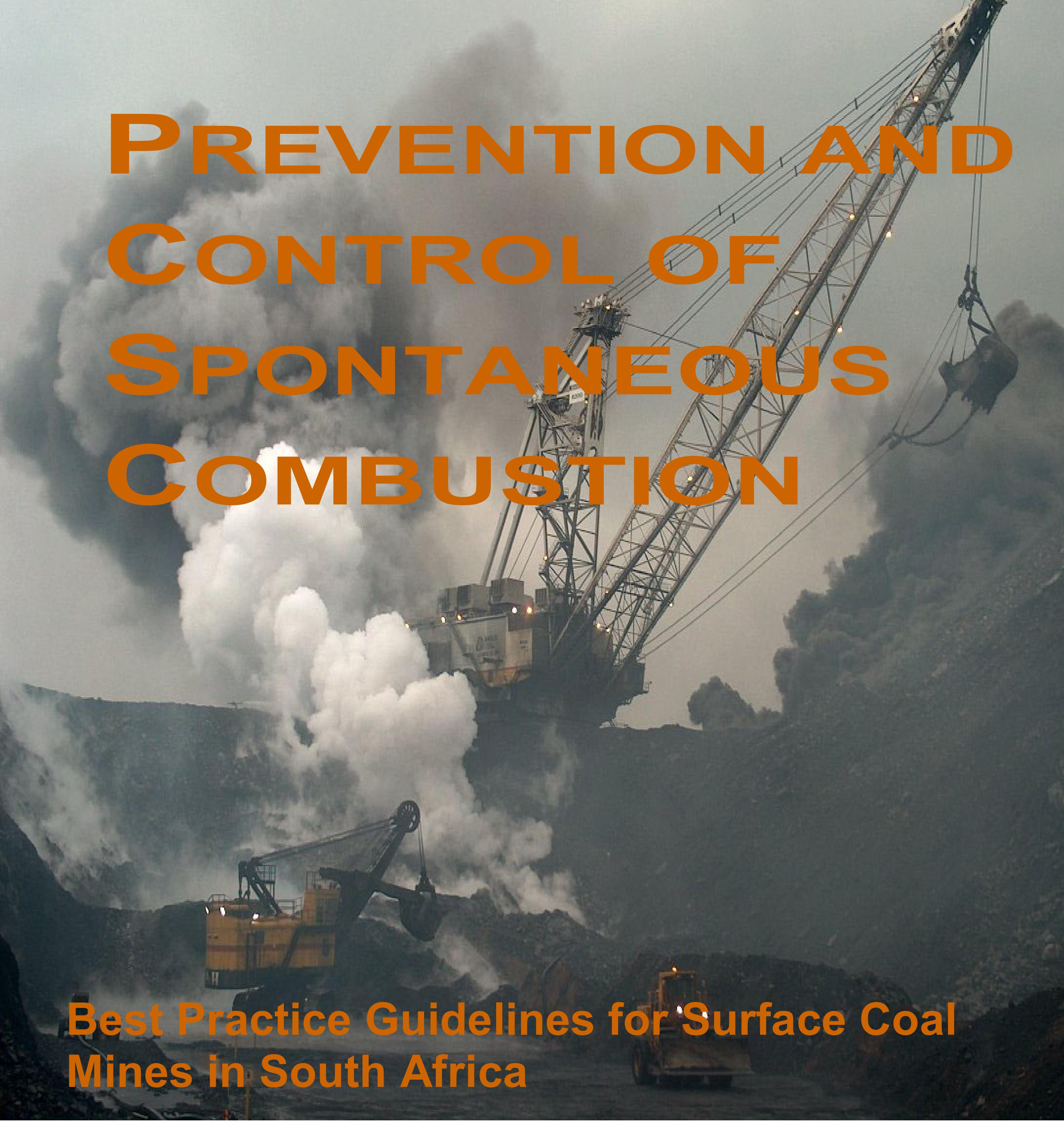
Prevention and Control of Spontaneous Combustion

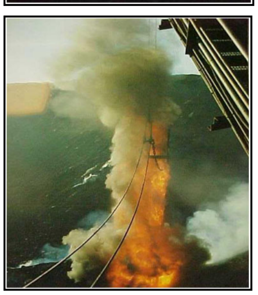


Best Practice Guidelines for Surface Coal Mines in South Africa

COALTECH Research Association






Foreword

The spontaneous combustion hazard is a concern in South African coal mining operations and should be managed carefully. The problem is a natural phenomenon that is aggravated by mining activities.

A number of methods exist to prevent, detect, monitor, control and manage spontaneous combustion in surface mining operations. While this guideline is directed towards surface mines, it does make use of experience from underground coal mines.

These best practice guidelines have been compiled by the School of Mining Engineering at the University of Witwatersrand and contain examples of spontaneous combustion prevention strategies and include concepts such as risk identification, detection, monitoring, control and management.

Coaltech is pleased to endorse the guidelines and asks that the management and responsible personnel working in South African surface coal mines become familiar with this document. The aims of the research are to improve health and safety, prevent the loss of reserves and significantly reduce environmental pollution from surface mines where the risk of spontaneous combustion exists.

Acknowledgements

Coaltech funded the development of the guidelines and the authors wish to thank the Coaltech Management Team for its financial support and patience during this research.

This work could not have been carried out without the assistance of the management of Anglo Coal, BHP Billiton and Xstrata, which gave permission for visits to their mines and, in particular, gave us free access to information regarding spontaneous combustion problems at their mines.

A number of individuals also gave freely of their time to discuss their experience in dealing with this problem. These include:

Reuben Hlatswayo – previously general manager at New Vaal Colliery

Gerhard Stenzel – general manager opencut technology at Xstrata Coal

Tom Rogans – previous technical manager at Kleinkopje Colliery

Collin Mulligan – manager at Atcom Colliery

Stephan Muller – general manager at Middelburg Mine

Stefan Adamski – Exxaro Head Office

The guidelines have also built upon previous work undertaken in an earlier study of spontaneous combustion undertaken by Coaltech 2020 (Project 3.4.1). The work of Conri Moolman, Nehar Eroglu and Sezer Uludag undertaken in 2002 and 2003 is acknowledged, since parts of their reports are reproduced in this current report.

Authors

The guidelines preparation team consisted of:

Huw Phillips (professor of Mining Engineering, University of Witwatersrand)

Sezer Uludag (former lecturer, School of Mining Engineering, University of Witwatersrand)

Kelello Chabedi (lecturer, School of Mining Engineering, University of Witwatersrand)

Contents

Introduction

What is spontaneous combustion?

Spontaneous combustion is an oxidation reaction that occurs without an external heat source. The process changes the internal heat profile of the material leading to a rise in temperature. This can eventually lead to open flame and burning of the material

Previous Coaltech sponsored research

Coaltech previously funded a comprehensive review of spontaneous combustion in mining. CSIR Miningtek undertook this work from 2001 to 2003. The principal authors of this work were Dr Nehar Eroglu and Mr Conri Moolman, with contributions by Mrs Sezer Uludag and Mr Elton Thyse. The project title was, *Develop Methods to Prevent and Control Spontaneous Combustion Associated with Mining and Subsidence* and the Coaltech Project number was 3.4.1.

It was never the intention of the current project to repeat the previous work. However, in reviewing the problem of spontaneous combustion in surface mines, information was drawn from the various reports prepared for Project 3.4.1 and sometimes this is reproduced in the preparation of these best practice guidelines. The reproduction of this material is acknowledged.

It is recommended that a copy of the report of Project 3.4.1 is kept at every surface mine that has a heating or spontaneous combustion problem. Managers controlling outbreaks of spontaneous combustion, or involved in the planning or operation of surface mines involving the mining of previously worked seams should be familiar with the contents of this report. Electronic copies of the report are available from the manager of Coaltech.

The report of Project 3.4.1 together with its eight appendices contains a large number of references. These give a wide-ranging insight into the causes and control of spontaneous combustion in coal mining and coal storage. In order to assist individuals who wish to obtain a deeper understanding of spontaneous combustion, the literature survey of Project 3.4.1 is reproduced at the end of this report as Appendix 5.

Because of the volume of information available in the previous report it has been possible to be brief in this current document and to focus on current best practices.

Development of best practice guidelines

This guidelines development project include:

- a literature review to collect relevant data
- site visits to selected surface coal mines
- consultation with various experts in the subject
- development of the guidelines and a pocket reference.

How to use the best practice guidelines

The guidelines consist of broad principles that individual mines can use to establish or adapt their standard procedures in a changing mining environment. They aim to assist mine managers, blasting engineers, planners and operators to implement standard procedures in the areas of prediction, prevention, detection, monitoring, control and management.

It is accepted that professionals will use their own judgment based on knowledge of their individual operations when applying the basic principles and specific recommendations of this document to individual cases of spontaneous combustion. A manager’s decision to adopt any particular recommendation must be made in the light of all available evidence collected during the monitoring process.

The objectives in the development of the guidelines, which are based on scientific knowledge and local case studies, include standardisation of prevention techniques and data collection to prevent or reduce future incidents.

Prevention and reduction of incidents require:

- increased awareness of the causes of spontaneous combustion
- increased use of risk identification management strategies
- knowledge of prevention strategies.

Principles of spontaneous combustion and general theory

Spontaneous combustion of coal is a fire initiated by the oxidation of coal. Coal fires require three basic elements to exist as shown in figure 1

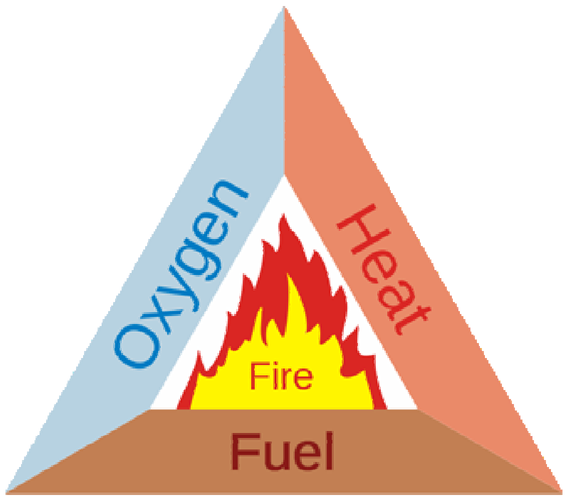


Figure 1: Fire triangle

The process leading to spontaneous combustion can be summarised as follows:

- Oxidation occurs when oxygen reacts with the fuel, i.e. coal
- The oxidation process produces heat
- If the heat is dissipated, the temperature of the coal will not increase
- If the heat is not dissipated then the temperature of the coal will increase
- At higher temperatures the oxidation reaction proceeds at a higher rate
- Eventually a temperature is reached at which ignition of the material occurs.

Heat dissipation depends on the thermal conductivity of coal and the surrounding rock, on convection processes caused by wind and barometric changes in the atmosphere and on the minor and major fracture density in the rock mass.

The tendency of coal to self-heat is a function of both intrinsic factors (coal type, geological setting and environmental conditions) and extrinsic factors (mining related).

Combustible matter can interact with the oxygen in the air at ambient temperature releasing heat. Favourable conditions for spontaneous heating would be the accumulation of heat caused by a rise in temperature and hence an increase in the reaction rate. Although, at ambient temperature, the reaction can be so slow that it is unnoticed, when heat accumulates the temperature is raised and, according to the Arrhenius law, the reaction rate increases exponentially:

$$v = c_r \cdot c_0 A \cdot e^{\frac{Ea}{RT}} \quad \textbf{Equation 1}$$ [1]

Where:

v = reaction (mol g^{-1} s^{-1})

c_r= combustible concentration (kg/m^3)

c_o= Oxygen concentration

A= Arrhenius Frequency Factor (s^{-1}or $s^{-1}C^{1-n}$)

Ea= Activation Energy (kJ/mole)

R= Universal gas constant = 8.314 J moleK^{-1}

T= Temperature (K)

An assessment of the self-ignition hazard must be undertaken for each mine site and circumstance. The most important parameters involved in the heat balance, and therefore in self-heating are:

- Size of the coal particles
- Quantity
- Calorific value
- Heat conductivity
- Geometry and dimensions of the mining operation or coal storage facility
- Heat transfer coefficient on the outside surface of the bulk
- Ventilation
- Degree of compaction.

Primary causes of spontaneous combustion

In underground mines, the primary cause of spontaneous combustion is crushed coal (either left in goaf areas or in highly stressed pillars) that is in contact with a sluggish airflow. Good

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1 Spontaneous Combustion Testing, Querol Aragón, E.; García Torrent, J.; Cámara Rascón, A. Dep. Ing. Química y Combustibles. Universidad Politécnica de Madrid Laboratorio Oficial J.M. Madariaga

ventilation will remove heat, preventing a rise in temperature, while extremely poor ventilation will not supply sufficient oxygen to support the process. On surface the major problems are usually associated with the stockpiling of coal, or waste dumps containing rejected coal material, in unconsolidated heaps where oxygen can come into contact with the coal and heat cannot dissipate. The problem is compounded when rainfall causes erosion, thereby progressively exposing more coal to the oxygen in the atmosphere. Very high ash carbonaceous shales will also spontaneously combust under the right conditions, particularly if they contain high levels of kerogen (a mixture of organic chemical compounds that make up a portion of the organic matter in sedimentary rocks.) These shales provide a major source of additional fuel for coal induced fires. Many strip mines have severe spontaneous combustion in the spoil heaps.

In addition to the known problems in stockpiles, waste dumps and spoil heaps, spontaneous combustion may occur in the following situations:

- Coal outcrops
- Shallow workings exposed by subsidence, either directly or through fissures
- Tailings dams.

To sustain combustion, oxygen, fuel and heat must all be present. The absence of any one of these elements will result in at least the temporary cessation of burning. Spontaneous combustion in stockpiles and dumps can usually best be controlled by handling high risk material in a way that limits its contact with oxygen, e.g. by compaction to minimise airflow, by cladding with inert material to prevent the ingress of air, by limiting the height of the dump and by orientation of the stockpile or dump with respect to the prevailing wind.

Fires in coal outcrops and in shallow underground workings present a special problem, both of detection and control, because of access difficulties. Such fires tend to have the general characteristics:

- Fires propagate in accordance with the topography and orientation of the mining activity, exposed seam or stockpile, and the direction of prevailing winds, owing to “funnelling” of air currents
- Venting fissures are present and extend to the surface, forming parallel to the ground contours and developing in response to stress release along existing fracture systems.

Although there have been many cases of spontaneous combustion in underground coal mines in South Africa, in surface dumps, in shallow workings in the vicinity of Witbank and even in ships carrying export coal from South Africa, the biggest problem now is in surface mining. While it is unusual for intact seams to burn in the highwall, the most common occurrence is when surface mines extract seams previously partially mined by underground bord and pillar operations. Once exposed to the air the pillars that were left over from the previous mining operations start to burn within days and require special prevention and control techniques.

Factors affecting the spontaneous combustion of coal

All coal seams have some propensity to spontaneously combust and it is important that a mine understands the risks associated with the coal it mines. The magnitude of the problem depends on a complex relationship of a range of factors, some of which are listed below and extracted from a thesis by S Uludag (2001)[2].

(a) Intrinsic

- Coal composition, rank and petrographic constituents
- Coal friability, particle size and surface area
- Moisture content
- The presence of iron pyrites.

(b) Extrinsic

- Climatic conditions (temperature, relative humidity, barometric pressure and oxygen concentration)
- Stockpile compaction, as related to height and method of stockpiling
- Dump consolidation, influenced by height, method of formation and equipment used
- Presence of timber or other organic waste material in abandoned areas or dumps
- Excavation stability and maintenance (for open-cut highwall faces)
- Strata conditions, method of working and ventilation (for shallow underground workings).

The result of interactions between these factors in a given situation is complex and the subject of on-going debate. However, in general, lower rank coals are more liable to self-heating. Friable, high-reflectance components, particularly fusinite in conjunction with vitrinite, are particularly susceptible to spontaneous combustion because of their tendency to create fine particles with a high specific surface area. The situation is aggravated by the presence of moisture and iron pyrites. The existence of geological disturbances, such as faults and dykes, may also contribute to the problem owing to the friable coal usually associated with such features.

Prediction of the spontaneous combustion risk

Based on inherent characteristics

Prediction requires a classification of coal based on its inherent properties, however, there is no universally accepted method of coal categorisation or for measuring the propensity for spontaneous combustion. The following techniques are available to measure the inherent characteristics of coal used to predict its behaviour.

2 Uludag S, (2001), Assessing Spontaneous Combustion Risk in South African Coal Mines Using a GIS Tool. M.Sc Dissertation, University of Witwatersrand. South Africa

Examination of chemical constituents

- Rank
- Petrological classification
- Moisture
- Volatiles
- Oxygen (DAF basis)
- Sulphur content.

Thermal studies

- Initial temperature
- Crossing point temperature
- Crossing and ignition point
- Modified CPT
- DTA method
- Russian tests of ignition temp
- Olpinski index
- Adiabatic calorimetry.

Oxygen avidity

- Glasser test
- Peroxy complex analysis
- Rate studies
- Russian U index
- Wet oxidation method
- H_2O_2 methods
- Other oxidation methods ($KMnO_4$ method).

Based on extrinsic characteristics

- Risk mapping
- Risk indexing.

Preventing spontaneous combustion

Spontaneous combustion is a time-dependent phenomenon. Early attention to the potential sources of problems may prevent occurrences of heating progressing to full-scale spontaneous combustion. Examples of commonly used methods of dealing with spontaneous combustion in different circumstances are detailed below.

Tailings (plant rejects) – Tailings dams should be capped with at least one metre of inert (non-carbonaceous) material, topsoil should be added and the whole area revegetated.

Coarse reject (discard) – Problem material should be placed in layers and compacted using a roller, particularly on the edges of the dump, so that the infiltration of oxygen is minimal. The total layer thickness should be no greater than 5m and each layer should be covered by a 1m thick layer of inert (non-carbonaceous) material. The final landform should be such that erosion and runoff is minimised and new areas of discard coal are not exposed to the atmosphere.

Spoil heaps in strip-mining – The sequence of spoiling should result in accumulations of coal material, particularly if pyritic, being buried under inert spoil. Although difficult to achieve, the most reactive material should be enclosed within less reactive material using the principles developed at Grootegeluk Mine. If this is not possible then rehabilitation of the spoil heaps should take place as soon as possible and a thick layer of softs should be used before topsoil is added.

Product (coal) – Product stockpiles and coal inventory in the cut should not be left longer than the incipient heating period. There is considerable variation in the time taken for heatings to occur, but most mines have an understanding, based on experience, of the time limits for their product. An indication of the length of this period can be obtained from specific tests, such as the CSIR Bunker Test. Both run-of-mine (RoM) and saleable product coal have been known to be susceptible to spontaneous combustion. Particular caution should be taken where there is segregation of material sizes because of the stockpiling/dumping technique. A layer of coarser particles at the base and edges of stockpiles may result in increased ventilation passing through the coal. The situation is particularly aggravated by prevailing hot, moist winds and this may lead to a higher risk of spontaneous combustion in the summer months.

Shape and orientation of stockpiles and dumps – The height of stockpiles and dumps may be a critical site-specific consideration. When the technique is feasible, considerable benefit can be obtained by building dumps in relatively thin compacted layers. Longer-term stockpiles, particularly of product coal, can be further safeguarded by spraying the surfaces with a thin (bituminous) coating to exclude air.

Highwalls at surface mines – Coal spalling from the seams should not be allowed to remain against the highwall. If the coal is liable to spontaneous combust, loose coal should be cleared away promptly and/or the highwall reinforced with soft, spoil material if it is to be left for an extended period. At the end of the life of mine complete rehabilitation and closing of the final void should take place. If this is not undertaken the highwall should be effectively sealed with water, clay or a thick blanket of inert spoil.

Detecting spontaneous combustion

Spontaneous combustion fires can be detected fairly early in their development, i.e. before any obvious smoke and/or flame. Any of the following may assist in early detection, depending upon the particular circumstances.

Temperature difference – Heat haze and "steam" plumes may be observed on cold mornings and in times of high humidity. Hot spots may also be detected by infrared monitoring instruments or photography. Routine surveying of stockpiles using infrared scanning devices is an excellent precaution in situations where spontaneous combustion may be likely to occur. This technology is also applicable to the detection of heatings in the highwall, but is not routinely practiced on mines for a number of reasons, including the fact that it may yield negative results for years before a heating is detected. Efflorescence caused by the decomposition of pyrites and sublimation of sulphur is a strong indication of heating in pyritic (high sulphur) coals.

Infrared cameras can be useful to detect near surface heating, as shown in figure 2.

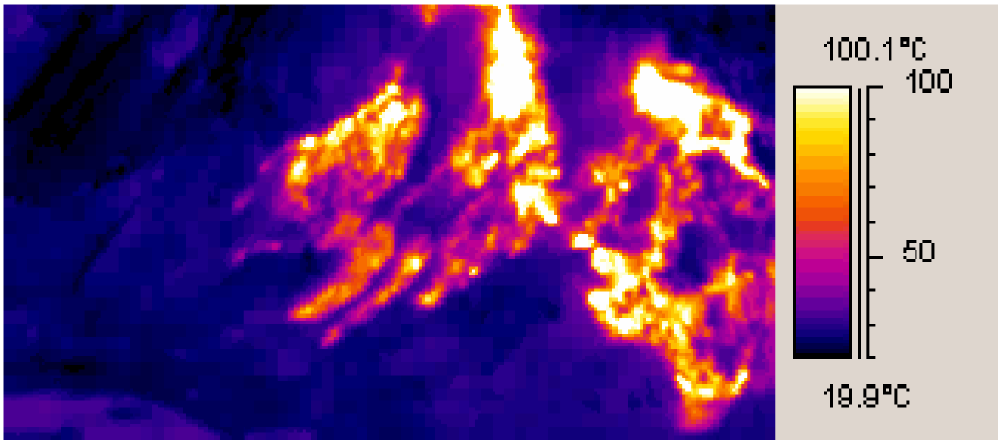

Figure 2: A typical thermal image of a spoil pile

Smell – Mine fires are readily recognisable by their distinctive smell. Oxidation of the coal causes a release of large volumes of noxious and flammable gases, which themselves may represent a hazard, owing to asphyxiation, poisoning, fires and, in enclosed places, the risk of explosions .

Notable toxic gases produced by spontaneous combustion include:

- Sulphur dioxide SO_2
- Oxides of nitrogen NOx,
- Hydrogen sulphide H_2S (also flammable)
- Carbon monoxide CO (also flammable).

Explosive gases that are most likely to be present during a heating and that are flammable are:

- Methane CH_4
- Hydrogen H_2
- Carbon monoxide CO.

Other gases, all of which are flammable that act as indicators of fire may also be present in small amounts. They may be detected by gas monitoring tubes and include:

- Ethane C_2H_6
- Ethylene C_2H_4
- Acetylene C_2H_2.

A large number of other hydrocarbons are also likely to be produced. These are usually only present in very small amounts and are unlikely to reach toxic levels.

Controlling spontaneous combustion

Effective control of spontaneous combustion can be achieved by using a combination of techniques. The control measures that can be applied in South African collieries can be listed in three groups:

Control measures to reduce or eliminate oxygen from the process

- Sealing agents
- Dozing over
- Buffer blasting
- Cladding of the highwall.

Control measure to reduce the temperature and hence the reaction rate

- Water cannons onto the highwall and in front of the dragline and during coaling
- Nitrogen injection into old workings
- Carbon dioxide injection into old workings.

Removal of the fuel

- Excavation of hot or burning material.

The efficacy of these control measures is dependent on individual situations such as mining layouts and the extent of the spontaneous combustion problem.

Small-scale fires[3] in stockpiles or areas exposed by mining may be extinguished or controlled by flooding with water or by removing the burning material. Caution must be taken when fighting spontaneous combustion fires with water as a dangerous reaction between the water and the heated coal can occur.

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3 Anonymous, Rehabilitation of Spontaneous Combustion Areas. In Technical Guidelines for the environmental management of exploration and mining in Queensland. ISBN 0724252606. Jan 1995.

In attempting to control heating by spraying or injecting water, it is possible to produce water gas[4], which is a mixture of carbon monoxide and hydrogen. Both these gases are highly flammable and are produced in the reaction between hot carbon and water. The chemical reaction for this is:

$$C + H_2O = CO + H_2$$

Because of the wide explosive limits of water gas (4% to 74%), the highly toxic nature of carbon monoxide and the presence of a source of ignition, production of water gas should be avoided as much as possible. The situation is made more hazardous by the large volumes of gas and associated steam violently produced from the solid-liquid reaction. Thus water should only be used to control heating if the heating can be inundated rapidly, limiting the amount of water gas produced and excluding air. Even in surface operations where the risk of explosion is lower, crews fighting spontaneous combustion by using water should monitor carbon monoxide and hydrogen levels.

Fire fighting foam has been used as an alternative to water with some success. A more widely accepted method is for the material to be spread out to cool and the ash disposed of in a manner suited to its chemical and physical properties, i.e. used as construction material or buried. Speed and safety are essential in such operations. Protective clothing and breathing apparatus should be provided and the equipment must be suitable for the particular work (i.e. no rubber tyres or petrol driven equipment).

