 6.2.

Table 6.1. Pressure at 60˚ louver angle

St. No.	Description	Pressure (Pa)	Pressure change (Pa)	% Loss
2	Before louvers	1,081		
4	After louvers	898	183	17
7	Bottom of shaft	373	525	58.5

Table 6.2. Pressure at 0˚ louver angle

St. No.	Description	Pressure (Pa)	Pressure change (Pa)	% Loss
2	Before louvers	1,081		
4	After louvers	941	130	12
7	Bottom of shaft	411	540	56.8

Based on the above results it is clear that there is a lesser effect when the angle of the louvers is at 60˚, as compared to 0˚. The greatest pressure loss is still at the elbow, as was observed in earlier tests.

6.3. Booster Fan Tests

The main aim of these testing was to collect the raw data for various ventilation conditions (single fan, two fans, and three fans.) All stoppings and doors were taped and sealed as much as possible to reduce leakage and to match the surface fan curve, and blade setting #5 was selected for each booster fan. In addition to the fan duties air flow rates were measured at 10 different stations. Table 6.3 shows the results of four tests: (1) using the main fan only, (2) using the main fan and the East booster fan, (3) using the main fan and the West booster fan, and (4) using all three fans.

Test Conditions:

1. Using the main fan only
2. Using the main fan and the East booster fan
3. Using the main fan and the West booster fan
4. Using all three fans

Table 6.3. MS & T experimental mine vent survey data

Test No.	Fan Duty						Stations Quantity, m^3/s			Power (kW)
	Pressure, Pa			Quantity, m^3/s						
	Main+	East B-Fan	West B-Fan	Main	East B-Fan	West B-fan	1	7	10	
1	246.9	*	*	19	*	*	17.7	12.9	10.5	6.7
2	161.5	112.7	*	18.8	19.2	*	18.5	15.8	11.7	8
3	212.9	*	81	18.2	*	19.7	18.8	19.5	11.9	7.5
4	148.9	91	76	19.1	19.5	19.8	19.8	21.3	10.7	9.9

+ Measured at the bottom of the intake shaft

The above results show that based on input power to deliver the required qunatity to the simulated worlking area the combination of Main fan and West booster fan is the best option for this study.

6.4. Vibration Analysis

Vibration tests were carried out on the two booster fans at the MS & T experimental mine. This was done using vibration sensors attached to the fan motor. A Hilliard vibration monitor was used to record the vibrations at different fan speeds and blade angles. The vibrations monitor automatically displays the highest reading between the sensors. Those readings are reported here (Feledi 2014). Figure 6.9 shows the instruments used during the survey.

For this report, only the West booster fan (see Figure 6.1 above) was studied. The East booster fan is due to be moved to a new location in a few weeks' time, so monitoring its condition is not important at this stage. Measurements were taken at different blade angles and various speeds. Figure 6.10 shows the results of the test runs measured at the highest possible angle for the Experimental Mine (blade angle 5).

Figure 6.9. Fan vibration sensor and recording box: (a) Vibration sensor, (b) Vibration recording box.

The results shown in Figure 6.10 indicate lower fan vibrations at higher speed, with a gradual increase as the fan speed is decreased. The industrial vibration cut-off limit for axial flow fans is 5.08 mm/s.

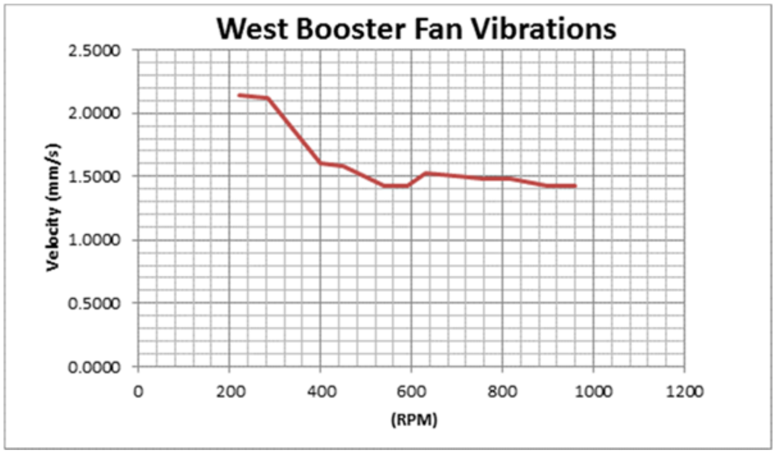


Figure 6.10. Fan vibration shown as velocity

Figure 6.9 shows that at lower fan speeds, vibration amplitude is abnormally high, in excess of 2 mm/s. Since the booster fan is new, it is likely that the vibrations were caused by lack of lubrication and the inadequate designed of the pad on which the fan is mounted. The booster fan is placed on a metal frame but the frame is not attached to the floor of the mine. This arrangement means that the fan is subjected to large shaking motion. The solution to such a scenario would be to add lubrication and construct a mounting pad based on sound engineering design, to which the fan frame can be properly attached. The lubrication schedule should be changed, to extend the booster fan life and effectiveness.

6.5. Leakage Investigation

Experiments were carried out to investigate the recirculation potentials caused by the use of booster fans. The results were then compared with simulation results from Ventsim software modeling. The results showed that most recirculation is concentrated at the stoppings that are closest to the booster fan while far from the booster fan there is just increased air leakage.

A ventilation quantity survey was undertaken at MS & T's experimental mine at the stoppings shown in Figure 6.1, above. During the experiment, the main surface fan and the West booster fan were operated simultaneously. While the main fan operated at a fixed blade setting, the booster fan operated at three different blade settings (1, 3, and 5). For each main-booster fan combination, two quantity readings were taken at each stopping: one reading at an upstream station (a), and another at downstream station (b). The difference between these two quantities is referred to as leakage quantity. The results are shown in Table 6.4 and indicate the amount of leakage or recirculation at each stopping. A positive difference indicates leakage and a negative difference indicates recirculation.

Table 6.4. Leakage and recirculation results

		Main Fan and West Booster Fan					
		Blade set 1		**Blade set 3**		**Blade set 5**	
Station		Q (m3/s)	Leakage	Q (m3/s)	Leakage	Q (m3/s)	Leakage
1	a	21		23		23	
	b	20	1	21	2	22	1
2	a	20		21		22	
	b	22	-2	23	-2	24	-2
3	a	22		26		25	
	b	20	2	23	3	26	-1
4	a	21		27		27	
	b	20	1	23	4	25	2
5	a	20		23		25	
	b	20	0	21	-2	28	-3
6	a	20		23		26	
	b	19	1	20	3	24	2
7	a	23		23		26	
	b	21	2	24	-1	27	-1
8	a	20		27		28	
	b	21	1	23	4	24	4

As indicated in Table 6.4, recirculation is more pronounced for the higher fan blade settings, which imply higher fan speed. Blade angles 3 and 5 showed the most recirculation. There is an anomaly observed at stopping 2 which does not conform to the observations made about recirculation at other stoppings around the mine. This stopping showed the same amount of recirculation regardless of the fan speed.

A Ventsim model based on the MS & T’s Experimental Mine was created and the air flow distribution in the mine simulated. The results, shown in Figure 6.11, were compared for a system without the booster fan and one with a single booster fan or both. The results showed the same outcome as in the experimental exercise, where the recirculation was concentrated at stoppings near the booster fans while the furthest stoppings showed increased leakage.

Figure 6.11. Ventsim model simulation using the West Booster and Main fans

6.6. Summary

This section presents a study that was conducted at the MS & T experimental mine. The study was undertaken on a 1.12-m diameter booster fan operating under different blades settings with speed of 1,200 rpm. A pressure-quantity survey was conducted inby and outby the booster fan with different blade settings to investigate pressure fluctuations specifically during fan startup. The pressure drop across the bulkhead was monitored during the experiments.

The pressure drop across the bulkheads was measured in each ventilation scenario to determine the amount of pressure added by the booster fans into the system. Taking into account the volume flow limits of the surface fan, blade settings 4 and 5 were determined as the best alternatives for the mine. Tests showed that the West booster fan running in series with the main fan is the optimal scenario. The power requirement of the booster fan (with blade setting 5 and operating at 860 rpm) was calculated at 7.5 kW while the minimum airflow requirement was met.

Fan vibration tests were also carried out on the two new booster fans to gauge their conditions. Vibration amplitudes in excess of 2 mm/s were recorded. This is quite high for these small fans. Since the booster fans are new, it is fair to conclude that this vibration is caused by lack of lubrication lack of a solid base for the fan foundations. The booster fans are placed on metal frames but those frames are only loosely laid on the floor of the mine. A solution to this problem would be to add lubrication and construct concrete floor to which the metal frame can be attached.

Tests showed that when the booster fan blade angle is correctly matched to the ventilation system the booster fan provides sufficient ventilation to the workings without introducing any recirculation. However, recirculation will take place when the booster fans are oversized as compared to the main fan, misplaced or when the stoppings are not properly installed.

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7. Measuring Leakage in Ventilation Systems

In underground mines, stoppings and doors are used to separate two types of airways, intakes and returns. Depending upon the complexity of the mine, the ventilation system may require hundreds of these structures. The air pressure differentials created across these structures will inevitably cause some loss of air, because some quantity of air will be short circuited without being used in the working areas. This loss of fresh air is referred to as leakage flow. Ventilation specialists have estimated that, in coal mines, this quantity can range from 30 to 60% of the total quantity induced by the surface fans (McPherson 1993, Richardson 1997).

In ventilation design, leakage paths are represented by highly resistive airways. When pressure-quantity survey data are available, the resistance of each path is calculated from Atkinson's equation ($P = R Q^2$), and sometimes, this equation is modified to reflect the flow type. Based on field measurements, researchers have found that the resistance for a 'good' single masonry stopping may vary between 560 and 782,800 Ns^2/m^8 (Bruce and Koenning 1987, Duckworth 1995.) It is the range of these values that makes ventilation design difficult and the leakage flow estimates questionable.

7.1. Leakage Flow Formulae

In the estimation of leakage quantity and leakage path resistance the following equations were used:

Percent Leakage Flow (%L). This percentage represents a fraction of the total quantity of air passed through the main fans that is short circuited before reaching the working areas. It is calculated by:

$$\%L = \frac{Q_T - Q_E}{Q_T} 100 \qquad (2)$$

Where: Q_T = total quantity of air circulated through the fans, m^3/s
Q_E = quantity of air utilized effectively at the workings, m^3/s.

Equivalent Leakage Path Resistance. For a number of leakage paths arranged in parallel, this resistance is approximated by Atkinson's equation:

$$R_e = \frac{\Delta P}{Q_d^2} \quad (3)$$

Where: R_e = the equivalent resistance for a number of stoppings, Ns^2/m^8

ΔP = weighted average pressure difference, Pa

Q_d = total leakage quantity, m^3/s.

Individual Leakage Path Resistance. Once an equivalent resistance has been estimated, an individual stopping resistance can be estimated by applying Kirchhoff's second law as follows:

$$R_i = R_e n^2 \quad (4)$$

Where: R_i = individual stopping resistance, Ns^2/m^8

n = number of stoppings in parallel arrangement.

7.2. Leakage Measurements in A Coal Mine

Pressure – Quantity Surveys. These surveys were conducted in the 4-East Main section of the SUFCO coal mine. The objective was to estimate leakage flow rates and head losses to determine resistance values for various sets of stoppings, doors and overcasts. Figure 7.1 shows the ventilation schematic of the surveyed area, between crosscuts 29 and 132 (n = 103 cross-cuts). It includes two rows of steel and concrete stoppings separating the intake and return airways from the belt line. In practice, each intake and return line consists of two parallel entries through which the air moves in the same direction. Each stopping on the intake side includes a small window to control the air in the belt line. The stoppings on the return side do not have regulators. The system is equipped with a 940-kW exhaust fan. When operated at 890 rpm, this fan can exhaust from the mine approximately 392 m^3/s of air at 1.79 kPa of static pressure.

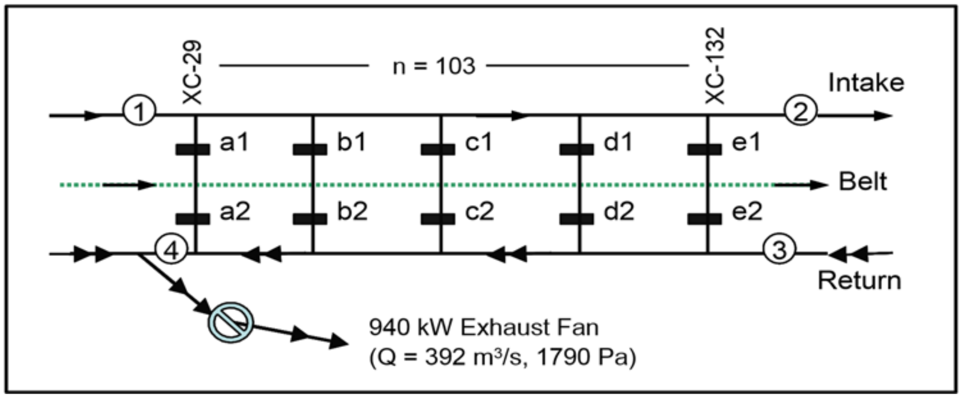

Figure 7.1. Ventilation schematic of a section of SUFCO mine

Table 7.1 shows part of the pressure-quantity measurements taken in this section. These were divided into three sets: one set to determine the overall efficiency of the system, and two sets to determine the leakage path resistances for both intake-line and return-line stoppings (Stephens 2011).

