

Coal Mine Safety and Preventing Self-Combustion of Coal

A. Arısoy

Technical University of Istanbul, TURKEY

ABSTRACT Spontaneous combustion can cause huge losses in revenue and more importantly, cause major problems with safety. Underground coal mines are required to manage the risk of spontaneous combustion and the initial part of this process is to obtain an assessment of the spontaneous combustion propensity of the coal.

There are a number of tests available to do this. The R_{70} test is used successfully for this purpose. This test has also been used to investigate the effects of various coal properties on self-heating rate. These effects can be divided into two groups. First group is related with coal properties such as rank, mineral matter, pyrite content and coal type. Second group is related mine conditions such as temperature of the mine, ageing of coal, coal particle size, moisture content, depth of the stored coal pile and amount of air flow passing through the coal bulk. A safe managing plan of coal mine should consider all those effects in a sufficient way. A review of the subject will be given in this paper.

1 INTRODUCTION

Spontaneous combustion of coal is an important problem in mining, long distance transportation and storage in terms of safety and economics. This is because coal reacts with oxygen in the air and an exothermic reaction occurs even at ambient conditions. A problem arises when the amount of heat produced by this process is more than that dissipated by heat transfer to the surroundings. The heat of reaction accumulates and the reaction becomes progressively faster and thermal runaway may take place to the point of ignition.

It is for these reasons; the phenomenon of spontaneous combustion of coal has been of fundamental and practical importance to scientists. However this phenomenon is more important in terms of underground coal mine safety. This unwanted outcome can cause huge losses in revenue and more importantly, cause major problems with safety. Turkey had experienced very bad

accidents in recent years causing hundreds of casualties.

To overcome these issues, all mines are required to develop an appropriate and technically sound Spontaneous Combustion Management Plan (SCMP). These plans need to be based on accurate measurements of spontaneous combustion behavior including the propensity of coal to self-heat under in-mine conditions and the associated gas evolution pattern as the coal self-heating. The initial part of this risk management plan is to obtain an assessment of the spontaneous combustion propensity of the coal and the next part is modelling the process and predicting the temperature development and gas evolution. The necessary precautions can be taken on time only with such model predictions.

In New South Wales leading industry practice is the development and implementation of a Spontaneous Combustion Management Plan (SCMP) that complies with the Spontaneous Combustion Management Guideline – MDG1006

(Industry and Investment NSW, 2011a). A supplementary document (MDG1006 – Technical Reference) accompanies the guideline (Industry and Investment NSW, 2011b). Operationally, mines mainly mitigate the sponcom hazard using a Trigger Action Response Plan (TARP) system and there are some mines who adopt a proactive goaf inertisation strategy (for example San Juan Mine in New Mexico (Bessinger *et al.*, 2005)). Another mitigation strategy is to apply inhibitors to the coal to delay the onset of spontaneous combustion.

Several theoretical and experimental studies have been performed on coal spontaneous combustion. The main purposes of these studies were to develop methods for determining the conditions at which the coal could undergo spontaneous combustion, to predict the safe operation conditions, and to determine the influences of factors contributing to the spontaneous heating.

The self-heating of coal is due to a number of complex exothermic reactions. Coal will continue to self-heat provided that there is a continuous air supply and the heat produced is not dissipated. The intrinsic coal properties that control propensity for self-heating have been the subject of many investigations. Relationships between these properties and self-heating indices have been published in a number of studies (Humphreys *et al.*, 1981; Moxon and Richardson, 1985; Singh and Demirbilek, 1987; Smith and Lazzara, 1987; Barve and Mahadevan, 1994; Beamish *et al.*, 2000, 2001; Beamish, 2005; Beamish and Blazak, 2005; Beamish *et al.*, 2005; Beamish and Clarkson, 2006).

Spontaneous combustion management plans (SCMPs) should contain data that can be used to assess the inherent propensity of the coal to self-heat. This usually involves obtaining results from small-scale laboratory tests.

One such test that is frequently used by the Australian coal industry is the adiabatic oven R70 self-heating rate test, which can also be used to study and quantify the factors that affect coal inherent self-heating propensity (Beamish *et al.*, 2000; Beamish *et al.*, 2001; Beamish and Blazak, 2005; Beamish and Hamilton, 2005; Beamish 2005). The test measures the average self-heating rate between 40 °C and 70 °C, known as the R70 self-heating rate index (Humphreys *et al.*, 1981). The higher the R70 value, the higher the propensity of coal for self-heating.

2 R₇₀ TESTING PROCEDURE

The R₇₀ testing procedure essentially involves drying a 150g sample of <212µm crushed coal at 110°C under nitrogen for approximately 16 hours. Whilst still under nitrogen, the coal is cooled to 40°C before being transferred to an adiabatic oven. Once the coal temperature has equilibrated at 40°C under a nitrogen flow in the adiabatic oven, oxygen is passed through the sample at 50mL/min. A data logger records the temperature rise due to the self-heating of the coal. The time taken for the coal temperature to reach 70°C is used to calculate the average self-heating rate for the rise in temperature due to adiabatic oxidation. This is known as the R₇₀ index, which is in units of °C/h and is a good indicator of the intrinsic coal reactivity towards oxygen. In addition, the data from this test can be used to obtain kinetic parameters for the coal self-heating up to the trip temperature, which is set at 160°C. These kinetic parameters can be used as input to numerical models (Arisoy *et al.*, 2006; Arisoy *et al.*, 2007; Arisoy and Beamish, 2008).

