Assessing and managing spontaneous combustion of coal

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, China, the European Commission, Germany, India, Italy, Japan, New Zealand, Poland, Russia, South Africa, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

Abstract

This report summarises the most common, practical methods used to determine the propensity of coal to self-heat and considers the external factors which can combine to result in a spontaneous combustion event. By understanding how and why coal spontaneously combusts, coal users can plan, predict and avoid accidents which could be costly in terms of coal lost, emissions of pollutants, and, ultimately, risk to the health and safety of those involved in the industry.

New techniques and technologies have been developed to predict coal heating behaviour and to analyse gas emitted from coal which is oxidising (an initial indication of self-heating). This information can be used to fine tune monitoring systems to give an early warning well in advance of a potential combustion or explosion event.

Spontaneous combustion management plans (SCMPs), which incorporate coal assessment as well as local and site-specific parameters, are becoming increasingly important in the coal industry to the point that they are becoming a legal requirement in countries such as Australia and, more recently, China. These SCMPs outline the monitoring which must be in place – from visual inspections through to specific on-line analysis systems – to predict and prevent incidents of self-heating. These plans also define trigger alarm responses, signals (visual, temperature or chemical signatures) which, once reached, initiate a pre-determined response. This response can be anything from simply increased vigilance or the treatment of a heating stock-pile, through to chemical spraying, fire suppression and site evacuation. SCMPs are somewhat 'living' documents in that they are altered to take into account any new information or concerns. They can therefore not only help avoid incidents and accidents but, following unpredicted events, can provide a learning exercise to expand on current knowledge, improve existing practice and lead to continued improvement of safety in the coal industry.

Acronyms and abbreviations

ACARP	Australian Coal Association Research Programme
ASBCUG	Asian Sub-bituminous Coal User's Group
ASET	available safe evacuation time
BS	British Standards
CCTV	closed circuit television
CEN	Comité European de Normalisation (European Standards Committee)
CPT	crossing point temperature
CSIT	critical self-ignition temperature
DNRM	Department of Natural Resources and Mines, (Queensland) Australia
GC	gas chromatography
GET	gas evaluation test
HRR	heat release rate
ICAC	Institute of Clean Air Companies
IEA	International Energy Agency
IEA CCC	IEA Clean Coal Centre
IMSBC	International Maritime Solid Bulk Cargo
IR	infrared
ISO	International Standards Organisation
MAB	moist adiabatic benchmark
MCA	Minerals Council of Australia
NMA	National Mining Association, USA
NSW	New South Wales, Australia
PAC	powdered activated carbon
PMHMP	principal mining hazard management plan
ppm(v)	parts per million (by volume)
PRB	Powder River Basin
PRCS	predictive risk control system
PRBUG	Powder River Basin User's Group
SCMP	spontaneous combustion management plan
TARP	trigger action response plan
UV	ultra-violet
VBFD	video-based fire detection
VDKi	Der Verein der Kohlenimporteure eV Germany

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1 Introduction

Despite significant advances in our understanding of spontaneous combustion in coal, incidents and accidents still occur. Most recent mining accidents worldwide are a result of equipment or vehicle failure, or human error – of the 16 deaths in US coal mines in 2014, not one was due to spontaneous combustion. However, in the Ukraine, over 30 miners were killed in an explosion in 2014 and so spontaneous combustion is still an important safety issue within the coal industry (World Coal, 2015).

Most underground mine explosions are due to a build-up of methane which is then ignited by a spark, usually from a piece of equipment or a friction event. However, spontaneous combustion or heating of coal in situ can also act as an ignition source which, together with elevated methane concentrations, will result in a mine explosion. Controlling explosions underground is therefore a combination of gas control (ventilation) as well as suppression of potential ignition incidents, including spontaneous combustion.

Even at the surface, once mined, coal can react with the oxygen in the air to initiate self-heating. This means that spontaneous combustion may occur during any stage of storage, handling and transport between the mine and the site of ultimate coal usage (utility or industry boiler). In addition to the potential hazard risk of a fire or explosion, self-heating is also a problem with respect to the coal value lost through such incidents as well as a pollution risk from uncontrolled emissions.

Previous reports from the IEA Clean Coal Centre (IEA CCC) have focused on the chemistry of spontaneous combustion (Nalbandian, 2010; Zhang, 2013) and greenhouse gas emissions from the process (Sloss, 2013). This report updates some of the most relevant information from these reports and focuses on the linkage of information from monitoring emissions to prevention and control of spontaneous combustion incidents.

Chapter 2 briefly summarises the causes of spontaneous combustion in coal. Chapter 3 looks at evaluating the changes in coal – the release of gases and increase in temperature – which can be used to monitor potential incidents of self-heating and, ideally, through the application of quick responses, prevent combustion events. Examples of national approaches and guidelines to prevent spontaneous combustion and to ensure a safe working environment for the coal industry are discussed in Chapter 4.

2 Spontaneous combustion

All coals oxidise when newly exposed to air, especially during and after mining. This tends to be more of a problem in lower rank coals. Powder River Basin (PRB) coal was first used in 1974 and, although the new PRB users were expecting challenges with respect to performance, they did not expect the major issues they faced in terms of fires and explosions (Rahm, 2014). Subbituminous coals such as PRB coals can have a high propensity to self-heat and this can cause dangerous and expensive accidents. For example, Rahm (2014) reports on a PRB dust explosion in a conveyor at a plant which cost the utility $11 million in repairs and also closed the plant for three months during the peak demand season.

In addition to being a fire risk, self-heating is also an issue as calorific value of the coal is lost during these exothermic reactions, something which coal users also wish to avoid. As a result of the risk not just to lives but to productivity and profit, significant amount of money and time has been spent on studying the propensity of coal to self-heat in an attempt to understand and ultimately control this phenomenon. The interested reader is referred to the previous IEA CCC reports by Nalbandian (2010) and Zhang (2013) which concentrated on the chemistry of self-heating. This report concentrates more on monitoring and control of spontaneous combustion events as a practical consideration at working sites.

Although methane explosions are not the topic of this report, the presence of methane around coal mining activities where spontaneous combustion is common can be a significant contributor to explosion incidents. Coal dust can also be a significant fire hazard. For the purposes of this document, consideration of spontaneous combustion issues caused or enhanced by the presence of methane and/or coal dust are included where relevant.

2.1 Propensity of coal to self-heat

Coal has been formed as a result of chemical and physical reactions over millennia. Although coal is stable underground, the exposure of coal to air during and after mining can result in reactions and oxidation which, in turn, result in self-heating and, in extreme cases, spontaneous combustion.

Figure 1 shows the standard requirements of a fire – heat, oxygen and fuel. All are required to start and maintain a fire and therefore removal of one of these components can also extinguish a fire. In spontaneous combustion, coal is the fuel, and the interaction of oxygen on the surface of the coal leads to oxidation reactions which result in heat and, eventually, if left untreated, fire.

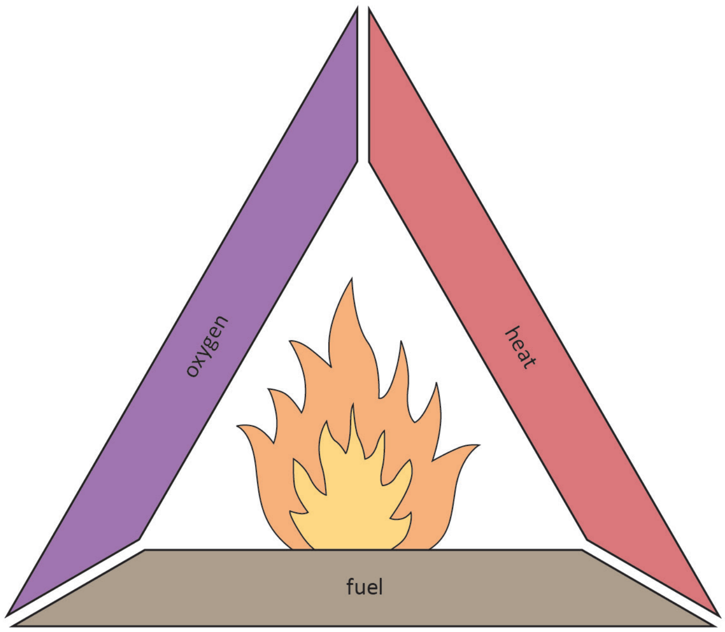

Figure 1 Fire triangle

All newly mined coals self-heat to some extent. Self-heating of coal becomes an issue when the rate of heat production exceeds the rate of cooling – resulting in the coal reaching a temperature where ignition may occur. The factors which affect self-heating include (Chalmers and others, 2012):

- rank;
- porosity;
- pyrites;
- moisture; and
- petrology.

However, over and above the characteristics of the coal, self-heating will also be dependent on (Chalmers and others, 2012):

- low air velocities;
- moderate differential pressures;
- broken coal (surfaces); and
- mining methods.

The air flow and pressures around the coal will affect the movement of the newly released gases from the exposed coal surface. If the differential pressure is low then the gases will remain at the coal surface, deprived somewhat of oxygen and therefore less likely to ignite. At high differential pressure the heat from oxidation is removed effectively and this also reduces the likelihood of an incident. There is a 'sweet point' of pressure and air flow which can create the perfect conditions for spontaneous combustion and this must be avoided.

Figure 2 shows the process of self-heating within a stockpile. The movement of oxygen and air over the surface of the pile causes oxidation which heats up the coal. This heat is transferred both inwards and outwards but the heat that travels inwards can build-up within the pile and lead to the formation of a high temperature hotspot. This hotspot will then continue to spread until it reaches a point on the surface. Here it will interact with oxygen in the air and this can lead to glowing embers and actual ignition of the coal pile. Sasaki and others (2014) provided a more detailed explanation of the chemistry of oxidation along with equations to evaluate the rate of oxygen consumption and heat production, to which the interested reader is referred for further detail. This phenomenon is not restricted to coal in stock-piles. Air entrainment also occurs on and around newly exposed mine surfaces which can lead to spontaneous combustion incidents underground. As discussed in a previous IEA CCC report by Sloss (2013) there are thousands of underground mines, surface mines and coal heaps worldwide which have ignited through spontaneous combustion and which contribute to local and regional air pollution problems.

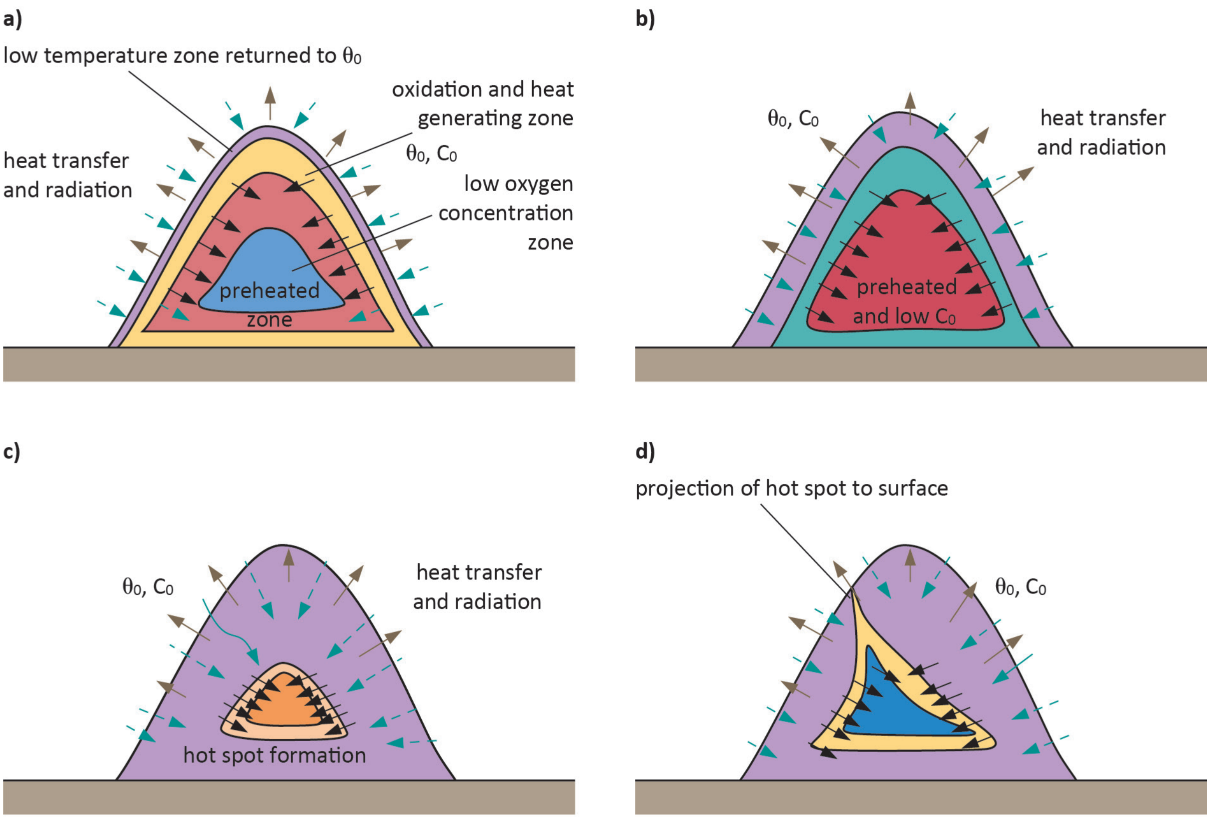

Figure 2 Schematic showing the self-ignition process of a coal stockpile (Sasaki and others, 2014)

As mentioned earlier, low rank coals are more prone to spontaneous combustion than higher rank coals. This is largely due to their higher porosity and greater internal surface area. Moisture on this expanded surface area is an important factor in spontaneous combustion. The PRB Coal User's Group (PRBCUG) has been established to help users of PRB and similar low rank coals to exchange information and expertise on how best to handle these coals. Indonesian coal mines began exporting subbituminous coals in 1994 and the PRBCUG organisation now has an Asian arm (ASBCUG, Asian Sub-bituminous Coal User's Group), established in 2010.

