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LABORATORY EVALUATION OF VENTILATION EFFECTS ON SELF-HEATING INCUBATION BEHAVIOUR OF A HIGH VOLATILE BITUMINOUS COAL

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ABSTRACT: The concept of a “critical velocity zone” in the longwall goaf environment for the development of a spontaneous combustion event has been supported by numerical modelling. However, there is no experimental data available for Australian coals to show ventilation effects on the self-heating incubation behaviour of broken coal in the longwall goaf. Recent incubation testing has been completed on a high volatile bituminous coal with an R70 self-heating rate value of 3.86 °C/h and a moisture content of 11.3% using flow rates indicative of sluggish ventilation, natural air leakage ventilation and medium ventilation. At the higher medium ventilation flow rate, the coal initially self-heats to approximately 8 °C above mine ambient temperature, before heat loss from moisture evaporation dominates and the coal begins to decrease in temperature. Under the natural air leakage flow rate, the coal self-heats to 28 °C above mine ambient temperature before heat loss again takes over due to moisture evaporation. However, at the sluggish ventilation flow rate the coal is able to incubate to thermal runaway after an extended period indicative of a site equivalent timeframe of approximately 3 years. These preliminary results are consistent with the “critical velocity zone” for hotspot development. They also have implications for the concept of hotspot migration.

INTRODUCTION

The influence of mine ventilation on the possible location for the development of a spontaneous combustion event in a longwall mining environment is illustrated in **Figure 1** in terms of the presence of a “critical velocity zone” (Smith et al., 1994). This concept highlights that in the immediate face area adjacent to the goaf fringe the air velocity is too high for heat to accumulate, but as the distance increases into the goaf the air velocity decreases to a critical zone where there is insufficient heat dissipation and a sufficient supply of oxygen to support self-heating. Consequently, in the event of a prolonged face stoppage ideal conditions may be present to allow a caved coal pile to incubate to thermal runaway. Deeper into the goaf the atmosphere becomes too oxygen deficient to support self-heating. While numerical modelling (principally CFD modelling – Yuan and Smith, 2008; Song et al., 2017) has often been used in support of this concept, there is no experimental data available for Australian coals to show ventilation effects on the self-heating incubation behaviour of broken coal in the longwall goaf environment.

Laboratory experiments have been conducted on US coal samples using flow rates ranging from 100 to 500 mL/min and a sample mass of 150 g (Yuan and Smith, 2012). The flow to mass ratio used in these experiments is much too high to replicate site conditions, and causes evaporation to dominate the heat balance in favour of heat loss. Hence, they partially dried the coal samples prior to testing and heated the coal to a temperature in excess of 100°C to create a heat balance where heat gain could be achieved to produce thermal runaway. For the three US coals tested a different combination of flow rate and applied temperature increase was necessary for each coal to induce heat gain to thermal runaway. Consequently, practical demonstration and characterisation of ventilation flow rate effects are lacking, particularly with respect to the range of coals being mined in Australia.

Until recently, existing spontaneous combustion index tests have produced relative ratings of spontaneous combustion propensity. These tests do not provide any context of the self-heating behaviour in an actual mine environment and they do not indicate any timeframe for an event to occur under mine site conditions. However, a new adiabatic Incubation Test method is now available that

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overcomes these deficiencies (Beamish and Theiler, 2019) and makes it possible to replicate site-specific conditions including different mine ventilation flow rate scenarios. This paper presents the Incubation Test results for a high volatile bituminous coal using three different flow rates indicative of sluggish ventilation, natural air leakage ventilation and medium ventilation, where the natural air leakage flow rate is double the sluggish flow rate and the medium ventilation flow rate is double that again.

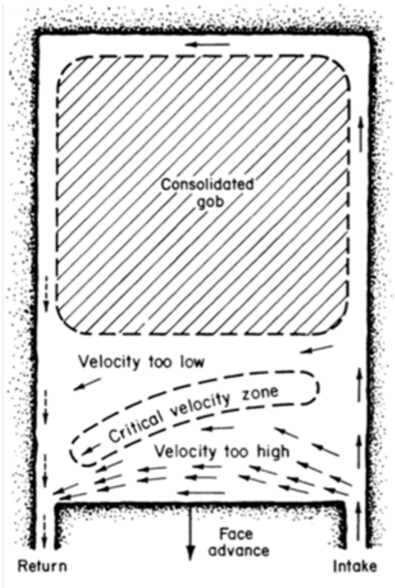

Figure 1: Schematic diagram of ventilation flow in the vicinity of the goaf fringe on a longwall face (from Smith et al., 1994)

SAMPLE DESCRIPTION AND ANALYTICAL DATA

The coal sample is from an underground mine in Australia and is high volatile B bituminous in rank. The mine has recorded minor heating events in the past, with minimal disruption to production. Proximate analysis, ultimate analysis and calorific value results for the coal are contained in **Table 1**.

