Prevention of Spontaneous Combustion Fires in U.S. Coal Mines

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SUMMARY

This paper describes research conducted under the U.S. Bureau of Mines (USBM) on the prevention of spontaneous combustion fires in U.S. coal mines. Recent results include the development of ranking schemes to predict the relative spontaneous combustion potential of coals, based on adiabatic oven and oxygen adsorption experiments. An expert system computer program, SPONCOM, was completed that determines a coal's spontaneous combustion potential and evaluates the impact of the coal properties, geologic and mining conditions, and mining practices on the spontaneous combustion risk of the mining operation. A recent study evaluated the use of bleederless ventilation systems in U.S coal mines. The study showed that these systems are not readily applicable to U.S. mining conditions, and that the greatest risk of coal self-heating was due to leakage around seals. The use of these systems require additional monitoring near the face and across the seals.

INTRODUCTION

Approximately 13 pct of reported underground coal mine fires in the United States between 1983 and 1992 were caused by the spontaneous combustion of coal (1). A reportable fire is one that burns for at least 30 minutes, or results in an injury or fatality. A spontaneous combustion fire occurred in 1985 at a Colorado mine in a longwall gob that required sealing and inert gas injection to suppress the heating (2). Another fire occurred in 1986 at a different Colorado mine in which the entire mine was sealed and abandoned (3, 4). Several self-heating events due to floor heave and the oxidation of pyrite have also occurred in an Alabama mine (5). The number of spontaneous combustion fires is expected to rise with the increased mining of lower rank coals, prevalent in the Western United States, and the growth in the size of longwall panel dimensions.

The U.S. Department of Energy, Pittsburgh Research Center (PRC) (formerly the U.S. Bureau of Mines) has an ongoing research program to understand the physical and chemical processes that contribute to the spontaneous combustion of coal and to develop practical methods to predict and prevent spontaneous combustion in underground coal mines. Recent results include the development of ranking schemes to predict the spontaneous combustion potential of coal based on the coal's self-heating temperature (SHT) in PRC's adiabatic oven or on the rate of oxygen adsorbed by the coal in PRC's sealed flask apparatus. Currently, research is being conducted to evaluate the effect of rank, moisture content, and other factors on the self-heating of lignite and subbituminous coals, and to identify the chemical composition of gases evolved during the self-heating process.

An expert system computer program, SPONCOM, was recently completed based on laboratory and field studies of mines that have experienced self-heating events. SPONCOM was developed to aid in the assessment of the spontaneous combustion risk of an underground coal mining operation. A prior knowledge of the spontaneous combustion risk of the coal and factors that increase that risk can be useful in the planning and development of proactive monitoring, ventilation, and prevention plans for the mining operation. The program determines a coal's spontaneous combustion potential and evaluates the impact of the coal properties, geologic and mining condition, and mining practices on the spontaneous combustion risk of the mining operation.

Coal-producing countries around the world have used ventilation schemes to limit the amount of airflow to areas prone to spontaneous combustion. In the United States, these are referred to as "bleederless" ventilation systems. However, these ventilation practices are not easily applicable to U.S. mines because of mining conditions, systems, and regulations. Only recently were U.S. regulations passed that allow the use of a bleederless ventilation system to control spontaneous combustion (6). A study was completed at PRC to examine worldwide bleederless ventilation practices for use as a spontaneous combustion control method in U.S. coal mines. The study showed that the greatest risk of coal self-heating using a bleederless ventilation system is due to the leakage of air around seals and behind the face supports. In U.S. mines using bleederless systems, this is dealt with by pressure balancing and monitoring behind seals for air leakage and self-heating.

SPONTANEOUS COMBUSTION STUDIES OF U.S. COALS

Adiabatic Oven Studies

The Pittsburgh Research Center uses an adiabatic oven to evaluate the relative self-heating tendencies of coals. The oven is designed to minimize heat losses from the reactive coal sample. Details of the oven and experimental procedure are found in reference 7. To assess the self-heating tendency of a coal, the coal's self-heating temperature (SHT) is determined. This is the minimum initial temperature that produces a sustained exothermic reaction, or thermal runaway, in the adiabatic oven.

The SHT's of more than 30 coal samples, ranging in rank from lignite to anthracite, were determined in the adiabatic oven (8). Table 1 shows representative coals of various ranks and their corresponding SHT's. The SHT's of these coals ranged from 35° to >140 °C. In general, the minimum SHT's increased with increasing coal rank. From these experiments, the following ranking scheme was established: coals with SHT's <70 °C are considered to have a high spontaneous combustion potential, those with SHT's between 70° and 100 °C, a medium potential, while those with SHT's >100 °C are considered to have a low spontaneous combustion potential.

