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GUIDELINES

MDG 1006-Technical Reference

Technical Reference for Spontaneous Combustion Management Guideline

Produced by Mine Safety Operations Branch
Industry and Investment NSW
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1 SCOPE

The content of this document applies to all underground coal mines in Australia.

2 PURPOSE

The purpose of this document is to provide historical and technical information to assist operators in the development of a Spontaneous Combustion Management plan that complies with MDG 1006.

The technical reference is not intended to be a complete reference work on the subject of spontaneous combustion but rather focus on some issues of importance. References are provided for other information on spontaneous combustion.

3 FUNDAMENTALS OF SPONTANEOUS COMBUSTION

Spontaneous combustion describes the process of self-heating of coal by oxidation. After exposure by mining, coal undergoes a continuous exothermic oxidation reaction when exposed to air.

A hazard exists when, in confined areas, the rate of heat accumulation due to oxidation exceeds the rate of cooling by ventilation or environment. The coal can then increase in temperature until combustion takes place leading to the emission of toxic and explosive gases together with propagation to open fire. The self-heating will then become a potential ignition source for an explosion if exposed to a flammable mixture of gas.

Spontaneous combustion of coal occurs by the following steps:

- Oxygen (from airflow and ventilation) reacts with coal. This is called oxidation.
- Oxidation produces heat. This is called an exothermic reaction.
- If this heat is lost to the surroundings (mine environment), then the coal mass will cool. However, if the mine environment favours the heat being retained, the coal mass will increase in temperature and the oxidation rate will increase leading to spontaneous combustion. Significant amounts of heat can also be generated when the coal absorbs moisture.

Heat generated is lost by some or all of the following mechanisms, depending upon the temperature and physical conditions of the mine:

- Conduction through the solid coal mass.
- Conduction and radiation to the ventilating air.
- Evaporation of moisture.
- Convection through the solid coal mass and ventilating air.

The oxidation process is complicated, and not fully understood, but the following stages occur as the temperature of the coal increases:

- The absorption of oxygen by the coal and formation of oxycoal without the production of carbon monoxide. This is a reversible process.
- As the temperature increases through the range 30°-40°C the coal/oxygen complexes break down and produce carbon monoxide and carbon dioxide. This reaction occurs irrespective of the presence of atmospheric oxygen.
- Further increases in temperature are associated with increased rates of oxidation and the production of increased quantities of carbon monoxide and carbon dioxide.

There are two conditions of oxidation equilibrium that can occur:

- If the quantity of air flowing over a coal surface is very small, then the rate of oxidation is low. This is the condition that occurs in high resistance air paths, such as through goafs and in sealed areas.
- If the air quantity is large, the heat due to oxidation is lost as quickly as it is generated and this cooling effect may be enough to prevent any significant rise in temperature. This is probably the condition that occurs in almost all the low resistance intake and return airways.

Should this equilibrium condition be destroyed by either an increasing airflow in the first case, or a decreased airflow in the second case, then the temperature will rise and spontaneous combustion may result.

All coals are liable to spontaneous combustion if the conditions are right.

4 PREDICTION

4.1 HISTORY

The history of spontaneous combustion events at a mine, adjacent underground and open cut mines and the same coal measures in other areas, is invaluable in providing guidance on the propensity for heating, location of heatings and behaviour of the coal (gas evolution) as it self-heats.

There may be considerable information where the coal seam has been mined extensively. This may indicate a high or low propensity for spontaneous combustion. Testing coal for propensity for spontaneous combustion is useful although there are limitations in its validity. Information from operating experience in the seam is of great value.

4.2 DEVELOPMENT OF HEATINGS

Conditions for the development of heatings typically exist in out of the way places such as goaves where they cannot be seen. Where they occur in ventilated and accessible roadways, they are hidden below the surface of coal stowage, or within the rib side of a pillar. Coal that heats on the surface of stowage etc. is cooled by the ventilation flow. Ideal conditions exist deeper in the coal mass.

Heatings are difficult to discover and are often not detected until well advanced. They may commence as small football size shapes, giving off low volumes of gas in a goaf, which is difficult to detect.

Gaseous products of heatings in goaves may not be easily detected in adjacent ventilated roadways because of the irregular and intermittent ventilation flow from the source, barometric changes, temperature variations and the passage of air through the goaf where absorption or dilution may take place.

A heating in a surface coal or refuse stockpile provides an opportunity to observe behaviour. Coal stockpiles are readily accessible although the heating sites cannot be seen in early stages because they develop below the surface within the coal mass.

Coal on the surface of a stockpile where it can be seen, does not self-heat. There is sufficient oxygen on the surface for oxidation to take place but not conditions that favour the retention of heat. Again, heatings tend to commence as small football sized shapes within the mass of the stockpile. The temperature in such a shape may be higher than normal (60° to 80°) and in the adjacent area, normal.

Unless there are attempts to monitor temperature changes within the heaps, spontaneous combustion is more likely to be detected in an advanced stage by smell, visual observation of shimmering (heating) of the air above the heap, or smoke and flames when the coal is loaded out.

4.3 LOCATION OF HEATINGS

An appreciation of the characteristics of spontaneous combustion and an understanding of the places in the mine where heatings may develop is critical to the development of an effective Spontaneous Combustion Management Plan (SCMP). Prevention, early detection, and control of the spontaneous combustion risk will not be effective unless the potential hazards and locations are correctly identified.

Places in the mine where heatings may develop include:

4.3.1 Longwall Extraction Area

The conditions required to initiate a heating are more likely to exist in a goaf than in other parts of the mine. The risk of heating in an active longwall goaf is greater as there are a number of flow paths available into areas that cannot be sealed by strata consolidation. The major factor preventing heatings is the exclusion of oxygen by accumulation of seam gases.

Spontaneous combustion in the active longwall goaf may be caused by air drawn behind the roof support line or leakage through a goaf edge seal. The area of greatest risk is the edge of the goaf where there is rib spall, voids, incomplete caving and close proximity to ventilated roadways. Air permeability is higher and high ventilation pressure and poor containment can allow air to enter the goaf.

Heatings are unlikely to develop in a fully caved area because the fallen rock buries the potential heating location and air permeability is low. (Consolidated area) Replenishment of oxygen in the fully caved area is unlikely to be adequate to sustain spontaneous combustion.

In mines where longwall gate roads have to be heavily supported, goaf formation alongside chain pillars may be delayed or incomplete resulting in cavities extending a considerable distance into the goaf. Air may flow into the goaf due to pressure differences around the panel (where bleeders are used) or into and across the goaf behind the longwall face. This was believed to be an issue at Moranbah North in Qld and at Dartbrook in NSW.

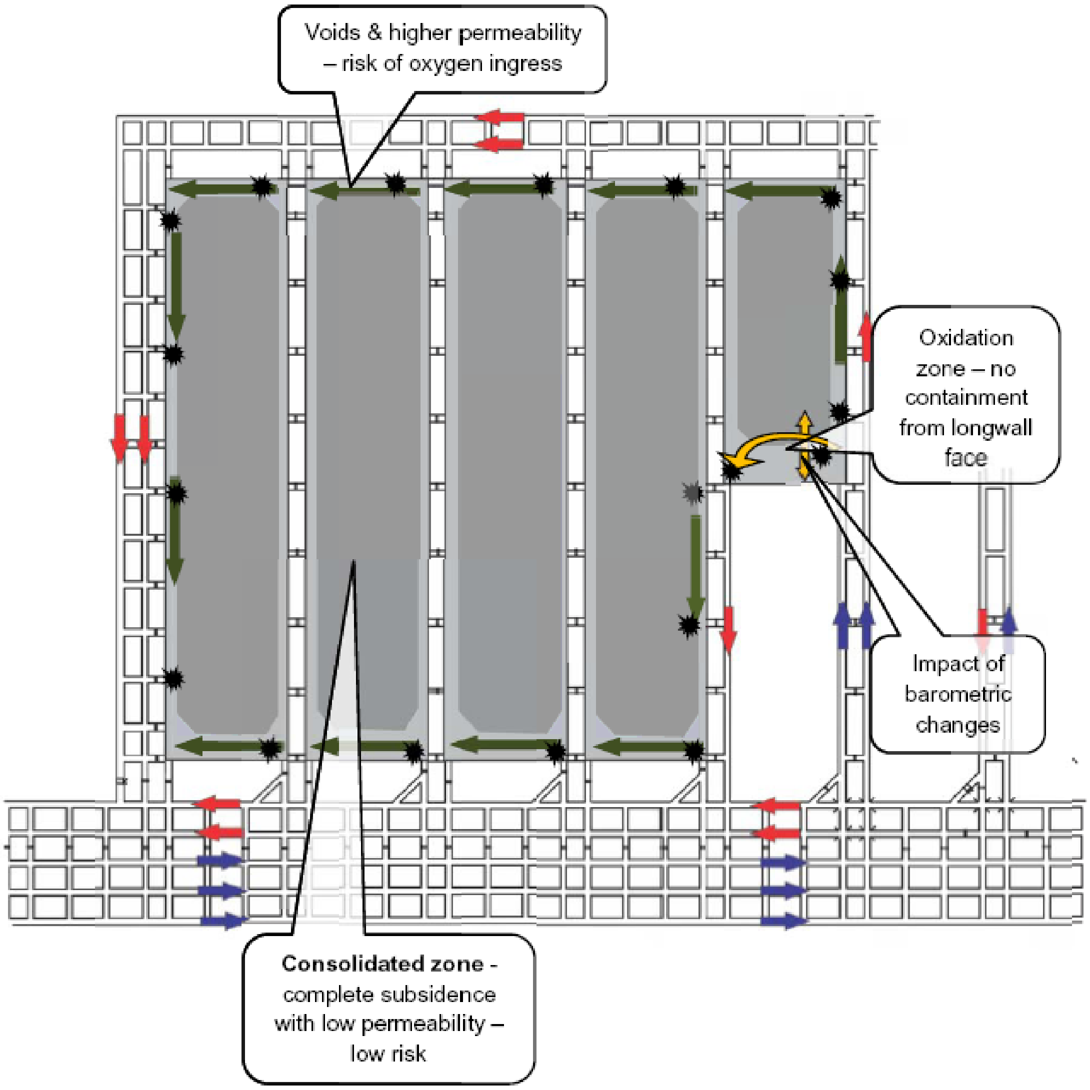
Sub critical extraction systems, (associated with limited surface subsidence) designed with stable chain pillars, may result in voids above the caved area permitting increased airflow paths across the goaf. Rider seams in the area where there are voids pose a risk of spontaneous combustion.

Active long wall panels have an unsealed side adjacent to the goaf where the longwall face equipment is located. Oxygen can enter the extracted area due to face ventilation airflow and barometric changes. Barometric variations exceed the ventilation pressure difference across the face and can have a significant effect by moving air, in and out of the goaf, by expansion and contraction.

In an active longwall panel, there may be sufficient oxygen to allow oxidation to take place approximately 150m to 400m into the goaf from the long wall face. The distance will vary according to the frequency and severity of barometric changes, dip of the seam and direction, natural inertisation processes and the standard of containment structures.
If operating conditions result in a protracted delay in long wall face retreat, there is a risk of spontaneous combustion developing in the goaf.

Figure 1 shows areas in a longwall extraction area where spontaneous combustion may develop if preventative measures such as the standards for stoppings and seals and ventilation pressure difference are inadequate.

Figure 1: Longwall goaf - hazards



Legend

	Consolidate zone - extraction completed, caving and full subsidence has taken place - low permeability, effective inertisation & low risk
	Area of voids & higher permeability alongside the fully caved goaf –risk of heating if containment poor and the impacts of high ventilation pressure result in ingress of oxygen – higher risk.
	Poor containment & high ventilating pressure may result in air ingress and air movement into the goaf in this direction.
	Possible heating sites

4.3.2 Bord & Pillar Extraction Area

The system of continuous miner extraction requires stooks to be left to protect operators in the working area. This ensures broken coal in the goaf, and may result in delayed caving.

Similar to a longwall, spontaneous combustion is controlled by:

- The consolidate zone where complete caving takes place,
- Inertisation as a result of containment, seam gases and oxidation,
- A regular and progressive extraction rate,
- Minimisation of pressure differences across & alongside sealed areas,
- Inspection and maintenance of seals and seal sites to control leakage, and
- Sampling and analysis of sealed area atmospheres.

Deficiencies in any of these control measures will increase the risk of spontaneous combustion.

Spontaneous combustion in sealed areas may be caused by air leaking into or through seals or the sealed area having an oxygen rich atmosphere.

Heavy weighting, seam structures and roof control problems may result in additional coal being left in the goaf. Incomplete extraction may delay caving, encourage greater air movement in the goaf and cause coal to be exposed to the risk of heating.

The rate of extraction with continuous miners is normally less than that of a longwall system.

Where discrete panels are developed with each panel having a barrier on 3 sides, containment and inertisation is effective except for the working area adjacent to the goaf.

Partial extraction systems are more often being adopted. Where such systems are used, caving may be incomplete and irregular, leading to voids and potential air paths in the extracted area. Stable pillars may be left and spans reduced to sub-critical. This results in voids in the goaf where air can flow and may increase the risk of spontaneous combustion developing within the goaf.

Figure 2 shows a system of panels isolated by barriers and typical locations where heatings can occur. With low depth of cover, or other seam workings within close proximity, there is the risk of interconnectivity through cracks and those areas of risk could extend to all goaf edges.

Heatings will only develop if inertisation is ineffective.

Figure 2 – Continuous miner isolated panels – hazards

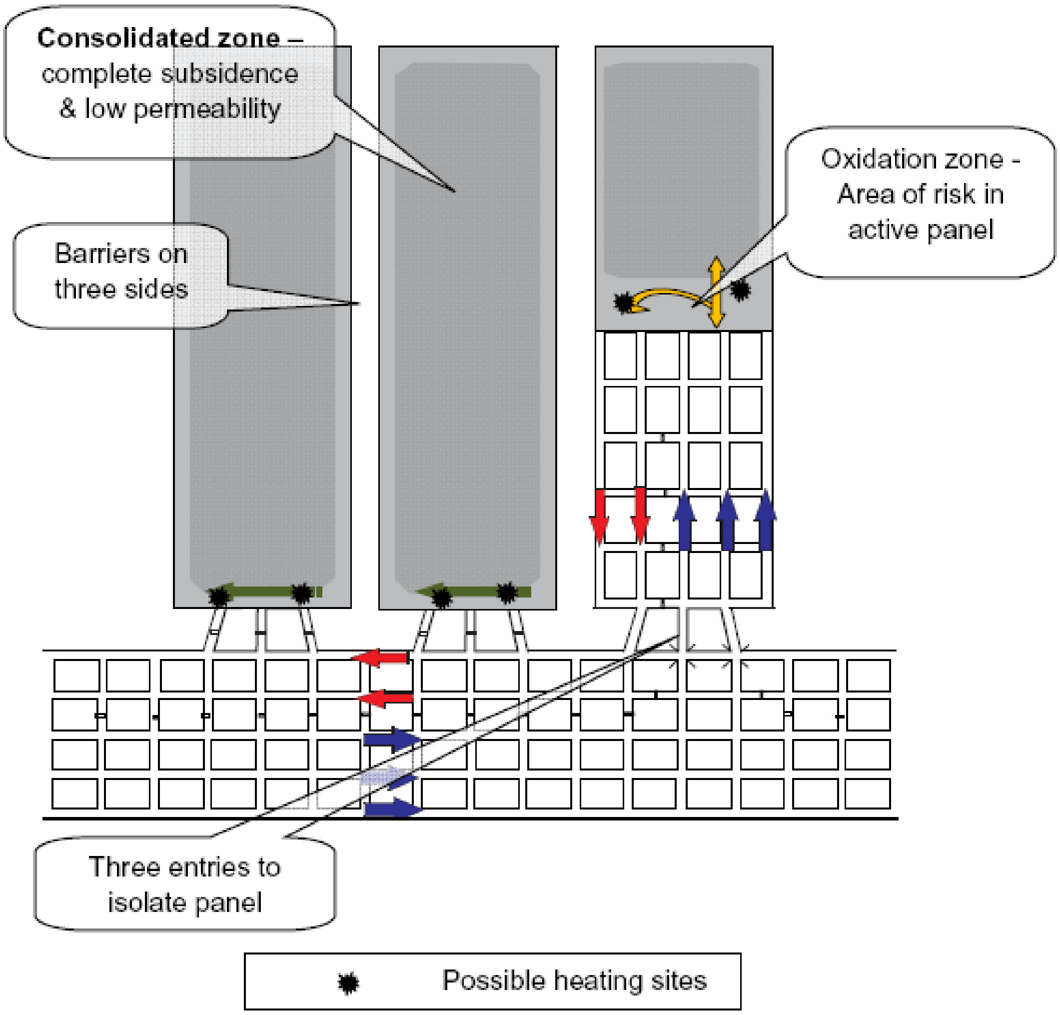
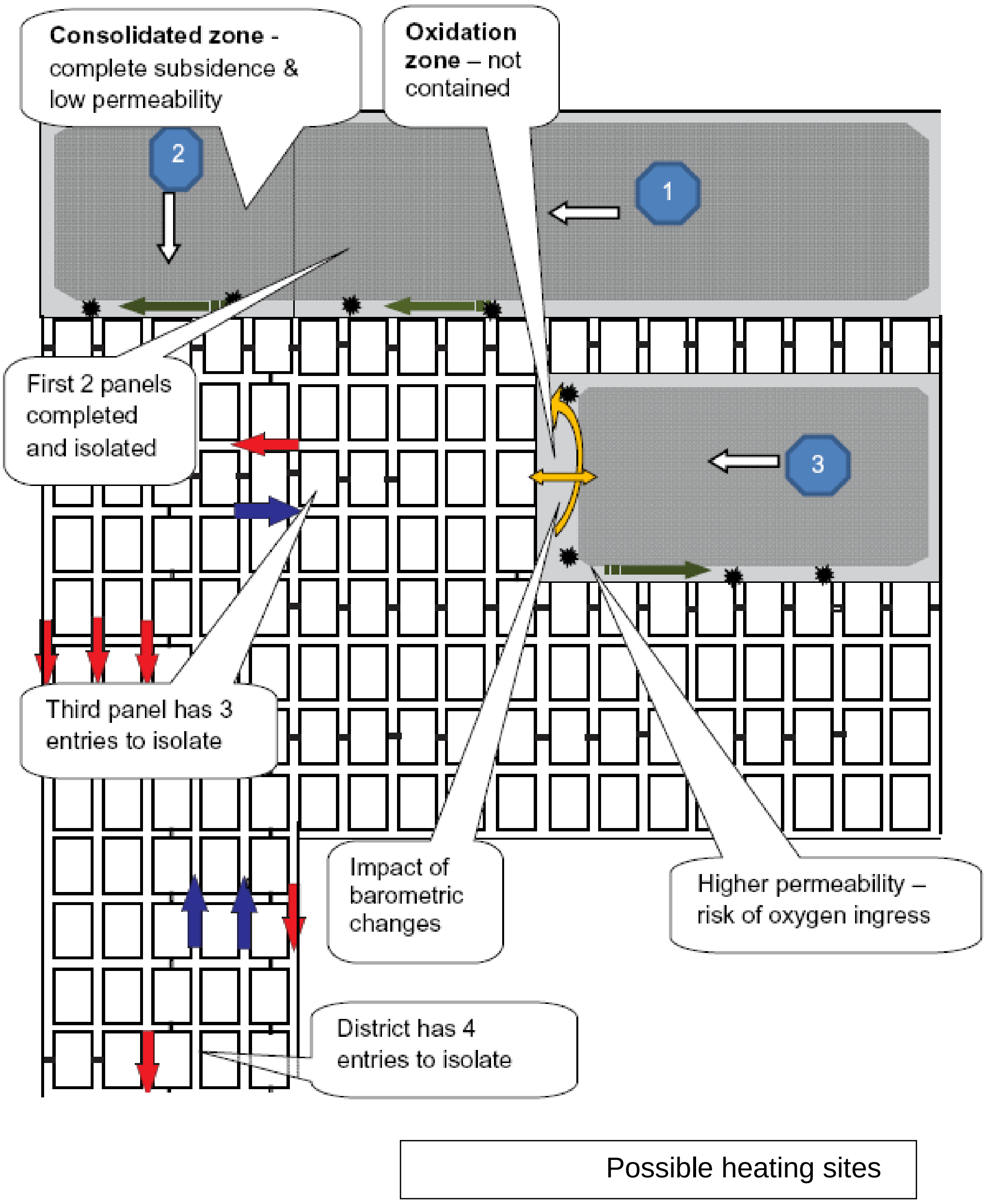


Figure 3 shows an arrangement where panels are not isolated by barriers and instead have reduced to manageable size by a line of stoppings. Areas of risk where heatings may occur in the goaf are shown. This assumes no interconnectivity from the surface, boreholes, or workings in another seam.

Heatings will only develop if inertisation is ineffective.

Figure 3 – Continuous miner interconnected pillars – hazards



4.3.3 Stowage (fallen tops & dumped coal)

A heating may develop in coal stowage or fallen top coal. Stowage can be likened to a surface stockpile where a heating develops. Conditions that favour the development of a heating in stowage include:

- Limited ventilation flow across the stowage or fall
- Height and mass of the stowage
- Ingress of moisture
- Ineffective inspection.

Long term storage of coal in a bin may self heat given the right conditions.

4.3.4 Rib Side Pillar

Pillar heatings, particularly where adjacent to ventilation stoppings, are generally caused by:

- High-pressure differential between intake and return airways and along a length of roadway.
- Fracturing in the rib side.
- Crushing of pillars.
- Presence of broken coal as accumulations or behind lagging.
- Flow of air to underlying or overlying workings.
- Air crossings with high differential pressures.
- Coals with high propensity.
- Leakage paths associated with cracks, cleat, fractures, faults, joints, friable seam bands, and unsealed boreholes.
- Box cut entries where the mine fan is located in the box cut and near the intake roadways result in high ventilating pressure in ground that may be damaged by blasting during construction of the box cut.

Shotcreting or equivalent sealing material is sometimes applied to control rib and roof stability and reduce leakage paths, particularly around return airway entries from box cuts, highwalls, drifts and shafts intersecting seams. The shotcrete is sometimes a contributing factor to either inhibiting the discovery of heatings by masking the heat present behind it, or reducing air leakage to a degree were oxygen is supplied but heat is not removed during oxidation of the coal. Cracks in shotcrete allow egress of air into the return airways from the intakes. These cracks in shotcrete require regular inspection for indication of changing gas emissions or radiation of heat.

Heating sites tend to be near and on the intake side of the stopping in the highest pressure difference area, i.e. closest to the mine entries. Such heatings may be difficult to detect until well advanced because of their relatively small size and the dilution of gaseous products by high volume airflows.

4.3.5 In-situ Coal

Heatings may occur in roof or floor coal that has been cracked or broken by convergence. Top coal or floor coal left in the mining process may be subject to heating under favourable conditions.

A heating has been known to take place in top coal in-situ in the roof. The coal was a few metres thick and subject to convergence and cracking. An adjacent area may have fallen, exposing one face of the tops to air ingress. The top coal fell and burst into flame. Edges of the roof fall from where the fall originated were hot enough to turn water from fire hoses into steam (Aberdare North Tunnel 1970).