Table 7.1 Leakage path survey data

Survey description	Pressure drop, Pa	Quantity, m^3/s
1- Primary Ventilation Survey		
Fan operating point	1,790	393
Fan airlock door	1,670	
Air-lock doors by overcast	700	
Longwall head gate		30.9
Bleeder entries		9.5
Continuous Miner sections (2)		35.4
Seals (mine out areas)		56.7
Underground shops		9.5
2- Leakage Flow – Intake to Belt		
Intake 1 (left of crosscut 29)		152.15
Path a1, n‡ = 15	168	4.91
Path b1, n = 1	87	6.05
Path c1, n = 29	75	7.65
Path d1, n = 29	60	7.65
Path e1, n = 29	62	7.61
Intake 2 (right of crosscut 132)		118.51
3- Leakage Flow - Belt to Return		
Return 4 (right of crosscut 29)		185.17
Path a2, n = 15	814	14.17
Path b2, n = 1	712	1.46
Path c2, n = 29	553	8.03
Path d2, n = 29	398	8.03
Path e2, n = 29	321	7.98
Return 3 (left of crosscut 132)		145.49
4- Resistance Per Stopping	Ns^2/m^8	
Intake to belt	757	
Belt to return	3258	

Figure 7.2 shows the pressure profiles for the two sets of stoppings. Because the fan is operated in exhausting mode, the stoppings on the near side are subject to higher pressure differences than those located on the far side. Another reason for the high pressure

differences on the near side is that in the belt line the air moves inby with the intake air and there are numerous feed points and small windows that are used to control the air in the belt line. This figure shows that the pressure differences decrease with the distance from the surface fan. For similar stoppings, the rate of change follows a decay function with high values near the fan and low values near the workings.

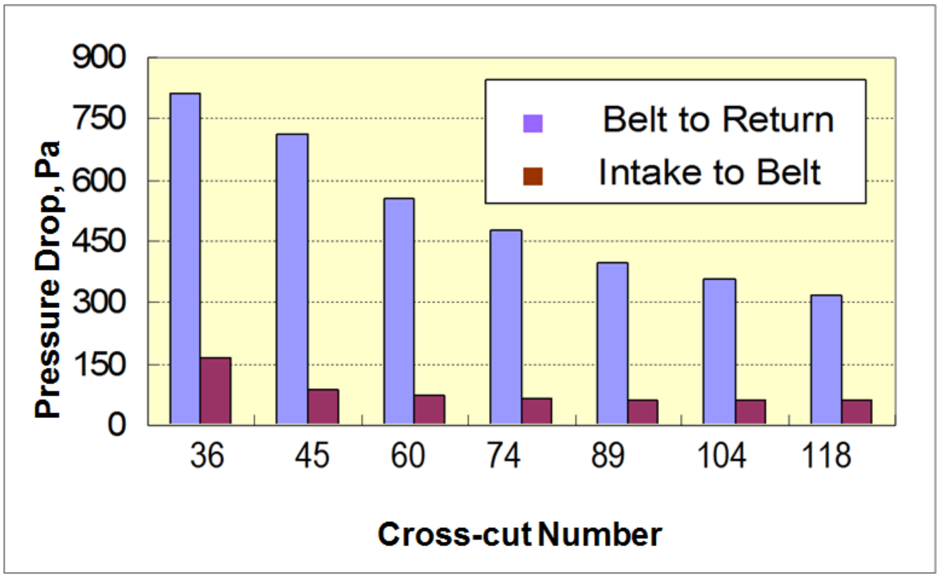

Figure 7.2. Pressure drops across stoppings

Analysis of Results. Two factors are evaluated in this section, percent ventilation leakage and leakage path resistances. The percent ventilation leakage represents a fraction of the total quantity of air that is lost through stoppings, doors, overcasts and other control devices and returned to the surface without any effective utilization, the higher the loss the lower the efficiency of the system. The amount of loss depends on several factors including the materials and techniques used to build stoppings, the maintenance program undertaken, and the pressure differences created by the main fan.

Based on the quantities of air directed to active workings, old seals, and underground shops (142 m^3/s), and the quantity of air passed through the main fan (393 m^3/s), the percent leakage was calculated using equation 2 as follows:

$$\%L = \frac{393 - 142}{393} 100 = 63.6\%$$

Out of this fraction, 29 % (114 m^3/s) of fresh air is lost in the old mining districts.

Leakage Path Resistances. By applying equations 3 and 4 to the measurements taken from the 4-East Main section (XC-1 through XC-3), the following leakage path resistances were estimated:

For the far side (intake to belt), this resistance was calculated as follows:

$\Delta P = (168*15 + 87*1 + 75*29 + 60*29 + 62*29)*29)/103 = 80.8$ Pa
$Q_d = 152.15 - 118.51 = 33.64$ m^3/s
$R_e = 0.0714$ Ns^2/m^8.

For n = 103, equation 3 yields:
$R_i = 757$ Ns^2/m^8.

By applying the same procedure, for the near side set of stoppings, the following resistances were estimated:

$R_e = 0.3071$ Ns^2/m^8 and
For n = 103, $R_i = 3258$ Ns^2/m^8.

The above figures show that the magnitude of the differential pressure across the return line stoppings was much greater than that across the intake line stoppings. The main reason for this is that in this mine the belt entry air is also used as a secondary intake to supply fresh air to the active workings. This means that the intake and belt airflow paths are in parallel and that fresh air is intentionally fed into the belt entry using regulators. This causes the intake stoppings to have artificially low resistance values.

7.3. Leakage Measurements at Missouri S&T Experimental Mine

Kennedy yielding stoppings are used throughout the MS & T experimental mine to direct the air towards the workings. A Kennedy steel stopping is a system of 0.3-m-wide, vertically telescoping steel panels installed under pressure in a drift to form a substantial and incombustible permanent stopping. During installation, the void areas (the gap between frames and walls) were sealed with a cementitious mixture to reduce leakage. Two types of doors are used at the MS & T experimental mine, Kennedy steel man doors and Kennedy steel machine doors. The man doors are made with galvanized steel designed for insertion in Kennedy stoppings.

Figure 7.3 shows some details of air pressure–quantity surveys conducted by a ventilation team.

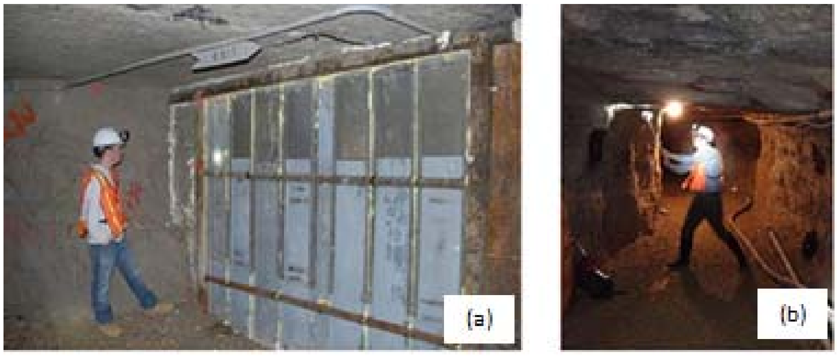

Figure 7.3. Ventilation surveys conducted by a ventilation team: (a) Measuring pressure drop across a stopping, (b) measuring air velocity.

The resistance of a Kennedy stopping was calculated using the Atkinson's equation. The pressure difference across the stopping was measured using a Magnehelic gage by inserting a tube through the stopping. The quantity of air leaking through the stopping was determined by calculating the difference of two air flow rates in a drift: upstream (a) and downstream (b) of the stopping. The pressure quantity measurements for one stopping are described below.

$\Delta P = 53$ Pa
$\Delta Q = Q_a - Q_b = 0.71\ m^3/s$

Using Atkinson's Equation, $\Delta P = RQ^2$, the stopping resistance is $R = 105\ Ns^2/m^8$. This resistance is relatively low compared to those reported for coal mines previously.

7.4. Tracer Gas Testing

The lab model at the University of Utah was upgraded to conduct tracer gas experiments for further accuracy and better understanding of air flow in the model. The available literature was reviewed to determine the best methods to use in those experiments.

<u>Literature Review.</u> Thimons et al. (1974) found that SF_6 had satisfactory properties for use as a tracer gas. It is odorless, chemically and thermally stable, and is convenient to handle and dispense in air. It does not absorb on reservoir sandstone or coal. Because it does not occur naturally, measurement of background concentration is not required, and even in 1974, it could be detected at 10^{-5} ppm. They further found that SF_6 had been successfully used in meteorological studies of moving air masses and the dispersion of airborne pollutants, ventilation systems and fume hoods in buildings, and the evaluation of the effectiveness of plugging oil wells to prevent well gas from entering coal mines.

Methods for tracer injection, sampling, and analysis were and developed at USBM facilities in Bruceton, PA, and several tests were conducted at the Safety Research coal mine there. Tests were also conducted in a multi-level metal mine in the western U.S. By 1982, the Bureau of Mines had used SF_6 to study the effectiveness of jet fans (Matta et al. 1978), characterize face ventilation (Vinson et al. 1980), and test the integrity of bagging-machine hood enclosures (Vinson et al. 1981).

At about the same time, other investigators were examining the use of radioactive isotopes for characterizing ventilation systems. Krypton (^{85}Kr) was used to measure airflow in a South African gold mine (Snyman et al. 1976). In uranium mines, naturally-occurring isotopes were used (Beckman and Holub 1979). Bigu (1989) provides a thorough discussion of such methods as developed in Canada, and compares the use of radioisotopes with that of SF_6.

The use of SF_6 continued. In 1985, testing in Australia was reported (Stokes 1985). Kennedy and Klinowski (1991) give a detailed report of tracer gas testing used in the Cape Breton coal fields, and describe methods for pressure-volume surveys, fan testing, auxiliary vent system testing, shaft and vent raise surveys, air leakage measurement, mine fire simulation, and controlled recirculation.

Wala (1996) identified a new radioactive gas, Xenon (^{133}Xe), for use as a tracer. Wala cited unspecified difficulties with the use of SF_6, and selected ^{133}Xe for three reasons: (1) It is detectable at a concentration that is five orders of magnitude below the detection limit for SF_6, (2) it does not deposit in the airway, and (3) it facilitates continuous measurement. Nonetheless, use of this gas is not reported by any other authors.

Use of SF_6 continues to be reported. For example, Singh et al. (2004) studied leakage through stoppings and a filled cement concrete plug in an underground coal mine. Recent work at Virginia Tech (Underwood et al. 2012) examined the use of perfluoromethyl-cyclohexane (PMCH) as a tracer gas. The substance showed promise, but because its use was reported just as tracer testing for this project was beginning, it was not considered.

Experimental Design. Two experiments were designed using the principles outlined in this report. One experiment was to be based on no recirculation of air and the other on controlled recirculation of air. In the planned tests, sulfur hexafluoride (SF_6) was to be the tracer gas, because it is non-toxic and commercially available. SF_6 was available from Air Liquide in Salt Lake City, and the gas collection syringes used in such tests were commercially available online.

Because the University of Utah does not have an SF_6 column for gas chromatography, the samples were to be tested at the Virginia Tech's mining engineering department. Virginia Tech was working on similar tracer gas experiments and agreed to test the U of U samples for a nominal cost.

<u>Experimental Results.</u> Figure 7.4 shows the schematic diagram of the upgraded booster fan lab model. The measuring stations for tracer gases are located on the return side near the exhaust duct so that the gas gets longest path to travel. There were to be two injection points in the system; one is near the main fan (station 3 in Figure 7.4) and other is at the face (station 9). It was thought that this would give enough time to take gas samples with syringes at the measuring stations.

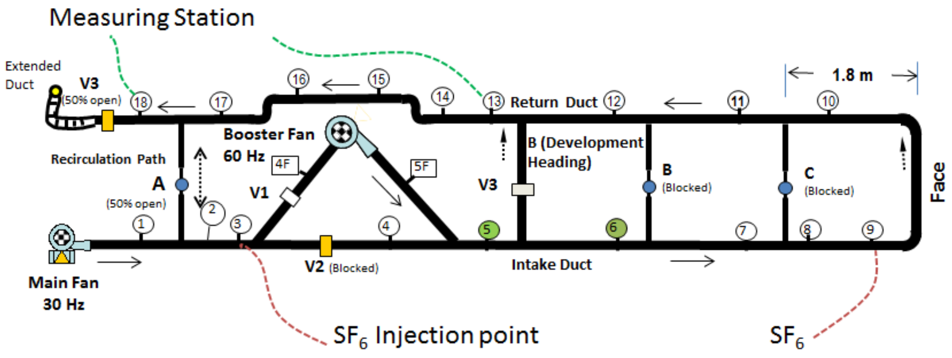

Figure 7.4. Schematic showing SF_6 injection points and measuring stations

Two significant problems were encountered in conducting these experiments. First, the length of the physical model was too short, so that the gas travel time was not long enough to get good mixing or allow collection of enough samples for conducting quantitative analyses. Second, it was found that the time required for shipping samples to Virginia Tech for analyses was long enough to allow unacceptable sample degradation, so that the analyses would not be sufficiently accurate to characterize leakage in the system. It was concluded that tracer tests with SF6 would not provide any information beyond that already determined in the experiments using CO_2 injection, described in Section 5.2 of Chapter 5 in this report. Therefore no tracer tests using SF_6 were conducted in the University of Utah model.

The same constraints led to a decision not to conduct tracer tests in the MS & T experimental mine.

7.5. Summary

Although each individual stopping or door is a flow path that allows leakage, air leakage through some stoppings is significantly higher than through others. This leakage quantity is dependent upon the pressure difference across a given stopping and on that stopping's ability to resist flow. High pressure differentials in a mine are located near fan installations, airlock doors, and air crossings, and through old workings. The pressure profile of a mine will indicate the high-pressure areas and thus areas where leakage will most likely occur. However, these profiles change gradually as mining progresses, making it difficult to identify a distinct location where leakage is no longer relatively insignificant.

Based on field measurements and literature review, this study has shown:

- It is not uncommon for underground coal mines to have 50–60% overall leakage.
- For similar stoppings, the rate of change follows a decay function with high values near the fan and low values near the workings.
- The amount of leakage depends on several factors including the materials and techniques used to build stoppings, the maintenance program undertaken, and the pressure differences created by the main fan.
- The pressure differential across a stopping has the greatest influence on leakage. Air leakage can significantly be reduced by coating a stopping with sealant.

Two experiments using sulfur hexafluoride (SF_6) as the tracer gas were designed at the University of Utah coal mine ventilation lab. Two problems were encountered in conducting these experiments. First, the length of the physical model was too short, so that the gas travel time was not long enough to get good mixing. Second, the time required for shipping samples to Virginia Tech for analyses was too long to avoid sample degradation, so that the analyses would not be accurate to characterize leakage in the system. Because of these problems, no tracer tests using SF_6 were conducted in the University of Utah model.