Literature review

Coal readily oxidizes causing problems in many coal mines world-wide. Most research has studied the relationship between spontaneous combustion and the inherent characteristics of coal. There are a limited number of publications on best practice in dealing with the self-heating of coal under operational conditions, perhaps because the level of understanding of the principles of spontaneous combustion is limited to scientific studies and to those individuals who need to deal with it on a daily basis. Certainly there are few good, practical publications in the international literature dealing with how to mine without causing spontaneous combustion and none dealing with the specific problem of surface mining of previously mined seams. In South Africa the previous work undertaken by Coaltech (Project 3.4.1) is really the only specific study of this problem, although several mines and mine managers have reported individual efforts to solve this problem.

Factors affecting spontaneous combustion

One of the earliest classifications of the factors affecting spontaneous combustion was done by Davis and Reynolds (1928)[5]. The factors are grouped under chemical and physical properties. The chemical factors to be considered, in order of importance, are: (1) presence of pyrites, (2)

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4 The Technical Guidelines for the Environmental Management of Exploration and Mining in Queensland, A publication of the Department of Minerals and Energy 1995. http://www.derm.qld.gov.au/register/p01206av.pdf

5 Davis, J.D. and Reynolds, D.A., 1928, Spontaneous Heating of Coal, USBM, T.P. 409, 74.

rank of coal, (3) weathering, (4) moisture, (5) organic sulphur, (6) chemical deterrents (calcium chloride and sodium bicarbonate), (7) ozone, and (8) bacteria. The physical factors are: (1) particle size, (2) moisture, (3) oxygen supply, (4) temperature, (5) “occluded” gases, (6) ventilation, and (7) conductivity.

Later Guney (1968)[6] classified important factors in a table as shown in table 1.

Table 1: Factors affecting spontaneous combustion of coal (Guney, 1968)

Intrinsic factors (nature of coal)	Extrinsic factors (atmospheric, geologic, and mining)
Pyrites	Temperature
Moisture	Moisture
Particle size and surface area	Barometric pressure
Rank and petrographic constituents	Oxygen concentration
Mineral matter	Bacteria
	Coal seam and surrounding strata
	Method of working
	Ventilation system and/or air flow rate
	Timbering
	Roadways

The following facts emerge from a more recent literature survey by Kaymakci & Didari (2002)[7]:

- Pyrite content may accelerate spontaneous combustion
- Changes in moisture content, i.e. the drying or wetting of coal, have apparent influence on the propensity for coal to self-heat
- As the particle size decreases and the exposed surface area increases, the tendency of coal towards spontaneous combustion increases

6 Guney M., 1968 “Oxidation and Spontaneous Combustion of Coal – Review of Individual Factors’. Colliery Guardian, 216, 105-110 and 137-143.

7 Kaymakci E & Didari V., 2002, “Relations between coal properties and spontaneous combustion parameters.” Turkish Journal of Engineering and Environmental Science 26, 59-64.

- It is widely recognised that lower rank coals are more susceptible to spontaneous combustion than higher rank coals. Any abnormalities in this relationship may be attributed to the petrographic constituents of coal
- Ash content generally decreases the propensity of coal to spontaneously heat. Certain constituents of the ash, such as lime, soda and iron compounds, may have an accelerating effect, while others, such as alumina and silica, produce a retarding effect. It is clear that some chemicals promote combustion while others inhibit its development. It is known that oil shale bands adjoining coal seams play an important role in mine fires
- The presence of faults and zones of weaknesses around faults may contribute to the danger by allowing air leakage into the coal mass
- Partial extraction underground mining methods, in which part of the coal seam is left in the goaf and in pillars, can contribute to the potential for spontaneous combustion. (This may have relevance to the mining of old workings, since surface mining will expose areas where crushed coal has been left for long period)
- Air flow rate is a complex factor because air provides oxygen while it also carries away the heat produced. There is a critical air quantity that supplies sufficient oxygen to allow the coal to oxidize but is insufficient to prevent the generated heat from accumulating
- Changing atmospheric conditions because of air moving in and out of coal seams. This is of particular relevance when old workings are exposed by surface mining.

Spontaneous combustion in South African collieries

Current literature indicates that spontaneous combustion is now rare in underground coal mines in South Africa. The Witbank and Sasolburg coalfields experience spontaneous combustion mostly in surface mines in areas previously mined by bord and pillar methods. The only surface mining operation in the Waterberg coalfield is known to have had serious spontaneous combustion problems with discards. The mining experience of spontaneous combustion within these coalfields has not been reported consistently or in detail.

The major coal bearing strata in South Africa are associated with the Karoo Basin and occur primarily on the southern and eastern flanks of the Kaapvaal Craton. The five recognised coal seams in the Witbank area are numbered consecutively from 1 – 5, the last being the youngest. These seams occur within a succession about 70m thick. Seam No. 2 and seam No. 4 have been extensively mined in the past. Bullock and Bell[8] give a description of the underground mining methods used and provide a case study of spontaneous combustion affecting a mine. In the 1960s and 1970s, before the advent of large-scale surface mines, nearly all South African production came from relatively shallow bord and pillar workings. For many years spontaneous combustion was a problem, with a few mines, e.g. Springfield Colliery, being particularly prone to heatings leading to underground fires. A number of case studies were reported in the

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8 S. E. T Bullock and F. G. Bell, Some problems associated with past mining at a mine in the Witbank coalfield, South Africa. Environmental Geology 33 (1) December 1997.

9 V C Barnes, F E Joubert and G P Badenhorst, Precautionary measures to reduce the probability of incipient heatings in coal mines, their early detection and safety procedures in dealing with colliery fires. Proc. Mine Ventilation Society Symposium on Colliery Fires and Explosion Hazards, March 1977 pp 5 to 22.

literature but probably the most important South African reference of this period was the paper by Barnes, et al.[9] This paper combined laboratory research undertaken at the Fuel Research Institute in Pretoria with practical observations at the site of heatings and provided sound advice to the underground mines.

Literature on the specific problem of heatings and spontaneous combustion in surface coal mines in South Africa is rare. However, Stenzel[10] has reviewed the history of spontaneous combustion at New Vaal Colliery and since it is pertinent to this study, it is worth summarising.

"The lease area, known as Maccauvlei East, forms part of the Sasolburg coalfield and contains three economically viable coal seams of the Vryheid formation. All three seams have been previously mined by underground bord and pillar methods. The underground colliery mined in this area from 1931 until closure in 1969 and was well known for its occurrences of spontaneous combustion. After closure the old mine workings were flooded and all access shafts were sealed off. Opencast operations started in 1983 with the first coal produced in 1985 from the virgin coal area alongside the river on the eastern boundary.

"When the flooded sections of the old workings were dewatered an ideal environment for spontaneous combustion was created by exposing the old pillars to the air. Poor roof conditions, which were caused by the proximity to the current opencast operation, existed, causing collapses and creating cavities that allowed carbonaceous interburden to fall into the voids. Crushing of the rib sides caused further complications and this left large quantities of fine coal exposed to oxidation and created conditions ideal for spontaneous combustion.

"The most important New Vaal events arose from spontaneous combustion during 1992 and 1993. During October 1992, the entire length of the main pit – about 4.5km – was burning. The fire also spread into the shales in the highwall. This resulted in some holes not being charged because of high temperatures, which in turn led to poor fragmentation and difficult digging conditions for the draglines and shovels. In May 1993, the mine stopped all pre-splitting and buffered the fire-ravaged areas in the underground workings. These measures slowed the fires and brought them under control. The extent of the buffer was increased from an initial 20m to about 120m. In addition to buffer blasting, the highwalls were clad with sand from the mine. To date the techniques have been successful in controlling spontaneous combustion and are a good example of buffer blasting working and how pre-splitting may aggravate the spontaneous combustion problem".

International literature on spontaneous combustion incidents at mines

Stracher and Taylor[11] (2004) listed major coal fires from around the world, namely: Xinjiang coal field in Northern China; Rujigou coalfield in Ningxia, China; Pennsylvanian coal fires in the United States; and the Jharia Coalfield in Bihar in India. In China, water-mud slurry is injected into the

10 G J Stenzel, The effects of spontaneous combustion on Safety, Health and the Environment of New Vaal Colliery. Mine Ventilation Society, 31 October 2002.

11 G B Stracher and T P Taylor, Coal Fires burning out of control around the world: Thermodynamic recipe for environmental catastrophe. International Journal of Coal Geology 59 (2004) p 7-17.

cracks created by subsurface burning or into a series of holes drilled into underground shafts, drifts and slopes in order to pump in the slurry to smother the flames. The surface is then covered with large amounts of soil to prevent entry of oxygen into the coal seams.

More than a third of the United States' abandoned mine-related problems occur in Pennsylvania and fires there have been fought using the same slurry-flushing and surface-sealing techniques as in China. Some underground mine entries have been sealed with brick, tile, cement blocks, or clay barriers to cut off the oxygen and reduce the risk of explosion (Stracher and Taylor, 2004).

India is also a major coal producer and most fires in the Jharia coalfield in India are ignited by the spontaneous combustion of coal subsequent to either opencast or deep mining. Exploitation, without fire-prevention codes prior to nationalisation, was responsible for the conditions that led to these fires (Stracher and Taylor, 2004). The reported techniques used to contain or extinguish fires include trenching and surface sealing. Inert gas injection, sand/bentonite slurry flushing, and surface sealing have also been used for subsurface fires.

Other information indicates that in mines where the time between exposure of coal and the start of heating is short, water may be used to prevent coal interacting with air until it is about to be mined. In one mine, with a sulphur content of 0.5%, coal started to burn within two weeks of exposure. To prevent spontaneous combustion, the mine used a 300m wide water barrier method (Miller, 2007)[12.] The technique involved flooding a 300m long section of the open-cut with water to a height of about one metre. The overburden was blasted about two metres above the coal, leaving stubs of overburden material intact to act as a barrier to contain the water within the section (See figure 3). The water prevents contact between the coal and air and is only removed immediately prior to mining the coal.

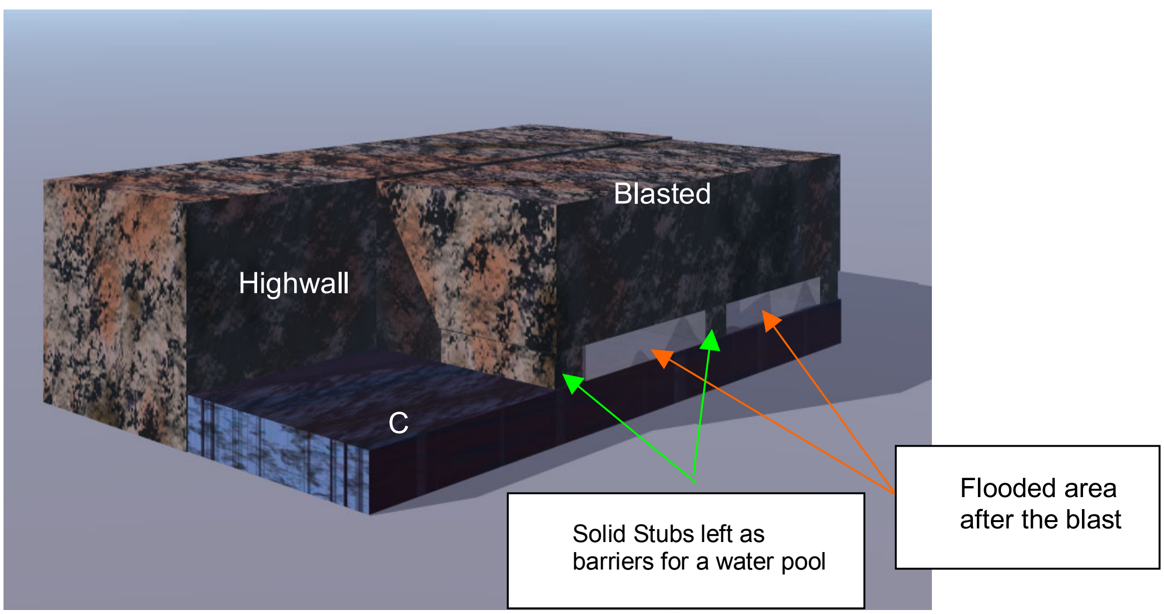

Figure 3: Water flooding technique to prevent coal catching fire

12 E Miller, Consultant Mining Engineer Atcom Colliery, Personal Communication, 2007.

In addition to heatings during mining activities, spontaneous combustion also occurs within stockpiles. Although this is not directly the subject of this study, loose coal left within the cut may be subject to spontaneous combustion and this can disrupt mining operations. Several measures to reduce heatings have been tested. These include periodic compaction, the use of a low-angle slope to minimise the effects of wind, protection of the coal stockpiled with an artificial barrier and covering it with an ash-water slurry made with fly ash. Wind tunnel tests were used to design an effective wind barrier. Of all techniques, the best appears to be to cover a stockpile with a wet layer of fly ash from a thermal power station. For many large surface mines in South Africa this might well be an option.

The Department of Energy in the United States, through its Office of Health, Safety and Security reported some characteristics of spontaneous combustion as well as guidelines for minimising the probability of a fire.[13] These may be summarised as:

- The higher the inherent moisture, the higher the heating tendency
- The lower the ash-free calorific value, the higher the heating tendency
- The higher the oxygen content in the coal, the higher the heating tendency
- Sulphur, once considered a major factor, is now thought to be a minor factor in the spontaneous heating of coal
- The finer the size of the coal, the more surface is exposed per unit of weight and the greater the oxidising potential, all other factors being equal
- Segregation of the coal particle sizes is often a major cause of heating. Coarse sizes allow air to enter the pile at one location and react with the high surface area fines at another location. Coals with a large top size (>100mm) will segregate more in handling than those of smaller size (<50mm)
- It is believed that the rate of reaction doubles for every 8°C to 11°C increase in temperature
- Freshly mined coal has the greatest oxidising characteristics, but a hot spot in a pile may not appear for the first one or two months
- There is a critical amount of airflow through a portion of a coal pile that maximises the oxidation or heating tendencies of coal.

All of the above points support the comments already made in this report.

Literature scan of techniques/technology to prevent and control spontaneous combustion at surface mines

In general the main factors contributing to fires in the highwall of open cast mines are:

- Presence of micro and macro cracks in the highwall that facilitate the entry of air
- Long exposure of the exposed seam to the atmosphere

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13 https://hss.energy.gov/nuclearsafety/techstds/standard/hdbk1081b.html

- Accumulation of loose coal on the floor adjacent to the highwall
- The specific problem of mining old workings, with the ready entry of air through exposed bords.

The above points are equally applicable to single-seam operations or to multi-seam, open-pit mining, where coal seams on benches may be a source of spontaneous combustion when exposed for protracted periods.

The literature consistently points out that to prevent or combat heatings and fires the guiding principles are based on the fire triangle (figure 1). Since the source of fuel is the coal being mined and the potential source of heat is the oxidation of that fuel, the only effective prevention techniques must be based on preventing air coming into contact with any coal that is prone to spontaneous combustion. The techniques used by South African mines will be discussed later in this report, but the most commonly discussed method in overseas literature is sealing of cracks.

The cracks may be sealed with a mechanical spraying device using fire protective coating material. The characteristics of a typical fire protective coating should include:

- Easy spraying
- Compatibility with coal
- Not washed down by water/rain
- When applied over coal surface, it forms a uniform thin coat
- Maximum resistance to air permeation
- Good fire resistant capacity
- Coating remains intact for a long time (more than a year)
- No cracks appears in the coating material and there is no scaling from the coal surface during blasting of the coal face
- The shelf life of coating material is more than one year.

Singh and Singh (2004)[14] used this technique in an opencast coal mine in India for a typical bench height of 20m. The system used 0.8 to 0.9 kg/sq.m and the resultant thickness of coating was reported to be 0.9mm after two coats. It is said that the coating remained intact even after heavy rains and the coated zone temperature remained at ambient.

Panigrahi, et al[15] reported on inhibitors that reduce the spontaneous combustion susceptibility of Indian coals. The following inhibitors were considered:

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14 RVK Singh and V K Singh, Mechanical Spraying Device-A novel technology for spraying fire protective coating material in the benches of opencast coalmines for preventing spontaneous combustion. Fire Technology, 40, 335-365, 2004 Kluwer Academic publishers

15 D C Panigrahi, G Udaybhanu, M D Yadav and R S Singh, Development of inhibitors to reduce the spontaneous heating susceptibility of Indian Coals. Eight International Mine Ventilation Congress. Brisbane, Queensland, 6-8 July 2005

- Mono-valents such as sodium chloride, potassium chloride and lithium chloride
- Bi-valents such as magnesium chloride, zinc chloride, calcium chloride, magnesium sulphate, ferrous sulphate and magnesium phosphate
- Tri-valents such as ferric chlorate and aluminium sulphate.

Laboratory-scale studies using these inhibitors were carried out, but there is no mention of field trials. Most of the inhibitors showed an increase in the crossing point temperature, i.e. the temperature at which spontaneous combustion occurred indicating an inhibiting effect of 5% to 10%. However, the additional cost of using inhibitors was not explored.

Current experience at South African surface coal mines

Introduction

As has been stated several times, spontaneous combustion problems are currently experienced in stockpiles, waste dumps, spoils heaps and in the highwalls of some South African mines. The most acute problem is associated with the surface mining of previously mined underground sections. This section reports the techniques and control measures currently used in South Africa. The information was gathered by visits to five mines with spontaneous combustion problems.

Case Study 1 (New Vaal Colliery)

Brief description of New Vaal Colliery

New Vaal Colliery is owned by Anglo Coal. It is situated south of Johannesburg on the Free State side of the Vaal River and mines the reserves of the old Maccauvlei Mine. Maccauvlei was established in 1898 on the Transvaal side of the river and began exploiting the Free State reserves in 1931. New Vaal was established in the early 1980s to service the Lethabo Power Station and delivered its first coal in 1985. Since then approximately 675 Mt of sales have been made.

Initially Lethabo was designed to burn 15.1 Mtpa with a 40-year lifespan. Later, the burn was increased to 18.4 Mt and New Vaal is currently developing its Maccauvlei West reserves (100 Mt) to produce 3 Mtpa from this area in the future. New Vaal is currently mining low-grade coal for power generation. The coal has a CV of 12 – 13 MJ/kg for the top seam, 15 –17 MJ/kg for the middle seam and >19 MJ/kg for the bottom seam.

The New Vaal coalfield is covered by 15m to 22m of sand and has three seams: top, middle and bottom, which do not appear to have any direct correlation with the seams of the Witbank Coalfield. The three seams are mined simultaneously to produce a blend of 15.6 MJ/kg for the power station. The coal seams in this area are undulating.

The lithology is quite variable over the mine but typically would be:

- Sand 20m
- Overburden 13m
- Top seam 7m
- Inter-burden 13m
- Middle seam 6m
- Parting 2m
- Bottom seam 4m

Approximately 87% of the sand is removed by dragline, by truck and shovel, or by bucket wheel excavator.

Most of the mine area was previously mined in underground sections and there are many instances of spontaneous combustion. The top seam, where it is mined at present, has no previous workings and has no spontaneous combustion problems, but future plans include the mining of this seam in areas previously mined. The middle seam was extensively mined by bord and pillar workings and spontaneous combustion problems have occurred during current mining operations. Because the old workings were flooded many years ago they now need to be dewatered before mining can take place. However, after dewatering the coal starts burning within days.

Summary of spontaneous combustion problems at New Vaal

All three of the existing pits have similar spontaneous combustion problems. In general the top seam does not burn when blasted, but remnants are left that can heat up, but do not flare into major fires. The problem of spontaneous combustion is only severe where previous underground working exists in the middle and bottom seams. In places the spontaneous combustion problem is so severe that it can compromise the stability of the highwall. Temperatures in the open bords have been inferred to be up to 2 000°C.

The mine has experienced difficulty in preventing spontaneous combustion because of the problem of locating underground workings and locating the bords when drilling owing to the inefficiency of the survey methods in the early days of underground mining.

Spontaneous combustion can lead to the heating of blast holes and creates a risk of premature detonation. Blasting is carefully conducted following the guidelines below:

- No detonators should be used at the bottom of the holes
- No charging of holes if the temperature exceeds 60°C
- Use boosters and detonating cord as downline
- Sometimes shock tubes may be used if the temperature allows. At high temperature shock tubes may melt before detonation takes place.

Control of spontaneous combustion at New Vaal

Since the mine has a plentiful supply of sand, cladding of heatings in the highwall is the most common technique for dealing with spontaneous combustion once it has occurred. The use of high-pressure water cannons has been successful where mining takes place, but not in the advance cuts. However, water cannons have proved ineffective for dealing with large heatings and the mine is well aware of the possibility of a water gas explosions within the old bords especially when temperatures exceed 2 000°C.

Prevention of spontaneous combustion mainly involves the creation of a buffer, which is usually maintained at a minimum width of 20m for a 60m wide cut. It is important to locate the old pillars for blasting purposes and surveyors need to have a significant input into the design of blast patterns, which must follow the layout of the old workings. If the bords are not filled with blasted material, air can leak into the underground workings and cause spontaneous combustion. The biggest challenge faced at New Vaal is the correct drilling of blast holes, as holing into the old workings can occur. A procedure must be in place that if a drill hole penetrates a bord it must be plugged immediately, since it acts as a chimney.

Case Study 2 (Middleburg Mine)

Brief description of Middleburg Mine

Middleburg Mine is a BHP Billiton (BECSA) opencast mine located near the town of Middleburg in Mpumalanga province. The mine has a RoM production of approximately 25 Mtpa and the sales tonnage is about 15.6 Mtpa. The mine is the sole supplier of coal to the Duvha power station (9.6 Mtpa) and also produces 6 Mtpa of coal for the export market.

The mine lithology consists of:

No. 5 seam – Overburden (sandstone and shales)

No. 4 seam – Interburden (sandstone and shales)

No. 2 seam consist of the No. 2 upper, No. 2 and No. 2 lower

Parting

No. 1 seam

The mine uses draglines to strip the overburden and a combination of shovels and trucks to mine the coal. Several pits are mined simultaneously, however, the focus of the information gathering visit was on the Boschmanskrans pit where the No. 2 and No. 4 seams are mined. The overburden on top of the No. 4 seam is about 20m and is mined by a truck and shovel fleet and the interburden on top of the No. 2 seam is approximately 30m and is mined by draglines.

Summary of spontaneous combustion problems at Middleburg Mine Services

Spontaneous combustion occurs in the No. 2 seam because of previously mined underground workings. There is no spontaneous combustion in No. 4 seam because there are no previously mined underground workings, i.e. mining takes place in virgin ground.

Spontaneous combustion was visible in the product stockpiles and in the highwall of the Boschmanskrans pit.

Problem areas observed and reported during the visit include:

- Spontaneous combustion occurring around the edges of pillars was visible at several locations in the highwall
- Spontaneous heating occurs where coal and shale were loaded together. It is suspected that this happens because the shale is more prone to spontaneous combustion than coal

- Burning spoils
- General problems with the sand cladding of highwall heatings
- Visibility problems during loading owing to particulate matter generated by hot coal
- Turnover of management leads to loss of continuity in the combating of spontaneous combustion.

Control of spontaneous combustion at Middleburg Mine

Buffer blasting techniques have been applied to prevent air from entering the old workings and causing spontaneous combustion. The size of the buffer is 15m on a 60m cut. This size of buffer was found to be smaller than at other mines visited. This means that of the original cut of 60m, 45m can be mined. When the next cut of 60m is blasted a buffer of 75m will be created and 60m can be mined keeping the minimum buffer at any time in the cycle at 15m.

Blasting takes place every three to four days and the explosive used is emulsion. Blocks 100m long are blasted at a time. The blast holes for the overburden are drilled 1m short of the total overburden depth to avoid blast holes from penetrating into the bords. Sometimes holes that have penetrated bords have not been sealed immediately and this has led to spontaneous combustion problems.

No more than 100m of coal is exposed at any time behind the dragline to assist in controlling spontaneous combustion. In general coal mining keeps pace with the dragline exposure. When the inventory was increased the problem of spontaneous combustion also increased.

It was observed that spontaneous combustion occurs around the edges of the pillars, which indicates that the bords were, in fact, not sealed properly despite the buffer blasting technique used. It is very likely that the reduced size of the buffer could be too small for the complete exclusion of air and this undoubtedly contributes to occurrences of spontaneous combustion.

Water cannons are used to cool the hot coal during loading, which results in water vapour and dust being released into the atmosphere and decreasing visibility, especially at night. Water cannons did not appear to be effective in combating the problem of spontaneous combustion during loading despite the efforts of the mine personnel and there appeared to be significant dust generated during loading.

The spoil side of the operation also seems to be a major problem, with the spoiled material burning. Cladding of the highwall is undertaken, however, it is not easy since sand for the cladding operation is not freely available on site.

During the visit, mine personnel suggested that, for effective control of spontaneous combustion, both overburden removal and the coaling operations should be under one manager. It is believed that the mine has now implemented this strategy.