3 EFFECT OF INTRINSIC COAL PROPERTIES ON SELF-HEATING RATES

3.1 Coal Rank

As a coal ages, becomes more buried and experiences more pressure, it undergoes a process called coalification". Rank is a measure of the degree of coalification and can be measured in different ways. The two most common methods are the ASTM and Suggate ranks (Sykes and Suggate, 1990; Suggate, 2000). As the rank changes, the coal undergoes a series of changes; cleats become more defined, moisture content decreases, carbon content increases and the general chemical composition changes as shown in **Table 1**. Whilst, for a given coal, the numbers in **Table 1** are likely to vary, the trends through each rank show that carbon content increases, hydrogen and oxygen content decrease, and nitrogen and sulphur content varies. Rank has the largest effect on a coal's ISCP (Index for Spontaneous Combustion Propensity). Originally this effect was not directly proven but observed in different coal mines that the lower rank coal seams were more likely to have heating issues (Humphreys, 1979).

Table 1. Elemental composition of coals according to rank.

Rank	Carbon %	Hydrogen %	Oxygen %	Nitrogen %	Sulphur %
Peat	55.0	6.0	30.0	1.0	1.3
Lignite	72.7	4.2	21.3	1.2	0.6
Sub-bituminous B	77.7	5.2	15.0	1.6	0.5
High Volatile Bituminous B	80.3	5.5	11.1	1.9	1.2
High Volatile Bituminous A	84.5	5.6	7.0	1.6	1.3
Medium Volatile Bituminous	88.4	5.0	4.1	1.7	0.8
Low Volatile Bituminous	91.4	4.6	2.1	1.2	0.7
Anthracite	93.7	2.4	2.4	0.9	0.6

Humphreys (1979) found that for Queensland coals, the self-heating rate decreased with an increase in carbon content and a decrease in oxygen content. A lower oxygen content and a higher carbon content indicate an increase in rank (Suggate, 2000) so Humphreys' (1979) result indicates that ISCP decreases with increase in rank. However, the picture is not that simple.

Work done by Beamish (2005) on a selection of Australian and New Zealand coals indicates that although the propensity of coal spontaneous combustion decreases through sub-bituminous to bituminous, it actually increases from lignite to sub-bituminous. This is shown in **Figure 1**.

Adiabatic self-heating curves for different coals are shown in **Figures 1 and 2**. Two figures are covering the complete range of the coal ranks. For a high rank coal can take almost 240 hours (10 days) to reach thermal runaway.

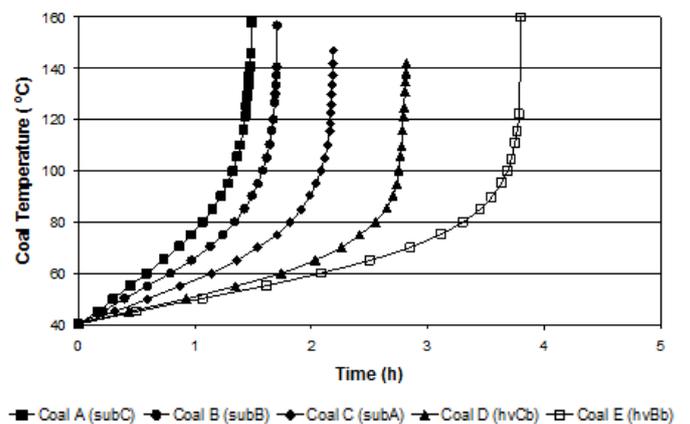


Figure 1 Adiabatic self-heating curves for coals ranging in rank from sub-bituminous C to high volatile B bituminous.

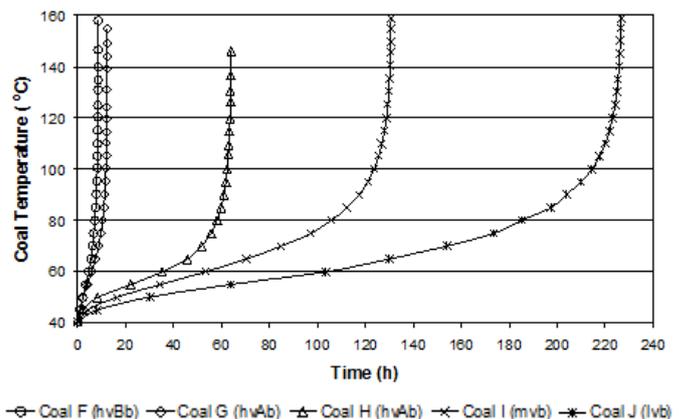


Figure 2 Adiabatic self-heating curves for coals ranging in rank from high volatile B bituminous to low volatile bituminous.

A comparison between the R_{70} self-heating rate values for each of these coals and the minimum self-heating temperature (SHT) calculated from the equation of Smith and Lazzara (1987) shows a significant

difference in the rank effect (**Figure 3**). The relationship between R_{70} and coal rank is clearly non-linear and is best defined by a third order polynomial as seen in **Figure 3**. This feature of the R_{70} index helps to highlight the importance of coal rank when assessing propensity.