Finely ground materials, especially coal dust and similar materials in the <420 µm size range, have the potential to cause dust explosions. There are five components required to result in a dust explosion, as shown in Figure 3.

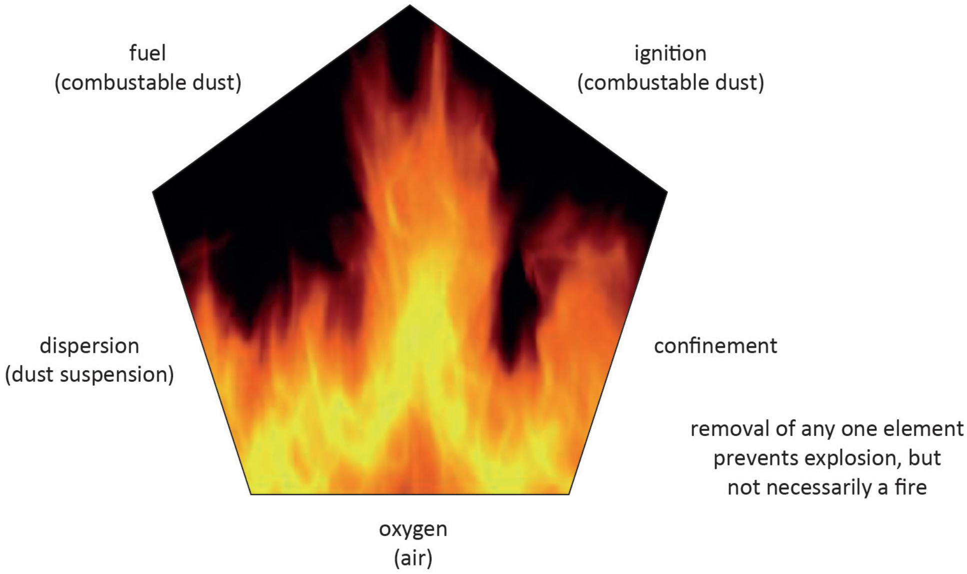

Figure 3 Dust explosion pentagon (Industrial Fire Prevention, 2015)

Reducing the risk of dust explosion is commonly achieved through targeting one of the five points of the pentagon. For example, eliminating oxygen and confining the dust through covering and storage management. Even without the dispersion and confinement issues, however, coal fires can still occur through the presence of fuel, oxygen and an ignition source, as shown in Figure 1. The difference between the fire triangle (Figure 1) and the fire pentagon (Figure 3) is the difference between a fire and an explosion.

Powdered activated carbon (PAC), used for mercury control in some power plants, can also be explosive. The Institute of Clean Air Companies (ICAC, 2015) have produced a white paper providing guidance on the use of PAC which includes information on how to avoid dust explosions. PAC is generally considered 'mildly explosible (sic)', and tends to smoulder slowly, sometimes without producing smoke or a flame. However, as with coal, the potential for ignition should be considered and controlled during all stages of production, transport, storage and use.

2.2 Emitted gases

A previous report from the IEA CCC (Zhang, 2013) discussed the formation of gases in coal stockpiles in great detail. Although the most relevant information on this process will be summarised here, this section concentrates on the formation and release of gases that are associated with the process of spontaneous combustion. A separate report from the IEA CCC (Sloss, 2013) concentrated on the quantification of greenhouse gases (mainly methane and CO_2) emitted from spontaneous combustion of coal for the purpose of reporting to emission inventories. This report concentrates on the emitted gases which contribute to the potential for a combustion event and/or which can be used to predict when such an event is likely.

The Department of Natural Resources and Mines (DNRM) of the Queensland Government, Australia, has published a factsheet on the flammable and toxic gases released from open cut coal mines. These are listed as (DNRM, 2015):

- **Methane (CH_4)** – colourless, flammable, non-toxic, odourless. Can cause asphyxiation if it displaces oxygen in sufficient quantities. Explosive at 5–15.4% in air, with maximum explosion risks as 9.46% but easiest to ignite at 7.5%.
- **Hydrogen sulphide (H_2S)** – colourless, sweet taste, pungent odour (rotten eggs). Can be detected by smell at 1 ppm but this is not reliable as a warning mechanism. Highly toxic irritant with a narcotic effect on the nervous system. Exposure > 500 ppm can be fatal. High density (1.19 times that of air) so tends to pool in wells and poorly ventilated areas. Flammable at 4.5–45%. Health and safety exposure levels are commonly in the 10–15 ppm range.
- **Carbon monoxide (CO)** – colourless, odourless, tasteless. Both flammable (12.5–74%) and explosive (especially at 29% in air). Potentially fatal as impossible to detect by taste or smell and causes cumulative poisoning. Short-term exposure can occur without the victim noticing but the carboxy-haemoglobin formed in the blood has a half-life of 4–5 hours and so cumulative exposure can be fatal.
- **Carbon dioxide (CO_2)** – colourless, acrid smell and soda water taste. Density is 1.53 that of air and therefore accumulates in low lying and unventilated areas. High concentrations cause unconsciousness and narcosis. Health and safety exposure levels are commonly 5,000–30,000 ppm depending on location and length of exposure
- **Sulphur dioxide (SO_2)** – colourless, strong odour above 3 ppm. More dense than air (2.26) but non-flammable and incombustible. Health and safety exposure limits are commonly around 2–5 ppm.
- **Nitrogen dioxide (NO_2)** – of the oxides of nitrogen, NO_2 is the greatest risk to miners. Reddish brown, acrid smell and taste. Density 1.6 times that of air but non-flammable and incombustible – but will support combustion. Extremely poisonous. At 100 ppm it will cause irritation of the respiratory system and may cause death at above 200 ppm for several minutes. Health and safety exposure limits are in the 3–5 ppm range.

Whilst not all of these gases are associated with spontaneous combustion, detection of any or all of these gases in elevated concentrations suggests poor ventilation and unsafe working conditions. In the IEA CCC report by Zhang (2013), it is noted that hydrogen (H_2) can also be emitted from coal during oxidation. Although the emissions tend to be in low concentrations (<10 ppmv), H_2 is highly explosive and should also be considered when planning coal handling strategies.

Spontaneous combustion is not the only risk from some of these emitted gases – DNRM (2012) report several incidents where surface coal mine workers were exposed to toxic gases associated with spontaneous combustion, including CO and SO_2. Most were taken to hospital for observation but recovered fully.

2.3 Comments

Coal is a naturally reactive material, especially when it is newly exposed to air following mining. The basic requirements for a fire or explosion are fuel, air and heat. Coal is relatively unique in that it can act as the fuel but, on reaction with oxygen, can also provide the heat to initiate a fire without any other external influences – coal can provide its own ignition reaction. Coal users are therefore keen to understand how best to control this behaviour in order to secure the safety of staff and equipment, to reduce the loss of stocks and revenue, and to avoid the creation of unabated emissions.

3 Prediction and prevention

The most appropriate way to avoid incidences of spontaneous combustion is to combine an understanding of the coal and its likelihood to self-heat along with measures to monitor any indication that self-heating is occurring. Whilst this report summarises the most common methods used to predict and prevent issues and how to build-up safety plans for individual sites, the guidelines provided by the Government of New South Wales (NSW), Australia, make an important point – '*a degree of discipline is also warranted as a means to detect, and effectively act upon, the often subtle changes in a mines operating environment which may be associated with the potential for spontaneous combustion*'. Simply put – situations change and no matter how carefully you plan, staff must remain vigilant and alert to sudden and unexpected changes in circumstances. However, forewarned is forearmed and the more specific information is available, the more likely incidents and accidents can be predicted and avoided

3.1 Coal evaluation and self-heating prediction

As mentioned in Chapter 2, some coals are more prone to spontaneous combustion than others. This Section concentrates on those coal properties which can be used most reliably to predict propensity to self-heat. Cliff and others (2014) have listed the factors which may affect the oxidation of coal, as shown in Table 1.

Table 1 Factors affecting the oxidation of coal (Cliff and others, 2014)

Intrinsic factors	Extrinsic factors
Low rank of coal	Faults
Low ash	Folds
High friability	Dykes
Weak caking properties	Weak and disturbed strata conditions
High reactivity	Seam thickness
High heat capacity	Steepness of seam
Low thermal conductivity	Shallow cover
High coefficient of oxygen absorption	Multi-seams in close proximity
High proportion of oxygen functional groups	Porous petrographic structure
High volatile matter	Increase amount of time of exposure of broken coal
Pyrites	Mine ambient temperature
Moisture content	
Particle size and surface area of coal	

Some of these factors are more important than others and some are easier to control than others, but the final cause of a spontaneous combustion incident will be a combination of at least two or more of these factors.

3.1.1 Coal analysis

Operators are advised to test new coal stocks to establish the potential for spontaneous combustion. Companies such as CB3 Mine Services Ltd provide services to evaluate the potential for spontaneous combustion in coals. The analyses include (CB3, 2015):

- How reactive is the coal?
- What is the incubation period for self-heating under various conditions?
- What are the effects of temperature, humidity or moisture on incubation periods?
- What are the implications of supply chain handling, stockpile, rail, barge and delivery on spontaneous combustion?
- What chemical treatments (inhibitors) are available?
- What is the optimal application rate for an inhibitor?

By obtaining answers to these questions, a coal user should have enough information to determine how best to handle, move and store a specific coal in order to ensure that a spontaneous combustion incident does not occur.

Different techniques are used to predict coal self-heating properties (Nalbandian, 2010):

- **Classical techniques** – these include minimum emission temperature (in ovens and dust clouds) and indexes related to oxidation potential (in the presence of hydrogen peroxide, the Maciejasz Index).
- **Thermal analysis** – based on thermo-gravimetry and differential scanning calorimetry. These methods measure the amount of mass loss through heating whereas scanning calorimetry identifies the temperatures at which different exothermic reactions occur.
- **Activation energy** – combines thermo-gravimetry and kinetics to provide a graph indicating, through the loss of mass, when the main thermal reaction events occur.
- **Isothermal heating** – using an oven to test the self-ignition temperature.

The R70 test is an adiabatic/non-isothermal heating test designed to provide a measure of the intrinsic reactivity of coal to oxygen. Beamish and Smith (2014) describe the testing of coals to evaluate their propensity to self-heat based on the R70 test method. The test procedure was summarised as follows:

- crushing of the coal (to below 212 µm);
- frying under nitrogen at 110°C for at least 16 hours then cooling to 40°C;
- stabilisation under nitrogen in an adiabatic oven at 40°C;
- flow switched to oxygen at 50 ml/min;
- temperature change monitored and recorded by computer.

The R70 value is determined as the average self-heating rate from 40–70°C, expressed in °C/h and provides a measure of intrinsic coal reactivity.

Figure 4 shows the R70 values for two different coals, as defined in °C/h. Coal B has a higher R70 value, meaning that it heats up faster and is more likely to result in spontaneous combustion than coal B.

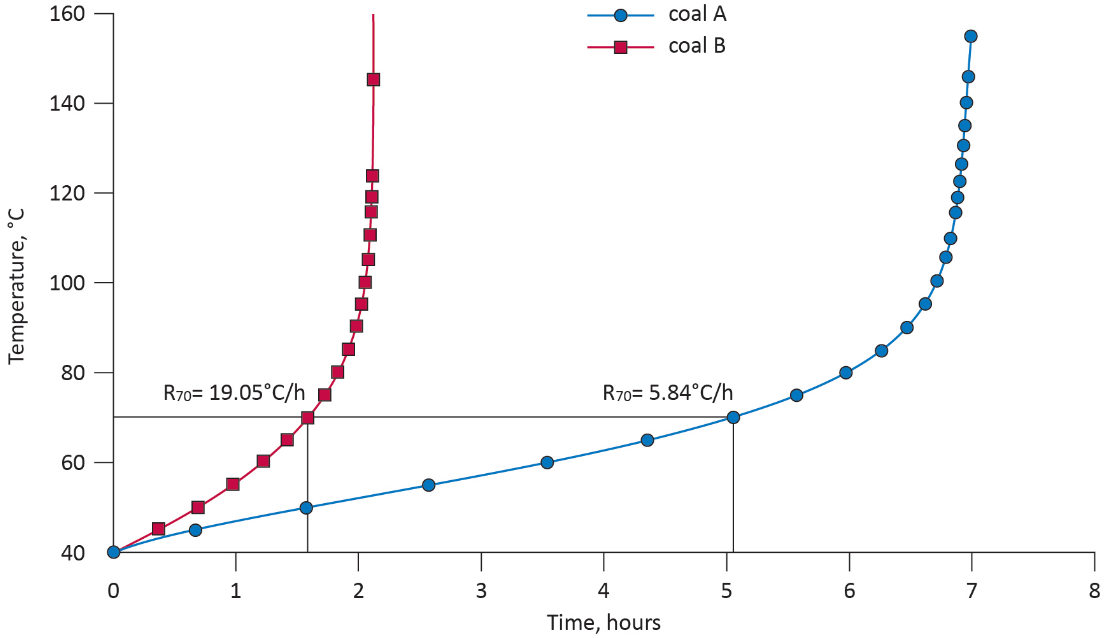

Figure 4 R70 values for different coals (CB3, 2015)

According to Beamish and others (2014a), the R70 value of a coal is strongly rank dependent with low rank coals having higher R70 vales. For lignites, the R70 value can be up to 99°C/h whereas high rank coals have R70 values as low as <0.5°C/h. However, other coal properties such as mineral matter and coal type (dull or bright) can also influence the R70.

