2005

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Publication Details

This conference paper was originally published as Carras, JN, Day, S, Saghafi, A and Roberts, OC, Spontaneous Combustion in Open Cut Coal Mines — Recent Australian Research, in Aziz, N (ed), Coal 2005: Coal Operators' Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy, 2005, 195-200.

Spontaneous Combustion in Open Cut Coal Mines — Recent Australian Research

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ABSTRACT

The control of spontaneous combustion in spoil piles is an area of concern for a number of open cut coal mines. Spontaneous combustion in spoil may occur when carbonaceous waste materials are exposed to air. In large piles, the relatively high voidage within the pile may allow sufficient movement of air through the pile to sustain oxidation and heat generation.

Over the past decade, ACARP and CSIRO have funded a number of projects aimed at providing a better understanding of the causes of spontaneous combustion in spoil piles and the development of control strategies. Work has focused on prevention measures but has also considered measures available to deal with well-developed fires. Field, laboratory and numerical modelling methods have been brought to bear on the issues.

Individual projects have addressed:

- causes of spontaneous combustion including the relative reactivities of mine waste materials;
- the use of cover layers to prevent spontaneous combustion;
- the use of flyash grout to control an active fire;
- the emissions of air pollutants; and
- the emission of greenhouse gases.

This paper provides a description of the work carried out to date with an emphasis on the major findings of the research and its application to open cut mines.

CONTROL AND PREVENTION OF SPONTANEOUS COMBUSTION IN SPOIL PILES

Spontaneous combustion in open cut mines

Self-heating and spontaneous combustion in coal mining spoil piles is a topic that has received rigorous scientific consideration only relatively recently. The main drivers have been:

1. The persistence of neglected old spoil fires, requiring that *fire control* measures be applied. While there have been many different techniques developed in Europe, USA, China, India and Thailand, no single technique provides assured success.
2. The scale of large open cut operations, where the environmental impact of spoil pile fires can be significant, requiring spontaneous combustion *prevention and control* measures.

A recent review by Walker (1999) has considered the major aspects of fires in coal mines, due to spontaneous combustion. This work has been practical in approach and has built on previous more fundamental approaches as reviewed by Glasser and Bradshaw (1990) and Carras and Young (1994).

In the USA, the Department of the Interior, Office of Surface Mining Reclamation and Enforcement maintains a database of 150 uncontrolled abandoned coal mine fires, which includes 80 surface fires with an estimated reclamation cost of US$ 300 million. There has never been a comparable study of uncontrolled coal fires in Australia. Most Australian sources refer only to reportable spontaneous combustion incidents in operating mines.

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Various techniques for extinguishing uncontrolled fires in abandoned mines and spoil piles have been tried by the US Bureau of Mines (Kim and Chaiken, 1993). These include:

- excavation,
- flooding and quenching,
- bulk filling,
- surface sealing,
- inert gas injection,
- chemical treatment, and
- burnout control.

The relative effectiveness of the various methods of *fire control* can range from high to poor. According to a review carried out in 1992 by the USBM, excavation, creating barriers and sealing generally rank from high to low in probability of success. Cost is also a major factor, with systems that involve extensive excavation incurring the highest costs.

For spontaneous combustion *prevention*, precautionary measures such as encapsulation of reactive material and compaction to deny oxygen access, are generally recognised as the best way of minimising the risk for spontaneous combustion becoming a problem in the future. However no quantitative guidance is available as to the minimum thickness of cover layers or the minimum voidage to ensure *successful prevention*.

Aspeling and Adamski (2002) provided a report on the spontaneous combustion prevention practice at the Grootegeluk mine in South Africa, which has been in operation since 1980. Until 2001, all wash-plant discards and carbonaceous interburden materials were stacked on out-of-pit dumps and spontaneous combustion of the waste material resulted on the discards dumps. During the period 1980 - 1988, many large-scale and laboratory tests had been conducted to determine the factors that contribute to spontaneous combustion, but no successful method of preventing or containing the problem had been found. After large-scale tests in 2000 - 2002, in-pit backfilling of the reactive waste materials into pre-built inert compartments was identified as the preferred method for prevention of spontaneous combustion, based on spontaneous combustion risk, safety and cost. The practice now adopted in the ten-year mine plan at Grootegeluk, is to backfill in three tiers of compartments, each 30 - 35 m high/deep, to a final height of 143 m. This includes two intermediate cover layers of weathered overburden, each 3 m thick, and a final cover layer of 9 m thickness and a topsoil layer of about 1 m. The compartments have widths of 130 - 300 m, and intermediate dividing walls, either pre-placed or tipped at the batters, composed of a minimum of 5 m of overburden and 25 m of sandstone.