4.4 HAZARD IDENTIFICATION

Matters that need to be addressed from the information collected and evaluated and in the identification of hazards that may lead to spontaneous combustion include the following:

4.4.1 Propensity to Spontaneous Combustion

Some coal seams have a higher propensity to spontaneous combustion than others. An evaluation of the liability to spontaneous combustion and an assessment of the hazards in a seam and mine environment should commence with tests on coal expected to be mined or affected by the mining operation.

Examples of scientific tests to determine coal properties relevant to spontaneous combustion include:

- Small scale tests such as the R70 and moist coal test (Beamish)
- Bulk testing of coal to simulate seam and goaf conditions
- Column tests to simulate gas evolution from coal as it heats

Refer to Table 1 for comparison of spontaneous combustion propensity.

Whilst tests are useful in determining propensity for self-heating, properties of the coal in the seam will vary in different parts of the mine and cannot be precisely simulated in the laboratory. A limited number of tests may not be indicative of the propensity for spontaneous combustion in all locations and conditions.

Figure 4: Adiabatic self heating curve

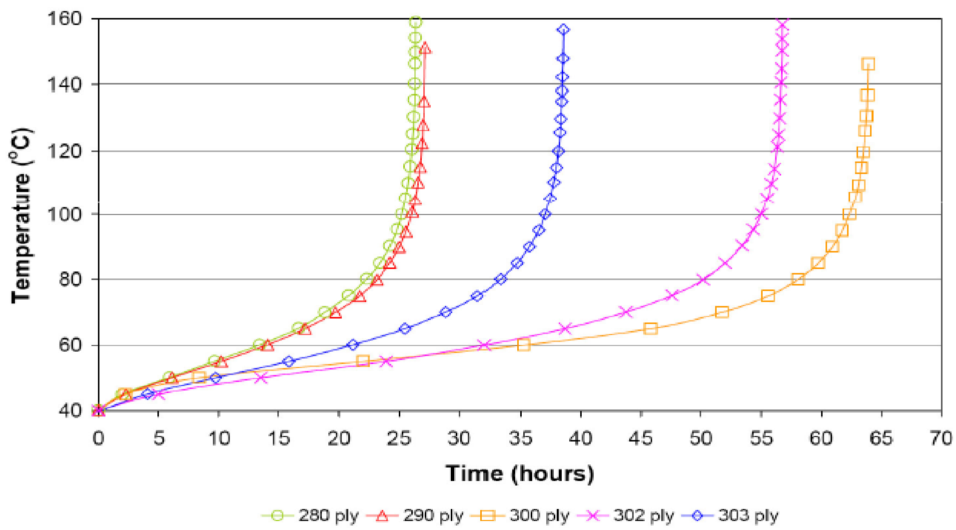


Figure 5: Self heating relationship with ash content and coal rank for Australian coals, showing intrinsic spontaneous combustion classes (chart courtesy of Bulga Coal)

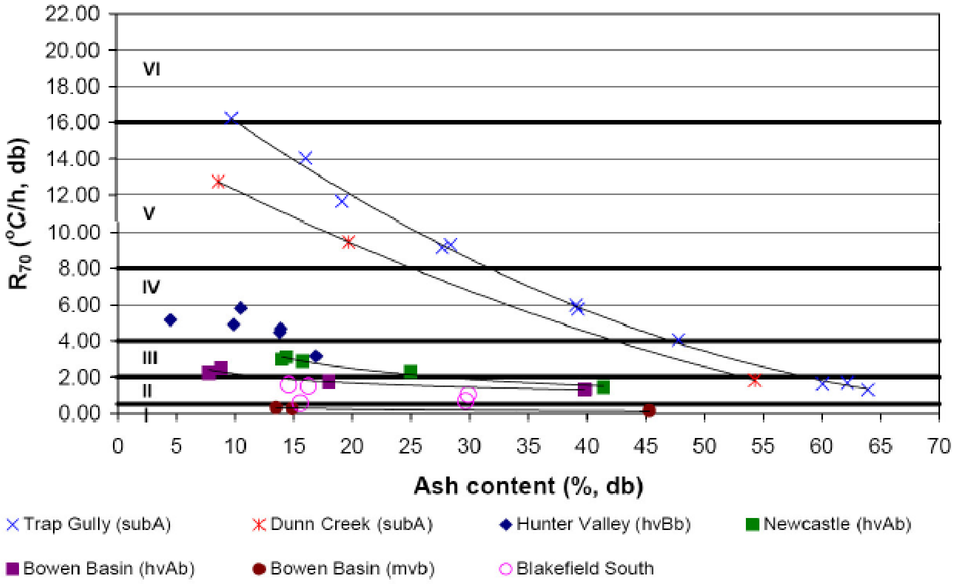


Table 1: Spontaneous Combustion Propensity Classification

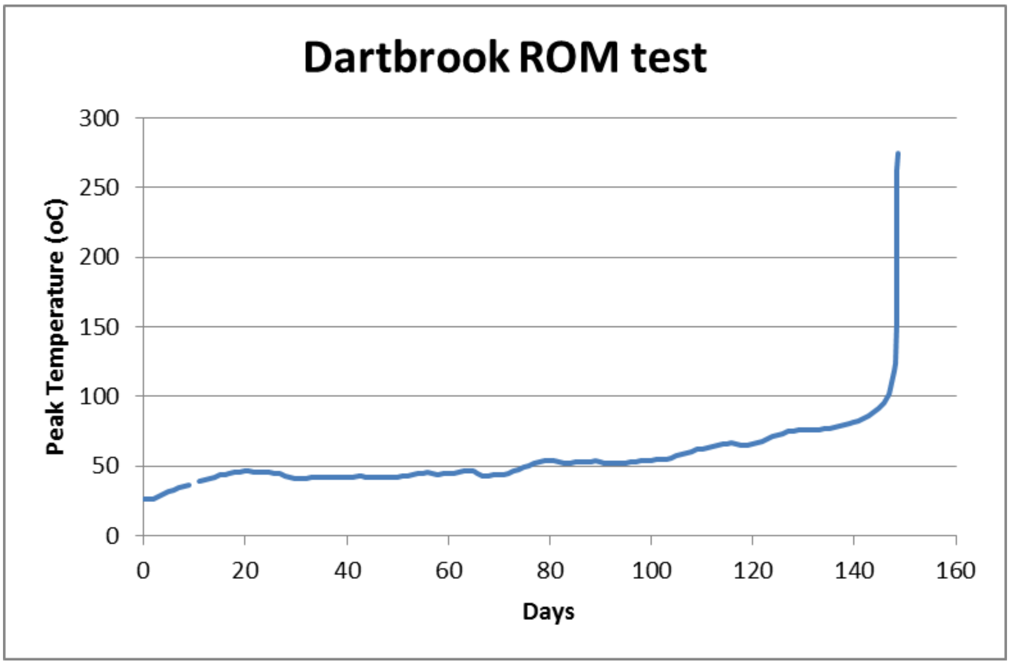
Intrinsic spontaneous combustion propensity classification (ISCP)
(based on Queensland and New South Wales coal conditions)

ISCP Class	Propensity rating	Queensland R_{70} value (°C/h)	New South Wales R_{70} value (°C/h)
I	low (L)	$R_{70} < 0.5$	$R_{70} < 1$
II	low-medium (LM)	$0.5 \le R_{70} < 1$	$1 \le R_{70} < 2$
III	medium (M)	$1 \le R_{70} < 2$	$2 \le R_{70} < 4$
IV	high (H)	$2 \le R_{70} < 4$	$4 \le R_{70} < 8$
V	very high (VH)	$4 \le R_{70} < 8$	$8 \le R_{70} < 16$
VI	ultra high (UH)	$8 \le R_{70} < 16$	$16 \le R_{70} < 32$
VII	extremely high (EH)	$R_{70} \ge 16$	$R_{70} \ge 32$

There is a different rating scheme used for New South Wales conditions and Queensland conditions. The two schemes are required to take into consideration the different start temperature conditions that exist in both settings.

Figure 6 is an example of a bulk sample test of coal in a large scale reactor. It shows a (very) rapid rise in temperature after being apparently dormant for several months. This test demonstrates that development and progression of spontaneous combustion is sometimes erratic and unpredictable.

Figure 6: Results of bulk heating test for Dartbrook coal



4.4.2 Coal Rank

Generally, as the rank decreases, the moisture and oxygen levels and volatile matter of the coal increases, and the carbon content decreases. It is generally accepted that the lower the rank, the faster the rate of oxidation and the greater the tendency to spontaneously combust.

4.4.3 Pyrites

Sulphur minerals, iron pyrite (FeS_2) and marcasite may be present in coal seams as veins of highly crystalline mineral or in a finely divided state throughout a seam. When present as veins, the surface area exposed to oxygen is relatively small and contributes little to any heating.

A significantly larger surface exists when these minerals are in a finely divided state, and are able to react with oxygen to produce heat and a product that has a larger volume. The heat produced from oxidation of the pyrite increases the temperature of the coal and the rate of oxidation, and the increase in volume causes fracturing of the coal that exposes a greater surface area for further oxidation. Generally, pyrite must be present in concentrations > 2% before it has a significant affect.

4.4.4 Ash Content

A lower value of incombustible matter generally means a lower propensity to spontaneous combustion. For a given coal the higher the ash content, the lower the R70 value.
However, if it is a reactive ash (mineral matter) such as pyritic or carbonate it can actually enhance the reactivity.

4.4.5 Coal Particle Size

During the mining process, coal is broken into fragments. As the coal breaks, the surface area is greatly increased; more coal surfaces are exposed to oxygen for oxidation to occur, and therefore an increased risk of spontaneous combustion. Common areas where broken coal may be found include:

- Around crushed ribs or pillars.
- Around seals and stoppings.
- In stowage.
- Goaves.
- Around conveyors.
- Floor heave.
- Faults and intrusions

4.4.6 Permeability

Highly permeable coals introduce other potential spontaneous combustion risks such as leakage paths through coal around gas drainage boreholes, seals, stoppings and even through pillars. Permeability may have a direction bias, i.e. be higher in some directions rather than others.

4.4.7 Effects of Moisture & Water

All coal has inherent moisture, the amount depending upon its rank. Coal seam moisture content also varies with the permeability of the seam and the degree of saturation. If moisture drains from a seam vacant space will be filled with gases.

Moisture can either remove heat or add heat, depending on the mine conditions. Evaporation of water from the surface requires heat – the latent heat of vaporisation. This heat is taken from the solid surface, cooling results, and causes a drop in temperature on the coal surface. This is the same principle as the cooling of a water bag.

On the other hand, if water vapour condenses on the coal surface, the heat of condensation (the opposite of vaporisation) causes a rise in coal surface temperature.

In stockpiles, the effect of rainfall may be to wash fines out of the coal. Pumping water into a goaf area, or other area where there may be broken coal has a similar effect. Ceasing to pump the water, and subsequently drying out, creates air leakage paths. Spontaneous combustion may be further facilitated by the heat released during the absorption of water into the coal. (This is thought to have been a significant factor in the development of a heating in the Great Northern seam at Wallarah Colliery)

A substantial make of water in a mine also serves to prevent and control heatings by covering broken coal in the goaf, and by reducing the gas volume in sealed areas, and thus reducing the ingress of air as a result of 'breathing' of the seals in response to barometric pressure changes.

Water build-up on seals may lead to increased pressure on the seals and the deterioration of the seals in the worst case, a breach of a seal may result in inrush of water or gas into the workings of the mine.

The effect of water accumulation in roadways is to increase ventilation resistance. This increase in resistance along the planned ventilation path facilitates the formation of new leakage paths in unwanted areas.

4.4.8 Seam Gas

Spontaneous combustion has occurred in mines with a seam gas and also mines without a seam gas. The consequences of spontaneous combustion in a mine with a flammable seam gas may be catastrophic and it is vital to prevent any fire in any mine.

Oxidation of the internal surfaces of coal will normally be delayed by desorption of seam gases into the mine atmosphere. This situation will tend to prevail as long as the seam gas pressure exceeds the mine atmospheric pressure. Desorbed seam gases may be used to develop inert atmospheres in sealed-off areas in the mine.

A major factor in reducing the risk of spontaneous combustion is the presence of moderate to high makes of seam gases. As the early stages of development of spontaneous combustion are highly sensitive to the availability of oxygen, any significant make of methane or blackdamp will reduce the chance of oxidation developing into a heating.

Gases will act to exclude oxygen from the area immediately adjacent to the face, and will restrict percolation of air into fractures and cavities. However, where a ventilation circuit exists across a goaf, through a length of fractured roof, or through a failed pillar, airflow will occur, seam gases will be diluted and heatings may occur. Where the gas make is inadequate to fill the waste, a particularly difficult situation may arise wherein a heating develops in broken coal on the floor in the goaf, while the upper section of the goaf is filled with methane, possibly in explosive concentrations.

The type of atmosphere that develops in a goaf and the explosive ranges of the various gases should be considered. Explosive gases including carbon monoxide, hydrogen and methane are produced by spontaneous combustion. The gaseous products of oxidation can create an explosive mixture that may be ignited by a heating.

4.4.9 Gas Drainage

Generally it appears that pre-drainage of gas from the coal may increase the likelihood of spontaneous combustion occurring. Gas drainage using negative pressures may contribute to the development of a heating by promoting a flow of air into a permeable coal seam or a mined out area. Ideally the rate of gas extraction should not exceed the desorption rate.

The hazard exists when the oxygen level in the drained mixture rises above 8%. Sampling of the drained gas should be practised to reveal any entry of oxygen and to determine the levels of carbon monoxide within the system.

Pre-drainage of the coal seam also removes much of the free water. The water is drawn out of the drainage holes with the gas flow. Drying the coal makes it more powdery which increases the dust generated during mining. This produces dry, more finely divided coal dust that may settle in the goaf. This increases the reactivity of the coal and consequently the likelihood of heatings. The removal of the water from the seam also increases the permeability of the goaf and increases the ingress of air into the seam.

4.4.10 Seam Thickness & Coal Recovery

The thicker the coal seam, the greater the area of coal surface exposed to oxidation and the more liable it is to spontaneous combustion.

Where the coal seam is too thick to be mined in one lift, top or bottom coal may be left in the goaf. This broken coal is prone to oxidation and heating.

For a given production rate, the thicker the extracted section, the slower the rate of face retreat and the greater the time available for oxidation of coal left in the goaf.

The volume of spalled and fractured coal along the sides of roadways and coal ribs increases with seam thickness which increases the potential for spontaneous combustion.

No mining system can guarantee total recovery of coal. Some remnant coal will be left in a goaf and may be liable to heating. The risk of heating in a goaf can be reduced by full seam extraction. Where this is not practical, mining the upper part of the seam, can reduce the amount of broken coal. If the bottom part of the seam is left in the goaf, heave and cracking of bottoms can still occur.

A risk may arise due to the crushing of longwall chain pillars. Airflow along the pillar edge may create conditions for a heating to develop. In continuous miner extraction areas, the extraction edge is less regular and ventilating pressure differentials in the face are usually lower. These factors result in a decreased risk of a heating. Should a heating be detected equipment can be more easily removed and the area sealed.

4.4.11 Multiple Seams

A seam split or another seam (above or below) may be exposed by the mining process and broken coal may be exposed to oxygen. These seams are often of poorer quality or not thick enough to be commercially mined, and yet may be the source of gas and broken coal in the goaf.

Where there are a number of overlying seams within a lease, there may be a risk of interconnectivity between workings and air movement between seams. Air movement will depend upon permeability and pressure difference.

Seams that are worked in close proximity are most at risk. The interval between seams that constitutes a risk is dependent upon the extraction thickness and other geotechnical factors.

Adjacent seams may be a hazard due to their propensity for spontaneous combustion and location etc.

4.4.12 Structures & Geological Anomalies

Structures such as faults, dykes, and open joints may be associated with zones of weakness that require extra support and reduce the rate of extraction. The slower the rate of extraction, the longer a particular area of coal is exposed to air. This increases the potential for spontaneous combustion. The probability of roof bed separation and cavities is increased with accompanying low airflow through the fractured strata. Roadside and rib spalling tend to increase in structure zones and may further increase the likelihood of spontaneous combustion.

Where a structure zone passes through a roadside or barrier pillar that is subjected to the differential ventilation pressure between intake and return, extra care must be taken to ensure that air leakage paths do not develop and increase the risk of spontaneous combustion.

Faults and intrusions become focal zones of increased stress and may require special attention.

4.4.13 Depth of Cover

The effect of seam depth is somewhat contradictory. Increasing depth will tend to reduce seam permeability due to increased pressure of the strata. Increased depth will mean that higher loads are redistributed to pillars and coal ribs, tending to increase fracturing and spalling of coal and therefore increasing the likelihood of spontaneous combustion.

Where extraction takes places at relatively shallow depths, interconnection between the surface cracks and above seam caving cracks or voids is possible with sufficient permeability to permit air circulation from the surface into the extracted area and mine roadways. Extraction thickness and strata types have an influence on interconnection.

There is a recorded case of a heating in a panel extracted by longwall where the depth of cover was 110m and the extracted seam thickness 3.8m. Steps should be taken to ensure closure of these cracks and to control these leakage paths.

4.4.14 Direction of Mining

The direction of mining and seam dip may affect the ability to efficiently inertise a goaf on the basis that ventilation problems are compounded (or created) by buoyancy effects in the goaf or along the roof in workings. If methane is the predominant gas given off in the goaf, mining to the dip will result in the buoyancy of methane causing it to flow to the upper end (start) providing efficient inertisation.

If the direction of mining is to the rise, methane may migrate towards the face and result in poor inertisation of the deeper areas of the goaf and an unwanted concentration of methane in the working area. On the other hand it may be considered beneficial to bring the gas fringe nearer to the face and into the location of maximum risk of oxidation and heating.

If carbon dioxide is the predominant gas given off in the goaf, this migrates to the dip side, providing effective inertisation if mining advances to the rise, and less effective inertisation if mining advances to the dip.

4.4.15 Extraction Systems

Full extraction and super critical systems leave less coal behind in the goaf, resulting in complete caving and consolidated areas where there is a low risk of spontaneous combustion. Longwall mining results in more complete extraction than continuous miner extraction.

Partial extraction may result in more coal and voids in the extracted area with a risk of spontaneous combustion in what would have been a consolidated zone if full extraction was practised.

Subcritical extraction systems designed to control surface subsidence may result in voids in the strata above the seam. Coal at this horizon may be at risk of spontaneous combustion. Tables 2 and 3 detail the relative risk of heating for various extraction systems.

Ventilation flow and inertisation of the extracted area are important factors.

The relative risk of spontaneous combustion for various mining systems is shown in the following tables:

Table 2: Relative Risk of Heatings - Continuous Mining Methods

Solid development (full seam thickness in one pass)	LESS RISK
Solid development (tops of thick seam)	
Solid development (middle or bottom of thick seam)	↓
Shortwall extraction (full seam thickness in one pass)	
Shortwall extraction (tops of thick seam)	
Shortwall extraction (middle or bottom of thick seam)	
Wongawilli extraction (full seam thickness in one pass)	
Wongawilli extraction (tops of thick seam)	
Wongawilli extraction (middle or bottom of thick seam)	
Pillar extraction by split and lift (full seam thickness in one pass)	
Pillar extraction by split and lift (tops of thick seam)	
Pillar extraction by split and lift (middle or bottom of thick seam)	
Wongawilli extraction in descending lifts (thick seam)	
Wongawilli system (top coal from bottom development)	
Partial extraction of pillars (full seam thickness in one pass)	
Partial extraction of pillars (middle or bottom of thick seam)	
Loading of top coal in thick seam after continuous miner development	
Random pillar extraction (full seam thickness in one pass)	MORE RISK
Random pillar extraction (middle or bottom of thick seam)	

Table 3: Relative Risk of Heatings - Longwall Methods *

Retreat Mining (full seam thickness in one pass)	LESS RISK
Retreat Mining (in tops of thick seam)	
Retreat Mining (in middle of thick seam)	↓
Retreat Mining (in bottom of thick seam)	
Retreat Short Longwall (full seam thickness in one pass)	
Retreat Short Longwall (in tops of thick seam)	
Retreat Short Longwall (in middle of thick seam)	MORE RISK
Retreat Short Longwall (in bottom of thick seam)	

* Risk will increase with wider longwalls due to relative rates of retreat

In longwall workings there are voids along the edges of the goaf adjacent to ventilated roadways where fresh air can intrude and flow if the goaf is not efficiently contained and inertised.

Areas where voids in the goaf exist and the likelihood of the development of heatings increase are:

- Face Start Line - air may percolate into the original face start line. This may be due to the high standard of support in this installation roadway.
- Face Finish Line - This is controlled by rapid salvage of face equipment and by design of adequate final barrier pillars. The risk may arise if face recovery is delayed by equipment failures, industrial action or mining conditions.

4.4.16 Highwalls & Box Cuts

Punch or highwall mining may increase the risks of spontaneous combustion developing due to the effects of open cut blasting, pre-splitting and endwall stress effects, and subsequent highwall slumping, causing mining induced fracturing.

These effects may exacerbate any pre-existing geological anomalies in the near vicinity of the highwall, such as faults, joints, and cleat. The results are potential air leakage paths in the near highwall area from either highwall face, or surface, or intake to return, airways.

4.4.17 Ventilation Pressure Difference

A pressure difference between two areas in a mine will cause air to flow from the higher to the lower pressure area. The amount of air that flows along each path depends upon the resistance to flow. This can result in unplanned ventilation flows and air leakage.

High ventilation quantities and pressure differential may result in air leakage into or from a sealed area or through or around pillars which will increase the risk of spontaneous combustion. A good example of this is the pressure difference between an active longwall face and the ventilated gate road alongside the goaf of the active longwall, especially if it is a return.

4.4.18 Abutment Load & Pillar Crush

Excessive pillar yield may result in air being able to be drawn through the pillar by ventilation pressure differential.

Yielding pillars or 'sacrificial roadways' may be designed in order to prevent heave in the maingate and to improve conditions at the face end. These should not be used in areas with a moderate to high propensity for spontaneous combustion unless adequate investigation and design work is carried out on the ventilation aspects of the design.

Pillar heatings have been encountered between intake and return airways, often near pit bottom. They are normally associated with crushing of pillars or other mechanisms such as high ventilation pressure difference and open joints that create potential flow paths.

The abutment load from extraction areas will be carried on surrounding pillars. Roadway convergence near stoppings may cause leakage to occur and result in poor inertisation of the goaf.

4.4.19 Reduced Extraction Rate &/or Unplanned Disruption

Continuance of a rapid rate of retreat ensuring that coal in the goaf is sealed or immersed in an inert atmosphere before accelerated oxidation occurs, is an effective means of preventing spontaneous combustion in a goaf.

An unplanned disruption to mining, or significantly reduced extraction rate could result in an increased risk of spontaneous combustion. These events can occur due to geological & geotechnical factors, industrial action and slowness in moving a longwall after panel completion.

Means to increase the rate of retreat include:

- Reschedule planned maintenance
- Operate weekend shifts that may not be planned for production

4.4.20 Extracted Areas

Goaves are a potential source of heating if not sealed. Ventilation may be such that the oxygen supply is adequate to promote oxidation but the cooling effect is inadequate to prevent heating.

