SPONCOM - A COMPUTER PROGRAM FOR THE PREDICTION OF THE SPONTANEOUS COMBUSTION POTENTIAL OF AN UNDERGROUND COAL MINE

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Abstract. The United States Bureau of Mines (USBM) developed SPONCOM to aid in the assessment of the spontaneous combustion risk of an underground 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. Interactive data input screens prompt the user for information about the coal's chemical and physical properties, the geologic and mining conditions encountered in the mining of the coal, and the mining practices employed. During the input process, 'expand' screens provide the user with specific information on each input parameter. This information includes a description of the parameter and its effect on the overall spontaneous combustion risk.

The program logic determines the coal's relative spontaneous combustion potential, based on the coal's proximate and ultimate analyses, and heating value. The program then evaluates the impact of the coal properties, geologic and mining conditions, and mining practices on the spontaneous combustion risk of the mining operation. The program output provides details on each factor that increases the risk of spontaneous combustion.

INTRODUCTION

In the United States between 1983 and 1992, approximately 13 pct of underground coal mine fires were caused by the spontaneous combustion of coal (Pomroy, 1995). Spontaneous combustion fires usually occur in worked-out or gob areas and are not easily detected. These fires present a serious safety hazard to mine personnel and are difficult to extinguish, often requiring sealing large sections of the mine or the entire mine for long periods, resulting in severe economic losses. The number of spontaneous combustion fires is expected to increase with the increased use of low rank coals, deeper mines, and the growth in the size of longwall panel dimensions.

The spontaneous combustion of coal occurs when the heat that is produced by the self-heating process is greater than the rate of heat dissipation, resulting in a net temperature increase in the coal mass. Under conditions that favor a high heating rate, a fire ensues. Many factors can contribute to the spontaneous combustion process in an underground coal mining operation. These include the self-heating potential of the coal, the coal properties, the geologic and mining conditions, and the mining practices. A prior knowledge of the self-heating risk of the coal and what factors increase that risk can be useful in the planning and development of proactive spontaneous combustion monitoring, ventilation, and prevention plans for the mining operation.

Prior to the 1970's, various test methods were used to evaluate the spontaneous combustion potential of coals. These included crossing point temperature methods, adiabatic and isothermal heating methods, and oxygen adsorption techniques (Kim, 1977). Up to that time, no predictive methods took into account the role that geologic and mining conditions and mining practices played. In 1973, Feng developed a risk index that considered the mine environment as well as the coal's spontaneous combustion potential in assessing the spontaneous combustion risk in a mining operation (Feng, 1973). In 1982, Bhattacharya developed a classification system based on a coal factor, a geologic factor, and a mining factor (Battacharya, 1982). Also in 1982, Banerjee developed a risk analysis method based on the spontaneous combustion potential of the coal and 22 different mining parameters (Banerjee, 1982). This method provided criteria for assigning high or low risk values for each of the 22 parameters. Singh developed an index for assessing the spontaneous combustion risk in longwall mining and was among the first to attempt to computerize the method using an expert system format (Singh, 1986 and 1990).

The U.S. Bureau of Mines (USBM) developed a ranking method to predict the self-heating potential of a coal, based on the coal's minimum self-heating temperature (SHT) in its adiabatic heating oven. This is the minimum initial temperature from which a coal undergoes a sustained exothermic reaction in the adiabatic oven, and is a measure of the coal's reactivity (Smith, 1987). The minimum SHT's of more than 30 coal samples, ranging in rank from lignite to high volatile A bituminous, were determined in the adiabatic oven. The minimum SHT's ranged from 35° to 135 °C. From these experiments, and correlation with the spontaneous combustion history of these coals, a ranking scheme was established with respect to a coal's minimum SHT. Coals with minimum SHT's <70 °C were considered to have a high spontaneous combustion potential, those with minimum SHT's between 70 ° and 100 °C a medium potential, while those with minimum SHT's >100 °C were considered to have a low spontaneous combustion potential (Smith, 1987).

