Historical Development of Technologies for Controlling Methane in Underground Coal Mines

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ABSTRACT: For 100 years, a major emphasis has been placed on controlling methane in underground coal mines in order to improve worker health and safety. This emphasis and related research, as well as legislative actions, have led to new mining equipment and methods which have changed methane control practices in coal mines. The U.S. Bureau of Mines (USBM), and more recently the National Institute for Occupational Safety and Health (NIOSH), have been an integral part of many of these developments which have improved mining health and safety, either by initiating research programs or by collaborating with the U.S. mining industry. Two primary goals of this research have been to reduce underground methane explosions by controlling methane emissions from the coal bed and the gob, and diluting methane gas that has been liberated in the face areas. The decreased number of fatalities due to methane explosions clearly shows the success of this program. This paper discusses several milestone events that show the progress of this methane control research.

INTRODUCTION

Most explosions in coal mines occur when an explosive methane-air mixture is present. Since its inception in 1910, the U.S. Bureau of Mines and the National Institute for Occupational Safety and Health have conducted research to help prevent methane explosions. Some of this methane research has been in direct response to underground explosions. Other research has been the result of applying new technologies to reduce the likelihood of underground explosions (for example, degasification with directional drilling). This paper examines several of the major technologies that the USBM and NIOSH developed for controlling methane in underground coal mines. The technologies are grouped and discussed according to the decade(s) of their development.

BACKGROUND

In 1907, following the explosions in four mines that killed over 600 miners, the United States coal mining industry gained an international reputation as "…being the most backward of the civilized nations" and was characterized as "…callous where financial interests have weighed against human lives."(Colliery Guardian 1908). Responding to the large loss of life in the mines, the United States public demanded that safety in U.S. coal mines be improved. In 1910, the existing U.S. Geological Survey department was used to form the basis for the U.S. Bureau of Mines.

CHRONOLOGICAL DEVELOPMENT OF METHANE CONTROL TECHNOLOGIES

1910 to 1950

In the early 1900s, it was a common belief that most mine explosions were the result of unsafe practices that occurred throughout the mines. Early USBM research, therefore, emphasized education of the mining industry. It was assumed that a more educated mining community would act in a way that would result in safer mines.

In 1910, the Bureau of Mines opened an experimental mine in Bruceton, PA. From 1914 to 1925, the Bureau focused almost exclusively on the causes of explosions and ways to prevent them. Explosion demonstrations conducted at Bruceton for the public did not explain why methane ignitions occurred, but graphically showed the effects of igniting dust or methane gas in a coal mine (Figure 1).

Early Ventilation Studies

Only limited ventilation research was conducted in the early 1900s because there was a common belief that explosive methane-air mixtures would accumulate in face areas regardless of the quantity of air provided by the ventilation system. The emphasis of the research was on removing sources of methane ignitions, such as explosives and open flame lights, rather than improving ventilation.

The quantities of air normally provided in mines were considered adequate (Harrington and Denny 1938). As long as coal was loaded by hand, relatively small amounts of fresh air were needed to

Figure 1. Early explosion test at the U.S. Bureau of Mines

Figure 2. Mining conditions at a work place

dilute the quantities of methane released at the face. Health requirements of the workers and animals, not methane control, usually determined the amount of air provided to the working places (Miller 1940) (Figure 2). In the 1930s and 1940s, airflow quantities increased as more mines began to use mechanical fans for ventilation.

Ignition Sources

Permissible Explosives. The USBM played an important role in the development and testing of permissible explosives which, when used properly, would not ignite methane. As mines began to use permissible explosives, the number of ignitions decreased; however, at some mines with less gassy seams, people continued to think permissible explosives were not necessary. Opposition to use of the permissible explosives also came from miners who said they were too expensive and broke coal into pieces that were too small. That is, the miners who were paid for lump coal saw their incomes decrease when they used permissible explosives.

