Development of coal mine face ventilation systems during the 20th century

During the 20th century, the increased emphasis on worker health and safety and the advent of new mining equipment and methods led to many changes in mine face ventilation practices. Efforts by government and private industry to improve and modify ventilation practices resulted in better health and safety conditions for workers.

This article focuses on U.S. Bureau of Mines (USBM) and National Institute for Occupational Safety and Health (NIOSH) research to examine factors that had a significant influence on mine face ventilation design during the past century. Several "milestone" events are discussed along with the impact they had on worker health and safety. Significant ventilation research efforts by government and private industry are presented. This brief ventilation history highlights innovative face ventilation designs and a consistent commitment to mining health and safety.

Ventilation has always been a concern in underground coal mining. For many years, there was no appreciation of how ventilation could be used to remove harmful contaminants from the air or how to control airflow quantities. The first known problems with ventilation date back to the 14th century, when it was recognized that lack of air was a major impediment to the expansion of mines. The common method of solving ventilation problems at that time was to abandon the existing mine and start a new one nearby.

Ventilation in the early days of coal mining was accomplished by means of a natural draft, created principally by a difference in the weights of columns of air between the intake and return openings. Later, in the 18th and 19th centuries, a furnace was introduced underground to increase the updraft in the return shaft. This allowed for a larger quantity of air in circulation. When mines went deeper and became larger, mechanical ventilation became necessary and was first accomplished by steam-driven fans. These fans became more prevalent as furnaces were prohibited in underground mines, especially after the Avondale disaster in Pennsylvania in 1869 (Roy, 1876). Eventually, these fans were replaced by more powerful, electrically

FIGURE 1

Rescue workers at the Darr Mine explosion, Jacobs Creek, PA, Dec. 19, 1907.

FIGURE 2

Historical summary of the Jacobs Creek Mine disaster (Humphrey, 1960).

December 19, 1907: Darr Mine, Jacobs Creek, Pa.; 239 Killed

(*From State inspector's report, 1907, pp. xviii–xxvii, 869–870*)

At 11:30 in the morning * * * an awful rumbling followed by a loud report and a concussion that shook the nearby buildings was felt within a radius of several miles. The Darr mine was never deemed a very dangerous mine as it generated only a small percentage of gas and was worked with open lights. The explosion had * * * terrific force * * *. Progress by rescuers (fig. 4) was very slow owing to the fact that all the stoppings were blown out. * * * Only one man escaped * * *; he was on his way to the engine room for oil. * * * The cause may have been the projection of flame into a gaseous and dusty atmosphere * * * by an open light or a blown-out shot. * * * The system of workings * * * does not provide for efficient ventilation * * *. We recommend * * * the development on a four-entry system, * * * that ventilation be controlled by overcasts instead of doors, * * * that flameless explosives be used for all blasting, * * * that competent shot firers * * * prepare, charge, and fire the shots after workmen are out of the mine, * * * that all stemming be with clay or other incombustible material, * * * that a water system be installed for wetting and laying the dust, * * * that all accumulations of dust be loaded out, * * * that the mine be worked exclusively with locked safety lamps, * * * that enough firebosses should be employed to make careful examinations of the mine * * *, and that the mine foreman devote the whole of his time to his duties as described by law and maintain rigid discipline. * * *

driven centrifugal fans in the 20th century. (Forbes, 1929; Redmayne, 1911).

As mines went deeper, underground explosions began to occur. The source of the new danger was a mysterious gas called firedamp that exploded violently when it came in contact with open lights. Persons working in the vicinity of such ignitions were often killed by the force of the explosion or were burned to death. It was recognized in the 17th century that the buildup of this gas was the main cause of the underground coal mine explosions. But there was no way to prevent this gas, known as methane, from entering the mine because it was continuously liberated from the coal seam. It was not until the 20th century that ventilation techniques would be used to control the levels of methane.

Conversely, coal dust was not recognized as a danger until the early 19th century (Redmayne, 1911; Lee, 1971). The health hazard from this dust was thought to be related to silica or silicosis. It was not until 1934 that coal dust was recognized as a cause of a progressive and fatal respiratory disease in Britain. It was 30 years later before coal dust would be officially recognized as a health hazard separate from silicosis in the United States through the Federal Coal Mine Health and Safety Act of 1969 (Lee, 1971). In the interim, ventilation was not thought of as a means to control this dust. The application of water was the primary means to reduce airborne dust levels.

Up to and throughout the 20th century, mine explosions killed hundreds of miners at a time. The public outcry became loud enough in the United States that action was taken to form an agency that would investigate ways to make mining safer. While discussions of the formation of this new agency were ongoing, four large underground explosions occurred in a short time period: 361 coal miners were killed in Monongah, WV, on Dec. 6, 1907; 239 were killed two weeks later at Jacobs Creek, PA (Figs. 1 and 2); 154 were killed at Marianna, PA, Nov. 28, 1908 and 259 were killed at Cherry, IL, on Nov. 13, 1909 (Kirk, 1996).