The results of the R70 test are not always conclusive. There is also a moist adiabatic benchmark (MAB) test which determines the time taken by a coal to reach 'thermal runaway'. The MAB is estimated as follows (Beamish and Smith, 2014):

- test is carried out with as-received moisture content (no drying);
- larger samples are used compared with R70 testing;
- lower oxygen flow rates are used compared with R70 testing;
- high mass to flow rate ratio may be more indicative of reality;
- provides quantification of initial coal self-heating from low ambient temperatures where moisture effects can have a strong moderating influence;
- thermal runaway time can be benchmarked against coals with known self-heating histories.

The results of the R70 and MAB tests do not always agree (Chalmers and others, 2014). The main difference between the R70 and MAB tests is the presence of moisture in the sample in the latter. Moisture can have different and sometimes competing effects on coal heating properties. Low moisture content coals show a steady increase in temperature over time whereas in high moisture coals, the temperature may increase rapidly initially, followed by evaporation which results in the temperature reaching a plateau, usually around 80-90°C. However, once evaporation is complete, the temperature will rapidly increase again until it reaches runaway. Further complications can arise when water, such as rain, is applied to a dry stockpile – heat may be generated from the 'heat of wetting effect' as the coal re-absorbs moisture. This can lead to premature thermal runaway in a coal pile (Beamish and Beamish, 2012). Counterintuitive as it may be, adding water to a coal pile may cause combustion rather than avoid it.

Beamish and Beamish (2012) argue that coal analysis to determine the propensity for spontaneous combustion actually only gives information of the coal's reactivity to oxidation and does not truly represent what happens in the real world. Self-heating is strongly moderated by the intrinsic coal reactivity and the moisture content of the coal. The MAB test may give more real-world applicable results than the R70 test. Beamish and others (2014a) also note that the R70 method has no established repeatability or reproducibility limits as it is a specialised test which only a limited number of laboratories are able to perform. Further, an inter-laboratory study of the test would be costly. However, a dual lab study by Beamish and others (2014b) has shown that the R70 test can give high repeatability and reproducibility (±5%). Consistency of results with older data was also demonstrated which suggests a good degree of consistency of data over time.

Numerous models and mathematical systems have been developed in order to understand and predict the propensity of coal to self-heat. One of these is the Frank-Kamenetskii model, developed in 1959, which expresses the heat balance between the heat generation rate in the centre of a coal pile and the heat transfer out from the surface of the coal pile. This model is often used to predict the best size and shape to keep coal piles safe. The model, however, does not define critical self-ignition temperatures (CSIT), an indication of the specific temperature of a coal pile which, when reached, will mean temperature runaway towards ignition. Sasaki and others (2014) have carried out some modelling work to try to establish a method of evaluating the CSIT for different sized coal piles in different ambient air temperatures. This information could be used to set alarms specifically to protect individual coal piles based on their chemistry and arrangement.

The gas evolution test (GET) can be used to predict gas evolution characteristics of seams being mined. A sample of coal is treated with wet air and the temperature and gas emission profile is monitored. The coal is heated in steps up to 200°C with regular gas samples being sent for gas chromatography (GC) analysis. This method can be used to predict the CO/O_2 deficiency ratio associated with spontaneous combustion of a specific coal which can then be used to calibrate monitors (Morla and others, 2013). Gas monitoring is discussed in more detail in Section 3.2.

3.1.2 Models to predict coal behaviour

Recently, several different groups have been working to produce models to predict coal stockpile behaviour based on coal analyses. Zhang and others (2011) give details of the development of an artificial neural network model for forecasting spontaneous combustion based on testing and monitoring gas indices. These models, however, do not appear to have moved into practical use in the field yet.

CB3 (2015) have made their model commercially viable and have produced an analysis programme called SponComSIM™ which can give expected timings for coal self-heating incidents in certain conditions, such as mine or stockpile configuration. The programme also provides predictions for the most effective chemical treatments to delay or reduce the risk. The model takes into account factors such as ambient temperatures and moisture evaporation as well as the intrinsic R70 value of the coal. The model is based on an extensive database of coals analysis performed internationally and is available from www.cb3mineservices.com

Some parameters of coal characteristics are somewhat specific to the location. For example, the crossing point temperature (CPT) of a coal seam is defined as the point where the coal temperature exceeds the surrounding temperature during testing procedures. So a coal seam could have a CPT of 160°C which means that, once it has reached this temperature, it enters the 'runaway' phase and will ignite and combust. This CPT is sometimes used as an indication of propensity of coal within a mine to spontaneously combust. Morla and others, 2014 explain this as follows:

- a coal seam with a CPT of 160°C and a moisture content of 2% has a low susceptibility to spontaneous combustion;
- a seam with a CPT of 140–160°C and a moisture content of 2–5% is moderately susceptible to spontaneous combustion;
- a seam with a CPT of 120–140°C and a moisture content of more than 5% is highly susceptible to spontaneous combustion.

Spontaneous combustion during mining is a particular problem due to the sudden exposure of coals to oxygen in a limited amount of space. Newly mined coal in goaf regions and mine shafts can also be a risk. Whilst ventilation can reduce the risk of CO build-up, it also introduces oxygen into the working area. It is the balance of gases at the face of a coal seam which is vital to keeping the combustion risk low. Cliff and others (2014) argue that the most important area of improvement in the control of spontaneous combustion incidents in underground coal mines is through the design of mining operations. Modelling, especially computational fluid dynamic modelling, based on pressure differentials around goafs can help identify potential areas of concern to allow proactive treatments such as coating with inert materials or changes in air flow (*see* Chapter 4), is a powerful safety tool.

Figure 5 shows the pattern of heat growth through a coal seam followed by an image of the oxygen distribution within the seam area. This image is included here to show the detail of information available from monitoring and computational systems which can map out where incidents are occurring, how fast they are occurring and can therefore help identify the best means to control the reactions which may lead to a combustion event (Cliff and others, 2014).

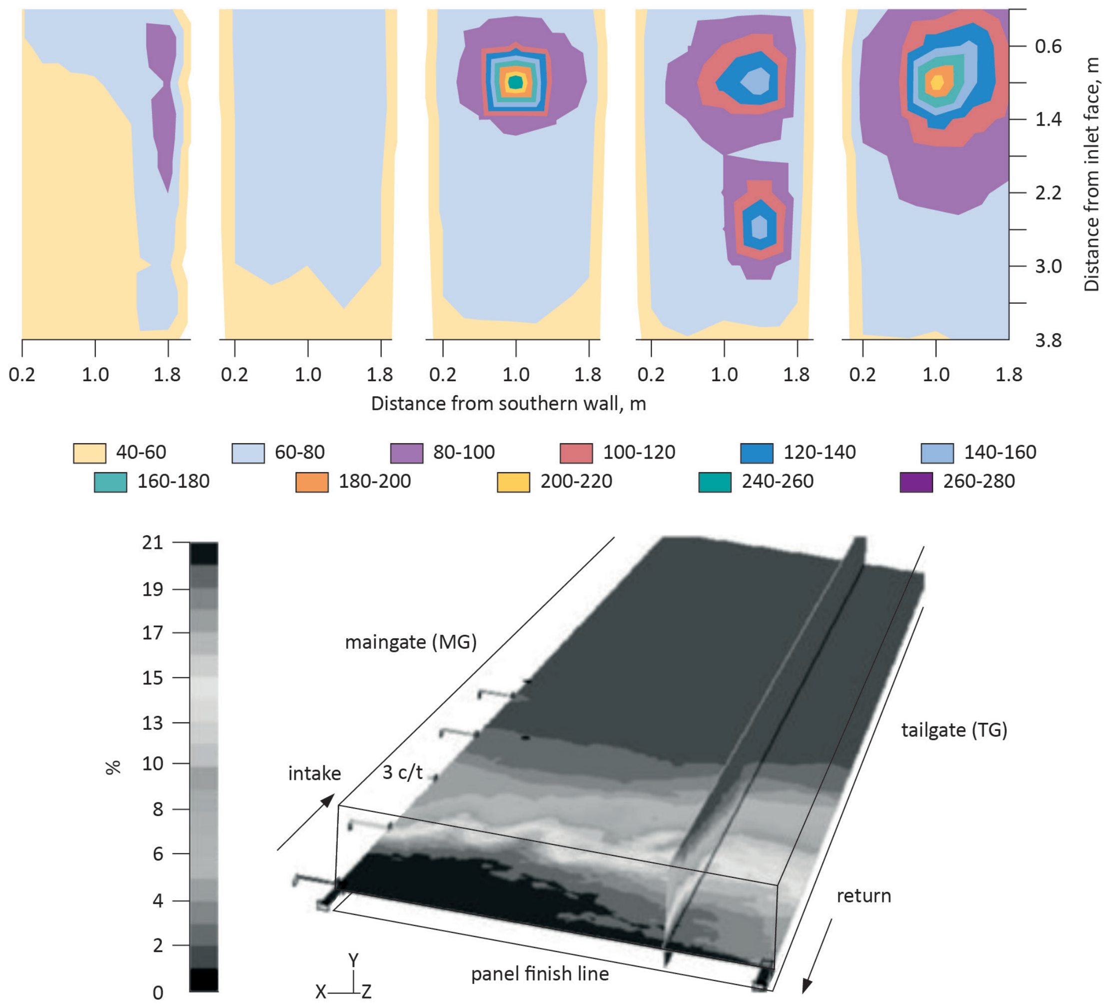

Figure 5 Hot spot development and oxygen gas distribution in a long-wall goaf (Cliff and others, 2014)

At the moment, mathematical models like this are still complex and expensive. However, ACARP (Australian Coal Association Research Programme) has coordinated significant work in Australia which has meant that coal operators have tools to hand to help prepare site management plans. As will be discussed in Chapter 4, modelling and analysis are intrinsic to determining site specific information and establishing best practice approaches both at the onset and during continued production at coal mines.

3.2 Monitoring as a preventative measure

The prevention of spontaneous combustion events relies heavily on the monitoring of gases and conditions which indicate that a problem is developing. In all cases of spontaneous combustion, there is a build-up period of gases and heat before any flame arises. This reaction and smouldering period theoretically gives plant and site operators a chance to detect and prevent an event before it occurs.

Figure 6 shows the process of a smouldering fire that never reaches the flaming stage. Figure 7 shows the build-up of a smouldering situation into a full fire and then the fire decay. Figure 6 demonstrates a common situation in coal piles where heat is generated but no fire actually occurs. However, this still results in a loss of coal and the generation of polluting gases. Figure 7 shows what happens in a spontaneous combustion incident. Ideally detection systems will identify heat or gases produced from the coal during the growth phase and will allow preventative measures to be made in time to avoid any fire outbreak (Mendham and others, 2012).

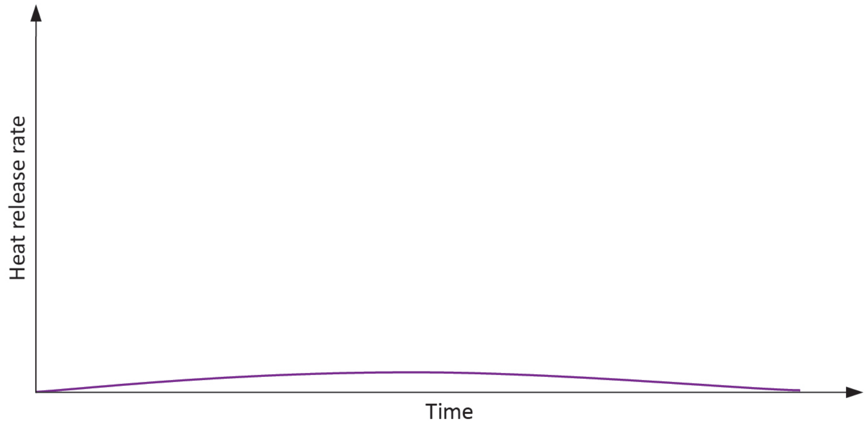

Figure 6 Design fire cure for smouldering fire (Mendham and others, 2012)

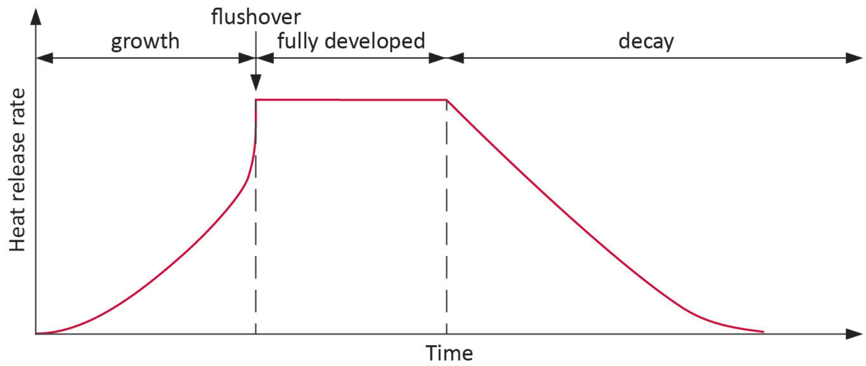

Figure 7 Full extent fire curve (Mendham and others, 2012)

Newcastle Coal (2014) have defined five stages of spontaneous combustion, as shown in Table 2.

Table 2 Stages of severity and risk of spontaneous combustion (Newcastle Coal, 2014)

Risk level	Stage of severity	Condition
Low	Stage 1	Coal gives off steam
	Stage 2	Coal gives off localised white smoke
High	Stage 3	Coal gives off plumes of white smoke
	Stage 4	Coal burns with yellow sulphur smoke
	Stage 5	Coal burns with flames

The identified stage of spontaneous combustion can help determine what remedial action should be taken – dozing, suppressant and so on (*see* Chapter 4).