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8. Fan Selection Program Using Genetic Algorithms

Currently, primary ventilation network problems are solved using numerical simulators such as VnetPC, VUMA, and Ventsim. In these simulators, fans of different sizes are tested on a trial-and-error basis until an acceptable solution is found. For complex networks with multiple fans, the process can be tedious and the optimal combination of fans may never be achieved.

As mines become deeper or more extensive, the emissions of air contaminants may increase and the overall mine resistance will become larger. Under these conditions, and in systems without booster fans, the required quantities of air to the working areas can only be supplied by increasing the pressure provided by the main fans. An increased pressure also increases the leakage flow rates, thus reducing the efficiency of the ventilation system (McPherson 1993). The installation of booster fans may alleviate this problem, not only by redistributing the fan pressures efficiently but by decreasing the leakage quantity. However, such a reduction has a lower limit beyond which the system may become ineffective and cause airflow recirculation. To date, there is no single computer software that can be used to determine the best combination of fan pressures that eliminates the onset of unwanted recirculation.

This section presents a computer program that can be used to determine the best combination of fan pressures and regulator resistances for a complex ventilation network problem. This is a modular program that combines the features of a set of genetic algorithms (GAs) developed by MIT, and a ventilation simulator developed by Mine Ventilation Services, Inc. The program solves a network problem subject to an objective function (total airpower) and a set of practical constrains (Lowndes 2004 and Acuña et al. 2010). It requires a ventilation network, a set of airways with fixed flow requirements (working areas), fan locations, an objective function, and practical constraints. For a given network problem, the program generates an output file showing the fan pressures and regulator resistances that minimize the total power requirement.

8.1 Genetic Algorithms

Genetic algorithms are based on the mechanics of natural selection and natural genetics, where each individual is assigned a fitness value based on a fitness function to test its survival rate in a competitive environment. In GAs, individuals of lower fitness value will die out, while those of higher fitness value will survive and become eligible parents for the next generation.

8.2 Mechanism of GAs

Figure 8.1 shows the general functioning mechanism of GAs, which start with an initial population of potential solutions to a problem.

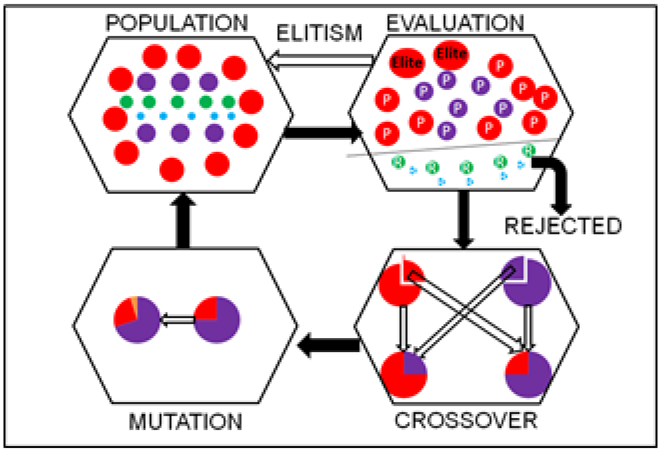


Figure 8.1. General mechanism of GAs

GA Parameters. A genetic algorithm that yields good results to many practical problems depends on the wise selection of three key parameters: reproduction (selection), crossover, and mutation. These are briefly described below.

Reproduction. Reproduction is the process in which individual strings are copied as eligible parents according to their objective function. A string with a higher value possesses higher probability of contributing one or more offspring to the next generation.

Crossovers. A crossover operator is used to combine two strings to yield a better string. In this operation, different individuals are created in successive order by combining genes from two individuals of the previous generation. In order to preserve some of the good strings in the mating pool, few strings are not used in the crossover process. Such elite individuals transfer directly to the next generation.

Mutation. Mutation introduces diversity in the population whenever the population becomes homogeneous due to repeated use of reproduction and crossover.

Evaluation of Population. A fitness function is derived and used to evaluate the individuals of a population. The fitness function is used to allocate reproductive traits to individuals in the population and as a measure of goodness of fit.

8.3 Fan Selection Program

The modular fan selection program discussed here is described in detail by Shriwas (2014). The program is used to solve a ventilation network problem for fan pressures and regulator resistances that optimize a fitness function. A ventilation network, a set of airways with fixed flow requirements, fan locations, and an objective function are used to create an input file. Upon execution, the program generates an output file showing the fan pressures, flow quantities, regulator resistances, and total air. These results are then evaluated against a fitness function and a set of constraints until the optimal or near optimal solution is achieved. Essentially, the program consists of seven building blocks; a ventilation network, the GA parameters, the GA routines, the ventilation simulator, the fitness function, the practical constraints, and an evaluation routine. A brief description of these blocks is presented below.

Ventilation Network. The network is a collection of branches and nodes. A branch represents an airway such as a drift, shaft, or active working, and a node is an intersection of two or more branches.

GA Parameters. These parameters are used to control the population size, the number of generations, and the manner in which the individuals of a population are created. The following GA parameters are used in this program.

Size of population (n):	100
Number of generation (N):	30
Crossover rate (X):	0.26
Mutation rate (m):	0.015
Pressure range	0 to 6 kPa

These parameters were selected based on parametric studies carried out on sample ventilation models.

GA Routines. The following libraries are used in this program:

```
#include<ga/GASimpleGA.h>:
#include<ga/GA1DArrayGenome.h>
#include<ga/GA2DArrayGenome.h>
```

All these routines reside in the MIT GAlib library (Walls 1995).

Ventilation Simulator. An executable xyz.c ventilation program, developed by Mine Ventilation Services (MVS 2013), is used to solve a network problem. It is based on three basic laws; Kirchhoff's first and second laws (conservation of mass and conservation of energy), and Atkinson's square law ($P=R*Q^2$).

Fitness Function. In this program, the total air power (AP) is used as the fitness function. Airpower is defined as a product of pressure (P) and quantity (Q). For multiple fans, the total air power is determined as the sum of individual fan air powers. The optimal solution is found by minimizing this function.

Practical Constraints. Practical constraints are used to check the results for recirculation and negative regulator resistances. A negative regulator resistance indicates the need for a booster fan.

Evaluation Routine. The results of this program are evaluated for regulator resistances, leakage through stopping, and air power. The regulator resistances are evaluated against a preset resistance (≥ 0.005 Ns^2/m^8). Only alternate solutions with positive regulator resistances are evaluated. The solution to the problem is the one that satisfies the practical constraints and minimizes the power function.

8.4 Methodology

Figure 8.2 shows a schematic of the fan selection program. For any given ventilation network, the program starts by generating the entities (individuals) of the initial populations. In this case, an entity is represented by an array of fan pressures, and a population by a set of entities and their corresponding attributes. Next, the program is executed to determine the flow distribution in the network, and the results are evaluated against the fitness function. Only the fit and the elite individuals are preserved for the next generation.

The program continues by generating other populations randomly. The newly generated individuals are used to update the input file and to solve the network problem for regulator resistances (R_R), leakage flow rates through stopping (Q_{SL}), and air power (AP.). The regulator resistances are evaluated against a preset value , 0.005 Ns^2/m^8. For any population, alternative solutions with positive regulator resistances are evaluated and the power function is minimized (to a local minimum). The procedure is repeated for all the entities of the population (n=100) and the pre-set number of generations (N=30). The local minimum (P_{lm}) of each generation is stored in a file. The minimum (P_{cm}) of the current generation is compared to the local minimum of the previous generation. Alternative solutions can be found by changing the initial GA parameters.

This procedure is repeated until the global minimum is obtained. If at any point the search process does not show any improvement in power reduction, the program is terminated and the current total air power is labeled as the global minimum.

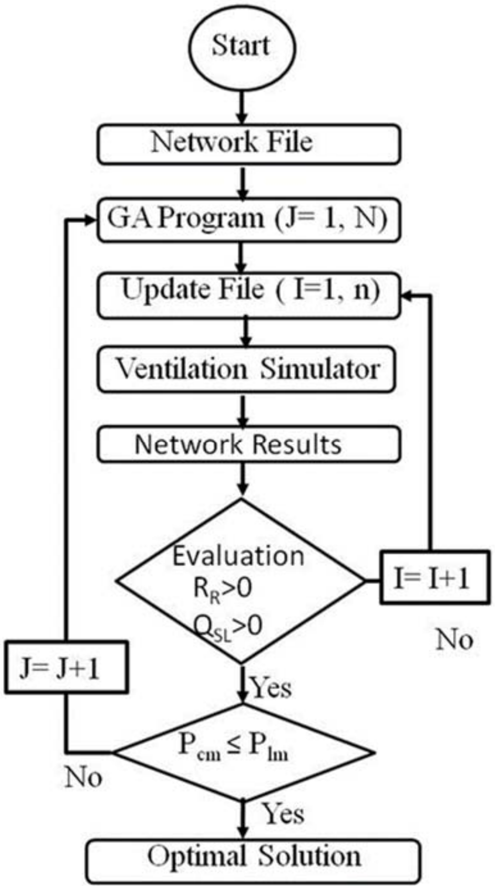


Figure 8.2. Schematic of GA-based fan selection program

8.5 Application of the Fan Selection Program

The GA-based program was used to solve a sample ventilation network for fan duties to satisfy a set of flow requirements. Two cases were considered: (1) single surface fan system, and (2) two-fan system (one surface and one booster).

8.6 Sample Problem

Figure 8.3 shows the ventilation network for this problem. It includes 65 branches, 45 nodes, six working areas, one return airway, and two intake airways. Table 8.1 shows the air flow requirements in the mine. The problem is to determine the best operating pressure for the surface fan, if only one fan is used, and the best combination of main and booster fan pressures if two fans are used. The airway resistances and other network parameters are shown in Appendix A.

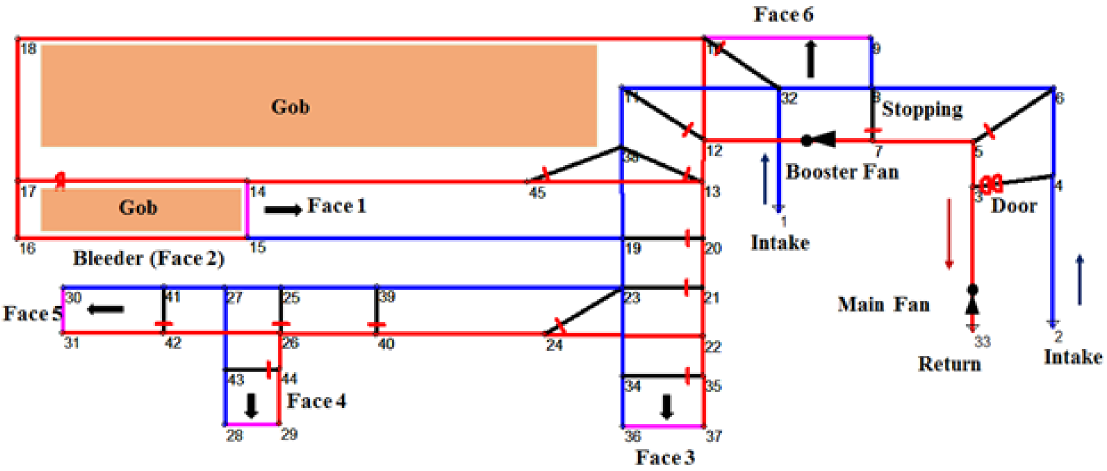


Figure 8.3. Sample ventilation network

Table 8.1 Flow requirements

Branch	Airflow requirements, m^3/s	Working areas
15-14	**47**	**Face 1**
15-16	15	Bleeder
36-37	40	Face 3
28-29	33	Face 4
30-31	33	Face 5
9-10	20	Face 6
Total airflow requirement: 188 m^3/s		

The sample network is solved for the fan pressures and their corresponding airpowers and regulator resistances, first using the GA-based program and then using a ventilation simulator. In each case, two scenarios are considered, a single surface-fan system and a two-fan system that includes a booster fan.

Solution Using GA-based Program. Based on the network data (Appendix A), two input files were created, one for the single fan system and another for the two fan system. These, together with the GA parameters, listed previously, were used to execute the program and generate the results.

Single Fan System. Figure 8.4 shows how the total power converges as the number of generations increases. The power function converges at about 2,500 kW in 10 generations.