Australian research

ACARP has co-funded a number of research projects into the causes of spontaneous combustion and the development of appropriate control and prevention methods. These studies have been conducted by CSIRO and ACIRL, working in collaboration.

Carras *et al* (1994) measured the intrinsic oxidation rate of coal and carbonaceous shales routinely sent to spoil at five open cut coal mines in the Hunter Valley. The oxidation rate, which is directly linked to the spontaneous combustion propensity of the samples, was found to be a linear function of the non-mineral carbon content of the sample. Measurements of the heat generated by oxidation of the carbonaceous shales was measured and shown to be similar to that produced from coal oxidation. This meant that essentially the same chemical processes were involved in each case.

Carras *et al* (1994) also installed temperature and oxygen concentration measurement probes at three mines in the Hunter Valley to provide fundamental information on self-heating and active combustion in large spoil piles. These measurements were continued by Carras *et al* (1999) with field measurements in spoil piles having been made for periods up to 6.5 years. The probes provided unique data on the phenomenology of heating, and cooling spoil piles. In particular a hot spoil pile at one mine was battered and covered with a clay layer (5 - 15 m thickness) as a means of combating spontaneous combustion. Figure 1 shows the temperature measurements, for this spoil pile, as a function of time since the installation of the probes.

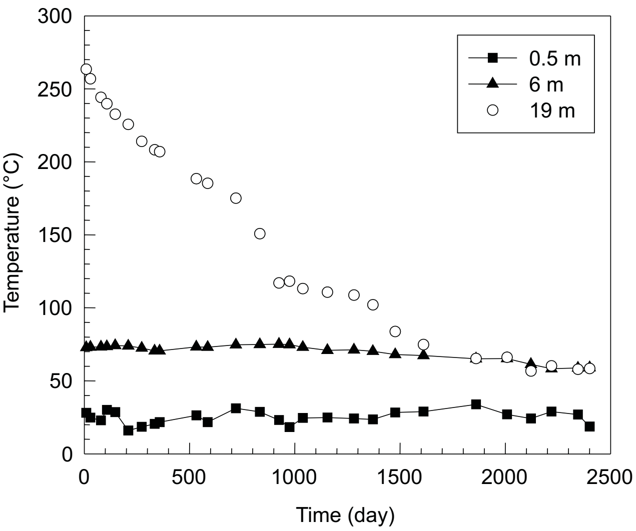

FIG 1 - Plot of temperature versus time for a spoil pile that had exhibited spontaneous combustion and remediated by capping with a clay layer 5 to 15 m thick.

The data in Figure 1 has shown a temperature decline, at the hottest location (19 m) from ~260°C to 65°C during the 6.5 years over which measurements were made.

In a subsequent project, Carras *et al* (1997) extended the CSIRO mathematical model of self-heating (SPLGOF) to predict self-heating in spoil piles. In addition, two small spoil dumps were constructed at a Hunter Valley mine and instrumented with temperature and oxygen probes. The material comprising the dumps was subjected to laboratory oxidation rate measurements so that its reactivity could be quantified. One of the dumps underwent self-heating and provided the opportunity to compare directly the predictions of the CSIRO model of self-heating with measurements of the temperature and oxygen profiles. Allowing for the approximations necessary to run the model, the model predictions were in good agreement with the data from two of the probes but not the third, indicating that while considerable progress had been made in the modelling of self-heating there were still mechanisms which needed to be included.

Carras *et al* (1997) also undertook a trial of flyash grouting as a fire control method on a section of hot spoil at one of the Hunter Valley mines. Both dry flyash and a water-flyash slurry were used as the grout. The trial took place in a section of spoil, which had been instrumented with four temperature and oxygen probes and contained an active fire. A total of 108 tonnes of flyash was injected over a period of three days. While the grouting had an immediate effect on the temperatures in the spoil pile it is now apparent that grouting was successful in extinguishing the spoil pile fire in a very small volume of the order of 100 m^3.