The management of Middleburg Mine recognises that the spontaneous combustion is serious and that the mine is one of the most affected in South Africa.

Some of the readily identifiable reasons for the problems experienced at the mine include:

- Newly appointed managers need time to develop an appreciation of the role of buffer blasting in the control of spontaneous combustion
- There have been occasions when the buffer was mined
- All the available information and discussions indicate that no clear and documented standard code of practice exists to deal with spontaneous combustion. The mine was supportive of the present study to develop guidelines
- At the time of the visit there was a general acceptance that spontaneous combustion caused by mining activities is inevitable and it should be dealt with as and when it occurs.

Case Study 3 (ATCOM Colliery)

Brief description of ATCOM Colliery

Arthur Taylor (ATCOM) Colliery is an Xstrata opencast mine situated about 27km south of Witbank. The mine produces about 4 Mtpa of export coal. Surface mining started in 2003 and it operates in an area previously mined by bord and pillar workings during the period 1930 to 1970. This is referred to as the Old Phoenix Village area. These old workings are in the northern part of the lease area, while the eastern portion is virgin ground.

The seams being mined are the No. 2 and No. 4 seams. The yield for the No. 2 seam is 50% and it is 70% for the No. 4 seam. The No. 3 seam is not mined since it has a high sulphur content and is also extremely prone to spontaneous combustion. Mining of the overburden is by a dragline and the length of the pit is about 4km.

The mine lithology consists of:

- Overburden: 0m – 25m, average 8m –10m
- No. 4 seam: average 2.5m
- Interburden: 20m – 25m, average 22m
- No. 2 seam: 4m – 5m.

The mine makes use of 50m wide cuts. The coal seam is undulating and therefore careful surveying is essential to ensure blast-holes are drilled accurately.

Summary of spontaneous combustion problems at ATCOM Colliery

The mine has spontaneous combustion problems associated with the previous workings in the northern part of the lease area and the problem usually manifests itself in the interburden. However, this has not become a major problem because of the commitment at the mine to prevent spontaneous combustion. There are some combustion problems in the spoil piles.

Various methods are used to deal with spontaneous combustion and these methods are discussed below.

Control of spontaneous combustion at ATCOM Colliery

ATCOM Colliery has an established system to prevent and control spontaneous combustion and the mine has a code of practice to implement the specific drilling and blasting techniques that work best for the mine. The code of practice is included in this report as Appendix 1.

There is a good understanding of the spontaneous combustion problem at the mine and this influences all mining decisions.

The mine uses buffer blasting and management believes that the size of the buffer is critical for effective prevention of spontaneous combustion. A buffer size of 0.75 x bench height is used, but management would be prepared to increase this to 1.5 x the depth of cover when warranted. In linking buffer width to bench height, the argument is made that the higher the bench, the greater any "chimney effect" and the wider the required buffer ensures that air is prevented from entering the old bords. There is no scientific proof of this statement but intuitively it appears to have merit. Lately, the mine uses a 50m buffer on a 50m wide cut to control spontaneous combustion.

A coal length of up to 50m is left exposed by the dragline before being mined. However, no spontaneous combustion problems are experienced, which shows that the coal being mined is not particularly prone to spontaneous combustion.

The mine is fortunate in that the highwall is oriented in a north/south direction, as is the prevailing wind direction. This means that the wind does not force air through the buffer into the open bords beyond.

Cladding of the surface of the overburden is by dozing using the red soil immediately following blasting. Material taken from the overburden of the No. 4 seam makes excellent cladding material as it becomes hard after dozing over.

The blast holes are typically 250mm in diameter and 22m in length – 1.5 m short of the total interburden thickness. This prevents coal damage and also prevents the chimney effect caused by blast holes that penetrate into the old bords.

Blast holes are sealed immediately after drilling to prevent the ingress of air. In the past the mine used a plug in hot blast holes that comprised a cone with two chemicals, which were mixed by removing the membrane separating them after they had been lowered to the bottom of the blast hole. Once mixed the chemicals formed a foam that expanded to seven to eight times its original size and which sealed the hole. It was reputed to withstand the force of the explosion. Soft shales can easily be sealed with these chemicals. It is understood that this practice has ceased because of cost considerations and holes are now sealed by air bags or a section of old tyre placed at the top of the blast holes.

Case Study 4 (Landau Colliery)

Brief description of Landau Colliery

Landau Colliery is an Anglo Coal opencast mine situated to the west of Witbank in the Witbank Coalfield. Underground mining commenced 40 years ago with conventional bord and pillar mining. The mine currently extracts the No. 1 and No. 2 seams, which are separated by a parting that ranges in thickness from 0.5m – 2m. Landau mines two reserve blocks, namely the Kroomdraai and the Excelsior blocks. Kroomdraai produces 6 Mtpa while Excelsior produces 0.72 Mtpa for the export market. The coal is transported about 2.3km from the pit to the plant.

The dragline mines 60m cuts in a single cut with simple side casting. The pit is 2.2km in length. The depth of the overburden varies from 28m to 35m and the stripping ratio ranges from 3.5:1 to 4:1.

Summary of spontaneous combustion problems at Landau Colliery

Landau Colliery had a severe spontaneous combustion problem until 2003. The problem was particularly acute at the time when the parting between the two seams was at its thickest because the coaling operations needed to be conducted in two passes. This resulted in delays in removing the coal and, because the parting was hard and needed to be blasted, the coal was subjected to additional fragmentation. Management believes that spontaneous combustion can be prevented using the existing technique of buffer blasting, but the risk will never be completely eliminated while opencast mining is used in the subsequent mining of previously mined bord and pillar workings. At the time of the visit spontaneous combustion was not a problem and only localised heatings were being monitored.

Control of spontaneous combustion at Landau Colliery

The risk of spontaneous combustion is taken very seriously at Landau and the mine has a long-term and consistent approach to the problem. The philosophy at the mine is that prevention is better than cure since, in a mine with spontaneous combustion problems, a quick fix is not possible and the problem will have to be solved progressively with an improvement from cut to cut. Experience at Landau has shown it takes about five cuts to eliminate the spontaneous combustion through buffer blasting.

At Landau the maximum time required to mine a cut is kept to three months. This avoids prolonged exposure of coal and overburden and prevents heat build up within the highwall. It is thought that a turnaround time of anything less than three months is adequate to substantially decrease the probability of spontaneous combustion.

In summary, the control measures found to be effective at Landau are:

- Buffer blasting. The dragline mines 60m wide cuts with a 20m buffer maintained at all times. Buffer blasting has been used successfully for a number of years and the results are an obvious success
- Buffer blasting is used in conjunction with cladding

- The use of a pre-split blasting is avoided as it creates cracks around the highwall allowing oxygen into the old workings
- Constant monitoring of the highwall is carried out and any change indicating a heating is acted on
- No dewatering is done ahead of time
- Venting holes and hot holes are dealt with immediately
- Flower pots and gas bags are used to close hot holes
- A hot hole procedure exists, which details how hot holes should be treated and how drilling should be done near hot holes
- A maximum of three weeks of coal production is left exposed in the pit.

Geological and dewatering holes are monitored constantly while in use and the holes are either concreted and/or sealed when no longer needed.

The concept of "just-in-time drilling" should be implemented and effectively managed. If a dragline stops uncovering the coal and drilling continues, there is a risk that the holes will act as chimneys and after a critical time has elapsed the coal can catch alight. Hence reducing the blast inventory may be a solution if the buffer does not prevent spontaneous combustion.

The blast pattern should be designed to give a wide fragmentation size distribution, i.e. a good spread of large material mixed with fines provides a better seal in the old bords and the buffer becomes more effective. The current buffer plan is shown in figure 4.

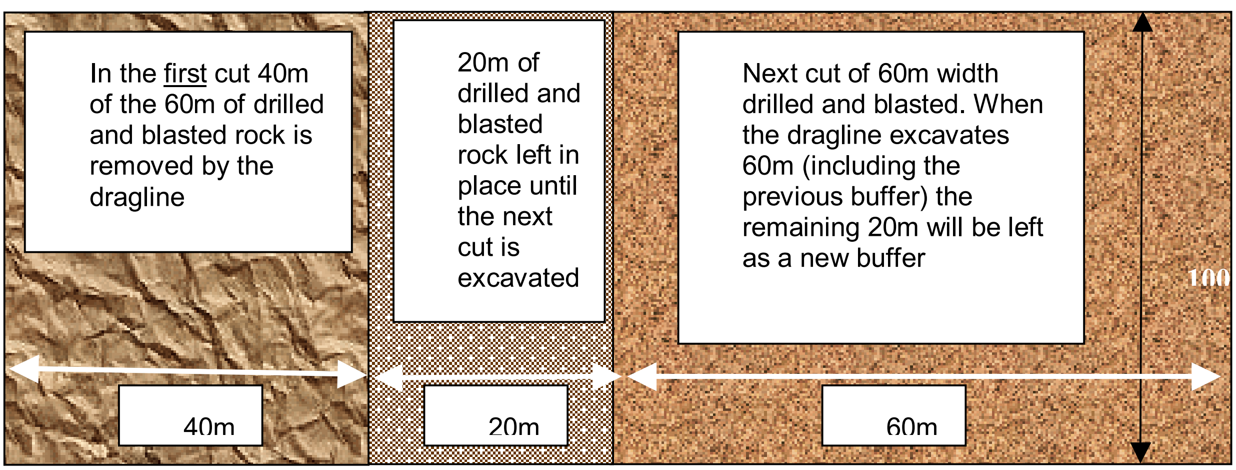

Figure 4 Section through the overburden showing a 20m wide buffer.

Case Study 5 (Kleinkopje Colliery)

Brief description of Kleinkopje Colliery and its spontaneous combustion problems

Kleinkopje Colliery is an Anglo Coal multi-product opencast mine situated 10km south-west of Witbank. Opencast mining commenced in 1979, although there had been underground mining in the Kleinkopje area since the early 1900s. The mine produces 8 Mtpa RoM, leading to export sales of 4.5 Mtpa. The mine typically makes use of four or five draglines.

Kleinkopje Colliery has a unique geology. There is a massive syncline structure and the seam gets deeper towards the east. There are currently four pits operating at the mine, namely 5 west south, 3A north, 2A north and 2A South, with most mining taking place in the No. 2 seam, which was mined previously. The coal reserves are predominantly found in the No. 1, No. 2 and No. 4 seams.

The mine is currently experiencing serious spontaneous combustion problems in the highwalls and, in addition, spoils begin to burn after about two months. The problems in each of the four pits are discussed separately.

5 west south – This pit is predominantly mining virgin No. 2 seam, with a portion of production coming from the No. 1 seam. The coal is poor quality and typically has a calorific value of 18 MJ/kg to 19 MJ/kg. Once the highwall is exposed it starts burning. Burning also takes place on the edges of the spoil material.

3A north – In this pit mining can potentially take place in the No. 1, No. 2 and No. 4 seams. Currently this pit is mining virgin No. 4 seam coal. However, the No. 2 seam has been pre-mined and mining in the No. 1 seam has not yet started. There is a massive syncline in the highwall of this pit and the overburden thickness is between 15m and 30m with an interburden of between 18m and 25m. Since overburden thickness is not constant, accurate drilling becomes problematic and sometimes blast holes penetrate into old workings. These open blast holes usually create a chimney effect and this is a contributory factor in the spontaneous combustion problem. The depth of the No. 2 seam is between 60m and 70m because of a scissor fault. There is very little sand or soft material available in this pit to combat spontaneous combustion, which results in insufficient and intermittent cladding of the highwall to control the outbreaks of spontaneous combustion.

2A north – Mining takes place in both the No. 2 and No. 4 seams. The overburden thickness is on average 25m, with the top 15m being soft overburden. Spontaneous combustion is not prevalent in this pit, however, some heating has been experienced in the eastern part of the pit during coaling operations.

2A south – Three seams: No. 1, No. 2 and No. 4 are being mined and this area was extensively mined by underground operations, with these previous workings being flooded. Because the pit has experienced extensive spontaneous combustion problems, interventions have been developed and tried over several years. These include buffer blasting, double cuts, dewatering at 5 ML/day and constant monitoring. One of the major challenges in this pit is an intersection point between two ramps R10-9 and R7-6 that, at the time of the visit, turned the highwall through an angle of 113^{o} thus increasing spontaneous combustion because air entered the old workings from two directions

2A south is the only area in the mine where there is sufficient sand and soft material in the overburden to ensure proper cladding. Roughly 15m to 30m of the overburden is suitable for this purpose. However, in the rainy season mining condition deteriorates and, in the interests of safety, no cladding is undertaken.

Control of spontaneous combustion at Kleinkopje Colliery

Buffer blasting was used in the early days of the mine, but was discontinued as it was felt that the first row of holes near the highwall acted as a chimney. It is understood that since the visit buffer blasting is gradually being re-introduced.

Temperature monitoring of the interburden is practised continually using available drill holes. The temperatures it typically found to be in the range 20^{o}C – 25^{o}C.

Smaller diameter blast holes (160mm compared with 311mm) are used, together with a closer spacing of holes to obtain better fragmentation of the overburden. This is intended to prevent the ingress of air and oxidisation of the coal and is thought to compensate for not undertaking buffer blasting.

Cladding, when properly sequenced, is found to be effective, but the fact that it is not always undertaken leads to problems.

Dewatering of the old workings is essential and is currently taking place at 5 Ml/per day. However, it is known that this process increases the risk of spontaneous combustion.

Over the years management at Kleinkopje Colliery has been very concerned about the spontaneous combustion problems. It is one of the few mines that has a spontaneous combustion document outlining key performance indicators (KPI) for the prevention of spontaneous combustion. This is attached as Appendix 2. However management is concerned that further documentation is required to offset the problems associated with the turnover of management and the subsequent loss of experience and technical expertise.

To achieve the spontaneous combustion KPIs a number of interventions were listed by management, as follows:

- Single cut operation
- Cladding of the highwall whenever heatings are detected
- Interburden drilling with a burden and spacing of 10m x 12m
- A hot hole procedure is in place
- No more than a week's coal is left between the dragline and the coaling operation
- 350mm cladding is placed on top of the overburden
- The drilling crew is responsible for plugging all the venting holes
- A spontaneous combustion team has been formed to plan and measure the performance of each section
- There is raised awareness of spontaneous combustion throughout the mine
- Increased vigilance is practiced in summer months as the risk of spontaneous combustion rises in wet conditions.

Conclusions and recommendations

Spontaneous combustion occurs when coal and/or carbonaceous material is oxidised by contact with air and the heat generated by this process is greater than the heat lost from the site of this reaction. The resultant temperature increase leads to an increased reaction rate and eventual ignition of the material.

Intact coal seams, when extracted by surface mining, are generally unaffected by spontaneous combustion unless they are of poor quality. The major occurrences of spontaneous combustion in South Africa are associated with the surface mining of seams previously partially extracted by bord and pillar mining. Under these circumstances the opportunity exists for airflow to penetrate into the seam through open bords in the highwall. Airflow through the old workings can also be encouraged by the “chimney effect” created by cracks in the overburden and open blast holes that have penetrated a bord.

Small-scale mining of previously mined areas, where pillars are excavated one at a time are not normally affected by spontaneous combustion. However, the large operations, which are necessary to achieve the required high outputs, must rely on blasting multiple pillars simultaneously.

Spontaneous combustion of virgin coal seams occurs far less frequently, but heating of broken coal left in stockpiles in the cut or elsewhere on the mine can occur after a period of time, depending on the properties of the coal. Two important factors that trigger spontaneous combustion are the presence of pyrites in the seam and changes in moisture content of the coal or carbonaceous shale. Several mines have reported that spontaneous combustion has occurred after dewatering and it is known from the literature that changes in moisture content are an important trigger for spontaneous combustion. Drying of coal exposes fresh surface areas that were previously prevented from oxidation by the presence of water. Repeated wetting and drying of stockpiles should be avoided at all costs, while dewatering of in-situ pillars should take place shortly before they are excavated, i.e. within the incubation period for spontaneous combustion in that seam.

Since many of the previously mined areas need to be dewatered before surface mining can proceed, the rate of dewatering and its distance in advance of the highwall needs to be carefully considered.

Since spontaneous combustion is caused by the interaction of coal and oxygen, its prevention relies on two mechanisms:

- Prevention of airflow
- Mining the coal before heating occurs.

In surface mining operations prevention of airflow can be achieved by cladding the surface of the highwall with sealant, blocking the ingress of air to the old workings by sealing the open bords with soft material, or by collapsing the overburden into the bords by means of buffer blasting.

Where spontaneous combustion occurs at the highwall owing to the length of time the coal is exposed, then scheduling of the mining operations to ensure exposure time is minimised and is within the time taken for spontaneous combustion to occur, can substantially reduce the risk of coal ignition.

The consensus (all but one of the affected mines consistently practice this) is that buffer blasting of the overburden is the most effective technique to control spontaneous combustion in previously mined areas. The buffer must be maintained throughout the mining cycle to prevent ingress of air from the highwall. Some mines recommend that the buffer must never be less than a third of the width of the cut. Since cuts are typically 60m wide this results in a minimum buffer width of 20m. One mine, ATCOM, has suggested that the width of the buffer should not be a function of the cut width, but rather should be a proportion of the height of inter/overburden above the seam, i.e. the height of any potential chimney should determine the width of the buffer. Since the use of a buffer is the most effective method of dealing with the spontaneous combustion problem, a description of how a buffer can be created is given in Appendix 3.

The biggest problem in creating an effective buffer is locating the pillars, so that blast holes can be drilled to intersect them. Old plans are notoriously inaccurate and so as much information as possible on the location of pillars must be gathered during exploration drilling and while drilling blast holes. This information should be used to predict the position of pillars but, if a blast hole drilled to intersect a pillar penetrates a bord, it should be sealed and further holes drilled until one positively intersects the pillar, thereby ensuring it will be blasted into the surrounding bords.

Since airflow from the old workings can also take place through blast holes, unsealed exploration boreholes and cracks to surface, these routes should also be sealed. In particular, blast holes should be monitored for increases in temperature and hot holes effectively sealed as soon as possible. Pre-spilling is suspected of aggravating the spontaneous combustion problem by creating cracks to surface and the conclusion is that it should not be practised. Buffer blasting can also create cracks to surface, but with grading of the surface to seal obvious cracks, buffer blasting remains the most effective method of preventing airflow into the old workings.

The risk of spontaneous combustion will always exist when surface mining of old workings takes place. Prevention of this problem is much better than dealing with the issue once it has occurred. Planning should always include the need for buffer blasting since prevention is always preferable. Experience has shown that once spontaneous combustion has taken hold in old workings it may take up to five cuts, each with a buffer in place, to eliminate the problem.

During mining the temperatures at the highwall and in blast holes should be monitored routinely and remedial action taken immediately if a heating is detected, e.g. sealing of bords by tipping soft material over the highwall and sealing of hot blast holes.

Reducing the blast inventory and amount of coal exposed in between the dragline and the coaling operation is important in mines where spontaneous combustion is a problem.

Since hot blast holes will inevitably be encountered, it is recommended that research continues into the development of devices for monitoring hole temperatures reliably. Similarly, there should be research into explosives suitable for use in hot holes as the risk of premature detonation will always be present when dealing with blast holes in areas prone to spontaneous combustion.

In the interim it is essential that the risk of premature detonation be reduced by each mine by implementing a code of practice for dealing with hot blast holes. An example of such a code of practice is given in Appendix 1.

The report of the previous research into spontaneous combustion undertaken by Coaltech was made available in 2003. However, because of the high incidence of personnel movement in the meantime, many people currently involved with this problem are unaware of its existence. It is recommended that it is redistributed to all mines with existing or potential spontaneous combustion problems.

Finally, it is recommended that management at mines with spontaneous combustion problems, or at mines where management is contemplating the mining of seams previously mined should visit other, similarly affected mines to see the practices used to control the problem.

Appendix 1

ATCOM Colliery Hot Hole Procedures

(Courtesy of ATCOM Colliery)

Drilling, charging up and blasting into underground workings

Objective

To provide a standard operating procedure (SoP) for the drilling supervisor and drill operators to carry out their duties safely and effectively and to ensure that correct drilling patterns are adhered to thus enhancing the occupational health and safety of fellow employees.

Scope

This SoP is applicable to ATCOM North and South Pit.

Responsibility

The mine overseer, surveyor, drill supervisor, blasting supervisor, blasters and drill machine operators are responsible for the compliance with this SoP.

References

- Mine Health & Safety Act.
- Recommendations from supplier, AEL.

Definitions

Hazard – A source or situation with a potential for harm in terms of human injury or ill health, damage to property, damage to the workplace environment, or a combination of these.

Hot Hole – Any hole, whose temperature exceeds 60ºC, will be treated as a hot hole.

Procedure

Drilling Patterns

In-pit

- Table 1 shows in-pit drilling patterns and will be staked by the drilling section assistant
- Only the drill & blast overseer may alter these patterns
- He will prescribe drilling patterns for any secondary drilling, or any other drilling required.

Drill hole (pre-split and in-fill) control

- The drill & blast overseer will co-ordinate this process.

Pre-split holes

- Pre-split holes will be drilled 5m apart in all in-situ areas on the overburden and interburden, on the 50m line, down to the bottom of the 2 and 4 seam

- The survey department will design the pattern on Modelmaker, showing the hole position and general depth. The plan is then exported from the survey department into the Aquila System on the Pit Viper and DMM2.

Test holes

- Test holes are drilled in undermined areas
- These holes are drilled 25m apart on the buffer perimeter
- These holes should hole. All the holes must be plugged by the drill operator, directly after the drill has moved off the hole position.

Infill holes

- The surveyor will extract and collect all the data for the pre-split and test holes from the Aquila system
- The strata logging on each hole will determine the top of seam position
- He will build an infill plan and model, showing the exact position and depth of each hole to be drilled.
    - The 4 seam overburden infill holes must be drilled to the top of 4 seam lower level, minus 50cm.
    - The 2 seam interburden in-situ infill holes must be drilled to the top of seam, minus 1m
    - The 2 seam interburden undermined holes must be drilled to the top of seam, minus 2.5m
- The operator will ensure that every hole is drilled at the right position to the predetermined depth. Any hole holed into underground workings must be sealed and marked before any other hole is drilled
- Sealing will be done with an upside-down cone pressed down into the hole and dirt placed in the cone. Another cone will be placed on the hole, facing upwards, with a stake indicating the hole number and holed depth. The drill operator is responsible for this procedure. Each hole that holes must be reported to the supervisor
- All infill holes must be re-drilled 1m away on spacing line and 2m shorter than the original depth
- All buffer holes must be drilled with 200mm rotary bits and infill holes with 250mm bits
- Table 1 indicates the drill patterns
- A and B line infill holes next to the void will only be drilled in daylight hours
- If for any reason, i.e. cracked floor, hole on gradient, close to highwall, etc., a hole cannot be drilled at the required position, the supervisor will move the hole to a safe position, plot the position on the plan, log the change and notify the mine overseer. The survey department will import all the reports from the drills and keep them on file
- The drill supervisor will report the production and any anomalies to the mine overseer on a daily basis.

Spontaneous combustion prevention measures (hot hole)

- Temperature/test holes must be drilled on every block north-west corner and kept two strips ahead
- Monitor the hole temperatures on a weekly basis and keep records
- The holes must be holed in underground workings
- The holes must be kept closed at all times and will only be opened for monitoring purposes
- The holes must be numbered and recorded on a survey plan
- A strata log must be kept of each hole
- Monitor the water level if available
- Monitor the general airflow – in or out
- This record must be signed off by the mine overseer and colliery manager.

Buffer blasting

- 200mm diameter holes are drilled to 1.5m from the 2 seam top horizon
- If more than three holes hole prematurely, 0.5m must be added to the shorter depth. The mine overseer must authorise the change
- A smaller burden and spacing will be employed – 6m x 8m
- A 30m buffer will be drilled with a 20m overlap into the solid in situ area
- No conventional pre-split will be drilled
- Test holes will be drilled 25m apart on the back line.

Hot hole area

An area is identified as a hot hole area by:

- Hole temperatures above 60ºC
- Smoke or steam coming out from holes
- Hole temperature increases by 10ºC above 40ºC.

Action

- All holes within 100m from the affected holes will be treated as hot holes or cool holes
- All holes within 100m of an identified hot hole area, must be measured and recorded daily
- No sleeping over of explosives will be carried out.

Hot hole area preparation

- Areas to be blasted must be limited to 200m in length
- All blast holes must be staked, indicating the hole number, depth and temperature measured. Use measured temperature as an indicator:

White stake – measuring -40ºC

Green stake – measuring 40 - 60ºC

Red stake – measuring +60ºC

- Measure all holes shortly before charging up operations begin
- At least three bulkmaster explosive trucks or two with rapid reload system, must be available (sufficient backup in case of breakdowns)
- Ensure that all equipment is safe and in reliable working condition
- Retreat all persons not involved in the blasting operation
- Brief the blasting crew
- Never work over holes
- Charge hot holes (red tag) holes last without primer
- Mid prime hot holes only when ready to blast
- Brown, yellow and white fumes indicate rapid oxidation – remove workers downwind who could inhale the fumes. Do not insert booster and initiate blast as soon as possible
- Intersected holes must be indicated with a green flag.