As a result of these explosions and fatalities, the U.S. Bureau of Mines (USBM) was formed on July 1, 1910. Part of the USBM mission was to investigate mine explosions and enhance the safety of miners by preventing accidents and improving working conditions in mines (Kirk, 1996). The USBM conducted many research investigations on underground coal mine ventilation. This research continues today at the National Institute for Occupational Safety and Health (NIOSH) under the Centers for Disease Control, U.S. Department of Health and Human Services. It is understood that ventilation research has been conducted by many agencies, public and private, worldwide. This overview focuses on research conducted by the USBM until 1997 and subsequently by NIOSH. It gives a picture of how this research has impacted face ventilation systems, which has led to safer mining with fewer fatalities and injuries due to explosions and face ignitions. This research has been shaped by a commitment to make mining safer while providing ventilation techniques that complement current mining technology.

USBM ventilation research from inception through the 1940s

Much of the early interest in mine ventilation research was related to a concern for the physical well-being of the miners who worked underground. The effects of dust and gases on the workers were understood and publicized, as were the impacts of temperature and humidity of the ventilating air. Guidelines were published on recommended air velocities at certain air temperatures and humidity levels to maximize the comfort of the miner. The cost of maintaining the air at these temperature and humidity levels and velocities was shown to be recouped through the increased productivity of the miner (Sayers and Surgeon, 1922). An early recommendation from the USBM, "The quantity in cubic feet of pure intake air flowing per minute in any ventilation split should be at least equal to 100 times the number of men in that split."

This standard was based on the need to provide a working environment that would promote the health and productivity of the worker. All of this was accomplished by focusing on improving the overall mine ventilation system.

The lack of adequate and efficient ventilation was recognized as the primary cause of gas ignitions in coal mines. It was believed that explosive gas did not accumulate in properly ventilated mines (Harrington and Denny, 1938). However, most of the early studies to reduce methane ignitions were based more on removing the sources of ignitions rather than improving ventilation. Three of the major sources of ignitions were:

- Use of nonpermissible explosives or the improper use of permissible explosives.
- Improper installation, maintenance or use of electrical equipment.
- Use of open lights and misuse of safety lamps.

Following the organization of the USBM, acceptance and use of permissible explosives had a great effect on reducing the number of underground explosions. When the original tests on explosives were developed, very little was known about the mechanism of the ignition of methane-air mixtures. The USBM considered this one of its most fundamental research problems. The first approach to solving it was to view it as a flame study. This was based on the belief that the longer the flame and the longer the time it endured, the greater is the chance that such a flame would ignite flammable mixtures of gas and air. Further methane and coal dust testing in the 1920s, as shown in Fig. 3, studied the characteristics of the explosion process, such as the shock wave, gaseous products, type of flames involved and nature of ejected particles (Fieldner, 1950).

The danger of methane ignitions due to electrical sparks became an issue as more electrically powered equipment was introduced into mines. Because of this danger, the use of animal haulage or permissible storage-battery locomotives was recommended in other than pure intake air and the use of booster and auxiliary fans was discouraged (Forbes and Ankeny, 1929; Harrington and Denny, 1938). The USBM recommended that booster or auxiliary fans not be used for supplying air to working faces (Forbes and Ankeny, 1929). Nevertheless, such fans were installed in gassy mines regardless of the hazards involved, sometimes with disastrous consequences (Harrington and Denny, 1938). It was not until many years later that the USBM enforced standards for permissible fans.

Open lights were a source of ignition throughout the early 20th century. The development of safety lamps in the 1800s reduced the danger of an ignition due to the flame of an open light. However, for many years there remained a controversy about when it was necessary to use the "closed" versus the "open" lights. This classifica-

FIGURE 3

Explosion from the Experimental Mine at the U.S. Bureau of Mines Bruceton laboratory.

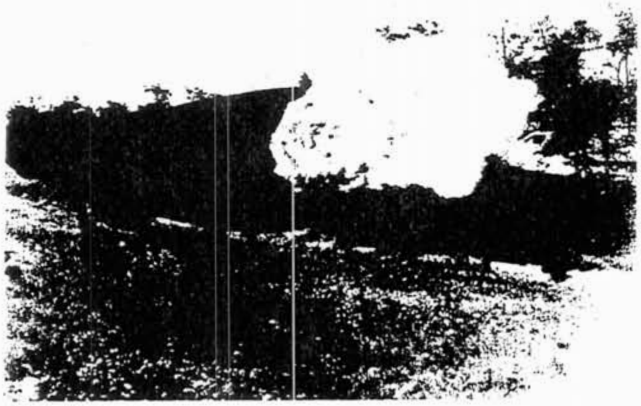
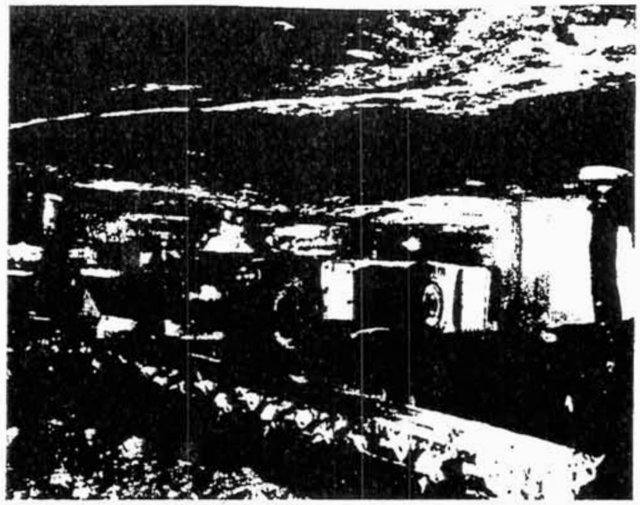