Table 1.–Minimum SHT's of representative coal samples evaluated in the adiabatic heating oven

Seam	Apparent rank	Minimum SHT, °C
Lehigh bed	lignite	35
No. 80	hvCb	40
F	hvCb	40
No. 6	hvCb	70
Pittsburgh	hvAb	90
Pocahontas 3	lvb	110
Blue Creek	lvb	135
Anthracite	an	>140

A statistical analysis of the experimental results was conducted to determine if the minimum SHT of a coal sample could be predicted based on the chemical constituents of the coal obtained from the coal's proximate and ultimate analyses. The results showed a correlation between the minimum SHT of a bituminous coal sample and the sample's dry-ash free (DAF) oxygen content:

$$\text{SHT, °C} = 139.7 - [6.6 \times \text{oxygen, \%(DAF)}] \quad (1)$$

The resulting expression had a correlation coefficient of 0.934 and an average relative error of 10.6% (7).

The predictive formula was used by a major coal company in the evaluation of spontaneous combustion occurrences at two of its mines, and in the design of spontaneous combustion monitoring and prevention plans at a third mine (2). Dry-ash free oxygen values obtained from existing core hole, belt, and channel samples were used in the predictive formula to compute SHT data points. These values were then used to generate SHT isotherm maps to characterize the self-heating potentials of the coals in these mines.

Spontaneous combustion events are often detected by smell before being detected by mine-wide gas monitoring systems. To identify the compounds responsible for the smell, a gas chromatograph/mass spectrometer has been coupled to an isothermal flow calorimeter to allow direct sampling of the exit gas stream of the oven. In order to first identify the compounds, tests were conducted with a bituminous coal at temperatures of 275 °C and above. The results showed that low weight carboxylic acids and phenol derivatives were the first higher hydrocarbon compounds that evolved from the coal at these temperatures.

Sealed Flask Studies

A simple sealed flask test method, based on the adsorption of oxygen by coal, was developed for evaluating the self-heating tendencies of bituminous coals (9). The apparatus consists of six 500 cm^3 laboratory flasks that were modified to accommodate a miniature pressure transducer and a gas sampling port. Fifty gram samples were sealed in each flask and pressure readings were taken at various intervals over the next seven days. At the end of the test period, gas samples were taken from each flask for analysis by gas chromatography.

A suite of six bituminous coals were used for the study. The minimum SHT's of the coals were determined in the adiabatic oven and ranged from 35° to 105° C. Four size fractions were then tested in the sealed flask apparatus. A statistical analysis showed an excellent correlation between the minimum SHT's in the adiabatic oven and the pressure change measured after 7 days (ΔP_7) in the sealed flask apparatus, independent of size below 1,200 μm. The resulting expression was:

$$\text{SHT, °C} = 128.9 - (0.52 \times \Delta P_7, \text{ mm Hg}), \qquad (2)$$

with a correlation coefficient of 0.972. In similar fashion to the adiabatic oven results, a ranking scheme for predicting the relative spontaneous combustion potential of bituminous coals was established, based on equation 2. Prototype field units were assembled and are currently being evaluated at several coal testing laboratories and coal mine sites.

In current studies of lignite and subbituminous coals in the adiabatic oven and sealed flask apparatus, excellent agreement was found between the SHT's determined by both test procedures. This indicates that either test can be used to predict the spontaneous combustion potential of subbituminous and lignite coals. Results also indicate that the test period for subbituminous and lignite coals in the sealed flask apparatus can be reduced to one or two days.

SPONCOM EXPERT SYSTEM

While the laboratory methods described above provide valuable information about the spontaneous combustion potential of coals, they do not consider other factors that may contribute to self-heating. These include coal properties, geologic and mining conditions and mining practices. An expert system computer program, SPONCOM, was developed to aid in the assessment of the spontaneous combustion risk of an underground mining operation by taking into account these other factors (10). To develop SPONCOM, information was gathered from the literature, from interactions with experts in ground control, ventilation, and geology, and from mine personnel that have experienced self-heating events at their mining operation. The information was correlated with PRC's experimental studies on the self-heating tendencies of coals to form the knowledge base for the expert system.