Hole treatment

	Normal	Cool	Hot Hole
Temperature	-40ºC	40 – 60ºC	+ 60ºC
Stake colour	White	Green	Red
Solid hole	Charge normally	Charge normally	Apply coolant for 1 metre in hole with an airbag on top.
Intersected	Close and re-drill (6.1.3.2. d, e, and f)	Close and re-drill (6.1.3.2. d, e, and f)	Close and re-drill (6.1.3.2. d, e, and f)
Surface	Noisemasters with 12m/s in front line and 75,100 m/s to back	Noisemasters with 12m/s in front line and 75,100 m/s to back	Noisemasters with 12m/s in front line and 75,100 m/s to back
In hole	1m HTD Noisemaster with (200 – 450m/s) delay	1.5m HTD Noisemaster with (200 – 450m/s) delay	1.5m HTD Noisemaster with (200 – 450m/s) delay
Detonator	8D	8D	8D
Booster	400gm	400gm	800gm
Position	10m – 15m down	10m down	Keep on top and drop down when ready to blast.
Stemming	5m chippings	5m chippings	4m – no stemming
Green flag holes	Intersected holes will not be charged	Intersected holes will not be charged	Intersected holes will not be charged
Tie up	Normal	Normal	Normal

Monitoring, revision and document control

- Monthly PTOs must be conducted and recorded as per Planned Task Observation schedule
- The following documents must be kept in a safe place by the responsible mine overseer for a period of one year
- This SoP must be revised annually or when necessary and kept updated by the responsible department (drill & blast section).

Revision Date:	**Responsible Person:**	**Paragraph**	**Reason for Amendment / Revision**

DRILLING PATTERNS											
DRILL RIG	**MARION/DMM2**		**DRILTECH**				**XL 635**				
BIT SIZE	**251mm**		**171mm**				**102mm**				
Source	**Over Burden**	**Mid Burden**	**1#**	**2#**	**4#**	**½ Parting**	**1#**	**2#**	**4#**	**½ Parting**	**Over Burden**
Depth	**Burd/Spac (m)**		**Burd/Spac (m)**			**B/S (m)**	**Burd/Spac (m)**			**B/S (m)**	**B/S (m)**
0 - 1.0	-	-	3 x 3	3 x 3	4 x 4	3 x 3	3 x 3	3 x 3	4 x 4	3 x 3	3 x 3
1.0 - 2.0	-	-	4 x 4	4 x 4	5 x 5	3 x 3	4 x 4	4 x 4	5 x 5	3 x 3	3 x 3
2.0 - 3.0	-	-	4 x 4	4 x 4	6 x 6	3 x 3	4 x 4	4 x 4	6 x 6	3 x 3	3 x3
3.0 - 4.0	-	-	4 x 4	4 x 4	6 x 6	3 x 3	4 x 4	4 x 4	6 x 6	3 x 3	3 x 4
4.0 - 5.0	6 x 8	-	-	4 x 4	6 x 6	3 x 3	-	4 x 4	6 x 6	-	3 x 4
5.0 +	6 x 8	Survey Plan	-	4 x 4	-	-	-	4 x 4	-	-	3 x 4

North Pit Pattern

General Rules on 2 Seam

TABLE 1

In Situ				Buffer Front Strip				Buffer Strip			
Line	Burden	Space	Stem	Line	Burden	Space	Stem	Line	Burden	Space	Stem
A	6	9	6	A	6	9	6	A	4	8	4
B	7	9	6	B	7	9	6	B	6	8	4
C	8	9	6	C	8	9	6	C	6	8	4
D	9	9	6	D	9	9	6	D	6	8	4
E	9	9	6	E	9	9	6	E	6	8	4
F	9	9	6	F	9	9	6	F	4	4	4
P/Split	2	5		Test		25					
Total	50				48				32		

Test Holes25m apart on 50m Block line

4# Overburden

Line	Burden	Space	Stem
A	6	8	6
B	6	8	6
C	6	8	6
D	6	8	6
E	6	8	6
F	6	8	6
G	6	8	6
H	6	8	6
P/Split	2	5	
	50		

DRILL RIG	DM30			DR2
BIT SIZE	171mm			102mm
Source	Coal		Cap ping	Cap ping
Depth	2#	4#	B/S	B/S
0 - 1.0	3X3	4x4	3x3	3x3
1.0 - 2.0	4x4	5x5	3x3	3x3
2.0 - 3.0	4X4	6x6	3x3	3x3
3.0 - 4.0	4X4	6x6	3x3	3x3
4.0 - 5.0	4X4	6X6	3x3	
5.0 +			-	
P.f	0.24	0.18	0.55	0.55
kg/ton	0.16	0.11		

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FORM 1

DATE : ……………………………………

CHARGING INSTRUCTIONS

DRILL & BLAST SECTION

SOURCE:			PARTING	BURDEN	PRE-SPLIT	COAL
RAMP:		W1	W2	W3	W4	W5
SEAM:			4L	2		
PATTERN:		3x3	4x4	5x5	6x6	x
HOLE DIA.:		102mm	171mm	251mm		

AVE. HOLE DEPTH:			POWDER FACTOR:			Kg/HOLE:

SLEEVING(LINE)	A	B	C	D	E	F
	END HOLES					
AIRBAG:		YES		NO		
EXPLOSIVES TYPE:		P400		P700		ANFO
BOOSTERS:		150		400		
DOWN LINES:		P/CORD		BUNCH MASTER		
SURFACE LINES:		P/CORD		NOISE MASTERS		
		DOG BONES		BUNCH BLOCKS		
TIMING:		PLAN		STANDARD		
STEMMING:		STANDARD		M		

NOTES

S/VISOR	**OVERSEER**	**BLASTER**	**DATE**

ATCOM

DRILL & BLAST SECTION

AECI/DRILL & BLAST CONTROL SHEET

FORM 2

BLOCK NO. ______ DATE ______

LINE NO. ______

STEMMING HEIGHT ______

PRODUCT ______

KG / METER ______

HOLE NO.	PLAN DEPTH	DRILLED DEPTH	RE-DRILL REPORT TO SUP	BACK-FILL	REQUIERED TONS	TRUCK NUMBER	ACTUAL TONS PUMPED	DISCREP. ±	BLASTER SIGN. DISCREPANCIES

SIGNATURES AECI TECHNICIAN ______

BLASTER ______

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FORM 3

DRILL & BLAST SECTION
BLASTING COST REPORT

DATE:.. **RAMP:**.................................... **BLOCK:**..

BLAST TYPE:

PRESPLIT	○	PARTING	○
OVERBURDEN	○	COAL	○
MIDBURDEN	○	OTHER	○

INFO:

No. ROWS		No. HOLES	
No. LINES		AVE. DEPTH	
PATTERN		BCM'S/TONS	
HOLE DIA.		POW. FACTOR	

EXPL.	UNIT	R / UNIT	QUANTITY	COST
ACCESSORIES				
AGENT ANF.				
P701 COAL				
P/SPLIT PARTING				
P701 BURDENS				
	DENSITY TEST			
BENCHMASTERS	10m x 475ms			
	m x ms			
HT DA	12m			
BOOSTERS	150gr x 38mm			
	400gr x 53mm			
LEAD IN (REEL)	200m			
POWERCORD	8gr x 250m			
DOGBONE RELAYS	40 m/s			
ELEC. DETONATOR	CARRICK			
SLEEVES	425mm x 250m			
GAS BAGS	250mm			
			TOTAL	
			COST / BCM - TON	

BLAST RESULT:

WEATHER	SUN ○	CLOUDY ○	RAIN ○
FRAGMENTATION	GOOD ○	AVE. ○	POOR ○
FLY ROCK	NO ○	YES ○	
BACK BREAK	NO ○	YES ○	

MISSFIRES; ACTION TAKEN ....

....

BLASTER ....

SUPERVISOR ....

M/O ....

iMpunzi Division

ATCOM

TABLE 4

DRILL & BLAST SECTION

BLASTING COST (FOR SURVEY DEPT.)

DATE: ....

SOURCE									
COAL	VOTE No	BASE	BUDGET	BLOCK	LINEAR	WIDTH	HOLES	TONES	SEAM
		COST			LENTH				
	A106	R0.37							

PARTING	VOTE No	BASE	BUDGET	BLOCK	LINEAR	WIDTH	HOLES	BCM
		COST			LENTH			
	A105	R1.40						

PRE-SPLIT	VOTE No	BASE	BUDGET	BLOCK	LINEAR	WIDTH	HOLES	M 2
		COST			LENTH			
	A107	R2.53						

OVERBURDEN	VOTE No	BASE	BUDGET	BLOCK	LINEAR	WIDTH	HOLES	BCM
MIDBURDEN		COST			LENTH			
	A104	R0.85						

EXPLOSIVES	
SUPPLIER	AECI
TYPE	
DENSITY	
ORDER No	

KG EXPLOSIVES	
KG / HOLES	
P.F.	
KG TON COAL	
EXPL. COST	
ACCESS. COST	
TOTAL COST	
COST / UNIT	

FORM 5

ATCOM

DRILL & BLAST SECTION

BLASTING ACCESSORIES ORDER

FROM : BLASTING SUPERVISOR
TO : MAGAZINE MASTER

DATE : ____________________

PLEASE ISSUE THE FOLLOWING ACCESSORIES AS PER REQUEST

TYPE				REQUEST	ISSUED	RECEIVED
BENCHMASTERS		millisec	meters	units	units	units
	HTDA					
NOISEMASTERS		millisec	meters		units	units
PENTOLITE BOOSTERS			grams	units	units	units
POWERCORD			grams	reels	reels	reels
DELAYS			millisec.	units	units	units
DETONATORS			IED	units	units	units
LEAD INS			meters	reels	reels	reels

SIGNATURES	SUPERVISOR	MAGAZINE MASTER	BLASTER
	BLASTING SUPERVISOR		

iMpunzi Division

ATCOM

FORM 6

DRILL & BLAST SECTION
BLASTING ACCESSORIES BOOK BACK FORM

FROM: BLASTING SUPERVISOR
TO: MAGAZINE MASTER

DATE: ____________________

TIME: ____________________

PLANS CHANGE ○
WEATHER CONDITIONS ○
OTHER - SPECIFY ○ ____________________

YOU ARE HEREBY REQUESTED TO BOOKBACK THE FOLLOWING INTO THE EXPLOSIVE MAGAZINE

____
M/O SIGNATURE

TYPE	SPECIFICATIONS

POWERCORD	BOXES	REELS	REMARKS

____
SUPERVISOR SIGNATURE

I HEREBY DECLARE THAT I HAVE ACCEPTED THE ABOVE LISTED EXPLOSIVES / ACCESSORIES AND BOOKED IT BACK INTO STOCK

____
MAGAZINE MASTER

Appendix 2

Kleinkopje Colliery Sponcom KPIs

(Courtesy of Kleinkopje Colliery)

SPONTANEOUS COMBUSTION

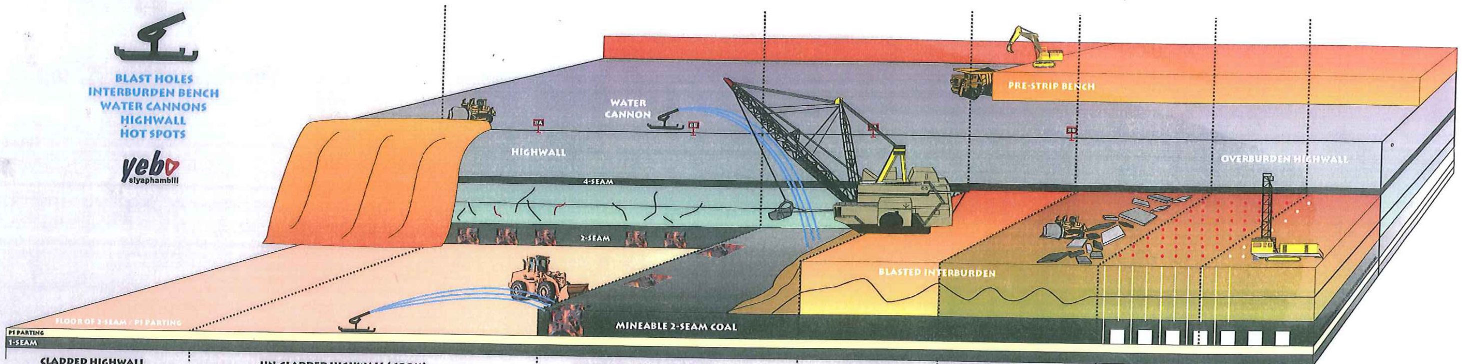
SPONCOM KPI'S

(KEY PERFORMANCE INDICATORS)

"BEST PRACTICE"

BLAST HOLES
INTERBURDEN BENCH
WATER CANNONS
HIGHWALL
HOT SPOTS

yebo siyaphambili



ALL AREAS - GEOLOGY TO MANAGE THE ADHERENCE TO THE KPI'S (MANAGE RISK ITO AREA OF HIGH, MEDIUM AND LOW RISK).

FIVE (5) POINT ACTION PLAN:

1. OPEN BLAST HOLES MUST BE PLUGGED, AND HOLES TOO HOT TO BLAST MUST BE SEALED.
2. HOT BLASTED INTERBURDEN BENCH MUST BE LEVELLED AND CLADDED.
3. WATER CANNONS MUST BE USED TO COOL DOWN HOT INTERBURDEN AND EXPOSED COAL RESERVES.
4. THE HIGHWALL MUST BE CLADDED.
5. ALL HOT SPOTS MUST BE IDENTIFIED AND TREATED.

COALING RESPONSIBILITY:

KPI # 1
NUMBER OF BURNING / STEAMING HOT SPOTS NOT LOADED OUT.

- ZERO REMAINING PER BLOCK (50M X 50M), UP TO LOADING FACE.

KPI # 2
WATER CANNON MUST SPRAY DOWN HOT COAL (HOT SPOT MONITORING).

- USE WATER CANNON, SPRAY INTERBURDEN DOWN WITHIN BOOM POINT.
- USE WATER CANON, SPRAY LOADING FACE DOWN.

KPI # 3
MINEABLE RESERVES BEHIND DRAGLINE CAN NOT EXCEED 1 WEEKS LOADING.

KPI # 4

DRAGLINE RESPONSIBILITY:

KPI # 1
BLASTED OVERBURDEN AND INTERBURDEN DRILL BENCHES TO BE LEVELLED AND HOT / VENTING AREAS TO BE CLADDED.

- 350M BEHIND DRAGLINE.

KPI # 2
AMOUNT OF OVERBURDEN / INTERBURDEN HIGHWALL CLADDED.

- CLAD HOT OVERBURDEN AND INTERBURDEN HIGHWALL'S USING SOFTS ON AN AD HOC BASIS.

PRE-STRIP RESPONSIBILITY:

KPI # 1
DISTANCE OF HIGHWALL UNCLADDED.

- 100M BEHIND ACTIVE COAL FACE (2-SEAM)

KPI # 2
NUMBER OF BURNING / STEAMING AREAS PLUGGED WITH SOFTS.

- ZERO REMAINING PER BLOCK (50M X 50M).

DRILLING RESPONSIBILITY:

KPI # 1
NUMBER OF VENTING BLAST HOLES ON DRILL BENCHES.

- ALL VENTING HOLES TO BE PLUGGED BY ACCEPTABLE MEANS (I.E. CONES / GAS BAGS).
- ALL HOLES TOO HOT TO BE BLASTED, MUST BE SEALED.

KPI # 2
NO MORE THAN 7 LINES TO BE DRILLED BEFORE BLASTING IN HOT AREAS.

Appendix 3

Description of drilling and blasting requirements to develop a buffer

All of the mines experiencing serious spontaneous combustion problems are multiple seam operations, with at least one seam having been previously mined by bord and pillar operations. Heatings are usually associated with the previous workings and, depending on the severity, may spread to the other seams. Buffer blasting is generally accepted as the most effective way to control this problem. The method is explained below.

Top soil removal

Strip mining operations start with clearing the vegetation and then the top soil is removed (figure 4) and stored for rehabilitation. The strip width depends on the type of the equipment used, the mining method and the production requirements. A typical fleet of equipment would consist of at least one dragline, shovels, trucks and drilling and blasting equipment.

Stripping width may also depend on whether buffer blasting is being practiced or not. Buffer size may affect the strip width. Most mines use buffer blasting techniques as an effective measure to control and slow down spontaneous combustion.

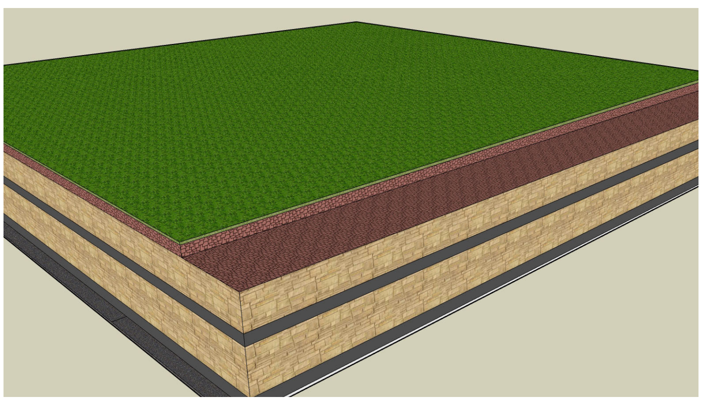


Figure 5: Top soil removal

Overburden removal

After the topsoil is removed overburden removal and excavation start along the strip exposing coal in the top seam. If the top seam has not been mined previously this is considered a safe stage of the operation. However, if spontaneous combustion is at an advanced stage in the underlying strata, it may have spread to the top seam. The evidence of this will be venting of the drilled holes. As a precaution the drilled blast holes' temperature should be measured and these holes covered with plugs to prevent oxygen entering the strata. There is a possibility of air entering the underlying seams through the already existing fracture network within the interburden and top coal. Since there is no way of knowing or predicting this, the blast holes need to be covered to stop any air ingress.

The incubation period of coal within the Witbank Coalfield is fairly short (it can be as little as 3 – 4 days). During the incubation period of coal there may be no evidence of self-heating visible through smoke or temperature increase within the drilled holes. Therefore the operation should not be assumed free from spontaneous combustion because these signs are not immediately apparent.

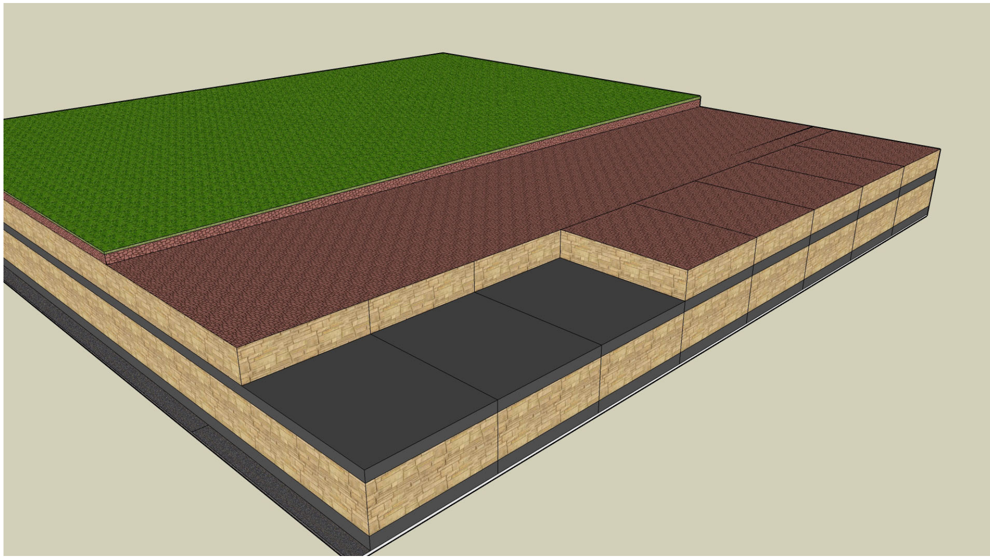


Figure 6: Overburden removal along the strip

Prior to overburden blasting, a sequence of procedures needs to be in place.

If a pre-split is being used these holes are drilled prior to the normal drilling operations. The holes should go down to the bottom of the lowest seam if this seam was not previously mined. Test holes are required along the buffer perimeter. Test holes should always be two strips ahead of the current mining strip and should be monitored weekly for any temperature changes. Test holes as well as pre-split holes are used to extract information about the position of the seams and the thickness of each. Since test holes may hole into the old workings they need to be plugged immediately to prevent air going into the old workings. A typical seal would be an upside-down cone pressed down into the hole with dirt placed in the cone. A second cone is placed facing upwards and a stake is placed indicating the hole number and hole depth.

Strata logging of the top coal can be done manually or by using drill management systems such as Aquila. Drilling of the overburden is performed in such a way that the coal below the overburden is not damaged. The overburden needs to be drilled half a metre short of the overburden thickness to prevent coal damage. Blasting of the overburden will indirectly fragment the coal below into a size distribution for easy loading during coaling.

Upper seam operations

Top seam excavation (figure 6) starts immediately after overburden removal by the dragline. The dragline operator plays a key role during the uncovering of the top seam. The coal is uncovered in a planned manner so as not to expose too much coal at any one time. Therefore, drilling, blasting, overburden removal and coal excavation should be carefully sequenced.

During the top coal removal, the interburden being exposed may show signs of spontaneous combustion from below particularly if the lower seams have been previously mined. If this is the case the interburden now being exposed needs to be levelled and clad with sand to cover any existing cracks and fractures. In addition, excavators are now standing on interburden, which may not be stable enough to carry this equipment. This depends on the thickness of the interburden and the quality of the rock. There are two types of excavators used in coal excavation; hydraulic and rope shovels. Rope shovels are less expensive to run than hydraulic excavators. However, should a rope shovel sink into a cave owing to previously mined areas, it cannot easily be saved. On the other hand, hydraulic shovels are flexible enough to dig themselves out quickly when they sink into a hole created by a collapsed bord.

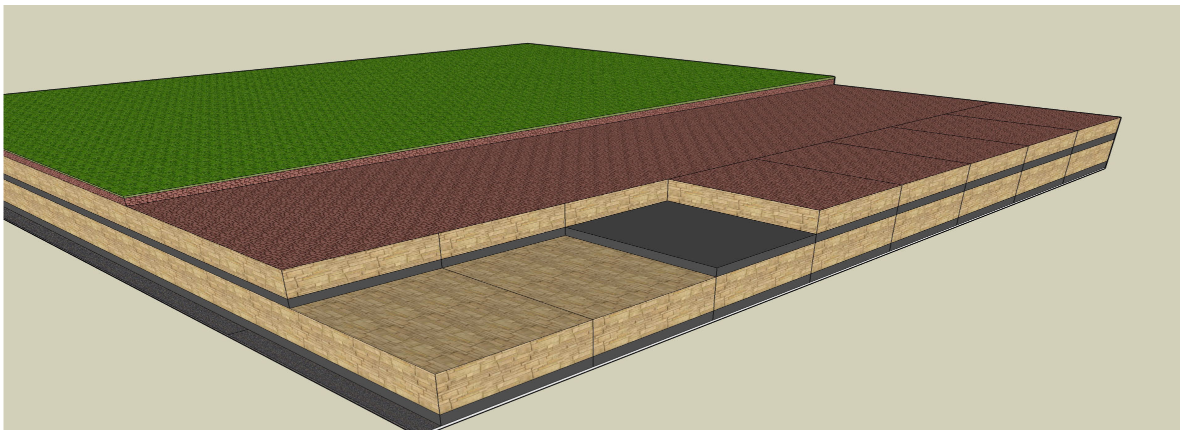


Figure 7: Coaling in the top seam

Interburden drilling

If the underlying seam or seams have been previously mined, the drilling pattern design depends on the layout of the previous workings and the thickness of interburden and the coal seam. During test drilling, information about the location of the pillars and the seam depth should be gathered. Figure 7 shows a drilling layout that takes into account the pillars left from previous mining. The black coloured blast holes are the ones drilled into the centre of each pillar. Old mine plans may be useful to identify the location of these pillars, however the accuracy of the plans is always suspect. Therefore drilling needs to be monitored continuously just in case the pillar is missed. Under these circumstances the drill hole will penetrate into the bord between the pillars. When this happens air will enter through the drilled hole into the old workings and, in addition, a chimney has been created. This hole now needs to be inspected to determine whether it is a hot hole or to find out if the interburden has caved into the bord. If there is caving it means the interburden thickness will be less than normal. If it is a hot hole the blast hole needs to be re-drilled about 1m away from its current position and the previous hole needs to be sealed off completely. This will cause a change in burden and spacing of the blast pattern and may result in inefficient fragmentation.