FIGURE 4

Jay boom cutter used in conventional mining.



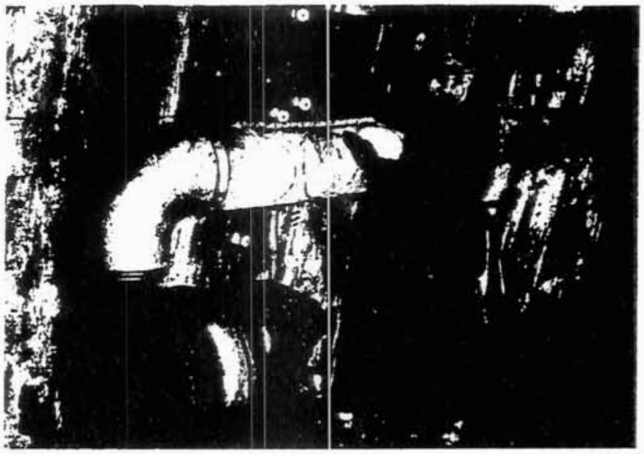
tion was the precursor to nongassy and gassy mines. And, often, it was a question of whether a mine, or part of a mine, was gassy or had the potential to accumulate dangerous quantities of methane gas. Mines were referred to as open- or closed-light mines depending on the relative ignition hazard. Additionally, some argued that the flame safety lamp was an underground hazard since there was the potential to misuse the lamp. There were many documented cases of workers taking a safety lamp apart underground and attempting to relight them with matches (Tomlinson, 1944). Many explosions with loss of life were due to this practice. Ignitions due to open lights became less of a problem as permissible electrical lights became more prevalent and the flame safety lamp was delegated from a source of light to a means of methane detection.

The first guidelines for ventilation design were presented in 1929. These guidelines included recommended airway velocities, minimum volumes of air for a split and the optimum amounts of intake air that should reach the face. It was recognized that a ventilation system would be adequate if the following guidelines were followed. Airway velocities were not to exceed 9.1 m/sec (1,800 fpm) in smooth-lined airways, 4.1 m/sec (800 fpm) in normal ribbed entries and 3 m/sec (600 fpm) in main haulage airways. The minimum velocity was to never fall below 1 m/sec (200 fpm). The recommended minimum volume for a split of air was 4.7 m^3/sec (10,000 cu ft/min). The amount of intake air from the shaft that should reach the face was recommended to be 50 percent, although 80 percent to 85 percent was stated to be more desirable and attainable through proper installation and construction of stoppings, doors and overcasts (Forbes and Ankeny, 1929).

The main focus of ventilation studies was on proper design of the overall ventilation system with emphasis on the proper construction and installation of stoppings, doors and overcasts.

FIGURE 5

Auxiliary fan used to provide fresh air to the face.



USBM coal mine ventilation research from 1950 to 1970

The period between 1950 and 1970 was an important turning point in mine ventilation research. Before 1950, procedures for improving face ventilation were based on actual operating conditions observed in underground coal mines. After 1950, many recommendations for improving face ventilation were based on controlled research experiments conducted in the laboratory and underground.

During this time, conventional and continuous mining methods were used underground, with continuous mining becoming more common. Each mining technique presented specific ventilation requirements for methane control. One of the first reports of this time period focused on the ventilation of a coal face undercut with a cutting machine, as shown in Fig. 4. It stressed the importance of keeping the line brattice close to the face in order to clear the kerf (undercut) of methane. For blowing brattice, this distance was no more than 1.5 m (5 ft) from the face. This practice was emphasized as a way to prevent future explosions; by eliminating the methane, the possibility of explosions was removed (Stahl and Dodge, 1956).

The continuous miner machine changed coal mining. These new machines advanced working faces rapidly, generating coal production tonnages never before seen. However, when using a continuous miner, methane was released more rapidly from the face. Additionally, the large size of these mining machines made it difficult to get enough air to the face to adequately dilute the methane. It became necessary to conduct research to develop improvements in face ventilation techniques that could reduce the dangerously high methane concentrations that resulted from continuous mining. Ventilation, in addition to water sprays, was important for dust control (Fieldner, 1950). However, most studies during this time focused on ventilation controls to remove methane liberated at the face.

The greatest problem was the challenge of providing sufficient quantities of air to the face using line brattice. Significant losses in air quantity were known to occur between the last open crosscut and the face end of the curtain or tubing. Guidelines for installing line brattice systems were publicized by the USBM in the late 1920s.