SPONCOM is written in ANSI C programming language for use on microcomputers. The program is designed to gather information from the user about the coal properties, geologic conditions, mining conditions and practices, and spontaneous combustion history for a mining operation. This is accomplished through the use of interactive data input screens that prompt the user for the information. During the input process, expand screens provide the user with specific information about each input parameter with respect to its particular impact on the overall self-heating risk. The information includes a brief description of the parameter and its effect on the overall spontaneous combustion risk. The input information can be stored to a data file for future use.

The program logic first determines the coal's spontaneous combustion potential, based on the coal's predicted minimum SHT, and any effect that the mine's ambient temperature or previous spontaneous combustion history might have on this potential. This value is then used in the evaluation of the effect of the coal's properties, the geologic and mining conditions encountered in the mining of the coal, and the mining practices employed to mine the coal on the spontaneous combustion risk of the operation. Table 2 shows the 27 factors that the program considers. The program logic determines the degree of risk for each of the factors, and outputs those factors that are determined to increase the overall spontaneous combustion potential of the mining operation.

Table 2.–Factors evaluated in SPONCOM Expert System

Coal properties	Geologic conditions	Mining conditions	Mining practices
Rank	Overburden	Ambient temperature	Recovery ratio
Moisture	Geothermal sources	Coalbed thickness	Pillar design
Friability	Faults	Coalbed gradient	Rate of advance/retreat
Previous oxidation	Cleat density	Floor heave	Panel dimensions
Pyritic sulfur	Joints	Rib sloughage	Face ventilation leakage
Impurities	Channel deposits		Caving height
	Clay veins		
	Dikes		
	Natural burn zones		
	Rider beds in roof and floor		

The program output gives the spontaneous combustion potential of the coal, its rank, and SHT. SPONCOM then lists each of the factors that increase the risk of spontaneous combustion in the underground mining operation, along with the degree of risk, and details of why the factor increases the risk.

SPONTANEOUS HEATINGS IN U.S. COAL MINES

There have been several published reports of spontaneous heating events in U.S. coal mines. In 1985, a self-heating occurred at a Colorado mine, in a longwall gob, during extraction of the second panel. The ventilation scheme used was a typical bleeder system to ventilate the gob. Prior to this time, the mine had employed a room and pillar mining method with no indications of spontaneous combustion. The area was sealed and inert gas was injected into the gob to control the self-heating. The mine changed to a pressure balanced, bleederless ventilation system utilizing timber squeeze seals to isolate the gob, and periodic gas sampling behind each seal for early detection. The ventilation scheme and the use of the squeeze seals were successful, and no further self-heatings occurred (2).

Timko et al. (4) describes a fire at a Colorado room-and-pillar operation in 1986, believed to be caused by spontaneous combustion. This mine had a history of pillar heatings near the portal area, which is located within a burn line that extends 150 to 180 m into the mountain, due to high pressure differentials across the pillars. At another mine located adjacent to this mine, an extensive temperature and gas monitoring system was implemented in the portal areas, as well as water infusion techniques to control the pillar temperatures. In addition, a change in the ventilation system was made to reduce pressure differentials across the pillars. These methods have been successful in preventing subsequent heatings in the portal area (2).

Koenning (11) describes two self-heatings at a Wyoming mine using longwall mining with a bleederless ventilation scheme. The isolation stoppings consisted of a wooden packwall, a 3- to 5-m-thick slurried sandfill, and a 1.3 m-thick stopping built of wooden crib blocks. The heatings were attributed to stopping leakage caused by poor roof contact with the sandfill between the stoppings. A 1.7-m-thick cementitious foam was substituted for the sandfill.

Miron et al. (5) reports on a deep coal mine in Alabama that has experienced 14 floor self-heatings. The heatings all occurred in a section of the mine separated by a fault line, where an expanded seam containing large amounts of pyritic sulfur exists beneath the floor. Because of the depth of the mine and the amounts of methane released, high ventilation rates are required. This results in high pressure differentials across stoppings and seals. Floor heave exposes the floor material to a continuous supply of air and moisture, resulting in self-heating of the pyrite and carbonaceous materials.

SPONTANEOUS COMBUSTION CONTROL IN U.S. MINES

In coalbeds that are prone to self-heating, critical low-velocity airflow over the reactive coal increases the risk of spontaneous combustion. Coal-producing countries around the world use ventilation methods to limit the amount of airflow to areas prone to spontaneous combustion. Various types include the "U", back return "U", and "Y" systems. These systems, referred to as "bleederless" systems in the United States, are described in more detail by Smith et al. (12).