Table 1: Analytical data for a high volatile bituminous coal sample

Proximate Analysis (air-dried basis)	
Moisture (%)	6.1
Ash (%)	5.2
Volatile Matter (%)	24.0
Fixed Carbon (%)	64.7
Total Sulphur (%)	0.32
Calorific Value (MJ/kg)	30.42
Ultimate Analysis (dry ash-free basis)	
Carbon (%)	85.7
Hydrogen (%)	4.43
Nitrogen (%)	1.92
Sulphur (%)	0.36
Oxygen (%)	7.6
ASTM Rank	hvBb

SELF-HEATING TEST PROCEDURES

Adiabatic oven R_{70} self-heating rate

Full details of the adiabatic oven are given in Beamish, Barakat and St George (2000). The sample to be tested is crushed and sieved to <212 μm in as short a time as possible to minimise the effects of oxidation on fresh surfaces created by the grinding of the coal. A 150 g sample is placed in a 750 mL volumetric flask and a unidirectional flow of nitrogen at 250 mL/min applied to the flask inside a drying oven. Precautions are taken to ensure the exclusion of oxygen from the vessel prior to heating the coal for drying. Hence, the air is flushed from the system at room temperature for a period of one hour. After one hour, the oven is ramped up to 110 °C and the coal is dried under nitrogen for at least 16 h to ensure complete drying of the sample. All R_{70} tests are performed on a dry basis to standardise the test results.

At the completion of drying, the coal is transferred into the reaction vessel and left to stabilise at 40 °C in the adiabatic oven with nitrogen passing through it. The reaction vessel is a 450 mL thermos flask inner. When the sample temperature has stabilised, the oven is switched to remote monitoring mode. This enables the oven to track and match the coal temperature rise due to oxidation. The gas selection switch is turned to oxygen with a constant flow rate of 50 mL/min. The temperature change of the coal with time is recorded by a datalogging system for later analysis. The oven limit switch is set at 160 °C to cut off the power to the oven, and stop the oxygen flowing when the sample reaches this temperature. When the oven cools down, the sample is removed from the reaction vessel, which is then cleaned in preparation for the next test. The results are used to classify the intrinsic spontaneous combustion propensity of the sample according to the rating scheme published by Beamish and Beamish (2011).

Adiabatic oven self-heating incubation

This test is designed to replicate true self-heating behaviour from low ambient temperature. As such, the normal in-mine temperature is used as the starting point for the test. The nature of the test also assumes that in the real operational situation there is a critical pile thickness present that minimises any heat dissipation (represented by the adiabatic oven testing environment) and there is a sufficient supply of oxygen present to maintain the oxidation reaction. A larger sample mass and lower oxygen flow rate is used, compared to the R_{70} test method, to produce conditions that more closely match reality (Beamish and Beamish, 2011). The sample either reaches thermal runaway, or begins to lose heat due to insufficient intrinsic reactivity to overcome heat loss from moisture release/evaporation and/or heat sink effects from non-reactive mineral matter. The results are used to characterise the self-heating incubation behaviour of the sample as well as quantify if thermal runaway is possible and if so, does this occur in a practical timeframe for the mine site conditions.

ADIABATIC SELF-HEATING RESULTS AND DISCUSSION

Intrinsic spontaneous combustion propensity

The R_{70} value for the coal sample is 3.86 °C/h as shown in **Figure 2**, which indicates an intrinsic spontaneous combustion propensity rating of high for Bowen Basin conditions or alternatively a rating of medium for Sydney Basin conditions. This rating does not take into account any moderating self-heating effect of the moisture content that is present in the coal since the R_{70} value is obtained on a dry basis with the moisture removed. Also, like the majority of spontaneous combustion index parameters, the R_{70} value does not provide any indication of the timeframe for a heating to develop to thermal runaway.