In 1997 dollars, the cost of the grouting trial was $18 000. It is considered that this cost could be reduced significantly for grouting carried out in a large-scale commercial project. Nevertheless the relative cost of the grouting compared with other options, such as excavation, water quenching or covering is probably prohibitive for all but the most critical applications.

An important outcome from this series of projects was the guide on spoil pile self-heating management prevention and control produced by Haneman and Roberts (1997). The guide was based upon the experience of four Hunter Valley coal mines and incorporated the research findings of Carras *et al* (1994, 1997). The guiding principles were:

- identify and control all fuel sources going to spoil,
- minimise the quantity of fuel going to spoil,
- reduce oxygen pathways in spoil piles, and
- avoid dumping hot materials.

Truck dumping practices which were identified as effective in prevention of self-heating include:

- controlled placement of carbonaceous overburden and partings within inert 'pockets';
- limited lift height (15 m max);
- cover all final surfaces with 5 m layer of inert material; and
- compact final surfaces, and intermediate surfaces wherever possible.

Clay capping was identified as effective if the clay seal could be maintained. Measures which reduce erosion gully development, such as drainage bunding, drop structures and prompt revegetation, are also helpful in the prevention of self-heating in spoil piles.

Carras *et al* (1997) also undertook a preliminary investigation into the properties affecting the performance of cover layers in inhibiting oxygen penetration into spoil. Measurements of the diffusion rate of oxygen through three inert overburden materials, including a clay from one mine, pre-strip material from another mine and marine conglomerate from a third mine, showed that the diffusion coefficient for oxygen depended on the air filled voidage of the spoil. Calculations of the penetration of oxygen by diffusion through an inert surface layer show that very thick layers of low voidage material are required to significantly reduce the flux of oxygen. Such low voidages are not normally achieved by tipping and compaction of dry spoil. Water is required in the surface layer to reduce the diffusive flux of oxygen significantly. Consequently, the water holding properties of potential cover materials are critical.

In the most recent work, Roberts *et al* (2004) extended the research to model directly water transport in the cover layers and the self heating properties of the spoil. Mathematical modelling was carried out by using the two computer codes SPLGOF (Carras *et al*, 1997) and SWIM (Verburg *et al*, 1996). SPLGOF solves the equations of heat and mass transfer for a porous body and accounts specifically for oxygen transport, reaction with the carbonaceous material and release and transport of heat. Input to SPLGOF includes the air-filled voidage of the cover layer and of the spoil, as well as the reactivity of the spoil. The latter depends on the carbonaceous content of the spoil and its particle size distribution. SPLGOF only considers heat and mass transfer by the transport mechanism of diffusion.

SWIM (also developed by CSIRO) calculates the transport of water within soils and was used to simulate the infiltration of rain and the flow of water through the cover and spoil. The presence of water acts to reduce the air-filled voidage of the cover layer and hence the ingress of oxygen and the subsequent rate of self heating. As SWIM does not include thermal effects, the two models SPLGOF and SWIM were coupled in order to account for water flow, evaporation and spoil self-heating.

Computer simulations were performed using historical Hunter Valley, NSW, weather records and a range of cover and spoil properties. The results of the computer simulation results showed very different degrees of self-heating depending on the initial conditions. For instance, if the cover layer was initially wet, with the lower spoil reactivities, the simulated spoil piles showed very little self heating even after 24 years. If the covers were applied dry over the more reactive spoil, the simulations predicted run-away heating in some cases but not others, depending on the nature of the cover material and the thickness of the cover.

The mathematical modelling also showed that the ingress of oxygen into the cover depended strongly on the occurrence of rain events. The oxygen flux dropped markedly with infiltration into the cover following rain, but returned to pre-rainfall, near-steady values during dry periods.

In order to obtain an empirical ranking of cover materials, and as a further method to provide a test of the computer model predictions, an area of spoil pile at a Hunter Valley mine was used to create eight cover layer plots from six different materials. An oxygen fluxmeter was used to measure the oxygen flux into the spoil both prior to and after a period of six months after the covers had been emplaced (Timms, 2002). The values of oxygen flux into the spoil showed wide variation reflecting the high variability of spontaneous combustion activity and of the properties of the near surface spoil. When the average of all the oxygen flux values for bare spoil was compared with the average values of oxygen flux through the covers, a reduction in the flux of oxygen into seven of the eight cover plots was observed. However this result is sensitive to the value of oxygen flux attributed to bare spoil, and given the large variability of the latter, this result cannot be taken as conclusive. However, the magnitude of the measured oxygen fluxes through the different covers, and their ranking, were in broad agreement with the computer model predictions.