Open Flame Lights. Use of open flames for underground illumination was known to be hazardous, but there were few alternatives until the Bureau helped to develop the electric cap lamp (also known as a "closed light"). The Bureau issued the first permit for an electric light in 1914 (Fieldner 1950), but the use of open flame lights continued in many less gassy mines where they were considered safe. Initially, mines were not required to use the electric lights. Mines were often identified as either "open light" or "closed light" depending on whether they were considered non-gassy or gassy, respectively.

Some miners preferred open lights because they provided more light than early electric lights, and the electric lights had heavy batteries that often leaked electrolyte (Figure 3). Some workers opposed the use of electric cap lamps because they believed ventilation would be neglected in mines that used electric lights. There were reports that some companies tried to force workers to mine in gassy areas of the mine while wearing the electric lights.

Figure 3. Thomas Edison with early electric cap lamp

Early Coal Bed and Gob Degasification Studies

The potential benefits of using boreholes to drain gas from coal in advance of mining were recognized in the early 1900s, especially when mining deeper and

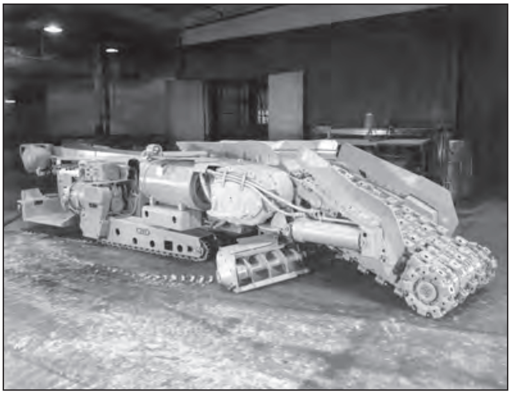

Figure 4. Early continuous mining machine

Figure 5. Miner with safety lamp

more gassy seams (Diamond 1994). However, the quantities of methane removed by drilling short horizontal holes in the mine ribs were small (Lawall and Morris 1934). From the early 1930s until 1950, some mines tried methane drainage technologies developed in Europe, with some success. Two methods used were drilling holes in broken sandstone above gassy coal seams (Coal Age 1938), and using cross-measure boreholes to drain the gas and move it to surface (Diamond 1994).

1950 to 1969

In the 1950s and 1960s, the introduction of new mining equipment and mining methods had a big effect on how ventilation was used to control methane concentrations.

Continuous Mining Machines

One USBM researcher noted that the continuous mining machine (Figure 4) revolutionized coal mining (Stahl 1958). Methane liberation rates during continuous mining were much higher than during conventional mining, due to the faster coal extraction rates. Methane concentrations during continuous mining sometimes exceeded 5% (the lower explosive limit for methane gas) at distances as far as 20 feet from the face (Stahl 1958). Ventilation practices available at that time were inadequate for controlling methane during continuous mining.

Face Airflow Control

Although the increased use of mechanical fans resulted in more airflow underground, much of the air was lost before it could reach the working faces due to leakage through doors and curtains. Tests examined ways to improve delivery of air to the face.

- *Curtains*— Most curtains were made of jute fabric. Air leakage increased with increasing porosity. Less porous materials, such as plastics, along with better installation techniques that allowed less leakage between the curtain and roof were recommended (Dalzell 1966).
- *Tubing*— When permissible auxiliary fans became available for underground use, studies examined factors affecting the delivery of air to the face using fans with attached tubing. Tubing materials and construction techniques were tested to determine how airflow shock losses could be reduced and airflow quantities increased (Peluso 1968).
- *Blowing versus exhausting ventilation*— Studies using comparable blowing and exhausting face ventilation systems with curtains measured methane levels near the mining face for a range of operating conditions. The blowing systems were on average more than 5 times more effective for diluting methane in the face area (Luxner 1969).