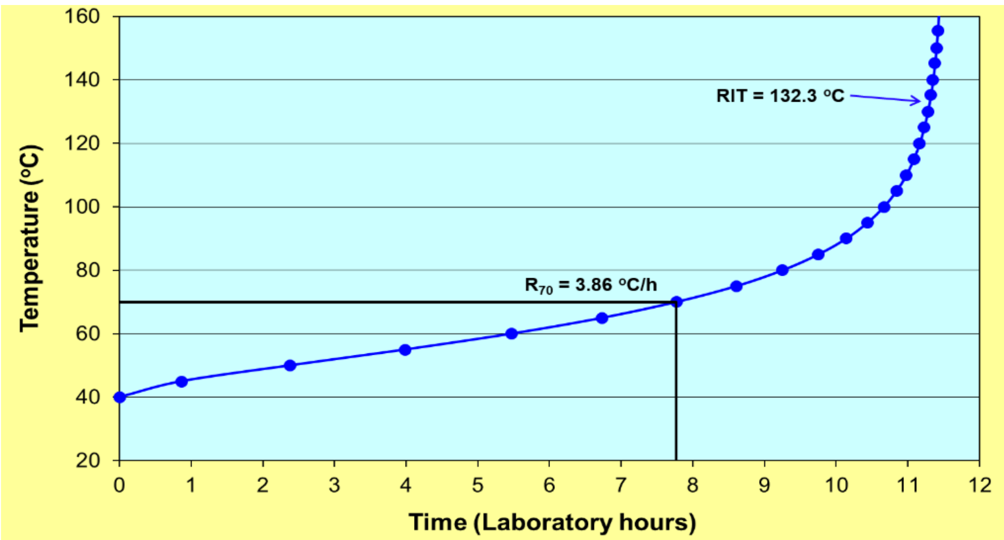

Figure 2: Adiabatic R_{70} self-heating rate results for a high volatile bituminous coal

Self-heating incubation behaviour under different flow rate conditions

Using a medium ventilation flow rate of 20 mL/min the coal initially self-heats from the start temperature of 27.0 °C in the Incubation Test as shown in **Figure 3**. However, it only reaches a maximum temperature of 35.2 °C before evaporative heat loss overcomes the heat released from oxidation. The laboratory hours obtained from the test have been converted to a site equivalent timeframe based on case study benchmark results, which indicates that it takes 8 days to reach the maximum temperature. After 48 days the temperature of the coal has dropped to 29.0 °C and it is apparent that no thermal runaway is possible under this ventilation scenario. When the flow rate is reduced by half to 10 mL/min, replicating natural air leakage, the coal again initially self-heats and reaches a maximum temperature of 55.0 °C in a site equivalent timeframe of almost 43 days as shown in **Figure 4**. Evaporative heat loss then takes over and the coal temperature falls to 45.0 °C after 102 days.

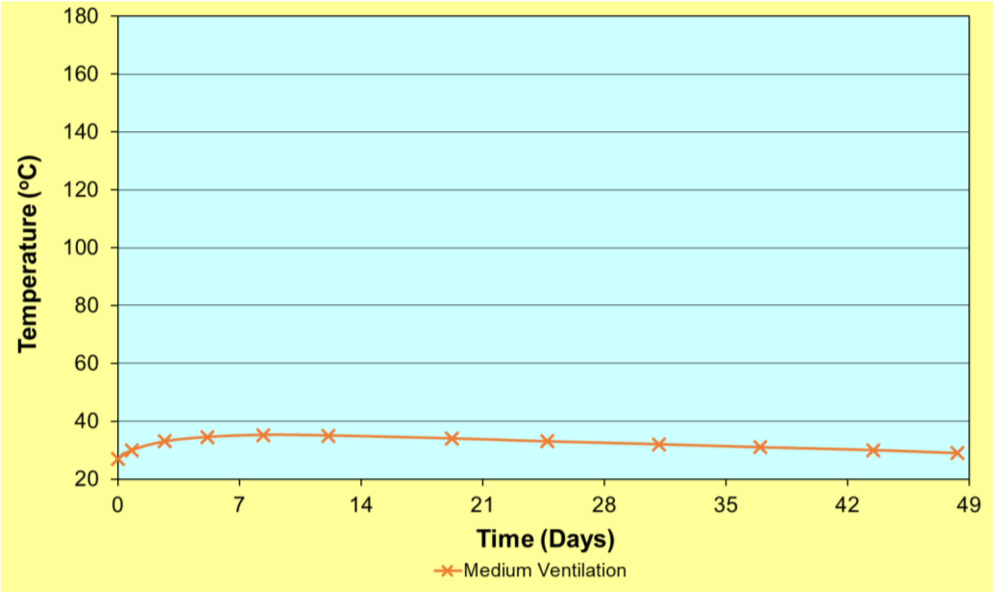

Figure 3: Adiabatic Incubation Test results for a high volatile bituminous coal under a medium ventilation flow rate