The field and laboratory work showed that the most significant properties of a cover layer material were the water retention characteristic and saturated hydraulic conductivity of the unconsolidated ('minesoil') material. These hydraulic properties were determined for typical overburden strata at two Hunter Valley mines, by size analysis and using published correlations to relate the size distribution to the water retention function and hydraulic conductivity.

The main conclusions from the field-work and the computer model simulations, were the following:

1. the use of a cover layer can significantly reduce the rate of self-heating of a spoil pile;
2. the three materials used in the simulations, namely clay, marine conglomerate and weathered sandstone, can be ranked in that order as to their effectiveness as cover layer materials, according to their soil-like hydraulic properties, ie the water retention characteristic and saturated hydraulic conductivity;
3. the computer modelling showed that:
   - cover effectiveness depends on the cover thickness with thicker covers being more effective than thin ones;
   - cover thicknesses (1 - 2 m) of highly water-retentive clay-rich materials limited self-heating in spoil, for the spoil reactivities assumed and under Hunter Valley conditions; and
   - the use of *sufficiently thick* (greater than 5 - 10 m) layers of the low water-retentive materials, such as sandstone, can also reduce the likelihood of self-heating.

A practical methodology for predicting cover layer effectiveness was developed from the computer simulations. From fundamental considerations, the relative effectiveness of a cover layer will depend on:

1. the composition, particle size distribution and bulk density of the cover layer;
2. the water content of the cover layer;
3. the air filled voidage of the cover layer, which in turn depends on points 1 and 2 above;
4. the heat transport property (thermal diffusivity) of the cover layer, which in turn depends on points 1 to 3 above; and
5. the oxygen transport property (oxygen diffusivity) through the cover layer, which in turn depends on points 1 to 3 above.

The relative effectiveness of a cover material can be developed by considering the ratio of its thermal diffusivity to its oxygen diffusivity. The manner by which this can be related to soil properties are described in detail by Roberts *et al* (2004).

Roberts *et al* (2004) also develop a stability index (S) for a cover material with effectiveness (C_e) and thickness (L_c), for a particular location (ie climatic conditions). The stability index can be expressed as:

$$S = C_e L_c$$

The stability index was determined from the computer simulations and is a measure of whether a spoil pile of a certain reactivity, cover layer effectiveness and thickness will lead to spontaneous combustion, or not. The above expression shows that greater cover effectiveness (ie high thermal diffusivities and low oxygen diffusivities) and greater thicknesses, lead to higher stability, while the inverse is true for less effective cover materials and thinner layers.

The results of the computer simulations from Roberts *et al* (2004) based on real mine materials are shown in Figure 2, where the cover material effectiveness has been plotted as a function of bulk density for different sand contents of the cover layer material. Clays through to sands are covered. As anticipated the clay like materials are clearly most effective.

While the parameters of the computer simulations were matched, as far as possible, to Hunter Valley conditions, there are a number of issues which require further consideration before the results shown in Figure 2 can be put to routine operational use (see Roberts *et al*, 2004). Briefly, they include:

- The role of vegetation and its effect on the subsurface water profile.
- The modelling assumption of uniformity of properties within particular layers.
- The reactivity data of the spoil used in the current work were obtained by extrapolation of laboratory measurements. *In situ* values should be obtained and used.
- The representativeness of the hydraulic and thermal properties of cover materials and spoil.
- The impact of run-off on slopes, non-uniform surfaces, and large contiguous voids in spoil, which may lead to channelling of water and air rather than the diffusional transport processes, which were assumed in the modelling.

GREENHOUSE GAS (GHG) EMISSIONS FROM SPONTANEOUS COMBUSTION

One of the environmental issues of increasing significance for spontaneous combustion is the emission of greenhouse gases. While spontaneous combustion of coal has been recognised by the Inter-Governmental Panel for Climate Change (IPCC) as a