3.2.1 Gas monitoring

The sampling of gases from mines and coal stockpiles can be problematic because of the random size, shape and conditions of the areas to be monitored. As discussed in a previous IEA CCC report by Sloss (2013), quantification of gases emitted from these sources is possible, but requires standardisation of sample position locations followed by the use of appropriate activity values to scale the estimate up to account for total volumes. For gas monitoring, this level of quantification is not necessary – rather, monitoring is continuous and is more concerned with detecting rises and peaks in emissions than actual total volumes over time. Gas monitoring in mines and workplaces associated with coal is largely performed for two reasons:

1. to detect and avoid incidences of dangerous levels of gases, which could lead to poisoning, asphyxiation or combustion; and/or
2. to monitor and assess possible long-term exposure to elevated levels of potentially harmful gases.

There are numerous systems designed to monitor and measure gaseous emissions, based on simple real-time light and wavelength analysis through to more complex chromatography and other wet chemical approaches. This report is only concerned with monitors which can assess emissions from coal in an online, real-time manner.

According to Rahm (2014) the first line of defence in fighting a fire in a coal handling system is to install carbon monoxide (CO) detectors as well as fire detection and suppression systems. CO is an early indicator of self-heating activity and can be indicated as a map to the operator to allow identification of the areas of concern within a pile. CO is preferred over heat as an early indicator since it provides an earlier advance warning (Geijs and Ruijgrok, 2014). CO monitors will be set-up to suit each location on a case by case basis but are often set to trip at concentrations of around 5 or 10 ppm (Mendhan and others, 2014).

However, Mendham and others (2014) suggest that CO detection is not always suitable as an early fire detection option. Tests carried out in Queensland, Australia, implied that the CO produced from a simulated overheating conveyor belt bearing housing did not display a reading on the CO sensors but the situation did result in the tripping of the VBFD system (*see* Section 3.2.2). Mendham and others (2014) suggest that background CO levels could mask levels of CO associated with an early stage flame incident which could result in delayed fire detection.

According to Cliff and others 2014, gas detection systems have improved significantly in recent years and the systems used are faster and more sensitive than they used to be. Gas analysis times, even with complex gas chromatography systems, have been reduced from over 30 minutes to under one minute and the sensitivity is now in the ppm range for most gases. Most mines will employ monitoring systems which detect the major gases of concern – CH_4, O_2, CO and CO_2.

Du Plessis and Spath (2014) note that active suppression systems, which respond immediately to potential explosive situations, comprise five main components:

1. **Detecting sensors** – to detect certain wavelengths generated by an explosion (normally Dual IR), several of the gases listed earlier or to monitor heat/light (normally UV).
2. **Suppression containers** – these will be pressurised containers filled with a suppression agent that will be released upon activation.

3. **Electronic controls and self-checking systems** – to allow automatic and manual calibration and checking as required.
4. **Dust containers** – this will be a filter or impactor to keep the gas monitoring system clear but can also be used to evaluate the level of dust build-up in the area as well as to provide potential samples for further analysis.
5. **Flow nozzles** – the rate and volume of air flow are required to monitor and calculate the volumes and concentrations of gases in the mine.

Flow monitoring is intrinsic to calculating the concentration of gases in a space. Flow monitoring is also intrinsic to gas flow throughout a working mine, to ensure clean air flow to those working underground. Flow monitors will therefore be involved in both gas monitoring systems and air ventilation systems. Belle (2013) argues that flow monitoring is still liable to large errors – ±20% is accepted in some situations. Ventilation velocities are commonly set to suit different locations within an operational mine. Ventilation shafts will have higher ventilation velocities than downcast shafts. The balance of air movement within the mine is critical to safe operations. Belle (2013) suggests that real-time air velocity monitors are critical to the safety of mines and suggests that they are not used widely enough in the industry, especially in Australia. As shown in Figure 2 in Chapter 2, air flow is often the key to the rate at which spontaneous combustion occurs.

Belle (2013) gives a simple image in Figure 8 which demonstrates the critical hazards of different minerals, including coal, which will be used to define minimum air velocities required in a mining situation – that is, the defined maximum level for any component which, should not be exceeded. The values given in the figure are examples, but give an idea of the kinds of levels which may apply in some mines.

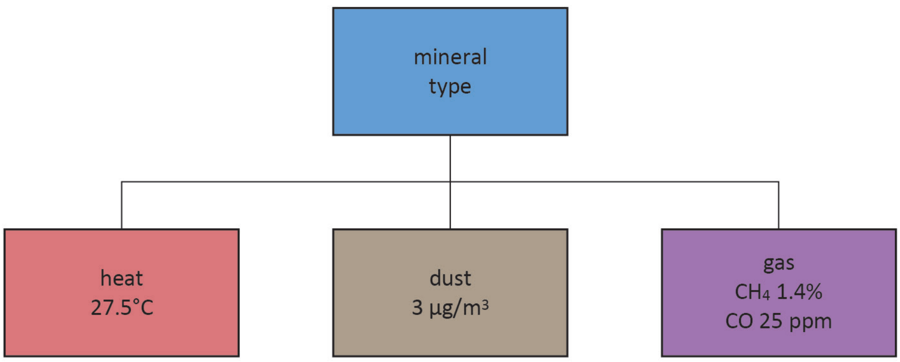

Figure 8 Critical hazards in defining minimum air velocities (Belle, 2013)

The ratio of gases is often used as a trigger to predict when spontaneous combustion may occur. There are several ratios used (Mason, 2012):

- Graham's – CO x 100/(oxygen deficiency). Ranges from <0.4 in normal air to >3.0 in an active fire
- Young's – CO_2/(oxygen deficiency). Used more for confirmation than indication of a fire
- Jones-Trickett – (CO_2 + 0.75 x CO – 0.25 x H_2)/(oxygen deficiency)
- Morris – (nitrogen excess)/CO+CO_2)

The suitability of the type of ratio used and the actual trigger value will be determined on a case-by-case basis to suit the coal and the test site. This will be done with a combination of modelling and expert judgement based on previous experience and site-specific analysis.

Coaltech (2009) suggest that the use of a hydrocarbon 'signature' has advantages for early detection since hydrocarbon release occurs at low temperatures. A signature also has an advantage over a fixed trigger level in that it is not affected by dilution – it is independent of the concentration of other components such as O_2 and CO_2.

Some mines in Australia and China have radon monitors at the surface of mines detecting radon which is released from ground heating events (Cliff and others, 2014).

CB3 (2015), who developed the SponComSim™ model discussed earlier have developed a further testing programme, called SponComGas™, to evaluate the unique gases which are emitted from different coals as they heat. This gas signature, determined by gas chromatography, tends to be coal-dependent and can be used to fine-tune the gas detectors used at a site to provide a more accurate indication of potential self-heating and combustion events.

As mentioned earlier, CO is a good indication of oxidation but, since CO is also present in the background air at some sites, it is the change in CO concentration rather than a fixed value which is important. Hydrogen can also be monitored although Levi and others (2013) suggest that hydrogen production is not necessarily related to the temperature of the hot spot in a coal pile but rather more related to how much moist coal is downstream of the hot spot. The presence of ethylene and continued increase in ethylene concentration is a reliable indicator of an advanced self-heating event. It is therefore useful as a high level trigger in a Trigger Action Response Plan (TARP).

The selection of monitoring systems is site specific, depending on the legal requirements in terms of health and safety, as well as the site-specific requirements to deal with challenging coals or mine structures. Most mines will involve one or more of the following systems (Mason, 2012):

- **Telemetry fixed sensor systems (in situ underground, providing real time data)** – these could be gas, temperature, flow and light/UV monitoring systems.
- **Tube bundles -** systems providing a trapped sample for later analysis.
- **Portable gas detection systems** – which will be moved along with the coal face, machinery or relevant member of staff.
- **Gas chromatographic system** – can detect with far more accuracy than other systems.

Telemetric and tube bundle systems are the most common and will normally be used to monitor O_2, CH_4, CO and CO_2. Portable gas systems also monitor these gases but tend to be smaller units for carrying about.

Mason (2012) emphasises that these monitoring systems are suitable for real-time analysis but cannot always be relied upon to provide accurate and valid data following a combustion or explosion event. Systems become damaged and sample readings skewed. This will mean that there will be an issue trying to make sense of gas data around the time of the incident and afterwards. This will of course hamper studies to determine the gas concentrations of an area and, in some cases, will mean that it is unclear whether an area is safe to re-enter following an event.

On 19 November, 2010, 29 miners were killed in the Pike River coal mine in New Zealand as a result of a series of explosions (Figure 9). Although there were monitors in place, the main fan underground failed during the explosion as it was not explosion protected (Lewis, 2014). Also Pike River was a mine with 'difficult geological and topographical conditions' the disaster 'was avoidable' according to a Royal Commission investigation (Bell, 2013). Typical methane gas contents at the mine were 3–6 m^3/t at a seam depth of 60–100 m, managed by a combination of pre-drainage and ventilation. Ventilation was provided by a single fan adjacent to the base of the up-cast shaft, extracting about 120 m^3/s of air. The investigation found that the mine had a sub-standard gas monitoring system and no fully functioning gas monitors in the mine ventilation return.

Figure 9 Fire burning at top of fan shaft after fourth explosion (Bell, 2013)

The explosion at the mine is estimated to have involved around 10,000–30,000 m^3 of methane. Even after the Royal Commission investigation, it is not clear what ignited the gas but it is not believed to be a spontaneous combustion event. Three more explosions occurred after the initial event. This incident led to significant reassessment of the management of risk within coal mines. Changes to spontaneous combustion management plans (SCMPs) which resulted in New Zealand as a result of this event are discussed more in Chapter 4.

When working properly, a monitor will measure and record the emissions and build-up of selected gases. Each value will be analysed within a site-specific system which is established such that the alarm or trigger point is safe. This means that the alarm is set to trigger a response (such as increased ventilation or site evacuation) based on parameters which have been set based on local conditions to ensure the safety of all staff and equipment. These guidelines and trigger response plans are discussed more in Chapter 4.

3.2.2 Heat/light monitoring

One of the most obvious ways to determine if a coal pile is heating is to monitor the temperature. Thermocouples are often used in long standing coal piles to record and monitor changes in heat profiles. However, Coaltech (2009) do not recommend fixed thermocouples as they may be damaged in use and have proved unreliable at some sites. Calibrated thermocouples are superior. Light sensitive UV (ultra-violet) and IR (infrared) monitors facing coal piles can provide an image which will pin-point areas of concern within a coal pile which may not be picked up by randomly placed thermocouples. In many situations, visual monitoring for signs of smoke or glowing are enough to identify a problem. It is common for temperatures in long standing piles to be monitored regularly and recordings made. Depending on the situation, trigger or alarm temperatures may be defined which will initiate further action. For example, Newcastle Coal (2014) list their stockpile temperature monitoring triggers as follows:

- <50°C – continue scheduled observations (weekly)
- 50–70°C – continue daily observations and measure temperature daily
- >70°C – implement remedial action. Continue daily observation and daily temperature measurements, if safe to do so.

A previous IEA CCC report by Nalbandian (2010) gives a detailed review of computer- and internet-based monitoring and prediction systems which can be used to monitor heat build-up in stock-piles in a real-time basis.

In the SCMP produced by AngloCoal (2008), there is a statutory reporting requirement for monthly visual inspections of all areas of a site including the requirement to produce a quarterly map of areas affected by spontaneous combustion. These inspections must be accompanied by a monthly action plan as to what action should be taken to limit any risk.

In the Jharia coalfield in India there are commonly several fires under way in underground locations and these are monitored from the surface using thermal IR sensing. Uncontrolled fires in remote locations can be viewed by such IR or with night-time thermal imagery, often from the air (Coaltech, 2009).

Since mines are generally dark and dusty work environments, video sensing is not commonly used for normal monitoring purposes. However, Mendham and others (2014) suggest that VBFDs are often superior to CO monitors for the detection of potential fire incidents. VBFDs can monitor a change in light which signals development of a flame (light) or reduction in visibility (smoke). Demonstration scale tests concluded that the very early detection with the VBFD in simulated fire conditions out-performed the CO sensor. However, VBFD systems do need to be tested on robustness to ensure their applicability in mining situations. VBFD systems are basically CCTV (closed circuit television) cameras which are protected from the mine environment to be intrinsically safe. For the moment, Mendham and others (2012, 2013, 2014) suggest that both VBFD and CO systems are used simultaneously.

3.3 Prevention of spontaneous combustion during transport, handling, storage and stockpiling

All coals can self-heat and the longer coal is left unguarded, the more likely self-heating will occur. Spontaneous combustion can occur almost anywhere where coal is left for extended periods. Movement can help – by breaking up hot spots – or hinder – by creating increased air flows. Coal must be watched and monitored at all stages of the coal chain. Coal storage vessels are commonly designed to limit self-heating. Since air is often a contributor to the reactions which result in ignition, controlling the air flow to the coal is an important part of limiting incidents.

Coaltech (2009) summarised five main rules for the prevention of spontaneous combustion:

1. Stop heating by stopping airflow or keep O_2 below the critical concentration.
2. To prevent heating becoming combustion, the velocity of airflow must be enough to remove the heat as fast as or faster than it is being produced. The likelihood of spontaneous combustion increases with an increase in the pressure differential across the material.
3. The likelihood of spontaneous combustion increases with an increase in resistance to airflow
4. The pressure differential can control an event – the relationship between path resistance and quantity of airflow is critical to ventilation systems in problem areas.
5. The likelihood of spontaneous combustion increases with an increase in depth.

It is clear that understanding and controlling the air flow around coal is the key to controlling the rate of a spontaneous combustion event. The following sections look at the methods used to prevent coal self-heating through the coal transportation chain.