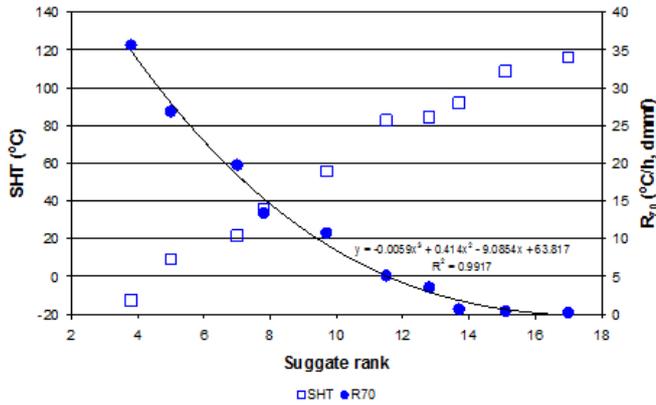


Figure 3 Relationship between coal rank and spontaneous combustion index parameters SHT and R_{70} .

3.2 Coal Petrology

Coal is a complicated substance, mainly composed of materials called “macerals”, which are defined by the original vegetation from which coal is formed. The three main groups of macerals are vitrinite, liptinite and inertinite and much study has been done on their influence on spontaneous combustion propensity. Vitrinite, liptinite and inertinite have varying chemical compositions due to their different origins. Vitrinite comes mainly from the leaves and stems of land plants and has more oxygen at a given rank than the other two groups, liptinite comes from algae, pollens, resins and cuticles and has more hydrogen and inertinite has more carbon and is formed by the oxidation of vitrinite (Cotterell, 1997; Humphreys, 1979).

Despite the volume of literature on the subject, no definite conclusions have been derived (Humphreys, 1979). It seems that each set of tests produces different conclusions, Humphreys’ (1979) tests indicate that spontaneous combustion

propensity increases as vitrinite content increases, Cotterell (1997) could not find a correlation between maceral content and spontaneous combustion propensity. At present, maceral content is not an effective parameter for estimating the propensity of coal to spontaneously combustion.

3.3 Mineral Matter and Coal Type

Oxidation of a coal particle in atmospheric conditions is a complex process. There are many competing chemical and physical processes occurring simultaneously at low temperatures. One of the important parameters affecting the inherent self-heating propensity of coal is the mineral matter content. A definite negative correlation exists between mineral matter content and the R_{70} self-heating rate of coal. Similarly, the heat release rate (reactivity) of dry coal under adiabatic test conditions from 40 to 160 °C also displays a negative correlation with mineral matter content.

This relationship is partly due to the mineral matter in the coal acting as a heat sink. If coal and ash are simply admixed with each other, then only the heat sink effect of the mineral matter is observed. However, if the mineral matter is naturally disseminated in the coal then the heat sink effect does not account for the total observed decrease in the coal self-heating rate. In this case the mineral matter inhibits oxygen reaching carbon surfaces and probably acts on the chemical reaction mechanism (Beamish and Arisoy, 2008).

As the R_{70} value is obtained on a dry basis, the best way to graphically represent the data for ply results from the same seam is to plot it against the ash content (on a dry basis, **Figure 4**). By doing this, any variations within the seam will become immediately obvious and consequently coal type and mineral matter effects can be distinguished.

The ash content of coal is closely related

to the mineral matter present, which is the inorganic constituents of the coal that modify the coal behavior in many combustion processes. In the case of the coal self-heating, the mineral matter has generally been considered a diluent, effectively creating a heat sink due to its heat capacity (Humphreys et al., 1981; Smith et al., 1988). However, mineral matter may also create blockage of access to oxidation sites, lowering the self-heating rate of the coal even further (Beamish and Arisoy, 2008).

A general trend of decreasing R_{70} value with increasing ash content can be seen in **Figure 4** for all of the seams. In particular, Seams G and H show a gentle linear trend with ash content, which corresponds closely to that expected for a simple heat sink effect. However, Seams B and D show a much steeper relationship with ash content. A simple explanation for this would be that there is a difference in coal type influencing the self-heating rate. In the case of Seam B this is possible as there is a significant increase in vitrinite content for the higher ash content sample. This would appear contrary to published effects of maceral composition (Walters, 1996). However, Seams E and F correspond to premium coking coals from New Zealand and New South Wales respectively and it is clear that these coals have a substantially lower self-heating rate than their steaming coal rank equivalents. Again, the fundamental difference here is that the steaming coals contain a higher proportion of inertinite and the coking coals are predominantly vitrinite-rich. The New Zealand premium coking coal (Seam E) is particularly anomalous in this regard and is almost pure vitrinite. Hence, the higher the vitrinite content of the coal ply the lower the self-heating rate, particularly if this is combined with increased ash content as seen in the case of Seam B.

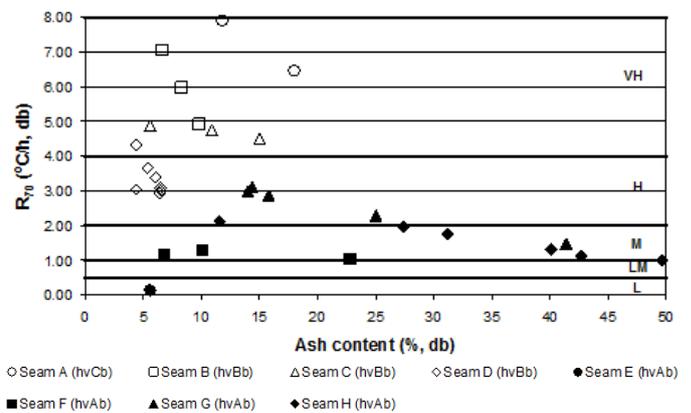


Figure 4 Relationship between ash content and R_{70} self-heating rate index for seam ply samples of high volatile bituminous coals with intrinsic spontaneous combustion propensity classes.