The primary function of mine ventilation in the United States is to dilute and carry away dangerous accumulations of gas and dust from the working area. Only recently were U.S. regulations passed that allow the use of a bleederless ventilation system to control spontaneous combustion (6). Two mines in the United States currently use a bleederless ventilation system (12). Both use a modified-"U"-type ventilation scheme with multiple predeveloped entries. Seals are constructed in entries and crosscuts to isolate the gob. Air is directed up the headgate entries, across the face, and back along the panel return. A limited amount of intake air is coursed through the headgate entry adjacent to the sealed gob to maintain access for seal examinations, monitoring, gob pressure balancing and entry maintenance.

Although a bleederless ventilation system is designed as a spontaneous combustion control measure, certain design parameters provide potential spontaneous combustion risks. The two areas with the greatest risk of heatings are around seals and behind the longwall face supports. If high levels of methane exist in the gob, there is the additional risk that methane concentrations within the explosive range will be located behind a leaking seal or behind the supports.

Self-Heatings Behind Seals

The use of multiple development entries for longwall panels lead to the extensive use of seals in a bleederless ventilation design to isolate the gob. Each seal provides the potential for a self-heating event, through air leakage around or through the seal. Also the larger number of entries increases the number of coal pillars which can be exposed to critical airflows when trying to implement a bleederless ventilation system.

Heatings around seals can occur in the floor behind the seal or in the pillars and roof adjacent to the seals due to air leakage. Therefore, seal design must take into account all mining conditions and consequences that can lead to air leakage. These include high pressure differentials across seals, weak floor or roof strata, fractured, weathered, or permeable coal pillars, and ground control problems and pillar stability. Seal construction must utilize appropriate materials and construction methods to meet or exceed the design specifications. Inspection and maintenance of seals is critical for continued optimum performance.

Title 30, Part 75.335 of the U.S. Federal Regulations requires that seals be able to "...withstand a static horizontal pressure of 20 pounds per square inch..." The USBM and the Mine Safety and Health Administration (MSHA) recently completed full-scale explosion tests on four types of seal construction materials; solid-concrete blocks, cementitious foam, low density foam blocks, and wood-block convergence seals. Details of the seal materials and test designs are found in reference 13. Based on the results of these tests, all four seal construction materials were approved by MSHA for use in underground coal mines.

The U.S. mines with bleederless ventilation systems use wood convergence seals and pressure balancing techniques (2, 11). At one mine, isolation stoppings are constructed in the crosscuts of the headgate entry prior to the longwall face passing. The stoppings consist of a wooden pack wall, a 3- to 5-m-thick slurried sandfill, and a 1.3-m-thick wood crib block stopping. Even with this method, heatings behind the seals continue to be a persistent problem because of leakage through and around the seals. At this mine, the leakage is primarily due to the weak roof conditions, which allow leakage through the roof. At another mine, timber squeeze seals are built in advance of the face. As the longwall passes the seal, ground convergence "squeezes" the timbers, isolating the gob. No self-heatings have been reported at this mine using this type of seal in a bleederless system.

Reducing the number of entries is beneficial for bleederless ventilation systems in terms of potential sources of air leakage, but in turn increases the mine ventilation network resistance. A higher ventilation resistance increases the pressure differentials throughout the mine if trying to ventilate with the same air quantity at the mining faces. Higher pressure differentials increase leakage through ventilation controls such as stoppings. Work conducted by the USBM has shown that for a newly constructed conventional block stopping (dry-stacked with mortar applied to one side) leakage was 4 m^3/min per 2.5 mm of water gauge pressure differential and the leakage more than doubled after 1 year of use with slight roof convergence (14). A newly constructed universal (keyed into ribs with a poured footer) stopping leaked 1.4 m^3/min per 2.5 mm of water gauge pressure differential and the leakage more than doubled after 1 year of use with slight roof convergence. It was shown that a stopping maintenance program could restore stopping integrity to its original effectiveness.

Self-Heatings Behind Face Supports

Since it is impossible in practical terms to prevent face ventilation air from entering the gob behind the supports, an oxygen gradient develops. Just behind the supports, where the oxygen concentration is the highest, the air velocity is too high, so that any heat due to self-heating is carried away. Deeper in the gob, the air velocity is too low to provide sufficient oxygen to support spontaneous combustion. However, there exists a critical air velocity zone in the gob where the airflow and oxygen concentration is conducive to self-heating. The incidence of self-heating depends on how long the coal is subjected to this critical air velocity. If the time is long enough for the heat to build up to an imminent self-heating event, referred to by many as the incubation period, a fire may result. Therefore, the rate of face advance is extremely important in preventing self-heating behind the supports. A similar critical area exists with respect to explosive methane concentrations behind the supports in gassy coalbeds. This makes the prevention of self-heating even more critical in this situation, since the body of methane could be ignited.