Methane Monitors

Until the 1950s, the flame safety lamp (Figure 5) was the primary means used for detecting methane in mines (Ilsley 1933). The effectiveness of the ventilation system was determined more by observing operating conditions than by measuring gas levels. In 1958, the Bureau of Mines initiated programs to develop a methane detector system that would provide continuous monitoring of methane at the mining face (James 1959).

Eventually all mining machines had to be equipped with these machine-mounted methane monitors [(30 CFR § 75.342(a)(1)]. Data from these monitors became the basis for evaluating ventilation effectiveness for methane control and compliance with methane standards.

Improved Methane Drainage

- *Hydraulic stimulation*— The efficiency of vertical degasification wells was improved by using hydraulic stimulation (Spindler and Poundstone 1960). In one coalbed, there was more than a 16-fold increase in gas production. In another study, the methane content in the main return air currents after stimulation was reduced more than 86% (Diamond 1994; Merritts et al. 1963).
- *Methane drainage on longwall panels*—Use of vertical boreholes reduced methane concentrations in the returns while decreasing the level of ventilation required for methane control (Elder 1969).

1970 to 1980

1969 Coal Mine Health and Safety Act

The Federal Coal Mine Health and Safety Act of 1969 set standards for methane and dust control. Several research projects in the 1970s examined ways to improve ventilation and reduce airborne dust levels to the new required levels. Most of the studies concluded that exhaust ventilation was needed for adequate dust control (Kingery 1969; Mundell 1977). Earlier work had shown that blowing ventilation was better for methane control (Luxner 1969) (Figure 6), and some mines wanted to continue using blowing ventilation systems. These mines began cooperative studies with the Bureau to develop a machine-mounted dust scrubber (Tomb 1973). The flooded bed machine-mounted scrubber was shown to lower dust levels when using blowing ventilation. Initially, there were concerns that scrubber recirculation would cause methane levels to increase, but tests showed that concentrations did not increase as long as the scrubber exhaust did not reduce intake air flow to the face.

Developments in Coal Bed Methane Drainage

In the 1970s, studies examined techniques for removing methane from longwall gob areas.

- Use of an exhauster with a slotted vertical pipe allowed faster mining rates and lower ventilation airflow in the mine (Moore and Zabetakis 1972).
- Isolating panels during degasification improved gas removal by 70% (Findlay et al. 1973).
- The best levels for bit thrust and rotational speed for rotary drilling of holes were investigated to find the optimum combination to stay in the coalbed and drill ahead of coal production (Cervik et al. 1975).
- Horizontal boreholes drilled from the bottom of the shaft in virgin coal reduced methane emissions at the working face by 50% (Diamond, 1994).
- Hydraulic stimulation had only minimal effects on improving degasification of a longwall panel (Maksimovic et al. 1977), but boreholes stimulated with foam and proppant sands significantly reduced methane emissions (Steidle 1978). The stimulation treatment did not cause damage to roof or floor.
- Water infusion techniques developed by the Bureau of Mines were used to move gas away from face areas and into the return airways. Use of this technique reduced gas emissions in the more permeable coal seams by almost 90% (Cervik 1977).