The same explanation cannot be used for Seam D. There is no change in coal maceral composition for the plies from this seam. Therefore, the cause of the steep ash content trend for these samples can only be linked to the mineral matter type. Beamish and Sainsbury (2008) showed that results from an ash analysis of these samples yielded a strong association with sodium content, which has been identified in the form of the sodium zeolite mineral analcime ($\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$). Further work is progressing on this association to confirm the effect that has been observed in the dramatic drop in self-heating rate due to the presence of this mineral.

New work is also in progress on coals from the Surat Basin in Queensland that have high liptinite contents. Earlier work by Beamish et al. (2000) showed that the presence of resinite in New Zealand low rank coals lowered the self-heating rate of the coal. This same effect has been noted in follow-up tests on coals from the Huntly North Coalfield in New Zealand and preliminary results on Indonesian coals of similar rank. Initial testing of Surat Basin coals has recorded similar findings.

4 THE INFLUENCE OF MOISTURE ON COAL SELF-HEATING

The influence of moisture on coal self-heating has been investigated by a number of studies. It is generally accepted that there are competing influences of heat of wetting and moisture evaporation depending on the environmental circumstances of the coal (Hodges and Hinsley, 1964; Guney, 1971; Bhattacharyya, 1971, 1972; Bhat and Argarwal, 1996). Numerical model studies by Arisoy and Akgun (1994) showed that moisture effects extensively on self-heating of coal. In the case of low moisture content coals, the maximum temperature increases steadily with time. In the case of high moisture coals, temperature increases rapidly initially before evaporation dominates and the temperature reaches a plateau value (generally around 80-90°C). Once the coal becomes dry locally the temperature will increase rapidly towards thermal runaway.

Recent studies by Beamish and Hamilton (2005) and Beamish and Schultz (2008) have re-emphasized the importance of moisture on coal self-heating. As a result of these studies, Beamish and Beamish (2010) proposed a new moist coal adiabatic oven test that can be used to benchmark laboratory performance against actual site performance.

Adiabatic oven test results of same coal with different moisture content are seen in **Fig.5**. Effect of moisture content is seen clearly in this figure. Dry coal reaches thermal runaway in 7 days, however same coal containing 12% moisture doesn't reach any thermal runaway. Moisture prevents coal temperature rise over 63 °C, this coal can be considered as a safe coal. If the moisture content is 9% again a self-combustion can start eventually in 25 days, moisture delays the thermal runaway but doesn't prevent totally.

Moisture in coal is held in three distinct forms 1- Free or adherent moisture

(essentially surface adsorbed) possessing the physical properties of ordinary water. 2- Physically bound or inherent moisture of vapor pressure lowered by the small diameter of the pores of the coal structure in which it is absorbed. 3- Chemically bound water of hydration or combined water.

The form of moisture is important and effect of moisture on self-combustion is depend on the form of moisture extensively. The moisture form referred above studies is mainly in the second group.

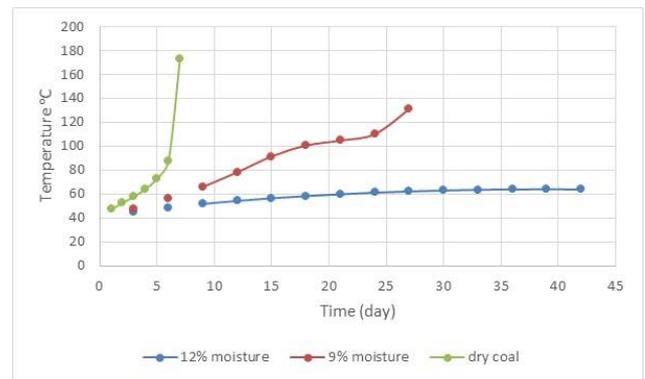


Figure 5 Adiabatic self-heating curves for samples tested using the moist coal adiabatic oven test procedure. Same coal with different moisture content displays totally different behaviors.

The results show that the moisture content of the coal significantly inhibits the coal self-heating. Therefore the moisture state of the coal from the mine face to the stockpile will be an important parameter in determining the overall spontaneous combustion risk of the coal.

4.1 Quantifying Seasonal Effects on Coal Self-heating

Anecdotal evidence suggests that coal self-heating in stockpiles can take place following a rain event and this often occurs during the wet season in Queensland. Simulated wet season and dry season conditions have been applied to a reactive ($R70 = 9.38^{\circ}\text{C}/\text{h}$) Bowen Basin high volatile bituminous coal in the adiabatic oven with an as-received moisture content of 14.1 per

cent using moist oxygen and dry oxygen flows respectively. The contrast in the test results is quite dramatic (Figure 6).

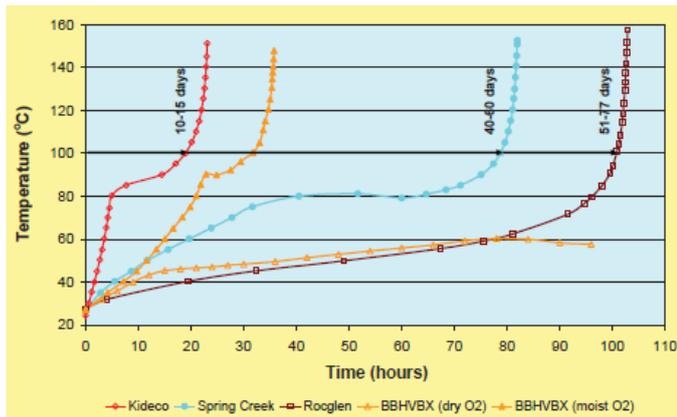


Figure 6 Moist coal adiabatic benchmark test results for a Bowen Basin high volatile bituminous coal (BBHVBX) under dry (dry O₂) and moist oxygen (moist O₂) flows with relative scale comparing projected minimum days to thermal runaway for loosely piled coal found in coal roof falls and uncompact stockpiles.