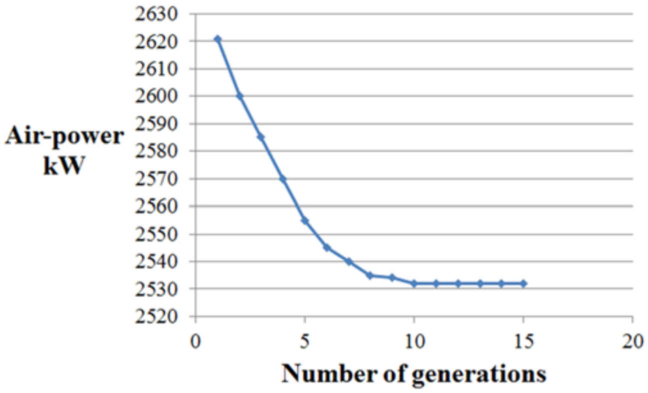


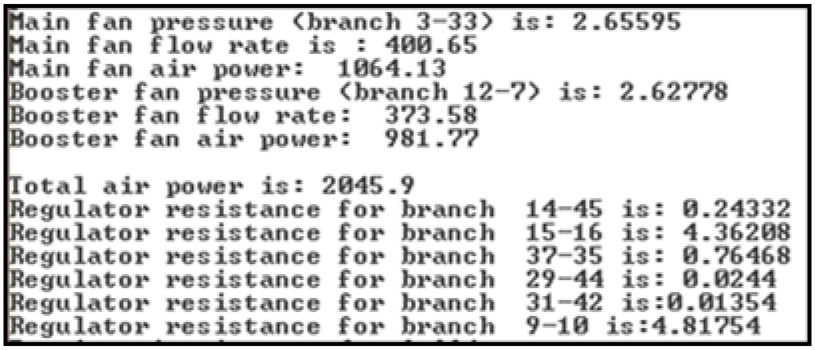
Figure 8.4. Convergence diagram for air power

Table 8.2 shows the optimal solution to the single fan system. Based on these results, of the total quantity handled by the surface fan, 255m^3/s, 188m^3/s is directed to the workings and the remainder short circuited to surface (Q_L= 255m^3/s)

Table 8.2 Optimal solutions to single fan system using GA

Fan System	P, kPa	Q, m^3/s	AP, kW	Total AP, kW	Q_L, m^3/s
Main Fan	5.72	442.66	2,533	2,533	255

Two-Fan System. In this case, the GA program randomly generates a population of two-parameter individuals. Of these two parameters, one represents the main fan pressure and the other the booster fan pressure. The booster fan was placed in a fan branch (nodes 12-7 in Figure 8.3), in line with the surface fan. The input file was then updated, and the program executed. Upon execution, the results were evaluated against the fitness function. The procedure of updating and solving the network for flow rates and regulator resistances was repeated for different arrays of individuals and for different generations until an optimal or near optimal solution was found. Figure 8.5 shows a screenshot of the optimal solution to the problem for the two fan system. It shows the fan duties and the regulator resistances in SI units. Table 8.3 shows a summary of the best combination of fan duties for the two fan system using this approach.



```
Main fan pressure (branch 3-33) is: 2.65595
Main fan flow rate is : 400.65
Main fan air power:  1064.13
Booster fan pressure (branch 12-7) is: 2.62778
Booster fan flow rate:  373.58
Booster fan air power:  981.77

Total air power is: 2045.9
Regulator resistance for branch  14-45 is: 0.24332
Regulator resistance for branch  15-16 is: 4.36208
Regulator resistance for branch  37-35 is: 0.76468
Regulator resistance for branch  29-44 is: 0.0244
Regulator resistance for branch  31-42 is:0.01354
Regulator resistance for branch  9-10 is:4.81754
```

Figure 8.5. Screenshot of GA-based program for a two-fan system

Table 8.3 Optimal solutions to two-fan system, GA approach

Fan System	P, kPa	Q, m^3/s	AP, kW	Total AP, kW	Q_L, m^3/s
Main Fan	2.66	400.65	1,064	2,046	213
Booster Fan	2.63	373.58	982		

The data in Tables 8.2 and 8.3 show that for the same network, the two-fan system yields a lower surface fan pressure and a lower total power requirement than the single fan system. The implementation of this system would reduce the surface fan pressure from 5.72 to 2.66 kPa, the leakage quantity from 255 to 213 m^3/s, and the total power requirement from 2,533 to 2,046 kW.

Solution Using VnetPC (Ventilation Simulator). Using this method, the ventilation network is first created, the flow requirements determined, the fan pressure initialized, and the problem solved iteratively using a simulator (Calizaya 1987). Two cases are considered: single surface fan system and two fan system. In each case, the fan duties are determined to satisfy the airflow requirements and minimize the power consumption.

Single Fan System. In this case, the network problem was solved in three steps. First, the fan pressure was initialized and the network solved for regulator resistances. Next, the regulator resistances were evaluated and the critical branch (minimum resistance) was identified. If all the regulator resistances are positive, the trial pressure is decreased by a fixed amount (step size); otherwise, this pressure is increased. This procedure is repeated until the resistance of the critical branch is close to a predefined value, 0.005 Ns^2/m^8. When this condition is satisfied, the optimal solution is found. Table 8.4 shows an optimal solution for the single fan system.

Table 8.4 Optimal solution to single fan system – VnetPC approach

Fan System	P, kPa	Q, m^3/s	Total AP, kW	Q_L, m^3/s
Single surface fan	5.72	443	2,532	255

Two-Fan System. In this case, the single fan system was modified by adding a booster fan in the main return airway (branch 12-7 in Figure 8.3). Now, the problem was to determine the optimal combination of pressures for the two fans. As a starting point, the booster fan pressure was set at 200 Pa and the main fan pressure decreased successively from 5,720 Pa to 3,000 Pa. For each combination of fan pressures, the total air power was recorded. This procedure was repeated for other booster fan pressures in the 200–3,000 Pa range. Then, the results were evaluated graphically.

Figure 8.6 shows the booster fan pressure-total air power relationship. The optimal combination of fan pressures was determined graphically as the lowest booster fan pressure that minimizes the power function. Table 8.5 shows a summary of result for two fan system. In this case, the best combination of fan pressures is given by: 2.63 kPa for the main surface fan and 2.60 kPa for the booster fan. Under these conditions, as compared to the single fan system, the total power requirement decreased from 2532 kW to 2016 kW.

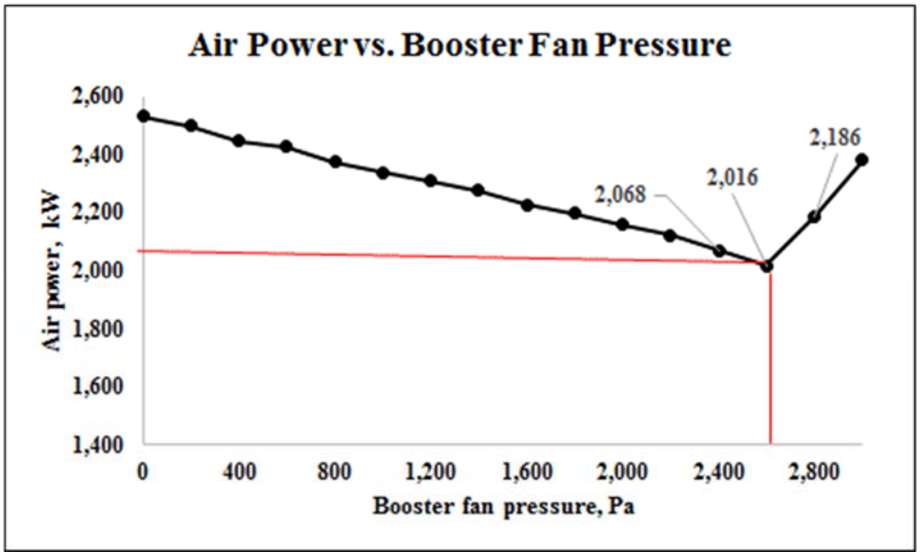


Figure 8.6. Solutions for a sample network

Table 8.5 Optimal solutions for two fan system - VnetPC approach

Fan	P, kPa	Q, m^3/s	AP, kW	Total AP, kW	Q_L, m^3/s
Main Fan	2.630	399	1,049	2,016	211
Booster Fan	2.600	372	967		

These results are within 0.5% of those generated by the GA program.

8.7 Summary

A comparison of results generated by the two approaches (the GA-based program and VnetPC) to solve the sample network problem shows that the GA-based program is able to replicate the results generated by the VnetPC within 0.5% for flow rates.

Using VnetPC, these results were achieved after several trials and correlation studies, a process that took 2-3 days. Using the GA-based program, it took less than one hour to achieve practically the same results with very little manual involvement.

The GA-based program is an efficient and effective fan selection tool. The results are very convincing and appealing not only for small network problems, but for real mine ventilation networks

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Appendix A: Sample Network – Airway Resistance Table

From Node	To Node	Resistance Ns^2/m^8	From Node	To Node	Resistance Ns^2/m^8
7	5	0.006	29	44	0.00084
6	8	0.006	2	4	0.09
10	12	0.1	32	11	0.0015
1	32	0.006	12	7	0.0015
3	33	0.006	11	12	6
13	12	0.001	5	3	0.0015
20	13	0.001	4	6	0.0015
21	20	0.001	18	10	0.0015
22	21	0.001	17	18	0.0015
14	17	5	23	39	0.04989
25	27	0.0015	23	24	6
24	22	0.0015	35	22	0.01
26	40	0.03488	34	35	6
4	3	6	34	36	0.05
6	5	6	37	35	0.01
8	7	6	36	37	0.25
19	20	6	23	34	0.0015
8	32	0.0015	38	13	6
30	31	0.25	11	38	0.001
16	17	0.0015	38	19	0.002
15	16	1	14	45	0.04821
15	14	0.25	39	25	0.03011
28	29	0.25	40	24	0.04512
25	26	6	39	40	6
19	23	0.0015	41	30	0.00095
23	21	6	42	26	0.00548
19	15	0.08	41	42	6
8	9	0.08	43	28	0.00057
9	10	0.2	44	26	0.00066
27	41	0.00055	43	44	6
31	42	0.00481	45	13	0.01949
27	43	0.00093	38	45	6
			32	10	6

9. Booster Fan Monitoring System

A monitoring system is a basic requirement in the operation of booster fans in underground coal mines. To prevent the recirculation of air contaminants and ensure the normal operation of the fan, the system should include for the least the following sensors (Robinson 1989):
Fan condition monitors

Pressure differentials across the fan and interlock doors
Vibration (fan and motor bearing)
Bearing and motor temperatures
Motor current and input power

Environmental monitors

Methane concentration (in coal mines), upstream from the fan
CO concentration, upstream and downstream from the fan
Smoke, downstream from the fan
Oxygen concentration

In addition, the system should be equipped with visual and audible alarm devices to provide warnings to workers at the affected areas and at the control room. These devices should be activated when abnormal conditions are detected. The collected data must be evaluated continuously by the control room operator. This person should have the training and authority to take actions in response to all monitoring signals including alarms, alerts, and equipment malfunctions.

The present day technology of atmospheric monitoring systems (AMS) 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 installations similar those used to monitor main surface fan duties can easily handle the conditional and environmental monitoring for a booster fan.

In the U.S., the major manufacturers of AMS are Pyott-Boone, AMR, CONSPEC, MSA, and Rel-Tek (Francart 2005). 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 and booster fan duties.

9.1. Mine Monitoring Systems

A monitoring system consists of an intelligent master station, a data transmission network, outstations, and transducers. The master station is usually located on the surface, in a control room, and the data transmission lines, outstations, and transducers below ground. Figure 9.1 shows a schematic of a mine monitoring system,

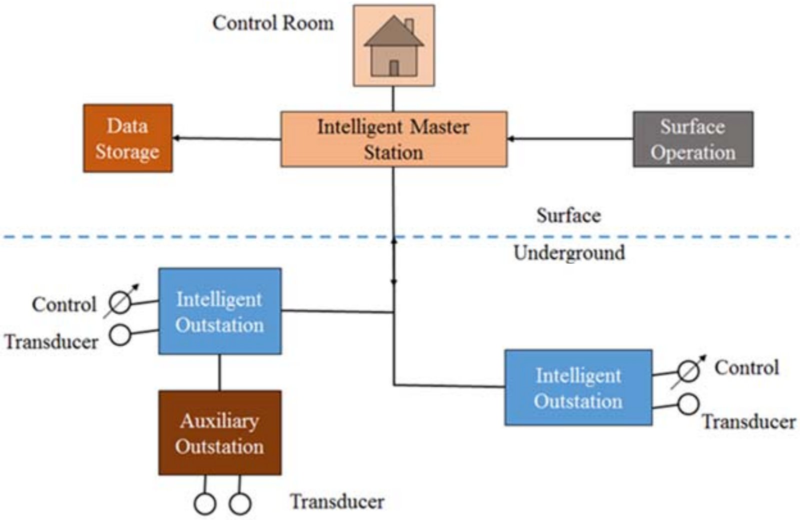

Figure 9.1. Schematic of a telemetering system with an intelligent outstation

Since booster fans are not currently used in U.S. coal mines, the information available on fan monitoring is restricted to main fans, and essentially includes two sections: fan condition monitoring and environmental monitoring.

9.2. Data Transmission Network

Programmable Logic Controllers. Programmable logic controllers (PLCs) are used widely for automation and control of electromechanical systems. PLCs first came into use in underground mining in the 1970s, using mini-computers on the surface for computational functions. The remote outstations were not intelligent, being wholly dependent on the remote mini-computers to collect information and make logical decisions. Currently, PLC systems allow the end-user to continuously monitor and control several processes for underground mining operations. Monitors are placed along the belt lines to detect any rise in CO or combustible gases, providing 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.

Fiber Optic Systems. A fiber optic monitoring system transmits information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. Over the last several years there has been much research in the area of fiber optic sensing, though little of this work has impacted the mining industry. This partly because of the small return on investment possible in the limited mining market, but perhaps a bigger reason is the perception that optical fiber is unable to withstand the hostile mine environment. Compared to wired systems, which use electrical systems, fiber optic systems can be installed over greater distances in large mines and communicate at higher speeds. One can detect methane concentrations as low as 0.05% as far away as 2 km over a fiber optic cable. The system requires no electrical power within the mine so it should operate safely under emergency conditions (Dubaniewicz 1992). Fiber optic technology has the potential to revolutionize the way mines are monitored and controlled. The drawbacks with fiber optic systems is their high initial cost, high maintenance costs, and downtime costs occasioned in the repair or replacement of broken optical fibers.

Telemetry. A telemetry system is a form of electronic information transmission. it requires the use of communication channels in much the same way as the mine telephone system. Telemetry monitoring systems also have intelligent outstations and an intelligent master station on surface (Ketler 2008). Conventional AMS installations for CO, CH_4, O_2 and air velocity throughout underground mines are usually limited to a modest 3- to 5-mile extent. To communicate further and faster has always been a problem, because data reliability degenerates with excessive distances and high speeds. Because of this, very large mines often install more costly fiber optic media, using expensive cables and repeaters to obtain the necessary coverage.

9.3. Fan Condition Monitoring

In coal mines, fan condition monitoring includes the measurement and evaluation of vibration, differential pressure, input power, motor and bearing temperatures, and air quantity. A few of these factors are discussed briefly here.

Vibration. Variations in normal operating conditions of mine fans produces significant changes in vibration level, and causes wear or deterioration of the fan. There are two different modes for measuring vibration, velocity and acceleration. The measurement of velocity of vibration is the most commonly used in mines to identify various problems related to vibration such as misalignment and looseness in the structure, bearings, or foundations. After reviewing the current literature, it was found that at least six velocity-type vibration monitors are required—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.