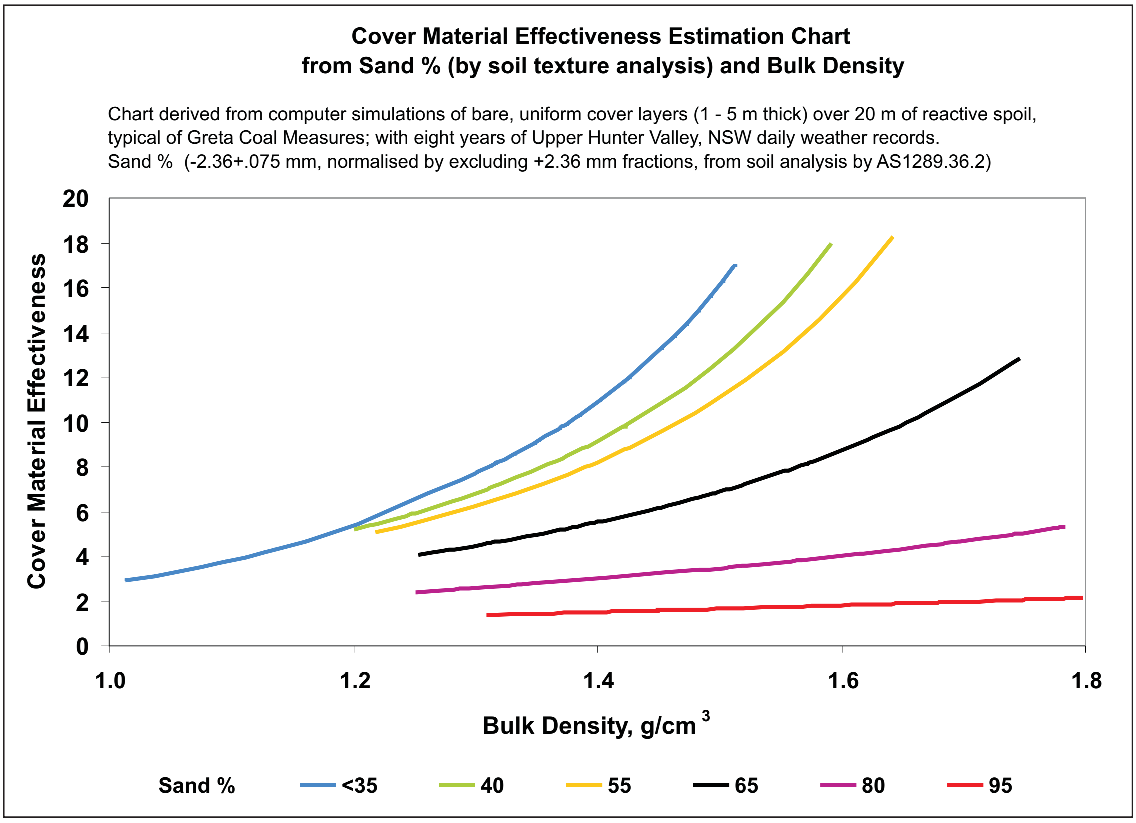

FIG 2 - Plot of the relative effectiveness of cover materials as function of their soil analysis and the degree of compaction.

potential source of greenhouse gas emissions, it has been excluded from greenhouse gas inventories as it is considered that there is no acceptable method for estimating the emissions.

In recognition of this, ACARP and CSIRO have carried out three projects to explore methods for establishing greenhouse gas emissions from spontaneous combustion. The first (Carras *et al*, 2000) sought to provide methods, supported by direct measurement, to quantify the emissions of greenhouse gases. Measurements of emissions from spoil piles, coal rejects and tailings were conducted at 11 mines in the Hunter Valley in NSW and the Bowen Basin in Queensland using a chamber technique. The results of this work led to the development of emission factors for several broad categories based on the extent of spontaneous combustion present. These were:

- Category 1 – intense spontaneous combustion characterised by smoke and steam, major cracks, surface discolouration and obvious signs of venting.
- Category 2 – spontaneous combustion with less well pronounced signs, small cracks, surface discolouration and occasional wisps of smoke and steam.
- Category 3 – no sign of spontaneous combustion.

While the project provided the first systematic study of greenhouse gas emissions from spontaneous combustion in open cut coal mines, there were practical problems in applying the results to estimate greenhouse gas emissions from operating mines. While the chamber technique provided direct emission measurements, it was labour intensive and required many measurements to obtain representative values. In addition, it is difficult to obtain an objective measure of the extent of spontaneous combustion in spoil piles. However, one of the key findings of the research was that the emissions from spoil piles without spontaneous combustion were similar to the background emissions from vegetation and biota from surfaces such as forest floor and domestic lawns. This suggests that the carbonaceous material within the spoil piles is not being exposed to oxygen and hence not contributing in a significant way to greenhouse gas production.