Under dry season conditions (dry oxygen flow), the coal initially self-heats at a rapid rate to just over 40°C, but then the self-heating rate begins to slow down. The coal then reaches a maximum temperature of 60°C before it begins to lose heat, presumably due to the fact that the heat loss from moisture evaporation is exceeding the heat gained from oxidation.

Under wet season conditions (moist oxygen flow) the coal rapidly self-heats to thermal runaway, with only a brief respite at around 90°C as moisture is released from the coal. From the benchmark scale, in wet season conditions this coal would create heating issues in 16 - 25 days. Therefore strict stockpile management would be required to ensure the coal is being moved in less than this time frame.

The moisture moderating behavior that is displayed in these tests is in agreement with the earlier work of Guney (1971) and Smith and Lazzara (1987). The dramatic difference

between the dry and moist flow conditions are attributed to the additional heat from the heat of wetting effect and the synergistic role of moisture in the self-heating process (Smith and Lazzara, 1987). This feature of coal self-heating can only be quantified using the new test method.

5 PARTICLE SIZE

Specific particle surface area increases as the particle size decreases, meaning that there are more sites for oxidation to occur as the particle size decreases. This, in turn, increases the spontaneous combustion propensity.

A large-scale apparatus has been used to evaluate the effect of particle size on the spontaneous heating of a coal stockpile. To accomplish this, coal with various ranges of particle size (between 2 and 50 mm in diameter) was oxidized in a cylinder of 3-m length and 0.3-m diameter. A critical range of particle size was observed, below which spontaneous heating leads to thermal runaway (Akgun F. and Arisoy A., 1994). From the results of the oxygen consumption and the temperature of the coal bed, the influence of particle size on the oxidation rate has been analyzed in greater depth.

The reaction of a coal particle with oxygen may be divided into three regimes depending on the reaction temperature, particle size and porosity of the coal. These comprise the chemically controlled, chemically and pore diffusional controlled and external diffusional controlled regimes. In fact it is difficult to clearly distinguish transition between these regimes.

In chemically controlled regime, it has been assumed that when a very small porous coal particle reacts with oxygen at low temperatures, the oxygen can diffuse easily to the interior of the particle without any diffusional restrictions. In this case, volumetric reaction occurs and the reaction rate does not depend on particle size. In the

case of the chemically and pore diffusional controlled regime, the oxygen may reach the center of the particle but a concentration profile of oxygen occurs within the particle. As a result, the overall reaction rate is controlled by combined effects of pore diffusion and chemical reaction. An extreme case may occur for almost nonporous particle in which the chemical reaction occurs on the external surface of the particle. In that case reaction rate is considered to be inversely proportional to the particle size.

There have been several studies of the effect of particle size on the oxidation rate. It was found by (Carpenter and Sergeant, 1966) that the rate of oxidation increases with decrease in particle diameter until a critical value is reached, below which no further increase in rate of reaction occurs. This critical diameter was found to be 138 and 387 μm , depending on the oxidation stage. Above the critical value the oxidation rate is approximately proportional to the 0.3 power of the specific external surface area of the particle. When the particle size is larger than a certain critical value this has to be taken into account in modelling of the spontaneous heating process. (Akgün and Arisoy, 1991) defined an effectiveness factor for the coal- oxygen reaction to take into account the coal particle size.

6 THE INFLUENCE OF MOISTURE AND PYRITE ON THE PROCESS OF COAL SELF-HEATING

The influence of moisture and pyrite on the process of coal self-heating has been investigated in a number of studies (Hodges DJ and Hinsley FB., 1964; Guney M., 1971; Bhattacharyya KK., 1971; 1972; Bhat S, Agarwal PK. 1996; Beamish BB, Hamilton GR. 2005; Beamish BB, Schultz TJ., 2008). Recently, the moderating influence of moisture in as-mined coal on thermal runaway performance has been investigated

experimentally by (Beamish B, Beamish R., 2010; Beamish B, Beamish R., 2012) using an adiabatic oven.

The presence of pyrite has commonly been referred to as a coal self-heating accelerant when present in concentrations above 2% (Walters AD. Joseph C., 1996). However, Beamish B, Beamish R., 2012, have shown that it is the type of pyrite present in the coal that governs whether accelerated self-heating will take place and not simply the amount of pyrite. In addition, pyrite does not react effectively without the presence of moisture and in a dry state does not contribute to the thermal runaway process. This has been demonstrated by Beamish et al. 2012, where coal samples with increasing reactive pyrite content do not reach thermal runaway any faster in a dry state, but in a moist state they do. Hence, the key exothermic pyrite reaction takes place with oxygen in the presence of moisture.

As well as the reaction equation, there are rate data for pyrite oxidation available in the literature. However, there is no available kinetic data for this reaction from coal self-heating experiments. Wang and Luo, 2014, used simple Arrhenius kinetics to compare against laboratory data for reactive pyrite in coal. However, this approach is too simplistic and does not take into consideration the mutual effects of reactive pyrite and moisture. The study Arisoy and Beamish, 2015, has derived empirical kinetic data from the adiabatic oven test results of a New Zealand coal and a Bowen Basin coal investigated by Beamish and Beamish, 2011. At the same time, an existing model for the moist coal self-heating process (Arisoy A, Akgun F., 1994) has been modified to include pyrite oxidation and the derived reaction data has been introduced to the model. The model predictions of adiabatic oven tests are compared with the measured values. This model can also predict the moisture variation in the coal sample with

time. It has been shown in this study that moisture removal from coal due to pyrite oxidation should also be considered as an additional accelerating effect.