Figure 9.2 shows the vibration severity chart from the International Standards Organization (ISO 10816-3 2009) adopted by various mining countries. Based on this chart, the alarm level for large fans (> 300 kW) should be set at 4 mm/s.

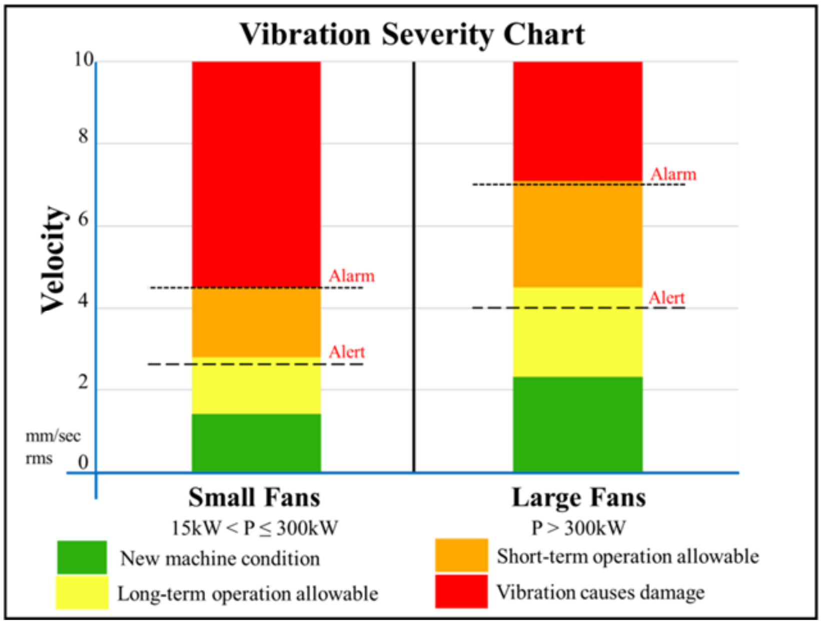

Figure 9.2. Vibration Severity Chart *(Source: ISO 10816-3 2014)*

Air Pressure and Quantity. Main fans are one of the most important pieces of equipment for any underground mine, so it is essential to continuously monitor their duties, that is, their pressures and flow rates. Commonly, fan pressures are measured using manometers and flow rates by measuring the air velocity and the cross-sectional area of the airway. Air velocities are monitored by using Pitot tubes and manometers, ultrasonic anemometers, and vortex-shedding anemometers. Commonly, velocity transducers are located near the roof of a mine entry, so they collect point velocities. These readings are then corrected (calibrated) using hand-held instruments and set to display flow rates. It is recommended to place the monitor at a distance of 2–4 diameter lengths away on the intake side of the fan or 6–10 drift diameter lengths away on the exhaust side (Daly 1992).

The operating pressure of a booster fan is determined by measuring the pressure differential (or gage pressure) across the bulkhead. This gives an approximate reading without any additional installation of monitoring parts. In some cases, when measuring the pressure differential across the bulkhead is not possible, pressure can be measured at the nearest airlock door for an approximate reading.

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. Bearing temperature is one of the most reliable indicators of bearing condition. 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. Various methods are used to estimate the temperature rise in 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. Each 10°C increase in operating temperature shortens bearing life by 50%. Bearing temperature monitoring can indicate problems related to fluid-film bearings, including overload bearing fatigue or insufficient lubrication. The allowable 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.

9.4. Environmental Monitoring

Environmental monitoring in underground coal mines includes the measurement and evaluation of the following factors: concentrations of methane, carbon monoxide, oxygen, and air temperature. Factors such as the type and number of sensors and their locations in relation to the main and booster fans were reviewed. The applications of these sensors are limited by the sensing technology used to detect the parameters of interest. A few of these factors are discussed briefly here.

Methane. Methane (CH_4) is one of the most common strata gases in coal mines. It is not toxic but it is flammable and can form explosive mixtures with air. Methane has a density that is a little over half that of air. This gives rise to a dangerous behavior of the gas under certain conditions. At air velocities of 0.5 m/s or less, methane can form pools or layers along the roofs of underground openings. Any ignition of the gas can then propagate along those layers to emission sources. This has resulted in the deaths of many thousands of miners. The common sensors that are used in monitoring of methane are based on the principles of catalytic oxidation or thermal conductivity. In the U.S., according to 30 CFR § 75.342, only MSHA-approved methane monitors may be installed on all face cutting machines, loading machines, and other mechanized pieces of equipment used to extract or load coal within the working place. Such sensors are also used to monitor the gas concentration at the return air end of a working section. When booster fans are used, it is recommended that methane concentrations be monitored in the motor room and at the fan site, with the alarm levels set at 0.5% in the motor room and a maximum of 2% through the fan housing. The motor room should be monitored for methane to protect against the effects of any longer term recirculation (Ogle 2011).

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 it 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. Since CO is one of the first products of combustion, it also acts as an indicator 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, or infrared absorption principles. When booster fans are used, carbon monoxide sensors should be located in the motor room and on either side of the fan so the location of any fire can be determined.

Smoke. Smoke is an aerosol that is formed by incomplete combustion. It 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 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 case of optical absorption, the reduction of transmitted light due to absorption and scattering is measured.

In general, 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).

Oxygen Concentration. Oxygen is an important part of the mine atmosphere as it is required for human respiration. In mines, the oxygen concentration is maintained at levels between 19.5 and 23%. There are several techniques available for monitoring the oxygen concentration. One common method used in 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.

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 in internal combustion engines and open fires also consumes oxygen. The oxygen concentration can easily drop below 19% in poorly ventilated areas such as old workings, bleeders, etc.

9.5. 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. The sensors also provide data on the emissions from the working area.

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 booster fan installations. 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 inby and outby the fan, whereas the CO and smoke monitors are located only inby 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. When 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 bearing temperature.

For an AMS to provide a specified level of protection for an underground mine, only minimal 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.

Lateral Placement. In general, an AMS is 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. 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 of the roof, 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, the sensors should be located in such a manner that they provide for the estimated best coverage of that entry.

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 their expected locations.

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. Full stratification usually occurs a few hundred feet from the source of the fire. Because of this effect, POC fire sensors should be located at a carefully chosen vertical distance from the maximum entry height. For example, in an entry with a height of 2 m, the maximum sensor distance from the roof is recommended at 0.3–0.5 m. If the height of the entry is 2 m and the height of largest vehicle is 1.8 m, then the monitor should be placed on either side of the entry with at 0.3–0.5 m from the roof.

Spacing. The most difficult part in the design of an AMS for a mine is to determine the spacing of monitors. In the U.S., the regulations for spacing and location of monitors in underground coal mines are given in 30 CFR § 75.351. The principles on which these regulations are based can also be applied used when booster fans are used.

9.6. Booster Fan Monitoring System – Sample Installation

Figure 9.3 shows a schematic of a booster fan installation in a British underground coal mine with significant methane emissions and 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 fan system is designed to deliver 160 m^3/s at 7.0 kPa pressure with the surface fans delivering 280 m^3/s at 5.5 kPa. In this mine, booster fans are viewed as an essential component of the ventilation system.

The booster fan system is equipped with condition monitors and environmental monitors located upstream and downstream the booster fan and in the fan control room. The fan condition monitors include differential pressure across the fan bulkhead and airlock doors, velocity transducer, upstream of the fan, and bearing temperatures and fan vibration transducers at the fan site. Because fire in the ventilation system is a significant risk, the following environmental monitors are used: methane transducers and tube bundle to monitor for methane concentrations and to limit the potential for the formation of an explosive atmosphere, and carbon monoxide concentration, to detect the early stages of combustion.

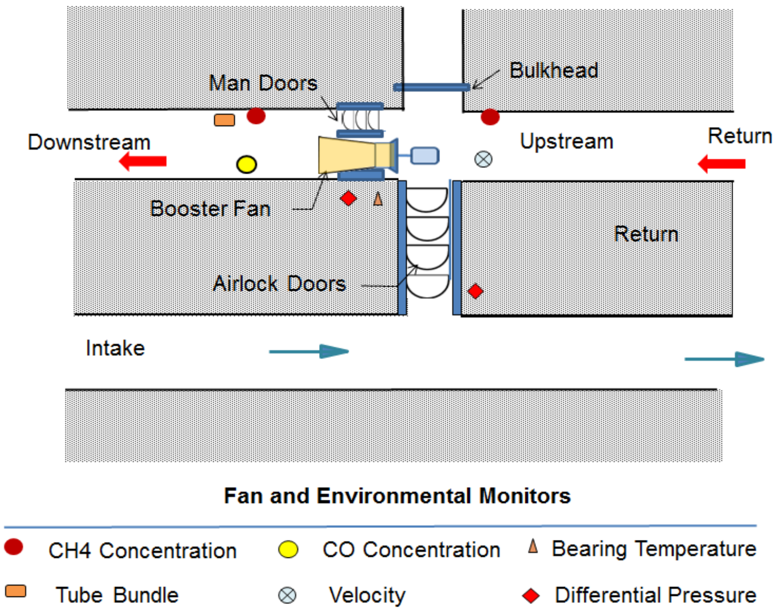

Figure 9.3. Plan view of a single booster fan in a British coal mine

9.7. Summary

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 selecting the type or number of monitors for booster fan installations; that selection depends on the specific installation and conditions of the mine.

For condition monitoring, the parameters that need to be monitored are vibration, differential pressure, airflow, electrical power, and motor and bearing temperatures. For monitoring vibration, six velocity-type vibration monitors are required.

The differential pressure is measured across the bulkhead, and the nearest airlock doors or stopping. Airflow is probably the most important parameter that should be monitored continuously underground. The monitor should be placed at a distance of 2–4 diameters from the fan, on the intake side.

Electrical power is another important parameter that should be monitored continuously. Power monitoring gives a good indication of the efficiency of the fan. Motor and bearing temperatures should also be monitored continuously, as they are good indicators of any malfunction in the fan installation.

The environmental parameters that should be monitored are carbon monoxide, smoke, and methane. Redundancy is also very important for a reliable environmental monitoring system. It helps the AMS operator and mine management make decisions with a greater confidence level, in case of an emergency. Most commercially available gas sensors have response times between 10 and 30 seconds. Response times for catalytic gas sensors used to monitor CO and CH_4 range from 10 to 15 seconds, and those for IR sensors used to monitor CO and CO_2 range from 15 to 30 seconds.

Carbon monoxide monitors based on the infrared absorption principle should be used near the fan as the primary monitors. They should be placed approximately 4–6 diameters away from the fan on the exhaust side. For redundant monitors should be the electrochemical type used traditionally in mines.

Methane monitors based on the catalytic oxidation principle should be the primary monitorzs because they can accurately measure concentrations within the 0–5% range. Secondary monitors based on thermal conductivity should be used since they are good for a range from 5–100%.

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.

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10. Hazard Identification and Risk Analysis

A booster fan is often installed in a return airway, isolated from the intake airways by a set of stoppings and airlock doors. The main reason for this location is to avoid obstruction to safe travel in the intakes and to dissipate heat from the fan into the return air. A booster fan, to function safely, requires a monitoring system with control interlocks. Adequate selection, installation, and operation of a booster fan will decrease the main fan pressure, reduce leakage and power consumption. However, an inadequate installation can increase the likelihood of the buildup of air contaminants due to flow recirculation, and may lead to fires. In most coal mining countries, identification of hazards and risk analysis are part of the ventilation planning process, especially, when booster fans are used. In the U.S., the regulations of the Mine Safety and Health Administration (MSHA) require mine operators to apply general hazard awareness and control in all operations, but do not require a comprehensive risk management program. This section presents a summary of potential hazards associated with the usage of booster fans, the risk analysis tools and control measures to mitigate the risks to acceptable levels.

10.1. Booster Fan System

Figure 10.1 shows a typical arrangement of a booster centrifugal fan system in a coal mine.

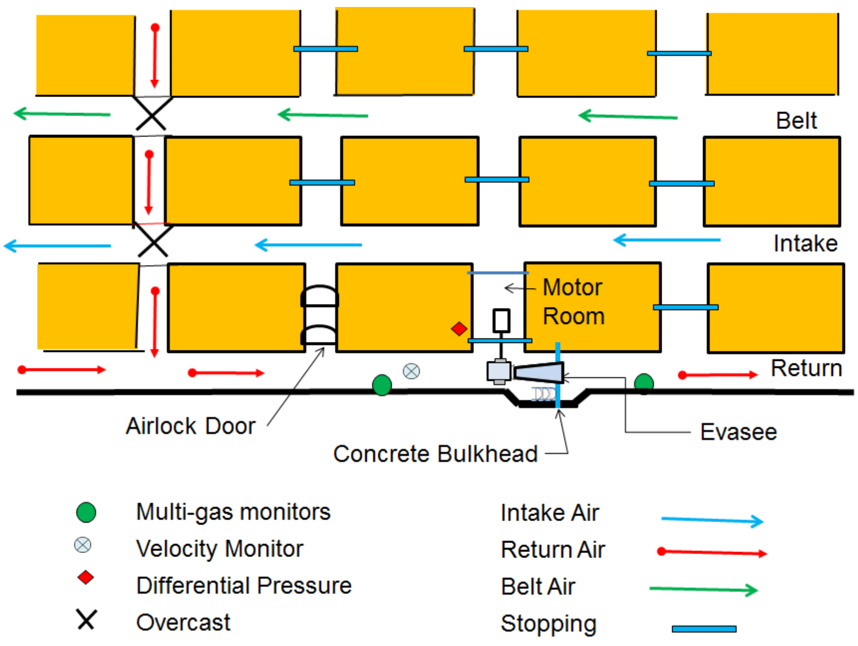


Figure 10.1. Typical arrangement of a booster fan system

In Figure 10.1, the booster fan is installed in the return airway and equipped with airlock doors and a set of environmental and condition monitors. The motor room and fan site are fully monitored for methane and carbon monoxide. Differential pressure and velocity transducers are used to monitor the fan duty, and vibration and bearing temperature to assess the fan operating conditions. In addition, the fan is equipped with an interlocking system to cut off the power to the fan in the event of main fan failure, and an automatic visual and alarm system that is activated when abnormal conditions are detected. The fan, before commissioning, should be tested for its stability and performance. This is usually accomplished, by running the fan first under no load conditions, when the airlock doors are kept wide open, and then, tested under half load, and full load, when the doors are fully closed. After commissioning, the fan operating conditions are monitored and evaluated against pre-established standards continuously.