A statistical analysis of the adiabatic oven results showed that the minimum SHT of a bituminous coal was strongly dependent on the dry ash-free oxygen content of the coal, a value readily available from a routine ultimate analysis (Smith, 1987). Thus a bituminous coal's relative self-heating potential could be determined by a simple empirical expression. These results were incorporated into an expert system computer program that allowed the assignment of the self-heating potential of a coal without the need for laboratory experiments (Smith, 1992). The program, however, evaluated only the relative self-heating potential of the coal, and did not take into account other important factors in the spontaneous combustion process, such as coal properties, geologic and mining conditions, and mining practices.

The expert system computer program, SPONCOM, was developed to aid in the assessment of the spontaneous combustion risk of an underground coal mining operation by taking into account these other factors. An expert system is a computer program that uses available information to make decisions based on a series of rules provided by the programmer. It is an interactive, user-friendly, and inexpensive method of conveying "expert" advice. Information was gathered from the literature, from interactions with experts in ventilation, geology, ground control, and other areas, and from mine personnel that have experienced self-heating events at their operations. This information was correlated with the USBM's experimental studies on the self-heating of coal to form the knowledge base for the expert system.

PROGRAM STRUCTURE AND OUTPUT

SPONCOM is written in ANSI C programming language for use on IBM (or compatible) 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, either high, medium, or low, 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 to evaluate the effect of the coal properties, the geologic and mining conditions, and the mining practices on the spontaneous combustion risk of the operation. The program determines the degree of risk for each factor, either low, moderate, high, or very high, based on program ranking criteria and the self-heating potential of the coal, and outputs those factors that increase the overall spontaneous combustion potential of the mining operation.

Most of the input factors are readily definable, such as the moisture content of the coal, the depth of cover, the coalbed thickness, or the type of longwall pillar design. Other factors require the user to rate certain less definable factors, such as the degree of coal friability, geologic factors, such as the density of coal joints, dikes, and channel deposits, and mining conditions, such as the degree of floor heave and rib sloughage. Rating scales for these factors are given in the program, with values from 0 to 100, where 0 is the smallest degree and 100 is the largest. For example, in rating the degree of floor heave, 0 represents a low degree, 50 represents a moderate degree, and 100 represents high degree.

The program output gives the spontaneous combustion potential of the coal, its rank, and SHT. The program then outputs each factor that increases 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. The program output can be printed to the terminal or to a hard copy printer.

DETERMINATION OF SPONTANEOUS COMBUSTION POTENTIAL

The method used to determine the spontaneous combustion potential of the coal is described by (Smith, 1992). The values from the coal's proximate and ultimate analyses and its heating value are used to determine the rank of the coal, based on the ASTM D388 classification system (Anon., 1983). If the rank of the coal is lignite or subbituminous, the coal is assigned a high spontaneous combustion potential. If the rank is anthracite, the coal is assigned a low spontaneous combustion potential. If the rank is bituminous, the coal's predicted SHT is determined by the empirical expression:

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

It is generally agreed that the oxidation of coal is a temperature-dependent reaction that obeys an Arrhenius-type rate law, where the reaction rate increases exponentially with increased temperature. To account for the increased (or decreased) reactivity of a coal due to ambient in-mine temperatures, the value for the minimum SHT determined from Equation (1) is adjusted based on the ambient in-mine temperature of the coal. A value of 12.8 °C (55 °F) is used as the baseline in-mine temperature.

$$\text{SHT}_{adj}\text{, °C} = [\text{SHT} - (T_{ambient}\text{, °C} - 12.8)]. \quad (2)$$

Coals with adjusted SHT's <70 °C are assigned a high spontaneous combustion potential, while those with adjusted SHT's >100 °C are assigned a low spontaneous combustion potential. Coals with adjusted SHT's between 70 and 100 °C are assigned a medium spontaneous combustion potential. The program uses this adjusted value in the evaluation of the effect of the various factors on the spontaneous combustion risk of the mining operation.