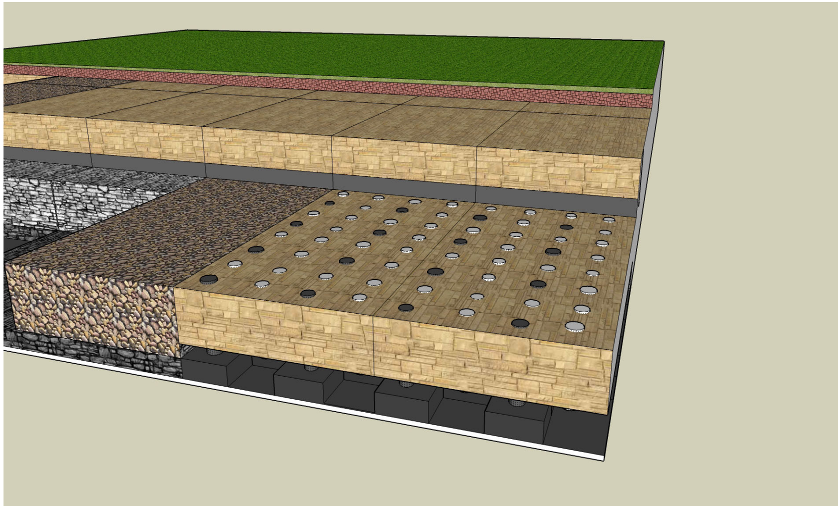


Figure 8: Drilling layout showing the pillars in the lower seam

Drilling of holes into pillars is normally extended to the bottom of the pillars (black holes in figure 7) and then backfilled with sand or drill cuttings up to the contact between coal and overburden. Thus the explosive energy will be enough to fragment the pillars and throw the coal sideways into the bords. This coal, together with the blasted interburden should completely fill the bords, preventing air movement and thereby preventing spontaneous combustion.

The remaining holes are drilled 0.5m to 1m short of the bottom of the overburden (white colour holes in figure 8). This way the explosive will be contained within the overburden. If a drilled blast hole holes through into any cavity it needs to be plugged at the bottom and backfilled to a height of about 1m to make sure the explosive will not flow into the cavity. In cases where widespread caving above the previous workings has occurred, plugging at the bottom may not be practical and, in this case, the drilled hole needs to be sealed and abandoned.

If the blast hole temperature is more than 60°C it means there is spontaneous combustion activity beneath it. Under these circumstances the blast hole needs to be completely sealed at both the bottom and the top.

Interburden blasting

Double seam operations can be very complex and require careful planning. If the bottom seam has been previously mined conditions can be very unstable, with many cracks in the interburden. In addition, the bottom seam may have been flooded and needs dewatering in a controlled manner before being mined. Coal pillars in flooded workings deteriorate owing to cracks being formed and the increased porosity of coal because of the action of water. Dewatering allows the coal to come in contact with air and there is the very real risk of spontaneous combustion. Under these circumstances it is essential to limit the contact between the air and the coal and this is best achieved by buffer blasting. This technique involves filling the voids, i.e. the old bords, with blasted material to choke off the flow of air. Drilling and charging of holes to achieve buffer blasting is illustrated in figure 9, where the red colour shows the charged portion of the drilled blast hole. The blast holes that are drilled into the pillars are lightly charged so as not to over fragment the coal. The infill holes, i.e. those that are located between the pillars, are drilled 0.5m short of the seam. In cases where they are over drilled and extend right down to the interburden-coal contact, then they need to be backfilled about 0.5m to 1m to prevent explosives damaging the coal. The blasting energy should be enough to collapse any top coal into the bord to seal it effectively.

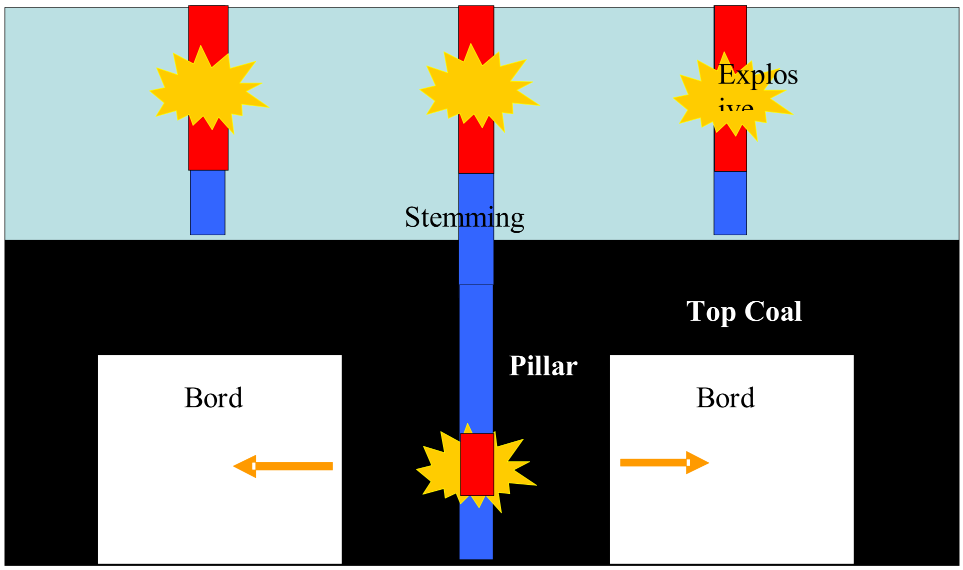


Figure 9: Layout of blast holes and explosives for a buffer blast.

There are two major objectives of buffer blasting:

- To fragment the rock and coal in such a way that they will stay in place without lateral movement of the rockmass. As blasting takes place the coal and overburden will heave in an upward direction. Horizontal movement should be avoided to prevent coal and overburden mixing.
- The second objective of buffer blasting is to seal the bords by fragmenting the pillars and collapsing the top coal, together with overlying strata, into the previously mined and dewatered bords. The blast is designed in such a way that the pillars that are blasted will expand horizontally into the bords and overlying material will also collapse into the bords, thereby sealing them and preventing any further air movement into the bords. An example of this is shown in figure 10.

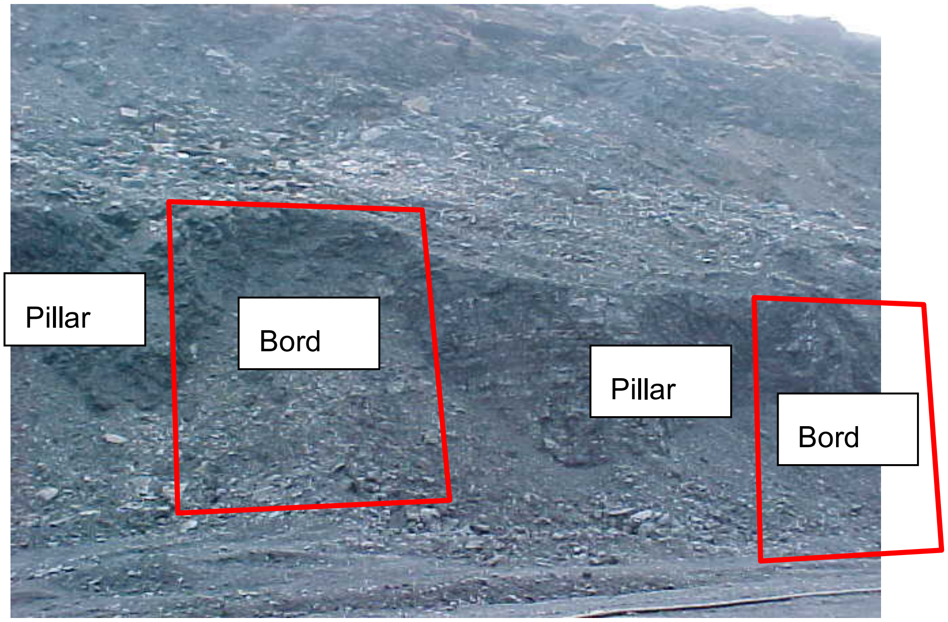


Figure 10: Bords filled with material from blasted pillars

Buffer blasting only provides an effective seal provided the entire width of the blasted area is not excavated. There may be a tendency to excavate the entire buffer zone owing to production pressures. However, removal of the entire buffer blasted area will result in the exposure of open bords and an immediate risk of spontaneous combustion. Figure 11 shows this situation with open bords in a highwall, i.e. a high-risk situation, while figure 12 shows a subsequent incident of spontaneous combustion. Removing the buffer to meet production requirements may be advantageous only over a short period, but may cost the mine dearly because of the increased risk of spontaneous combustion. Reinstating a buffer zone may take up to six months or even longer depending on the cut width, the length of the highwall and the rate of mining.

Figure 11: Open bords when buffer blasting is not practiced or the buffer has been excavated

When buffer blasting is not practiced the open bords will be ideal places for spontaneous combustion to take place. An example of this is shown below.

Figure 12: Open bords in which spontaneous combustion has occurred

Double seam with buffer blasting

Since it is generally accepted that buffer blasting and keeping a buffer of blasted material in place at all times is the most effective way to prevent air entering bords in the highwall, it is appropriate to reiterate the sequence of operations necessary to achieve a buffer. These are shown below in figure 13

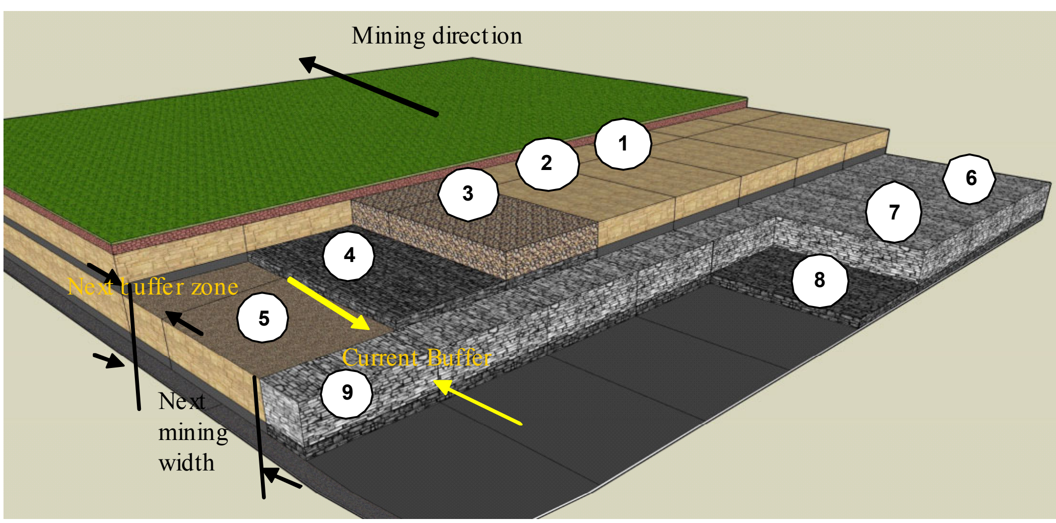


Figure 13: Sequence of operations to develop a buffer

The locations of the individual operations are numbered in the diagram and listed below.

1) Previously stripped and levelled overburden
2) Overburden drilling area
3) Drilled and blasted overburden
4) Coal is being exposed and ready for coaling by excavators
5) Interburden exposed and ready to be levelled and clad
6) Buffer blasting zone ready to be drilled
7) Buffer blasted interburden ready to be removed
8) Bottom coaling
9) Buffer zone left unexcavated to protect the next strip from spontaneously combusting. This strip of blasted material needs to be clad as a further deterrent to the ingress of air and the consequent risk of spontaneous combustion.

The objective of buffer blasting is to fill all the previously mined bords to prevent airflow from initiating spontaneous combustion in the old pillars. Similarly, leaving a buffer in place prevents open bords from being exposed in the highwall. The final product, a sand clad buffer, is shown in figure 14.

Figure 14: Buffer zone clad with sand to prevent the ingress of air

Appendix 4

Definitions

Definitions

Buffer blast – A surface mining technique used for mining coal seams that have previously been partially extracted by bord and pillar workings. Buffer blasting ensures that any overlying coal seam, or the overlying strata is collapsed into the open bords to prevent air ingress to these voids.

Chimney effect – A badly blasted highwall leaves sufficient voids for airflow to take place. When a heating occurs at the bottom of the blasted zone, hot air rises and creates a pressure difference resulting in more airflow into the highwall. In the case of multi-seams operations the flow of hot air through the upper seam may result in spontaneous combustion spreading to the upper seam.

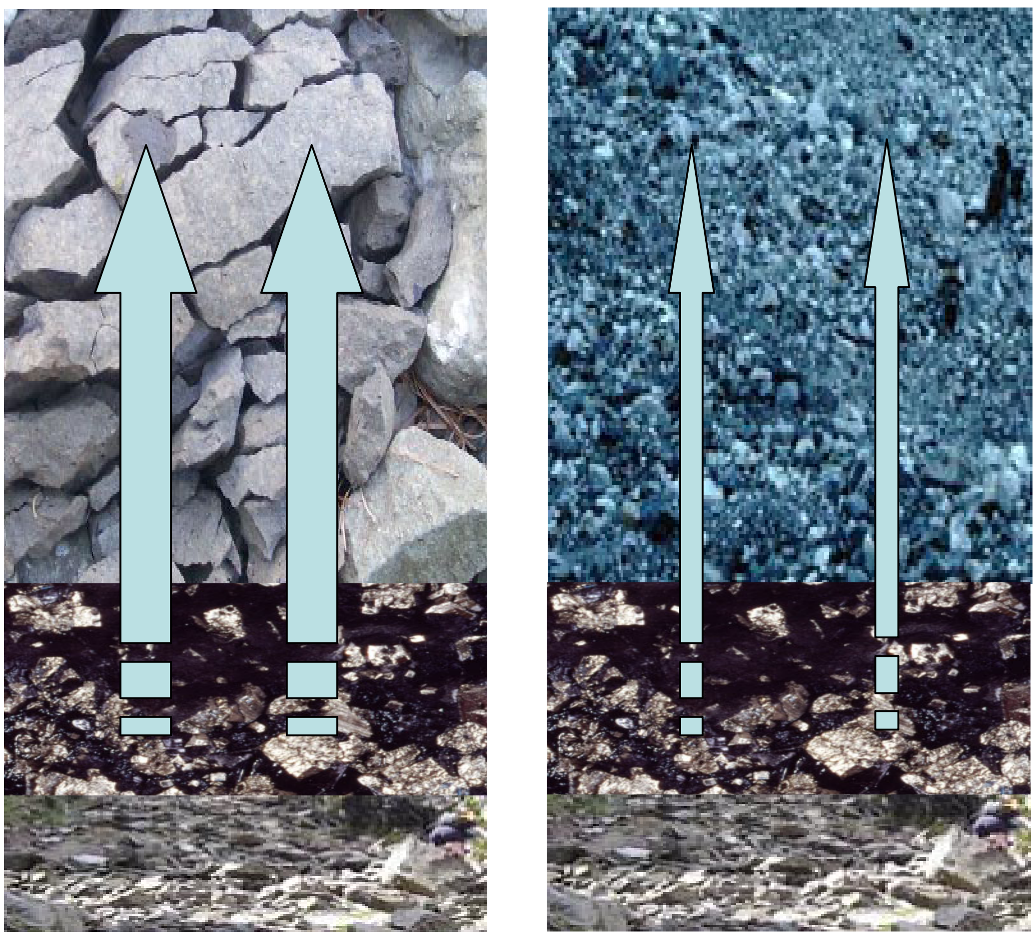


Figure 15: Effect of fragmentation on the amount of air movement through the blasted rock

Cladding – Covering of the highwall or the overburden surface with a layer of inert material, usually sand or soft soil excavated during the removal of overburden.

Figure 16: Cladding by tipping over the highwall

Figure 17: Open bords sealed by sand cladding

Coaling – Coal loading and hauling after the overburden is removed.

Cone seal – These are devices in the shape of an inverted cone used to seal holes that accidentally penetrate the old bords during drilling.

Effloresence – A growth of salt crystals on a surface caused by the evaporation of salt-laden water. In the case of coal mining it may indicate self-heating deep within the coal seam. Hot coal releases volatiles and water vapour that mix with the air flowing through cracks. When this mixture reaches the surface and cools the minerals carried in the vapour are deposited.

Hazard – A source or situation with the potential for harm in terms of human injury or ill health, damage to property, damage to the workplace environment or a combination of all these.

Highwall – The unexcavated vertical face of exposed overburden and coal in a strip mining operation.

Hot hole – Any blast hole where the temperature within the hole exceeds 60ºC is considered a hot hole in a coal mining operation.

Figure 18: View down a hot hole

Hotspot – A location within a coal seam or spoil pile where self-heating or spontaneous combustion has raised the temperature to 60°C or above

Incubation period – The incubation period is the time between the activity causing spontaneous combustion and the appearance of the first symptoms, e.g. the time between exposure of the seam by removal of the overburden and the observation of steam and smoke.

Pre-stripping – Removal of top soil in a coal mine operation. This material is normally stored for use in reclamation.

Sealing agents – Any inert chemical that is used to seal open cracks to prevent spontaneous combustion of coal.

Water cannon – Water cannons are used to direct a high pressure water jet over hot coal to improve visibility for the machine operators and to cool the material prior to loading.

Figure 19: Spraying of hot coal using a water cannon before loading coal into the trucks

Figure 20: Reducing dust and haze caused by hot material

Water gas – Water gas is a mixture of carbon monoxide and hydrogen, both highly flammable, and is produced in a reaction between hot carbon and water. The chemical equation for this is:

$C + H_2O = CO + H_2$.

It is highly explosive over a wide range of concentrations (4% to 74%).

Appendix 5

COALTECH 2020

A literature survey of methods to prevent and control spontaneous combustion associated with mining and subsidence

Task 1 of Coaltech 2020

Project 3.4.1

Task leader

N Eroglu

September 1999

Preface

The purpose of this report is to examine the spontaneous combustion problem through an extensive literature survey.

Over the years the coal industry has advanced in many areas, including the prediction, prevention, monitoring and control of spontaneous combustion. However, the vast amounts of information gathered are not always easily accessible. This literature survey therefore looks at the available published information, and identifies the spontaneous combustion problem. It reviews current practice in detecting, monitoring, preventing and controlling spontaneous combustion at all stages of coal production. Affected areas include underground, surface and abandoned mines, spoil piles, dumps, storage and transportation.

The existing information that has been collected so far has been recorded in a database called Microsoft Access, which makes it easy to extract information that is relevant to any aspect of the subject. The number of papers and reports collected so far exceeds 300. These will be reviewed later in a more detailed literature survey report and are listed here in Appendix I. This is a draft chapter of the main report planned. Although the structure of the chapter will not be changed, there may be additions to it.

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1 Introduction

Spontaneous combustion of coal has been a major hazard associated with the coal mining industry over centuries. It was the major cause of underground fires in South African collieries and also a common problem at opencast operations, usually spoil heaps and stockpiles.

During the project the spontaneous combustion problem will be well defined with a literature and mining practice survey. There are four main headings under which spontaneous combustion is explained in detail in this interim report: prediction, prevention, monitoring and control.

Spontaneous combustion incidents can happen anywhere in the coal mining industry from mining, transport and storage to waste disposal. Underground fires can develop in pillars, old workings, faces and roof strata, each area requiring a different approach and control technique. The damage caused could range from minimal to life threatening. The trigger mechanism could be natural heating or a mechanical cause in mining or transport equipment. Pillars left underground could also develop self-heatings and cause stability problems. The selection of mining methods, extraction rate, ventilation rate, etc. is therefore important during the planning. This necessitates the use of the methods and techniques available for predicting possible future heatings as an aid to planning.

Long-term exposure of open-pit walls could result in stability problems in walls, leading to cracks, and eventually to smoldering, which end up as spontaneous combustion.

During transportation by sea or rail, metallurgical and steam coal may be able to develop heatings. This in turn may damage coal intended for the international market, causing all kinds of problems from the quality of the exported coal to adverse effects on trade.

Stockpiling of coal is an equally important area of concern and prevention of spontaneous combustion is a major problem, especially in bigger stockpiles. Although management tends to make stockpiles smaller to avoid heatings, the problem exits.

Inappropriate handling of waste material and discards creates atmospheric and water pollution due to the outbreak of fires. In South Africa, the Witbank area has this kind of problem. The old unplanned waste dumps have become a new problem for today’s management.

Spontaneous combustion is not always a result of mining activity but can sometimes be caused by lightning, forest fires and long-term weathering. It is a threat to natural resources.

Old mine workings that are burning due to spontaneous combustion have become a cause of concern for many countries. Those reported to be affected in this way are: India (Jharia coalfield), China and the USA. Sometimes even war can have an adverse effect on coal mines. In Bosnia due to delays in mining operations in one of the open-pit mines, faces and dumps, which had started burning, had to be renovated.

2 The theory of spontaneous combustion

2.1 Early findings on spontaneous combustion

One of the early findings on the phenomenon of spontaneous combustion (Harger[1]) is that coal removes oxygen from air without producing carbon dioxide.

He suggests that: In a mine the cause of the removal of the oxygen can be traced to whether it has been brought about by oil-lamps or respiration on the one hand, or by the coal on the other. By carefully designed sampling of the air in various places in a pit subject to gob-fires, it has been found that it is possible to detect places where heating-up in the goaf is taking place, long before there is any petrol smell or gob-stink.

He also draws attention to the existence of higher hydrocarbons in a sample of liquid taken at 100°C with an average n value of 12,6 carbon atoms, and to the fact that the n value decreases to 3,9; 4,7 and 5. It is worth mentioning that in recent years monitoring for the presence of higher hydrocarbons has been put forward as a means of detecting spontaneous combustion.

Research done in 1916 by Drakeley[2] to find out whether pyrites has an effect on coal heating resulted in the conclusion that iron pyrites does have a minor effect. Coals that cannot be regarded as pyritic are among those most liable to spontaneous combustion. Drakeley also mentioned that a fault or a poor roof might have a more predominating influence on the question of the ignitibility of the coal than its percent of sulphur. He also concluded that the results of the experiments appear to indicate that the effect of pyrites, although a subsidiary factor, was not entirely negligible, contrary to common knowledge in those days.

The products of combustion were examined in research done in 1917 to find out why hydrogen sulphide is produced during the initial stages of a gob fire. When the author concluded his experiments, he could not deny that the presence of pyrites could be assisting in the spontaneous ignition of coal[3].

2.2 Factors affecting the spontaneous heating of coal

Davis and Reynolds did one of the earliest classifications of the factors affecting spontaneous combustion4. The factors were grouped under chemical and physical headings. The chemical factors to be considered, in order of importance, were: (1) **presence of pyrites**, (2) **rank of coal**, (3) **weathering**, (4) **moisture**, (5) **organic sulphur**, (6) **chemical deterrents** (calcium chloride and sodium bicarbonate), (7) **ozone** and (8) **bacteria**. The physical factors were: (1) **size**, (2) **moisture**, (3) **oxygen supply**, (4) **temperature**, (5**) occluded gases**, and (6) **ventilation and conductivity**.

From the practical mining point of view, self-heating results from a combination of circumstances, which include the physico-chemical and petrographic properties of the coal substance, the nature of the strata above and below the seam, and the methods of working. These conditions in turn depend upon geological, mining and atmospheric factors, which may affect, to a greater or lesser degree, the incidences of dangerous heatings in a mine. The factors may be classified as endogenous and exogenous.

Pyrites

The oxidation of pyrites has been considered to be a primary factor, a contributory cause and without effect upon the spontaneous combustion of coal. No single factor has been so greatly disputed as the influence of pyrites. However, it is a generally accepted fact that pyrites would oxidise in the presence of moisture, to form ferrous sulphate, as well as producing heat. The following equations by different researchers[5,6] describe the in situ oxidation of pyrites as associated with coal:

$2FeS_2 + 7O_2 + 16H_2O \rightarrow 2H_2SO_4 + 2FeSO_4 7H_2O + HEAT$

However, Miyagawa[7] stated that pyritic oxidation was not represented by the equation given above, but by the following equation:

$FeS_2 + 3O_2 = FeSO_4 + SO_2$

He maintained that the sulphur dioxide that was produced by oxidation was strongly adsorbed onto the surface of the pyrites, thus preventing further oxidation. Removal of this gas by water, however, allowed further oxidation to occur.

$FeS_2 + O_2 = FeS + SO_2$

The ferrous sulphide was then further oxidized to ferrous sulphate[8]

$FeS + 2O_2 = FeSO_4$

By this mechanism, all the oxidation products of pyrites are accounted for.

Particle size and surface area

Sondreall and Ellman[9] indicated that the effect of particle size was represented by the equation:

$r = C.S. [1-\exp(-K/S)]$

where
- r = rate of oxidation
- S = specific external surface area
- C = a constant, indicative of the reactivity of the coal
- K = a constant.

Porosity

Falcon[10] mentions that porosity is a characteristic of extreme importance to spontaneous combustion. It provides an indication of firstly, the extent of the total surface area, which may be subjected to processes related to oxidation, and secondly, the total volume of the voids or spaces, a factor directly proportional to the amount of moisture and gas which may be stored in such a coal.