3.3.1 Storage conditions

Cliff and others (2014) summarise the most important factors affecting spontaneous combustion in stockpiles:

- reactivity of the coal (as described earlier);
- shape and size of the stockpile;
- time in storage;
- particle size distribution;
- moisture content;
- access to oxygen.

The key to avoiding spontaneous combustion is to control as many of these factors as possible. In simple coal piles, air entrainment can be limited in a number of ways (Geijs and Ruijgrok, 2014):

- reducing the surface of the exposed pile;
- minimising water percolation into the pile (water creates channels which can increase airflow once the pile has dried);
- reducing segregation during handling;
- compressing the coal to reduce the voids between the particles.

The shape of coal piles is also important. The angle of repose can be manipulated to keep wind ingress to a minimum. To some extent, this approach is dependent on the local knowledge and skill of the staff working at the handling site.

Coaltech (2009) describe several methods which are used to monitor coal stockpiles in order to reduce self-heating:

- **Dynamic cone penetrometer (compaction testing)** – to confirm consistent compaction;
- **Densimetric testing** – compaction testing based on void detection and minimisation;
- **Gas testing** (as discussed earlier) to detect oxidation events and to determine where air flow is occurring in order to pin point areas requiring further compaction.

Silos are designed to provide suitable storage for coal whilst reducing combustion risks. Coal stored in a silo has much less exposure to air and water. The piling of coal in tall thin silos also promotes compression of the coal to reduce airflow. Silos which fill from the top and empty from the bottom, via a hopper, mean that all the coal has a shorter residence time – first coal in is the first coal out. However, because of the effectiveness of the compression effect, self-heating is actually more likely in the top layers of coal stored in silos, where the surface area meets the air. This means that many silo systems operate a 'first in – last out' approach. In the Vattenfall Tiefstack project, comprising two silos, coal has been stored for over 15 years. The Salmisaari plant in Helsinki, Finland, has four underground silos and is reported to store coal for up to six months without any problems (Geijs and Ruijgrok, 2014).

Silos can be fitted with monitoring systems (*see* Section 3.2) to monitor coal during long-term storage and air flow in and out can be closely controlled with valves and baffles.

Geijs and Ruijgrok (2014) report on the spontaneous combustion incident that occurred at the new Vattenfall power plant in Hamburg-Moorburg. Temperatures in the storage dome reached 70°C and 50 t of coal were lost. Geijs and Ruijgrok argue that the open circular design of the storage area meant that the large exposed surface area of the coal could not be adequately monitored for CO.

Figure 10 shows the layout of Duernrohr coal-fired power plant in Austria. The coal is stored in a large open coal yard behind the plant. It has been noticed that coal with a volatile content above 40% is 'frequently' found to lead to potential spontaneous combustion events. To control this, the coal is kept compacted by heavy machinery. Infrared cameras were considered but these have been found to be unnecessary (Kinger, 2015).

Figure 10 Duernrohr Power Plant, Austria (Photograph courtesy of Kinger, 2015)

According to Cliff and others (2014) self-heating prevention is best achieved by controlling the air ingress to stockpiles and spoil piles. The covering material should limit the inflow of air as much as possible and for this reason, moist materials work well – they reduce the voids in between the particles of coal at the surface of the pile. Clay rich materials have high water retention capacities and are useful for creating barriers 1–2 m thick. Sandstone has a low water retention and therefore covers need to be much thicker (5–10 m). If stockpiles or spoils are to be left for extended periods of time then the covering material must be resistant to erosion and geotechnical instability.

In addition to stockpiles, newly mined coal can also be prone to spontaneous combustion during transport. In some cases the most risky areas are those around loading and unloading stations, under vehicles, conveyors and silos, where spilled coal can accumulate and react. These areas are commonly marked within operational guidelines and SCMPs as of concern and will be regularly monitored, either by monitoring equipment or by routine visual checks from staff (Newcastle Coal, 2014).

Residence time can be an important safety key – the faster the coal is moved to its final destination, the less time there will be for spontaneous combustion to occur. As with silos, discussed earlier, most plants will operate a first-in first-out system so that no coals are left longer than is necessary. Any stockpiles created will be inventoried but will also be accompanied by a stockpile monitoring system. This will include (Newcastle Coal, 2014):

- date of stacking;
- coal origin;
- moisture content (scheduled but also recorded daily);
- type of coal and susceptibility to self-heating;
- weather conditions (scheduled and recorded at 15 minute intervals);
- stockpile temperature readings (scheduled and recorded at eight hour intervals);
- further comments and observations;
- reclamation date.

Newcastle Coal (2014) have a system in place whereby the system will provide an alert if a stockpile has a residence time approaching two months. At this point the coal will be prioritised for movement. In some situations, thermal imaging can be introduced. Recirculating the coal stockpile by picking it up and relocating it via the reclaiming and conveyor system can also be used as a method to dissipate heat (Anglocoal, 2008).

3.3.2 Inhibitors/suppressants

As discussed in Section 3.3.1, compaction and/or covering of the stock with inert material can reduce the air flow which is the major cause of spontaneous combustion. This material can be rocks or earth at a mine site, or more specific materials during transport, handling and storage at a power plant

Inert and flame resistant materials have been developed which can be sprayed onto stock-piles to both limit the air flow to the coal to reduce spontaneous combustion chemistry, and also to suppress any heat activity before it becomes a flame.

GE has developed an anti-oxidant material to control spontaneous combustion (US patent 5,576,056) that was reported on by Beamish and Smith (2014; *see also* Beamish and others, 2013). This material has been sold commercially by GE Ltd in the USA and internationally. Figure 11 shows the oven test results (to quantify the propensity to spontaneously combust) for various tested coals.

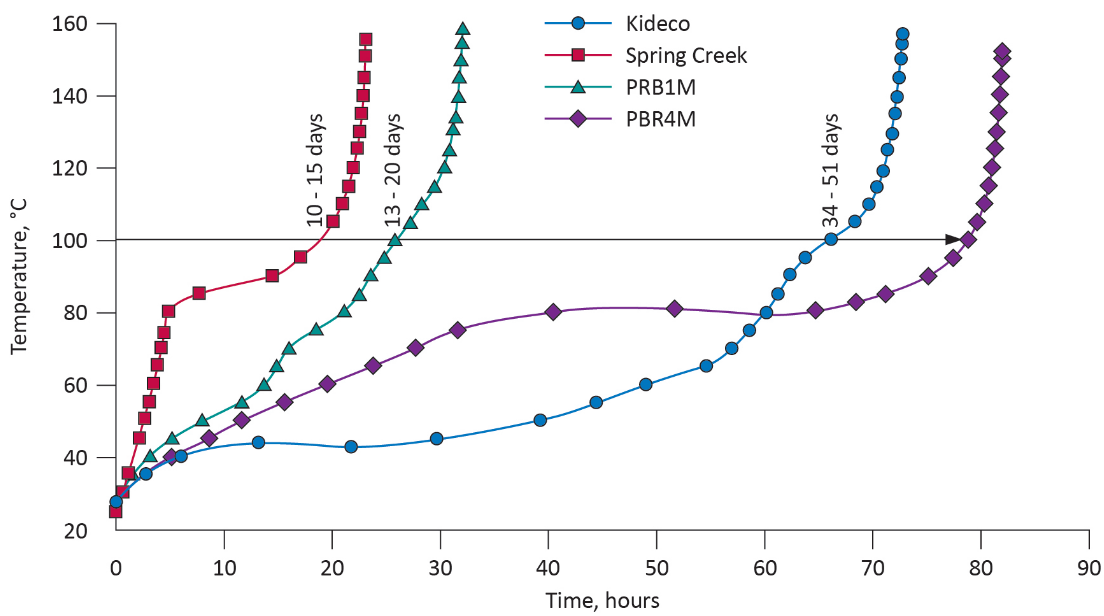

Figure 11 Adiabatic oven test results for raw and treated PRB coal (Beamish and Smith, 2014)

The graph shows that Kideco coal, an Indonesian low sulphur, low ash subbituminous coal, is highly prone to self-heating whilst the Spring Creek coal is a significantly less reactive bituminous coal from New Zealand. The PRB coal is almost as reactive as the Kideco coal, with self-heating reaching a runaway state within 13–20 days. However, with the added anti-oxidant material, the PRB (PRB4M) remains stable for much longer. Similar levels of success have been reported for other coals, with coals being safe to store for up to three times longer than in the untreated form.

Beamish and Smith (2014) report other advantages of using the anti-oxidant application:

- less coal degradation, reducing dust issues;
- preservation of calorific value;
- reduction in environmental and safety impacts from gas emissions associated with hot spot development.

The treatment has proven successful in field tests too, as shown in Figure 12.

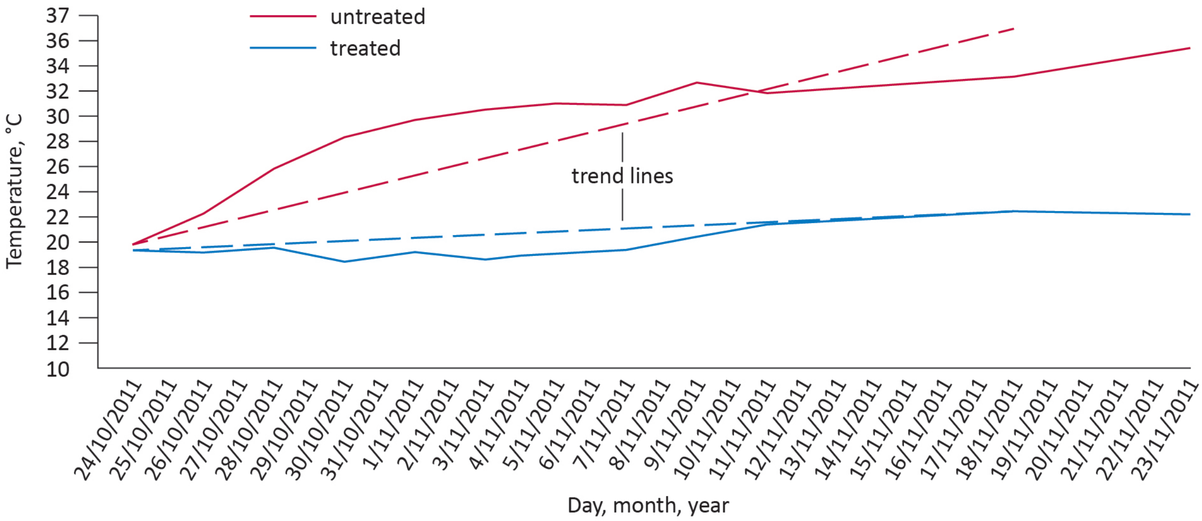

Figure 12 Field experience with the use of anti-oxidant B (Beamish and others, 2014b)

The raw data and simplified trend lines in Figure 12 show the distinct difference between the heating rate for treated and non-treated coals in stock piles. Tests continued up to 60 days showed that the temperature of the treated coal remained well below temperatures of concern. Although monitoring to ensure complete safety is always necessary, treatment like this will help limit the risks commonly associated with storing volatile coals for extended periods of time.

Figure 13 shows the results of testing the anti-oxidant at an unnamed storage site. Without treatment, the site reported an average of 5.8 fires occurring per month. With the application of the treatment, the average number of fires per month dropped to 0.875. During the same period, the dust measured in the storage and handling areas also dropped significantly – around 84% in the trestle drop and 91% in the hopper drop. This reduction in dust will significantly reduce the risk of dust fires/explosions, plus it will mean a cleaner working environment and a reduced loss in stock over time. The temperature control effect of the anti-oxidant continued through the hoppers and dumper offload, suggesting that the effect remained in place even through coal handling and transport. There is no mention of any negative effects on the coal combustibility once it is delivered to a utility boiler. GE has developed the anti-oxidant material to control spontaneous combustion (US patent 5,576,056) that was reported on by Beamish and Smith (2014; *see also* Beamish and others, 2013 and 2014b. The anti-oxidant materials developed by GE and reported on by Beamish and Smith (2014) are sold commercially through GE Water http://www.gewater.com/products/coalplus-anti-oxidants-binders.ht

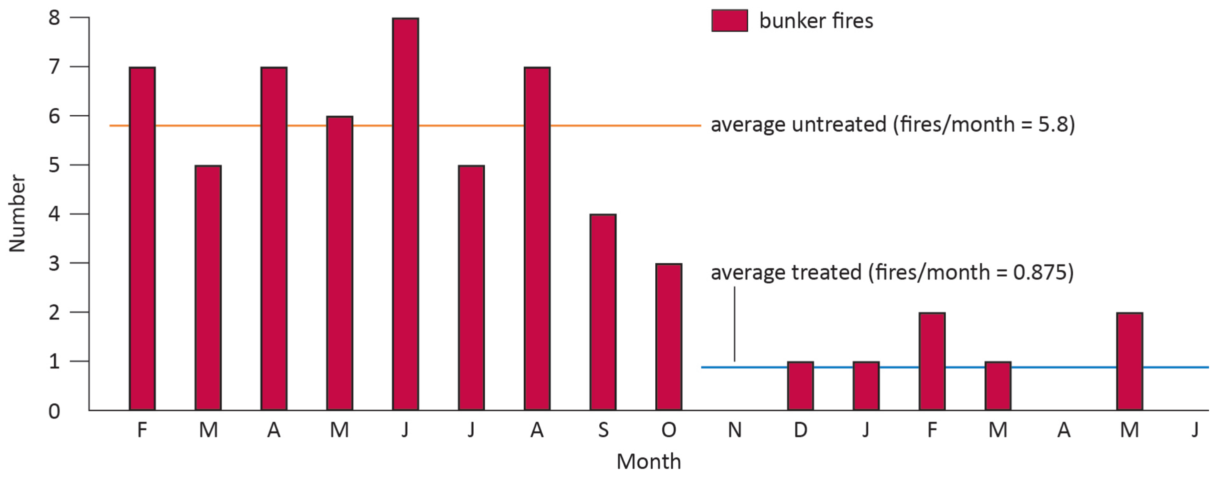

Figure 13 Field experience with anti-oxidant B in bunkers (Beamish and others, 2014b)

Figure 14 shows the application of suppressant to a spontaneous coal incident in a coal pile in Indonesia. Suppressants are supplied by commercial companies such as Daya Mitra Multipratama in Jakarta (DMM, 2015).