10.2. Hazard Identification

When the ventilation plan includes the use of booster fans, the associated hazards should be identified in each of the following stages: mine planning and design, installation and commissioning, and operation. A summary of these is presented below (Benson 2012 and Calizaya et al. 2014).

Planning and Design. The location, size, and type of the fan are determined during the planning and design stage. Potential hazards at this stage include:

Oversizing the Booster Fan. Oversizing the booster fan may lead to flow recirculation, which in turn can lead to the buildup of air contaminants at the working face. Determining the best combination of main and booster fan pressures using ventilation simulators may reduce these hazards.

Inadequate Monitoring System. 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 calibrated against primary standards. Furthermore, the system must be equipped with redundant units.

Poor Design of the Airlock Doors and Bulkheads. The airlock doors and bulkhead are provided to direct the air to where it is needed and to minimize leakage. The doors must be designed and installed to operate at high pressure. Poorly maintained doors can lead to “struck by” and “caught between” type accidents.

Poor Design of the Fan Foundation. A booster fan requires a strong foundation. Misalignment and excessive vibration can lead to a number of unwanted events. The foundation design for the fan motor and casing must be site-specific and include provisions to facilitate fan repair and maintenance.

Installation and Commissioning. Inadequate installation and commissioning of the fan may also lead to hazardous situations. Potential hazards include:

Misalignment of Shafts. Misalignment can result in excessive vibration, shaft fatigue, and irregular bearing wear, leading to excessive friction. This can act as a source of ignition and trigger a mine fire. Alignment tests must be conducted periodically and after any major repair.

Fan Performance Tests. During testing, the fan is usually operated under three different conditions: no load, half load, and full load. For a no load condition, the airlock doors are kept open, then partially closed for a half load, and totally closed for full load. Parameters such as motor and bearing temperatures and vibration are measured for each condition. These are compared against pre-set standards. The fan is commissioned only when all the specifications are met.

Operation. The potential hazards during this stage include:

Power Failure to the Mine Site. Power failure to mine site will result in the buildup of air contaminants and a reduction in the total quantity of air. Controls should be in place to de-energize the mining equipment and to reduce the gas emissions in the mine.

Failure of the Main Fan. The main fan can fail due to mechanical or electrical problems. If the booster fan is left running, uncontrolled recirculation can create unsafe conditions. To mitigate this hazard, the booster fan and all underground equipment must be de-energized immediately upon main fan failure.

Failure of the Booster Fan. As soon as booster fan failure is detected, the airlock doors must be opened and the quality of air at the workings re-evaluated. Although a booster fan stoppage reduces the quantity of air directed to a section, the opening of the doors will allow part of the air circulated by the main fan to reach the workings. If this quantity is not sufficient to dilute the contaminants, the work load should be reduced.

Failure of the Interlocking Mechanism. If for any reason, the main fan stops, the booster fan must also stop. The malfunctioning of the interlock that controls this action may lead to uncontrolled recirculation.

Failure of the Monitoring System. Gas sensors, pressure transducers, and other monitoring devices are subject to wear and malfunction. Workplace assessment using faulty units can result in unsafe and unhealthy conditions. To avoid this problem, transducers should be calibrated frequently. Redundant units and uninterruptable power supplies should be provided for critical monitors.

Failure of the Fan Motor or Bearings. The fan motor or bearings may fail under loads greater than their respective rated capacities. 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.

Spontaneous Combustion and Fire. Although the likelihood of spontaneous combustion near the fan installation is low, it can occur in low rank coal mines, when the coal comes in contact with oxygen through the cracks around the periphery of the fan bulkhead. This may lead to a fire in the fan housing. To control the problem the fan drift should be covered with inert material. An alternative is to install the fan in a drift driven in the overlaying strata.

10.3. Risk Assessment

Risk assessment is the process by which the outcomes of risk analysis are compared against the risk acceptance criteria established to this purpose and understood by all parties. Identification of potential hazards and evaluation of risks associated with utilization of booster fans in coal mines are two major steps of risk assessment for the use of booster fans. If requirements are not met, changes to the system should be made and the process repeated. Figure 10.2 shows a flow chart of the risk assessment process used in this study. The process starts with the inventory of hazards and a list of unwanted events. These are then compared against the risk acceptance criteria. A risk assessment team and a risk matrix are needed to determine the critical hazards.

<u>Risk Assessment Team</u>. Before any analysis, a team must be formed. The members must be familiar with the hazards to be investigated and capable of identifying the vulnerabilities of the process or facility, analyzing the results, and developing action plans to mitigate the consequences of failures.

<u>Risk Matrix</u>. 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 each of the undesired events. It increases the visibility of the risk and assists the management in making timely, informed decisions (Chapanis 1986, Grayson 2001, and Joy 2009). Table 10.1 shows the risk matrix used in this study.

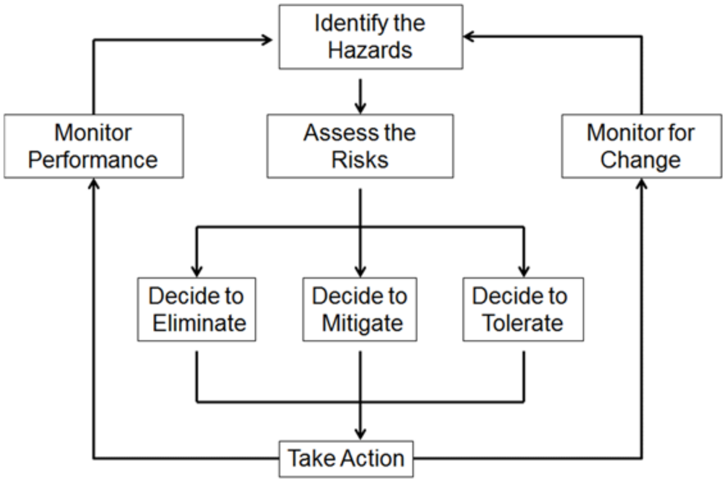
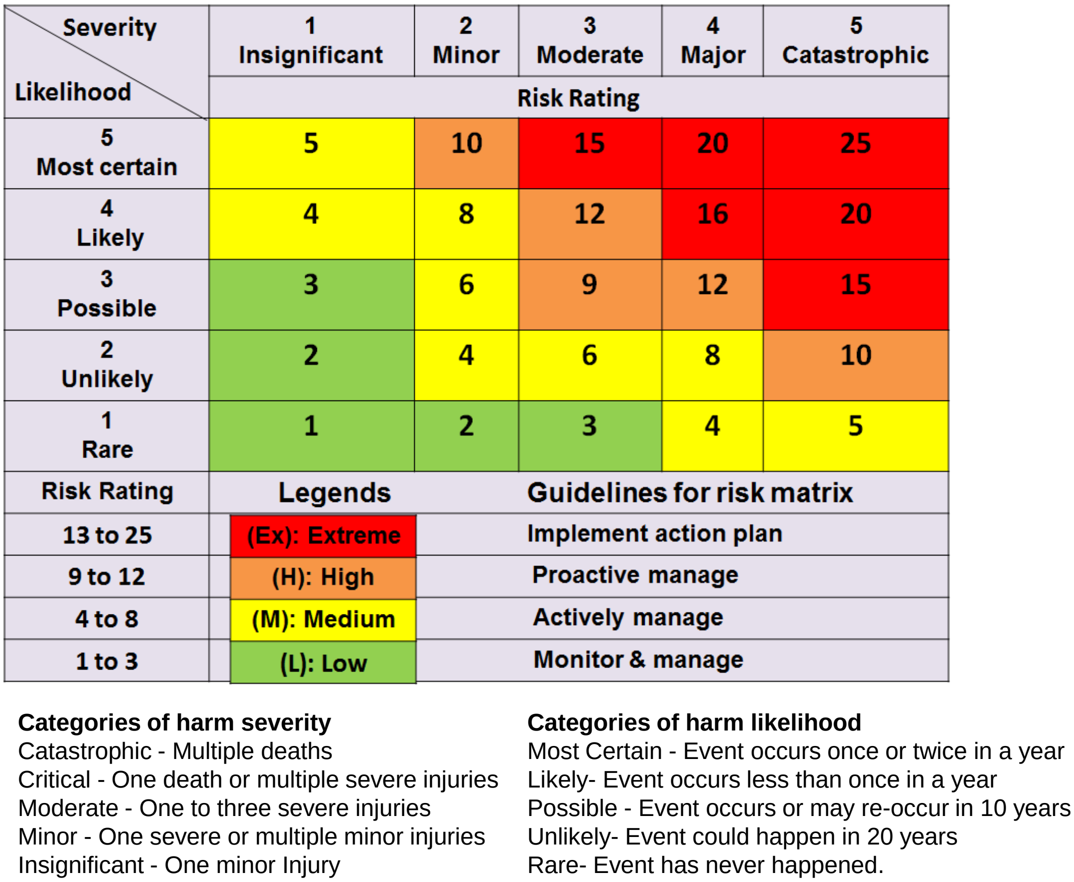


Figure 10.2. Process of risk assessment

Table 10.1 Risk matrix



Severity Likelihood	1 Insignificant	2 Minor	3 Moderate	4 Major	5 Catastrophic
	Risk Rating				
5 Most certain	5	10	15	20	25
4 Likely	4	8	12	16	20
3 Possible	3	6	9	12	15
2 Unlikely	2	4	6	8	10
1 Rare	1	2	3	4	5

Risk Rating	Legends	Guidelines for risk matrix
13 to 25	(Ex): Extreme	Implement action plan
9 to 12	(H): High	Proactive manage
4 to 8	(M): Medium	Actively manage
1 to 3	(L): Low	Monitor & manage

Categories of harm severity
Catastrophic - Multiple deaths
Critical - One death or multiple severe injuries
Moderate - One to three severe injuries
Minor - One severe or multiple minor injuries
Insignificant - One minor Injury

Categories of harm likelihood
Most Certain - Event occurs once or twice in a year
Likely- Event occurs less than once in a year
Possible - Event occurs or may re-occur in 10 years
Unlikely- Event could happen in 20 years
Rare- Event has never happened.

Risk Assessment Tools. There are number of techniques that can be used to analyze risks associate with the utilization of booster fans. These include: Workplace Risk Assessment and Control, Failure Mode Effective Analysis, Fault Tree Analysis, Bow Tie Analysis, Job

Safety Analysis, and Safe Operating Procedures (Shriwas, 2013), A brief description of two of these techniques are presented below.

Workplace Risk Assessment and Control (WRAC). WRAC is a qualitative risk ranking method. It breaks down the work into steps in a process map and evaluates each unwanted event using a risk matrix (Joy 2009). In the booster fan case, the analysis is performed during three stages: planning and design, installation and commissioning, and operation. Risk ranks are determined and post-evaluation control measures established.

Failure Mode Effect and Criticality Analysis (FMECA). FMECA is used for evaluating the effects of potential failure modes of subsystems, assembly components, or functions (Ericson 2005). It is a bottom-up evaluation technique which evaluates the effect of failure modes on the system and other items using the current and recommended control measures. Severity and probability evaluations of failure modes provide the user a prioritized list for corrective actions. This tool is often used to identify single component failure modes, but hazards can be the results of multiple failure modes. For this reason, this tool should only be used in conjunction with other tools such as Job Safety Analysis (JSA) and Safe Operating Procedures (SOPs).

10.4. Application of Risk Assessment Tools

Workplace Risk Assessment and Control. A WRAC was performed for the installation and use of booster fans. The risk assessment team included a mechanic, an electrician, a ventilation engineer, and a manager. Table 10.2, at the end of this chapter, shows the WRAC for design, installation, and operation of booster fans. This table also shows the outcomes of the analysis using this method. The L and C values for each of the hazards were assessed by the risk assessment team, and risk rate (R) was calculated as the product of L and C.

Inventories of hazards and unwanted events were identified for each of the stages described above. Major hazards and related unwanted events were addressed, existing controls evaluated, and risk ranks established. These were used to determine critical hazards. Based on this study, fire and flow recirculation were identified as the major hazards that required special attention. These were followed by the hazards from the failure of the electrical interlocking mechanism. Finally, mitigation controls were established for each critical hazard. The recommended measures, if implemented correctly, can reduce the risk to a tolerable level. WRAC includes a list of all the potential hazards with their existing controls, risk ranks, and recommended control measures.

Failure Mode Effect and Criticality Analysis. During the operation of a booster fan, three groups of failure modes were distinguished: electrical, mechanical, and physical. The effects of each mode on the system were evaluated, the risks ranked, and post-evaluation control measures recommended. Table 10.3, also at the end of this chapter, shows three critical hazards associated with the operation of booster fans; power failure to the mine site, failure of the monitoring system, and failure to detect flow recirculation. This table also shows the results of the risk analysis of hazards associated with the operation of booster fans using FMECA. These results shows that the booster fan system, when equipped with reliable airlock doors and fire sensors, can be operated safely. Power failure to main fan, while the booster fan is still operating, may result in buildup of air contaminants. This problem can be overcome by activating the interlocking system.

During the analysis described here, two critical failure modes were identified: failure to monitor combustion products and power failure to mine site. The recommended control measures, if implemented, can reduce the associated risks to tolerable levels. This study points out all the potential hazards, risk ranks, and recommended control measures required to reduce or eliminate the hazards associated with the safe operation of a booster fan in an underground coal mine.

10.5. Discussion

Identification of potential hazards and evaluation of risks associated with utilization of booster fans in underground coal mines are two major steps of risk assessment. This task was performed by a team of experts formed to this purpose. Two methods were used to identify the critical hazards: Workplace Risk Assessment and Control (WRAC) and Failure Mode Effect and Criticality Analysis (FMECA.)