The program also considers the spontaneous combustion history of the coal and mining operation in the evaluation of the effect of other factors on the spontaneous combustion risk of the mining operation. If a spontaneous combustion event has occurred in any in-mine area, the program logic uses a high spontaneous combustion potential in the determination of the impact of other factors on the spontaneous combustion risk. If a spontaneous heating has occurred during the storage or transport of the coal, it is noted in the program output as a spontaneous combustion risk.

FACTORS THAT AFFECT THE SPONTANEOUS COMBUSTION RISK

Coal Properties

The coal properties evaluated in SPONCOM include the moisture content of the coal, its friability, previous oxidation, pyritic sulfur content, and impurities in the coal. These properties primarily influence the rate of heat generation during the self-heating of coal. These factors, their ranking criteria, the increased degree of self-heating risk, and the program output for each factor are shown in table 1.

Self-heating occurs when the rate of heat generation exceeds the rate of heat dissipation. Two mechanisms contribute to the rate of heat generation, coal oxidation and the adsorption of moisture, known as the heat-of-wetting effect. The reactivity of a coal is a measure of its potential to oxidize when exposed to air. The coal's minimum SHT is used as a relative indication of its reactivity. In general, a coal's reactivity increases with decreasing rank. Although the mechanism of coal oxidation is not completely understood, it is generally believed that at low temperatures, the oxidation occurs at the oxygen-containing moieties in the coal molecule.

Table 1: Coal Properties

Factor	Spontaneous Combustion Potential	Factor Ranking Criteria	Increased Self-Heating Risk	Output
Moisture	high	>5.0 and <7.5 pct		Heat generation due to heat-of-wetting effect.
		>7.5 and <10.0 pct		
		>10.0 pct		
	medium	>7.5 and <10.0 pct		
		>10.0 pct		
	low	>10.0 pct		
Friability	high	>40		Generation of fresh surfaces available for oxidation.
	medium	>50		
	low	>75		
Previous oxidation	high, medium, or low	Yes		Air and water leakage due to high pressure differentials, increase in coal friability.
Pyritic sulfur	high	>2.67 pct	moderate	Heat generation due to pyrite oxidation, degradation of coal particles.
	medium	>2.67 pct	moderate	
	low	>4.0 pct	moderate	
Impurities	high or medium	Yes		Heat generation due to oxidation of impurities.

The amount of moisture that a coal contains is also an important parameter in the rate of heat generation of the coal. The adsorption of moisture on a dry coal surface is a heat-producing reaction. Thus, if a coal is partially dried during its mining, storage, or processing, that coal has the potential to readsorb moisture, producing heat. Therefore, the higher the moisture content of the coal, the greater the potential for this to occur. In general, the moisture content of coals increases with decreasing rank.

The oxidation of pyritic sulfur is also a heat-producing reaction. The heat generated can increase the temperature of the surrounding coal, increasing the rate of oxidation. In addition, as the pyritic sulfur oxidizes, it expands causing coal degradation to occur. Reactions involving impurities, such as resins, can also be a source of heat generation. In general, the presence of these types of impurities increases the spontaneous combustion risk.

Friability and previous oxidation of the coal are also important factors in the self-heating process. The friability of the coal is a measure of the coal's ability to break apart into smaller pieces. This exposes fresh coal surfaces to air and moisture, where oxidation and moisture adsorption can occur. Previous oxidation of coal makes coals more friable. Although the oxidized matter is less reactive, the porous nature of the oxidized coal makes the coal susceptible to air and water leakage when exposed to high pressure differentials.

Geologic Conditions

Geologic conditions that can influence the self-heating process include properties of the coalbed and surrounding strata, such as the depth of cover and the presence of geothermal sources, and conditions that affect the transport of air and moisture to the coalbed, such as the presence of faults, cleat density, joints, channel deposits, clay veins, dikes, and natural burn zones. In addition, the presence of rider beds and pyrite deposits in the floor or roof, in close proximity to the coal bed, can increase the spontaneous combustion risk. These factors, their ranking criteria, increased self-heating risk, and program output are shown in table 2.

