

# Results of Self-Heating Tests of Australian Coals Conducted in a 16 m<sup>3</sup> Reactor

F Clarkson<sup>1</sup>

## ABSTRACT

A research and testing facility has been developed at Simtars to allow the spontaneous combustion testing of coal on a large scale. In this adiabatic reactor, the coal particle sizing is closer to that which could be found in the goaf and therefore the reaction is more likely to simulate the underground situation. This allows aspects of the spontaneous combustion process and methods for detecting a heating to be investigated which cannot be done in an operational mine. Up to 18 tonnes of run of mine or crushed coal is loaded into the reactor and allowed to self-heat while the temperature and gas profiles within the coal pile are monitored. The gases evolved from the coal are analysed using a fixed gas monitor system and gas chromatography to determine which of the common mine fire indicators and ratios can be used to predict the onset and progress of coal heatings. Benchmarking of the inherent propensity of a coal to spontaneously combust at both the large- and laboratory-scale is also possible by comparing the sample against previously tested samples.

It has been found that the coal particle size affects both the time it takes for the coal to react and the location of the developing heating. The heatings generate approximately one metre from the inlet but in the crushed coal case do not progress to an advanced heating stage until the 'hot spot' migrates towards the coal surface where there is an increased oxygen supply. Physical properties such as the compressive strength of the coal also affect the heating size and the time it takes for a heating to develop. Higher strength coals appear to oxidise more slowly and therefore take longer to self-heat as oxidation of the coal is the heat-generating step in the spontaneous combustion process.

The best indicators of the state of the heating were found to be CO make and Graham's ratio which are independent of air flow. Investigation of a potential spontaneous combustion should begin as soon as the CO make or Graham's ratio exceed the background levels. The results from the tests undertaken on a number of Queensland and NSW coals are reported here together with the implications for the mining industry.

## INTRODUCTION

Large-scale testing of coals aimed at gaining a better understanding of the processes involved in spontaneous combustion have been undertaken around the world for over a hundred years. The mass of coal used in recent tests has ranged from one to five tonnes of dry ground coal (Chauvan, Lodel and Philippe, 1985) in the Centre d'Etudes and Recherches de Charbonnages de France (CERCHAR) tests, ten tonnes in the Safety in Mines Research Station at Buxton in the UK (Mason and Tidswell, 1939), to 13 short tons of coal in the United States Bureau of Mines (USBM) tests (Smith, Miron and Lazzara, 1991). These reactors have been used to study the heating profiles of various coals enabling assessment of the risk of spontaneous combustion in a mine, during transportation, in stockpiles and development of mathematical models in the case of the CERCHAR tests. The detection of heatings by smell and by monitoring of carbon monoxides levels were investigated in the Safety in Mines Research Station tests at Buxton. The dependence of self-heating on coal reactivity, particle size, freshness of the coal surface, heat of wetting, and availability of oxygen were studied in the USBM tests.

The 16 m<sup>3</sup> adiabatic reactor Simtars has been developing for the last eight years is similar to the USBM reactor and requires 16 to 18 tonnes of coal depending on the particle size of the test coal. Early tests in the Simtars reactor involved three coals from mines with known histories of spontaneous combustion in Queensland and New South Wales. These tests showed that although initial self-heatings were achievable, they did not proceed to thermal runaway due to heat losses from the reactor. Successful heatings were however obtained when the coal was artificially stimulated using a buried heating element.

Following installation of an insulated cover, a further five tests were undertaken on three New South Wales and two Queensland coals in order to investigate the effect of particle size, oxidation rate and initial coal temperature on the development of a heating. Analysis of the exhaust gas stream and also gases from selected sites within the coal pile was conducted to investigate the effectiveness of mine gas ratios currently used in Australia to detect a spontaneous combustion event.

## EXPERIMENTAL

The apparatus described here is the current unit, which has been developed from the original reactor that had no thermal cover and only nine gas sampling ports. Details of the original reactor design were included in the final report for ACARP Project C5031 (Cliff *et al*, 2000b). Approximately 15 - 18 tonnes of run of mine or crushed coal were arranged in a pile 2 m wide, 2 m high and 4 m long between the two block walls of the reactor (Figure 1). One-metre long plenum chambers were established on both ends of the coal test section for uniform circulation of air through the coal. Two steel grids were used to separate the plenum chambers from the section of the reactor where coal was held. Air was passed from one end to the other of the sealed reactor with a nominal internal air flow up to 100 L/min in order to allow the coal to dry out without excessive oxidation.

Gas analyses were conducted using a fixed O<sub>2</sub>, CO, CO<sub>2</sub> and CH<sub>4</sub> monitor in addition to periodic analysis by gas chromatograph on samples taken from up to sixteen gas sampling tubes inserted into and across the central axis of the reactor and also the exhaust gas outlet (Figure 2).

Five layers each of 50 thermocouples were used to monitor the temperature profiles throughout the pile. The distance between any two thermocouples in the pile was 0.4 m. In addition the inlet and exhaust pipes of the plenum chambers are instrumented to determine the airflow and humidity. A data acquisition system was used to monitor both thermocouple readouts and the inlet and exhaust readouts for this project.

The current apparatus also includes a thermal cover to reduce the heat losses thus simulating a larger body of coal and facilitating the self-heating of the coal. The air space was heated using a recirculated air system, which included a blower and inline heater. Heating the air space formed meant that the equivalent ambient temperature could be controlled thus increasing the chances of a natural self-heating in the test coal. A second blower fed fresh air directly to the inlet plenum via a heat exchange box in the cover air space to ensure the inlet air temperature matched the temperature of the air space surrounding the coal.