Rank and petrographic constituents of coal

It is generally agreed that spontaneous combustion is a rank-related phenomenon. Davis and Bryne[11]demonstrated that as volatile matter and oxygen contents increased, the rate of self-heating also increased.

The reactive macerals, i.e. the petrographic components of coal, are vitrinite and exinite; the unreactive types include inertinite.

In a literature survey done by Sullivan[13], he sums up by stating that if circumstances are similar, a low-rank coal will heat more easily than a coal of high rank. Although it appears that vitrinite is the most reactive constituent, it must be said that all the constituents, including the inertinites, play important parts in the oxidation reaction. Four visible ingredients in banded coals are fusain, vitrain, clarain and durain, which are listed here in decreasing order of oxidation rate.

Chemical constituents and mineral contents of coal

Many researchers believe that the chemical constituents of coal influence its rate of oxidation and heating. Some believe that the presence of mineral matter in coal generally decreases its tendency to ignite spontaneously, while others indicate that inorganic constituents speed up the oxidation process. Falcon[10] believes that the distribution and form of pyrites affects the rate of oxidation. For example, very small nodules (less than 20mm) may be trapped in organic matter and therefore rarely exposed on the surfaces. Larger nodules and cleats are likely to be more readily available.

Chakravorty and Kolada[12] grouped the critical factors contributing to spontaneous combustion into intrinsic, i.e. those that cannot be controlled (coal properties and geological features), and extrinsic, i.e. those that can be controlled (mining practices). Table 2.2.1 shows these factors.

Table 2.2.1: Critical factors contributing to spontaneous combustion

Coal Properties	Geological Features	Mining Practices
High volatile matter	Thick seams	Leaving roof and floor coal during mining
High moisture	Presence of inferior pyrite bands and carbonaceous shale	Poor maintenance of roadways and old districts
High pyrites	Presence of faults	Inadequate measures to prevent air leakage through air crossings, doors, gateside pack
High exinite	Weak and disturbed strata conditions	Caving to surface under shallow overburden
High friability	High strata temperature	Close proximity to multi-seam working
		Poor ventilation management

Exogenous factors[5]

Temperature in mines: A rise in temperature greatly accelerates the rate at which coal is able to absorb oxygen.

Barometric pressure underground: During a period of falling barometric pressure, gases are removed from old workings, whilst during a rise in barometric pressure; air is forced into the same workings. There are indications that when the relative humidity of the air falls and the difference in the equilibrium of coal and air increases, the incidence of spontaneous combustion increases. However, changes in barometric pressure appear to be a secondary cause of spontaneous combustion, as Sullivan suggests[13].

Moisture in mines: It appears to be generally accepted that the presence of moisture accelerates the rate of heating of coal at low temperatures, but there are differences of opinion concerning the actual mechanism of the reaction.

Oxygen concentration or partial pressure: It is generally believed that the higher the concentration of oxygen, the greater the rate of oxidation, this rate being directly proportional to the partial pressure of oxygen.

Bacteria: Since bacterial activity is known to cause hay to combust spontaneously, it could also be one of the factors causing spontaneous combustion. Coward, Graham and Winmill are a few of the authors who mention bacterial activity[5].

Seam thickness: If a seam is too thick to be mined in one pass, some coal is left. Since there tends to be somewhat less ventilation in unworked sections than in working sections, it follows that a location of this type would be potentially susceptible to spontaneous combustion. There may also be banding in thick seams, which may result in one section of the beam being more liable to heatings than other sections.

Seam gradient: In inclined seams, the spontaneous combustion process becomes more complex due to convection currents, buoyancy, etc.

Caving, faulting and depth of cover: If a roof is friable and of a carbonaceous nature, then it is best to allow it to cave rather than supporting it by pillars. However, in the presence of faults there is then the possibility of finely crushed soil, which is prone to heatings. If the depth of cover is insufficient, in some cases surface cracks may appear, causing the ingress of air into the underground workings and perhaps even into areas sealed to prevent spontaneous combustion, in which case depth of cover could add to the problem.

Size of pillars: If a pillar is not large enough to prevent it from being crushed, then material will spall from the pillar, causing a potential spontaneous combustion hazard.

Roof conditions: An unstable or broken roof permits air to percolate through it, which could initiate heating.

Rate of advance: In longwall mining, the faster the rate of advance, the less the possibility of heating.

Ventilation system and quantities: Ventilating pressure has a considerable effect on the outbreak of fires. Due to pressure differences, fresh air can migrate into a gob, causing oxygen absorption and heating in the waste. Although it is known that additional air quantity could dissipate the heat, this is not the case in isolated areas in the gob where the quantity of air will make no difference.

2.3 Initiation mechanisms for spontaneous combustion

Around the 1910s, various researchers such as Katz, Fayol and Threlfall reported conflicting results from their experiments on the effect of moisture and pyrite content. Katz and Porter[14] did experiments on several coals to determine the effect of moisture content. They observed that under actual storage conditions, both coal and air always contained a considerable amount of moisture. This led to their conclusion that moisture in stored coal was not of practical importance as far as its chemical effects on oxidation are concerned. They also found from the experiments that the rates of oxidation of different coals were not affected uniformly by moisture[14] .

Guney and Hodges[15] constructed an adiabatic apparatus for spontaneous combustion tests. It contained a 100-g-capacity reaction tube with a vacuum jacket, a propeller stirrer, and differential and measuring thermocouples, all of which were placed in a silvered Dewar vessel filled with oil. The temperature of the oil was automatically thermoelectrically controlled by means of a galvanometer-photoconductive cell unit and 48-element thermocouples. In spite of the simplicity of the device, it retained its accuracy and the temperature increase of the coal was reflected in the oil bath to within 0.2ºC. The rise in temperature in the reaction tube was attributed to the spontaneous heating of the coal.

An examination of the experimental results for the normal oxidation of coals and for simultaneous oxidation and adsorption/desorption of water vapour on coals showed that the auto-oxidative tendency was related to the presence of water in coal, particularly in the oxidising medium. The experimental results led to the conclusion that when coal, oxygen and water were present together, the oxygen would attack the coal under mine atmospheric conditions, producing a coal-oxygen-water complex. These mechanistic reactions were chain processes and the first gaseous products were carbon monoxide, carbon dioxide and water vapour. Guney[16] observed that the $CO:O_2$ deficiency ratio was not a criterion of the degree or temperature of spontaneous heating under all experimental conditions.

The impression was gained that when the difference between the equilibrium humidities of coal and air becomes greater due to fluctuations in the ventilating air and to mining and geological disturbances in underground mines, serious incidents are more likely to occur in the gob areas and faces[17].

Guney further concludes that the oxidation process is accelerated by the adsorption and retarded by the desorption of water vapour on coal[18].

2.4 Incubation period

Each coal has an incubation period, after which self-heating accelerates. If this period can be established, it can be used to determine the risk of spontaneous combustion. It can also be used in situations where coal is being mined underground from thick seams or for long-term storage. This incubation period can therefore be a useful planning tool, for example in the retreat method of extraction, in that the production rate estimation can be based on the incubation period of that particular coal.

However, as the incubation period was used in planning the 512 Panel at Moura No. 2 Shaft where two major explosions occurred, it seems that use of the incubation period on its own is not be enough to prevent spontaneous combustion.

There was an explosion at Moura No. 2 Coal Mine on Sunday, 7 August 1994. A second and much more violent explosion occurred on Tuesday, 9 August 1994. Prior to these explosions, there had been two other explosions at the same mine in the space of 20 years, both of which were related to spontaneous combustion.

The primary defence against another spontaneous combustion incident had been to completely extract and seal the panel within the supposed incubation period (of six months) for the D seam coal.

Roxborough[19] states that several aspects of the design of the 512 Panel were incompatible with the known requirements for minimising the risk of spontaneous combustion. The method of mining bottom coal led to much more loose coal being left behind than with other previous panels. Accumulations of small loose coal are notoriously prone to spontaneous combustion, especially when unventilated.

Although the quantity of ventilation in the 512 Panel was fairly high, when passing through the very large goaf area it would be quite sluggish. There would be parts of the goaf that the ventilating current did not reach or visited only intermittently, and to a varying extent.

The Panel had been designed for the secondary working phase to be completed in three to four months, which would therefore be well within the presumed incubation period for the coal of six months. This probably led to a false sense of security and therefore to management being less alert or responsive to the numerous signs that had begun to appear, according to the evidence, up to seven weeks before the Panel was sealed.

The inquiry after the explosions suggested that there was a mismanagement leading to spontaneous combustion. A summary of the failures and responses is given below:

- Failure to prevent the development of a heating within the 512 Panel (where the explosions occurred).
- Failure to acknowledge the presence of such heating.
- Failure to effectively communicate, capture and evaluate numerous signs over an extended period.
- Failure to treat the heating or to identify the potential impact of sealing, with the Panel consequently reaching a state in which methane gas accumulated into the explosive range within it.

Ultimately, there was failure to withdraw people from the mine while the potential existed for an explosion. Accidents of this kind will be repeated in the future if the spontaneous combustion phenomenon is not taken seriously enough to warrant immediate action.

2.5 Incident types

2.5.1 Underground mines

Fires in underground mines can be mechanical or natural in origin. Natural fires (related to spontaneous combustion) could occur in unbroken rock, gobs or pillars. Spontaneous heating within a coal mine pillar can be predicted using some of the techniques described by Timko and Derick20. However, the effectiveness of monitoring of gases within a pillar to predict a heating needs some additional research to prove or disprove.

2.5.2 Abandoned mines

The inadequate sealing of old mines could pose problems later when there is a need to reopen them. Some of South Africa's coal reserves could fall into this category and careful identification of these areas is needed through literature surveys, laboratory tests and monitoring with infrared thermography for identification.

2.5.3 Surface mines

The possibility of spontaneous combustion developing within surface mines increases with the amount of time that the coal surfaces have been exposed. Dragline, shovel and truck operations generate large volumes of overburden. Since these are not homogeneous, dumping can cause segregation, providing channels for internal flow.

If selected mining is applied as in the case of most modern mines, then some of the extracted seam surfaces may be dumped within the stripped overburden. This overburden is the most liable to spontaneous combustion. Hot spots tend to develop within the overburden, and therefore it should be sealed properly.

2.5.4 Spoil heaps

Brooks and Glasser[21] have conducted extensive research into spoil heap design at the Chemical Engineering Department of the University of the Witwatersrand. They identified the following mechanisms as being the possible means for ingress into a coal dump:

a) *Natural convection* – The air inside a dump gets hot and rises, and is replaced by cold air. The circulation supplies reactants to the dump. This is the chimney effect, and occurs only when the dump temperature is already different from ambient.
b) *Wind pressure* – The wind blowing on the inclined faces of the dump causes the ingress of reactants into the dump.
c) *Molecular diffusion* – If there is reaction of a component of the gas in a dump, then diffusion of this component into the dump will occur.
d) *Barometric breathing* – Changes in the ambient pressure will cause flow in and out of the dump.
e) *Thermal breathing* – Changes in the ambient temperature may cause flow in and out of the dump by the resultant natural convection[21].

They also identified the factors for designing a safe stockpile. These are: dump size, compaction, particle size distribution, effect of segregation, coal reactivity and time.

A mathematical model to predict spontaneous combustion in coal stockpiles was formulated. Breaking up the dump into three regions in which different effects dominate derives this model[1].

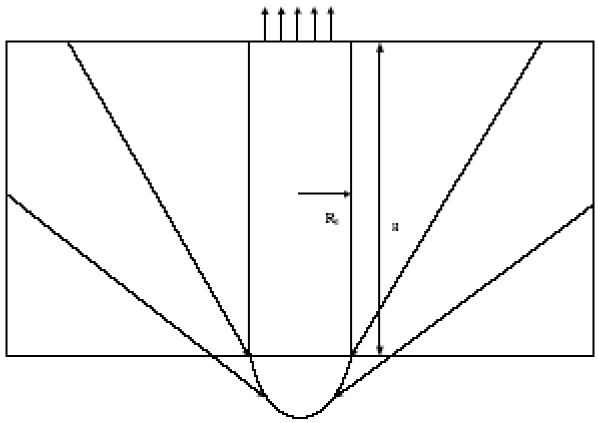

Figure 2.5.4.1: Regions of the spontaneous combustion model[22]

In each region different effects dominate. The chimney is a one-dimensional region in which heat transfer, flow and reactions occur. It is in this region that the highest temperatures exist.

Since the area through which the flow occurs is reasonably small, the velocities are relatively high. Their model predicts the existence of a worst depth for combustion. The boundaries between safe, conditionally safe and unsafe stockpiling can be predicted with this model.

2.5.5 Transport and storage

Bouwman and Frerics[23] conducted experiments on coal samples taken from a test pile of a bituminous coal, which was subject to spontaneous heating. Samples were taken at various depths and at three-month intervals.

The infrared spectroscopic study of the samples showed that initially a carboxylic acid-type compound was formed. This compound seemed to decompose during a later stage of the oxidation. Analysis of the results suggested that macropore oxidation predominated. Based on the spectroscopic data, it was further concluded that the penetration of oxygen was probably diffusion-limited, i.e. the oxidation of this particular coal proceeded predominantly across the macroscopic solid/gas interface. This could mean that removal of a small proportion of fines with a relatively large, specific macroscopic surface area results in a reduction of the spontaneous heating of the pile.

3 Prediction of spontaneous combustion

3.1 Underground mines

Carbon monoxide

The presence of high concentrations of CO (carbon monoxide) has been used as a prediction tool in many mines. However, by the time such high concentrations occur, the chances are that the reactions will have gone beyond easy control as Mitchell[24] suggests. Long before CO became evident, however, spontaneous combustion could have been detected by the telltale sweat on the roof and upper portions of cribs and posts, and by the sweet, musty odour of acrolein and other aldehydes in the air.

For CO or any other kind of fire detector to be practical requires: (a) pre-knowledge of where heatings are more likely to develop, and (b) little to no dilution of flows between the heatings and detectors.

Recommended detection: The miners best bet is to monitor the $CO:CO_2$ ratio. Although the monitoring of either oxide of carbon is adversely affected by dilution, their ratio is not. Assume, for example, that CO and CO_2 are 100 ppm and 1 000 ppm -a ratio of 0,1. Assume further that their outflow is admixed into another airflow, reducing the CO and CO– to 50 ppm to 500 ppm – the ratio is still 0.1.

Methods of predicting a coals proneness to spontaneous combustion are propensity testing and interpretation. The most meaningful classification[25] of these tests is as follows:

- Single index testing
- Composite indices testing
- Regression analysis
- Expert systems.

The most common single index testing procedures are:

- Adiabatic heating
- Crossing point temperature (CPT)
- Differential thermal analysis (DTA)
- Olphinski Index
- Oxygen absorption.

Adiabatic heating

This testing procedure has been used by many researchers as a laboratory technique that simulates the in situ situation, i.e. the energy changes associated with oxidation plus gas sorption and desorption are not allowed to dissipate from the test vessel. However, many researchers agree that obtaining adiabatic conditions in the laboratory is very difficult to achieve.

Initially the coal sample and vessel are brought up to an ambient start temperature, e.g. 30°C, in an inert nitrogen atmosphere that has been preheated as it passes through coils in the oven. Once steady-state temperatures have been achieved, the nitrogen source is replaced by oxygen, and the coal temperature is measured and plotted against time.

Researchers including Guney and Hodges, Davis and Bryne, Gouws, and Gibbon and Wade have used an adiabatic calorimeter to study the propensity of different coals to self-heating. A calorimeter was designed by Gouws and others based on a design by Shonhardt. It is capable of being operated in both an incubation and a rising temperature mode and was designed to run unattended, with a computer controlling the experiment and recording all relevant data. The self-heating propensity of coal was investigated using characteristics such as temperature rise, initial rate of heating, minimum self-heating temperatures and kinetic constants[26].

Crossing point temperature (CPT)

Gouws et al.[26] conducted a number of laboratory tests to determine the propensity of different coals to self-heat using the techniques of crossing point temperature (CPT), differential thermal analysis (DTA) and the adiabatic calorimeter described above. A sample bank of 70 coals from various South African collieries collected and stored under nitrogen was used for this purpose.

The apparatus used for the CPT Index is described by Gouws and Wade[27]. The apparatus consists of three cells containing finely sieved coal and another three cells containing a thermally inert reference material (calcined alumina) immersed in an oil bath that is heated at a constant rate of 1°C/minute. Oxygen is supplied to the cells by means of an air compressor at a rate of 400 ml/min. A computer records the temperatures of the bath and the six cells at 15-s intervals.

Initially, the temperature of the inert material heats up quicker than the coal samples, but after 100°C the coal temperature crosses the inert material temperature. This point is called the cross-over temperature. However, this index is not sufficiently indicative when used on its own.

Differential thermal analysis (DTA)

The propensity of different coals to self-heat was studied in the laboratory using both crossing point temperature tests and differential thermal analysis[27]. The results of tests on 58 South African coals were presented and analysed according to readily recognisable characteristic temperatures and rates of heating under non-adiabatic conditions. These indices have historically been considered to be predictors of self-heating liability. A DTA thermogram shows three distinct stages. Stage I shows the temperature of the coal falling relative to the temperature of the inert material. Stage II begins when the heat from the oxidation is greater than the heat losses in Stage I; Stage II is almost linear until it reaches Stages III. The change from Stage II to Stage III is called the transition point. It has been suggested that a lowering of

the transition point temperature indicates an increase in the propensity to spontaneous heating. The gradients of Stage II plots from the thermogram have also been used as indices of spontaneous combustion, the propensity increasing with increasing gradients.

For South African coals, however, these simple indices did not produce a significant classification. This led to the research on composite indices as discussed later.

Olpinski index

This index, used in Poland, determines the reactivity of coal at a temperature of 240°C, which is the boiling point of quinoline. Small particles of coal in the form of a pellet are heated in a stream of quinoline vapour and fresh air, the temperature of the coal being measured at intervals of approximately 15s. The temperature of the coal is plotted against time so that the gradient slope of the plot in terms of 0C/min can be obtained at 240°C, i.e. the crossing point temperature for coal and quinoline vapour[25] .

This slope, denoted as SZa, is used to calculate the index SZb as follows:

SZb = SZa 100 /{100 – Aa}

where SZB = spontaneous heating index of ash-free coal
Aa = Ash content of the coal expressed as a percentage.

Indian researchers have standardised the testing using -72 mesh BS coal, formed into a 450-mg pellet, with an oxygen flow of 80 cc/min.

Oxygen absorption

The basic principle involved is to measure the amount of oxygen absorbed by a known quantity of powdered coal in a closed vessel. One of the techniques is described by Karmakar[28].

Glasser developed another, very simple method for the oxygen absorption test. It has been used at ISCOR and is said to be a very practical and quick way of testing oxygen absorption[29]. In this test the coal sample to be tested does not have to be fresh from underground and sealed in an inert environment. The results correlate well with those of conventional absorption tests. The coal is finely crushed and placed in a container, which is connected to another glass container into which liquid paraffin is put. The connector has air inside it. As the coal draws the oxygen, the liquid paraffin rises in the connector. Samples are drawn at equal intervals to test for gases.

WITS-EHAC index (composite indices)

Simple indices used to predict the self-heating liability of coals are often found to give contradictory results. Gouws therefore developed a composite index to predict the propensity of South African coals to spontaneous combustion and called it the WITS-EHAC index. This index examines two features, namely the crossing point temperature and the Stage II slope. It is accepted that a high-risk coal has a lower crossing point temperature and a steeper Stage II slope than a low-risk coal.

Feng et al.[30]: had previously proposed a composite index (the FCC index) based upon CPT testing:

average heating rate (110°C to 220°C)

$$FCC = \frac{\text{average heating rate } (110 - 220)\ ^{\circ}C}{\text{crossing point temperature}}$$

Gouws and Wade[27] found with their apparatus, which eliminated some of the thermal conductivity effects present in the equipment used by Feng et al., that some of South African coals had crossing points below the 110°C threshold nominated in the FCC index. Furthermore, all the coals had reached the transition point and entered Stage III of the thermogram below 220°C. They modified the index as follows:

$$\text{WITS - EHAC Index} = \frac{\text{Stage II slope}}{\text{crossing point temperature}} * 500$$

A comparison of DTA thermograms for a coal with a known risk of heating and a coal with a known low risk is shown in figure 3.1.1.

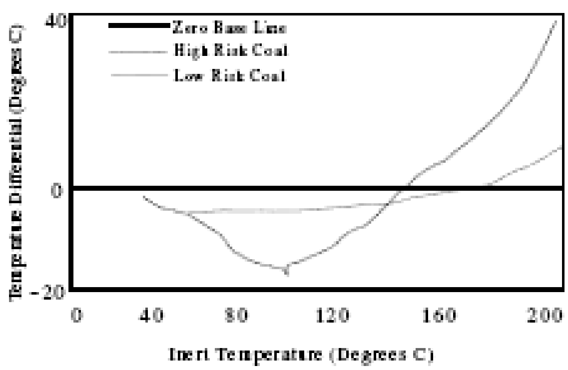

Figure 3.1.1: Comparative Differential Thermal Analysis thermograms of known high and low-risk coals[31]

Regression analysis

Some investigation and evaluation of various coals was done by Singh and Demirbilek[32]. This was carried out by means of a multiple regression analysis between the initial rate of heating and the total temperature rise, using thirteen independent variables that are intrinsic properties of coal, namely: relative density (RD), calorific value (CV), moisture content (M), volatile matter (VM), fixed carbon (FC), ash (A), superficial moisture (SM), total moisture (TM), total iron (TI), non-pyritic iron (NPI), total sulphur (TS), pyritic sulphur (PS), and the organic and sulphur contents of coal (OSS). Based on this statistical analysis, a set of equations for predicting the propensity of coal to self-heat was generated, as listed in table 3.1.1.

Table 3.1.1:Predictive equations derived by multiple regression[32]

Equation No.	Equations derived by Multiple Regression	Correlation Coefficient	Standard Error Estimate
(1) All coals	I.R.H.= 12.4+0.707ln(TI)-0.229ln (NPI)+0.1461ln(TS)-.3941ln(PS)-0.3791ln(OSS) -4.42(RD)+0.0001(CV)+0.071(M)+0.055(VM)+0.0023(A)+0.058(TM.)	0.736	0.730
(2) All coals	T.T.R.= 35.6+1.461ln(TI)-0.2681ln(NPI)-0.541ln(TS)-0.41ln(PS)-0.1931ln(OSS) +16.5(RD)+0.0004(CV)+0.185(M)+0.0112(VM)-0.014(A)+0.173(TM.)	0.731	2.117
(3) High volatile A bituminous coals	I.R.H. = 17.8+1.5ln(TI)-0.2111ln(NPI)-2.7ln(TS)+0.331ln(PS)+0.65ln(OSS)-.4(RD) -0.0004(CV)-0.29(M)-0.136(VM)-0.346(A)+0.463(TM.)	0.95	0.289
(4) High volatile A bituminous coals	T.T.R. = 23.5+0.473ln(NPI)+0.765ln(PS)-2.07ln(OSS)-1.44(RD)-0.0003(CV)-.4(M) -0.135(VM)-0.245(A)+0.916(TM.)	0.913	0.685
(5) High volatile B bituminous coals	I.R.H. = 180.0-313ln(TI)+0.977ln(NPI)-0.092ln(TS)+2.24ln(PS) +0.27ln(OSS) +0.59(RD)-0.0001(CV)+1.91(M)+2.03(VM)+1.92(A)+1.86(FC)+0.185(TM.)	0.970	0.298
(6) High volatile B bituminous coals	T.T.R. = -17.0+0.432ln(NPI)+1.15ln(OSS)+19.9(RD)-0.0004(CV)-0.509(M) +0.109(VM)-0.273(A)+0.64(TM.)	0.96	0.933
(7) Medium volatile bituminous coals	I.R.H. = -4.38+4.55ln(TI)-4.36ln(NPI)+1.39ln(TS)-1.70ln(PS)-1.85ln(OSS)-6.75(RD)+0.0001(CV)+3.26(M)+0.074(VM)+0.017(A)+0.15(TM.)	0.998	0.208
(8) Medium volatile bituminous coals	T.T.R. = 0.487+2.18ln(TI)-2.91ln(NPI)+2.36ln(TS)-1.91ln(PS)-2.84ln(OSS) – 16.8(RD)+0.0001(CV)+10.7(M)+0.3(VM)+1.07(TM.)	0.997	0.780

Expert systems

Denby and Ren[33] developed an expert system called ESSH at the University of Nottingham. The expert system is designed as follows:

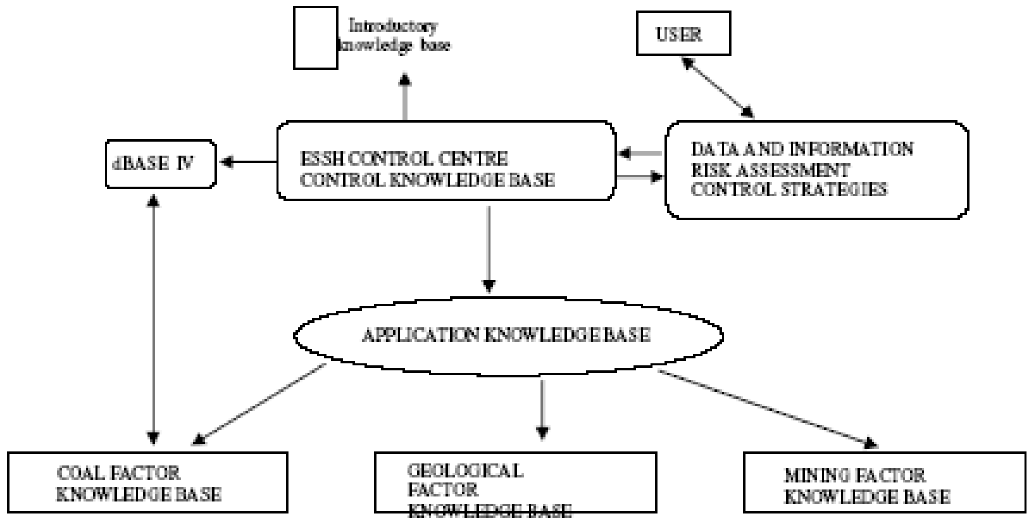

Figure 3.1.2: ESSH expert system architecture[33]

The user can enter information regarding the inherent properties of the coal sample, together with details of local geology and mining operations, to obtain an overall risk rating of spontaneous combustion.