Where goaves are sealed, there may be a risk of a heating where there is leakage of air through or around seals, and a high pressure differential exists. There will be no effect in the deep-seated regions but areas near sealing sites may be continually supplied with oxygen from barometric pressure fluctuations.

4.4.21 Barometric Variations

Flow into sealed areas results not only from differences in the mine ventilating pressure, but also from the large volumes of such areas, affected by barometric changes creating inflow and outflows.

Barometric changes may range from about 960 to 1040 millibars and rapid changes in barometric pressure can occur as a result of storm activity. This represents a change in absolute pressure of 8Kpa, which is significantly greater that the pressure differential at which mine fans typically operate.

The rate of change has the greatest influence. This pressure differential acts on the seals in a mine. Well-constructed seals and surrounds can act to restrict the volume flowing and retard the changes in sealed areas by reducing the effects of peaks and troughs in the barometric pressure fluctuation.

4.4.22 Integrity of Stoppings & Seals

Stoppings and seals that allow significant leakage will prevent efficient inertisation of the goaf. Matters to be considered in the design of goaf edge stoppings and seals are detailed in 5.7.

4.4.23 Boreholes & Wells

Unsealed boreholes or wells may provide a conduit for air to flow from the surface into a goaf area, or allow the atmosphere in the goaf to flow to the surface.

Boreholes placed in areas affected by subsidence pose a risk, even if not drilled all the way to the coal seam.

4.4.24 Accessibility of Roadways Adjacent to Goaf for Inspection

If the roadway adjacent to the stopping or seal becomes inaccessible there is the risk of a damaged and leaking stopping and the non-detection of a heating. If a stopping or seal is to be relied upon to contain and inertise a goaf, then its integrity should be able to be confirmed by periodic inspection.

4.4.25 Integrity & Effectiveness of Monitoring System

Detection of increasing levels of oxygen in goaves and early signs of heating will rely upon effective monitoring and inspection systems. The location and number of monitoring points is critical to the effectiveness of the system.

If the monitoring and inspection system is not properly designed, implemented and maintained, there is a risk that spontaneous combustion will not be detected until a serious problem develops.

Sample turnaround time is a factor. If the information is not provided promptly, decisions and corrective action may be delayed.

4.4.26 Reporting & Tracking of Information

Recording of results of inspections and historical data is important as is the review and action as a response to this information. Information recorded should be specific in terms of the time, location, quantities etc. if it is to be of value.

Inspections missed, or inadequate interpretation of information is a hazard.

Integral to a comprehensive and effective reporting system is an audit & review process to provide checks and balances in the mine's stated controls for spontaneous combustion.

4.4.27 Sample Turn-around Time

The time taken to analyse and interpret a sample taken from and heating site has delayed decision making in a number of spontaneous combustion events (refer to "Events" in the Appendices). This is a factor where the analysis has to be carried out remote from the mine site.

4.4.28 Surface access

Access may be required to surface areas of the mine for the purpose of monitoring, or remedial action in the event of a heating. This needs to be considered for an effective and prompt response to an incident.

5 PREVENTION

5.1 MINE PLANNING PROCESSES

5.1.1 Research & Collection of Information

The following information should be collected, evaluated and considered in the development of a spontaneous combustion hazard management plan.

- A comprehensive mine plan showing seam contour, seam dips and water collection areas should be collected as an aid to spontaneous combustion management and gas behaviour.
- A detailed and precise description of the mining method and any "recent" changes to the mining method should be made. The presence and amount of slack coal in the goaf should be determined as this material may alter the spontaneous combustion risk. Rib spall and other signs of broken or failed strata containing coal or carbonaceous shale should be noted. Regional stress and depth of cover should be noted.
- A comprehensive ventilation plan showing all aspects of the ventilation system should be collected. Ventilation quantities should be determined. Pressure differentials should be noted, particularly across and around sealed areas. Gas composition in ventilation currents should be noted and any changes monitored.
- The progressive history of seam gas (and gas from other sources) should be collected and collated. The desorbable gas content of the seam should be determined. Gas sources from the roof and floor following the breaking of surrounding strata should be noted.
- The development and nature of atmospheres within sealed areas of the mine should be determined. These measurements should apply to panels where spontaneous combustion has developed and also to those panels where it did not. Comparison of results may be vital in understanding how, why and where events may occur.
- The nature of gases in existing sealed area atmospheres should be taken, any changes in these should be monitored.
- An assessment of the development of explosive atmospheres within the mine should be made. This would include ventilation currents, goaf areas and sealed areas.
- Trending of all gas measurements should be conducted.
- The condition of all seals to extracted areas should be determined, the method and materials of construction should also be noted. The effectiveness of sealing should be determined or estimated. The location, depth, diameter and condition of Boreholes to the surface including the nature of sealing and/or capping. The incidence of subsidence cracking should be noted.

5.1.2 Impact of Other Mine Site Hazards

The Spontaneous Combustion hazard must be managed in conjunction with other hazards at the mine. Optimum prevention measures may not be able to be implemented because of the need to control other hazards and adapt to other constraints.

Examples of hazards that need to be managed and constraints that require special consideration are:

- Requirement for gas drainage to control outburst or high gas levels
- Working of multiple seams, particularly those within close proximity
- Need to control surface subsidence and limit extraction width
- Shallow workings
- Working of thin seams or seams remote from entries that require higher ventilation pressures
- Presence of seam structures
- Size and shape of coal lease

The process for mine planning should focus on the need for management of all hazards together with the provisions that need to be implemented to control spontaneous combustion in the circumstances at the particular mine.

5.1.3 Measures to Prevent Spontaneous Combustion

Mine planning processes to prevent spontaneous combustion include:

- Type of extraction & percentage extraction for each type
- Extraction thickness to be mined from the seams
- For continuous miner extraction panels, design to provide barriers on both sides.
- For longwall panels, reducing the number of goaf entries to be contained.
- Extraction of as much of the coal seam as possible
- Consideration of the risks of permeable subsidence cracks when mining under shallow depth of cover
- Minimum number of entries to panels with provision for rapid sealing
- Controls on stowage of material in roadways
- Controls on accessibility of roadways alongside goaf areas
- Eliminating restrictions in roadways to reduce airflow resistance and pressure difference
- Maintenance & quality control of ventilation structures and operation
- Ventilation system & pressure difference in various locations
- Systems to balance pressure on seals where required
- Avoidance of main intake and return entries in proximity to a box cut or entries in shallow cover
- Control of mine water removal and placement
- Provision for inertisation of extracted areas

5.2 MINE DESIGN

5.2.1 Behaviour of the Atmosphere in the Longwall Goaf

As the active longwall panel retreats, oxidation takes place in the area behind the face until the goaf is inertised by containment, seam gases and goaf consolidation. The distance into the goaf from the longwall face in which oxidation takes place varies and depends upon these factors and particularly barometric changes. Frequent and significant changes in the barometer can pump fresh air a considerable distance back into the goaf.

In the oxidation area, CO and CO_2 will be produced. At the inbye end of the goaf where inertisation is effective, CO should not be detected.

The ACARP Project report C12020, "Proactive Inertisation Strategies and Technology Development" - Rao Balusu, Ting X Ren and Patrick Humphries Dec. 2005 contained a Computational Fluid Dynamics (CFD) base model of the atmosphere within a longwall goaf prior to any inertisation. A number of scenarios were modelled with varying results.

Figure 7 shows one scenario; the goaf atmospheric oxygen in a longwall with a face ventilation flow of $50m^3/s$, MG intake 20m lower than the TG return and goaf gas emissions of 600 l/s. There does not appear to be any allowance for barometric variations.

Results show that oxygen ingress into the goaf was high with oxygen levels on the maingate side well over 14% at 350 m behind the face and over 10% even at 600 m behind the longwall face.

Analysis showed that intake airflow and ventilation pressures seem to have a major influence on gas distribution up to 50m to 150 m behind the face, and beyond that, goaf gases buoyancy seems to play a major role on goaf gas distribution.

Figure 7: CFD Model of Goaf Atmosphere

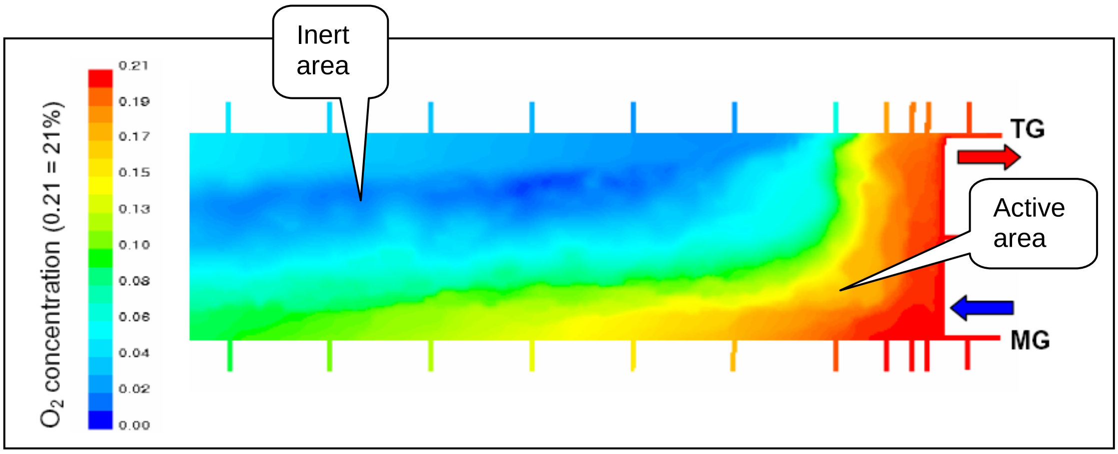
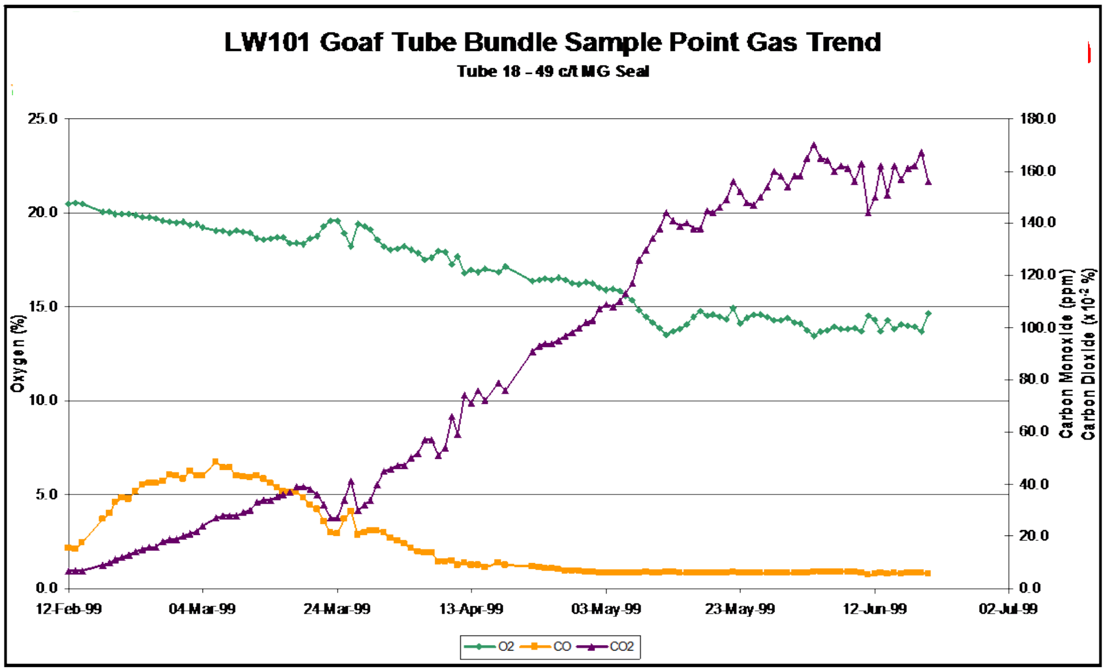


Figure 8 shows the changing goaf atmosphere as the longwall retreats away from a fixed sampling point and demonstrates that the atmosphere eventually becomes inert. Oxygen reduces, carbon monoxide initially increases due to oxidation, and then reduces as the face retreats and oxygen decreases.

Figure 8: Goaf atmosphere analysis as Longwall retreats



5.2.2 Control Measures for Longwall Extraction

Control measures in longwall extraction include:

- Enclosing the goaf as the longwall retreats with effective seals.
- Minimising pressure differential across the goaf.
- Maintaining a constant rate of longwall retreat.
- Prompt recovery of longwall equipment at panel completion.
- Monitoring of longwall tailgate goaf atmosphere as the longwall retreats.
- Monitoring of goaf atmosphere adjacent to the ventilated roadways
- Inspection of seals, longwall return and goaf edges.

In an active longwall, the goaf alongside the working area cannot be enclosed and there is a risk of spontaneous combustion developing should there be a protracted face delay. Reliance on the incubation period and rate of retreat is the normal control.

The time taken for a heating to develop (incubation period) is unpredictable and variable. It depends upon factors such as the properties of the coal and environmental conditions. This requires consideration of provision for inertisation and rapid sealing in the event of a protracted production delay which results in a heating.

Acceleration of the rate of extraction by extending operating time is a control that has been used for many years in both longwall and continuous miner extraction.

The system shown in Figure 1 is most common for Australian longwalls. Bleeder roads have the advantage of ventilating the future tailgate for the successive longwalls and avoiding the drivage of single entry development for gate roads. They do provide a risk of air passing into the goaf from the adjacent bleeder road if containment and inertisation is not effective.

An option for a longwall mine with a high propensity for spontaneous combustion is to drive single entry roadways either side of the block, or to leave barriers between sets of gateroads.

5.2.3 Control Measures for Bord & Pillar extraction

Similar to a longwall, spontaneous combustion is controlled by:

- complete caving,
- effective inertisation,
- a regular and progressive extraction rate,
- minimisation of pressure differentials across sealed areas,
- inspection and maintenance of seals and seal sites to reduce air leakage, and
- sampling and analysis of sealed area atmospheres.

Figure 2 shows a most effective system of containment of the goaf. The panels are of such a size that extraction will proceed reasonably quickly and there are only three entries into the extracted area that will need to be sealed on panel completion. This would be appropriate where there is a high propensity to spontaneous combustion.

In some circumstances it may not be possible to plan continuous miner extraction panels as in figure 3. There may be pillars already formed from earlier workings or there may be other constraints on mine planning. Large areas of pillars can be reduced into manageable panels by placing stoppings such that the panel width is reduced and there are a minimum number of entries to seal off on completion, or prior to completion in the event of a heating.

Figure 3 shows a method of dividing a large area into a number of smaller panels that are capable of being isolated quickly in the event of onset of spontaneous combustion. A number of variations to this theme are possible. The extent to which panels need to be reduced in size and barriers provided for isolation depends upon the propensity for spontaneous combustion and the efficiency of Inertisation.

5.3 MULTIPLE SEAMS

Where overlying seams lie within the influence of mining, migration of air from one seam to another and into sealed areas may cause spontaneous combustion. Balancing of pressure between seams and sealing of strata cracks are controls (5.5.1 & 5.5.2). Flooding of lower seams is most effective.

5.4 VENTILATION SYSTEM

Ventilation design tools to prevent spontaneous combustion include:

- Reducing mine resistance and ventilation pressure
- Providing a high standard of stoppings and seals & roadway support
- Using low flow/ low pressure drop roadways alongside goaf areas

- Using balance chambers to contain sealed areas
- Injecting inert gases into balance chambers
- Providing for inertisation or flooding of goaf areas

There should be a process in place for reviewing the potential impact on the spontaneous combustion risk prior to significant ventilation changes being implemented.
Ventilation systems that minimise pressure differentials across goaves or waste workings and along roadways adjacent to a goaf reduce the spontaneous combustion risk.

The simple 'U' system of ventilation is considered to be the most effective in preventing spontaneous combustion in longwall workings. However, this has a disadvantage in the return airflow passing alongside the adjacent goaf. Leakage through stoppings in this area will generate an induced airflow through the goaf, which may lead to a heating.

5.4.1 Pressure Difference

Placing values on the pressure difference across a goaf and along a roadway adjacent to a goaf is important in setting a standard for the mine that reduces the risk of spontaneous combustion.

A low pressure difference across a goaf can significantly reduce leakage through seals and stoppings. Setting values is important to establish a standard for the mine.

Values are dependent upon the circumstances in the mine and may include:

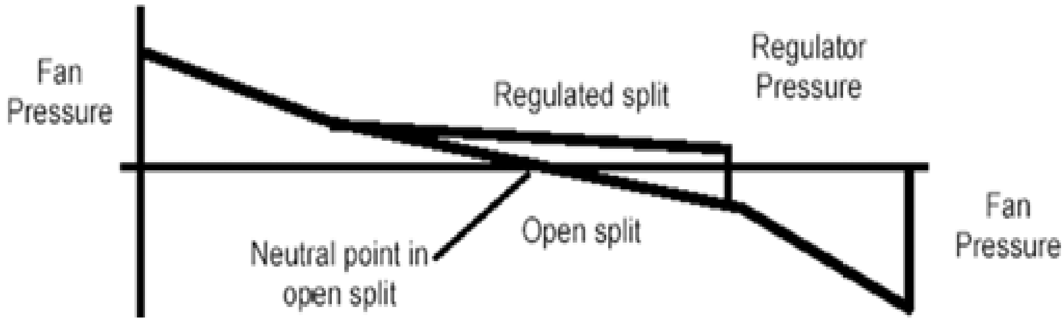
- Extracted seam thickness
- Length of longwall block
- Number of access roadways
- Standard of stoppings and seals
- Gas make in the goaf
- Pillar and seal stress environment/regime

Reducing the pressure difference is not the only control adopted for prevention of spontaneous combustion. The impact of barometric variations is significant and values most often exceed the pressure difference across a goaf. Reliance on minimising leakage is dependent upon the standards of seals.

Blakefield South mine in the Hunter Valley area of NSW has adopted an innovate approach to the control of spontaneous combustion and the risk of air leakage from the surface to seams above and within the currently mined seam.

The mine's primary ventilation system incorporates a pressure balancing (force-exhaust) ventilation system. Refer to Figure 9. The "neutral point' and pressure difference between seams and the surface are controlled by varying the duty of the forcing and exhausting fans.

Figure 9: Pressure drop and neutral point for force-exhaust system



5.4.2 Balancing Pressure

Balancing the pressure across a group of seals enclosing a goaf is an effective technique to minimise air movement in and out of the goaf. Techniques include balance roadways and balance chambers.

The need to balance pressure can arise where there are a large number of seals enclosing the goaf and/or there is high airflow and significant pressure differences in the ventilated roadway adjacent to the seals.

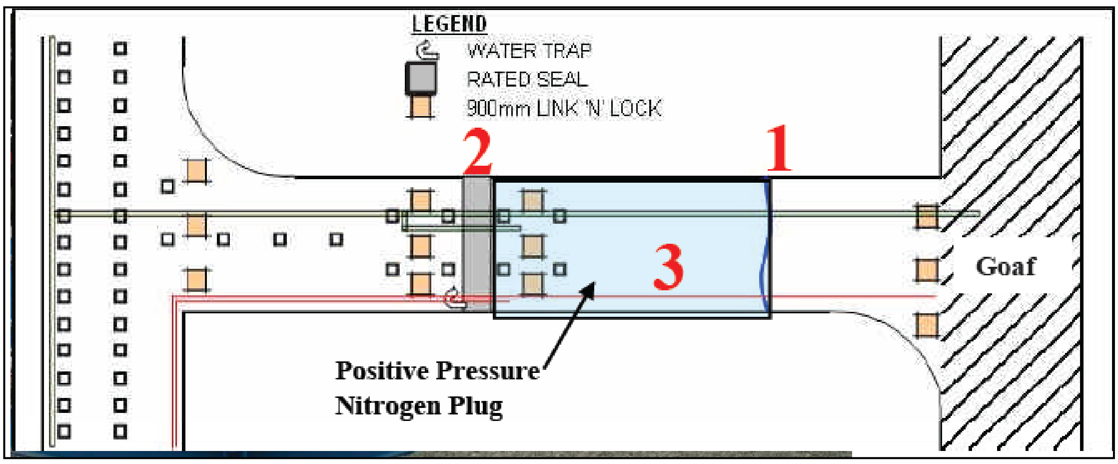
A dedicated roadway alongside the goaf with a low airflow and low pressure differential will assist to balance pressures across a number of goaf seals.

Balance chambers can be constructed by placing two seals in the roadway alongside the goaf. Chambers can be balanced with one another by means of the following:

- A pipe line connected into each chamber
- Surface to chamber boreholes
- Pressurising each chamber with a vent fan
- Pressurising each chamber with an inert gas.

Austar Coal mine in NSW makes use of a technique that effectively prevents leakage of air into the goaf as detailed in Figure 10. The goaf is contained by constructing two stoppings in each access roadway. The area between the two stoppings is pressured by piping inert gas from a unit located on the surface.

Figure 10: Goaf seal arrangement with balance chamber



5.4.3 Ventilation Monitoring

Monitoring of the ventilation to determine if the ventilation performance is matching the design intent is good practice.

Monitoring of pressure differentials is particularly important in detecting changes in roadway resistance, goaf containment and air flow into goaves. Routine monitoring of pressure differentials is recommended.

Readings should be recorded and trended to identify issues of concern. Consideration should be given to inclusion of ventilation measures in TARPs.
Real time recording of ventilation quantity in a Control Room is of value in determining CO make.

5.4.4 Seam Gas emission management

High levels of seam gas may require large air quantities to dilute the gas thus generating significant pressure drops across the face and increased air ingress into the goaf.

5.5 INSPECTION & MONITORING

An effective inspection and monitoring system will detect early variations from the planned ventilation and gas management values and assist in the prevention of spontaneous combustion.

5.5.1 Access to Stoppings and Seals

Where there are stoppings and seals containing a goaf they should be inspected regularly in accordance with a plan. The sites may also be required to sample the atmosphere in the sealed area behind the seal.

Roadways adjacent to seals and stoppings and cut-throughs where seals are placed should be kept in an accessible condition at all times Figure 11.

A fall in the access roadway or the dumping of material in the roadway can result in the following consequences:

- Damage to seal or convergence not discovered
- Inability to sample atmosphere behind seal
- Inability to transport materials to site for repair of seal or roadway
- High resistance in roadway causing air movement into goaf
- Development of spontaneous combustion

5.5.2 Monitoring of Seals

A register of seals should be kept with details for each seal of:

- Seal type and date constructed
- Secondary support placed both sides of the seal
- Sample pipe, water traps & injection pipes placed in the seal
- Seal condition on inspection & date
- Roadway condition on inspection & date

- Evidence of abnormal leakage
- Evidence of water build up
- Repairs affected

Seals should be regularly inspected and samples taken of the atmosphere behind the seals on a periodic basis. The interval should be based on past performance and risk.

Figure 11: Stowage against goaf stopping impeding access

5.6 VENTILATION CONTROL DEVICES (VCD's)

All VCD's will leak because of the limitations on seal construction, coal permeability, convergence, and the pressure difference created by the mine ventilation system or fluctuations in the barometric pressure. Installation of ventilation structures to a high standard with measures to minimise roadway convergence will reduce the leakage and provide for effective natural goaf inertisation.