6.1 Coal samples and properties

Two coal samples (one from New Zealand and one from Australia) were selected for this study (**Table 2**). The New Zealand sample was a low ash, low sulphur high volatile bituminous coal from the Spring Creek Mine in the Greymouth Coalfield. The Australian sample was a medium ash, high sulphur high volatile bituminous coal from the Bowen Basin. The sulphur content of the Bowen Basin coal was 4.20% on an air-dried basis and consisted of 42% pyritic sulphur, 54% organic sulphur and 4% sulphate sulphur. The equivalent pyrite content of the coal (**Table 3**) was calculated using the conversion factor reported by Miron et al., 1992. The type of the pyrite present in the coal is very important.

Table 2. Coal quality data and test parameters for Spring Creek and Bowen Basin coal samples.

Sample	R70	Volatile matter	Calorific value	Ash content	Sulphur content	Moisture content	Start tem.
	°C/h	(%)	kJ/kg	%, db	%, db	%, ar	°C
Spring Creek	5.87	41.3	31,973	1.2	0.30	11.7	27.0
Bowen Basin	6.02	38.0	29,964	7.3	4.54	9.8	27.2

6.2 R70 test results for Spring Creek and Bowen Basin coal samples

The R70 self-heating curves for each sample are shown in **Fig. 7**. It can be seen that the self-heating rates are almost identical despite the differences in coal

quality as shown in **Table 2**. Their respective

Table 3. Pyrite content of Bowen Basin coal.

	% (air-dried)	% as-received
Moisture	7.5	9.8
Pyritic S	1.76	1.72
Pyrite	2.45	2.39

R70 values are 5.87 °C/h (Spring Creek) and 6.02 °C/h (Bowen Basin). Based on the coal rank it could be expected that the Bowen Basin coal sample would have a higher R70 value than the Spring Creek coal sample (Beamish BB, Arisoy A., 2008; Beamish BB, 2005). However, the higher mineral matter content of the Bowen Basin coal sample creates a heat sink effect (Beamish BB, Blazak DG., 2005) that counterbalances the reactivity due to the lower rank compared to the Spring Creek coal sample. As such the intrinsic reactivity of both samples is effectively the same. It must be remembered that R70 tests are executed on dry samples and in this state exothermic pyrite oxidation reactions are not effective and the heat loss due to moisture evaporation does not occur.

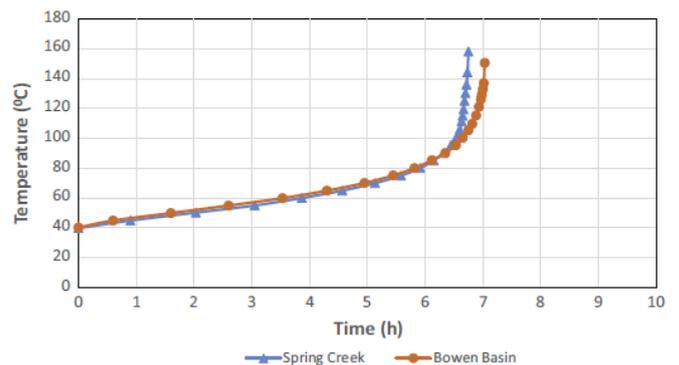


Figure 7 R70 self-heating rate test results for Spring Creek and Bowen Basin dry coal samples.

6.3 Self-heating behavior of moist coal tests

The adiabatic oven tests can also be conducted on coal with their as-received moisture contents (Beamish B, Beamish R.,

2010)]. Moist adiabatic test results for the Spring Creek and Bowen Basin coal samples (non-pyritic moist coal and pyritic moist coal respectively) are shown in **Figure 8**. Additionally, the dry non-pyritic coal sample adiabatic test result is also shown in **Fig.8** for comparison.

In the case of moisture containing non-pyritic coal, the temperature increases initially before evaporation dominates and the temperature reaches a plateau value (around 70 °C). Once the coal becomes dry, the temperature increases rapidly again towards thermal runaway.

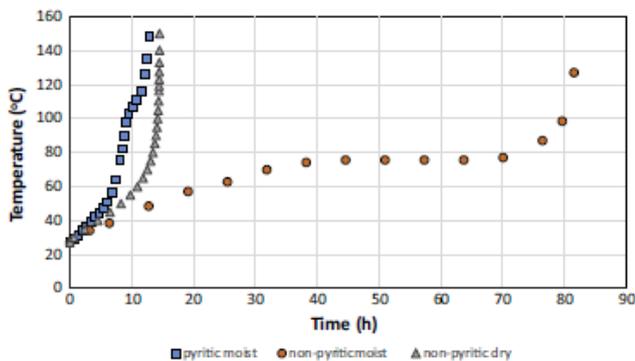


Figure 8 Time–temperature history graphs of pyritic moist, non-pyritic moist and non-pyritic dry coals.