Another expert system has been developed by the US Bureau of Mines, which predicts the spontaneous combustion potential of a coal based on the coals rank and dry, ash-free oxygen content. The program requires the input of a coals proximate and ultimate analyses and its heating value. It can evaluate the self-heating tendency of a single sample, an entire database of samples, or a selected group from a database.

3.2 Surface mines

No prediction methods have been developed for surface mining since they would be impractical considering the large scale of operations. Visible emissions of smoke or haze from hot spots in exposed coal or in highwall seams normally make detection only a matter of observation by sight or smell. Image-processing techniques can be applied to detect any heatings in surface mining operations.

Infrared heat detectors have been used in some applications to indicate parts of a dump that have higher than normal temperatures. They can also identify vents from which hot gases are being emitted. However, they can only measure the surface temperature of the material and cannot penetrate into the spoil itself.

Detection systems have been used successfully at Optima Energy’s Leigh Creek Mine employing high-resolution infrared surveys to assess the incidence and extent of heating in both the mine and waste dumps.

Optima Energy has adopted a mining and coal-handling strategy that minimises the risk of spontaneous combustion. The mine is operated as an open cut, and smoke from in-pit fires could have an adverse affect on visibility during mining operations. Experience has shown that coal left for a significant period between the blasting and loading was liable to self-heat and, for this reason, all broken coal is removed promptly after blasting.

3.3 Stockpiles and coal handling

Baum[34] developed a mathematical prediction method for estimating the critical conditions for the occurrence of spontaneous combustion in beds of finely divided fuel. Using this mathematical model he concluded that, for such beds, combustion conditions might be adequately predicted by assuming that there exist, within the bed, mutually orthogonal sinusoidal temperature profiles when conditions are critical. For irregular or non-Cartesian bodies, a rectangular/cuboidal envelope can be used as a basis for calculation. The sinusoid hypothesis, by creating a pseudo-theoretical base, permits the determination of a global value for activation energy from a laboratory experiment. This, in turn, can then be used to predict critical conditions for similar beds of different sizes.

3.4 Waste dumps and abandoned mines

Wherever waste is involved, be it underground or surface, there is always a possibility of spontaneous combustion occurring if it contains carbonaceous material. It is known that anthracite has the lowest propensity to spontaneous combustion, but if it exists within a mine discard, one should be aware of the possibility of hot spots developing. When the conditions are suitable, spontaneous combustion can occur in almost any material containing some sort of fuel.

Environmental problems are also associated with burning spoil heaps, especially in China. Abandoned open-cast mines could be monitored for predicting future environmental problems by using image processing using satellite information. Image-processing options have been considered for detecting environmental pollution in a coal-mining district in Spain. Mines that are closed due to economic constraints could present a serious problem for future environmental control[35] .

3.5 Transport of coal

Prediction methods should be applied to any coal in transit, as it is always possible that it could combust spontaneously during transport by sea or rail. The transport of coal from one port to another always takes a relatively long time and time will also pass before it reaches the end-users. Extensive investigations have been carried out from time to time on the problem of spontaneous combustion in transported coal, and the causes of the phenomenon and the means of preventing an outbreak of spontaneous combustion are now reasonably well known. This knowledge can, however, only be applied if reliable data on the characteristics of the coal and the conditions of storage or shipment are available. When shipment or long-term storage of a new variety of coal is contemplated, some of the data suggested by van Doornum[36] must be collected by conducting appropriate experiments. He documented some mathematical formulae and practical implications of the storage of coal in bunkers. He also describes a factor called M, which, if smaller than unity, means that coals will not combust spontaneously. The criterion $M<0.63$ is quite useful as it indicates that coals satisfying this requirement are incapable of any appreciable spontaneous heating. He also suggests that most South African coals of nut size and larger meet this criterion. However, he points out that self-heating may occur at any time at transfer points or ports.

4 Prevention of spontaneous combustion

4.1 Underground Mines

- Chakravorthy and Kolada[12] summarised some of the known techniques for preventing spontaneous combustion which are explained below.
- Mine layout is the most important factor in preventing spontaneous heating. Working districts should be designed so that a particular section can be isolated at short notice without affecting production in others. Sites for preparatory seals should be identified and marked during planning.
- With coal seams that are highly susceptible to spontaneous combustion, the retreat method of working is preferred. This is because the gob is not subjected to a large difference in ventilation pressure.
- Coal pillars should be designed to resist excessive crushing. The panel system of working is preferred, particularly for mining coals that are susceptible to spontaneous combustion. The size of each panel is calculated based on the incubation period and the rate of extraction.
- Controlling air leakage is also important for controlling spontaneous combustion. This is usually achieved by minimising the ventilation pressure difference, proper siting of doors, and avoiding unnecessary stopping and starting of fans. Air leakage is also reduced by sealant coating, injection of cements into cracks and crevices, and by maintaining good gateside packs.

The application of inhibitors to control spontaneous combustion met with limited success. They also mention that borate solution or Montan powder sprayed in the gob area or infused into a low-rank coal would reduce the possibility of spontaneous combustion.

4.2 Surface mines

Although there is no practical prevention technique to be found in the literature for preventing heatings in highwalls, there are some key factors in designing active spoil piles. These are mentioned elsewhere in this document[21].

4.3 Stockpiles and coal handling

4.3.1 Practical implications

The design and the maintenance of dumps can be done on the basis of the following points[37]:

a) Compaction makes oxygen-limited dumps safer. It also provides a certain amount of surface crushing which is helpful in preventing oxygen from getting deep into the dump. However, compaction may also make certain dumps less safe by effectively increasing the reactivity owing to the increase of surface area per unit bed volume.

b) Selecting the particle size distribution of the stockpiled coal may be another way of ensuring a safe dump. Again, if the dump is mainly medium to fine material, then making it finer or adding fines will help. However, if the dump consists of a coarse material of a relatively low reactivity, then removing the finer material may help.

c) Avoiding segregation is very important. Segregation can occur as result of the stacking method used, or from rainstorms or high winds.

d) Preparing and maintaining the dump should enjoy a high priority. Every effort should be made to avoid any means whereby oxygen may get into the dump, e.g. building the dump on a foundation of coarse sand. Dump maintenance (including recompaction) may be crucial in avoiding channels whereby oxygen may more easily get deep into the dump.

e) Covering the dump may be considered. Broadly speaking, a dump may be covered with either an inert or reactive material, and a permeable or impermeable covering such as sand may be used. The balance between heat loss and oxygen ingress must always be borne in mind. Enough sand must be put down to substantially cut down on oxygen ingress, recognising that one is insulating the dump at the same time.
If an attempt is made to cover the dump with an impermeable material (e.g. tar), then it must be recognised that cracks in the covering may lead to large localised flows of oxygen into the dump, possibly giving rise to a hot spot.
Covering the dump with a reactive material such as a fine coal may ensure that the dump is of the safe, oxygen-limited type, by the oxygen being scavenged close to the surface where the heat can be easily dissipated. The practicalities of this method may depend on wind and rain factors.

f) Previous experience of stockpiling similar coal can be invaluable in deciding on a safe stockpiling method. It is highly unlikely that a dump similar in characteristics to another pre-existing dump will give problems if the first one did not. Conversely, if a previous dump did give problems, then some or all of the steps outlined above should be taken to make the new dump safer.

- The most satisfactory method for safe storage is to have well-compacted heaps. Care should be taken to avoid segregation -particularly lumps rolling down the sides of a coal pile. The sides should be thoroughly consolidated and hollows at the top avoided.
- Road tar provides an effective seal to air leakage and is recommended for coal stacks likely to be left standing for a long time. Road tar also helps prevent channels caused by rain.
- Storing coal in vertical bunkers or coal silos is common at mine sites. Such bunkers or silos reduce air leakage to some extent. Blanketing the coal with nitrogen could further reduce the risk of spontaneous heating. Artificial ageing and treating the coal with carbon dioxide can also reduce the risk of spontaneous combustion.

4.3.2 Selection of the site[37]

- The base should be clean and firm, and should not be an expandable clay or shale, as such materials crack and shrink due to changes in moisture content and this promotes drainage from the pile or dump.

- The base should be reasonably level. Coal should be added in horizontal layers and should be graded and compacted to obtain a level surface for the further addition of material.
- A valley-like site may be selected for restricting airflow into the base or lower sides of the stockpile.
- Any drainage from the proposed dump into water courses should be taken into account beforehand.
- The size and area of the dump should be based on not only the estimated tonnage of material to be accommodated but also design principles to prevent spontaneous combustion as described by Glasser.
- Coal or discard must be stacked into a continuous whole rather than in adjacent heaps which may promote self-heating.
- The axis of a stockpile should be in the direction of the prevailing winds.

4.3.3 Creating an inert atmosphere

Van Vuuren[37] observed that coal, especially the carbon contained in the volatile substance, will gradually oxidise at ambient or slightly higher temperatures to form carbon dioxide which, being heavier than air, blankets the active sites from further oxidation. The oxygen becomes partly depleted with time, and it appears that the composition of the atmosphere reaches a point of stability with the carbon dioxide content around to 6% to 8% or even higher, and the oxygen content down to 12% to 14%.

Apart from some other hydrocarbons such as methane, the atmosphere contains mostly water and nitrogen. Under these conditions the atmosphere can be considered completely inert, provided there is no fresh ingress of air.

Some other useful and practical suggestions may be found in Van Vuuren's report, but they will not be discussed here.

4.4 Waste dumps and abandoned mines

The prevention of any heatings whatsoever in abandoned mines and waste dumps could be costly and time-consuming. This subject was therefore not discussed in any of the literature in detail nor was it given any importance.

4.5 Transport

From the practical information available in other reports and papers relevant to the prevention of spontaneous combustion during transport, most of the prevention remedies can be summarised as below:

- Damp coal should not be loaded onto weathered or dry coal.
- Some authorities recommend that coal should not be loaded if its temperature is 10% above ambient.
- Air penetration should be minimised.

- Coal should be levelled during loading to prevent the possibility of pockets of methane or hot spots forming.
- If the coal is known to be prone to self-heating, it should be sealed.
- Adequate ventilation of the space above coal cargoes will be needed before unloading to ensure that any gas has been fully dispersed.
- Ventilation should be supplied not only directly onto the coal but also to disperse any gases on the surface.

Van Vuuren[37] reported that very reactive coals are known to self-combust in rail trucks. If coal is left in the trucks for lengthy periods, and excessive rains wet dried coal, the risk is increased. However, due to the large surface area of the sides and top of the trucks, the heat dissipation relative to the mass of coal that is loaded is high and cooling generally takes place, proportionately to the area of the coal exposed to oxidation.

Conical heaps are formed in trucks during loading, and the final surface of the coal should be levelled. The best precautions for safe storage are to load into the railway trucks coal containing some superficial moisture, and not to leave the coal in the trucks for lengthy periods. Wet coal should not be added to dry coal.

A major advance in long-distance bulk haulage of coal is the usage of unit trains as they:

- are dedicated to haulage of a single commodity
- move directly from producer to consumer
- provide modern loading and unloading, with fast turnaround times.

Spraying the coal surface with aqueous emulsions of hydrocarbons or lime does inhibit surface oxidation. However, the motion of the cover barrier may disturb the seal coat. The cost of applying these barriers is high and they may cause deterioration in the quality of the coal due to contamination with the inert barrier products[37].

5 Monitoring of spontaneous combustion

5.1 Underground mines

5.1.1 Gas chromatography

Years of research and application have shown that the spontaneous combustion of coal can generally be classified into three stages: the stage of low-temperature oxidation (the latent period), the stage of accelerated oxidation (the self-heating period), and the stage of drastic oxidation (igniting and burning stage). Japanese researchers, as described in a 1996 publication, achieved marking of the three stages of spontaneous combustion[38].

The publication describes a simulative apparatus for studying the whole process of the spontaneous combustion of coal, its fundamental performance, and the properties of experimental coal samples. More than 400 coal samples of three basic coal types -lignite, bituminous coal and anthracite – were used for the experiments. The compositions of the fire gases at different stages during the spontaneous combustion of different types of coal samples, their regularity in terms of characteristics of appearance and their relationships to coal temperature were studied. Based on data analysis and optimisation, sensitive gas indices, (which can clearly differentiate the spontaneous combustion of coal into three stages-slow oxidation, accelerated oxidation and intensive oxidation) are selected, and an applied criterion is also given.

5.1.2 The tube bundle system

A tube bundle system for mine air monitoring for the early detection of spontaneous combustion has been installed at Bowen No. 2 Colliery, Collinsville, Queensland, Australia[39]. The system is being used to monitor the development of the goaf atmosphere in the caved areas of a thick-seam experimental panel. The tube bundle system consists of four sub-systems, namely the sampling system, the analysis system, the control system and the display system. The sampling system draws sampled gas up to the surface from the remote sampling points. It also cleans and dries the gas sample before presentation to the analysers. The analysis system consists of the appropriate gas analysers, which determine the gas concentrations present. This information is then passed on to the control system, where it is evaluated and stored for later retrieval. The control system is responsible for the continuous operation of the tube bundle system and for the acquisition and storage of data.

The heart of the sampling system can be considered to be the tube bundle itself. The tube bundle connects the pit-bottom box, from which individual sampling tubes extend to the surface installations. Tube bundles are available in a number of configurations, depending on the number of tubes, their size, etc.

The tube bundle system used in Collinsville is regarded as being a successful monitoring system. Gas analysis can be performed three times an hour, and it was possible to gather a good deal of information about the conditions of the goaf atmosphere prior to, during and after the sealing.

5.1.3 Smell and other signs

One of the earliest methods for detecting a fire is by smell. The smell is commonly described as a paraffin or benzene-type smell, depending on the stage of the spontaneous combustion. D W Mitchell suggests that a smell is apparent before sufficient CO has been emitted to trigger a gas-monitoring system. However, we cannot rely on human senses only as sometimes the smell may not be reported to the management (as was the case with the Moura explosion in Australia).

Higuchi et al[40] developed a smell sensor at Hokkaido University. They listed the progress of spontaneous combustion as indicated in table 5.1.3.1 below.

Table 5.1.3.1: Progress of spontaneous combustion in coal[40]

Temperature ^{0}C	Phenomenon
30-40	Appearance of vapour, sweating of wall
40-50	Drying of the gallery, decomposition of wood
60-100	Smell of paraffin, increased rate of temperature rise, appearance of CO and CO_2
100-200	Appearance of C_2H_2 and C_2H_4

The most sensitive sensor was found to be the 112AJ. Carbon monoxide gas was detectable at temperatures above 60°C and its concentration increased after 72°C. However, the smell ensor could detect the fire at around 30°C. The measurements of gas produced during the burning of wood and rubber are also shown in the paper for the purpose of comparison, and it can be seen that there are large differences between the shape of the data for a coal sample and the shapes of the data for rubber and wood samples.

Ogha and Higuchi[41] discussed the same experiments in somewhere else about using smell detectors. They state that they used various coals (South African and Japanese coal) and that the results did not change when different kinds of coal were used.

5.1.4 Temperature monitoring

Temperature monitoring has not found application in common detection methods, the reason being that the temperatures measured might not be accurate because of other heat sources present, such as diesel equipment. However, it is used in small-scale operations such as detecting heating within a pillar.

The Cyprus Orchard Valley Coal Company (Colorado, USA) and the USBM carried out a research project using thermocouples inserted into pillars through boreholes, in conjunction with hand-held thermal imaging, to detect heatings within a pillar[42]. After surveying a pillar with an infrared camera, a spontaneous combustion fire was discovered along the belt entry pillar rib. They concluded that most analytical methods yielded an increase in temperature immediately following a fire but failed to provide adequate prior warning to the fire. The most obvious trend was the data showing a continual increase in temperature. Although the Litton Ratio was able to detect combustion as it occurred, both the hydrocarbon ratio and the hydrogen:methane ratio appeared to be able to predict combustion.

5.1.5 Aerospace surveys

Satellite broadband thermal infrared data of the TM6 type have found use in various resources applications such as hydrology, oceanography, meteorology and environmental surveillance, but their application for studying subsurface coal fires is a relatively less-explored field of study. There are a couple of mines where it has been applied and many papers have been published on remote sensing by ITC. Two case studies will be explained here. One case study will look at the Jharia Coalfield (India), which is said to be very prone to spontaneous combustion: Out of the 158 known occurrences of coal fires in Indian coalfields, 96 have occurred in Jharia alone[43]

Case Study 1: Jharia Coalfield is located in the Dhanbad district of Bihar State, and is named after the main mining area of Jharia.

In the Jharia Coalfield, it is noted that subsurface fires in various coal mines are associated with surface thermal anomalies, and this has also been confirmed by ground checks. Depth estimation of fires has been carried out using field structural geology data and pixel locations of thermal anomalies. It is inferred that the depth of a surface coal fire ranges between 45 and 55 m in most cases, which is in general agreement with the field data. However, the limitations of the method are also recognised.

In thermal infrared sensing, radiation emitted by objects on the ground is measured for temperature estimation. If the amount of radiation emitted from the ground can be measured by a remote sensor, the ground temperature can be estimated, using the Plancks radiation equation:

$$w_\lambda = \frac{2\pi h c^2}{\lambda^5} \frac{1}{\left(e^{hc/\lambda kT} - 1\right)^{e_\lambda}} \qquad (1)$$

where

λ = wavelength in metres

w_λ = special radiance

h = Planck's constant = 6.62×10^{-34} Js

k = Boltzmann's constant = 1.38×10^{-23} JK^{-1}

T = temperature in K

C = speed of light = 3×10^8 ms^{-1}

e_λ = spectral emissivity of the surface, ranging between 0≤ and ≤1. For most natural materials, it ranges between 0.7 and 0.95. In the case of broad-band thermal sensing, variations in lateral emissivity across an area may generally be ignored.

This can be rewritten as

$$T = \frac{C_2}{\lambda \ln\left([e_\lambda c_1 \lambda^{-5} / w_\lambda] + 1\right)} \qquad (2)$$

where

C_1 $2\pi hc^2 = 3.742 \times 10^{-16}$ Wm^2

C_2 $hc/k = 0.0144$ mK

Using the above equation (2), the temperature of any object can be estimated if the emitted spectral radiance is measured.

Ground evidence of subsurface coal fires in the Jharia coalfield was collected to form the basis of the TM6 thermal data interpretation. Field data confirms the presence of numerous fires at varying depths, some just near the surface. A comparative study of the subsurface fires detected from the TM6 data and those provided by the field organisations was carried out. It was observed that in many cases, the coal fires shown by the Landsat data matched the field data.

The second case study is described in an extract from the actual report and shows the results of research on environmental monitoring of spontaneous combustion in the North China coalfields[44].

Estimating the depth of subsurface coal fires was done with the help of field information on the dip of strata. The depth of a subsurface fire can be computed using simple planar geometry.

The limitations arising from a number of factors are:

a) the rather coarse spatial resolution at 120m of the TM6 data
b) ignoring the atmospheric effects
c) non-uniform ground material
d) ignoring lateral variation in the spectral emissivity of the ground material
e) distances being measured in multiples of 30m, which means that depth estimates possess a least count of (30 x tan 80)
f) fires at greater depth may be associated with a correspondingly poorer surface thermal anomaly.

Case Study 2: Spontaneous combustion of North China coalfields.

The joint project, Detection, measurement and monitoring of spontaneous combustion of coal in Northern China, was started in 1994 with the financial support of the European Community and carried out by ITC. The main objectives are:

1) Investigating methods for the detection and location of coal fires
2) Developing methods of measuring coal fires
3) Developing methods of monitoring and prediction of coal fires by making use of remote sensing data and GIS techniques.

In other words, by integrating remotely sensed data with other data (geological, geomorphological, etc.), ways are being investigated to not only detect coal fires but also derive the fire characteristics such as size, temperature, depth and direction of spreading direction from the remotely sensed data.

After one years research, the following conclusions were drawn:

1) General image-processing techniques to extract coal fires from different remotely sensed imagery can be developed. Thresholding can be used in night-time airborne thermal imagery and night-time TM imagery. Principal components transformation is practical for daytime airborne imagery and multiband combination for daytime TM imagery is an effective approach to extracting information on coal fires and burnt rocks.
2) It is possible to establish links between remotely sensed information and actual ground parameters through image measurement. The temperature and depth of a coal fire can be calculated or estimated by using multiband TM imagery.

3) SPOT Band 3 and TM Bands 5 and 7 are especially useful for delineating burnt rocks due to the higher reflectance of burnt rocks in these bands.
4) Two atmospheric windows for transmitting thermal infrared radiation in the 3mm to 5mm and 8 mm to 12.5mm wavelength bands are suitable for detecting active coal fire areas. Data from the 3mm to 5mm band can be used for detecting surface and shallow fires, which usually cause intense thermal anomalies, while data from the 8mm to 14mm band are effective for detecting the thermal anomalies caused by deeper underground coal fires.
5) TM Bands 5 and 7 can also be used to detect ground active coal fires with very high temperatures.
6) Integration of the thermal infrared band data with the visible band data are useful in determining the exact fire area, this having being confirmed by employing a series of image-processing techniques.
7) The extinguishing activities started in 1992 are shown by the temporal monitoring to have been successful.

5.2 Storage and coal handling

The monitoring of stockpiles is discussed in detail by Van Vuuren[37]. Stockpiles are monitored firstly to check for adequate compaction, and for gases and temperature. Several methods are described and these are summarised below.

Dynamic Cone Penetrometer (compaction testing): This is used to check for consistent compaction, which will show fairly uniform results; inconsistent results indicate some under-compacted coal underlying-or overlying well-compacted layers.

Densimetric tests (compaction testing): A better method of measuring the degree of compaction of a stockpile is to determine the below-surface voids on an air-dry basis. Voids (air-dry basis) below 15% are considered very satisfactory, and voids from 15% to 20% are generally acceptable. However, these may vary depending on coal characteristics.

*Gas tests: Subsurface gas test results indicate the inertness of the atmosphere and the extent of oxygen depletion. When reducing conditions prevail, and even when 50 ppm of CO above the residual CO is present, this suggests internal temperatures in excess of 70°C. Air entry or exit points should be determined, the points closed off, and where possible the areas should be re-*compacted.

Temperature recordings: Fixed probes fitted into stockpiles are not recommended as these are damaged by various stockpiling activities and have proved unreliable. Calibrated thermocouples are preferred. All coals tend to heat in transit or storage, but temperatures below 50°C can be considered unconditionally safe. Temperatures below 70°C are still manageable, but need to be monitored on a regular basis.

5.3 Spoil heaps and abandoned mines

Monitoring the dump. Measuring the gas concentration as a function of depth may be a good way of monitoring an oxygen-limited dump. Suppose there is effectively no oxygen at a certain depth below the surface of the dump. If this situation does not change with time, then one can be fairly confident that the dump is safe. Conversely, if a rise in oxygen concentration is observed at this depth, then one may have to take certain measures, such as recompaction. If it is suspected that the dump is causing a problem, one should drive a temperature probe into the dump to measure. One must be aware that the effect of putting in a probe may be to provide a mechanism whereby oxygen can get into the dump, and thus care should be exercised.

Infrared photography is a good way of getting an overall picture of the temperature behaviour of a whole dump. The interpretation of such photographs is, however, not entirely straightforward.

The US Bureau of Mines so-called mine fire diagnostic methodology for locating and monitoring fires in abandoned mines and waste banks is based on the controlled sampling of the mine atmosphere to determine changes in the concentration of hydrocarbons desorbed from heated coal. To provide background data for this methodology, a laboratory study was conducted in which samples of coal and coal wastes were heated under controlled conditions. Gas samples from the combustion furnace were analysed for the standard gases, namely CO_2, CO and C (1) and C (%) hydrocarbons. In all the tests, the concentration of desorbed hydrocarbons increased during heating and decreased during cooling. A dimensionless hydrocarbon ratio was developed by Kim45 as a signature for heated coal. This ratio determines a signature criterion for locating and monitoring fires in abandoned mines. The ratio, R1, is defined as:

R1 = ((1.01[THC] -[CH4])/([THC] + C00 *1 000

where

[THC] = total hydrocarbon concentration, ppm
[CH_4] = methane concentration, ppm
C = a constant, 0.01 ppm.