1. Simtars, PO Box 467, Goodna Qld 4300.  
Email: fiona.clarkson@nrm.qld.gov.au

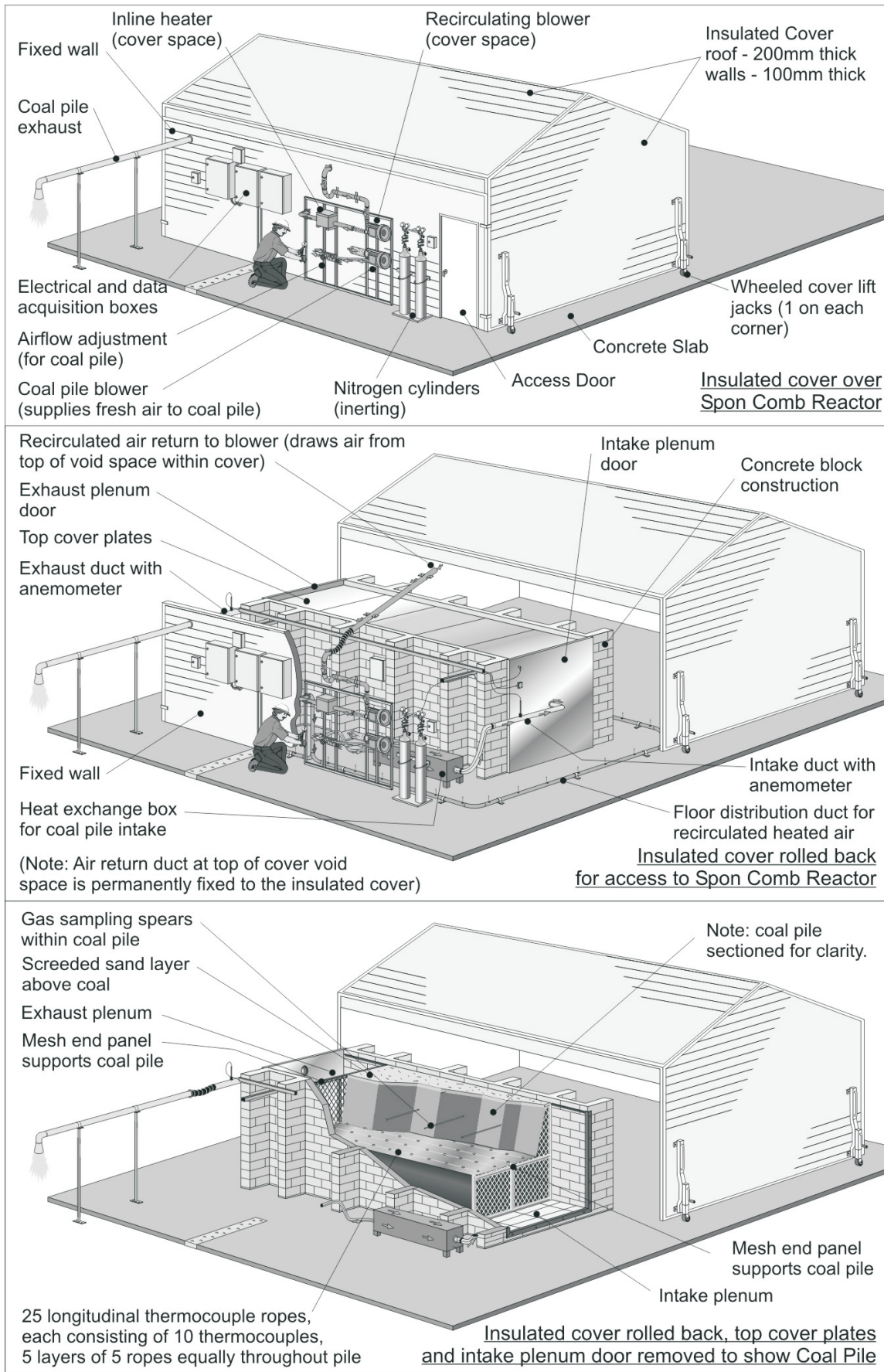


FIG 1 - Schematic of 16 m<sup>3</sup> reactor.