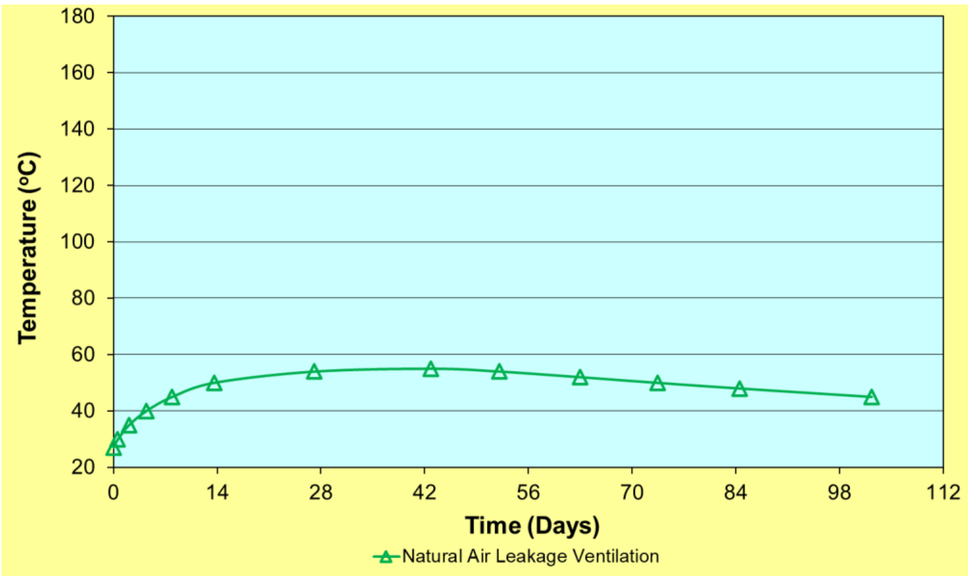

Figure 4: Adiabatic Incubation Test results for a high volatile bituminous coal under a natural air leakage flow rate

When the flow rate is reduced to 5 mL/min, replicating sluggish ventilation, the coal steadily self-heats to reach a temperature of 80.0 °C over a site equivalent timeframe of approximately 147 days as shown in **Figure 5**. Evaporative heat loss then reduces the self-heating rate for an extended period of time in the order of 890 days till the coal reaches 105.0 °C. Over the next 40 days the coal locally dries out and a well-defined hotspot develops that is then capable of self-heating and migrating to thermal runaway. The timeframe error bars shown in **Figure 5** are the minimum incubation period lower and upper limits for the coal under the sluggish ventilation flow rate conditions.