The ratio R1 was defined to meet the following criteria: (a) that it would equal zero when and only when the concentration of total hydrocarbons was zero, (b) have a unique value when methane was the only hydrocarbon, (c) eliminate the possibility of division by zero – a consideration in the computer processing of data, and (d) increase as the temperature increases.

The use of a hydrocarbon ratio as a fire signature has several advantages. Hydrocarbon desorption occurs at relatively low temperatures. Since the source (mass of coal) is large, the signature is more sensitive. Since a ratio is used, if the concentration is above the detection limit, dilution with air or other combustion products is not a factor. The hydrocarbon ratio is independent of the concentration of other components, such as oxygen and CO_2, and temperature-dependent desorption is the only mechanism by which hydrocarbons are produced in an abandoned mine. The use of hydrocarbon ratios is a positive and sensitive indicator of remote subsurface combustion.

In one of the case studies, an aerial infrared survey, surface inspection, and borehole temperature monitoring had been unable to locate the source of fumes and vapours emitted from fractures and vents. The CO^2:CO results were ambiguous, but the hydrocarbon values indicated the presence of three noncontiguous combustion areas. However, there is one disadvantage of this monitoring technique: areas in which hydrocarbon combustion signatures could not be detected coincided with areas of high water influx, indicating that surface moisture could be preventing the desorption of hydrocarbons from the coal.

6 Control of spontaneous combustion

6.1 Underground Mines

6.1.1 Containment

Mitchaylov[46] in his book suggests several rules for controlling a spontaneous combustion, as described below.

Spontaneous Combustion Rule 1. To stop a heating, stop airflows. If this cannot be done, maintain oxygen below the critical concentration. Rule 1 is generally attempted after the damage has been done. Before that, note that all of the reactions produced heat. This leads to:

Spontaneous Combustion Rule 2. To prevent spontaneous heating from going over to combustion, the velocity of the airflow must be great enough to remove heat as fast or faster than it is being produced. The likelihood of spontaneous combustion increases with an increase in the pressure differential across materials prone to spontaneous combustion.

Spontaneous Combustion Rule 3. The likelihood of spontaneous combustion increases with an increase in resistance to airflow. Associated with this is the most important of all spontaneous combustion rules, particularly when attempting to stop reactions by zero-pressure differential.

Spontaneous Combustion Rule 4. The likelihood of spontaneous combustion increases with an increase in the pressure differential across the mass of broken coal, carbonaceous shale, or wood. The pressure differential results from interrelationships between path resistance and quantity of airflow; the latter depends on the mine fan(s) and ventilation networks. In deep mines, abandoned mines, and some sealed areas of active mines, pressure differentials and airflows are developed by differences in elevations, barometric pressures, gases and temperatures.

Spontaneous Combustion Rule 5. The likelihood of spontaneous combustion increases with an increase in depth.

Fuel-rich fires

The definition of a fuel-rich fire is one in which gases and tars in the atmosphere downstream from the flames are increasing and exceed the quantity that could be reacted by the available oxygen supply. This occurs when:

a) temperatures are hot enough to continue pulling-out gases and tars from the wood or coal, and
b) the oxygen concentration is less than required to sustain flaming.

Control of a fuel-rich fire is difficult and dangerous. The measures include:

- Reacting promptly
- Removing downstream fuels

- Maintaining the ventilation airflow until unquestionable, compelling reasons dictate otherwise.

Mithaylov[46] mentions several remedies for controlling spontaneous combustion in his book. The first, *Zero-Pressure Differential*, is based on Rule 4. It is the most effective for all kinds of heatings, provided it can be used safely. There are three important zero-pressure differential techniques: regulators, auxiliary fans and low-pressure splits. Details of these methods will not be discussed here since further information can be obtained from the reference.

The second remedy, *Waxwalling*, is based on the first part of Rule 1 – stop airflows. Its use is limited to pillars and around stoppings. This technique was developed in the 1950s in Czechoslovakia where spontaneous combustion was extraordinarily serious in coal pillars. Waxwalling, as its name suggests, is intended to make walls (pillars) impervious to air. This is done by injecting a sealant into the skin of the pillar.

Sealant: The sealant combines an inhibitor of coal oxidation, such as calcium chloride (CaCl), with a binding agent and filler, such as bentonite. Known oxidation inhibitors, by themselves, have poor stability when applied as either a coating on coal surfaces or a filler in cleavages and fissures in pillars. Clays such as bentonite flow readily into cracks, and swell and fill the cracks. When the bentonite and CaCl are homogenised, the resulting mixture has long-term stability.

Injection: The purpose of injection is to fill all cleavages, fissures and cavities in the pillars skin without stressing the coal.

The third remedy, *Inert-gas flows*, is based on the second part of Rule 1 – reduce oxygen. Of all the techniques, it is the least effective and most expensive.

Note that the relatively common technique of water infusion is not included. By itself, water infusion may worsen spontaneous combustion because of the adverse effect of moisture.

Bleeders should not be used in areas of mines where spontaneous combustion has been experienced in gobs. The probable methane contents of spontaneous combustion-prone coals should be low. Methane from the coal and, more particularly, methane from strata overlying spontaneous combustion-prone coal, is best removed by and through boreholes -horizontal and cross-measure where vertical holes are impractical. The purpose of bleeders is to establish and maintain pressure differentials across gobs. The higher the differentials between faces, gate roads and bleeders, the greater the chance air will be forced through tight places. High differentials and tight places develop slow-moving, sluggish air streams, so conducive to spontaneous combustion.

Michaylov and Vlasseva[47] discussed a method for a three-phase foam preparation recipe optimisation. The optimisation approach has been applied in underground coal mines in the Bobov Dol coal basin. They based their selection of inerting gas on the fact that the solubility of nitrogen in water is 55 times less than that of carbon dioxide. They demonstrated that the recipe optimisation for three-phase foam generation, used for preventive and operative purposes, plays different roles in delaying the process of coal oxidation and the suppression of spontaneous combustion. These roles are discussed briefly below:

Liquid phase: Cools by conduction and increases the humidity of coal and rocks; restricts the access of oxygen during the period of foam existence; inerts regions of porous media when reaching high-temperature zones. A significant compacting effect is observed when this phase is injected into rocks with high clay content.

Solid phase: Creates a wet solid layer on the surface of coal pieces and fills filtration channels, which inhibits convective and diffusive oxygen transfer.

Gas phase: Ensures treatment of coal masses located in high zones of gob by increasing slurry viscosity. Inert gas dilution during foam destruction makes this zone inert. There are mathematical solutions as well as laboratory test results for optimisation, which are discussed in detail in the paper.

6.1.2 Extinguishing

6.1.2.1 Inert gas injection

The tube bundle system has been used to assess the use of inert gas injection as means of controlling spontaneous combustion. Nitrogen or carbon dioxide is injected into goaf areas affected by a spontaneous heating to help control the heating by excluding oxygen and to give a cooling effect. The favoured gas is nitrogen as it is cheaper and more easily expelled from the mine after the heating has been controlled than is carbon dioxide.

Three nitrogen inerting experiments were done at Bowen No. 2 Colliery at Collinsville. The experiments were conducted to find the optimum nitrogen flow rate and configuration of the injection points. At the end of the experiments, they were not able to draw a conclusion about the effectiveness of inert gas injection as a means of controlling spontaneous combustion.

Major advances have been made using inert gases to control spontaneous combustion. The objective of inerting is to reduce the concentration of oxygen in the atmosphere. To ensure the prevention of spontaneous combustion, it is necessary to reduce the oxygen content below 3% by volume.

One essential condition is that nitrogen should be applied quickly. It is common in Germany to have inertisation plants at the mine site. This enables them to apply nitrogen to a fire area at very short notice, often within four to 12 hours after detection. Many fires have been controlled in German mines using the technique of inertising with nitrogen (Kock and Linberg (1985)).

Carbon dioxide may be used for inertisation instead of nitrogen, and is sometimes preferable to nitrogen. Because its density is higher than that of air, carbon dioxide is particularly suitable in situations where the heating is taking place at the bottom of a steeply sloping area or at the bottom of a shaft.

Generating an inert gas at the mine site is usually cheaper than obtaining a supply of carbon dioxide or nitrogen. In this way, it is also possible to produce gases at a greater flow rate. However, some disadvantages are mentioned:

- The need for a large volume of cooling water

- Non-compliance with flame-proof requirements
- Difficulty in controlling the rate of generation and delivery
- The need to locate the generation activity close to a fire because of low delivery pressures.

Designs and methods of using inert gas generators are now being improved[10].

6.1.2.2 Sealant technology

Recent developments in sealant technology have been well summarised by Chakravorty and Kolada[12] who categorised them into three main groups: gypsum-based, cement based and others. The last group includes sealants incorporating rubber, latex, urea-formaldehyde, phenolic resins and bentonites.

Gypsum-based sealants usually have additives such as perlite, vermiculite, granulated mineral wool, or fibreglass that help increase their strength and elasticity. Such sealants are also of low density and harden rapidly after application. These properties make this type of sealant particularly suitable for providing a thin, airtight seal to the surface walls and roofs of mine roadways. The low density prevents stressing of the surface material of the mine walls and, hence, reduces the possibility of spalling.

The additives used to increase elasticity allow for moderate strata settlement. Due to the rapid setting rate, the sealant can be built up to span gaps, fissures and cracks. In many applications, the setting is too fast and additives are included to extend the natural setting time, which is about 20 minutes.

The materials used for cement-based sealants are the same as those normally used in construction -Portland, high-magnesia and oxysulphate. The properties and uses of these sealants vary from very elastic coatings, which are used as fire retardants, to concrete compositions used for structural support. Both cement and gypsum can be used with foaming agents for applications as fillers.

Latex sealants have seen only limited use. They are difficult to store for any length of time and the surface to be sprayed usually has to be prepared in advance of the necessary two applications. Their main advantage is that the sealant will remain airtight while the strata settle.

Urea-formaldehyde foam products have been developed to supersede the polyurethane foams that were toxic and flammable. This foam is suitable for filling between and under chocks or between the shuttering and the side of the pack. The foam sets in 24 hours and becomes increasingly impermeable under pressure from the strata. Suspected long-term health problems restricted its use.

Phenolic resins were also developed to supersede polyurethane foams.

Bentonite is natural clay that swells to many times its original volume when mixed with water. Bentonite injection is usually used to seal within a specific area and is not normally used for general application.

6.1.2.3 Biotechnological methods

In a study conducted in Canada[48], methane-oxidising bacteria were used to control methane concentrations in silos. The bio-oxidation of methane to carbon dioxide follows this pattern:

$CH_4 + 2O_2 = CO_2 + 2H_2O$

The methane-oxidising bacteria used in this study are aerobic, i.e. they require molecular oxygen to oxidise methane to carbon dioxide. Two important factors were illustrated in this study. First, there is a decrease in the concentration of methane in the silo after the bacteria are added. Secondly, the amount of oxygen present in the silo is rapidly depleted to insignificant levels. Thus, the biological technique has the additional benefit of inerting the voids, thereby reducing the possibility of an explosion.

These tests show that there will be a spin-off benefit for spontaneous combustion during the storage and transport of coal because of lack of oxygen within the coal pile, as spontaneous heating in coal silos and coal shipholds is often responsible for methane explosions.

6.1.3 Reopening

When mine fires get out of control it is usual for the entire zone to be sealed off until the fire dies because of lack of oxygen. The problem management then faces is to decide how many days should be allowed to lapse before the zone can be reopened. Opening too early could restart the fire, while needless delay represents a significant loss in production.

If it is necessary to reopen the section closed due to a spontaneous combustion, the gases in the closed-off area should be measured to determine the oxygen levels. Mitchell[24] reports that flames begin to die out when the oxygen concentration is less than 5%. Active flaming often stops while the oxygen concentration remains at or below 1%. Smouldering incandescence can continue indefinitely, even in the absence of the air. Where the temperature of the rocks or smouldering materials exceeds 150°C, rekindling is probable should the oxygen concentration rise above 5%.

It is essential to ask the question Why unseal? Too often that question was asked too late, and more often the answer was, There was no good reason. The procedure for unsealing a fire area is explained in detail in the related reference.

6.2 Surface mines

Spontaneous combustion in surface mines can happen in stockpiles and in benches. Stockpiles are discussed in Section 5.4.

In Indian opencast mines, coating material was applied to prevent spontaneous combustion. If the coating had not been applied, the coal would have caught fire within the incubation period. Singh et al.[49] report that loose coal (freshly cut) lying at the toe of the benches was also prevented from spontaneous heating by the application of a fire-protective coating in Karkatta OCP, Dakra. There was no indication of heating even after two months. After that, the coal bench was blasted and the covered portion was extracted out; again freshly exposed loose coal deposited at the toe of the bench that was not covered caught fire within one-and-a-half months.

They observed that the temperature of the coated loose coal remained near ambient for about six months.

6.3 Waste dumps and abandoned mines

Unless the situation is sufficiently serious to warrant complete re-excavation of the affected material, encapsulation is the preferred means of controlling existing spoil pile fires (see figure 6.3.1).

This system uses the deprivation of oxygen to extinguish a fire by means of capping and can be used in any spoil pile or any active pile. Other systems are surface sealing, deep-layer grouting, surface excavation and the use of high-pressure water sprays to extinguish a fire. Fly ash can also be used to seal active fires within spoils.

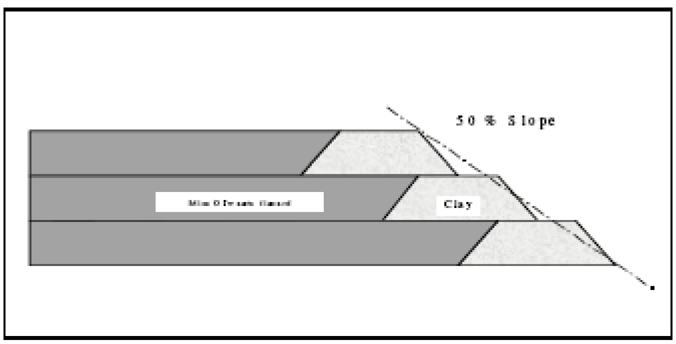

Figure 6.3.1: Safe storage of mine waste or discard in compacted layers with clay seal[50]

Controlling a burning abandoned mine is vital for environmental reasons, especially when it is close to an urban area.

A case study[51] is explained in detail below on how mine fires and waste were handled in a particular abandoned mine.

Case Study 3:

During the past 30 years in the town of Mostar (Bosnia and Herzegovina) a surface coal mine was in function so that the entirely included area has been devastated. Working levels in spoil banks are not shaped and interactively linked in an orderly manner, while the crater part is absent of adequate and functional forms and acceptable final contours. Large quantity of water is accumulated at the bottom of crater being in connection and on the level of the Neretva River, which flows through the centre of the town.

6.4 Stockpiles and coal handling

Regular monitoring of coal stockpiles is essential as a first measure for controlling fires. When the temperature of the stockpile exceeds 60°C, it is a clear indication that control measures need to be implemented. These are either to use the coal immediately or to move it, allow it to cool and then re-compact it.

Accessing hot spots is usually a problem, since the exact location of the fire is difficult to estimate. When the first indication of a hot spot is detected, earth-moving equipment can be used to excavate the hot material. The excavated part then must be recompacted. The use of water can be dangerous and may aggravate the fire. Therefore, it cannot be recommended.

The techniques available for the control of spontaneous combustion are: excavation, flooding and quenching, bulk filling, surface sealing, installing plugs in tunnels, inert gas injection, chemical treatment, burnout control and abandonment. CO_2 can be used to control and extinguish fires in silos.

6.5 Coal transport

The control of a fire in a ships hold is usually achieved by sealing the hold. It is not possible to inert a hot spot in a ships hold because neither nitrogen nor CO_2 will be available. The next best thing to do is to make for the nearest port that has specialised fire-fighting equipment available.

"For a long time a shallower part of the coal layer in the pit is burning, developing hazardous gases and spreading smoke which disturbs work and life of local citizens." Sanitation of the space (forming the sanitary depot, extinguishing fire) and technical recultivation of degraded areas require the redistribution of large masses of refuse and this may be achieved by direct and limited coal production (sanitary exploitation). The authors report that the liquidation of the fire zone includes bringing in a considerable number of overburden layers with previously filled-in crevices and in addition, injected the pit with clay-earthen material, which can be obtained by cleaning the bottom of the lake in the crater.

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ANNEXURE 1

Premature detonations and blasting in reactive ground

Premature detonations and blasting in reactive ground

Background

Reactive ground is a term used in the mining industry to describe ground in which the reaction between sulphides (especially iron and copper sulphides) contained in rock and the ammonium nitrate contained in explosives may take place. This is normally prevalent in the iron and copper mines, but a number of incidents have recently occurred in opencast coal mines.

The reaction of ammonium nitrate with sulphide containing minerals is an auto-catalysed process, which can, after some induction time, lead to runaway exothermic decomposition even if the starting temperature of the mixture is around an ambient temperature of 20°C. The reaction scheme developed over the last 30 years of research by groups such as the US Bureau of Mines and others is described in a simplified form below.

Chemistry

Natural oxidative weathering of iron sulphides such as pyrites by atmospheric oxygen generates solutions of ferrous irons and acid. This process occurs whenever the sulphides are exposed to air along cracks, in drilled holes, in the muck pile after blasting, on pit walls and in old workings. No nitrates are required for this to occur.

Iron sulphides + Oxygen + water →Ferrous ions + Sulphuric Acid

This reaction is exothermic and can, for particularly reactive ores, lead to hot blast holes. This temperature increase can be as little as 2°C or as much as several hundred degrees.

On contact with ammonium nitrate, the ferrous and acid species from weathering can begin to catalyse the breakdown of nitrate. The breakdown process is autocatalytic in that it generates its own catalysts as it proceeds.

Ammonium Nitrate + Iron sulphides + Ferrous ions + Sulphuric acid →Nitric Oxide + Ferric Ions + heat

The nitric oxide and ferric ions produced in this stage react with more pyrites, generating more ferrous ions and sulphuric acid.

Iron sulphides + Nitric oxide + Ferric ions →Ferrous ions + Sulphuric acid

Although these reactions are exothermic, their rate may initially be so slow that little or no temperature rise is detectable. This is because of the concentration of catalytic species building up to some critical level. The time taken for this to occur is often referred to as the induction period. When sufficient catalysing species have built up, the reaction rate increases sharply and the heat generated causes the temperature to become so high that a rapid, potentially violent decomposition of the remaining ammonium nitrate is inevitable.

Ammonium Nitrate + heat (220°C or less) →Explosion

Some known recent incidents

- 2010 Goedgevonden reactive premature detonation
- 2010 Drayton reactive premature detonation
- 2009 Liddell reactive premature detonation
- 2008 Mt Gordon reactive premature detonation x 2 (ANFO)
- 2007 Donaldson reactive combustion of spilt heavy ANFO
- 2006 Gajiski copper, Russia reactive premature detonation, pH 5.9
- 2006 Mexico reactive premature detonation (ANFO)

Factors affecting reactivity

Mixtures of all iron sulphide bearing minerals and nitrates are thermodynamically unstable and may be reactive.

The rate of the reaction depends upon the type of mineral, the level of oxidation, particle size of the mineral and thermal conductivity of the surrounding rock, porosity of the crystal structure, surface area of the crystals and the amount of water and oxygen available. It has so far proved impossible to predict which deposits will be sufficiently reactive to present problems in blasting since none of the above factors correlate reliably enough with reactivity.

If a deposit is reactive, the amount of heat potentially generated will increase with sulphide content, simply because this provides more fuel for the reaction.

Indicators of potential reactivity

Some of the indicators of potential reactivity include:

- Spontaneous combustion of the coal or shale
- The presence of sulphur dioxide
- Faster than expected rusting of rock bolts, etc. because of the sulphuric acid
- Warmer than usual air rising from blast holes, owing to the oxidation of the rocks
- Acidic ground water owing to sulphuric acid.

Note that none of the above is in any way a perfect predictor of reactivity.

Testing for reactivity

The recommended method for determining if iron sulphide bearing minerals are reactive is by chemical compatibility testing. Explosives' suppliers can perform a direct compatibility test between the rock and ammonium nitrate. Alternatively, laboratory testing companies can perform a DTA (differential thermal analysis) test for compatibility, although this method is less informative because of the very small sample size and other technical considerations.

Samples of minerals for testing must be selected with the advice of the mine geologist. The recommended procedure for doing this is described below.

Sampling rocks for reactivity

The aim of all reactive ground sampling is to collect samples containing iron sulphides. In the first instance, a judgmental or authoritative method for collecting rock samples can be used. This entails a look at the "worst-case" samples present in the mine based on the local geologist's knowledge of the pit. Typically, this will involve sampling black shale or massive sulphide units. Coal that is high in the spontaneous combustibility index should also be tested for reactivity.

Only samples that are high in iron sulphides, or are pyritic in nature, need to be collected at this stage. If there are large amounts of this type of rock present, then the pit geologist can advise further on which samples are likely to contain the highest amounts of iron sulphides.

This investigation should result in at least two to three samples but no more than about 10.

The exact location of the origin of the sample must be identified by the geologist and recorded, as this will aid in the systematic sampling that will occur later if the samples prove reactive.

It is not recommended that the samples be drill cuttings for the purpose of this investigation, as this can potentially dilute any worst-case sample that might exist. Care should be taken to ensure that the sampling taken has not fallen from a higher point or been moved from a different location. Samples picked off walls are useful for this investigation. Geological borehole cores are ideal, but must be “fresh” and not have been left lying in core boxes for weeks.

Each sample should be approximately 0.5 kg to 1.0 kg and individually packaged in a plastic bag. The analysis of the samples should be co-ordinated through the explosives supplier, who will advise on the correct testing facility if they are not able to do it themselves.

This method of sampling and testing will provide information on whether or not the pit does in fact contain reactive ground.

Subsequent action

If the reactivity result is negative, then some ongoing sampling and testing may be required as different geology units are encountered or other incidents cause mine personnel to believe they have a reactive ground issue.

If the reactivity result is positive, then it is recommended that:

- Only explosive products containing an inhibiter are loaded into that geology type (usually urea). It is also recommended that this type of product be introduced immediately.
- Barriers, which prevent the rock from contacting the ammonium nitrate, can also be used. These include blast hole liners (plastic sleeves) and packaged product.
- Use temperature measuring devices in the holes that provide warning of heating.

- Do not use detonators in blast holes, use six to 10 gram detonating cord with suitably sized boosters, depending on the hole size. Every hole should be individually delayed with a surface delay and should not be interconnected with detonating cord to prevent the risk of one hole initiating a series of holes.
- Sleeping of holes must be avoided, and where this is not possible avoid stemming the holes. Stemming should take place just prior to blasting and the stemming material should be an inert material and not drill hole chippings that can react with the explosives.
- It is suggested that an integrated risk management approach be followed and controls be put in place that will not expose workers to unacceptable levels of risk.

The extent of reactivity is often then determined if deemed necessary. This will typically involve looking at other geological units within the mine. This sampling must also be done in consultation with the mine geologist. A systematic investigation can be used for this type of sampling and should be based on coverage of the geological domains rather than levels of sulphide content.

The results of this programme can then be used to formulate a long-term strategy on the way to effectively manage the risk from reactive ground at a particular site to ensure the safety of all personnel.

Use of inhibited products

An analysis can be performed to determine the level of inhibiter required to quench the reaction for 12 hours. Most explosive suppliers have a range of products to satisfy customers with reactive ground, including bulk wet hole and dry hole products for the opencast market, and bulk and packaged explosives for the underground market.

Talk to your explosive supplier about the product best suited to your mine.

The inhibiter is added to the emulsion phase and slows down the reaction, but does not prevent it. Consequently, a 12-hour sleep time maximum is recommended. Sleep times greater than this can be authorised, but are only recommended if additional extended lab testing has been completed.

As the presence of heat in blast holes can cause the reaction to occur faster, and the initial oxidation (weathering) reaction can produce heat, it is recommended that temperature logging of blast holes is performed in reactive areas of the mine. A number of temperature measuring devices are currently available from the explosive suppliers. Once it is established that a certain geological unit does not show any evidence of warming before explosives are added, then temperature logging can cease. However, if the holes do show that the oxidation reaction is occurring rapidly and producing heat, then no holes over 50°C should be loaded with conventional explosives.

Disclaimer

All information contained in this annexure is accurate and up-to-date as February 2011. Since conditions vary vastly from mine to mine each operation must assess the site risks in conjunction with its explosives suppliers and draft drilling and blasting standards to address the risks. There are numerous publications and papers available on the subject of reactive ground available from the explosives suppliers.