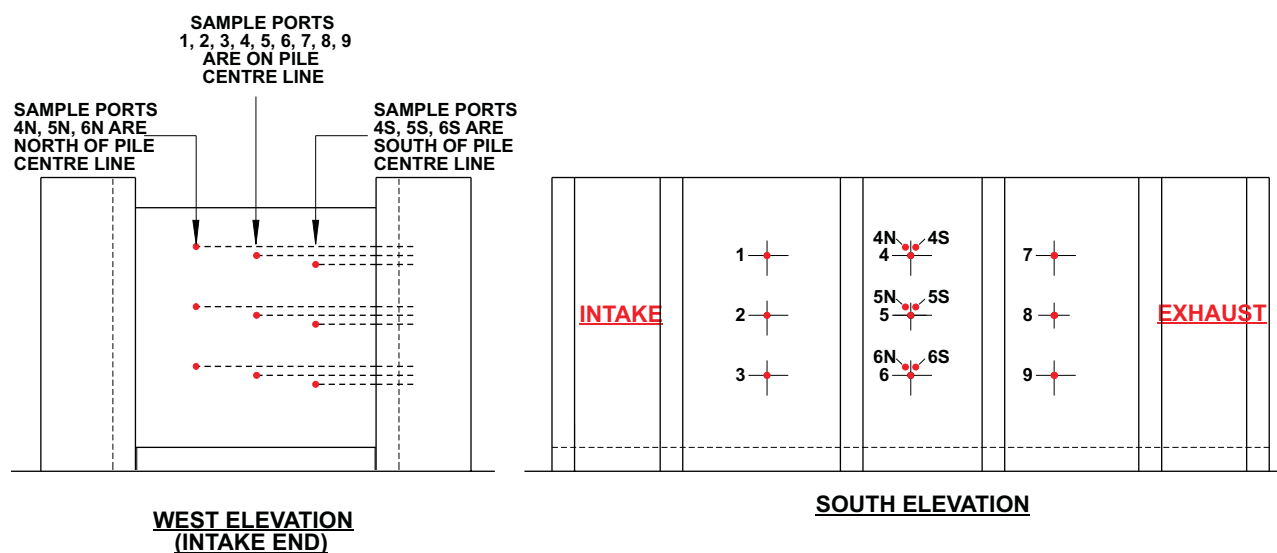


FIG 2 - Coal pile sample tube location and identification.

## RESULTS AND DISCUSSION

### Tests without a thermal cover

One sample of Moura D and two samples of Dartbrook coal were allowed to self-heat for varying periods with airflows as outlined in Table 1. Full details of these coals and the test results were reported in the final report for ACARP Project C5031 (Cliff *et al*, 2000b).

The initial heating of the Moura D sample was affected by heat losses due to the seasonal ambient air temperature, which could vary from 4 to 24°C during the day. Installation of a fan heater in the inlet plenum chamber stabilised the inlet air temperature allowing a maximum temperature of 56°C to be reached after 64 days. Further attempts to reduce the heat loss resulted in the peak pile temperature falling more than 20°C over a 12 day period. The self-heating phase was terminated at this point after 77 days and the buried heater element used to stimulate a heating.

The stimulated heating phase ran for a further 20 days while the temperature of the buried heater element was gradually increased from 80°C to 450°C over a nine day period in line with temperature increases in thermocouples up wind of the element. An intense smell of 'fire stink' was detected in the area close to the reactor at day 97, four days after the heating element was switched off. Infrared images of the exposed coal in the inlet plenum chamber showed the hot spot had migrated to the inlet coal face, reaching a maximum temperature of 488°C. The heating generated was finite in size decaying rapidly in temperature with distance from the inlet. The nearest thermocouple 200 mm downwind from the hotspot measured a coal temperature of only 212°C.

The Dartbrook 1 sample was allowed to self-heat for 36 days attaining a peak temperature of 36.2°C after 26 days. The self-heating phase of the test was terminated after 36 days when the peak pile temperature fell to 34.5°C when the airflow through the pile was increased at day 29 in an attempt to promote moisture removal from the coal.

The stimulated heating phase of the test ran from days 36 to 54 of the test. During the nine days the buried heater unit was held at 200°C, the coal pile peak temperature only increased to 68.1°C. The buried heater set point was then increased at day 44 to 400°C and held at this temperature until day 51. A hot spot with a temperature of 568°C developed in the third layer at the centre of the southern wall three days later. Smoke was visible at the exhaust pipe and a petrol smell was also detectable. This hot spot behaviour was very similar to the previous Moura sample, in size and behaviour.

**TABLE 1**

*Details of self-heating, without a thermal cover.*

Coal	Duration of self heating (days)	Air flow (L/min)	Maximum temperature (°C)
Moura D	77	93 - 450	56.0
Dartbrook 1 (NSW-D1)	36	56 - 403	36.2
Dartbrook 2 (NSW-D2)	51	155 - 334	63.9

The crushed Dartbrook 2 (NSW-D2) sample was allowed to self-heat for 51 days attaining a peak temperature of 63.9°C after 36 days. The self-heating phase of the test was terminated after 51 days when the peak pile temperature fell to 62.3°C. Experience gained from the previous tests had shown that a consistent drop in temperature was characteristic of heat losses to the surroundings exceeding the heat generated by the oxidation process. Further evidence to support this conclusion was obtained by monitoring the gases from the reactor exhaust, which indicated that the coal pile was in a steady state with no sign of self-heating occurring.

The stimulated heating phase of the test ran from days 51 to 85 of the test. The buried heater element was held at 400°C for 16 days and then increased to 500°C for a further five days before the buried heater was switched off. Infrared images on day 85 of the exposed coal in the inlet plenum chamber showed that a hot spot with a maximum temperature of 357°C had developed at the inlet coal face. As was found with the previous tests, the hot spot was relatively confined and inclined to move upwind to the exposed coal surface (Figure 3).

Analysis of the gas from the exhaust by gas chromatography (GC) found that no ethane or ethylene could be detected during the self-heating phase of these tests. Carbon dioxide was found to be present as seam gas and in the case of the Dartbrook samples methane was also present. Carbon monoxide levels when detectable were of the order of 5 - 15 ppm. Overall, the gas evolution data indicated that no exponential self-heating was occurring during the self-heating phase.

During the stimulated phase of the testing, hydrogen, ethane and ethylene were in general not detected in the reactor exhaust gas stream until the final day of each test when the hot spot reached the inlet coal face where the oxygen supply was unrestricted. Carbon monoxide and carbon dioxide levels showed significant increases during the last few days of the test which are characteristic of exponential thermal runaway.