Due to the difficulties with the chamber approach Carras *et al* (2002b) investigated the use of remote sensing techniques such as airborne infra-red thermography to investigate whether more accurate and cost-effective monitoring of the extent of spontaneous combustion in spoil piles and the associated greenhouse gas emissions could be achieved. This approach was based on the finding by Carras *et al* (2000) that an approximate relationship existed between the emission rate of greenhouse gases and the average surface temperature of the spoil pile surface. Figure 3 shows a plot of the cumulative area greater than a given surface temperature for the same section of spoil over a 13 month period and for two different pixel resolutions ie 7 × 7 m and 2 × 2 m.

The results in Figure 3 show that for the 7 × 7 m pixels, the total area greater than a given temperature has changed over the 13 month period. The data from the 2 × 2 m pixels shows greater areas at the higher temperatures due to the enhanced resolution's ability to capture local 'hot spots'. However, the above results are subject to a number of assumptions in their analysis and require detailed ground validation.

From data such as those shown in Figure 3, Carras *et al* (2002b) concluded that airborne infra-red data could be used to monitor the long-term behaviour of spoil piles subject to spontaneous combustion. The same data could also be used to estimate greenhouse gas emissions for spontaneous combustion. However, due to the complexity of the processes involved in producing heating and its surface manifestation and the associated emissions of greenhouse gases, the emissions estimates were still subject to significant uncertainty. Nevertheless (and the scatter in the data notwithstanding) over a suitable time period the method could be used to monitor the progress of spontaneous combustion in spoil piles and associated emission of greenhouse gases.

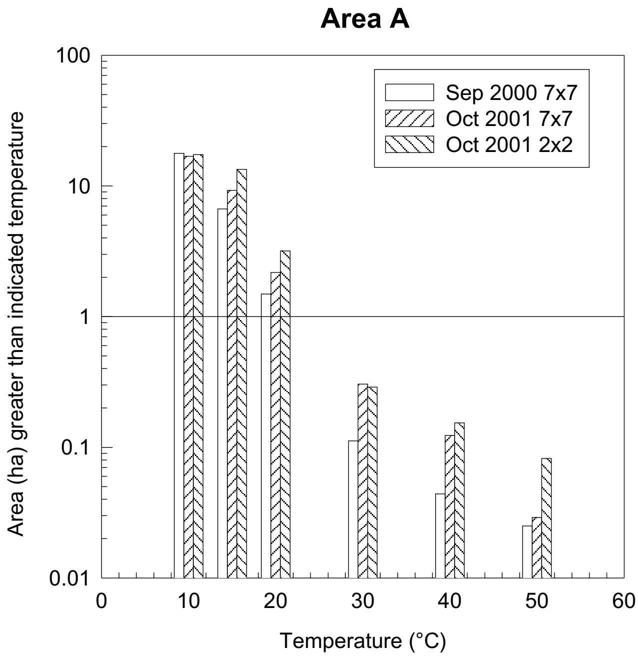

FIG 3 - Plot of the cumulative greenhouse gas emissions for the same area of a spoil pile exhibiting spontaneous combustion, but taken 12 months apart.

A further approach which has been considered in estimating emissions from spontaneous combustion requires the direct measurement of emission fluxes by mapping out the concentration of GHG as a function of crosswind distance, height above the ground and wind speed, to allow a direct estimate of the emission rate. This technique has been employed previously by Carras *et al* (1991) and Carras *et al* (2002a) to measure:

- the fluxes of methane emitted from Sydney, Melbourne and Brisbane;
- the volatile organic compounds (VOC) emitted from the Kwinana industrial region; and
- the emissions of VOC and nitrogen oxides (NO_x) emitted from Hong Kong.

While this approach is the most direct it requires traverses of the downwind plume at various heights above the ground. However, ground level sources require very low level passes (<50 m) through the plume. While these can be achieved above the sea such traverses are vastly more difficult and dangerous above land. Thus and notwithstanding the appeal of this approach for open cut coal mines, safety issues preclude this option.

A variation of the direct flux measurement approach described above is to traverse a ground based CO_2 detector across the plume and to use knowledge of micrometeorology and plume dispersion to estimate the horizontal and vertical extent of the plume and hence calculate the emission rate. This approach was used by Williams *et al* (1993) in their estimates of methane fluxes from open cut coal mines.