Matters to be considered in the design of goaf edge stoppings and seals include:

- The environment in which stoppings and seals are placed
- The permeability of the coal seam
- Designing chain pillars to be stable and not subject to excessive spall
- Overpressure resistance
- The reduction of gas leakage from within the extracted area
- Stopping or seal construction type
- The location of ventilation structures in a stable area (mid pillar)
- Support of the stopping or seal site to minimise convergence due to abutment loads
- Provision for sample pipes and inertisation
- Protection against water build up behind the seal
- Inspection to confirm stopping & seal integrity.

A number of stopping types are available for use. Some types are stiff and can resist strata movement but are susceptible to cracking. This results in air leakage through the stopping. Other stopping types will yield without cracking but allow strata movement with resulting air leakage through the strata.

A common issue with some stopping types is poor sealing and adhesion between the stopping and the roof, sides or floor because of the thickness of the stopping and irregularities in the roadway profile. An example of a stopping type that deals with this issue is the "Micon". These stoppings have a polyurethane core between two layers of cement blocks which penetrate fissures and the brick joints which provides an excellent bond between roof, ribs and floor. Micon stoppings are able to withstand considerable convergence without cracking, but are not "stiff" enough to control roadway convergence. Figure 12 shows convergence in a gateroad. Secondary support may be required. Active support is better than passive support.

If goaf stoppings and seals are constructed to a high standard, leakage of gas into the adjacent bleeder roadway will be reduced even with significant barometric change. This allows the ventilation quantity required to dilute the gas in the adjacent roadway to be reduced. A reduction in air quantity results in a reduction in ventilating pressure along the roadway and across the goaf and the risk of spontaneous combustion. It is good practice when constructing a seal to first inject the surrounding strata with a quality sealant.

In many cases it is not leakage through the stopping or seal that is the problem but the leakage around the sides, under and over the VCD. The coal in these zones is usually fractured and when a pressure differential is applied across the cracks, cleat planes, floor heave or roof convergence air will pass into or out of the sealed area or between intake and return.

If the rate of leakage is unacceptable roadway convergence and fracturing can be corrected by:

- Additional support
- Strata injection or
- Strata sealing

Strata injection is usually more effective than strata sealing.

Figure 12: Roadway convergence

The above photograph shows a roadway that has undergone convergence, been re-supported and is now stable. There will obviously be voids in the roof and ribs, resulting from the convergence, that allow the movement of a significant quantity of air across a stopping or seal placed in the roadway. Strata injection or sealing of the strata is necessary in these circumstances to provide effective containment.

Because seals (other than water seals) cannot prevent air flowing into a sealed area certain precautions must be taken when siting and constructing seals. Seals should be sited only in areas of unbroken coal where limited surface area will be presented to the airflow. As the rate of oxidation is related to surface area this will decrease the risk of heating.

Where coal is broken and no other suitable site is available, strata around the stoppings should be grouted to seal cracks and fractures. Seals should also be sited in large pillars or in solid coal to ensure that airflow cannot occur through a pillar. Coal seams with high permeability and roadways with convergence require special consideration for the design of seals and seal sites.

5.7 CONTAINMENT & INERTISATION

Natural inertisation of the atmosphere within the goaf takes place through oxidation of carbonaceous material and displacement by seam and strata gases. The oxygen content should be 2% or less for oxidation to cease.

In seams where the coal is highly reactive and/or there is liberation of significant quantities of gas into the goaf from the strata, remnants of seam mined or seams above or below, inertisation can occur quickly. Where the coal is not very reactive and there is little or no seam gas, this process may take some time.

The natural inertisation process can be assisted by adding inert gas such as nitrogen or carbon dioxide, or by making use of methane that is rendered inert because of its concentration as further discussed in Section 7.4.

Inertisation of an extracted area requires stoppings and seals to be placed in access roadways to contain the inert gases and to prevent other sources of air ingress from above and below the seam. Sources where air ingress may take place include:

- Workings above and below the seam, particularly extracted areas where strata may be disturbed and cracked due to subsidence effects.
- Uncapped surface to seam boreholes
- Exploration or service boreholes that may be capped but are within the subsidence affected zone
- Water bores
- Shallow workings and subsidence cracks

In an active extraction panel, containment of the goaf alongside the working area is not possible. Reliance is placed upon the incubation period to prevent the risk of spontaneous combustion. The rate of advance of the extraction unit and the development of caving is usually enough to prevent the development of heatings. Additional controls may include monitoring and provision for inertisation.

Extraction systems that use partial ventilation through the goaf should be avoided. Ventilation of all parts of the goaf is difficult to achieve and can't be verified.

Where gas make in a seam is very high and attempts at containment result in an unacceptable increase in gas in surrounding roadways, consideration may be given to the release of the gas to reduce the pressure within the goaf. Gas wells placed near the edges of the extracted area are a viable option. The risk of spontaneous combustion must be considered in conjunction with other major hazards at the mine and a total systems approach adopted.

The best form of inertisation of the extracted area is flooding. This excludes oxygen and cools any incipient heating. Other inertisation methods reduce oxygen but do not cool the heating site.

An option to reduce goaf void space is the introduction of water, inertisation gases, and fly ash slurries or washery slimes.

5.8 SEGREGATION OF PARTS OF THE MINE

In a mine that is prone to spontaneous combustion, extracted areas should be segregated so that they are of manageable size. Consideration should be given to limiting the length of longwall panels, the number of openings into the goaf and the number of successive long wall panels to avoid large numbers of stoppings being required to contain the goaf. The number of successive extraction panels could be reduced by leaving barriers periodically.

Even with a high standard of stoppings and seals, there is a limit to the size of the containment area. If a large number of stoppings and seals are relied upon to contain the area and allow it to inertise, there may be difficulty in lowering the percentage of oxygen in the sealed area to safe levels. Even seals constructed to a high standard will leak. The combined leakage from a large number of seals may not be offset by the natural inertisation processes. Another reason for segregation is to rapidly seal parts of a mine where a heating may develop.

Mines should assess the need for segregation that is supported by a risk management approach.

5.9 CONTROLS ON STOWAGE

Accumulations of carbonaceous materials in roadways should be avoided. Such accumulations may come from fallen top coal, dumped material or convergence in top or bottom coal.

This material is best cleaned up and removed from the mine. Where this is not a practical option, the material can be stowed underground in a manner that controls the risk of spontaneous combustion, i.e. by sealing in specially driven roadways, or by spreading in thin layers along the roadway and compacting.

The dumping of stowage material, carbonaceous or not, against stoppings and seals enclosing the goaf is be avoided. Stowed material in these areas will impede inspection, sampling and repair of stoppings and roadway surrounds.

If stowage must be placed underground and the roadway is not to be sealed, it should be placed in such a manner that it is ventilated and can be inspected easily without a person having to crawl over spoil heaps.

5.10 PILLAR DESIGN

Pillars where stoppings and seals are to be placed to contain a goaf should be designed so that they are stable when subject to abutment loading. Rib spall and convergence make it very difficult for stoppings and seals to provide effective containment. Properly supported roadways and stable pillars are important.

The design of pillars involves the selection of dimensions and geometries which will ensure that when the pillar is fully loaded, yielded zones on the sides of the pillar remain separated by a competent core of confined, high strength material.

The extent of the yield zone can be controlled by sound pillar design and by the installation of adequate rib support to ensure the yielded material remains partly confined.

Rib side pillar heating risk can be minimised by maximising the separation of intake and return airways near pit bottom, minimising the number of cut-throughs in this area, and by driving multiple roadways for both intake and return airways to minimise the pressure drop along the length of a pillar.

5.11 BOREHOLES & WELLS

Boreholes, if not required for further use, should be filled using a method that ensures the hole is completely filled without air gaps. Details of the driller, process used to fill the hole and company supervision etc. should be recorded.

A register of boreholes, wells, or gas wells placed anywhere in the lease should be kept with the following information:

- Location
- Depth
- Diameter
- Condition as at date
- Purpose
- Capped/ uncapped/ filled
- Driller & drillers log

Boreholes placed within the area of the subsidence effects of a goaf should be monitored to ensure that air is not passing into the goaf. The flow from gas wells may reverse at some stage when gas pressure in the goaf reduces.

6 DETECTION

6.1 IMPORTANCE OF EARLY DETECTION

Early indication of the onset of spontaneous combustion will most often provide time for action to be taken to control the heating before the need for people to be withdrawn from the mine.

There has been debate about the incubation period for spontaneous combustion and its value as a control method. Reliance on a specific incubation period is problematic.

Detection of a heating in the early stage of the incubation period is very difficult. The length of the incubation period will depend upon environmental conditions as well as the properties of the coal. Panels at Moura No.2 were designed to be completed within 6 months as a control against spontaneous combustion. The time taken for development of the heating that led to the explosion was less than this period.

While the oxidation process occurs at relatively low temperatures, a heating may not be detected until the temperature reaches 2 or 3 times the ambient temperature.

While gaseous indicators of spontaneous combustion such as CO and CO_2 are commonly not given off until about 30-45^0 C from some coals, reactive coals may produce large quantities of these gases at similar temperatures.

Experimentally H_2 has been shown to be given off at temperatures below 100^{0}C and C_2H_4 at 100-120^{0}C. These temperatures are approximate and will vary for different coals. The use of modern detection techniques now allows traces of these gases to be detected sooner in the self-heating process.

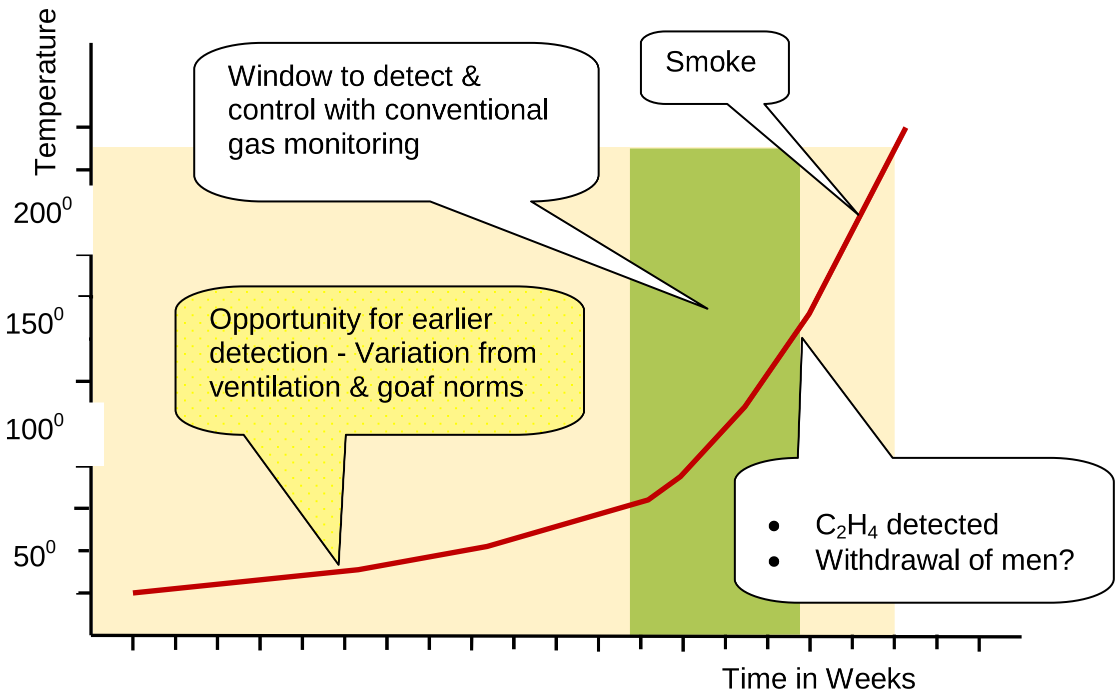
As temperatures exceed those required for the evolution of gases such as ethylene, the situation is rapidly approaching thermal runaway and would be at the stage where the mine goaf spontaneous combustion TARPS will require withdrawal of people.

It is important to realise that all the time taken for a heating to develop to a dangerous stage is not available because there is no way to be certain when the heating has started. Time will elapse before the heating is first detected. Only the time from when the heating is first detected to when men must be withdrawn is available for effective action. This may be weeks or even days depending upon the coal type and environmental conditions.

Early warning techniques include detection of a rise in oxygen in a sealed area and unplanned changes in ventilation pressure and flow. These techniques may provide an opportunity for early warning of spontaneous combustion rather than waiting for the detection of products of combustion.

Figure 13 shows the relatively small window of opportunity to detect and control a heating if reliance is solely upon detection and interpretation of gaseous products of spontaneous combustion.

Figure 13 – Incubation period of a Heating



6.2 GAS EVOLUTION TESTS

Gas evolution tests are useful in determining the behaviour of the coal as it heats and the development of gaseous indicators for early detection and use in TARPS. These tests may be performed using small scale or bulk scale techniques.

The following figures 14, 15 and 16, show the “fire ladder” or hierarchy of development of gases during the development of a heating for several different coals.

Figure 14: Fire ladder for Moura coal

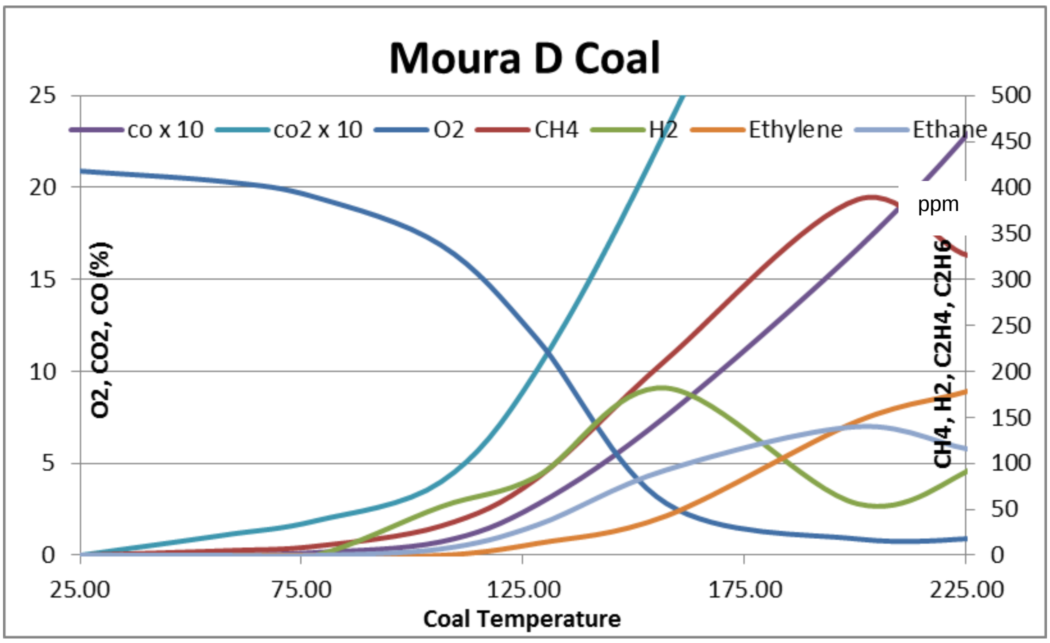


Figure 15: Fire ladder for New Zealand coal

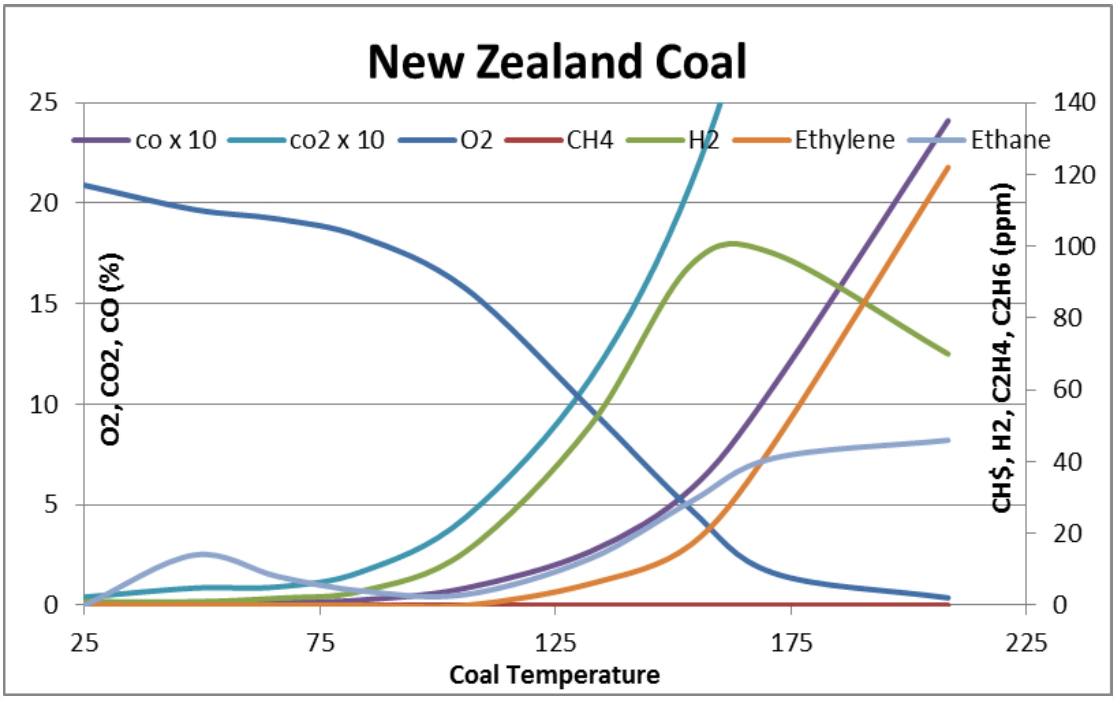
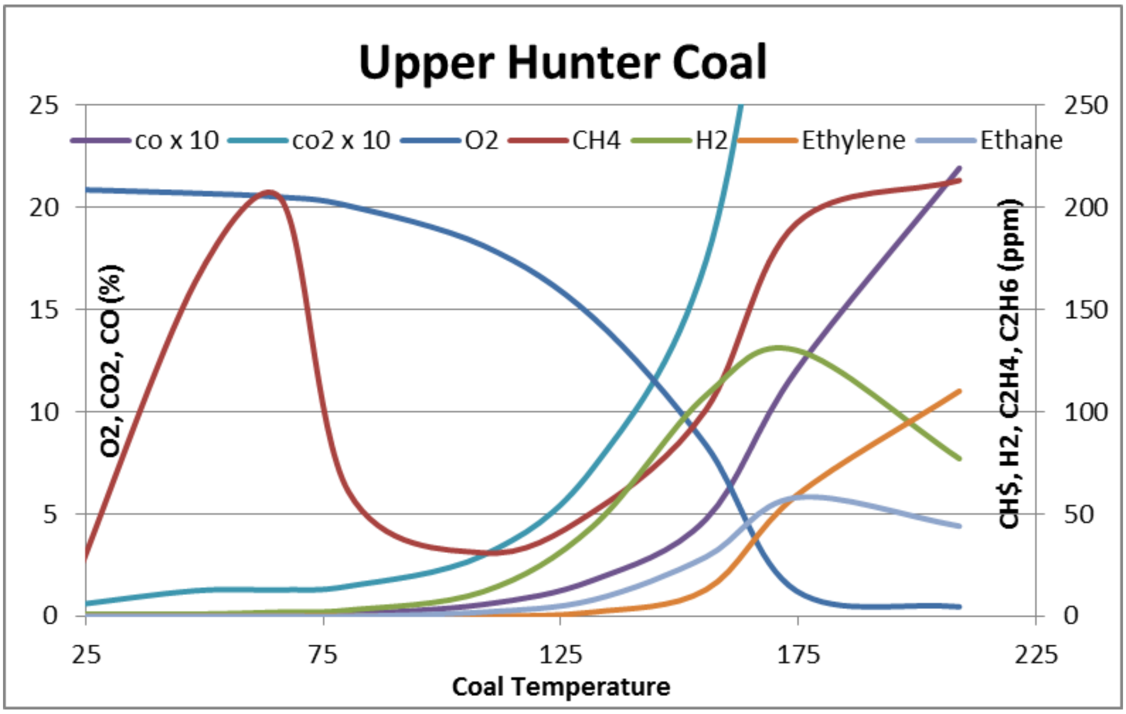


Figure 16: Fire ladder for Upper Hunter coal



The following figures 17, 18, 19 and 20, show a comparison for several different types of coal of the evolution of gases produced by heating coal. Absolute temperature values vary but behaviour is similar.