**Tests with a thermal cover**

An insulated cover was installed over the reactor to reduce the heat losses to the environment and facilitate self-heating. Two samples of Dartbrook coal (NSW-D3 and NSW-D4), a Newcastle region coal (NSW-M1) and two Queensland coals from the Bowen Basin (QLD-BB1, QLD-BB2) were allowed to self-heat for varying periods with air flows as outlined in Table 2. Full details of these run of mine coals and the test results were previously reported as follows, Dartbrook coal samples NSW-D3 and NSW-D4 in the final report for ACARP Project C5031 (Cliff *et al*, 1998, 1999, 2000a, 2000b; Clarkson and Davis, 2000), NSW-M1 in Appendix A of ACARP Project C10015 (Clarkson, 2004). QLD-BB1 has not previously been reported. QLD-BB2 is to be included in the report for ACARP Project C12018.

The crushed Dartbrook 3 (NSW-D3) sample was allowed to self-heat without assistance from the buried heater element. Although the NSW-D3 sample exceeded both the maximum temperature of the NSW-D2 test and the so called 'critical' 70°C mark, achieving a temperature of 147.3°C after 131 days, the reaction did not proceed to thermal runaway as had been

predicted. Beyond this point the maximum coal pile temperature showed a stepped behaviour consistent with the heating migrating past the thermocouples towards the inlet coal face where the oxygen supply was less restricted than in bulk of the reactor (Figure 4). A peak temperature of 221.6°C was attained after 172 days when the hot spot migrated to within 1 m of the inlet face. The test was terminated at this point as the oxygen demand exceeded the volume able to be supplied by the blower units (Cliff *et al*, 1999).

The run of mine Dartbrook 4 (NSW-D4) sample was also allowed to self-heat and was terminated after 149 days due to the exponential increase in maximum pile temperature which reached the order of 25°C/h (Clarkson and Davis, 2000). In this instance, the 261.8°C hot spot generated approximately 1 m from the inlet and tended to migrate vertically rather than horizontally probably due to the heat flux warming the coal above the initial hot spot, in the presence of surplus air (Cliff *et al*, 2000b).

The removal of moisture from the coal was considered to be the rate-limiting step in the self-heating process for both these samples.

**Dartbrook 2 Day 85**

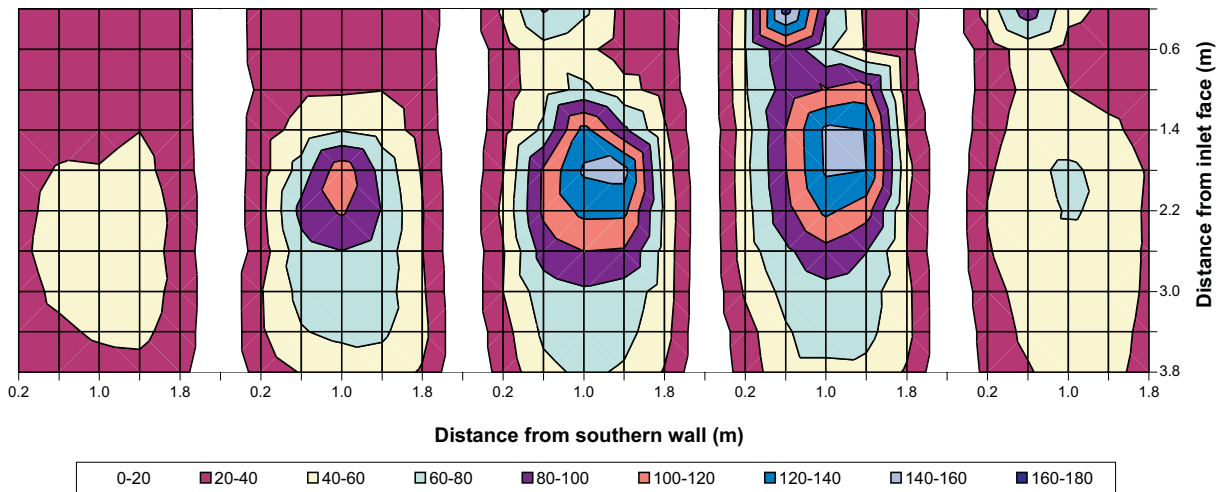


FIG 3 - Simulated heating layer temperature distribution of Dartbrook 2.