Figure 14 Application of spontaneous combustion suppressant (DMM, 2015)

High pressure and liquid nitrogen can be used to suppress fires but are more often used in response to actual outbreak events (*see* Section 3.5).

3.4 Prevention of spontaneous combustion in mines

The majority of mining explosions are the result of a build-up of methane which is then ignited by a spark. In most accidents this spark comes from a piece of equipment within the mine or some friction incident. Spontaneous combustion of coal within mines could cause ignition of this methane and so this is mentioned briefly here.

3.4.1 Ventilation

The explosive range for CH_4 in air is around 5–15%, with maximum explosive risk at a range between 6.5% and 7.5%. The minimum ignition temperature is around 650–750°C but can be as high as 1000°C, depending on the size of the ignition source. The resulting explosion can take between 0.3 seconds for a 9.6% methane composition to 8.0 seconds in 12–14% mixtures. There are therefore 'sweet points' at which explosions will occur and these will vary according to the different conditions at the time (Belle, 2013).

Up to one third of the power required at an underground coal mine is used to operate the ventilation systems. The most important piece of the ventilation system is the primary fan. The importance of these fans is reflected in the number of national and international standards (such as ISO – International Standards Organisation; BS – British Standards) which apply to the testing of fan installation and performance (Lewis, 2014).

Modern mines have monitoring systems installed to measure O_2, CO_2, CH_4 and CO down to 1 ppm. The output from these monitors is commonly recorded and reported in real time to ensure that operators and staff can be aware of the situation at all times and also so the data can be used to automatically regulate fan operations and ventilation, such as the MineBoss 2.0 monitoring and control system (Lewis, 2014). MineBoss is a commercial centralised control system which aims to coordinate everything in a mine (*see* Figure 15). Data from monitors and sensors feed into the control centre in a real time manner which allows the mine operator to ensure a clean, safe and efficient working environment in all areas simultaneously. MineBoss is produced by PBE (2015), although other commercial systems available.

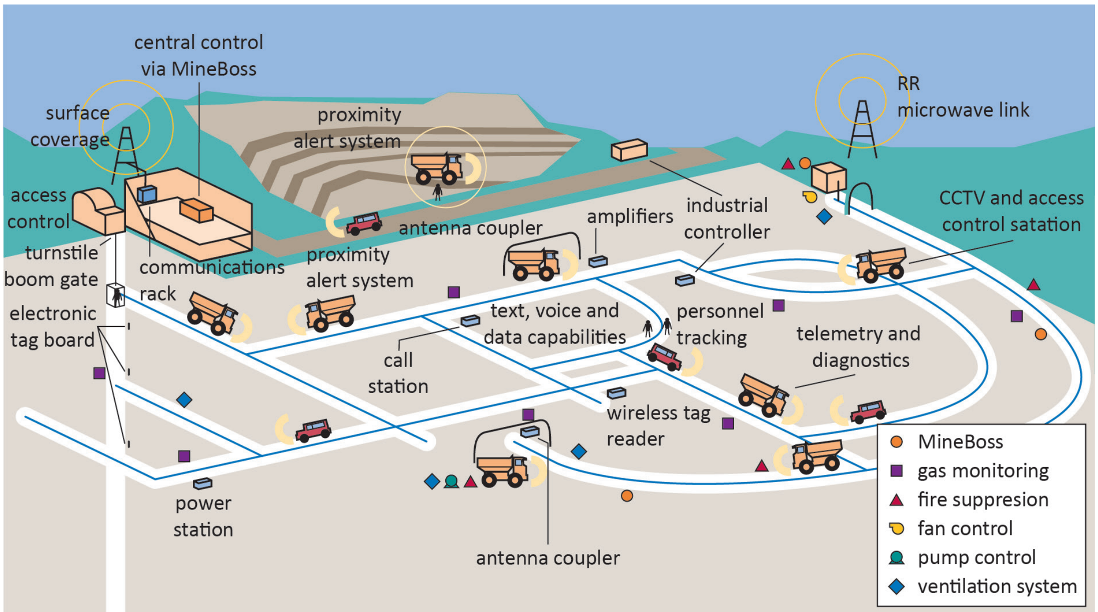

Figure 15 MineBoss system to coordinate sensors, monitors and ventilation within a working mine (PBE, 2015)

Morla and others (2013) noted that the early stages of spontaneous combustion at the steep incline mine at Singareni Collieries in India were signalled by a release of CO. However, the ventilation flow within the mine ensured that the CH_4 in the mine was moving in a different direction, thus reducing the risk of an explosion. The coal mining in this mine is carried out with blasting as the seams are relatively thick (up to

15 m). The risk of explosions is minimised by coordination of the timing of the blasts with appropriate ventilation procedures.

Cliff and others (2014) note that a number of mines now maximise air ingress in active long-wall goafs by constructing pressure balancing chambers. These chambers can be manipulated to either remove pressure differentials between areas in the mine or can be pressurised to prevent air ingress.

3.4.2 Spark avoidance

Within mines there are strict rules relating to the banning of naked flames and the use of intrinsically safe electrical equipment to avoid sparks. The mine disaster in Nova Scotia in 1979 which claimed 12 lives was due to frictional ignition (Belle and others, 2012). Even gas monitoring systems and their associated electronic equipment can pose a spark risk. For this reason, Aminossadati and others (2014) proposed fibre-optic based monitoring systems for underground mines in order to remove all risk completely.

Chilled water sprays are often used to prevent frictional ignition in coal mines. According to Belle and others (2012), historical data suggests that frictional ignition has been the greatest cause of major explosions in mines. Chilled water sprays are commonly used in deep mines, especially in South Africa, as a means to managed heat and dust. The spraying of chilled water onto picks and cutting surfaces as well as the seam face area has been shown to result in rapid cooling and the avoidance of frictional ignition.

Spontaneous combustion can be the cause of ignition of an explosion. This may come from a newly exposed coal face or from deposits of newly mined coal in the working areas. Inert materials can be sprayed onto surfaces (*see* Section 3.4.3 to follow) or mixed with any coal dust deposits to reduce this risk (du Plessis and Spath, 2014).

3.4.3 Coatings on pillars and exposed surfaces

According to Ashton Coal (2014) spontaneous combustion may occur in a pillar in a mine due to high pressure differentials (increasing the rate of flow of gases); dry, cracked or stressed coal surfaces; or boreholes or geological structures forming air paths through the coal. The best means to reduce combustion events are therefore methods that reduce the differential air pressure (reducing air flow, redesigning ventilation circuits) or sealing and spraying surfaces. The materials discussed in Section 3.3 for coal stockpiles can also be sprayed onto exposed coal surfaces and pillars to reduce spontaneous combustion events. High pressure foam plugs containing air, N_2 or CO_2 can be specifically applied in awkward corners and gaps. Fillers and sealants can be used to exclude oxygen from areas of concern in mines and goafs. These are commonly guar gum-based gels which act as sound sealants as well as lasting up to twelve months in situ. Shotcrete can also be used. Cliff and others (2014) also report on the use of water mists containing additives and retardants in targeted areas.

The Jharia coalfield in India is prone to spontaneous combustion in both opencast and deep mines. These fires have been treated with inert gas injection, sand/bentonite slurry flushing and surface sealing (Coaltech, 2009). Coaltech (2009) reviewed some work carried out in India to evaluate various chemical materials as spontaneous combustion inhibitors. These included sodium chloride, potassium chloride, lithium chloride, ferrous sulphate, ferric chlorate and aluminium sulphate. However there is no evidence to suggest that these tests ever reached the field trial stage.

Cliff and others (2014) note that problems occur with open cut mining of old underground mines in South Africa. During cutting, air can enter through cracks into the old underground workings and cause combustion. Numerous methods to reduce incidents are employed, depending on the circumstances:

- **Cooling agents** – high pressure water;
- **Sealing agents** – combining an inhibitor (such as calcium chloride) with a binding agent and a filler such as bentonite. These materials may be unstable and require widespread application which can make them an expensive option;
- **Dozing over** – sand is dumped to close off old workings. This has to be done carefully and completely to avoid any remaining venting;
- **Buffer blasting** – collapsing of old roadways to close of ventilation routes. This has the added advantage of improving stability of the site;
- **Cladding** – placing weathered overburden on top of the working area to exclude air flow and heat.

Chalmers and others (2012) report on the Tasman mine in New South Wales, Australia, where a glowing orange pillar indicated an incident of self-heating. This was detected early enough for preventative measures to be taken. Water was injected to reduce the temperature of the pillar and holes were drilled to ensure that the effect travelled into the pillar itself. Infrared imaging was used to detect the area affected. Shotcrete was then applied in an effort to restrict the amount of oxygen available at the pillar surface, however much of this fractured and fell away. In this instance the concern to the mine was not necessarily an explosion, which could be avoided through control of the ventilation air, but more due to loss of the pillar and collapse of the mine in this area. The final solution to the problem was the application of a flexible membrane made of inert material over the pillar and the system sealed with inert spray foam. The differential pressure between the pillar and the membrane is lower than in the mine itself, thus reducing the oxidation chemistry at the coal surface. Water injection continues as required and the situation is regularly monitored using infrared cameras. The cost of this approach was estimated at $32,000 AUD and has meant that the mine has remained open and continues to operate productively and safely.

Some mining methods for thick coal seams involve blasting. For example, in the past Charbonnages de France used a method called blasting gallery to extract thick seams at their Carmeaux Colliery. The method is suitable for seams up to 15 m thick where the seam is being developed with the board and pillar system (Coaltech, 2009). A similar approach is now being used at some deep mines in India (Morla and others, 2013). This blasting method has been reported to be risky with coals which are liable to spontaneous combustion. In situations such as these, samples of the coal must be collected and analysed as quickly as possible, with minimum exposure to air, to give an accurate representation of the behaviour of newly exposed coal surfaces. A study at a steep incline mine at Singareni Collieries in India, showed the coal to be highly prone to spontaneous combustion with a CPT of 138°C (Morla and others, 2013). This required that the mining proceed in a controlled manner to reduce the risk of explosion with ventilation being coordinated accordingly.

Coaltech (2009) describes the methods used in several South African mines to reduce spontaneous combustion events. 'Just-in-time' drilling is implemented at many sites to ensure that newly uncovered coal is mined soon after it is exposed to the air. In some mines, drilling and blasting is coordinated to leave buffer sections in place. A first section is blasted and excavated and then the next section is blasted and excavated 20 m away. Once these sections are cleared and a third section is being blasted and excavated, the buffer zone is drilled/blasted and the coal removed. This limits the amount of coal that will be lost should an ignition incident occur.

3.5 Response and control

This Section looks at what is required once the point of no return has been reached – that is, an explosion is imminent and an immediate response is required. Although it is beyond the scope of this report to list every relevant standard, many countries do have standards which apply to fire monitoring and prevention devices and equipment. For example, China has an official standard MT 694-1997, which applies to coal-mine explosion prevention devices (du Plessis and Spath, 2014). Rahm (2014) notes that "over 90% of the fire suppression and detection systems in coal handling systems are inadequate". Rahm (2014) also argues that the majority of installed systems are standard systems which would be used in hotels or warehouses and do not take the idiosyncrasies of coal fires into account.

3.5.1 Fire detection

Du Plessis and Spath (2014) describe the basis of fire detection systems. Ignition may be detected through sensors which are sensitive to light in the UV and IR range. The signal from the sensor triggers the suppression system (*see* Section 3.5.2) which will attempt to halt or control the explosion.

According to Spath (2015), many flame suppressant systems are passive and are activated by a shockwave emanating from an explosion event. This means that the control is relatively slow to react and means that an explosion would be fatal to any personnel within 100 m, or perhaps more, of the blast initiation site. With active barriers, the detection is instantaneous and therefore far more effective at ensuring staff safety. For example, ExploSpot™ (Figure 16) is a methane and coal dust explosion detection and suppression system that is reported to create an extinguishing barrier within 100 milliseconds of an incident. The system includes sensors which monitor target areas for methane gas or coal dust explosions, based on detecting wavelengths emitted by the explosion. The discharge assemblies are also designed to suit the specific site to ensure that the fire-retardant powder is distributed to effectively extinguish any explosion or ignition.

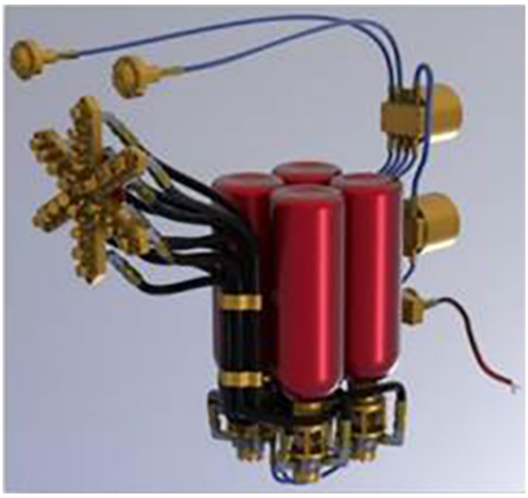

Figure 16 Example of Explospot system (Spath, 2015)

The flame is detected by the elements on the left of the Figure and verified within 3 milliseconds. Within the following 2 ms the valves open and extinguishing agent is released. The systems can be mounted at various locations acting as barriers and also on moving equipment and barriers. This means that these systems can be moved along with personnel as they continue through a working zone and barriers can be provided for each area where staff are currently deployed (Spath, 2015). The system is currently being deployed in South Africa at Sasol mines and Anglo coal operations and has already suppressed methane gas ignition on five separate occasions. Over 400 of the systems have been deployed in China within long-wall operations, road-headers and active barrier installations. According to Du Plessis and Spath (2014) these systems have become legally mandatory on road-headers in all mines in the Shanxi and Liaoning Provinces. A simple internet search provides information on numerous commercial systems which are available for fire control in mining situations.