Table 2: Geologic Conditions

Factor	Spontaneous Combustion Potential	Factor Ranking Criteria	Other Factors	Increased Self-Heating Risk	Output
Overburden (1)	high	<76 m		high	Air and water migration to sealed areas from surface.
	high	<152 m		moderate	
	medium	<76 m		moderate	
Overburden (2)	high or medium	>457 m		moderate	Air leakage into sealed areas due to floor heave.
Geothermal source (1)	high	temp. increase >10° F		high	Increased oxidation rate due to increased coal temperature.
	medium	temp. increase >15° F		moderate	
	low	temp. increase >25° F		moderate	
Geothermal source (2)	high or medium	Yes		high	Increased oxidation rate due to increased coal temperature.
	low	seam affected >10 pct		moderate	
Faults (1)	high or medium	Yes	longwall mining	moderate	Gob heating due to delays mining through fault.
Faults(2)	high or medium	Yes	overburden <152 m	moderate	Air and water migration to sealed areas from surface.
Cleat density	high	butt cleats >4 or face cleats >1		high	Air leakage through cleated coal due to pressure differentials, increased coal surfaces due to breakage of coal.
	medium	butt cleats >6 or face cleats >2		moderate	
Joints	high	>20		high	Air and water leakage into sealed areas, roof control problems, intragob communication.
	medium	>40		moderate	
Channel deposits	high	>20		high	Air and water leakage into sealed areas, mining delays.
	medium	>40		moderate	
Clay veins	high	>30		high	Mining delays.
	medium	>49		moderate	
Natural burn zone	high, medium, or low	Yes		moderate	Increase in coal friability, air and water leakage due to high pressure differentials.
Dikes	high	>30		high	Mining delays, increase in friability, changes in coal.
	medium	>49		moderate	

Table 2: Geologic Conditions--Continued

Factor	Spontaneous Combustion Potential	Factor Ranking Criteria	Other Factors	Increased Self-Heating Risk	Output
Rider beds in floor	high, medium, or low	distance from floor <2 times average coalbed thickness mined	floor heave >30	high	Exposure to air and water due to floor fracturing, leakage under seals.
	.do	. .do	floor heave potential	moderate	Do.
Pyrite deposits in floor	high, medium, or low	distance from floor <2 times average coalbed thickness mined	floor heave >30	high	Exposure to air and water due to floor fracturing, leakage under seals.
	. .do	. .do	floor heave potential	moderate	Do.
Rider beds in roof	high, medium, or low	distance from roof <5 times average coalbed thickness mined	longwall mining	moderate	Exposure to air and water in gob after caving, near seals due to high pressure differentials.
	.do	distance from roof <2 times average coalbed thickness mined	room-and-pillar mining	moderate	Do.
Pyrite deposits in roof	high, medium, or low	distance from roof <5 times average coalbed thickness mined	longwall mining	high	Exposure to air and water in gob after caving, near seals due to high pressure differentials.
	.do	distance from roof <2 times average coalbed thickness mined	room-and-pillar mining	moderate	Do.

The depth of cover, or amount of overburden, can affect the self-heating process in many ways. If the overburden is shallow, communication paths with the surface can develop, allowing air and moisture to migrate to mined-out areas. If the overburden is deep, the ambient temperature of the coalbed increases, which increases the rate of oxidation of the coal.

In general, the rank of the coal increases with increasing depth of cover, so that deeper mines are usually less susceptible to self-heating. However, higher ranked, deeper coalbeds usually emit greater quantities of methane requiring higher ventilation pressures. This increases the potential for air leakage into sealed-off areas. In addition, deeper mines are usually more prone to rib sloughage, which generates more fresh coal surfaces for oxidation, and to floor heave, which can expose rider beds or pyrite veins to ventilating air.