Figure 17: Gas evolution behaviour for various coals – CO

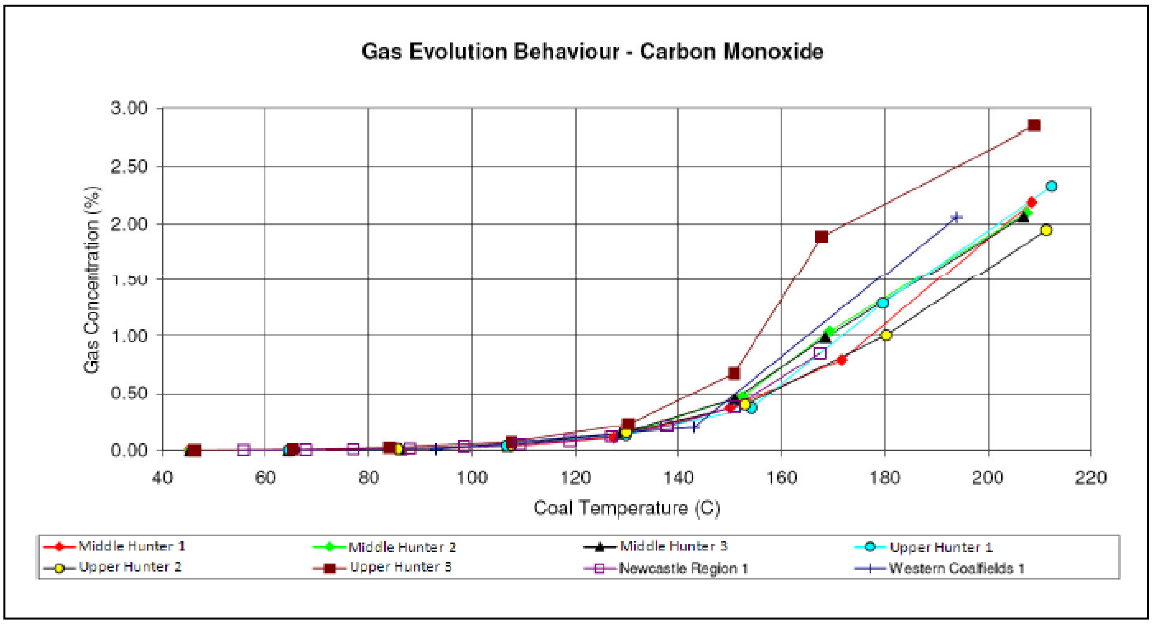


Figure 18: Gas evolution behaviour for various coals – CO2

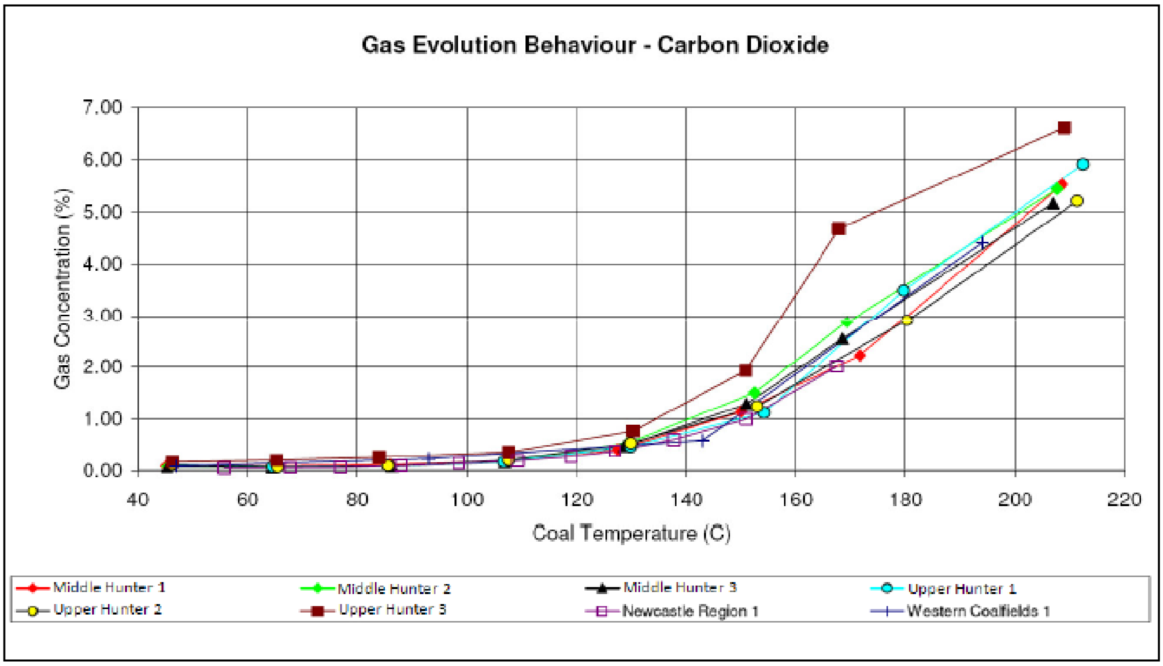


Figure 19: Gas evolution behaviour for various coals – H2

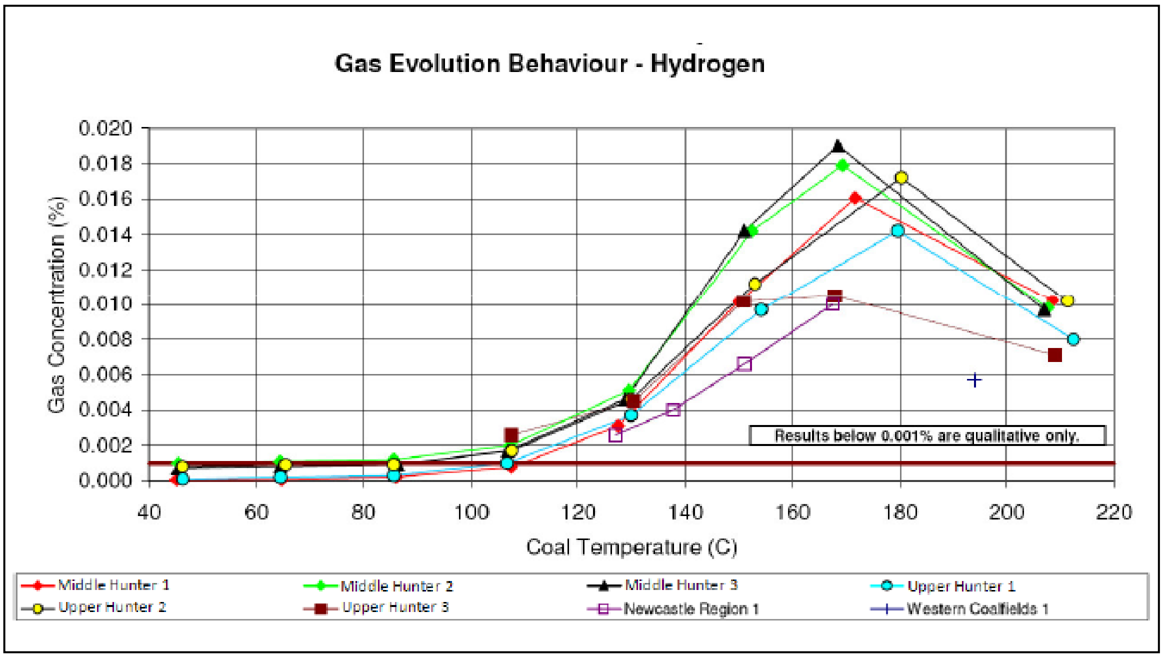
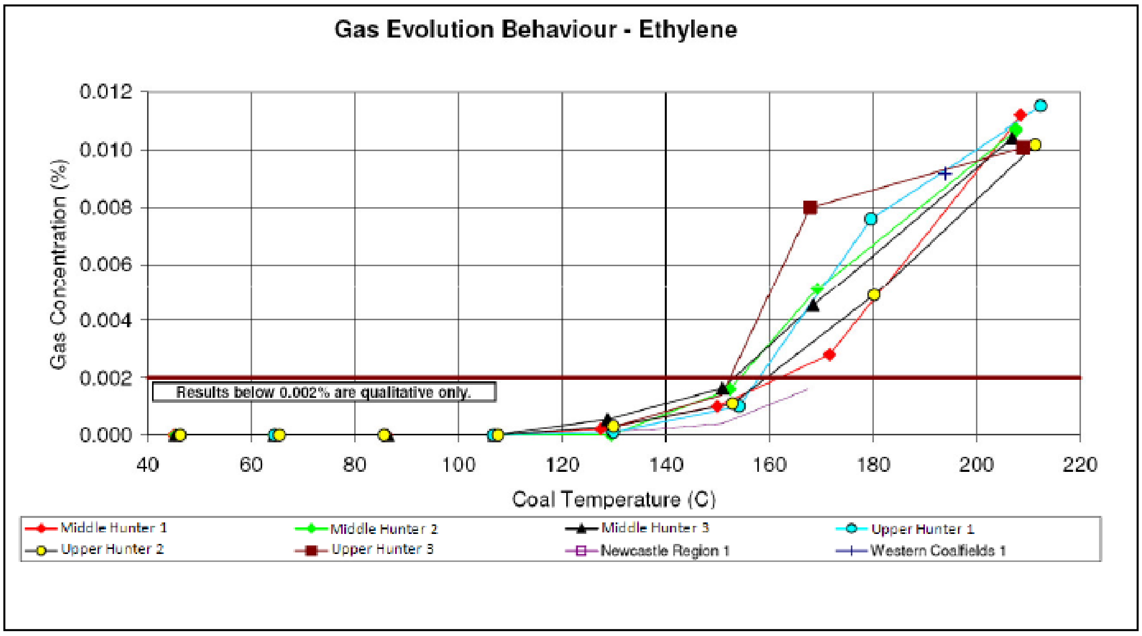


Figure 20: Gas evolution behaviour for various coals – C2H4



Indicators of spontaneous combustion risk should include both gas analysis based and other sensory or observation based indicators. Heatings can only be detected in the early stage if monitoring takes place in or near where heatings can occur.

6.3 METHODS OF DETECTION

Methods of detection and control of spontaneous combustion include:

- Physical inspection
- Monitoring of mine atmospheres in roadways
- Collection of atmospheric samples from goaves
- Thermography

Detection methods need to have these objectives:

- Determine when there are significant variations to the planned design of the ventilation system
- Ensure that containment of goaves is of a high standard
- Confirm the goaf areas are inert
- Confirm that stowage has been removed or otherwise contained
- Ensure standards for stoppings and seals and roadway surrounds are met
- Recognise early signs of spontaneous combustion activity

6.3.1 Physical Inspection

The observation of physical signs is an important method of detection. Physical signs are:

- Rise in temperature
- Sweating (approx. 100oC)
- Smell (approx. 110oC)
- Haze
- Smoke (approx. 300oC)

In some coal seams, very little CO is given off before the heating can be detected by smell or other physical signs. (Greta seam) In other coal seams, gaseous indicators may provide the best early warning. (Liddell seam)

Small quantities of CO may be missed (location and placement of sampling points etc.) or be considered erroneous because the readings were not repeated on a regular basis. Even a fleeting smell is distinctive to an experienced and trained person.

The key factor in the detection of spontaneous combustion is a change from normal conditions. Changes can be in airflow and direction, smell, temperature, gas levels etc. Any change should be fully investigated.

Inspection of stoppings and seals is important to ensure they are effectively containing the goaf. Matters to note when inspecting stoppings and seals include:

- Water trap if fitted is filled with water and not leaking
- Signs of water build up on the inbye side of the stopping or seal
- Sample pipe is in good order with valve turned off
- Presence of stowage in the roadway adjacent to the stopping
- Access to stoppings & seals are accessible and ability to inspect, repair and sample
- Abnormal changes in gas readings in the adjacent roadway when the barometer is falling, indicating stopping damage
- Condition of roof, ribs and floor
- Atmosphere adjacent to the seal on a falling barometer

Stoppings and seals that contain and inertise the goaf should be examined on a regular basis to confirm the integrity of the structures and roadway surrounds.

Roadways should be safely accessible to all stoppings and seals. If these sites become inaccessible due to falls in roadways or other reasons, there is a risk that damage to the structure or roadway surrounds will not be detected. If so the risk of undetected spontaneous combustion will increase. Access to seal sites is important to confirm integrity and allow samples to be taken from behind the seal as required.

A useful technique for examining stoppings or seals containing a goaf is to walk the roadway adjacent to the sealed area with a gas detector and take note of the change in gas levels when passing each cut-through. This should be done when the barometer is falling. Smoke tubes may be useful in detecting leakage.

A disproportional and significant change in gas levels indicates a badly leaking seal or stopping. Physical examination of the stopping or seal then can confirm if the problem is damage to the stopping or seal, roadway convergence, or both. Recording of results of changes in gas levels and the barometer is useful in determining trends in subsequent inspections.

In mine roadways, heatings in stowed or fallen coal and rib side pillars may be difficult to detect in the early stage. Reliance on monitoring changes in mine atmosphere should be not be relied upon as the principal method of detection. The observation of physical signs is important. Thermography may be useful.

6.3.2 Monitoring of Atmospheres in Roadways

The atmosphere in areas may be sampled by means of real time sensors, tube bundle lines and sampling bags. Surface analysers with tubes to various parts of the mine are most often used for sampling the mine atmosphere in ventilated roadways adjacent to goaves for signs of spontaneous combustion.

The time delay for gathering samples through the tubes is normally not critical for the detection of spontaneous combustion activity. The analysers are able to more accurately detect small percentages of gas than real time roadway sensors.

If power is lost in the mine, or access denied, the tube bundle system may continue to operate unless lines are damaged. The range of operation of the analyser may be an issue in an emergency situation where high concentrations of gas may be present.

No matter how extensive or sophisticated the monitoring system may be, unless it is sampling in the right areas it will not provide the necessary information.

6.3.3 Monitoring of Atmospheres in Goaves

Sample bags are often used to supplement the system as there is a limit to the number of tubes and sampling points per analyser.

If there is reliance only on the monitoring of the atmosphere in mine roadways adjacent to extracted areas, and not from within the extracted area, then the system of early detection will be deficient. Damaged stoppings may allow goaf air to exit to the adjacent roadway and this may, or may not be detected at the roadway sampling point.

The atmosphere in the goaf adjacent to adjoining ventilated roadways should be sampled on a regular basis commensurate with risk. Sampling interval may be extended when the atmosphere is demonstrated to be inert.

In the active longwall panel where there are usually large numbers of stoppings enclosing the goaf, samples should be taken along the perimeter of the goaf to confirm the goaf atmosphere is inert, and then resampled based on results and risk. Samples should be taken frequently until the atmosphere is determined to be inert.

Detection at intake seals is made more difficult by the inflow of air, which makes sampling by conventional means dependent on the state of the barometer. One useful technique to limit this effect is the “Buffer Zone” where a second stopping is established outside a seal (balance chamber). The distance between the seals is calculated from the volume of the goaf and the normal pattern of changes in barometric pressure, and is adequate to contain a substantial portion of the gas emitted on a falling barometer. An open pipe passes through the outer stopping.

It is important to understand the oxygen distribution in the goaf, the time required for coal to reach the cross over temperature at which oxidation accelerates (approx. 70^0C) and for action plans to be developed and implemented in the event of a face stoppage.

6.3.4 Goaf Sampling

Sample pipes placed in stoppings and seals should be made from materials that are not reactive. Copper is preferred. The action of acid mine water on galvanised iron can produce hydrogen.

The location of the sample pipe in a seal needs to be determined according to the purpose of the sampling and conditions in that part of the mine. Factors that influence the location and design of the seal sample point include:

- What is the purpose of the sample and what is to be sampled? If the purpose is to sample the atmosphere in the goaf, then the sample pipe should extend to that location.
- What are the gases likely to be in the roadway? If the gases are liable to layering, the sample pipe should be located at the required level.
- What is the dip of roadway? This may result in certain gases migrating
- Is there water behind seal? This may cause sample pipes located close to the floor to block up.

Sample pipes should be slightly inclined to eliminate water

For the purpose of the detection of spontaneous combustion, and given no other constraints, sample pipes are best located in the upper part of the roadway, with the inbye end adjacent to the goaf edge.

The Queensland Department of Employment, Economic Development and Innovation recently revised and reissued Recognised Standard 09 – The Monitoring of Sealed Areas. This document addresses in detail:

- The location of sampling points
- Parameters to be monitored
- Sampling frequency
- Maintenance of seals
- Analysis of information and response
- Storage of information
- Record keeping and reporting

The standard has been released to provide guidance on how to predict and adequately define the potential for an explosive atmosphere to occur within a sealed area, as well as monitoring to identify the potential for spontaneous combustion within the sealed area.

6.3.5 Monitoring of Stowage & Pillars

Thermography is an effective means for detecting rib side pillar heatings and stowage and leakage paths around seals.

Thermocouples can be installed into pillars where a high risk of heating has been identified. Gas sampling from boreholes in pillars is another option.

Physical inspection (using gas sampling and senses) remains one of the most effective means of detection.

6.4 GAS MONITORING SYSTEMS

A comprehensive gas monitoring system is an effective tool for the detection and monitoring of spontaneous combustion. Monitoring systems include:

- Tube bundle system with analysers located on the surface
- Real time (telemetric) system
- Routine inspections using portable devices
- Gas bag sampling for analysis at the mine or by a third party provider
- Gas chromatographic systems

Although a combination of all the above would offer the ideal gas monitoring system for a coal mine, not all mines utilise, or require all components for their particular site. Telemetry (fixed underground sensors) and tube bundle gas monitoring systems are most commonly utilised for monitoring underground atmospheres in Australian coal mines. While both types of systems provide an important and useful means for the routine monitoring of specific gases (i.e. methane, oxygen, carbon monoxide and carbon dioxide), they are generally not suitable for the accurate monitoring and trending of gases produced from an advanced oxidation or spontaneous combustion. In these instances, a gas chromatograph is the preferred analyser for effective decision making as it has the ability to not only accurately determine all the above gases, but also determine key indicators such as hydrogen and ethylene.

While telemetry and tube bundle systems are employed to essentially monitor the same gases, there are significant differences in the type of sensors that are used, the quality and also the range of detection for the individual gases.

6.4.1 Tube Bundle Gas Monitoring Systems

Tube bundle gas monitoring systems utilise sample points that are located for ongoing trending of the mine atmosphere and in areas that do not require immediate warning of contaminants.

The system was developed in Germany in the 1960s to detect and monitor the progression of oxidation and spontaneous combustion events. The fundamental components of the system include a series of plastic tubes extended from the surface to selected locations underground. The tubes are general high grade quality non leaching materials with a variable diameter from 6mm to 20mm (depending on the length) and lengths of up to several kilometres. Air sampling scavenging pumps located on the surface draw the gas from each tube simultaneously via drying, filtration and flame trap systems. Individual tubes are then sequentially diverted into a bank of analysers for analysis.

With minimal restrictions in terms of the intrinsic safety, certifications, approvals, etc. for the analysers used for tube bundle systems (as they are generally located on the mine surface), a broader selection and higher quality of analysers can be used. Non dispersive infra-red (NDIR) analysers are generally used for the monitoring of gases such as methane, carbon monoxide and carbon dioxide, while paramagnetic (or zirconia type sensor) analysers are commonly used for oxygen monitoring. In addition, the broader detection ranges available for these types of analysers facilitate the measurement of the higher gas concentrations found in underground sealed areas.

Although the analysers used for tube bundle systems are generally accepted as being of superior quality to the sensors used for telemetry gas monitoring systems, and do not have some of the cross sensitivity issues associated with some fixed type sensors, moisture in sample tubes can cause significant problems. Most tube bundle systems will have moisture removal devices that remove moisture from the gas sample streams. However, if these devices are not maintained and functioning efficiently, then the result is that any moisture entering the NDIR analysers will affect the accuracy of the readings. Mine sites with tube bundle systems will commonly have switching mechanisms that divert a dry calibration gas into the analysers to confirm the accuracy of the system. A mistaken assumption is often made that the moisture removal devices are working efficiently and, apart from checking individual water traps, no checks are made as to the effectiveness of the main water removal device/s. The result is that when the sample tubes are put back on line, comparative analysis with a gas chromatograph may show a discrepancy between the analysers.

Advantages:

- No explosion proof instruments required when flame traps are incorporated
- Easier maintenance as major components are located on the surface
- No underground power requirements
- A wide range of gases can be analysed
- Analysers can be calibrated on the surface

Disadvantages:

- Results are not in real time
- Leaks in tubes may not be immediately apparent.
- Condensation in tubes can results in blockages and erroneous readings on some types of analysers if moisture removal systems are not adequate
- Faults in tube system may not be immediately apparent.
- Tubes may be damaged by fires/ explosions

6.4.2 Telemetry Gas Monitoring Systems

Fixed sensors are generally located where real time data is required and can therefore provide early warning for the onset of an oxidation.

In relation to the types of sensors used for fixed sensor gas monitoring systems, the selection range is restricted to those certified by the relevant regulatory body. A combination of catalytic combustion (for methane detection), electrochemical (for carbon monoxide and oxygen detection) and simple infra-red detectors (carbon dioxide and methane detection) are typically used for these gas monitoring systems.

However, the sensors used for telemetry systems are often lacking in their range of detection, are generally less stable, can be cross-sensitive with other gases and have a much lower operational life expectancy than the types of analysers that are used for tube bundle systems. Despite these limitations, the real time monitoring capability of this type of system is very important in terms of providing rapid early warning for a mine site.

Advantages:

- Results in real time (rapid indication of potential problems)
- Relatively long distances from surface to sensors are possible
- Sensor failure is generally immediately recognised

Disadvantages:

- Relatively high maintenance
- Limited range sensors for ongoing monitoring of a spontaneous combustion

- Poisoning of methane sensor may occur
- Cross sensitivity for some sensors
- Loss of power when methane limits exceeded
- Limited sensor life
- Unsuitable in oxygen deficient atmospheres (i.e. behind seals).

6.4.3 Gas Chromatograph

Gas chromatographs have been used as an analytical tool for the analysis of underground coal mine atmospheres for decades. They have been useful in providing accurate analysis of components that are not routinely monitored by telemetry or tube bundle gas monitoring systems. These components include hydrogen and hydrocarbons such as ethylene and propylene.

While conventional gas chromatographic systems were initially utilised at some coal mines and other agencies in Australia, their analysis times were too slow for the high volume sampling rates required during mine emergencies. In addition, they required frequent maintenance and a relatively high level of operator expertise. They also had difficulties in analysing parts per million (ppm) levels of carbon monoxide in a balance of high methane and similarly ppm levels of ethylene in a balance of high carbon dioxide. These systems are no longer considered to be an appropriate analytical tool for the monitoring of a spontaneous combustion incident.

The introduction of ultra-fast micro gas chromatographs into the market in the 1980s resulted in a wider acceptance and use of gas chromatographic systems at coal mine sites. They provide analytical run times of between 1-3 minutes for the analysis of key spontaneous combustion gas components. They generally utilise a single detector type (Thermal Conductivity Detector, TCD), require less maintenance than conventional gas chromatographs and are relatively simple to operate.

It may be argued that due to restrictions in their operating systems, some models of ultra-fast micro gas chromatographs have similar limitations to conventional gas chromatographs when analysing low ppm levels of carbon monoxide in a balance of high methane. However, this is not the case for all micro gas chromatographs. There are ultra-fast micro gas chromatographic systems that are able to reliably and accurately determine low ppm levels of carbon monoxide in a balance of high methane. Hence the selection of the correct type of system is very important.

The main advantages in using this type of gas chromatograph for the analysis of coal mine atmospheres include:

- Ability to separate and analyse key spontaneous combustion components, including hydrogen, carbon monoxide, ethylene, ethane and propylene at ppm to percentage levels
- Ability to analyse other general gases found in coal mines including oxygen, nitrogen, methane and carbon dioxide
- Rapid analysis of the above components in typically 1-3 minutes
- Only one type of detector is required for analysis of mine atmospheres
- Relatively simple to operate

6.4.4 Sample Turn-around Time

The "turn around" time required to take the sample and produce a result should be considered. A gas chromatograph located on the mine site can produce results much more quickly than transporting off site to a laboratory that may not be open for business 24 hours per day.

Infra-red analysers located on the mine site will produce results quickly but not provide information on hydrogen and ethylene etc.

Obviously, if a heating is detected in the early stage, time is not critical. As the event develops, time does become critical.

Information on atmospheric conditions is critical to decision making in spontaneous combustion events.

6.4.5 Location of Monitoring Points

To be effective, the monitoring points need to be situated in locations where products of oxidation can be detected. In addition to monitoring the atmosphere in roadways adjacent to the goaf, the atmosphere within the goaf should be determined. (Refer to 6.3)

Alarm levels for monitoring points should be determined and integrated into TARPs.

6.4.6 Gases Sampled

Tube bundle systems should, at the very least, monitor CO, CO2, O2 and CH4. In addition to recording trends of gases produced by heatings, collecting information on all these gases will allow calculation of ratios that are useful for monitoring the development and progress of a heating.

The integrity of the monitoring system should be regularly confirmed.

6.4.7 Production of Gases not Related to Heatings

False alarms may be generated where the above mentioned gases are produced by means other than spontaneous combustion activity. Examples are:

- Use of galvanised iron as sample pipes
- Acid mine water on galvanised iron producing hydrogen and carbonates producing CO_2.
- CO and CO_2 from vehicle emissions
- Unplanned stowage of chemicals and oils
- Oil shales (volatile emissions)

6.5 MONITORING LOCATIONS

The location of monitoring points at strategic locations is of major importance. A single sampling point some distance from the source provides an indication only and can often lead to either an over estimate or under estimate of the seriousness of the hazard.

Points must be sited where heatings are likely to develop. There needs to be little dilution of flows between the heating and the detectors. Consideration must be given to layering of methane and warm combustion gases which may rise up dip in a sealed area.