3.5.2 Suppression and control

Coal silos can be fitted with nitrogen-purging systems which can be used to purge regions of the coal within or the entire contents of a container. The nitrogen is delivered in liquid form via a truck and piped into the bottom of the silo (Geijs and Ruijgrok, 2014). Nitrogen is also used in German mines to quickly suppress and control spontaneous combustion events in situ (Coaltech, 2009).

Within mines, mono-ammonium phosphate powder is a commonly used flame-suppressant, but commercial fire extinguishing agents, such as NAF SIII (a halon-based material) are also used at many mines (du Plessis and Spath, 2014). Commercial fire-suppressants are available to prevent and control heating and combustion. FIRESORB™ can be sprayed over the surface of stored coal or kept nearby to treat incidents. The gel acts to both seal off air and lower the temperature of the coal (www.creasorb.com). For large events complete oxygen removal from the area may be necessary. For example, in the Pike River disaster discussed earlier, a GAG engine was used. The GAG engine is a jet engine designed in Russia to burn efficiently, using aviation fuel, to remove all the available oxygen from a specified area. Mineshield (http://mineshieldky.com/) is a last resort option which provides a safe and protected, closed evacuation area where miners and support staff can evacuate to until the area is clear of any fire or related hazard. It is beyond the scope of this report to review all available fire suppression systems but a simple search on the internet will provide a wealth of available options to suit individual requirements.

There are two fire-suppressant testing facilities, one in Bochum, Germany and the other in Klopperbos, South Africa, which have tunnels to evaluate the performance of explosion suppressants in mining situations (du Plessis and Spath, 2014).

As discussed earlier, spontaneous combustion in coal piles can be avoided and contained using a combination of compression, movement or coverage. However, if a coal pile is actively on fire then there are several actions which may be implemented (Newcastle Coal, 2014):

- isolate the zone of concern;
- if practical, dig out the affected area (with a dozer or similar piece of equipment) and move to a safe area where it can be spread out, cooled, saturated with water, compacted or covered, as required;
- watering can actually make fires worse and therefore water should only be used by experts and in small amounts – sprinkled rather than sprayed;
- if the fire is becoming dangerous then the TARP should be initiated.

3.6 Comments

Prevention is better than cure – there are several ways to predict when a spontaneous combustion event may occur and these are commonly:

- **Coal properties** – determining the behaviour of a fuel and recognising it's inherent self-heating pattern
- **Gas emissions and temperature changes** – monitoring to determine when an event may be arising
- **Visible signs** – glowing embers and smoke emissions

With monitoring in place, early routes for control can be taken, such as ventilation control, dust reduction, and the use of chemical suppressants. In the event of an actual outbreak of fire then stockpiles can be moved, sprayed, or covered with inert materials. In mines, fire control is more challenging as there is a higher risk of explosion and/or roof collapse. Options include ventilation control, and spraying and coating areas of concern. As an emergency response, fire suppression systems are effective but may be costly. Physical clean up may be required after an event, along with investigations and reporting to determine the cause of the event and how to avoid repetition. This reporting and learning is an important part of any site's spontaneous combustion management plan, discussed more in Chapter 4 to follow.

4 Legislation, guidelines and management plans

This chapter looks at how different countries and industries within these countries are working to apply the technologies and approaches discussed in Chapter 3 in practice as part of safety management programmes. Table 3 shows the number of deaths in selected countries as a result of explosions or ground fall. Almost half of the deaths in the USA are due to these events, two thirds in China and just over a third in India. Underground incidents are more common than surface mine incidents. It should be noted that these 'explosion incidents' include accidents due to blasting and other such activities (Harris and others, 2014).

Table 3 Coal mining fatalities caused by explosions, fall of strata, open cut explosives, fall of ground and all fatalities (including other causes) in selected countries (Harris and others, 2014)

	Underground hazards			Open cut hazards			
Country	**Explosions**	**Strata fall**	**Combined**	**Explosives**	**Ground fall**	**Combined**	**~Total**
Australia	0	0	0	0	0	0	8
China	2145 (60.7%)	188 (5.3%)	2333 (66.1%)	17 (0.5%)	35 (1%)	52 (1.5%)	3532
India	74 (14.3%)	114 (22%)	188 (36.2%)	0	5 (1%)	5 (1%)	519
South Africa	3 (3.5%)	21 (24.7%)	24 (28.2%)	0	0	0	85
USA	49 (27.7%)	26 (14.7%)	75 (42.4%)	0	4 (2.3%)	4 (2.3%)	177

~ totals include fatalities due to other causes

Harris and others (2014) report that there were seven underground mine explosions in China between 2008 and 2011, each resulting in over 100 deaths. However, Harris notes the claim that mining deaths in China have been under-reported in the past and that the death toll may be much higher. Older statistics, which simply list an accident as being an 'explosion', do little to help determine how to avoid a repeat of such an event. As reporting requirements improve and the application of SCMPs becomes more common, more accurate and specific data on accidents will become available which will make it easier to identify the true causes of accidents in mines. This will give a fairer indication of what areas need more attention and what can be done to reduce accidents in future.

4.1 International legislation and guidance

There are numerous international standards which apply to safety in the work place and explosion control and avoidance. For example, EN 14591-4:2007 is the European standard for 'Explosion prevention and protection in underground mines'. The standard includes details of approved protective systems such as passive water trough barriers and automatic extinguishing systems. There are also standards relating to explosion suppression, venting, diverting and arresting (du Plessis and Spath, 2014). CEN (Committe European de Normalisation, European Standards Committee) standards are legally binding. These CEN standards are often copied or are translated into ISO (International Standards

Organisation) standards which are not legally binding but can be specified under national legislation. For example, ISO 31000 was introduced in 2009 and is a general standard on the implementation of risk management. It can be adopted or applied to any process or organisation and specifies a framework approach to evaluating risks and embedding management system reporting mechanisms. The standard is quite general, it is its application to the specifics of each industry or organisation which make it useful.

Judging by the number of published SCMPs available, Australia is by far the most active country with respect to this approach to mine safety and management. The Mine Safety Operators Branch of the Division of Resources and Energy in Australia have published MDG1006 – Spontaneous combustion Management Guideline. The document provides assistance in the development and implementation of SCMPs (Ashton Coal, 2014). The International Fire Engineering Guidelines of 2005 have been adopted within the Australian building codes and these have been used as a framework to evaluate the performance of mine fire detection (Mendham and others, 2012). Countries such as China, South Africa and the USA are following behind Australia, rapidly improving guidelines and training available which are appropriate to spontaneous combustion management.

As coal availability changes, the international trade of coal continues to increase. There are national and international laws in place to control the movement of materials some of which pertain to the prevention of incidents such as spontaneous combustion. Since some coals can be categorised as 'self-heating solids', multinational agreements are in place which provide guidelines on the safe storage, handling and transport of these materials. A previous IEA CCC report by Nalbandian (2010) reviewed these international laws in detail. This section will focus on the practical details which are pertinent to controlling the risk of spontaneous combustion events. For example, within Europe there is the 'European Agreement concerning the international carriage of dangerous goods by inland waterways'. Hard coal, coke and anthracite can be excluded from the European Agreement provisions if (Schmitz, 2015):

- the temperature of the cargo is not higher than 60°C before, during or immediately after loading of the hold;
- the estimated duration of carriage is not more than 20 days;
- if the duration of carriage exceeds 20 days, supervision of the temperature is carried out from the 21st day;
- if the master is provided with instructions on how to proceed should there be a significant heating of the cargo.

From this it is clear that coal is regarded as suitable for bulk carriage in vehicles such as ships as long as the temperature is monitored and kept under control.

There is also the 'Convention concerning international carriage by rail' which states that, when carried in bulk, hard coal, coke and anthracite may be carried in open wagons or containers, provided that (Schmitz, 2015):

- the coal is conveyed from fresh extraction directly to the wagon or container (without measuring the temperature); or
- the temperature of the cargo is not higher than 60°C during or immediately after loading. There is also the requirement that the maximum permissible temperature of the cargo is not exceeded during or immediately after loading.

According to Geijs and Ruijgrok (2014) bulk materials which exceed 55°C (104°F) are rejected and will not be accepted for transport under the International Maritime Solid Bulk Cargoes code: Section 4 (fire protection). If this temperature is exceeded during transport then monitoring is intensified. If the temperature exceeds 70°C in any coal being delivered it will not be added to the silo.

In Germany, coal makes up around 15% of the total traffic moving through inland vessels, at a total of 30–35 Mt/y. In 2011 there were 'some incidents' involving hard coal which was being carried in bulk on open dry cargo vessels along the Rhine. The coal self-ignited and the vessels had to be stopped and unloaded. After testing it was discovered that five of the seven samples contained coal which had characteristics which classified them as 'Class 4.2 packing group III' materials – an international standard which relates to the propensity of solid materials to self-ignite. Results from the study suggested that these incidents happen only 'under exceptional circumstances' and should not require the re-classification of coal under the current UN system. However, the German Government decided to consider possible classification of coal under UN 1361 which would require a change in the carriage requirements. Should a change in classification occur then coal shipped inland in Germany would need to travel as 'dangerous goods' within tank vessels. This would add cost to coal shipping and so VDKi (Der Verein der Kohlenimporteure eV; the German Coal Importers Association) took action to carry out comprehensive coal analysis to prove that only a minor number of coals would require this stricter handling regime. Results of the testing were provided to an international committee who agreed that coal (hard coal, anthracite and coke) would be exempt from being defined under UN 1361 and could continue to be transported in bulk under the provisions listed above. This means that coal which has been shown to have self-igniting properties under UN 1361 would require to meet more stringent requirements for transport whereas hard coal, anthracite and coke would not (Schmitz, 2015).

Although the SCMPs discussed in the section to follow concentrate on self-heating management in mines and stockpiles, there will be SCMP or equivalent guidelines defined by coal vendors and suppliers which provide guidance on the transport and handling of a coal based on tests such as R70 (outlined in Chapter 3) which will warn of the propensity of each coal to self-heat and will also include recommendations on monitoring and appropriate trigger levels.

4.2 Spontaneous combustion management plans

Prior to an operator receiving permission to mine, there is the requirement to demonstrate that the mine will be operated in a safe manner. These requirements will vary from country to country and even from region to region but will require the production of some form of guideline or plan. Although these plans may vary to some extent, they will all be based on a requirement to demonstrate that all precautions will be taken to reduce any risk of explosions or uncontrolled combustion. It is increasingly common for SCMPs to be required as part of planning consent for a new or expanded mine. Muswellbrook Coal Company Ltd in Australia, owned by Idemitsu Kosan in Japan, had to produce a SCMP as part of their Development consent to extend the existing mine area in New South Wales (MCC, 2010).

As mentioned earlier, SCMP are most prolific in Australia. The new National Work Health and Safety (Mines) Regulations in Australia have the following requirements under what are now termed Principal Mining Hazard Management Plans (PMHMP_ (GovAu, 2015). The mine operator of a mine must prepare a principal mining hazard management plan in relation to each principal mining hazard identified under the regulations. The PMHMP must provide for the management of all aspects of risk control in relation to the relevant principal mining hazard and be set out and expressed in a way that is readily accessible and comprehensible to persons who use it. It must:

- state the nature of the principal mining hazard to which it relates
- describe how a risk assessment will be conducted in relation to the principal mining hazard
- specify the results of the risk assessment
- specify all control measures to be implemented to control risks to health and safety associated with the principal mining hazard
- be prepared after considering the matters specified in the national schedule that apply to the plan.

In Australia, the focus is largely on these PMHMPs whereas the older term was SCMP still appears in much of the literature.

Other countries are following Australia's lead. Spontaneous combustion is relatively rare in underground mines in South Africa although the Witbank and Sasolburg areas still experience issues in surface mines. Collieries such as the Springfield Colliery had particular problems for a number of years. Some of the problems were caused by dewatering of old workings which exposed old, reactive pillars to the air (Coaltech, 2009). Blasting in South African coal mines is carried out in a very controlled manner, with the avoidance of spontaneous combustion being handled carefully and water cannons being used where necessary. The Middleburg mine is recognised as having the most issues with self-heating and so the management at the mine has gone through many changes and introduced new guidelines on operation to keep incidents to a minimum. Coaltech (2009) is a useful document outlining the issues at various South African mines and the measures which were introduced to deal with them.

4.2.1 Format and content

The Wilpinjong Project in New South Wales, Australia, has produced a Spontaneous Combustion Management Plan (SCMP) to comply with the local Department of Primary Industries (Wilpingjong Coal Pty Ltd, 2006):

… a spontaneous combustion management plan is to be presented to the Department's satisfaction and implemented prior to coal extraction taking place.

The Department of Planning in the region adds a requirement that:

… the proponent shall … implement all practicable measures to minimise off-site odour and fume emissions generated by any spontaneous combustion at the project.

The objectives of the SCMP include:

- minimising the risk of spontaneous combustion;
- managing any occurrence of spontaneous combustion effectively and efficiently;
- minimising off-site impacts of any incidents;
- minimising impacts to personnel on site.

Excellent examples of SCMP can be found in the reference section of this report, such as MCC (2010), Anglocoal (2008), Ashton Coal (2014), Newcastle Coal (2014), Xstrata (2013) and CoalTech (2009). The majority of these are Australian coal companies or are for sites based in Australia as this seems to be where this approach is being championed. The remainder of this Chapter selects examples of best practice within SCMPs.