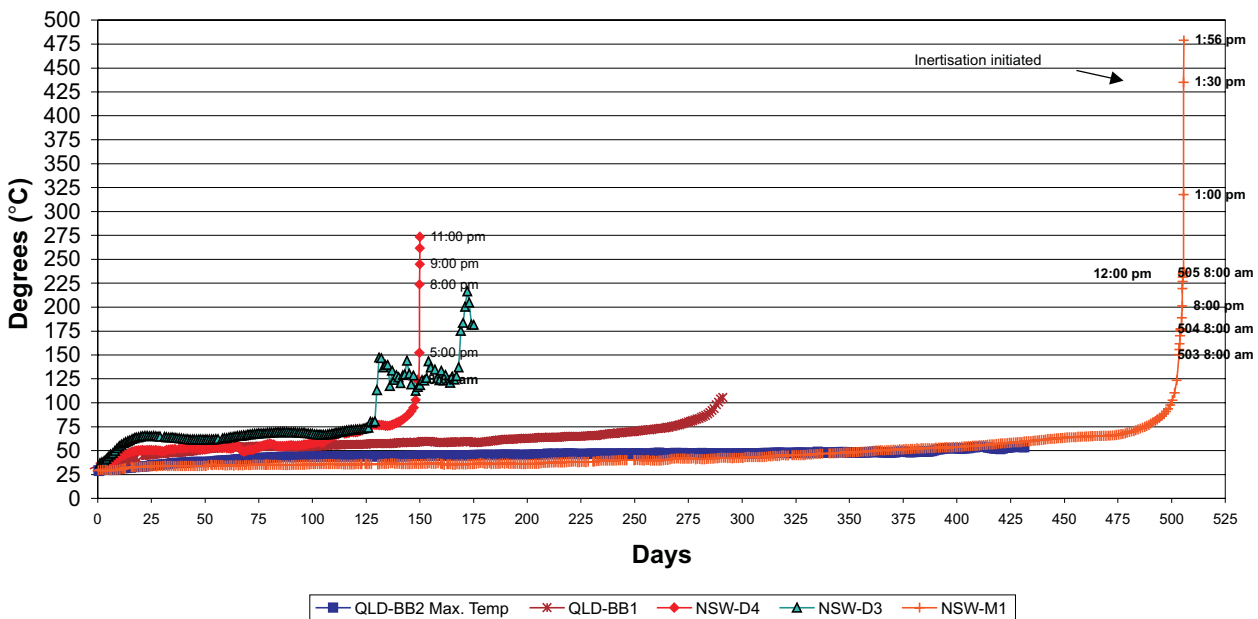


FIG 4 - Heating profiles coal with thermal cover.

Gas samples collected from up to ten ports including the exhaust in the NSW-D3 reactor test and 16 ports in the NSW-D4 test allowed the progress of both heatings to be monitored by GC. The effectiveness of the current mine gas indicators of spontaneous combustion were evaluated and compared to the small-scale tests (Figure 5). The results of these two tests are summarised in Table 3 (Cliff *et al*, 2000a).

The run of mine Bowen Basin sample, QLD-BB1, was allowed to self heat for 289 days attaining a maximum temperature of 100.7°C before being sealed in an attempt to slow the reaction for operational reasons. The reactor was reventilated 13 days later with an airflow of approximately 100 L/min. The peak coal pile temperature fell from 94.1°C to 71.6°C over the following 15 days (day 317). The test was terminated on day 352 at a

maximum pile temperature of 76.7°C, as the coal appeared to be reaching an equilibrium temperature with the cover temperature. At the request of ACARP the buried heater element was used to stimulate the heating from day 371. Within two days of the buried heater element being set at 400°C, the temperature of the surrounding coal had increased from 55.4°C to 100°C. Approximately 400 mm upwind of the buried heater element the coal temperature only increased by 0.5°C over the same time period. Six days later (day 379) the thermocouple at this point registered a temperature of 94.6°C, which escalated over the next 11 hours to 251.8°C.

The run of mine Newcastle region sample, NSW-M1 was allowed to self-heat for an extended period of time. The test was terminated after 506 days when an exponential increase in maximum pile temperature to 435.2°C was observed as the heating burnt through the insulation on a thermocouple strand. The peak temperature rose from 236.9°C to 435.2°C in an hour when the intake airflow was increased to approximately 1200 L/min for a period of less than four hours. The hot spot in this case generated approximately 1.22 m from the inlet, being located on the northern most thermocouple strand between the fourth and third thermocouples of the third layer. Coal samples retrieved from this area show signs of charring and loss of volatiles (Clarkson, 2004) (see Figure 6).

Compared to the previous tests, which had 'point source' heatings, the NSW-M1 heating involved a considerable volume of coal. Clarkson (2004) reported that in the NSW-D4 heating, the area involved at an advanced stage in the heating was

**TABLE 2***Details of self-heating, with a thermal cover.*

Coal	Duration of self heating (days)	Air flow (L/min)	Maximum temperature (°C)
Dartbrook 3 (NSW-D3)	172	42 - 115	221.6
Dartbrook 4 (NSW-D4)	149	48 - 483	261.8
Bowen Basin 1 (QLD-BB1)	289	54 - 115	100.7
Newcastle Region (NSW-M1)	506	38 - 115, 150 - 1204	435.2
Bowen Basin 2 (QLD-BB2)	384	84 - 111	49.1

**TABLE 3***Summary of experimental results.*

Observation	Crushed sample	Run of mine sample
Exponential temperature rise	No stepped increase initially	Yes
Time taken to initiate self-heating	172 days to thermal runaway	149 days to thermal runaway
Comparison with small-scale	Good at hot spot, deviation further away	Excellent correlation
Odour	Consistent with small-scale tests – not fire stink	Consistent with small-scale tests – not fire stink
CO make	Est 0.5 L/min at 120°C Est 1.0 L/min at 200°C	1.2 L/min at 120°C, 2.58 L/min at 200°C
Size of hot spot	Approx 400 mm in radius	Approx 400 mm in radius
Location of hot spot	Middle layer, at inlet face	Middle layer, 1 m from inlet