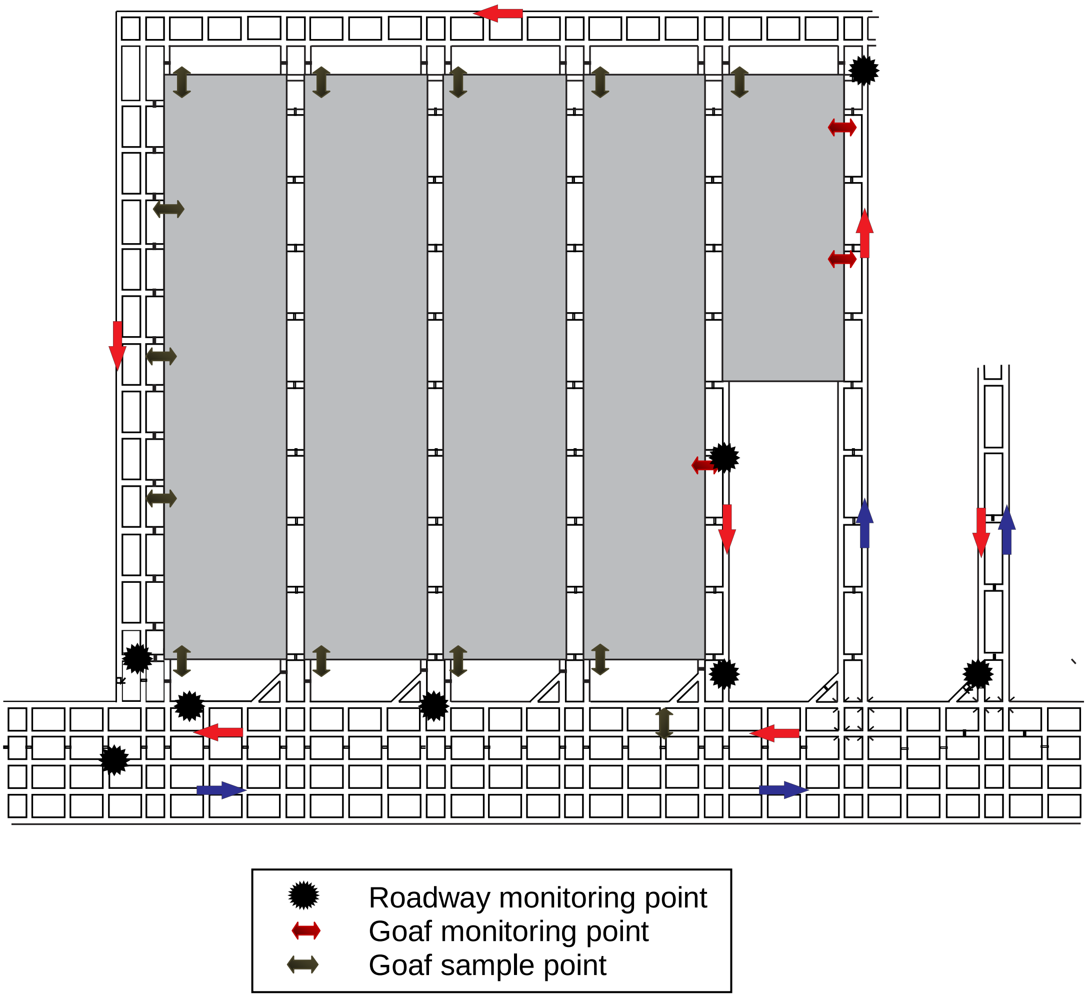
Ideally, sampling points should be in panel returns, behind stoppings and seals and in the main body of the ventilation circuit. All sampling points should be clearly located on the mine ventilation plan.

In identifying the location and number of monitoring points, the ability to determine where the contaminant is originating is important. If the ventilation from a number of possible heating sources passes over a single sampling point, the origin cannot be determined, nor the sample result confirmed

Figure 21 shows the suggested locations for the recommended minimum number of environmental monitoring points for a longwall panel. It includes surrounding roadway and goaf monitoring points for the current and adjacent longwall blocks.

Recommended sites for goaf sampling are shown. Location and frequency of sampling should be based upon results of atmospheric analysis, stability and an assessment of the hazard.

Figure 21 – Location of Monitoring Points



6.6 INTERPRETATION OF RESULTS

The trend in gas levels is important. Are the levels rising, steady or falling? Using gas values alone is problematic. Ratios and CO make are much better indicators.

There are a number of ways certain gases and their presence can be interpreted to determine the presence of a heating and its stage of development.

The ingress of oxygen into a contained goaf provides conditions for the development of a heating. It occurs well before the liberation of products of combustion and is a valuable early indicator for the development of triggers for the mine TARPS.

While there are well documented ratios and indices that are used for monitoring the progression of a heating, the following have shown to be of value:

- Graham's ratio
- CO/CO_2 ratio
- CO make,
- Trickett's ratio,
- Young's ratio,
- H_2/CO ratio
- air free analysis

Three of the most useful indicators for spontaneous combustion management plan TARPS are:

- Grahams ratio (GR) because values steadily increases as the heating progresses and it indicates the intensity or temperature of a heating. (but not the size)
- Similarly CO/CO_2 ratio because it also steadily increases as the heating progresses (not appropriate for mines with a high CO_2 seam gas composition)
- CO make because it compensates for varying air quantity

When setting trigger levels in the spontaneous combustion plan TARPS it is better to use a few important indicators so that people in the mine can be better trained for an effective response.

TARPS should be reviewed based on mine site experience and adjusted accordingly as part of a risk assessment review of the SCMP.

Most ratios are measures of the conversion efficiency of oxygen to products of oxidation and are therefore essentially equivalent. Oxygen consumed can be measured through oxygen deficiency compared with fresh air e.g. Graham's ratio, Young's ratio, etc. Or Excess Nitrogen compared with fresh air – Willett's ratio, Partington's ratio. Therefore there is no need to use a multitude of deficiency ratios as they should all tell the same story. Other ratios can be used to assist investigation but need not be part of TARPS.

Caution should be exercised in setting gas and ratio values based on gas evolution charts. Sampling limitations and goaf conditions dictate that more conservative values be adopted for TARPS. Factors impacting on atmospheric analysis when sampling from behind seals include:

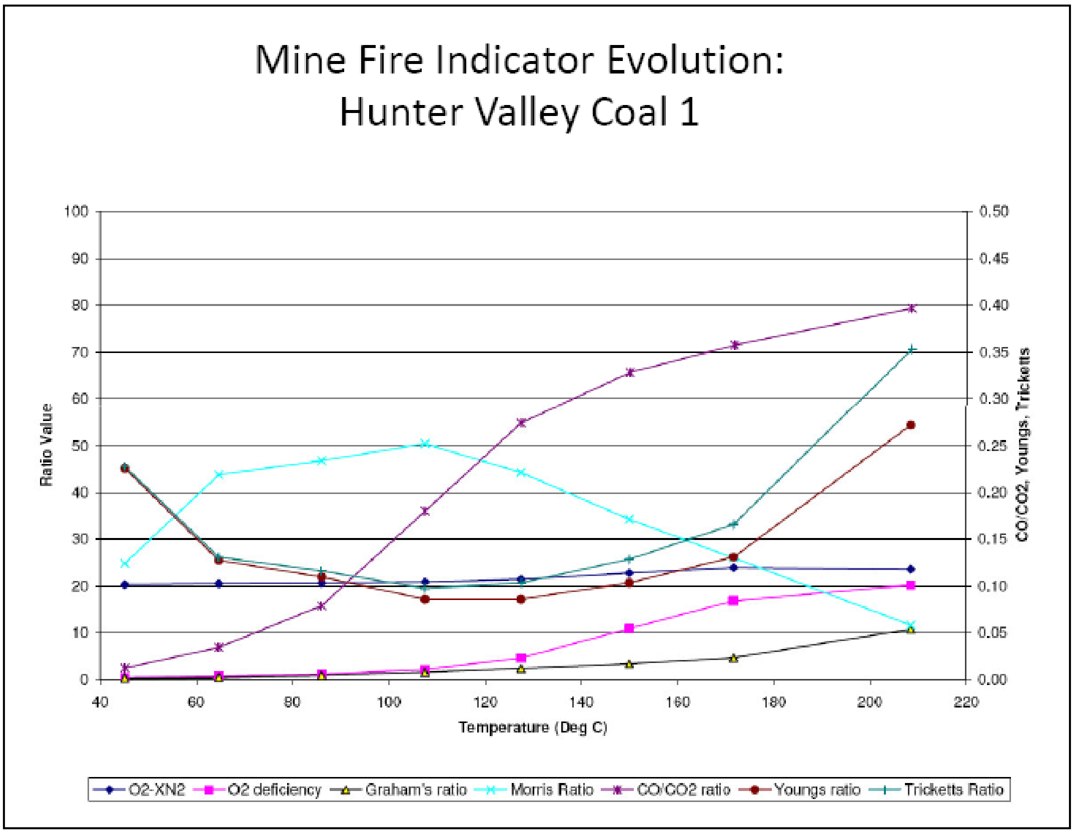
- Where there is no airflow, there is no purging of the sample stream.
- When monitoring over significant time periods, secondary reactions and loss mechanisms may apply.
- There may be a mixture of gas sources.
- Lack of oxygen can cause some sensors to read incorrect gas concentrations.
- The atmosphere sampled may be an average over time rather than current conditions

The discrepancy between the ratios and other indicators of spontaneous combustion activity is probably due to the presence of large amounts of broken coal in the goaf between the site of the heating and the monitoring location. This broken coal would be able to absorb oxygen and thus enhance the oxygen deficiency and act as a catalyst to destroy carbon monoxide or convert it to carbon dioxide. Thus the ratios would underestimate the severity of the situation. In general the effects of sealing on ratios underestimate the severity of a situation.

Determinations are only as good as the accuracy of the measurements taken and calibration of monitoring equipment. Concentrations should be adjusted for any background concentrations such as CO_2 in air.

Figure 22 Mine Fire Indicator ratios show a comparison of the behaviour of a heating shown by calculation of various ratios. The results are based upon laboratory tests of coal properties. The chart is useful in showing the progressive movements in the various ratio values. Caution should be used in considering absolute values for adoption in TARPS. Results may vary considerably for other coals.

Figure 22: Mine fire indicator ratios



When the results of a number of analyses of atmospheric samples from heating sites are plotted there will inevitable be a number of readings which appear to be anomalous. There is also likely to be a somewhat irregular progression from one sample result to another. This occurs because:

- Sampling may not have been taken correctly or been diluted or contaminated
- Barometric changes
- The variable path of products of combustion from the heating site to the sample site and changes in airflow and direction
- Dilution and absorption from areas other than the heating site

The general trend should still be able to be determined. Making decisions based upon individual absolute values is problematic.

6.6.1 Grahams Ratio

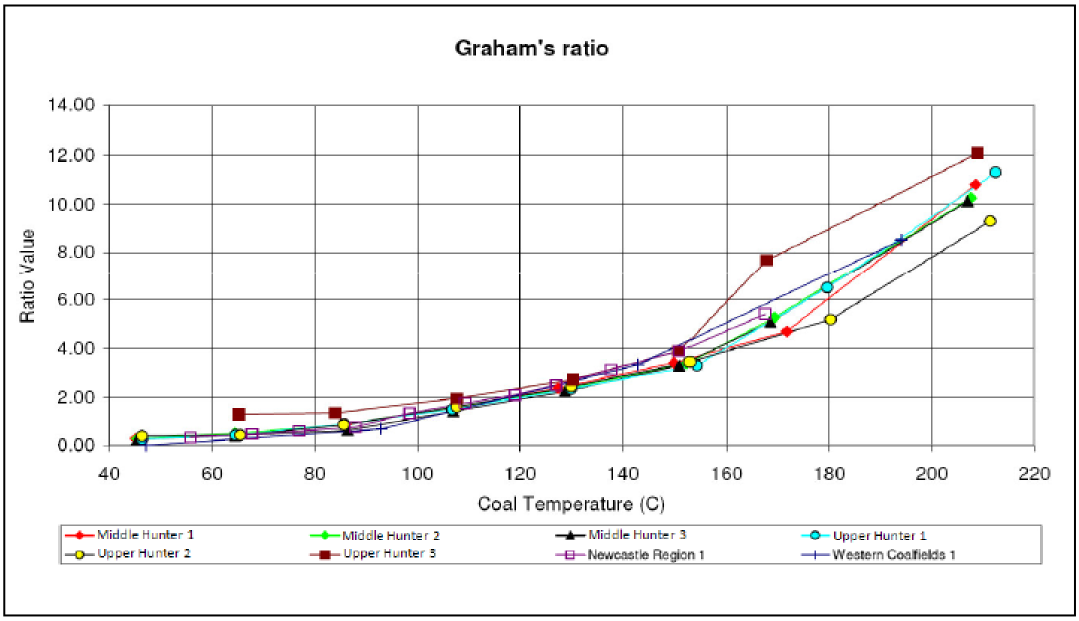
Graham's ratio (GR) is useful in low oxygen environments such as goaves and is also applicable in ventilated roadways.

In ventilated roadways there needs to be a perceptible oxygen deficiency. (The Qld regulations require graham's ratio to be monitored in all panel returns even though with the high flows in most longwall panels there is no perceptible oxygen deficiency)

GR is an indication of heating intensity and temperature and can discriminate between a large mass of coal oxidising and a small intense heating.

Figure 23 shows the laboratory test Grahams Ratio values for a number of coals. It is useful in that it shows the progressive rise in value commensurate with the temperature increase and a similar relationship for the coals tested. Absolute values should not be used for TARPS.

Figure 23: Grahams Ratio values for various coals



Values for Grahams Ratio quoted in a number of technical references are:

< 0.4	Normal
0.4 - 1.0	Investigate
1.0 - 2.0	Heating
> 2.0	Serious Heating or Fire

Operators should determine trigger points for TARPS based upon experience in the seam mined and the determination of risk. This may require lower GR values.

6.6.2 CO/CO_2 Ratio

The CO/CO2 ratio is suitable for both sealed & fresh air heatings. This ratio is independent of oxygen deficiency and so overcomes a lot of the problems associated with other ratios that are dependent on that deficiency. It defines typical coal temperature values. This index can be used only where no carbon dioxide occurs naturally in the strata.

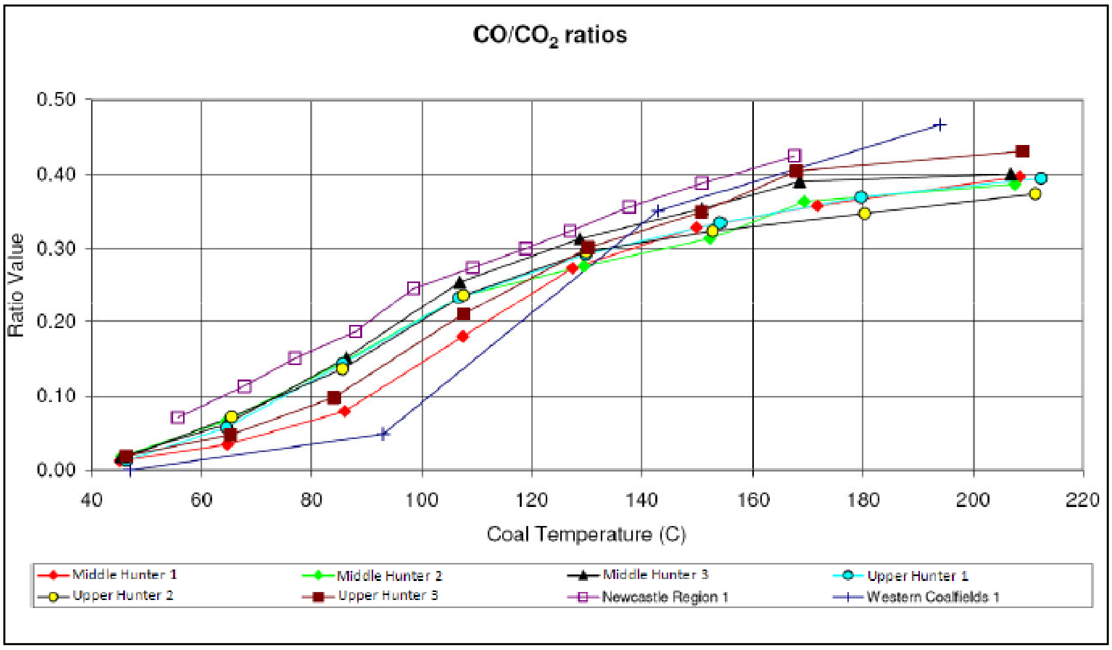
The index increases rapidly during the early stages of a heating, but the rate of increase slows at high temperatures as shown in Figure 24. However, the rate of change at higher temperatures is sufficient to provide a very useful indicator of the progress of a well-established fire. The ratio is independent of dilution with fresh air or seam gas except of course when the seam gas is carbon dioxide.

Typical values of this ratio for Australian coals are:

<0.02	Normal
<0.05	Coal Temperature <60^{0}C
<0.10	Coal Temperature <80^{0}C
<0.15	Coal Temperature <100^{0}C
<0.35	Coal Temperature <150^{0}C

This ratio is only intended as an early warning for heatings. If an active fire exists the ratio can actually decrease. Further this ratio is invalid if the nitrogen or oxygen deficient atmosphere is passed over any heating or if the oxygen concentration exceeds 20%.

Figure 24: CO/CO2 ratio values for various coals



6.6.3 CO Make

CO make is most useful in panel returns and back bleeder roads. It is the volume of Carbon Monoxide flowing past a fixed point per unit time. This indicator removes the effect of dilution by general body air.

The CO make is dependent upon the amount of coal reacting with air so that if conditions change and a larger goaf is ventilated then the CO make will increase without any actual increase in the intensity of the oxidation (larger volumes of goaf exposed to air are a concern in their own right.

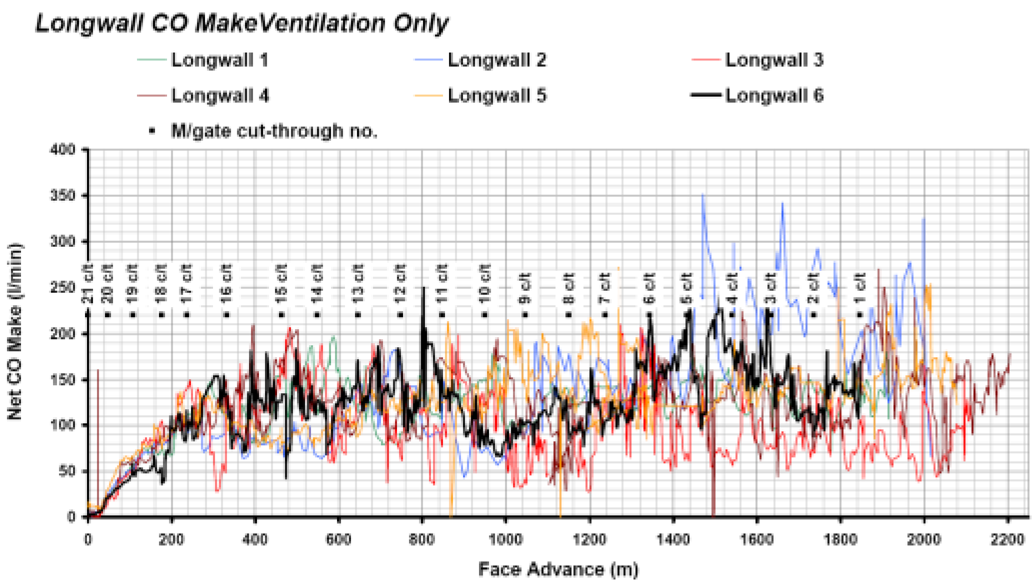
"Textbook" levels quoted are:

- Levels of production > 10 litres per minute require investigation.
- Levels of production > 20 litres per minute indicate that considerable danger exists.
- Levels of production > 30 litres per minute indicate that extreme danger exists.

Values should be set based upon conditions in the mine and these may be higher or lower than the above values.

Figure 24 shows the CO make in the longwall return in the Upper Wynne seam, Dartbrook Colliery NSW. The seam was thick and a high ventilation quantity was required to dilute the CO_2. One maingate seal left open behind the retreating face. Readings are high for most mines but the graph does show the "sawtooth" effect and trends. Several readings triggered the spontaneous combustion TARPS for the mine.

Figure 25: CO make in a longwall return



6.6.4 Air Free Analysis

The following information, in relation to "air", assumes that air contains 20.93% oxygen and 79.07% nitrogen (including inerts).

In many situations the atmosphere of interest is diluted by being mixed with other atmospheres, particularly fresh air. In some cases it is possible to remove the impact of fresh air through adjusting the gas concentrations. This can be achieved in a number of ways.

1. ***Assuming all the oxygen present is due to the diluent gas***

   In this case the gas concentrations are adjusted by removing the oxygen concentration and the associated nitrogen concentration (based upon 3.778 times the oxygen concentration. The residual gases are then normalised to 100 %. This is also used to estimate what the ultimate concentrations of gases would be if all the oxygen present was converted using the conversion efficiency of the sample.

   For example: Assume the fringe of a sealed area contains only the seam gases methane and carbon dioxide and no air contamination (i.e. 80% CH_4 and 20% CO_2). Assume then that the seal breathes in and that the atmosphere at the fringe behind the seal now contains 50% seam gas (40% CH_4 and 10% CO_2) and 50% air contamination (10.465% O_2 and 39.535% N_2 + inerts). To determine what the seam gas component concentrations are without the air contamination using this method is commonly termed an "air free" calculation. The air free calculation calculates the air contamination based on the normal air/ oxygen ratio of 4.778 and applying the resulting factor to the remaining components. The result would then be an air free concentration of 80% CH_4 and 20% CO_2 (i.e. the original concentrations).

   However, if an oxidation/heating occurs behind the seal then the reaction process will consume part of the O_2 in the air concentration. The consumption of the O_2 would produce CO and CO_2 and also result in an excess nitrogen concentration (relative to the original normal N_2/O_2 air ratio). The air free calculation using this method can sometimes be useful in monitoring the level of oxidation products to assist in determining if the process is continuing, or if increased/ decreased levels are purely the result of air moving between the sealed areas as a result of diurnal atmospheric pressure influences.

2. ***Identifying the degree of dilution through trending or comparison with other gas samples.***

   For example: it may be possible to use gases such as methane to indicate the degree of dilution. Methane may be expected as a goaf/seam gas to be in a range of values and yet is much lower due to dilution. This dilution is simply worked out based upon the ratio of the expected value to the actual value. The dilution factor is then applied to all gases other than oxygen and nitrogen. The oxygen and nitrogen concentrations are then calculated by difference, scaling them as per the original diluted gas mixture.

   This technique is most reliable when the degree of dilution can be confirmed by other gases.

   This technique can be used for adjusting the effect of barometric pressure as well. Where concentrations of gases are affected by barometric pressure the variation can be analysed to identify what the diluent gas mixture is. This diluent can then be removed and the residual gases scaled appropriately.

Automatically carrying out air free analysis is not recommended. It is best carried out only when the nature of the diluent atmosphere is confirmed, and by experienced personnel. For example: any attempt to air free an atmosphere that is close to fresh air will lead to wildly inaccurate estimates of the residual gases, due in part to the limitations on accuracy/reproducibility of the gas analysis.

6.6.5 Ethylene (C_2H_4)

Ethylene (C2H4) is a useful signature gas that results from spontaneous combustion and no other known cause. It does not appear until the temperature reaches approx. 1500C. It is not an early indicator but a very useful indicator as the heating develops.