In addition to the methods described above to determine area source emissions, another approach that has been gaining widespread use in recent years, particularly with regard to global greenhouse gas emissions, is the use of inverse modelling methods. Inverse methods, as the name implies arise from inverting the normal advection diffusion equation used to describe transport of gases and particles in the atmosphere. For instance, in conventional applications of atmospheric transport models such as air quality models, source strength and meteorological data are used as inputs to calculate the concentration of a species at downwind locations. By contrast, an inverse technique involves back-calculating the strength of an emissions source using a measured concentration time series at one or a number of selected sites.

While there has been considerable work on methods to invert air pollution concentrations in order to obtain estimates of the emission strengths of sources, developing a completely general inversion method is not possible as information is lost as the pollution cloud is transported and diffuses in the atmosphere. Other physical information is required to constrain the possible solutions to the equations and yield realistic results. In general, the greater the number of monitors and the 'cleaner' the signal from an individual source the better the solution to the inverse problem. In addition and for the case of CO_2 emissions from spontaneous combustion in the Hunter Valley, the importance of the concentrations from other sources in the Valley such as power stations and the major highway must be taken into account in order to design an appropriate experimental approach to provide greenhouse gas emissions from spontaneous combustion.

Lilley and Carras (2003) modelled the large sources of CO_2 in the Hunter Valley using a computer-based air quality model (TAPM, Hurley, 1998), which has been widely used in air pollution studies in Australia. An investigation of CO_2 sources in the Upper Hunter Valley showed that spontaneous combustion and power stations can give rise to significant concentrations at ground level. However the impact of the power stations emissions are most pronounced during the day time hours while the impact of the spontaneous combustion emissions are most pronounced during the night time. This is because the former are elevated while the latter are ground level sources. This suggests that concentration measurements should focus on data during the night time period. While the emissions from road traffic and rail are significant, their ground level concentration signature is not as pronounced as for the other two major sources.

Consideration of results of the air quality modelling suggests that monitoring sites for the inverse modelling should be sited such that:

- the sites are sufficiently close to the spontaneous combustion sources to enable a large measurable signal;
- the sites are chosen on the basis of meteorology to best capture the likely CO_2 spontaneous combustion signal; and
- the sites are chosen to minimise the influence of other sources.

The above work is continuing through a current ACARP project, which is applying the methodology developed and is due to be completed by mid 2006.

AIR POLLUTION

In addition to greenhouse gases, other air pollutants are emitted from spontaneous combustion. These include:

- SO_2 (arising from sulfur associated with coal, either as mineral matter or bound to the organic fraction);
- NO_x;
- CO due to incomplete combustion;
- fine particles;
- other hazardous air pollutants (eg Polynuclear aromatic hydrocarbons, PAH).

There has been relatively little work on these emissions that is available in the open literature. Carras *et al* (1999) carried out a study at a Hunter Valley mine where the exposure of workers, within the cabin of a bulldozer, working in the vicinity of spontaneous combustion was measured. These results showed that the PAHs measured within the cabin were below the values expressed by the occupational health and safety guidelines. In outside air and in close proximity to spontaneous combustion fires, the PAH levels may be sufficiently high to result in exposures which may be greater than the recommended values. Further work is required to quantify the emissions of these pollutants and to assess their overall significance.

CONCLUSION

The work carried out through the ACARP projects described above has advanced considerably the fundamental understanding of the processes responsible for spontaneous combustion. The research has also lead to practical guidance that can be used in an operational manner at operating open cut coal mines.

The outstanding issues for further research, remain:

1. field validation of the predictions of the mathematical models for preventing self-heating;
2. development of a method of adequate accuracy that can be applied in a routine manner to determine greenhouse gas emissions from spontaneous combustion; and
3. an assessment of the overall emissions from spontaneous combustion.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support of the coal industry through the ACARP process in co-funding the work presented above. In particular Jim Craigen, Roger Wischusen, and Alex Campbell are thanked for their contributions to the projects as ACARP monitors. The authors are also indebted to John Watson (Watson Mining Management) who served as industry monitor for all but one of the projects related to spontaneous combustion and reported above.

The authors would also like to acknowledge the considerable assistance provided by the open cut coal mines in NSW and Queensland where the research was carried out. Without this assistance the work would not have been possible.

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