### Small-Scale Testing

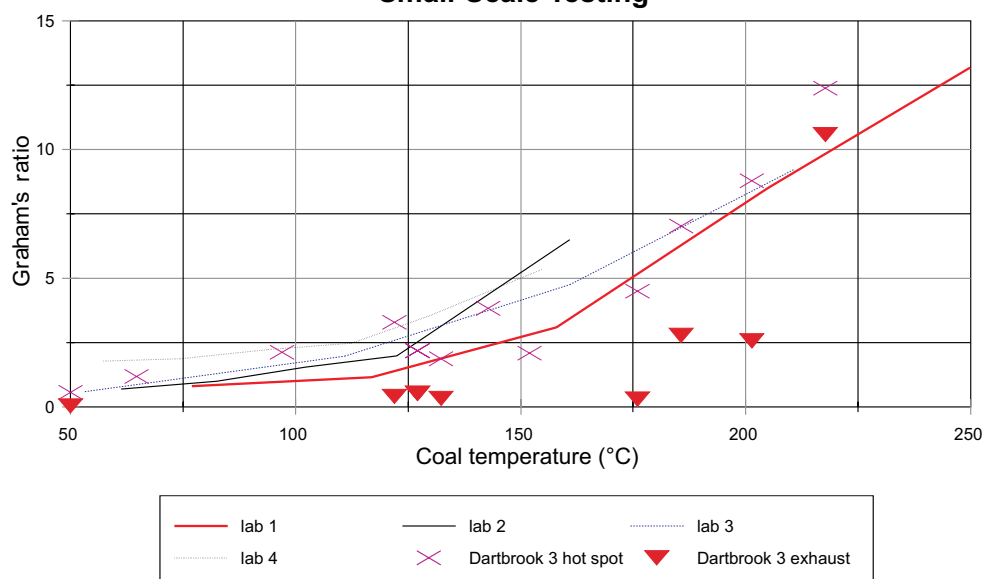


FIG 5 - Comparison of Graham's ratios from the Dartbrook 3 large-scale reactor test with small-scale (laboratory) testing results.

localised (ie the diameter of the area above 100°C was estimated to be 800 mm to 1200 mm and that above 200°C only a few hundred millimetres). In the case of the NSW-M1 coal, the area above 100°C was ellipsoid in shape with a width up to 1600 mm and length of up to 2400 mm. The area above 200°C was a 'U' shaped band and extended over at least 4 × 400 mm grids.

The coal in the reactor was inerted using nitrogen but although the peak temperature dropped to less than 260°C within a few hours of the nitrogen injection, 14 days later a large volume of the coal continued to exhibit temperatures ranging from 100°C to 179°C. Further injections of nitrogen into the reactor via the gas sampling ports had limited success in inerting the reactor. On day 530, water was eventually used to cool the coal, which still exhibited temperatures as high as 172°C even though the thermal cover had been removed as part of the initial inertisation and shut down procedure 25 days earlier.

Based on the results of the previous testing and a moderate to high rating from the small-scale tests, this sample had been expected to take eight to nine months to react. There are several factors, which could have influenced the heating time line. The seam from which this coal originated is now known to have a tight cleat structure and high compressive strength compared to

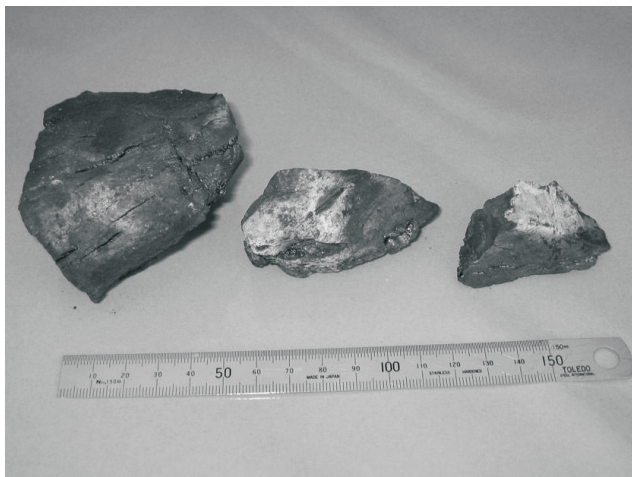


FIG 6 - Heat affected coal samples from near main heating site.

the Queensland QLD-BB1 sample, which had a low reactivity from the small-scale tests. It is possible that the high compressive strength of the NSW-M1 coal reduced the rate at which oxygen was able to penetrate the coal thus reducing the rate of oxidation, which is the heat-generating step in a spontaneous combustion event.

However the major factor in the longer heating time is now believed to be the start temperature of the test. It has been reported by Clarkson (2004) that the high reactivity NSW coal samples took between three and nine days to reach a maximum temperature of 40°C while the low reactivity Queensland coal, QLD-BB1, took 15 days to reach 40°C. By comparison the NSW-M1 coal sample took 242 days, eight months to reach 40°C and a further 263 days to complete the test (Figure 4). The time from 40°C to completion was just under nine months, which correlates with the original eight to nine month timeframe expected for the test.

During the self-heating phase of the NSW-M1 sample monitoring of the gases within the reactor showed that no methane or ethane were present as seam gas after 71 days. Carbon dioxide was however present, increasing with distance from the inlet, measuring 0.11 per cent 1 m from the inlet and 0.34 per cent, 3.2 metres from the inlet. Carbon monoxide levels throughout the reactor were only a few ppm until the coal began to dry out. The carbon monoxide levels measured 1 m from the inlet began to rise from a background of 2 - 3 ppm after 100 - 125 days. Deeper into the pile at the gas ports located 2 m from the inlet, the levels of carbon monoxide were not observed to begin to rise for approximately 200 days.

The CO/CO<sub>2</sub> and Graham's ratios were again found to be the best indicators of the state of the heating. Loss of carbon monoxide due to conversion to carbon dioxide or reabsorption onto the coal as it traversed the coal pile results in the severity of the heating being underestimated when measured in the exhaust (Figure 7).