6.6.6 Hydrogen

The presence of hydrogen in abnormal quantities is another indicator. Unlike ethylene, hydrogen has been discovered in circumstances at some mines where there was clearly no incidence of spontaneous combustion.

Hydrogen has been commonly determined at low ppm levels in longwall goaves and borehole drilling at regular intervals.

Hydrogen has also been identified during sampling as a product from acid water reaction with galvanised steel, and use of non-reactive sampling tubes is required to avoid this problem.

Care in the analysis needs to be taken to avoid mistaking helium for hydrogen as they have similar retention times in gas chromatography. Helium is commonly found as a seam gas and in goafs.

7 RESPONSE

7.1 TRIGGER ACTION RESPONSE PLANS (TARPS)

TARPS are a means of providing clear and concise triggers for mine personnel to react to abnormal conditions that may cause risk to property or persons. They provide a graduated response with each stage, if changing conditions are not corrected, becoming more serious. The lowest level response is intended to recognise change and provide time for corrective action before people are placed at risk.

TARPS will have graduated levels of response dependent upon the severity of the situation and risk. A spontaneous combustion management plan TARP system should contain at least 3 levels. Additional levels may be advisable after consideration of the risk and circumstances at the mine.

The three basic graduated levels of response are:

- A change from the normal conditions requiring investigation
- Evidence of a loss of control requiring action to correct
- A risk of harm to people requiring withdrawal of persons from the area

7.1.1 TARP Triggers

Trigger points for response should be clearly identifiable values or observations of change from normal conditions that are ideally not dependent upon a particular persons experience or judgement and not subject to misinterpretation.

The requirement for mine personnel to respond to spontaneous combustion TARPS will be irregular and infrequent. TARPS should be summarised simply in one or two pages so that persons required to action deviations or abnormalities can reference the information they need quickly and without misinterpretation.

TARP triggers will vary for different parts of the mine because of the atmospheric conditions in the monitoring point.

- Fully sealed goaf
- Active goaf
- Bleeder or perimeter roadway
- Extraction panel return
- Intake to return pillars

Circumstances of a heating in a goaf where there is no positive airflow and low oxygen will obviously differ from that of a heating in stowage in a normally ventilated roadway.

Triggers useful for the development of TARPS include:

- Loss of access to seal sites
- Damage to seals

- Unplanned significant increase or decrease in ventilating pressure
- Increase in gas levels in the roadway adjacent to seals indicating abnormal leakage
- Abnormal levels of CO
- A rise in the value of oxygen in an inert goaf
- A progressive increase in CO make in a longwall or continuous miner extraction panel return
- A progressive increase in CO make in a bleeder return
- A progressive increase in the grahams ratio, or other indicator ratios adopted for the mine.
- A change in smell or other physical conditions.

7.1.2 Early Stage Responses

There may be one or a number of stages in a mine's TARP system that can be considered an early stage response.

The first step in an early stage response is to confirm the condition. The number of erroneous readings from environmental monitoring systems may be significant and require readings to be verified. The reason for spurious readings can include:

- Ventilation monitoring system fault
- Environmental monitoring (EM) tubes being damaged with normal mine air entering a tube connected to the goaf.
- EM Filters and water traps not being serviced correctly
- EM analysers not cycling correctly so that residual air from the previous sample contaminates the current sample
- Incorrect location of tube sampling points in the roadway
- Analysers not calibrated correctly
- Analyser calibration drifting
- Flow failure

Some (spurious) readings may be "one off". A repeat sample may be normal. Readings may be confirmed by:

- Waiting for a second reading
- Sending a mine official to the site to inspect the area and confirm the condition by inspection

If the system of environmental monitoring is a tube bundle system with analysers located on the surface, the cycling of the sampling and analysis through multiple points can be altered to sample through one or two points and produce more rapid results from the problem area.

The response depends on the perceived severity of the alarm. If it is has the potential to cause harm to people then action should be taken to withdraw people from the area before confirming monitoring results. If it does not appear to constitute an immediate risk to people in the mine, it may be best to confirm the result before action is taken, assuming that this can be done quickly.

An example of a useful control for long wall panels with back bleeder roadways is to stopping off the back bleeder roadway which effectively reduces the ventilation pressure across the goaf and removes the necessity for a large number of goaf edge stoppings to contain the goaf. It is a short term solution that may cause a problem with holing out the adjacent longwall face and making use of the roadway for the next longwall tail gate.

Once abnormality has been confirmed control actions should be initiated and preparations made for more severe action whilst there is still time. Actions that should be considered are:

- Preparation for inertisation or sealing of areas.
- Preparation for withdrawal of key equipment should evacuation be considered.
- Dewatering arrangements

Time is of the essence so waiting some time to confirm a condition is not sensible.

7.1.3 Withdrawal of Personnel

When a spontaneous combustion heating develops to a stage where there is risk of fire or explosion, TARPS will require people to be withdrawn from the mine, a late stage response. The limitations on discovering a heating site and accurately determining the stage of the heating require a conservative approach, so that people are withdrawn well before exposure to the risk.

Use of inertisation equipment could allow people to remain in the mine to treat or isolate the heating site.

Re-entry arrangements should be considered via a risk assessment process.

7.1.4 Re-entry Provisions

Consideration should be given to the means of re-entry after having withdrawn personnel from the mine. Re-entry will normally be within the scope of the mine safety management plan and not be conducted under the provisions of the mine emergency system. TARPS may be determined for re-entry.

Issues are:

- Is the spontaneous event under control and safe for re-entry
- What are the atmospheric conditions in various parts of the mine and is it safe for re-entry
- Options for re-ventilation and method

Re-entry may require a mine rescue team to explore parts of the mine by entry through an air lock before the mine or part of the mine is re-ventilated.

Even after waiting several months before re-opening, it is wise to plan to make provision for rapid sealing of the part of the mine affected by the heating after re-entry. There are several cases of heatings re-activating within a few days after re-entry.

7.2 MANAGEMENT OF AN INCIDENT

7.2.1 Location of Surface Activities

The surface environmental monitoring analysers, the surface control room, muster room and the main fan controls should be located away from the mine entries where they are not at risk from an underground explosion or products of combustion. A 60 degree angle on both sides of the direct line of the seam entry is generally considered to be the area at risk of effect from an underground explosion. Noxious and explosive gases may accumulate in or near facilities located alongside mine entries.

7.2.2 Incident Management Team

An incident management team is the current convention for managing serious events. There should be provision to bring people in from other mining operations to participate and assist in the incident management team.

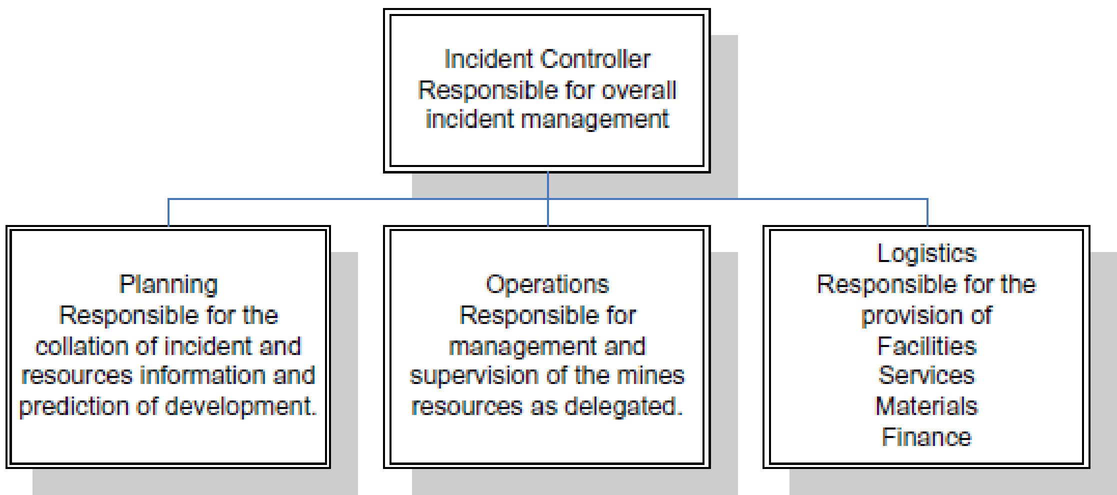
People working at the mining operation may be directly affected by the emergency, physically or emotionally. Knowledge and experience in the relevant disciplines should be considered in the selection of people for the team.

Those that may be expected to participate in such a team should be advised beforehand and provided with details of the mining and procedures for dealing with mine emergencies.

There is a tendency for incident management teams to become too large by including those that represent all interest groups in isolation rather than also considering the expertise and contribution individuals may make to solving very difficult problems.

A system adopted in most mines in Queensland, Figure 25, makes used of a management team approach that allows simultaneous tasking and improves the effective performance of the incident management group.

Figure 26: Incident Management Team



7.2.3 Monitoring under Emergency Conditions

The need to monitor under emergency conditions should be considered. Analysers that are suitable for normal operating mine environments may not be suitable for emergency conditions where gas levels exceed the range of the analysers.

The ability to monitor from the locations required under conditions that may negate access to underground workings should also be considered.

Surface access may be required to sample the atmosphere in the area of the heating by means of surface to seam boreholes. In a major event it is possible tube bundle lines could be damaged.

7.3 INTERACTION WITH OUTSIDE AGENCIES

In an emergency, assistance may be required from outside agencies such as Mines Rescue, Ambulance, Fire Brigade, mobile gas laboratory, etc.

Provision should be made for the placement of equipment provided by these agencies in a safe and secure area, clear of mine operational areas and mine entries. Such agencies will require communication, power etc.

Mobile gas laboratories and personnel to operate and interpret atmospheric analysis results are provided by two organisations in NSW:

- Coal Mine Technical Services (CMTS) in Wollongong – a division of Coal Services
- Department of Industry & Investment facility at Thornton

Arrangements for organising a gas laboratory on site can be made by contacting staff at the nearest NSW Mines Rescue station.

In Queensland, SIMTARS maintain a mobile gas laboratory facility.

7.4 INERTISATION

Inertisation of a goaf area can be an effective immediate control if provision has been made for it to done quickly. This allows time for investigation and implementation of a long term control.

If surface access is not available for inertisation and an underground supply system has not been installed, sealing the whole of the mine may be the only option. Inertisation of the whole of the mine will then extinguish the heating.

The following description of inertisation equipment is based on available information. Improvements in capacity, pressure, operation and monitoring are being developed for several items and should be researched by those seeking such equipment.

7.4.1 Flooding

Inertisation by gases is effective in controlling and extinguishing a heating but not in cooling the area. Flooding is most effective for this purpose. Conditions in the mine are conducive to the retention of heat and it requires several months for a significant reduction in temperature.

7.4.2 Seam Gas

Gas from gas drainage systems may be directed into a goaf area to render the atmosphere inert. Flammable gases are suitable provide that the atmosphere is rendered inert and no ignition source is present.

7.4.3 Mineshield

The “Mineshield” inertisation unit, Figure 27, is kept in readiness for use by NSW Mines Rescue at the Hunter Valley Rescue Station. The equipment kept on this site includes the evaporator units and not the prime movers.

The unit operates by vaporising liquid nitrogen on the mine site. The location at the mine site where the nitrogen is to be delivered requires a hardstand area with sufficient space for B doubles to turn.

Liquid nitrogen is supplied by a contracting firm using road tankers. Each tanker supplies between 20 and 28 tonnes of liquid nitrogen.

The flow rate is variable between 0.5 and 20 tonnes per hour. The long term flow rate is approximately 10 tonnes per hour and is dependent upon the road tankers continuing delivery of the liquid nitrogen. Drivers must be specially licensed and there are limitations on the number of trucks available, and the distance between supply depot and mine site

One (1) tonne of liquid nitrogen equates to 844 m^3 of gaseous nitrogen.

Advantages are:

- Relatively high flow rate
- Nitrogen is an inert gas
- Nitrogen is low temperature
- Sufficient pressure to conduct nitrogen through several km of pipeline

Figure 27: Mineshield inertisation unit

7.4.4 Ambient Air Vapouriser

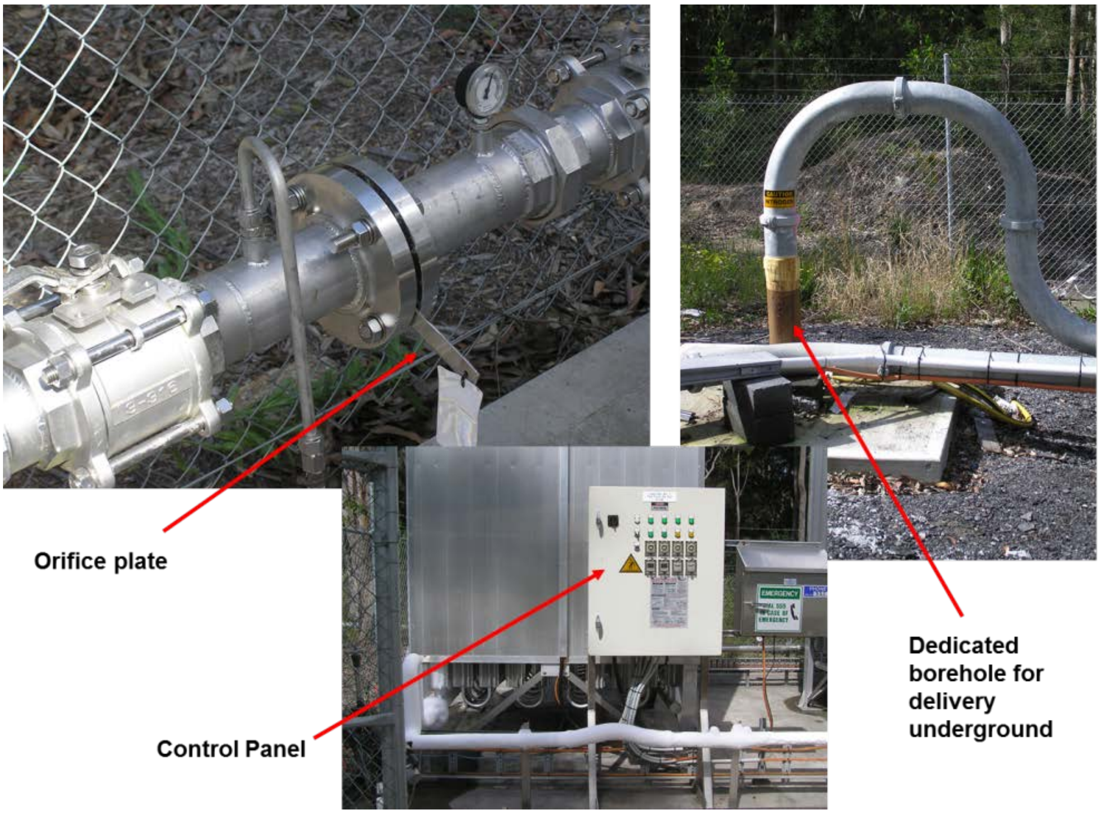
The ambient air vapouriser, Figure 28, is a nitrogen plant that can be set up on the surface of a mine site, perhaps for a longer term solution after the initial requirement was met by the NSW Mine Rescue mobile inertisation unit. A typical unit would have the following specification:

- 2 x 45,000l (30 tonne) liquid Nitrogen storage vessels
- 2 x vaporiser units, one operating and one on standby.
- Fully automated operation.
- Rates controlled by orifice plates, min 0.5t/hr. to max 5t/hr.

A telemetry system monitors operation 24 x 7 and when tanks are depleted they are refilled by a nitrogen supplier. Figure 29 shows the control pane land orifice plate that meters the flow of N_2 down a borehole.

Figure 28: Ambient Air Vapouriser

Figure 29: Control panel and orifice plate for flow rate control



7.4.5 Membrane Separation Nitrogen Generators

An example of a membrane separation nitrogen generator, Figure 30, is the Floxal system. Membrane separation units filter compressed air across hollow polymer membrane fibres, Figure 30, causing nitrogen to separate from oxygen and other components of atmospheric air. The compressed air is dried and filtered. Air temperature is heated 45^{0}C to maintain a constant temperature

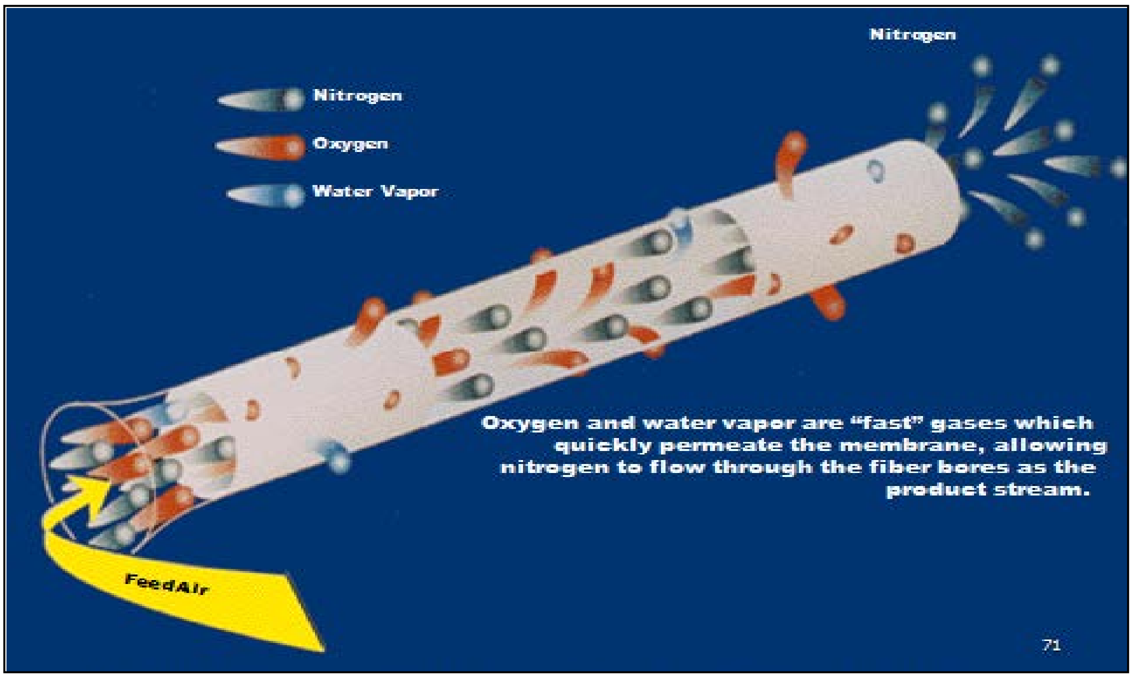
Units have been supplied with capacities of 500m^3/hr and 1,934 m^3/hr and are available with flow-rates in excess of 2000 m^3/hr. The nitrogen purity is set at 97% for optimum results but can be adjusted to 99%. Unit capacity depends upon the purity of the Nitrogen. For a nominal 1,934m3/hr unit:

- At 98% - capacity is 1517 m3/hr.
- At 97% - capacity is1934 m3/hr.
- At 96% - capacity is 2353 m3/hr.

The unit runs on electricity. No fuel or water is required. A 1,934m^3/hr. capacity unit requires 3 phase 415 VAC, 805 kW, 981 kVA. The Floxal system does not require an operator. The system starts up and shuts down automatically. Gas is delivered at pressure (230 Kpa reported on trial with a maximum potential of 800Kpa) and can be reticulated over 12.5 Km through a 4"pipe.

Figure 30: Membrane Separation Nitrogen Generator (Floxal)

Figure 31: Membrane Separation Generator technology



7.4.6 Tomlinson boiler

The Tomlinson boiler, Figure 32, produces exhaust gases from a diesel engine that can be discharged into a mine. Diesel usage for 100kw is 200l/ hr.

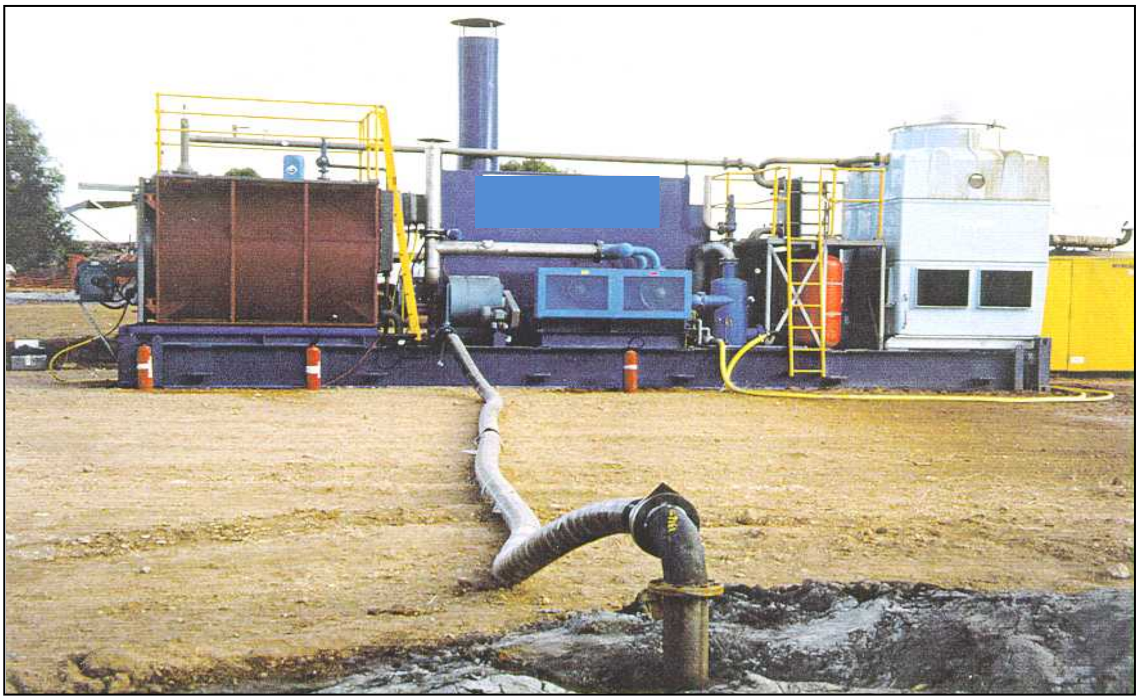
Composition of the exhaust gases is approx.

- 13% CO_2,
- 84% N_2,
- < 2% O_2,

Flow rate is 0.5 m^3/s current with plans to increase to 3 m^3/s. Pressure developed on one trial was reported as a maximum of 10Kpa.

The exhaust gas temperature is about 50^0C.

Figure 32: Tomlinson Boiler unit discharging down a borehole



7.4.7 GAG engine

The GAG engine concept was developed in Poland and demonstrated in Australia in 1997 (QMRS). It has since been used successfully in several mine incidents in Australia and overseas in recent years. Figure 32 shows the GAG engine set up on a pantechnicon for quick transportation and setup.

The exhaust from a jet engine is used to produce the inert gas. Engine capacity is (5 MW) + afterburner. Aviation fuel usage is about 1,500 l/hr. and 66,000 l/hr. water is required.

Flow rate is 25 m^3/s and this is the highest flow of all the inertisation units. It converts 40,000 l/hr. of water to steam. It is estimated that after the water vapour cools and drops out, there is $7m_3$/sec of inert gas.