Sources of Air Leakage

High pressure differentials across the gob and across seals or stoppings provide the impetus for leakage. In U.S. mines using the bleederless ventilation system, this is dealt with by attempting to pressure balance across the gob. However, because of pressure gradients in the gob, it may also be necessary to measure and adjust pressure differentials across seals. In addition, barometric pressure changes due to weather fronts can induce air infiltration into gob, causing spontaneous combustion. In addition, these fronts can cause outgassing to occur, resulting in high concentrations of methane and/or carbon monoxide in the face area.

Communication between adjoining gobs, the mine and the surface, and between mines in multiple-bed mining operations by way of overburden fracturing, can also provide sources of air for spontaneous combustion in the gob. This factor also makes it difficult to characterize gob gases and maintain pressure balancing, and should be considered in the mine design and planning stages, especially for multiple coalbeds and shallow overburden conditions.

Monitoring

Early detection is critical for the prevention and control of spontaneous combustion. The analysis of gaseous products of combustion is the primary method used in underground coal mines for early fire detection. Continuous monitoring of CO levels is the preferred method of spontaneous combustion detection worldwide. The most popular methods are telemetry or tube bundle systems. A significant problem in the detection of spontaneous combustion is in recognizing when a heating is developing.

The ambient levels of CO in a mine depend on the type of coal, the rate of mining, and many other factors. Transient spikes in CO can occur due to the use of diesel-powered equipment and changes in ventilation, as well as other factors. A new method that has been used by some mines with spontaneous combustion problems is that of trending. Data is accumulated over a period of time to establish normal ambient CO background levels. Averaging methods are employed to compare the continuous monitoring analyses to the ambient background levels. One U.S. mine that relies heavily on the use of diesel-powered equipment has developed a method to deal with transient spikes called wave trend crossing. This method uses two CO sensors sampling the same gas stream at different locations, along with computer analysis, to constantly update the ambient CO background level (15).

Another important aspect of monitoring for the detection of spontaneous combustion is behind seals. Continuous monitoring behind each seal constructed in the headgate entry is impractical, due to the large number of seals. In the two U.S. mines that are currently using a bleederless ventilation system, gas sampling tubes are installed through each seal so that periodic gas samples can be withdrawn and analyzed by gas chromatography. Samples are analyzed for O_2, CO_2, CO, CH_4, H_2, and some higher hydrocarbons. Koenning (11) describes the use of these samples at one of the mines to detect two spontaneous heatings behind seals. Information on the techniques and gas analyses at the other mine employing a bleederless system is not available.

CONCLUSIONS

The U.S. Department of Energy, Pittsburgh Research Center (formerly the U.S. Bureau of Mines) has an ongoing research program to understand the physical and chemical processes that contribute to the spontaneous combustion of coal and to develop practical methods to predict and prevent spontaneous combustion in underground coal mines. The program includes two laboratory methods to evaluate the relative self-heating tendencies of coal, an adiabatic oven and a sealed flask oxygen adsorption apparatus. Ranking schemes to predict the relative spontaneous combustion potential of coals have been developed, based on the coal's minimum self-heating temperature in the adiabatic oven, and the pressure drop caused by oxygen adsorption in the sealed flask apparatus.

An empirical expression has been derived to predict the spontaneous combustion potential of a coal based on its dry ash-free oxygen content. This expression has been used by a major coal company in the evaluation of spontaneous combustion occurrences at two of its mines, and in the design of monitoring and prevention plans at a third mine.

An expert system computer program, SPONCOM, has been developed that determines the spontaneous combustion risk of a coal-mining operation based on the coal's spontaneous combustion potential, coal properties, geologic and mining conditions, and mining practices. The program evaluates 27 factors and outputs each factor that increases the spontaneous combustion risk, the degree of risk, and details of why the factor increases the risk.

A review of worldwide spontaneous combustion control measures indicated that limiting the amount of air to areas prone to spontaneous combustion is the primary method used to prevent self-heatings. The use of this method, referred to as "bleederless" ventilation, is not readily applicable to U.S. mining conditions.

The two areas of greatest risk of self-heating were found to be around seals and behind the face supports. High pressure differentials across the gob and across seals is the primary impetus for the leakage. Monitoring for spontaneous combustion is critical to the success of this method, including monitoring behind the seals.

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