The guidelines stipulated that the line brattice be constructed from the crosscut to within 1.5 to 1.8 m (5 to 6 ft) of the face to conduct the air into the room and allow it to sweep the face. The line brattice also should be made of fireproof canvas material secured to wooden posts, anchored at the roof and floor. The intake side of the line brattice should have a smaller, cross-sectional area than the return side in order to maintain higher intake velocities to correctly sweep the face of any gasses that appear. Additionally, it should be constructed as airtight as possible, thereby reducing the explosion potential at the face (Forbes and Ankeny, 1929).

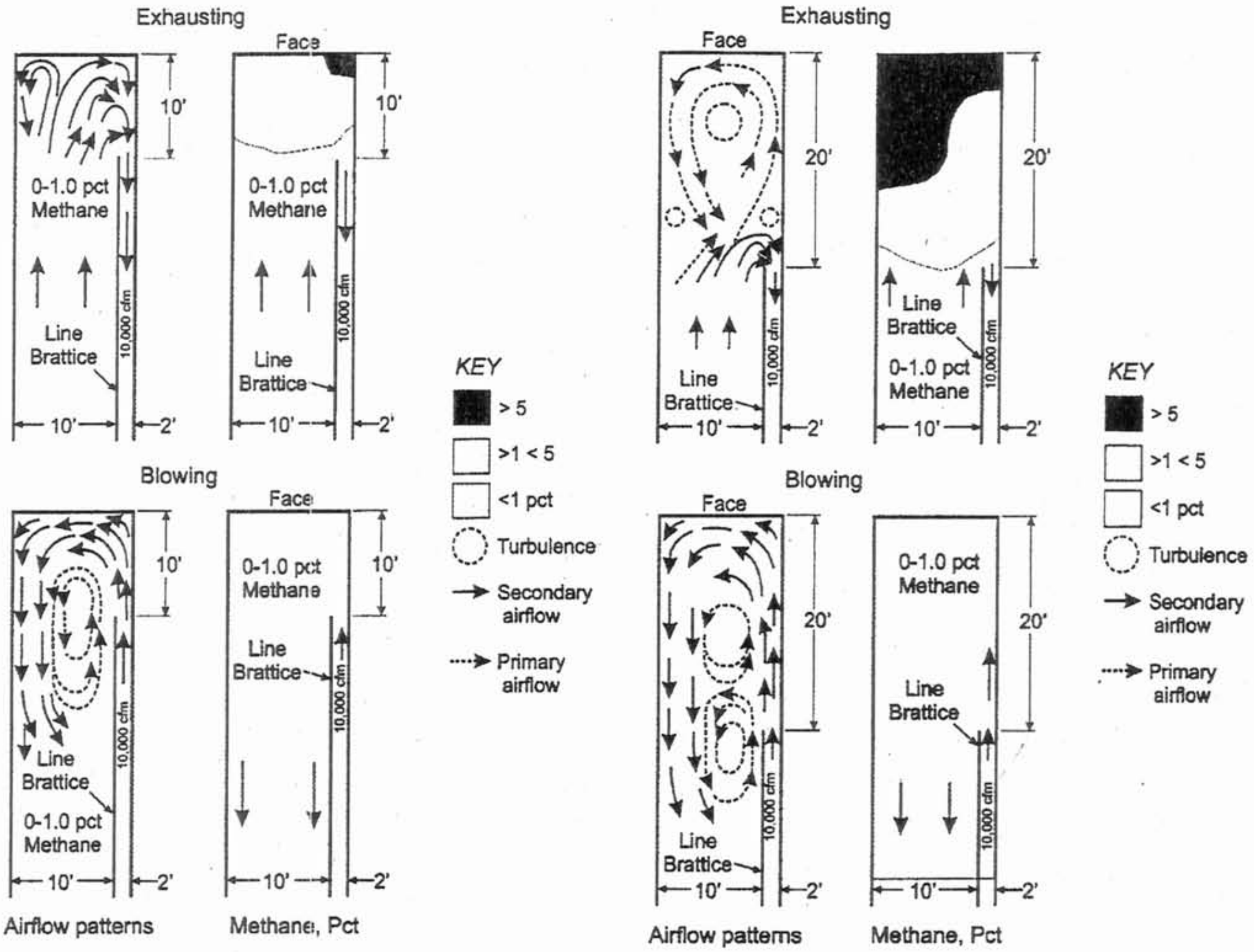
Additional work recommended that more durable and less combustible materials be used to replace ordinary canvas or jute brattice and ventilation tubes or conduits. These recommendations were made to increase the life of these materials, as they could be destroyed by fire, fungus rot or acid mine water. Consideration of the use of plastics, fiberglass, and other ceramic materials was suggested (Fieldner, 1950).