WRAC was used to identify critical hazards during the design, installation and operation of a booster fan. A Risk matrix was developed to evaluate and determine the levels of risk. During the analysis two critical hazards associated with the operation of booster fans were identified: potential of fire and flow recirculation. The recommended measures, if implemented correctly, can reduce the risk to a tolerable level. WRAC includes a list of all the potential hazards with their existing controls, risk ranks and recommended measures.

FMECA was used to evaluate failure modes associated with the operation of booster fans. During the analysis, two critical failure modes were identified: failure to monitor combustion products and failure of power to mine site. The recommended control measures, if implemented, can reduce the associated risks to tolerable levels. This study points out all the potential hazards, risk ranks and recommended control measures to reduce or eliminate the hazards associated with the safe operation of a booster fan in an underground coal mine

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Table 10.2. WRAC analysis and outcomes

Steps in process	Unwanted Event	Current Controls	L	C	R	Recommendation
During Design Stage						
Oversizing and poor location of booster fan	Recirculation and fire	Use vent simulator to size and site fans	2	4	8	Check for recirculation before implement the design
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.
During Installation and Commissioning Stage						
Fan guarding and testing	"caught between" moving parts	Fencing around the fan	1	5	5	Install safety screen and good illumination
Misalignment of motor and fan shafts	Excessive vibration can damage fan	Follow vendor's guidelines	3	3	9	Check alignment manually
Failure to test vibration and temperature	Damage to motor and fan parts	Fan monitoring system	2	4	8	Check manually, redundant sensors.
Failure to follow SOP	Fan breaks down frequently	Training	2	4	8	Refresher training
During operation stage						
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 or bearings	Regular maintenance	2	4	8	Keep spare motor and fan parts in hot room
Chemical	Fire and self-heating of coal	Eliminate ignition sources	3	5	15	Shotcrete fan drift and equip fan with firefighting units
	Build-up of air contaminants	Avoid flow recirculation	3	5	15	Provide fan with a good monitoring system
	Dust and smoke buildup on blades	Use water spraying during cutting	1	5	5	Frequent maintenance
	Recirculation	Constant monitoring	2	5	10	Evaluate CO and cut power to downside equipment

Table 10.3. Failure mode effect and criticality analysis

Failure Mode	Effects		L	C	R	Control
	Other Item	System				
Electrical						
Failure to detect fan condition or air contaminants	a) Undetected build-up of combustion products	Undetected spontaneous heating and fire	3	5	15	Equip monitoring system with redundant and calibrated sensors
	b) Change in vibration and temperature	Overheating of motor (ignition source)	3	4	12	Provide system with uninterruptable power supply (UPS)
Power failure to mine site	Main and booster fans stoppage	Whole ventilation system is down	3	5	15	Provide standby power source for the main fan
Mechanical						
Failure of main fan	Mining equipment is down	Mine air quality deterioration	2	5	10	Stop booster fan and downside equipment, open airlock doors and evacuate mine personnel
Failure of booster fan	Booster fan is down	Section air quality deteriorated	2	4	8	Stop downside equipment
Failure of airlock doors to open while booster fan is down	Flow through ventilation not restored	Potential for gas build-up	2	4	8	Inspect door conditions regularly
Failure to test recirculation	Build-up of contaminants	Fire or explosion	3	5	15	Monitor flow quantity and flow direction
Failure of couplings	Booster fan is down	Section air quality deteriorated	1	5	5	Examine bearing temperature and maintain couplings
Physical						
Roof and rib failure	Damage the fan	Mine vent system disrupted	2	3	6	Reinforce roof and walls, perform tests
Failure of fan foundation	Damage the fan motor	Mine vent system disrupted	2	3	6	Regular measurement of vibration and noise
Failure of bulkhead and man doors	Decrease of fan efficiency	Increased local recirculation	2	3	6	Monitor pressure drop across the bulkhead

L = Likelihood; C = Consequence; R = Risk Rank

11. Guidelines for Safe Operation of Booster Fans

A booster fan is an underground ventilation device installed in the main airstream (intake or return) to handle the quantity of air required by one or more working districts). It is often installed in the return airway in series with a main fan and used to boost the pressure of the ventilation air passing through it. The fan is installed in a permanent bulkhead and equipped with a set of airlock doors, stoppings, interlocking devices with the main fan, and an atmospheric monitoring and control system. When adequately installed, a booster fan can be used to reduce the "effective resistance" of the mine, thus reducing the main fan pressure, the leakage flow rate, and the total power consumption. However, an inadequate installation can increase the likelihood of mine fires and recirculation of air contaminants. Booster fans are used in most coal mining countries including the United Kingdom, Australia and Poland, but prohibited in the U.S. coal mines (MSHA 2013).

This section includes a summary of standards and regulations adopted by two coal mining countries, the applicable standards used in U.S., the basic requirements for the fail-safe operation of underground booster fans, installation principles for fan systems, and rules of safe practice.

11.1. Regulatory Requirements for Booster Fans

Each country has its own regulations for the use of booster fans. In this section, U.K. and Australian statutory regulations for the use of booster fans are summarized.

Although there are similarities between the mining technologies and practices in the United Kingdom, and Australia, there are legal and practical dissimilarities that have led each country to approach coal mine ventilation differently. Practices that contribute to the safe use of booster fans in the United Kingdom and Australia need to be identified and evaluated to determine the applicability of these practices to U.S. coal mines.

Increasing the capacity and efficiency of a ventilation system is one of the main motives for using booster fans, but as the efficiency of the system is increased by the use of booster fans, recirculation is more likely to occur. In fact, many ventilation systems that use booster fans experience a significant amount of recirculation. Most underground coal mines in the United Kingdom rely on booster fans and controlled recirculation to provide adequate air quantities and velocities; however, in the United States, recirculation is not an accepted ventilation practice. Methods to limit controlled recirculation in ventilation systems using booster fans should be further evaluated.

11.2. The U.K. Coal and Other Mines (Ventilation) Order of 1956

The Coal and Other Mines (Ventilation) Order of 1956 allows U.K. coal mine operators to use booster fans, provided that certain conditions are met. Two of such conditions, from Part 28 of the order, are listed below.

"No fan (not being an auxiliary fan) shall be installed at any place below ground in a mine, unless the manager is satisfied that it is necessary or expedient to install it at that place for the proper ventilation of the mine…"

"If any such fan is installed at any place below ground the manager shall forthwith give notice thereof to the inspector for the district, attaching thereto particulars of the survey and a copy of the report made in relation to that installation…"

In addition, the following standards are imposed:

<u>Planning</u>. The plan must specify the size and location of the proposed fan and give predictions as to its effect on all parts of the mine

<u>Half-Hourly Inspection</u>. The fan installation must be inspected at 30-minute intervals, and for the instrumentation (sensor) readings to be recorded every two hours

<u>Electrical Supply</u>. There must a dedicated power supply from the surface substation to the fan with an alternative supply available.

The installation of a booster fan requires a thorough ventilation survey and planning. The report and all other details of such survey must be sent to District Inspector for approval. The Mines Inspector has the prerogative to impose whatever conditions and requirements it sees fit, to further enhance safety (Leeming 2012).

11.3. Australian Coal Mine Safety and Health Regulations

In Australia, booster fans are used in two coal mining states, New South Wales and Queensland. In both states, the installation of booster fans requires a thorough evaluation and risk analysis and a management plan demonstrating adoption of best practices. The plan must be submitted to the state inspectorate for approvals. Some specific state requirements are listed below.

11.3.1. Queensland—Coal Mining Safety and Health Regulation, 2001

Part 11. Division 5

353 Using fans underground. "(3) The mine must have a standard operating procedure for using the following fans if the fans are used in the mine's ventilation system— (a) auxiliary fans, (b) booster fans; (c) scrubber fans …"

354 Provision for fans in principal hazard management plan for ventilation. The mine's principal hazard management plan for ventilation must state, "(b) if a booster fan is used at the mine— (i) the procedures for using the fan; and (ii) the action to be taken if a methane detector monitoring the air passing through the fan activates a visible alarm."

358 Dealing with underground auxiliary and booster fans. "(1) A person must not deal with a fan ventilating a place below ground at an underground mine unless the person—is the ERZ (Explosion Risk Zone) controller for the place; or is authorized by the ventilation officer to deal with the fan …"

11.3.2. New South Wales—Coal Mines (Underground) Regulation, 1999

Part 4. Ventilation, Division 5 Fan installations

93 Installation of monitoring system. "A system must be installed and maintained to monitor the operation of the main ventilation fan or fans at a mine. The system must provide for the giving of an alarm at the surface of the mine if the fan or fans stop."

95 Booster fans. "A booster fan must not be installed or used underground at a mine unless the installation and use of the fan is approved."

Booster fans are located in the return airways with their motors and electrical components in intake air. As part of the safety management plan all underground booster fans are equipped with environmental and fan condition monitors, airlock doors, and an electrical interlocking system. The possibility of mine fires is the major design parameter (Benson 2002 and Ogle 2011).

11.4. The Code of Federal Regulations Title 30 (U.S. Coal Mines)

Currently, Title 30 of the *Code of Federal Regulation*s, Part 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. In anthracite mines, booster fans installed in the main air current or a split of the main air current may be used provided their use is approved in the ventilation plan."

The 1969 Coal Mine Act did not specifically prohibit the use of underground booster fans in coal mines, though the requirement of main fans on surface acted effectively against the use of booster fans. In 1989, the Mine Safety and Health Administration (MSHA) published a new proposal for revising and updating the existing ventilation regulations. This proposal prohibited the use of booster fans in underground bituminous and lignite coal mines. Reasons cited by MSHA included several safety concerns, including recirculation, fires, fan control, noise, and dust (Martikainen 2010). The final rule was enacted in 1992.

11.5. Booster Fan Installation Principles

The design principles and operating practices mentioned in this report were gathered from mine visits and fan inspections conducted in underground coal mines where booster fans are used regularly. This section describes briefly the major steps that must be followed to ensure that these units are used in coal mines safely and efficiently. First, the booster fan must be sized and located to assist the main surface fan to overcome high resistances, reduce leakage, and minimize the total power consumption. Furthermore, to reduce potential hazards, booster fans must be equipped with condition and environmental monitors, and an electrical interlocking system to prevent the onset of flow recirculation.

Planning. Before any booster fan installation is considered, alternate options should be evaluated carefully. Options such as upgrading the main fan, repairing damaged bulkheads, and removing high resistance airways should be considered first. Planning for the use of booster fans almost always starts with ventilation surveys and estimation of ventilation loads and airflow requirements. This is followed by network modeling and simulation exercises for different ventilation strategies. Optimization procedures such as those developed at the University of California, Berkeley (Calizaya et al. 1987), and the University of Nottingham (Moll 1994) can be used for this purpose and economic solutions can be generated. Furthermore, these methods can be used to size fans and predict future requirements. However, the simulation results should be checked against practical constrains such as the need of driving bypass drifts, slashing existing drifts, and installing airlock doors.

Fan Location. Figure 11.1 shows the general layout of a coal mine ventilation system. It shows the location of the booster fan in relation to the active workings. The booster fan is installed in the return airway, in line with the main surface fan. This arrangement is preferred in coal mines with multiple entries where the fan motor, transformer, and other electrical components must be located in fresh air (Sartain 1989 and Leeming 2012).

Fan Installation. Following simulation exercises and fan selection, the next task is site preparation and fan installation. Site preparation often involves the widening of an existing drift or developing a bypass drift to house the fan and the airlock doors. This is followed with the installation of an overhead monorail, fan housing, bulkheads, airlock doors and a pre-fabricated fixture between the diffuser and the bulkhead.

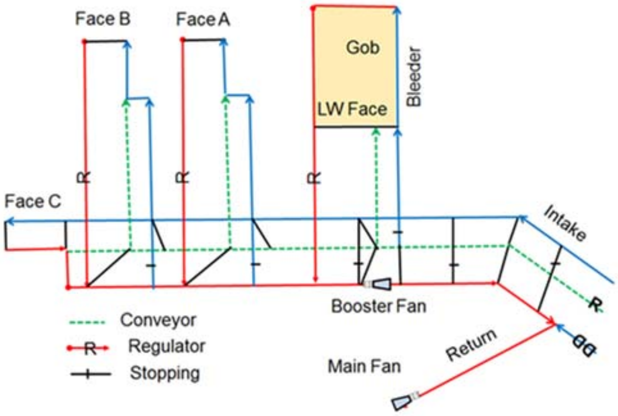

Figure 11.1. General layout of a coal mine ventilation system

Figure 11.2 shows the general layout of a booster fan system. The system is equipped with a centrifugal fan located in the return airway The reason for selecting a centrifugal fan is to allow installation of the fan motor and starter in the intake airway and the fan housing in the return airway. Figure 11.2 also shows the locations of airlock doors, Bulkheads, and overcasts. In addition, to minimize the risk of fire, the booster fan requires the installation of a fan condition and environmental monitoring system.

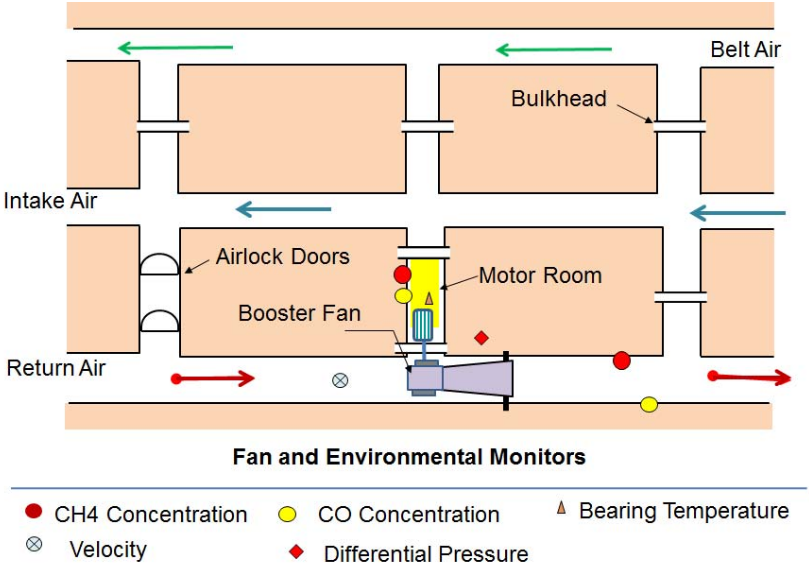

Figure 11.2. Typical arrangement of a booster fan system

By-pass Doors. Depending on the pressure differential generated by the booster fan, a set of at least two doors is required to complete the booster fan installation. These doors are used to prevent recirculation when the fan is running, and to allow the access of heavy equipment to both side of the fan during maintenance. They are equipped with control devices to close the doors when the fan is started and to open them when the fan is stopped. Most of these doors are designed to operate under the pressure difference generated by the fan (Ogle 2012).

