Appendix Y – Evaluation of Spontaneous Ignition Potential of Aracoma Alma Mine #1 Coal Sample

It is well known that some materials, under the right conditions, can undergo a self-heating reaction sufficient to allow the material to reach its auto-ignition temperature. Oxidation is usually the principle reaction driving this self-heating process. Coal is among the materials that have demonstrated the ability to undergo self-heated ignition.

Traditionally, the self-heating process has been referred to as "spontaneous combustion." However, the use of the word "spontaneous" in this phrase actually refers to the process leading up to ignition, rather than to the on-going burning after ignition has occurred. For this reason, the term "spontaneous ignition" is more appropriate and will be used in this discussion. This usage is also consistent with the growing trend within the fire science and research community to use "spontaneous ignition" when referring to the self-heating ignition process.

Not all coals tend to undergo spontaneous ignition, either in the laboratory or under real world conditions. Substantial research has demonstrated that a number of factors play a role in this process. These factors include certain chemical and physical properties of the coal, the location and physical condition of the coal, and the surrounding environment.

In terms of location and conditions, it has been observed that larger coal piles or accumulations have a greater tendency to self-heat than small accumulations. Small coal piles or accumulations are much less likely to undergo spontaneous ignition because, among other things, they are more effective at shedding heat created by any self-heating process. This is due to the smaller mass and greater surface area of the pile. The compactness of the pile is also a factor, with loosely piled coal more prone to spontaneous ignition than tightly compacted piles.

Ventilation can have a significant effect on the occurrence of spontaneous ignition. Continuous ventilation can provide an on-going source of oxygen; however, it can also act as a convective heat transfer media to provide cooling of coal accumulations that may be self-heating. Greater ventilation rates tend to discourage self-heating, while very low ventilation rates can encourage the process. The continuous replenishment of oxygen, in conjunction with a lack of cooling, can permit an excessive temperature rise to occur in the coal. Since the rate of oxidation has an Arrhenius temperature dependence (i.e., increasing exponentially with increasing temperature), the increasing temperature in the coal can become a self-sustaining process, with the reaction sometimes "running away" until ignition occurs (autoignition).

As evidence of the importance of these factors, Kutchta, et.al [1] reported that from 1952 through 1969, 877 fires occurred in underground coal mines. Sixty five (65) of these were due to "spontaneous combustion," with all of those fires restricted to gob areas. In another study, De Rosa[4] found that from 1990 through 1999, 84 mine fires occurred with 15 fires attributed to "spontaneous combustion." All of those occurred either in gob, sealed off, or abandoned areas. Gob areas are worked-out areas from which coal pillars have been partially or wholly removed. They usually contain loose coal left from the mining process and have sustained but limited ventilation.

The chemical and physical properties of the coal also play a significant role in spontaneous ignition. Of particular importance concerning the chemical and physical properties are the ability of the coal to adsorb water vapor, the amount of volatile matter within the coal, and the amount of oxygen contained within the chemical structure of the coal.

Kutchta found that self-heating of coal tends to be a two–step process. The first heating step occurs when dry coal adsorbs water vapor. In order to change from a liquid to a vapor, water must absorb a significant amount of heat. For example, this happens when sunshine evaporates water from a highway after a rainfall. When the opposite process occurs, that is, when water vapor re-condenses back into a liquid, the heat it gained during evaporation is given up to the surrounding environment. This process is sometimes referred to as the "heat of wetting." It is interesting to note that this same process is one of the primary heating mechanism driving thermal updrafts in thunderclouds. When coal adsorbs water vapor, the heat of wetting raises the temperature of the coal. The more moisture the coal can adsorb, the more heat that can be generated by the heat of wetting.

The rate of oxidation within coal that occurs at ambient temperatures is usually insufficient to initiate a self-sustained heating process. However, with sufficient heat of wetting, a critical temperature may be reached whereby the oxidation reaction can become dominant and take over the heating process. Two additional factors affect the likelihood of this happening. These are the amount of volatiles in the coal and the amount of inherent oxygen. Volatile matter in the coal is generally easier to oxidize than nonvolatile content, and additional oxygen in the coal further supports the oxidation process. Therefore, coals with higher volatile matter and oxygen content have lower critical oxidation temperatures. Smith and Lazzara [2] provided information on the role the amount of inherent oxygen plays in the spontaneous ignition of coal.