There is negligible pyrite in the Spring Creek coal as indicated by the low sulphur content, and therefore the oxidation reaction recorded is only due to the coal. In contrast however, the Bowen Basin coal sample contains both a considerable amount of pyrite and moisture. As such the Bowen Basin coal sample reaches thermal runaway in a very short time period. The accelerated self-heating of this sample compared to Spring Creek coal can only be attributed to the presence of the pyrite in the coal reacting with the oxygen and moisture, which shows quite a dramatic effect. Although the reactivity of dry samples of these two coals is the same, in the moist state they exhibit totally different behaviors.

7 REACTION KINETICS OF COAL OXIDATION AT LOW TEMPERATURES

It is important to understand the reactions kinetics of the coal oxidation process that takes place at low temperatures. The reaction rate of coal oxidation in terms of oxygen consumption is normally expressed by the conventional Arrhenius equation as follows:

$$\frac{d\rho_{ox}}{dt} = \rho_{ox}^0 \cdot A \exp\left(\frac{-E}{RT}\right)$$

where q_{ox} is the oxygen density in the gas phase and linear dependence of reaction rate on oxygen density is valid experimentally. In the Arrhenius equation, the reaction rate is expressed as an exponential function of coal temperature. Other physical and chemical factors influencing the reaction rate are accounted for by the two constants in the rate expression. These are the pre-exponential factor A and the activation energy E .

In above equation, it is assumed that oxygen can penetrate throughout the coal and the heterogeneous rate of reaction between gas and solid phases is expressed as if it is a homogenous gas phase reaction. This assumption can be made for low temperature self-heating of coal. Otherwise the effect of diffusion rate of oxygen in the coal particle should be considered by introducing an effectiveness factor (Akgün F., Arisoy, A., 1991). Hence, for every coal, specific E and A values should be determined experimentally. However, this Arrhenius equation does not completely reflect the experimentally measured low temperature self-heating behavior of coal in adiabatic oven tests.

New data are available from repeat adiabatic oven tests of a high volatile bituminous coal from different starting temperatures that can be used to study the reaction kinetics of the oxidation process at low temperatures. A new kinetic model is proposed that takes into consideration the

complex interaction between temperature and time as the coal self-heats from the oxidation reaction taking place (Arisoy A, Beamish B., 2015). This model can be used to explain the subtle difference between a coal that does not pose a spontaneous combustion problem and one that does.

The adiabatic test method has been extensively used to study the spontaneous combustion behavior of coals. The data obtained from testing a high volatile bituminous coal sample (HVHVB) from the Hunter Valley Coalfield of Australia is presented in **Fig. 9**. This test starts from 40 °C and ends at 125 °C. A plot of $\ln(dT/dt)$ versus $(1/T)$ clearly shows the non-linear nature of the reaction rate with temperature. If the reaction rate is in the Arrhenius equation, a reasonably straight-line fits the experimental results.

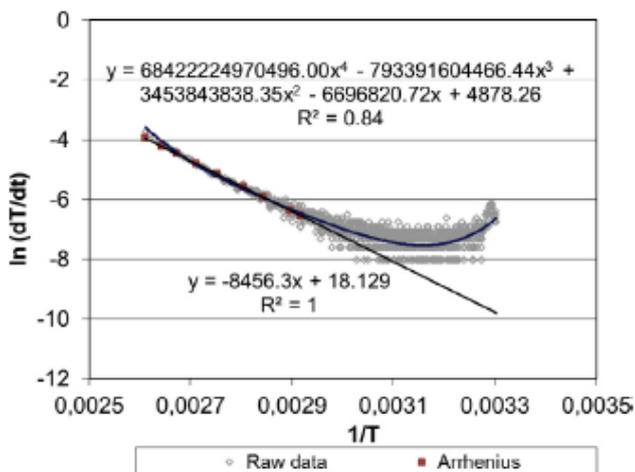


Figure 9 Reaction rate data for a high volatile bituminous coal sample (HVHVB).

A polynomial curve is a more appropriate fit to the data as shown. This curve indicates that the heating rate unexpectedly decreases initially before leveling out, and then remains constant for a period of time before increasing rapidly on the way to thermal runaway. At temperatures above 70 °C ($1/T = 0.0029$) the Arrhenius expression describes the specific reaction rate reasonably well as shown by the straight line added to **Fig. 9**.

7.1 Starting Temperature Effect on Reaction Rate of the Oxidation Process

The temperature of the fresh coal at the beginning of oxidation is defined as the starting temperature. In many mining situations, fresh coal in the mine is at a starting temperature that is below 40 °C. Depending on the starting temperature, the time to reach thermal runaway for the same coal can be quite different. The process and the reaction kinetics are influenced considerably by this parameter. Therefore, a realistic reaction rate expression should also take the starting temperature into account. A series of experiments were carried out on the same coal sample in the laboratory for the purpose of investigating starting temperature effect on self-heating rate. Duplicates of the coal sample were tested in an adiabatic oven at starting temperatures of 20, 30, 40, 50 and 57 °C.

Fig. 10 shows the self-heating curves obtained for different starting temperatures of the adiabatic oven tests **with the as-received moisture content removed**. As can be seen from this figure, a single curve and rate expression cannot be used for different starting temperatures.