Almost all other studies performed during this time period focused on face ventilation when using continuous miners. Some early recommendations, which are still valuable today, for improved face ventilation include the following (Stahl, 1958; Schlick and Dalzell, 1963):

- Line brattice can be used effectively to convey the proper amount of air directly to the face if it is properly constructed.
- The liberation of methane varies considerably from location to location.
- Using a blowing fan and tubing, as shown in Fig. 5, to force air to the face is effective for removing methane. However, the rib where the airflow passes must be kept wet or more dust will be generated.
- Using an exhaust fan and tubing is effective for removing methane from the face, provided that the tubing is kept within 1.5 m (5 ft) of the face.
- A combination of blowing and exhausting fans works effectively under the following conditions:
  - The exhausting tubing should be located close to the face and inby the blowing tubing.
  - The blowing tubing should be located 6.1 m

FIGURE 6

Airflow patterns for blowing and exhausting face ventilation systems.



(20 ft) or closer to the face but outby the exhaust tubing.
- The two fans should not be balanced to allow airflow in the shuttle car entry.

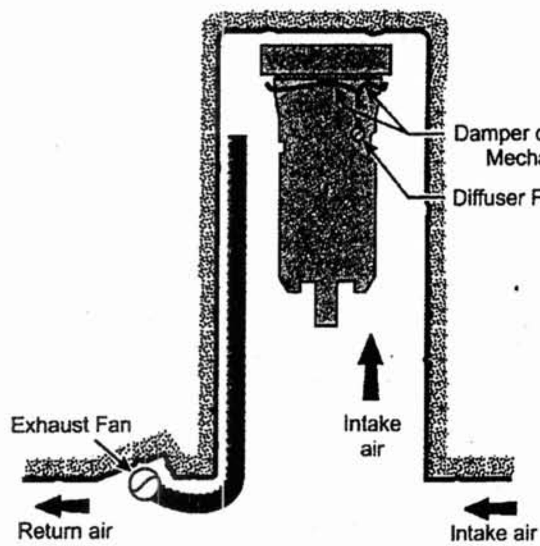
- The fans used for face ventilation should be permissible with the following guidelines:
  - Blowing fans should be installed on the intake side.
  - Exhausting fans should be installed on the return side.
  - The quantity of intake air available for face ventilation should be larger than the capacity of the fan.
- A blowing fan with a Y-shaped duct with the duct ends on either side of the continuous miner terminating at the face is effective. The Y-shaped duct is used to direct the air to either side of the miner as needed.
- Recirculation of air is not desirable:
  - When operations are idle, line brattice should be used to ventilate the face.
  - If the main ventilation current is disrupted, the face ventilation fans should be shutdown.

Other studies were completed to determine the ventilation properties of line brattice systems and ventilation tubing. These studies evaluated the friction and shock losses for the material types and installation methods of each type of ventilation system (Dalzell, 1966; Peluso, 1968).

However, probably the most significant study completed during this time period was one that determined the airflow distribution patterns for both blowing and exhausting face ventilation systems using line brattice. Figure 6 shows the airflow distribution patterns that have been established for blowing and exhausting face ventilation systems. This figure shows how the blowing face ventilation line brattice, with setback distances of 3 and 6 m (10 and 20 ft), is effective for removing methane concentrations from the face. However, the airflow patterns for the blowing system create turbulence and secondary airflow patterns, which are detrimental for dust control. It also shows the airflow patterns for the exhausting face ventilation system and corroborates the fact that the line brattice must be close to the face to remove methane effectively. Exhaust ventilation creates less secondary airflow and turbulence, particularly at the 3-m (10-ft) setback distance, which allows this system to minimize dust entrainment. By displaying the airflow patterns, the study demonstrated how the exhausting system becomes less effective as the curtain was moved further away from the face (Luxner, 1969). Figure 6 illustrates how a blowing face ventilation system can be beneficial for methane removal but detrimental for dust control, while the exhausting face ventilation system is advantageous for dust control, but disadvantageous for methane removal.

FIGURE 7

Diffuser fan with an exhausting face ventilation system.



USBM coal mine ventilation research from 1970 to 1990

The Federal Coal Mine Health and Safety Act of 1969 had the most significant impact on face ventilation research. Prior face ventilation efforts were directed towards removing methane from the face. The new Act now added the burden of controlling respirable dust to the face ventilation systems. Mine operators now had to keep respirable dust below 2 mg/m^3 in addition to keeping methane levels below 1 percent. The use of blowing face ventilation, which had been recommended as the best method for methane removal, could result in higher dust levels.

To maintain levels of respirable dust and methane at permissible levels, new recommendations were made for face ventilation. Blowing face ventilation was acceptable as long as the end of the curtain was kept outby the continuous miner operator. However, this required a waiver to allow the end of the curtain to be more than 3 m (10 ft) from the face. This practice, though, would not do anything to reduce the dust levels to the shuttle car operator positioned outby the mouth of the blowing ventilation. The best practice recommended an exhausting line brattice system for face ventilation with the end of the curtain maintained within 3 m (10 ft) of the face. Still, with this system there was the disadvantage of methane buildup at the opposite corner to the line brattice due to recirculation of air and the inability of the airflow to penetrate the off-curtain side corner. To overcome this disadvantage, a diffuser fan could be mounted on a continuous miner with the fan's exhaust directed to the problematic corner. To operate this type of diffuser face ventilation system, the exhausting line brattice or vent tubing must be inby the diffuser intake, as shown in Fig. 7 (Mundell, 1977).