Comparison of the gas ratios from the large-scale test results with that of the small-scale tests shows reasonable agreement of the Grahams ratio from both tests although the large-scale test results tend to slightly overestimate the degree of heating (Clarkson, 2004). In the case of the large-scale CO/CO<sub>2</sub> results, there is good agreement to approximately 100°C but thereafter the ratio severely underestimates the state of the heating (see Figure 8).

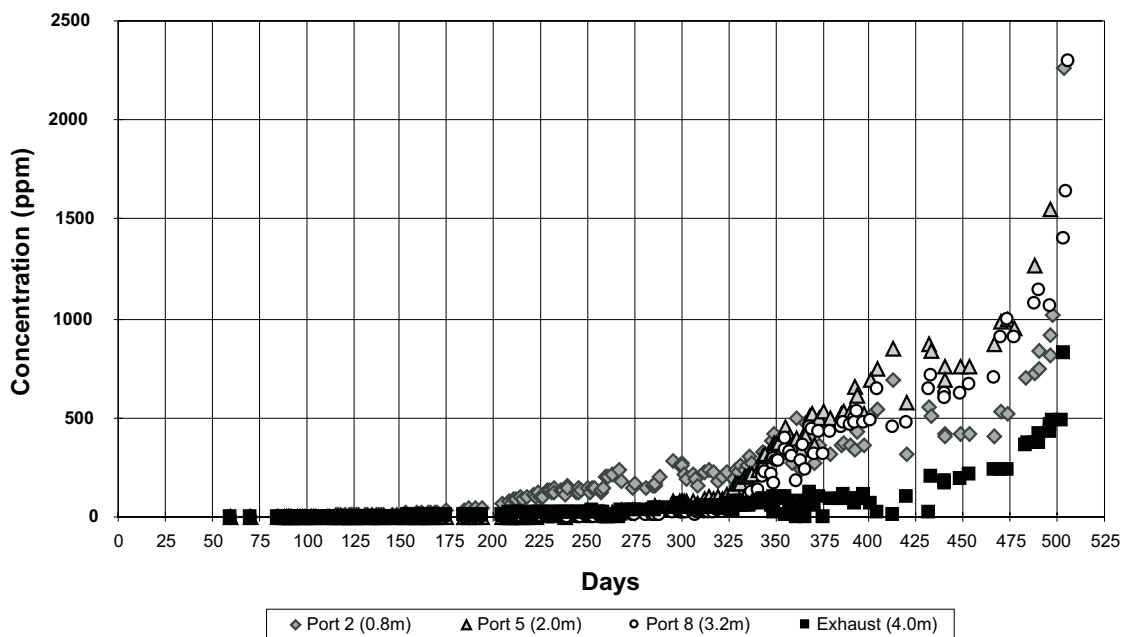


FIG 7 - Carbon monoxide profile of NSW-M1, shown full scale.

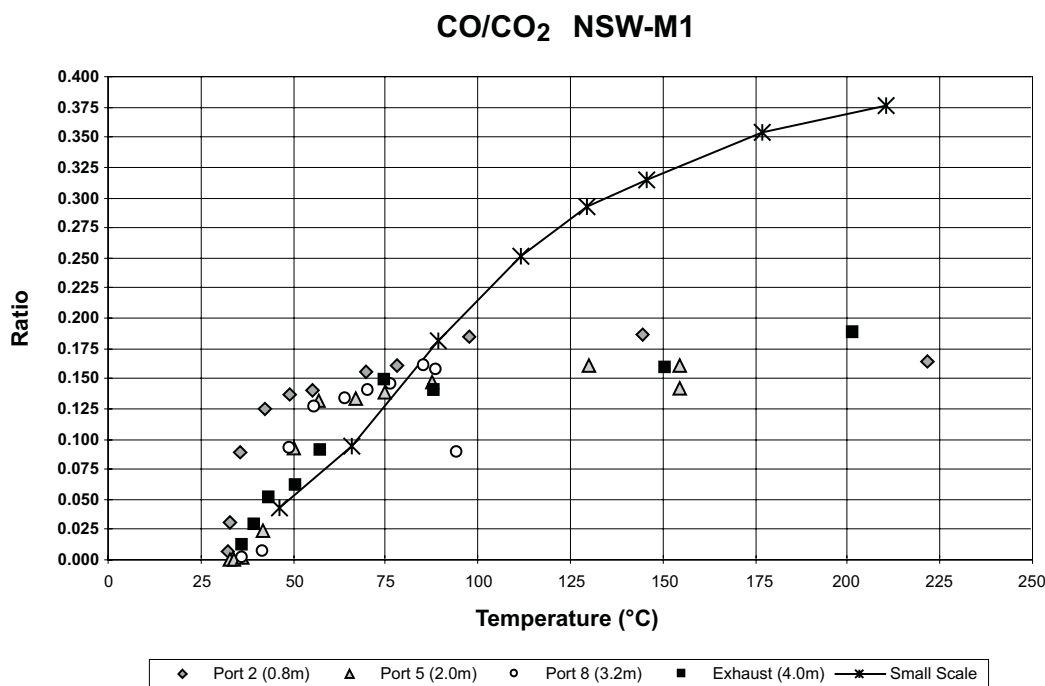


FIG 8 - Comparison of CO/CO<sub>2</sub> ratio from large-scale reactor with small-scale test results.

