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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 emissisons 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.

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/depth, 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.

![Temperature vs Time Graph](image)

**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 m³.

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 potentials
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...
3. the computer modelling showed that:

2. the three materials used in the simulations, namely clay, Valley mines, by size analysis and using published correlations to unconsolidated ('minesoil') material. These hydraulic properties properties of a cover layer material were the water retention magnitude of the measured oxygen fluxes through the different latter, this result cannot be taken as conclusive. However, the values of oxygen flux through the covers, a reduction in the flux oxygen flux into seven of the eight cover plots was observed.

4. 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 (Ce) and thickness (Lc), 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
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 measurement, 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 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.
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 (NOx) 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 CO2 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 CO2 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 CO2 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 CO2 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 CO2 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:

- SO2 (arising from sulfur associated with coal, either as mineral matter or bound to the organic fraction);
- NOx;
- 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 led 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.

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