Several studies were conducted to assess devices that would keep the line brattice within 3 m (10 ft) of the face. Some studies examined the use of extensible line curtain and ventilation tubing systems. The extensible line curtain, which was a device that allowed the line brattice curtain to be extended to the face without the miners having to go under unsupported roof, was better suited for use with blowing ventilation and could be used to increase face airflow (Thimons et al., 1999). It failed to gain acceptance because it was difficult to maintain and it led to air leakage problems. Extensible tubing systems, as shown in Fig. 8, were extended either independently of the mining machine or by attaching the end of the tubing to the mining machine. This system, while more readily accepted by the industry, tended to obstruct face visibility and restrict mobility of the mining machine (Monaghan and Berry, 1976; Muldoon, 1982).

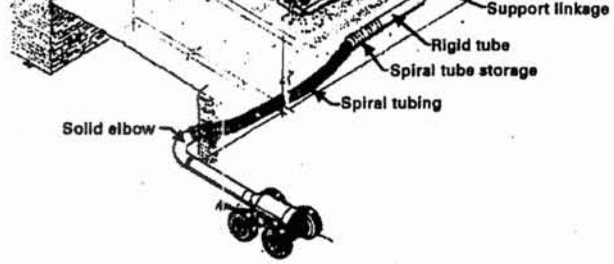
The use of auxiliary tubing that could be extended from an auxiliary fan without moving the fan was also investigated. Initially, tests were conducted with auxiliary fans that had no tubing attached. For a 12-m (40-ft) setback distance, these free-standing fans delivered more air to the face than a blowing curtain (Goodman et al., 1992). However, it would be difficult to use a freestanding fan during mining without interfering with the movement of equipment.

Other studies evaluated novel devices such as air curtains and sideboard devices to improve face ventilation. The use of an air curtain was evaluated as an extension of the line brattice curtain. The air curtain consisted of a thin, hollow pipe with holes perforated on the topside of its surface. This device was located on the continuous miner. When connected to a small centrifugal fan, air emanated from the perforated surface creating a curtain of air that flowed from the device to the roof. This device did reduce respirable dust concentrations at the continuous miner operator position. These reductions in concentrations, though, did not justify the amount of effort to install and operate this system (Krisko, 1977).

A sideboard device, which consisted of a 1.2- x 2.4-m (4- x 8-ft) sheet of plywood mounted on a continuous miner, was also evaluated. This device was shown to be effective. But it required the use of additional water sprays that were used to seal the open area between the sideboard device and the end-of-the-line brattice. This device never became widely

FIGURE 8

Diffuser fan with an exhausting face ventilation system.

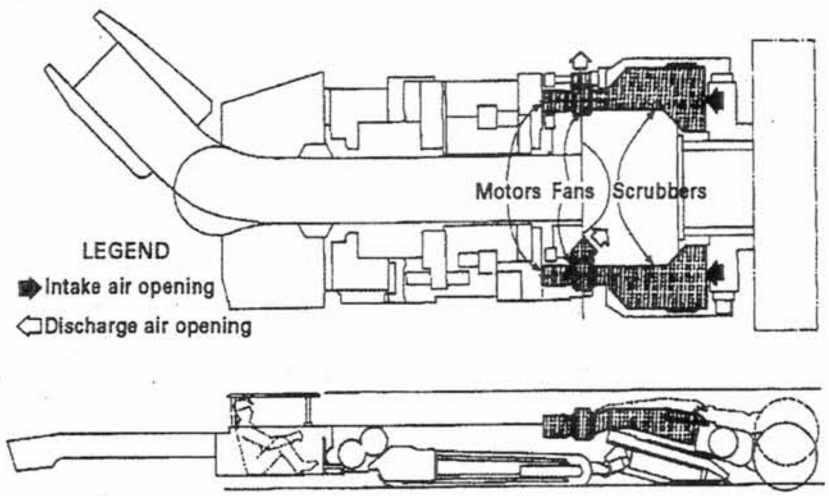


used because the extra water required for proper operation could cause floor problems. Additionally, there was the disadvantage that the sideboard blocked the operator's view of the side of the continuous miner on which the device is mounted (Divers et al., 1979).

Extensible brattice and tubing systems, air curtains and sideboards did not meet with much success because they were generally more difficult to implement than existing systems. Additionally, variances allowing the line curtain to be greater than 3 m (10 ft) from the face were easy to obtain as long as scrubbers and arrays of directed water sprays (spray fans) were in place (Muldoon et al., 1982). However, subsequent research dealing with flooded-bed dust scrubbers did yield successful results.

FIGURE 9

Plan and side views of a twin scrubber layout on a continuous miner.