The run of mine Bowen Basin sample, QLD-BB2, was allowed to self-heat for 384 days attaining a maximum coal pile temperature of 49.1°C. Attempts were then made to further encourage the development of the heating by setting the cover temperature above that of the coal edge temperature. The temperature of the inline heater for the recirculated air system was raised by 16°C over the next four days resulting in an increase in the cover temperature from 48.5°C to 54.6°C over the 12 days to day 396. Over the period of day 384 to day 410, the maximum coal pile temperature rose to 53.9°C in response to the heating stimulus. The test was terminated at day 429 with a maximum pile temperature of 53.9°C.

The QLD-BB2 sample had been expected to take of the order of nine to ten months to self-heat as it had come from the same seam as the QLD-BB1 sample. Small-scale testing of the QLD-BB2 sample including the Proximate and Ultimate analysis had characterised the large-scale sample as having a coal profile and spontaneous combustion potential typical of the originating seam, hence the predicted ten month time frame. The initial start temperature of this test was 29.6°C, which was almost identical to that of the NSW-M1 sample. In this instance the sample took 60 days to reach the 40°C mark. The low start temperature appears to be critical in the prolonged heating time of both the NSW-M1 and QLD-BB2 samples. By comparison the NSW-D3, NSW-D4 and QLD-BB1 had start temperatures of 36.7°C, 31°C and 33.1°C respectively having been started in late summer whereas the NSW-M1 and QLD-BB2 samples were started in early summer and late spring respectively. The implications from this for an underground mine are that the ground temperature may significantly influence the tendency to spontaneously combust with increasing ground temperature increasing the likelihood that a given coal will self-heat.

## CONCLUSIONS

Extrapolation of large-scale tests to the underground mine situation indicates that the ground temperature of the mine will significantly influence the tendency of the coal to spontaneously combust.

Heatings may be localised involving only a few tonnes of coal however more extensive heatings can develop. These heatings

will be harder to inert and keep inerted as the mass of hot coal acts as a long-term heat reservoir even after oxygen has been excluded due to the inherent insulating properties of the coal.

Graham's ratio, CO/CO<sub>2</sub> ratio and CO make are the best indicators of the state of a heating. These ratios can however underestimate the state of the heating where monitoring is remote from the site of the heating.

Investigation of a potential heating should begin as soon as ratio levels significantly exceed the background levels. Using standard values as action levels is meaningless.

Significant changes in oxidation products such as carbon monoxide, hydrogen, ethane and ethylene may only be measurable at an advanced stage of the heating.

Goaf monitoring needs to be carried out as comprehensively as time and resources allow so that all potential heating sites are monitored as close to them as possible. Heatings can only occur where there is sufficient oxygen, the coal is dry and the heat balance is in favour of heat retention (Cliff *et al*, 2000b).

## ACKNOWLEDGEMENTS

The contributions of Simtars staff past and present to this project is gratefully acknowledged. The permission of the Director of Simtars, Stewart Bell to publish this paper is also gratefully acknowledged. This work was supported by ACARP, Anglo Coal and the Centennial Coal Company Limited.

## REFERENCES

- Chauvan, R, Lodel, R and Philippe, J L, 1985. Spontaneous combustion of coal, in *Safety in Mines Research: Proceedings of the 21st International Conference of Safety in Mines Research Institutes*, (ed: A R Green) pp 465-473 (A A Balkema: Rotterdam).
- Clarkson, F, 2004. Detection of heating of coal at low temperatures, Interim report, Australian Coal Association Research Program, Project C10015 (ACARP: Brisbane).
- Clarkson, F and Davis, R, 2000. Spontaneous combustion early indicators, in *Proceedings NSW Mining Industry Occupational Health and Safety Conference: Safe Healthy Mining Business 2000*, pp 1-7 (NSW Minerals Council: Sydney).

- Cliff, D, Clarkson, F, Davis, R and Bennett, T, 2000a. The implications of large scale tests for the detection and monitoring of spontaneous combustion in underground coal, in *Proceedings Queensland Mining Industry Health and Safety Conference 2000: A New Era in Mine Health and Safety Management*, pp 421-428 (Queensland Mining Council: Brisbane).
- Cliff, D, Clarkson, F, Davis, R, Bennett, T and Smalley, M, 2000b. Better indicators of spontaneous combustion, Final report, Australian Coal Association Research Program, Project C5031 (ACARP: Sydney).
- Cliff, D, Davis, R, Bennett, T, Galvin, G and Clarkson, F, 1998. Large scale laboratory testing of the spontaneous combustibility of Australian coals, in *Proceedings Queensland Mining Industry Health and Safety Conference: New Opportunities*, pp 175-179 (Simtars: Brisbane).
- Cliff, D, Davis, R, Bennett, T, Smalley, M and Clarkson, F, 1999. Gas analysis of large scale laboratory testing of the spontaneous combustibility of Australian coals, in *Proceedings 1999 Australian Symposium on Combustion and the Sixth Australian Flame Days* (eds: B Moghtaderi, B D Z Dlugogorski and E M Kennedy), pp 86-90 (University of Newcastle).
- Mason, T N and Tideswell, F V, 1939. The detection of gob fires, *Transactions of the Institution of Mining Engineers*, 98(1):1-19.
- Smith, A C, Miron, Y and Lazzara, C P, 1991. *Large-scale studies of spontaneous combustion of coal*, United States Bureau of Mines, Report of investigations No 9346.