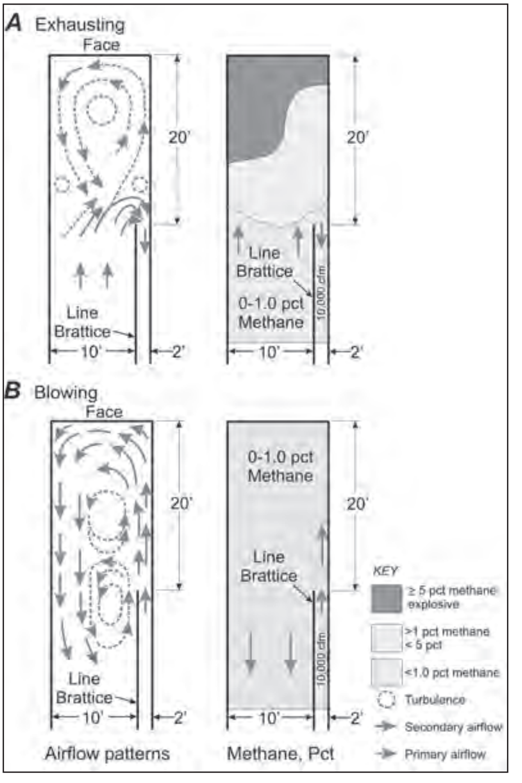

Figure 6. Data comparing blowing and exhausting face ventilation

1980 to 1990

By 1980, the Bureau of Mines had demonstrated effective face ventilation techniques for controlling both methane and respirable dust on continuous mining operations. Maximum curtain or tubing setback distances were usually 10 ft for exhausting and 20 ft for blowing ventilation systems. Most mining cuts were 20 ft deep and the machine operator sat at the rear of the machine. In the 1980s more machines were equipped for remote control operation.

Remote Control

As more mining machines were equipped with remote controls to remove the operator from the immediate face area, cutting depths in the 1980s increased to 35 ft and greater. Studies examined whether available face ventilation practices were adequate for controlling methane levels during deep cut mining (cut depths greater than 20 ft).

- The benefits of using directional water sprays for improving face airflow (spray fan system) had been demonstrated earlier by Kissell (1979). With exhausting ventilation and a modified spray fan system, cutting depths could be increased to 40 ft with no significant increases in methane levels (Ruggieri 1987).
- When using a machine-mounted scrubber with blowing ventilation, cutting depths to 50 ft could be attained without increasing methane levels (Volkwein 1986).

Most mines employing deep cut mining used scrubbers with blowing ventilation or a spray fan system with exhausting ventilation.

Longwall Methane Control

Longwall mining does not require curtain or tubing to ventilate the face. However, airflow must be maintained along the entire face for good methane control (Cecala 1986). Studies showed that:

- The highest methane levels were measured during cutting at the headgate. Placement of a curtain at the headgate diverted needed air flow away from the gob and down the panline (Cecala 1986).
- A modified water spray system on the shearer (shearer clearer) improved air flow over the mining machine by reducing eddy zones where methane could accumulate (Cecala 1986).

Frictional Ignition Suppression

Past research had eliminated most ignition sources from coal mines, but the number of ignitions at the mining face increased following the introduction of continuous mining machines. These frictional ignitions occurred when the metal machine bit in the rotating cutting drum became hot enough, usually during cutting in sandstone rock, to deposit a streak of hot metal on the rock surface. When the hot metal contacted a flammable methane-air mixture, an ignition could occur (Courtney 1990).

Figure 7. Methane frictional ignition test

Laboratory tests designed to simulate cutting in hard rock (Figure 7) showed that frictional ignitions could be reduced by changing bits more frequently and/or using bits with larger carbide inserts to reduce contact between the steel bit shank and the rock. Ignitions could also be reduced by cooling the rock surface with water directed from a nozzle mounted directly behind the bit (Courtney 1990).

Coal Seam Methane Drainage Research

- The Bureau of Mines developed a “direct method” for determining coal bed gas content (Diamond and Levine 1981) to make preliminary estimates of ventilation requirements and to determine if methane drainage would be beneficial (Diamond et al. 1986).
- A comprehensive report (Diamond 1982) detailed geological factors important during the drilling of degasification boreholes in order to achieve optimum methane control was written. Techniques for drilling boreholes from the surface to intercept coal beds were demonstrated (Oyler and Diamond 1982).
- Progress was made on developing numerical models for methane control in coal mines (Schwerer et al. 1984). The two-dimensional mathematical model and accompanying numerical model were used to predict methane influx into the coal mines under a variety of mining conditions.