Newcastle Coal (2015) provide an excellent list of the impacts of spontaneous combustion throughout the coal transfer chain, highlighting the potential impacts at each:

- **Rail infrastructure corridor –** accumulation of coal at unloading stations, or spilled from the conveyor system and at transfer points. Ignition possible from self-heating or from machinery.
- **Coal storage areas** – accumulation of spilled coal, resting stockpiles.
- Wharf facilities and ship loader areas, transfer points and buffer bins.

Table 4 gives an example of the considerations in a typical SCMP at a mine (after Ashton Coal, 2014).

Table 4 SCMP (based on Ashton Coal, 2014)

Area of concern	Cause and impacts	Management
Pillars	• high pressure differentials • dry, cracked, stressed coal • boreholes and cracks forming air paths	• reducing differential pressures (redesign ventilation) • sealing of leakage paths (grout or sprays) • monitoring (thermal and gas)
Surface ingress via fractures	• ingress of airflow as a result of ventilation pressures • direct impact of barometer fluctuation	• repair cracks and subsidence • sealing and isolation of roadways • pressure balancing of goafs
Spontaneous combustion in pillars	Initiated by influence of main fan pressure or discontinuities in the seam	Managed through baseline surveys and audits of high pressure zones to establish normal levels and identify risk status
In longwall goaf	• oxidation on broken coal from extracted seam • fractured coal in an overlying seam as a result of caving • surrounding pillars in a sealed goaf • coal adjacent to mine seals	• regular monitoring with tube bundles and real time monitors • sealing leakage paths and maintaining seal integrity • inertisation of goaf void • increasing production rates to bury the area and minimise oxygen • changing longwall flow volume • surface remediation of cracks • pressure balancing during production • pressure balancing when complete
In rider seams	Excavation of target seam will cause caving and subsidence in overlying rider seams. This can cause a pressure differential and potential for oxygen ingress	• monitoring • reducing pressure differential across seams • injection of inert gas (N_2 or CO_2) into the active goaf • injection of inert gas into overlying seams • sealing of surface cracks • balancing pressure differentials • sealing of the panel

Table 4 has been written for a specific mine and clearly is based on previous experience with areas of concern and how to deal with them. This is the basis of most SCMP – they are documents which evolve based on existing data, taking new developments and lessons into account.

One of the primary roles of the SCMP is to list those personnel who are involved with the plan and to assign individual duties. This ensures that there is always someone who is responsible for ensuring that the plan is being adhered to. SCMP will take into account the ASET – available safe evacuation time – of each location. Some areas within mines will take longer to evacuate from than others. The heat release rate (HRR) of a fire or explosion will vary according to the type of fire and the local conditions (Mendham and others, 2014). This type of information is produced based on the monitoring and modelling discussed in Chapter 3. For example, the Muswellbrook Coal Company carried out extensive mathematical modelling of spoil heaps – different sizes and shapes as well are varying coal characteristics – as part of their SCMP for extension of a coal mine in NSW, Australia. Field testing into existing spoil heaps and stockpiles, along with monitoring of emissions, helped to test and improve the model which was then used to determine the most appropriate way of handling the specific coal at the site. These recommendations included the selective placement and rapid burial of materials with a high carbonaceous content as well as the building of spoil piles with a maximum height of 5–15 m. The SCMP built upon experience at the site and records going back over 10 years which provided useful information on the occurrences of spontaneous combustion that had happened previously. The SCMP also had a built in self-auditing requirement for some of the control measures in place to be evaluated every three months and modifications made where necessary. The whole SCMP was to be reviewed every five years.

For the most part, SCMP follow similar formats:

- **Listing of materials involved** – coal types and propensity to self-heat
- **Identification of areas of concern** – such as pillars or stockpiles
- **Monitoring requirements established** – this can mean anything from regular visual inspections for signs of smoulder or smoke to more complex combinations of gas, smoke, light or heat monitors (thermocouples)
- **Determination of trigger alarm levels** – determined by the characteristics of the coal but also by the site (size, shape, ventilation rate) as well as physical considerations (such time taken to react to an event and evacuate all personnel; defined according to the methods outlined in Chapter 3)
- **TARP** – action to be taken in the event of an explosion or fire. This will include a list of qualified personnel on site, control methods in place (dozers to move piles of concern, flame resistant barriers in mines, sprays and so on) and evacuation processes and muster points, if required
- **Reporting** – at most coal handling facilities, there will be a requirement to record and report any events or accidents which have occurred
- **Auditing and review** – details from an event can be used to train staff and to improve operations and to avoid repetition of mistakes

4.2.2 TARPS and emergency responses

The risk of a significant spontaneous combustion event can be reduced through monitoring and preparation. At each stage, personnel should be assigned to take control and responsibility. TARPs should be defined to determine when an alarm is raised and what actions are taken according to the severity of the alarm. These TARPS will be set, as discussed in Chapter 3, based on an understanding of the coal characteristics as well as site specific variations.

Cliff and others (2014) note that TARPs are important as they define the triggers to which mine personnel must react but that they also provide a graded response depending on the severity of the situation. The highest level of response will be evacuation of all personnel from the site. However, at lower levels it allows for quick changes and corrective actions to be made to halt a potential situation arising. TARPs are location dependent within the mine site – sealed goafs, active goafs and development headings will all have different TARPs. The type of action taken will also vary depending on the severity of the incident. For example, Xstrata (2013) have five levels of reporting requirements for spontaneous combustion incident, as shown in Table 5.

Table 5 Action and reporting requirements for spontaneous combustion events (Xstrata, 2013)			
Classification		Description	Action
A	Major	Extreme safety hazard, open flame, extreme offsite impact	Immediate (within 24 hours)
B	Moderate	Likely safety hazard, extreme visible steam or smoke likely to burst into flame, Potential offsite impact	Within 48 hours
C	Minor	Possible safety hazard, visible smoke	Within 7 days, with monitoring
D	Other	Some physical evidence of spontaneous combustion such as cracks or sulphur crusting	Monitoring required
E	No impact		

This table is somewhat simplistic of what happens in practice. At most sites there will be a map of areas of concern (such as stockpiles and pillars). Monitoring will be established in these areas and there will be checklists to be completed at regular intervals to ensure all is well. Should any areas of concern arise, the SCMP will change, monitoring will increase in frequency and, if necessary, action will be taken. Trigger levels will be set based on the factors discussed in Chapter 3 – the coal type and the local conditions. Triggers and alarms will be set to activate at the prescribed point – either when the temperature has increased to a certain value or emissions or gas signatures hit a warning level. Then the prescribed response, be it cooling, suppressant spray or evacuation, will be initiated.

The TARPs are there to both prevent and solve problems. But they are also useful in hindsight to determine whether the response taken was appropriate.

4.2.3 Personnel and training

The Shenhua Group in China has 58 underground mines. According to Gui (2014) prior to 2005 Shenhua's approach to mine safety was somewhat inconsistent and passive. Since then, Shenhua have lead a nation-wide safety improvement initiative with emphasis on a comprehensive pre-emptive risk control system (PRCS). The PRCS involves the training of staff to follow well defined guidance in terms of risk assessment, hazard monitoring and early warning to actions including rectification. Also according to Gui (2014), 90% of accidents in Chinese coal mines are caused by 'unsafe actions'. Under the new PRCS there are monthly and quarterly assessments for branches and subsidiaries of the company and annual assessments for the whole of the Shenhua group. At the end of the year, a ranking is published to allow the assignment of awards and punishments. The national average for fatalities in China for 2013 was 0.293/Mt of raw coal. For Shenhua, the 2013 value was 0.004/Mt raw coal. This value represents a historical low for China and ranks above the best statistics globally.

According to Belle (2013), Australian coal mines are recognised as being the safest mines in the world with the extensive use of monitoring systems and health and safety management plans. However, they are not without incident. Of the 89 fatalities that occurred in the Australian minerals industry between 2003-04 and 2012-14, the Minerals Council of Australia (MCA) recorded that 9% occurred in underground coal mines and 7% in open-cut coal. Explosions accounted for 7% of total fatalities (Stutsel, 2014). The Australian mining industry prides itself on having a better safety record than that in the USA.

Also, within the last decade mining incidents have been entirely on a one-by-one basis as a result of 'more innocuous' hazards such as collisions, slipping or falling. Harris and others (2014) suggest that this could be as a result of the legislative change of the late 1990s which moved from compliance based to risk management approach. This involves a 'duty of care' concept which makes individuals legally responsible to take reasonable care so that others are not harmed. It is becoming increasingly common within the coal industry internationally for personnel to undergo detailed, compulsory and regular safety training which includes the avoidance and control of spontaneous combustion. The US National Mining Association (NMA) has established CORESaftety, a 'plan-do-check-act' model to train staff and ensure safety throughout mining activities (Watzman, 2014). Conferences and workshops dedicated to training in mine safety are available, such as http://www.scjmhsc.org/, where common issues and concerns can be raised and discussed. Human nature and error can never be fully accounted for in a SCMP. However, continued training and enforcement of best practice can help to reduce accidents.

ACARP (Australian Coal Association Research Programme) has produced RISKGATE, a web-based tool which provides a practical check-list for controlling risk across activities involved in coal mining. It is based upon thousands of parameters assessed by industry experts and includes spontaneous combustion in both deep and surface mines as well as in coal piles. The project has been rolled out as training workshops to the industry, including attendance by the main coal companies in Australia such as Rio Tinto, BHP, Glencore, Peabody and Caledon (Kirsch and others, 2014). The system, which can be integrated with individual company internal risk management software systems, can be explored at http://www.riskgate.org/

Following the Pike River accident, discussed in Section 3.2.1, the Royal Commission in New Zealand investigation came up with a number of recommendations which included (Bell, 2013):

- establishment of a specialist task force to set up an effective regulatory framework to avoid repeat incidents;
- establishment of a code of practice as soon as possible, to be replaced by the new regulations when they are completed.

The investigation made specific recommendations including:

- requirements for a statutory mine manager and ventilation officer, with associated key functions and training;
- defining the requirements of underground gas monitoring systems.

The Pike River disaster could have been avoided. But, as will all events, especially those with a SCMP and TARP in place, there are lessons to be learned which will improve future skills and help to avoid recurrences.

4.3 Comments

Accidents due to spontaneous coal combustion are still occurring but expertise is growing. The trend towards more detailed and site specific SCMPs and TARPs will mean greater reporting accuracy of both safe periods, when events were successfully avoided, and periods of concern, where accidents were either avoided or controlled. This will lead to a better understanding of the causes of these incidents and accidents which, in turn, will lead to better methods to predict and avoid future events. This will hinge on accurate methods of monitoring activity in coal in situ but also on the increased accuracy, applicability and availability of models which will help to plan the operation of coal handling sites.

5 Conclusions

All coals can self-heat but some coals, especially lower rank coals, are more prone to self-heating than others. Spontaneous combustion is not just a risk to health and safety on site, it is a source of uncontrolled pollution (including greenhouse gases) and can be a significant concern in terms of lost stock and lost working days. Investment in technologies and techniques to understand and control spontaneous combustion are regarded as very worthwhile by those in the industry.

Testing methods have improved significantly in recent years, taking into account parameters such as inherent coal moisture much more than they did in the past. In coal handling areas the surrounding conditions, especially air flow and oxygen availability, can be just as important in inducing a spontaneous combustion event as coal characteristics. Therefore, to be able to best prevent and control spontaneous combustion events, coal operators need to understand the coal but also need to monitor how the coal is treated as it passes through the production and distribution chain. Combined with advanced mathematical and modelling techniques, it is now possible for coal users to understand the conditions most appropriate to controlling self-heating in individual coals. This means that mining and handling systems can be fine-tuned to each coal type and to each location to provide the safest work environment possible.

Spontaneous combustion management plans are becoming increasingly common, with Australia leading the field in terms of detail and coverage. SCMPs are now being written into the standard requirements for mining applications, even before production begins. These SCMPs must include details on the coal type (its inherent propensity to self-heat) as well as predictions (in some cases modelling studies) to determine how to avoid spontaneous combustion at all stages of the coal chain on site. These SCMPs will include TARPs – coal and site dependent trigger action levels which indicate, well in advance of an ignition event, when self-heating is occurring. Gas emission signatures can be fine-tuned to the coal and location in order to ensure that self-heating is detected early and remedial action takes place. Treatments such as air flow control or the application of chemical suppressants can be very successful in controlling fire events.

However, incidents and accidents involving spontaneous combustion still occur. Depending on the level of alarm, the appropriate response may be fire suppressant treatment or even site evacuation. SCMPs require that such events are monitored and audited afterwards to provide feedback to update and, if necessary, re-write the SCMP to ensure such an event does not recur. An intrinsic factor in the success of any SCMP is the staff involved – training is imperative. With improvements in mine equipment and safety standards, human error is becoming one of the most common causes of mine accidents. The level of reporting within SCMPs is often specific to named members of staff who are responsible for different areas of the site and sections of the production chain. Records are kept, not just of accidents, but also of potential areas of concern where additional monitoring may be needed. To this end, many SCMPs are 'live' documents – the overall document may be reviewed every five years or so, but individual working sections will be updated possibly even daily to take into account areas of concern, such as a heat build-up in a stock-pile. Such events may not require immediate action (the stockpile may be planned for removal soon) but the issue must be raised and logged. In the worst-case scenario the outcome can be catastrophic with lives being lost. In such incidences, the monitoring equipment is destroyed. Unless appropriate recordings are made prior to such events, there is no way of understanding what occurred and, more importantly, determining how to avoid such an event ever happening again. SCMPs and the associated testing and monitoring skills have changed the coal industry significantly in recent years and will continue to do so in future.

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