Mine safety researchers have developed the concept of a minimum self-heating temperature, which will be referred to as the critical self-heating temperature, or CSHT, in this discussion. [1][2] The CSHT is a laboratory determined quantity that cannot be used to directly predict spontaneous ignition under specific real world conditions. However, this value can play an important role as an index for classifying the relative propensity of a coal to spontaneously ignite by correlating this value to coal fire history data.

In the referenced research, the CSHT was determined using pulverized dry coal samples. Samples were placed in an insulated (adiabatic) vessel and then exposed to a continuous steady flow of moist air of predetermined temperature. This exposure process continued for 24 hours, or longer, if temperature measurements in the sample indicated self-heating was occurring. If an initial limited temperature rise occurred, but then leveled off and remained constant throughout the 24 hour period, spontaneous ignition was deemed not to have occurred. Where self heating was evident, the test run was continued beyond the 24-hour cutoff time. If self heating led to an exponentially increasing temperature rise, then spontaneous ignition was either occurring or immanent.

For coal samples from a given coal seam, this experiment was repeated at various temperatures with fresh samples for each run. The lowest heating temperature demonstrating thermal runaway was termed the "minimum" self-heating temperature.

The time from the start of a heating experiment until ignition occurred is often referred to as the induction time. For cases in the referenced research where spontaneous ignition occurred, the induction times in those experiments varied from about 4 hours for airflow temperatures well above the CSHT, to induction times often 24 hours or longer for airflow temperatures at the CSHT.

Two different critical self heating temperatures have been identified, one based upon the amount of oxygen in the coal, the second based upon a combination of the water adsorption capability of the coal and the amount of coal carbon and volatiles. These last three values are incorporated into a quantity known as the "moist fuel ratio" or MFR.

Determination of the oxygen-based CSHT requires knowledge of the amount of oxygen in the coal on a dry, ash-free basis. This can be determined by an ultimate analysis (ASTM D-3176). Determination of the MFR-based CSHT requires the percent moisture content, percent volatiles, and percent fixed carbon, which can be determined by a proximate analysis (ASTM D-5142). All percents are on a mass basis.

Both a proximate analysis and an ultimate analysis were conducted by an independent laboratory on a coal sample from Aracoma Alma No. 1. The results are listed below.

% moisture	% volatiles	% carbon	% oxygen (DAF)
2.99	36.39	54.30	6.89

As stated, the percent oxygen is elemental oxygen on a dry, ash-free basis from the ultimate analysis. All other values are from the proximate analyses.

For the CSHT based upon oxygen content, Smith and Lazzara proposed the following empirical equation.

$$CSHT_{OX} = 139.74 - 6.57 \times O_{DAF}$$

Where:

$CSHT_{OX}$ = critical self heating temperature in °C based upon elemental oxygen level.

O_{DAF} = mass percent elemental oxygen on a dry, ash-free basis.

Based upon the ultimate analysis, the $CSHT_{OX}$ was calculated to be 94.5°C.

The CSHT due to the moist fuel ratio is based upon an empirical equation proposed by Litton and Page [3], who in turn, based their equation on data and results from Smith and Lazzara. This equation was given as:

$$CSHT_{VOL} = 117\left(1 - e^{-2.6x}\right)$$

Where:

$CSHT_{VOL}$ = critical self heating temperature in °C based upon carbon, volatiles, and moisture adsorption.

X = "moist fuel ratio" and is defined as:

$$X = \frac{\left(\frac{\%\,fixed\ carbon}{\%volatile\ matter}\right)}{\%moisture}.$$

Based upon the results from the proximate analysis, a value of 85°C was obtained for $CSHT_{MFR}$.

Smith and Lazzara proposed that for CSHT values less than 70°C, the coal should be classified as having a high potential for spontaneous ignition. Coals having a CSHT at or above 70°C, but less than 100°C, should be considered as having a moderate potential for spontaneous ignition. For coals having a CSHT equal to or greater than 100°C, the potential for spontaneous ignition should be considered low.

The average of the two values obtained in the analysis is 90°C. It is very important to note that the temperature ranges proposed by Smith and Lazzara, although not arbitrary, are set somewhat for convenience in that they are established at whole units of ten degrees. The results yield values toward the upper boundary between the moderate and low ranges of spontaneous ignition potential.

Conclusion

The results of this analysis strongly suggest that spontaneous ignition of coal accumulations in the No. 9 Headgate longwall takeup storage unit area was not the source of ignition for the fire on January 19, 2006.

Bibliography

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[4] De Rosa, Maria L. Analysis of Mine Fires for All U.S. Underground and Surface Coal Mining Categories: 1990–1999, National Institute of Occupational Safety and Health, Information Circular 9470, 2004