Monitoring System. In coal mines, a monitoring system is regarded as a main component of the booster fan installation. It includes fan condition monitors and environmental monitors. These monitors are located upstream and downstream of the booster fan and in the motor chamber. The fan monitors include those that measure differential pressure across the fan bulkhead, air flow rate, vibration, and bearing temperatures, and are used to determine the health of the fan. The environmental monitors, including methane and carbon monoxide sensors, are used to assess the air quality in the motor room and fan housing. If any monitor fitted to a main fan or booster fan detects a significant departure from normal operating conditions, the monitoring system must automatically activate a visible alarm, trip power to the fan, and record details of the event.

Fan Testing and Commissioning. Normally, a booster fan is tested for its stability and performance. This is accomplished by running the fan first under no load conditions, when the airlock doors are kept wide open, then under half load, and finally under full load, when the doors are fully closed. The various fan parameters including vibration and motor and bearing temperatures are measured during each test. The results are then evaluated against pre-established standards given by the fan manufacturing company and legislative bodies. Table 11.1 shows some of the common threshold limit values used in the industry.

Table 11.1. Standards fan parameters

Fan Parameter	Allowable Limit
Vibration	5.5 mm/s
Motor Temperature	85ºC
Shaft Alignment	5.5 mm
Fan Duty	± 5% of designed value
Bearing Temperature	85ºC

The booster fan is commissioned only when the measured parameters are consistently at or below these limits.

Fan Operation. Main and booster fans are operated as long as the workers are in the mine. A fan start-stop protocol is established to be followed when restoring power after any outage, including those scheduled for changing the fan duties. In addition to condition and environmental monitors, a booster fan is normally equipped with an interlocking device to cut off the power to the fan in the event of main fan failure. If the booster fan fails for any reason, the inby equipment must be de-energized and the airlock doors must be opened automatically. If the main fan fails for any reason, the booster fan and the inby equipment must be de-energized. These actions are performed to prevent the build-up of air contaminants. All main and booster fans must be maintained at least every four months, with fan cleanup every month.

Risk Analysis. Identification of potential hazards and evaluation of risks associated with utilization of booster fans in coal mines are two major steps of risk assessment for the use of booster fans. This task requires a team of experts that include the ventilation engineer and the end users. Workplace Risk Assessment and Control (WRAC) and Failure Mode Effect and Criticality Analysis (FMECA) can be used to identify the critical hazards. Once these hazards are identified and the risks ranked, control measures can be established. The implementation of these measures can reduce the associated risks to tolerable levels.

11.6. Fan Interlocking System

An interlocking system 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 flow recirculation in the mine. Most mines use electrical interlocking with the atmospheric monitoring system (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 air 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. 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 outage, including those scheduled for changing the fan duties.

To develop recommendations for fan interlocking, practices in the U.K. and Australia were reviewed. In Australia, 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 system in place. It is a common practice in Australia to have ventilation boreholes.

In the United Kingdom, electrical interlocking between the main and booster fan is not required. The coal mines in the U.K. are very deep—on the order of 800–1000 m. Therefore, it is difficult to have an interlocking system. Booster fans are accepted as a necessary part of an adequate mine ventilation system. 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 same 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.

Figure 11.3 shows a schematic of a fan interlocking system. Different pieces of equipment such as fans, airlock doors, and AMS are connected to a central interlocking system. This system provides an interlock between the main fan and booster fan and among other pieces of equipment.

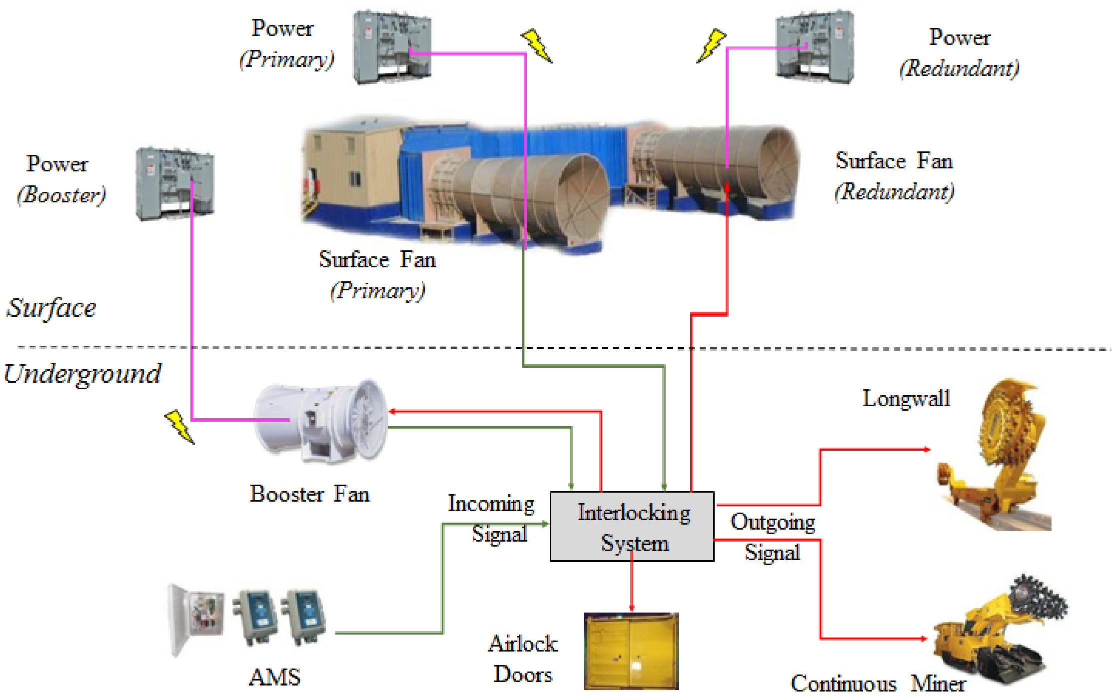

Figure 11.3. Schematic of fan interlocking system

11.7. Guidelines for Safe Operation of Booster Fans

Based on the experience gained from booster fan inspections in British and Australian coal mines, the following guidelines were developed:

1. The booster fan must be located and sized to assist the main surface fan to ventilate high resistance working sections. Computer programs such as the one developed in this research project can be used to determine the operating pressure of this fan.

2. The fan must be installed in a concrete bulkhead in either the intake or return airway. For practical reasons, it is usually installed in the return airway with its motor and other electrical components ventilated with fresh air. Both axial and centrifugal fans can be used as booster fans. The fan must be equipped with a monitoring system, a set of airlock doors, and an electrical interlocking system.

3. Once the decision to install a booster fan is made, a detailed plan justifying the usage of the booster fan must be developed. This plan must specify the size and type of the fan(s); the number, type, and strength of airlock doors; fan condition and environmental monitors; and details of the electrical interlocking system. In addition, the plan must include an inventory of hazards, risk evaluation results, and the control measures that must be implemented to bring the associated risks to tolerable levels.

4. The fan and environmental parameters that should be monitored are differential pressure, vibration, airflow, electrical power, motor and bearing temperatures, methane

and carbon monoxide. All the monitors should be connected to the surface control room. Preset alarm conditions should be listed on screens with an alert for the operator, and visually displayed on schematics.

5. The differential pressure should be measured across the bulkhead, at the nearest airlock doors, and across the nearest stoppings in the intake and return airways. Airflow is one of the most important parameters that should be monitored. 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.
6. Electrical power should be monitored continuously. Booster fans should have an independent power supply separate from the other equipment in the mine. Monitoring power gives a good indication of the fan efficiency.
7. Motor and bearing temperatures should be monitored continuously. They are good indicators of any malfunction in the fan installation. Booster fan installations should have four temperature probes on the bearings, two on the motor and two on the fan side. Motor current should also be monitored.
8. Methane concentrations should be monitored continuously in the motor room and at the fan site. The recommended alarm levels for these monitors are 0.5% in the motor room and 1.5% in the fan housing.
9. Carbon monoxide monitors should be placed approximately 4–10 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 quickly.
10. The position of the airlock doors should be monitored continuously to so that the doors are closed when the fan is running and open when the fan is down. If the doors do not open when the fan is off, an alarm must be activated and the pressure relief valves open.
11. The interlocking system should be connected to the AMS. If high concentrations of gases are detected, the booster fans should be turned off. In all the cases, the mining equipment and machinery inby (longwall shearer, continuous miners, shuttle cars, etc.) should be de-energized automatically.

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12. Conclusions

A booster fan system is a proven technology used in most coal mining countries including the United Kingdom, Australia, Poland, South Africa, Japan, and India. However, in these countries, regulations require mine operators to develop a comprehensive ventilation plan showing the need of the booster fan, and that all critical hazards are identified, the risks are evaluated, and the control measures to mitigate these risks are in place.

A booster fan, when properly sized and sited, can be used to decrease the surface fan pressure, reduce leakage and reduce the total power consumption. This is accomplished by boosting the air pressure in areas of high resistance, and decreasing the pressure difference across the stoppings outby the booster fan, thus reducing the leakage flow and power requirement. However, when the fan is not sized, operated, or maintained properly, it can induce flow recirculation.

For practical reasons, a booster fan is usually installed in the return airway and is equipped with heavy duty airlock doors, condition and environmental monitors, and an electrical interlocking system to avoid flow recirculation in the event of surface fan failure.

As part of this study, six underground coal mines using booster fans were visited: three in Australia and three in the United Kingdom. In these mines, booster fans are used regularly to overcome adverse conditions created by higher airway resistances and increased airflow requirements. In Australia, the booster fan installation requires a thorough evaluation and risk analysis and a management plan demonstrating adoption of best practice that must be submitted to the state inspectorate for approvals. In the United Kingdom, the 1956 Coal and Other Mines Regulations place a number of requirements on owners and managers both before these fans can be installed in a coal mine. One of these requirements is a detailed report on the intended use of the booster fan, and another is that the fan operating conditions must be inspected every half hour.

A comparative evaluation of current U.K., and Australian regulations on booster fan usage shows some differences. While recirculation is not allowed in Australian mines, some recirculation of less than 10% is accepted in British mines. Another difference is that electrical interlocking between the main and booster fans is required in Australian mines, but not in British mines. In the U.K., redundant surface fans are used instead.

Laboratory experiments were conducted at the University of Utah’s ventilation model to determine the effect of a booster fan size on the quantity and quality of air circulated through a simulated working area. The experiments showed that when the booster fan is operated at a pressure as large as or larger than the main fan pressure, then there is significant potential for recirculation. The closer the booster fan is to the development or production sections, the greater the likelihood of recirculation.

The experimental mine at Missouri University of Science and Technology was upgraded to include two12-kW booster fans, and various steel bulkheads and man-doors. Numerous tests were conducted to investigate the effect of the booster fans on pressure differences across the bulkheads, and volume flow rates at different blade settings and fan speeds. The results showed that when the booster fan blade angle is correctly matched to the ventilation system, the booster fan can provide sufficient ventilation to the workings without introducing any recirculation. However, recirculation will take place when the booster fans are oversized as compared to the main fan, misplaced or when the stoppings are not maintained properly.

A new fan selection program, GVENT, was developed as part of this project. The program, based on genetic algorithms (GAs) developed by MIT, and a ventilation simulator developed by Mine Ventilation Services, Inc., can be used to determine the best combination of fan pressures (surface and underground booster fans) that satisfy the mine flow requirements, reduce leakage, and minimize the power consumption. The program was tested using sample networks and real mine ventilation networks. The results generated by this program were compared with those generated by a ventilation simulator, and it was found that the results were within the 0.5% of one another. Using this new approach, the results were generated faster and with less human intervention than those generated by the simulator. As an example, a network of 65 branches, 45 nodes, six working areas, and two fans was solved for fan pressures in less than one hour. Using a ventilation simulator, these results were achieved after several trials and correlation studies, which took about 3 days.

A monitoring system is a basic requirement for the usage of booster fans in coal mines. It is used to diagnose the health of the fan, to provide warnings to workers when abnormal conditions are detected and to prevent the onset of flow recirculation. Based on field observations and best practice developed by mine operators, the following monitors are required:

Fan condition monitors

Pressure differentials across the fan and interlock doors
Vibration (fan and motor bearing)
Bearing and motor temperatures
Motor current and input power.

Environmental monitors

Methane concentration (in coal mines), upstream from the fan
CO concentration, upstream and downstream from the fan
Smoke, downstream from the fan.

In addition to condition and environmental monitors, a booster fan is normally equipped with an interlocking device to cut off the power to the fan in the event of main fan failure. If the booster fan fails for any reason, the inby equipment must be de-energized and the airlock doors must be opened automatically. If the main fan fails for any reason, the booster fan and the inby equipment must be de-energized. These actions must be performed to prevent the build-up of air contaminants.

Workplace Risk Assessment and Control (WRAC), and Failure Mode Effective Analysis (FMEA) were used to identify hazards and evaluate risks associated with the operation of booster fans in coal mines. During the analyses, for a sample problem, two critical hazards were identified: potential of fire and flow recirculation. Once these hazards are identified and the risks ranked, control measures can be established. The implementation of these measures will reduce the associated risks to tolerable levels.

Finally, based on the standards and regulations adopted by two coal mining countries, the U.K., and Australia, the rules of safe practices found in the ventilation literature, and the applicable standards used in U.S., a set of guidelines for the safe use of booster fans in coal mines were developed. These guidelines, including the basic requirements, the risks associated, and the recommended control measures, can be used for the design, operation and maintenance of booster fans in underground coal mines.

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