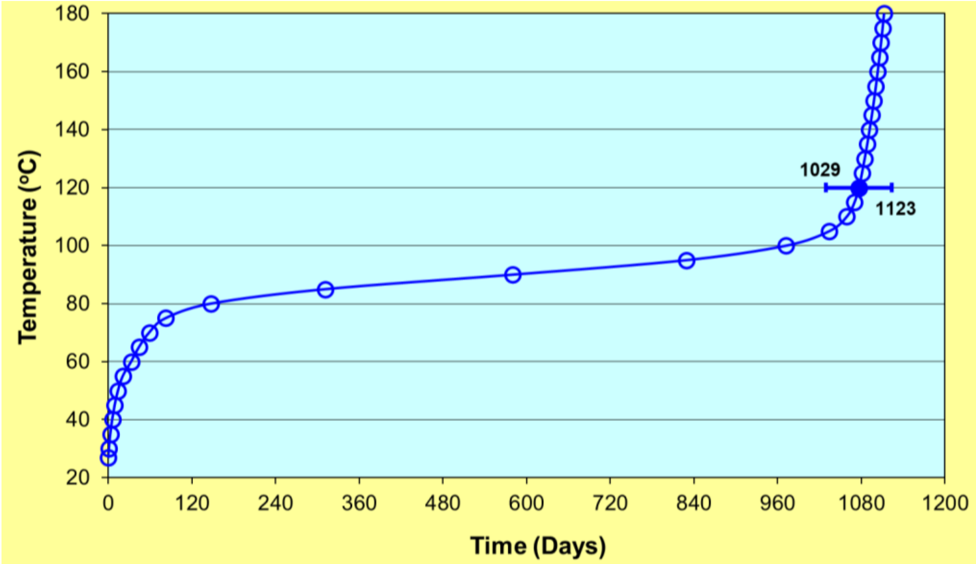

Figure 5: Adiabatic Incubation Test results for a high volatile bituminous coal under a sluggish ventilation flow rate

From the incubation test results it can be inferred that the critical velocity zone for a hotspot to develop into a heating event for this coal is where sluggish ventilation conditions occur. This would be at some distance in from the goaf fringe. In addition, once the hotspot has developed and reached a temperature in the order of 120 °C in the broken coal pile it would begin to migrate upwind and progressively move into a higher flow rate environment until such time as it reaches a free surface where ignition becomes possible. **Figure 6** shows the difference in thermal runaway behaviour created by the migrating hotspot, which is primarily related to greater oxygen availability in the higher flow rate environment. It can be seen that there is a rapid escalation in the hotspot temperature over a short period of time in the order of one to two days in the case of this particular coal once the hotspot begins to migrate.

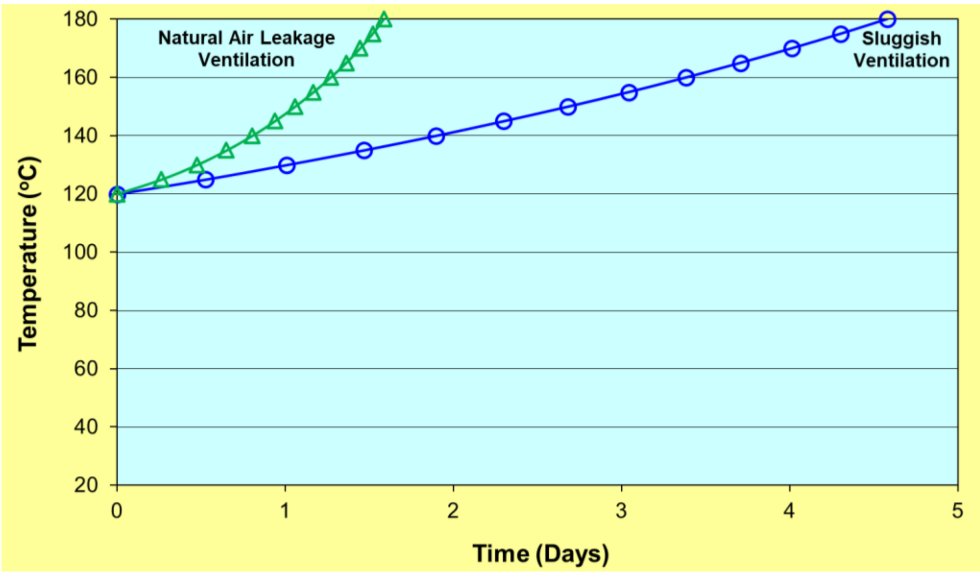

Figure 6: Adiabatic Incubation Test results for thermal runaway of a high volatile bituminous coal under sluggish ventilation and natural air leakage ventilation flow rates

CONCLUSIONS

Testing of a high volatile bituminous coal sample using the adiabatic Incubation Test procedure has confirmed that a "critical velocity zone" exists where the flow rate conditions are ideal for a hotspot to develop from coal self-heating. For the intrinsic reactivity and moisture content of this coal it can be seen that a sluggish ventilation flow rate condition creates the ideal environment for self-heating to incubate and progress to thermal runaway. The location of the hotspot development would need to be a considerable distance in from the goaf fringe, otherwise heat dissipation created by higher flow rate conditions would enable evaporative heat loss to dominate and prevent the coal from reaching thermal runaway. As long as the longwall face continues to retreat, this goldilocks zone would not be an issue for this particular coal as the minimum incubation period is in the order of 3 years. However, if this coal were present in older workings of a bord and pillar operation the likelihood of developing a spontaneous combustion event would be increased if the workings were kept open for an extended period of time under a sluggish ventilation regime.

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