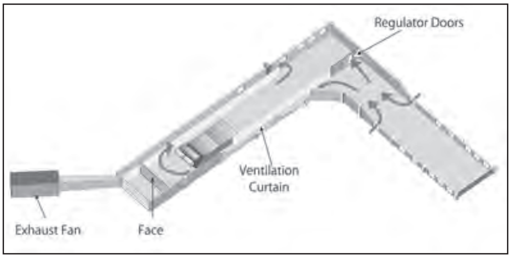

Figure 8. NIOSH ventilation gallery

1990 to 2000

In 1996 certain research programs of the Bureau of Mines were transferred to NIOSH. The emphasis of most research during this decade was on improving the effectiveness of available ventilation techniques and providing data needed by the mining industry for better implementation of existing technologies. A ventilation test gallery (Figure 8) was specially designed to evaluate factors affecting face ventilation and methane monitoring techniques.

Airflow Patterns and Methane Distributions
Earlier Bureau tests showed that mapping airflow patterns and methane concentration near the face helped during the design of face ventilation systems (Luxner 1969). A surface test facility was used to further study airflow patterns and methane distributions in the area between the ventilation curtain or tubing and the face. Study results showed that:

- The narrower the entry, the more likely flow to the face will be disrupted and methane levels will increase (Taylor 2005).
- Operation of machine-mounted water sprays and scrubber can increase face airflow by a factor of 5 (Thimons 1999).
- A spray fan system that uses water sprays directed toward the return air side of the face reduced methane levels by increasing airflow across the face. If the water sprays are directed straight toward the face methane levels are also reduced but concentrations can increase in some areas near the face, especially if intake airflows are low (Taylor 1997; Chilton 2006).

Instrument location on continuous mining machines. In the ventilation gallery, methane measurements made at the face and at multiple locations on the machine were compared. Researchers determined that methane concentrations should be measured on the return side of the mining machine, and that if alternative methane sampling locations further from the face are selected, action levels should be reduced to assure protection to worker is not diminished (Taylor 2001).

Instrument location on a roof bolting machine. Based on results from tests conducted in the ventilation gallery, Taylor (1999) proposed an alternative procedure for methane monitoring during roof bolting of deep cuts. The procedure calls for methane to be monitored continuously using a bolter mounted methane monitor, while a hand held detector with extendable probe is used to periodically "sweep" the area 16 feet inby the last permanent row of roof supports.

Methane Control Research
Studies concluded that:

- About 90% of the gas from longwall gobs comes from the overlying coalbeds (Diamond et al. 1992).
- On longwall panels, 77% more gas came from holes drilled at the end of the panels and at panel margins where strata were in tension compared to holes drilled in the center of the panel. Drilling gob vent holes in panel margins has become standard practice in most U.S. mines (Diamond et al. 1994).
- Methane emission rates increase as the length of the longwall face increases, but not necessarily in the same proportion (Diamond and Garcia 1999).

2000 to 2010

Emphasis was placed on improving the evaluation and use of methane monitors. Ultrasonic anemometers were used to plot airflow in face areas in order to evaluate factors affecting methane control at the face. Computer modeling was used to study the flow of methane gas through rock strata and after its liberation at the mine face

Methanometer Response Time
Methane concentration rise and fall quickly during mining. In order for instruments to read accurately they must response quickly to these changes. Researchers developed test procedures and equipment for measuring methanometer response times. Using the new procedures it determined that the design of the dust caps used to protect the sensor heads was the major factor affecting response times. Response data was presented for both machine-mounted monitors (Taylor 2004) and hand held detectors (Chilton 2005). Tests compared methane response times of instruments using infrared and heat of combustion sensors. Again, dust cap design was

the biggest factor affecting differences in response times. In the ventilation gallery where face airflow conditions were simulated, it was shown that when exposed to the same gas concentrations instruments with faster response times showed larger peaks and dips in concentration (Taylor 2008).

Methane Measurements Distant from the Working Face

Although regular methane monitoring is required near working faces, much less methane sampling occurs in areas distant from the face. Small person wearable methane monitors were evaluated. Equipped with aural, visual and vibratory alarms, the instruments provided alarms to warn workers when methane levels exceed preset limits (Chilton 2005).