The presence of a geothermal source in close proximity to the coalbed can significantly increase the risk of spontaneous combustion by raising the temperature of the coalbed. The degree of risk depends on the amount of the coalbed affected, and the temperature increase caused by the geothermal source.

Faulted areas, if relatively close to the surface, can also provide access of air and water to worked-out areas. The grinding action along the fault can also produce coal fines as well as act as a possible heat source if the fault is still active. An indirect risk factor of faults is the slowing down of the face advance in a longwall operation, which can lead to a buildup of heat behind the face supports.

Face and butt cleats are vertical fractures in the coal oriented perpendicular to one another. Since coal more easily parts along cleats, a high cleat density can lead to more finely divided coal in gobs and crushed-out areas, providing increased surface area for oxidation to occur. Highly cleated pillars can allow air leakage through the coal where high pressure differentials exist.

Joints, which are natural fractures occurring in the rock surrounding the coalbed, can also affect the spontaneous combustion risk by acting as pathways for air and water into the coalbed. The fractures can also impact roof control and can act as conduits for air and water leakage between sealed and unsealed areas.

Channel deposits, which are deposits of sandstone and shale sediments in ancient stream channels; clay veins, which are clay sediments in the fractures in the coalbed; and dikes, which are igneous intrusions in the coalbeds, can all cause delays in mining around them. This increases the risk of spontaneous combustion in active gob areas. Also, the heat generated during the formation of dikes can cause significant changes in the coal properties near the dike, especially in its friability.

The presence of natural burn zones in the coalbed, which are areas that have undergone previous oxidation, can also lead to air and water transport through the coalbed if high pressure differentials exist across portions of these zones. In addition, coal in these zones tends to be more friable, increasing the amount of coal surfaces exposed to oxidation.

Coal rider beds in the roof and floor may increase the risk of spontaneous combustion. If the roof rider bed is located within the caving height of the gob, the coal will likely end up in the gob. The specific risk depends on the reactivity of the coal, the type of mining method, and the ventilation scheme employed. Another risk factor is the potential exposure of rider coal in the roof to air and moisture if leakage occurs between working and sealed areas due to high pressure differentials. Exposure of coal rider beds in the floor to air and moisture, due to floor heave or leakage under seals due to high pressure differentials, can also produce large amounts of heat depending on the coal's reactivity.

Pyrite deposits in the roof and floor pose many of the same risks as coal rider beds. In addition, the heat produced by the pyrite oxidation, if in close proximity to coal, may act as a heat source to increase the coal temperature, leading to spontaneous combustion.

Mining Conditions

Mining conditions can also influence the spontaneous combustion risk of a mining operation. Among these are the ambient temperature of the coal, coalbed thickness and gradient, floor heave, and rib sloughage. These factors, their ranking criteria, the degree of self-heating risk, and the program output for each factor are shown in table 3.

The coalbed thickness can have an impact on the amount of coal that is left in the gob or other worked-out areas, where spontaneous combustion often occurs. In very thick beds, roof and/or floor coal is often left for ground control, or selective mining of higher quality coal is practiced. This results in a large fuel source for oxidation where self-heating can occur.

The coalbed gradient, or dip, can affect the movement of air and moisture in the mine. In coalbeds that are susceptible to the heat-of-wetting effect, seam gradients can cause water inflow into areas where dried or weathered coal has accumulated. In highly dipping coalbeds, convection currents due to buoyancy and temperature gradients can result in air flow into worked-out or gob areas, leading to the development of self-heating.

Floor heave can be extremely critical in the spontaneous combustion process, especially if there are rider beds or bands of impurities, such as pyrite veins, below the floor. These rider beds and pyrite veins provide a source of fuel in a well-insulated area, where heating may develop. This situation can be aggravated if the floor heave occurs in areas where water is present. Another serious situation exists in areas where pressure differentials can act to pull air through the heaved floor, such as at stoppings separating intake and return airways.

Rib sloughage provides a source of freshly exposed coal surfaces where oxidation can take place. This is especially critical when it occurs in main entries or gateroads, where the available ventilating air increases the risk.