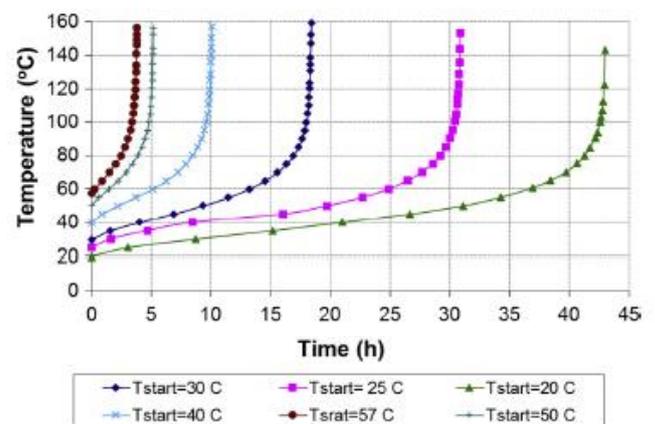


Figure 10 Adiabatic self-heating curves are given for a high volatile bituminous coal from different starting temperatures.

Figure 11 shows $\ln(dT/dt)$ versus $1/T$ plots for each test using a derived fourth order polynomial to fit the data. It can be seen

from **Figure 11** that above 70 °C, (the left-hand side of the plot), there is strong coincidence of the curves for all starting temperatures, with a reasonable degree of linearity. Below this temperature, there is a consistent differentiation between each of the start temperature curves. Therefore a single fourth order polynomial curve determined from the conventional adiabatic test cannot be used for different starting temperatures.

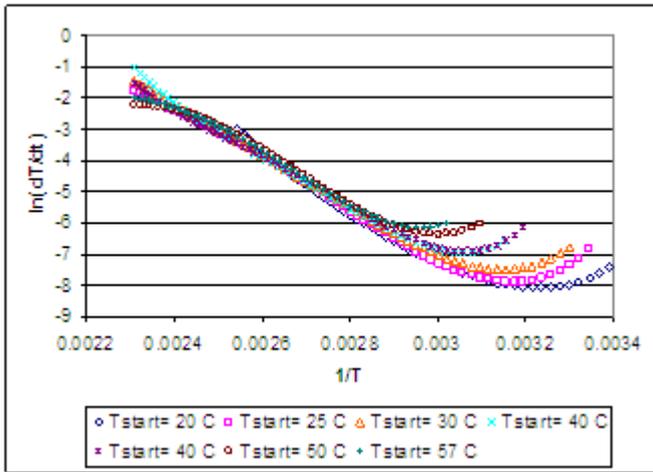


Figure 11 Fourth order polynomial curves which are fitted to the measured data of different starting temperature adiabatic oven tests for coal MACWHL.

7.2 The New Proposed Kinetic Model

The new kinetic model takes into consideration the interaction between coal temperature and the exposure time. This model also covers consideration the starting temperature effect and the non-Arrhenius behavior of the process. The final form of the proposed new kinetic model has been defined as follows:

$$\frac{d\rho_{ox}}{dt} = -A \cdot \exp\left(-\frac{E}{RT}\right) \cdot \left[a_{lim} + (1 - a_{lim}) \exp\left(-\frac{k_d}{a_{lim}} t\right) \right] \cdot \rho_{ox}$$

Both s and a_{lim} are functions of coal temperature.

8 APPLICATION OF SPONTANEOUS COMBUSTION PROPENSITY ASSESSMENT

8.1 Indexing From Coal Quality

This form of assessment is usually done at an early stage prior to coal samples being available for any testing. A range of index parameters can be applied from the literature. As shown in this paper a more encompassing predicted index value can be obtained for the R_{70} self-heating rate of the coal that covers a rank range from sub-bituminous C to low volatile bituminous. However, the variations due to mineral matter and coal type require samples to be tested to obtain true site-specific relationships and more realistic interpretations of spontaneous combustion propensity.

8.2 Mining Analogue Application

Knowing the intrinsic spontaneous combustion propensity of a coal with respect to other known coals is a good starting point to assess the risk of spontaneous combustion. Consequently, **Figures 3 and 4** also provide the opportunity to identify mining analogues that can be used to assist with future spontaneous combustion management planning. For example, Seam A (**Figure 4**) comes from a longwall mining operation in the Hunter Valley Coalfield of the Sydney Basin that has a history of self-heating events. Seam C (**Figure 4**) is from a Greenfield site in the Hunter Valley and consequently, spontaneous combustion management plans are already being developed from the test data obtained to date for proactive goaf inertization based on the mining analogy with Seam A. Other practices are also being developed in Australia to suit local conditions.

8.3 Modifying Influences on Spontaneous Combustion Risk

The modifying influences of other factors, such as coal start temperature, particle size and moisture content also need to be considered when assessing the meaning of an R_{70} value in terms of hot spot development. For example, Seam G is from a new longwall mining operation in the Newcastle District of the Sydney Basin. To date there has been no history of self-heating incidents, consistent with previous experience of mining this coal. Bulk testing of this coal also indicated a low propensity to develop a hot spot. Given the R_{70} rating of the coal (Class IV – high propensity) this appears to be anomalous. However, given the R_{70} test is a measure of the coals reactivity to oxygen at fine particle size, it must be remembered in bulk coal, hot spot development is dependent on a much larger particle size. Seam G has a very low Hardgrove Grindability Index (HGI). Consequently, production of a large volume of coal fines is reduced. Hence, hot spot development is inhibited as a result of this additional factor. There are other high R_{70} coals in the UQ database that are showing a similar relationship with HGI and this is being investigated in more detail.

The competing influences of coal start temperature and moisture content on hot spot development are best examined using numerical models. Preliminary work has begun using data from the R_{70} self-heating curves to extract kinetic parameters as input to a moist coal model (Arisoy et al., 2006; Arisoy et al., 2007). Further refinement of this work is in progress using data from coals in the UQ R_{70} database.

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