Face ventilation research continued on the use of scrubbers and on methods for improving exhausting line brattice systems. During this time, scrubbers were becoming more prevalent, as they were effective in reducing respirable dust levels while assisting the face ventilation system to ensure that methane levels were acceptable. Additionally, with U.S. Mine Safety and Health Administration (MSHA) approval, they allowed line brattice setback distances up to 6 m (20 ft). There was concern that recirculation of air caused by the scrubbers and auxiliary fans would lead to methane buildup at the face, which could potentially lead to explosions. A study demonstrated that recirculation of air did not create methane buildup as long as fresh air was maintained to the face. The airflow patterns of the fresh air at the face were influenced through the use of a scrubber, but the scrubber itself did not cause methane to buildup. Problems only occurred when the flow from the scrubber exhaust interfered with fresh airflow to the face (Kissell and Bielicki, 1975).

Further research was conducted to determine the best duct discharge configuration with the scrubber systems for methane dilution with an exhausting line brattice. There were three optimal discharge configurations for a twin scrubber configuration, shown in Fig. 9, with line brattice distances from the face varying from 1.5 to 6 m (5 to 20 ft). These configurations are, from lowest to highest methane removal efficiencies: left side perpendicular to the rib, right side 45° toward the face (looking towards the face); left side off (no flow), right side 45° toward the face; and left side 45° away from the face, right side 45° toward the face (Divers et al., 1981).

USBM coal mine ventilation research from 1990 to 2006

During the 1990s, the number of mines using remotely controlled continuous mining machines increased. Operating a mining machine remotely enabled a machine operator to cut to depths greater than 6 m (20 ft) without exposing workers to unsupported roof. Cutting depths of 11 to 15 m (35 to 50 ft) were common on many mining sections. With deep cutting, worker exposure to airborne respirable dust generally decreased as work locations became further removed from the face. However, with the deeper cuts it was more difficult to maintain curtain or tubing setback distances. The result was that a large percentage of the air delivered to the end of the curtain or tubing did not reach the face (Thimons et al., 1999). Consequently, face methane levels increased.

Research focused on the development of improved face ventilation techniques for deep cutting mining sections In general, it was assumed that the amount of intake air supplied to a mining entry was sufficient to ventilate the face and maintain methane levels below 1 percent. Improvements in face ventilation would result if more of the available air could be delivered to the face. The following two approaches were taken in researching techniques for ventilating deep cuts:

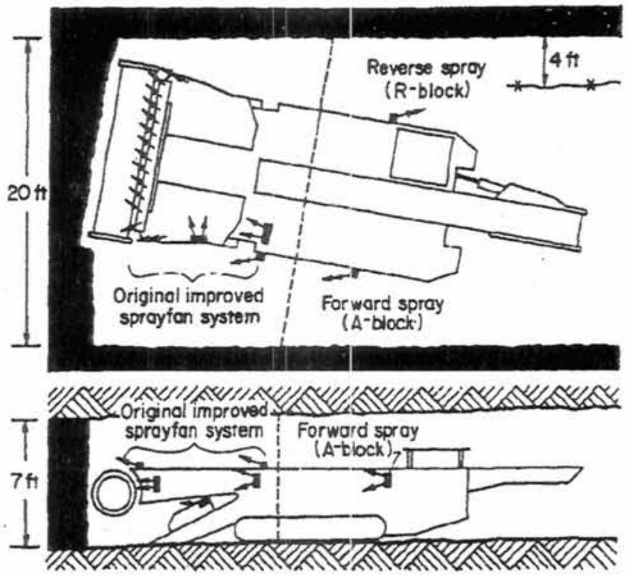
- Maintain constant ventilation curtain/tubing setback distance (advance the curtain or tubing as the mining machine advanced).
- Use auxiliary means to better use available intake air (use fans/scrubbers to improve ventilation effectiveness).

Earlier work showed that designs for extensible face ventilation systems did not work and could not be adapted to a deep-cut mining sequence. However, previous work with water sprays and scrubbers did show that they were effective for dust control. And, because they moved air, they helped to dilute and remove methane liberated at the mining face (Volkwein et al., 1985; Volkwein and Thimons, 1986). Tests evaluated how sprays and scrubbers might be used to improve airflow during deep cutting.

Scrubbers are effective in removing methane and respirable dust from the face for blowing and exhausting face ventilation systems with the most effective methane removal occurring when using a blowing face ventilation system (Taylor et al., 1996). When using scrubbers, it is required that the airflow at the end-of-the-line curtain be equal to or greater than the scrubber capacity. For exhausting face ventilation systems, this requirement had no effect on dust capture. However, for sections using blowing face ventilation systems, this airflow was thought to overpower the scrubbers, allowing dust to bypass the scrubber inlets.

FIGURE 10

Diagram showing location of water sprays on continuous miner.



This resulted in a phenomenon called dust rollback, where excessive levels of dust move over the continuous miner into the mining section (Goodman et al., 2000). Further research corrected this problem with the combined use of scrubbers and water sprays.