Measuring Airflow Speed and Direction

Researchers developed techniques for using ultrasonic anemometers to measure airflow direction and speed in the ventilation gallery (Taylor 2005). The anemometers were used to measure air flow direction and speed inby the ventilation curtain. Flow profiles drawn for different size empty entries showed that less air reaches the face when the entry is narrower. The same type of flow pattern can occur at the face when machine-mounted water sprays or scrubbers are not used. Data obtained using the anemometers showed an increases in face airflow when the scrubber was used (Taylor 2006).

Development of Computer Models for Face Airflow and Methane Distribution

Airflow and methane data obtained in the ventilation gallery was compared to data generated by a computer simulation model. The flow and the methane concentration data from the model were in good agreement with the empirical results.

Methane Control and Degasification Research

Besides the field work and observations, a special emphasis was placed on integrating analytical and numerical reservoir simulation techniques. Research in this area, based on the mining industry's need to respond to changing mining conditions and economic drivers, produced several outputs and recommendations. Study results showed that:

- The methane emission increase due to a face width increase can be controlled by increasing ventilation quantities and reducing shearer transit times (Schatzel et al. 2006; Krog et al. 2006), increasing the number of gob gas ventholes, and drilling boreholes on the headgate side close to the start up of the panel. These holes should be operated continuously (Karacan et al. 2005).
- Horizontal in-seam degasification boreholes can be effectively used for methane drainage of the coal bed prior to the start of longwall mining. The patterns of the boreholes can be optimized by using numerical reservoir simulations. In general, boreholes drilled perpendicular to face cleats produce more methane per borehole length and more effectively degasify the coal bed. Extension of methane drainage duration prior to mining start is also an effective way of decreasing methane emissions during mining. When this is not possible, the boreholes should continue producing until the mining face reaches their location (Karacan et al. 2007a).
- Entry development processes can be modeled by reservoir simulations. Methane emissions into the entries during their development can be controlled by using shielding boreholes drilled parallel to the entries. These boreholes can serve both degasification and shielding purposes (Karacan et al. 2007a; Karacan 2007b).
- Methane emissions during continuous miner operation are a function of mining parameters (Karacan 2007b) and coal bed reservoir parameters (Karacan 2008a). Optimum methane control strategies can be developed based on these two considerations.
- Geological and structural characteristics of the coal bed are important to decide where to drill the boreholes (Karacan et al. 2008) and how they can affect the borehole productivity (Karacan and Goodman 2008).
- Expert systems can be used in determining and optimizing longwall emissions (Karacan 2008b), degasification system selection (Karacan 2009a) and forecasting the performance of gob gas ventholes (Karacan 2009b).
- Longwall mining changes the hydraulic conductivity of the overlying strata. Hydraulic conductivity of the fractured zone affects the control of methane using gob gas ventholes. Hydraulic conductivities can be determined using slug testing methods (Karacan and Goodman 2009). It was determined that the hydraulic conductivities of gob gas ventholes vary based on the overburden thickness, the rate of the longwall face advance, and their locations over the panel (Karacan and Goodman 2009).

SUMMARY AND CONCLUSIONS

Research programs to prevent methane ignitions began with the establishment of the U.S. Bureau of Mines and remain an important part of the current NIOSH mining research program. The substantial reduction in the number of injuries and deaths due to mine explosions is probably the best indicator of the program's success. Although the potential for explosions resulting from methane in mines still exists today, with knowledge gained from Bureau and NIOSH research it is now possible to work underground much more safely than previously. Research into better ways to utilize ventilation for the control of methane gas by underground ventilation and extraction prior to mining continues.

References provided with this paper give more information about past Bureau of Mines/NIOSH methane control research. Additional sources of information include:

- "Handbook for Methane Control in Mining" (Kissell 2006).
- "Guidelines for the Prediction and Control of Methane Emissions on Longwalls" (Schatzel et al. 2008).

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