Again, there was considerable concern that use of the scrubber might increase recirculation of air from the face, resulting in higher methane levels, especially if scrubber capacity was larger than the amount of intake air available. Early and subsequent testing showed no increase in methane due to scrubber use as long as the quantity of intake air delivered to the end of the curtain or tubing did not decrease (Kissell and Bielicki, 1975; Taylor et al., 1997). Any recirculation that did occur was more than offset by improved dilution of methane due to increased airflow created by the scrubber (Taylor et al., 1997; Taylor et al., 2006).

Water sprays, shown in Fig. 10, are most effective in reducing respirable dust levels. And their use can also improve dilution of methane within a couple feet of the face (Goodman et al., 2000). However, additional face flow is needed to move the gas away from the face and into the return airflow. Angled sprays (30° angle from perpendicular to face) directed towards the return side of the face were found to provide better methane removal than straight sprays (perpendicular to face) by providing this additional airflow (Taylor et al., 2006). Earlier work (Jayaraman, 1984) showed that dust rollback in this situation could be minimized and face airflow maintained if a water pressure of approximately 690 kPa (100 psi) was maintained.

The combined use of angled water sprays and the machine-mounted dust scrubber can be most effective for diluting and removing methane gas from the face. However, it was found that respirable dust concentrations may not be reduced in the face area because the water sprays produce increased turbulence at the face, which resulted in dust rollback (Taylor and Zimmer, 2001). This problem was eliminated by adding more water sprays above, below and on the sides of the continuous miner boom. This configuration confines the dust cloud beneath the cutting boom allowing the scrubber inlets to remove the respirable dust. The additional sprays allow the combined use of the scrubber and water sprays of the continuous miner to be effective at removing methane and respirable dust (Goodman et al., 2000).

Summary

Significant progress has been made in face ventilation research since the beginning of the 20th century. This progress has resulted in improved worker health and safety. Specifically, the research during the past century has led to lower respirable dust levels and fewer methane ignitions at the face, while production levels have increased from 1.8 to 2.7 t (2 to 3 st) per miner per day in the early 20th century for nonmechanized mining methods to 4.5 to 8.2 t (5 to 9 st) per miner per day in 1940 to 1950 when conventional mining was prevalent. And then it improved to 12 to 13.6 t/d (13 to 15 stpd) from 1960 to 1980 when continuous mining displaced conventional mining as the preferred mining method (Energy Information Administration, 1991; U.S Department of Interior, USGS, 1892-1921; U.S. Department of Interior, Bureau of Mines, 1932-1972). Most of the changes in the last century occurred following public demands for safer working conditions, new regulations requiring improved air quality and changes in mining methods. The following four events that occurred in the 20th century had the greatest impact on the evolution of face ventilation systems:

- Mine disasters/explosions that resulted in the creation of the USBM.
- Increased productivity that resulted from changes in mining methods from nonmechanized to conventional and, finally, to continuous mining.
- The enactment of the Federal Coal Mine Health and Safety Act of 1969.
- The use of remotely operated continuous mining machines equipped with flooded bed scrubbers, which made deeper cutting possible.

The USBM provided the vehicle for researching new face ventilation techniques. Before developing the science of face ventilation, early research looked at ways to reduce explosions by removing sources of ignitions. When mechanization increased mining production rates, new ventilation techniques were needed to reduce methane concentrations. After the enactment of the Federal Coal Mine Health and Safety Act of 1969, ventilation systems had to be designed to control levels of methane and airborne dust, changing the recommended configuration of optimal face ventilation from a blowing system to an exhausting system. Machine-mounted water spray and scrubber systems were designed as auxiliary ventilation devices for use with blowing and exhausting systems. The use of remotely controlled mining machines provided a challenge to maintaining face airflow during deeper cutting.

Current research shows that a general optimal face ventilation system may be either a blowing or an exhausting system that consists of a line brattice to guide air to the face. The choice of face ventilation system depends on whether dust control or methane control is the greater problem. The distance of the end-of-the-line brattice to the face may vary anywhere from 3 to 12 m (10 to 40 ft). However, with these distances, water spray systems and scrubbers mounted on the continuous miner are essential to the face ventilation system to direct the air up to the face to dilute and remove methane and respirable dust. The specific details of a face ventilation system will vary between operations, as each mine has unique characteristics. These individual characteristics may influence the specific design of an optimal face ventilation system for that mine.

The research at NIOSH continues to find ways to improve the health and safety of underground miners by further reducing methane and dust levels at the face. Currently, the research emphasis is on timely recognition of factors that could result in harm to workers due to high dust or methane concentrations. Personal dust monitors that continuously give the wearer data regarding their dust exposure levels are being tested underground. Airflow and methane monitors that will respond more quickly to changes in airflow and methane concentrations at the face are being investigated. Future research will emphasize improving techniques for monitoring methane, dust and airflow at the mining face. Based on airflow, dust and methane data obtained from NIOSH laboratory studies, computer-based ventilation models will be developed to improve face ventilation systems. An important goal of this research will be to provide individual workers with techniques and tools for evaluating current ventilation requirements and designing new ventilation systems for future needs. (References are available from the authors.)