Exhaust gases composition is:

- < 2% O_2,
- CO_2 10% to 15%,
- CO varies but is usually 400 ppm when tuned correctly.

The output temperature is approx. 80^0C. The unit is suitable for inertisation of a mine before sealing but not for re-entry of persons until the high temperature air if flushed with cool fresh air.

Figure 33: GAG engine set up for transportation and use

7.4.8 Pressure Swing Adsorption

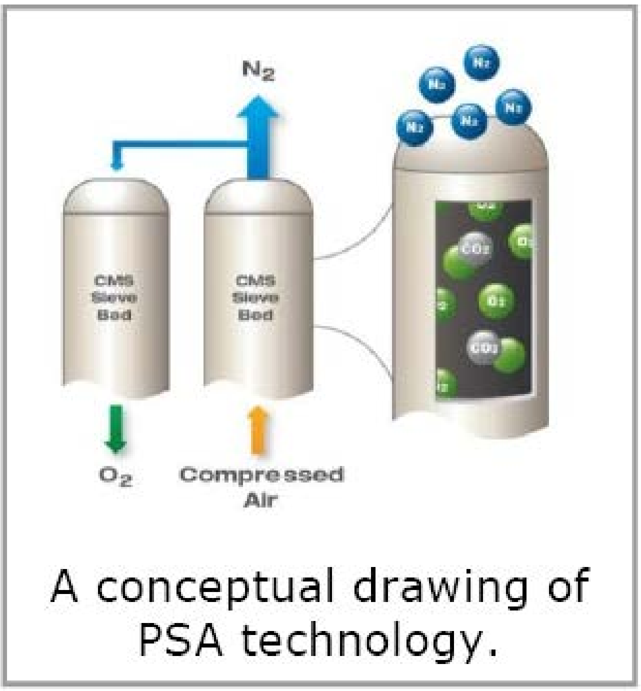
PSA technology uses a carbon sieve material and pressure to adsorb O_2 molecules while allowing N_2 molecules to pass through the sieve material as shown in Figure 33. Compressed air is used to pressurise a vessel filled with sieve material, which sifts the air molecules by physical composition or structure.

Later, the pressure in the sieve bed is reduced, drawing off N_2 molecules and collecting them in the surge tank for use in the application.

A valve is then opened in the sieve bed which releases the remaining pressure, and allows the escape of the O_2 molecules back into the atmosphere (the molecules of the released gas immediately diffuse back into the atmosphere at close to ambient percentages). This cycle is repeated continuously and, with multiple sieve beds working in opposition, a consistent flow of N_2 gas is produced.

A unit tested at the NIOSH Safety Research coal mine at Pittsburgh USA was capable of producing 0.15 m^3/s at a pressure of 335 Kpa. The O_2 content of a sealed area was reduced to 5.4% which was said to be close to the O_2 level produced by the PSA system.

Figure 34: PSA technology



7.5 RAPID SEALING

Provision for rapid sealing of parts of the mine is an important element of a spontaneous combustion management plan.

During the withdrawal process there is the possibility of isolating the part of the mine affected by rapid sealing such as closing doors etc. if this contingency has been foreseen and effective provisions put in place. If not, any actions taken to control or ameliorate the effects of the heating after withdrawal of people will have to be developed and designed and carried out remotely. This may be difficult and time consuming.

If there is surface access to the area above the heating site, the option of sealing the panel or part of the mine is available by using fly ash or other roadway filler. This also allows water or an inert gas to be introduced into the affected area from the surface by means of the Mineshield (nitrogen), Thomlinson boiler, Floxal unit or other means.

When making provision for sealing mine entries, the risk of explosion needs to be considered. Sealing the entries may have to be done without placing personnel in front of the entries where they may be harmed by an explosion.

7.6 REMOTE SEALING

If persons are withdrawn from the mine because of a serious spontaneous combustion event, sealing of the affected part of the mine will allow and facilitate recovery of the remainder of the mine. Techniques for remote sealing include:

- Injection of fly ash through boreholes
- Injection of roadway filler materials such as "Rocsil"
- Inflatable seals
- Remotely operated fire doors

A number of proprietary products are available for roadway filling, inflatable seals and remotely operated doors. Some are described here. Users are advised to research the specifications of these products and satisfy themselves as to the suitable application for the task.

7.6.1 Fly Ash

Fly ash is a by-product of coal combustion. It is a fine powder, light to dark grey in colour. Boiling/ melting point is > 1400^0 C. Specific gravity is 2.05 to 2.8. It is non-flammable. Approx. 20% to 40% of particles are below 7 microns in diameter. The material is composed primarily of complex aluminosilicate glass, mullite, hematite, magnetite spinel and quartz. Silica-crystalline as quartz is 1 – 5% and mullite 1 – 5%. It does not decompose on heating.

The Fly ash is readily available from Power stations and can be injected through boreholes to underground roadways in a wet or dry state. It has been used successfully in both forms in a number of events.

The angle of repose of fly ash when taken straight out the power station is about 3 degrees from the horizontal. When the ash has cooled and taken up some moisture the angle of repose is about 11 degrees from the horizontal.

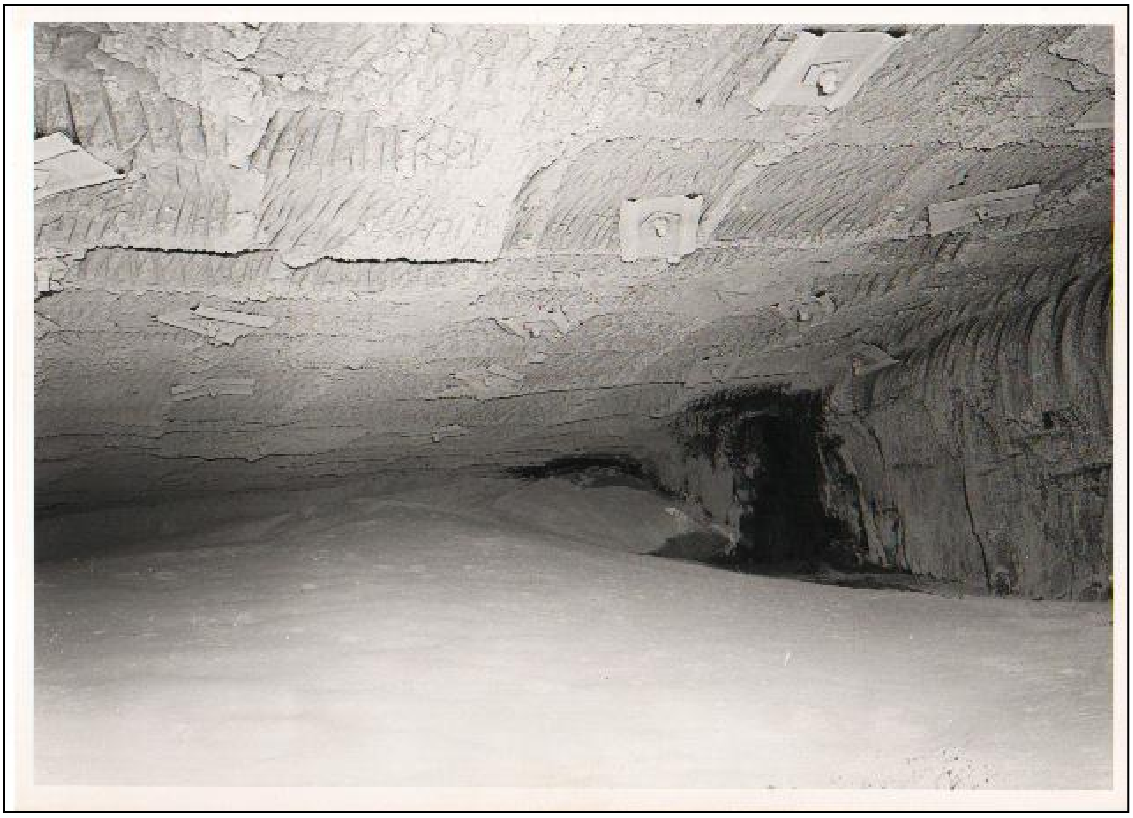
Fly ash can be placed dry in a way that gets the angle of repose up to 40 degrees from the horizontal and still get a very good seal in the roadway. This is achieved by first putting down the hole about 40,000 l of water. Dry fly ash is then pumped into the roadway as seen in Figure 34. Another 5,000l of water is placed and then more fly ash. This causes the ash to bank up on a steeper angle of repose.

For a roadway 3.5m high and 5.2m wide, on a level course, approx. 400 tonnes of fly ash would be required to plug the roadway.

Fly ash placed wet is first pre-mixed in a slurry plant as shown in Figure 35, to achieve the optimum pulp density for pumping down the borehole. There is less chance of blocking and wet fly ash can be pumped a greater distance.

Figure 35: Fly ash wet slurry plant

Figure 36: Fly ash seal in underground roadway at Moura #4



7.6.2 Roadway Filler Material

Examples of roadway filler materials are the Rocsil and Carbofill products. To fill a roadway via a borehole, two hoses are attached to a catenary wire and lowered into the borehole. Nozzle heads and check valves on hoses discharge two chemicals into the roadway. As the two chemicals mix the foam expands at about 10 to 1 and then to 35 to 1 as it sets. The phenolic foam sets to ultimate strength in about 5 minutes. Bulkheads or barriers are not required in the roadway to contain the foam.

The plug formed is estimated to be 5 to 6m wide. A description of the material flow properties is that it flows like lava, i.e., flows and sets with fresh material building on that previously discharged and set. Material strength when set is about 2 mpa. It is a sealant that should fill the roadway without voids. The material does not support combustion and has been used extensively for cavity filling and the control of spontaneous combustion.

7.6.3 Inflatable Seals

The Shaft Plug Void Sealing System (VSS), as shown in Figure 6, is designed to provide emergency and short-term sealing of an intake or exhaust shaft. The Shaft Plug can be installed remotely using a long boom crane and is also suitable for horizontal or inclined applications.

Figure 37: Inflatable Shaft Seal

The Ventstop ventilation control unit for use in underground roadways, as shown in Figure 38, has these features:

- Suitable for any size or shape of roadway

- Portable and re-usable
- Available in standard or FRAS (Fire Retardant Anti-Static) fabrics
- Continuous air trickle or bottle feed
- Available with sleeves through the seal

Figure 38: Inflatable roadway seal - Ventstop

Both the inflatable shaft seal and roadway seal require periodic topping up with compressed air to maintain the seal. In this regard they should be regarded as a short term solution. For a longer term solution, an option is to fill the bag with a foam material.

7.6.4 Remotely operated Doors

Doors that are capable of being remotely operated to close off an airway in the event of an emergency are available from a number of manufacturers. Issues in the successful design and operation of these doors include:

- Surface access
- Energy sources and means to operate doors remotely in an emergency
- Elimination of interference with door closure due to services in the roadway

The following Figures 39, 40 and 41, illustrate a system of remote door operation installed in a Queensland mine.

Figure 39: Remotely operated door

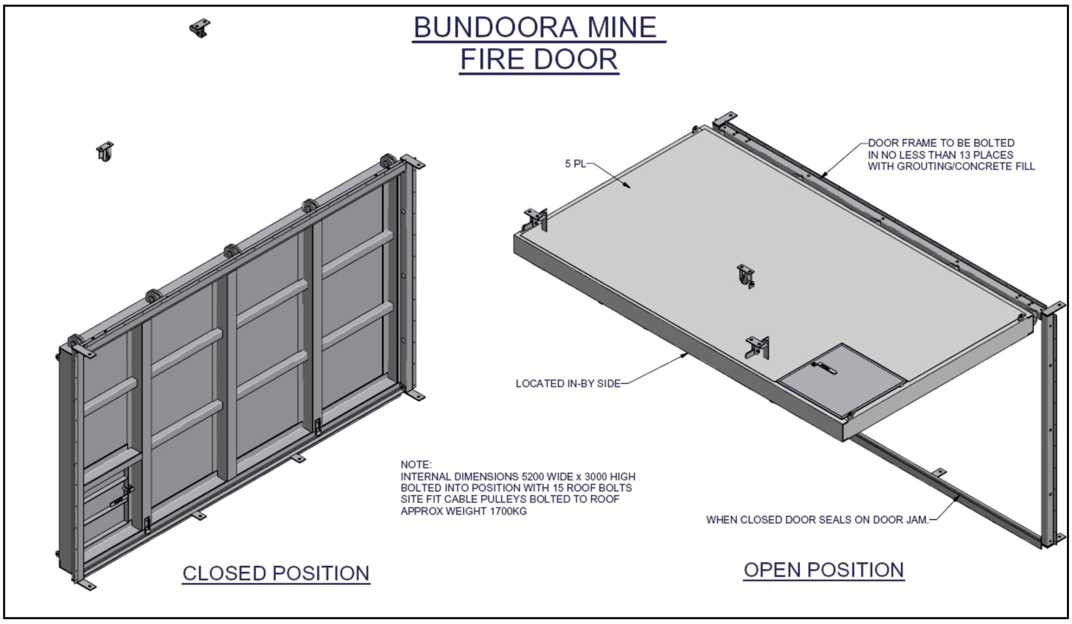


Figure 40: Remote door arrangement in an underground mine

Attached to the door is a manual winch, operated from the surface of the mine but which can also be configured to be operated from a location within the mine such as an outbye cut-through etc. The door resides in the open position & if required, (emergency), the winch firstly lifts the door slightly & the roof latches let go & allow the self-locking door to be lowered to seal the area.

Figure 41: Surface located winch to activate door

8 APPENDICES

8.1 EVENTS

There have been in excess of 125 incidents reported in NSW since 1960, most occurring in the Greta seam and Liddell seam. In Queensland, there have been in excess of 68 incidents since 1960. The following are some of the more serious or unusual events that have been documented.

An outbreak of spontaneous combustion is a potentially very serious event which can result in the following underground hazards causing harm to people:

- Fire
- Explosion
- Toxic gases
- Heat and humidity
- Poor visibility

The following events demonstrate the serious nature of heatings and different types. Common elements for a number of these incidents that should be considered in the development of a spontaneous combustion management plan are:

- Early warning signs were not detected or not acted upon
- Heatings were often first detected by a Deputy conducting a routine inspection
- Once detected, the development of the heating was very rapid

8.1.1 North Tunnel - 1970

A fall of top coal took place and the fallen coal was discovered to be on fire. Mines rescue teams were summoned and, using breathing apparatus, extinguished the flames and cooled the fallen coal.

The Greta seam has a high propensity for spontaneous combustion and there have been many spontaneous combustion events.

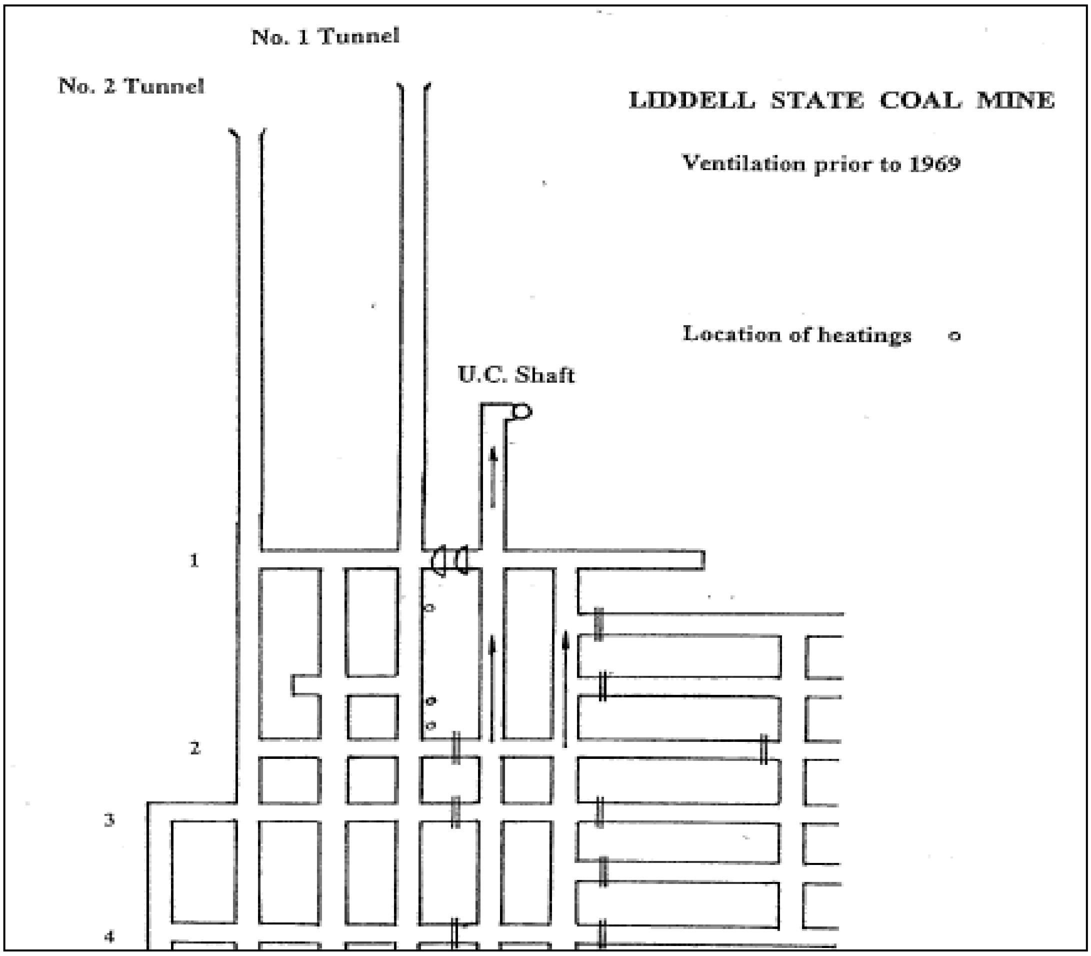
The roadway had been driven to 3m height with approx. 4m top coal supported with timber cross supports and props.

It was readily apparent that the heating had taken place in the top coal before the fall took place. The tops burst into flames after falling. Mine rescue teams report the fire hose discharge turned to steam when directed to the sides of the roof cavity.

8.1.2 Liddell - Oct 1971

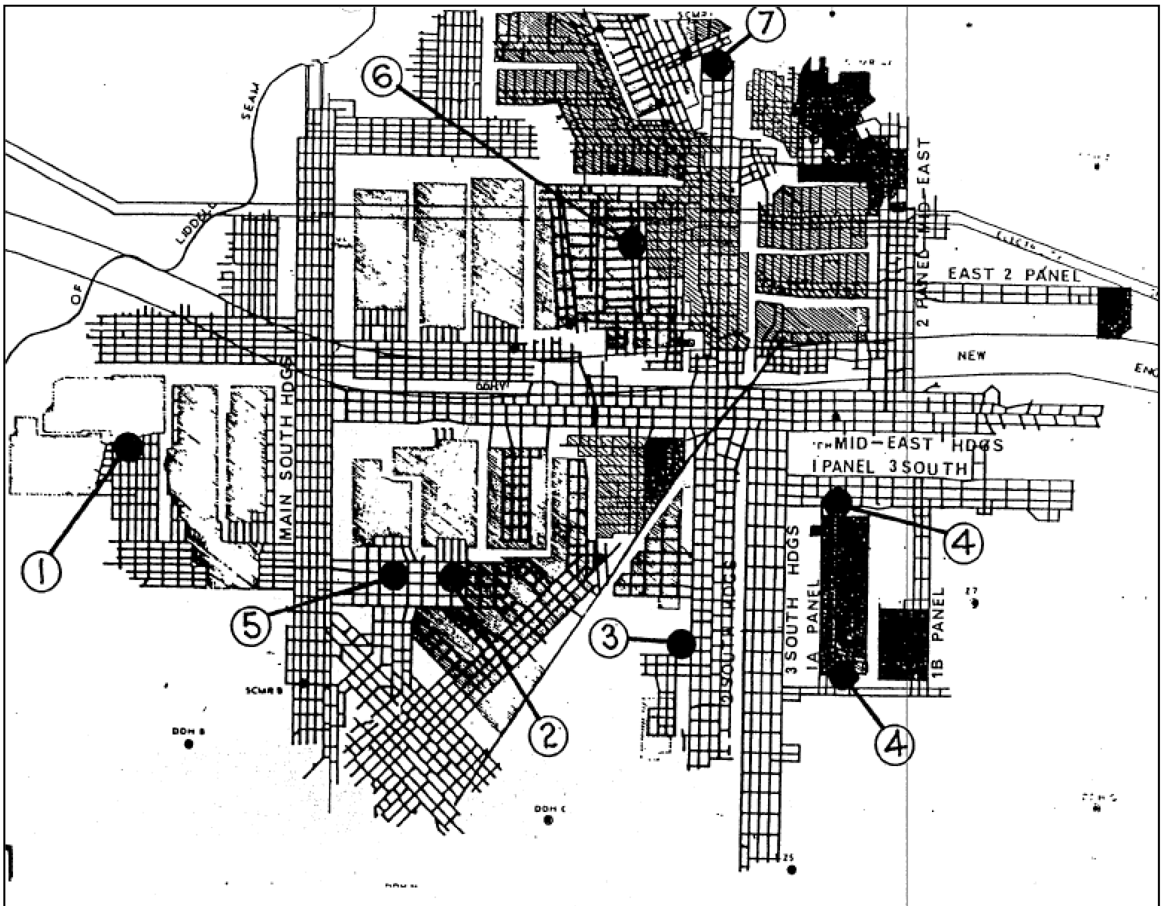
The seam mined was the Liddell. A number of heatings had occurred in the mine. Two heatings in bord and pillar extraction panels resulted in the panels being sealed. Roof falls invariably contained 0.5m or more of top coal and were another source of heatings. The background level for CO was around 3ppm and a concentration of 8ppm usually indicated a heating.

Prior to 1969 there were several heatings in the ribsides of pillars separating the main intake and return. These were dug out and the pillar treated with water infusion. An attempt was made to affect a more permanent solution by balancing the pressures around the pillar. No 2 Heading return was placed on intake pressure.



In September 1969 another heating took place in the ribside of the pillar between the intake and return. The heating was dug out and the pillar infused with water. No 2 Heading was sealed off completely between No 1 and No 4 c/t's and daily inspections and regular sampling carried out.

In October 1969 smoke issued from the edges of the seals and the carbon monoxide concentration rose from 1.04% to 2.53% on successive days. The temperature was 44^0 C. Leaks around the seals were repaired, the pillar ribs gunited and carbon dioxide injected into the area. There was improvement over the following weeks but the signs that heating was not under control. A rescue team entered the area found a heating in the ribside showing as white ash and a red glow. The seals in No 2 Heading were breached and a rescue team hosed and dug out the heating. Again water infusion was carried out.



LIDDELL STATE COAL MINE
SECTION HEATING LOCATIONS
1964 to 1973

In December 1969 a new return airway was driven and the pillars between No 1 and 2 Headings were put on intake pressure (Fig 4). Inspections and monitoring were carried out on a close regular basis. For 22 months there were no indications that anything was other than normal until a fire broke out on 21 Oct 1971. The mine was evacuated and sealed.

A pre-shift inspection of the mine at 9.30 pm on Sunday 24/10/71 determined nothing abnormal. A Deputy later said that there was some haze that he thought was diesel smoke in the transport road. The first transport left the surface at 12.10am on Monday 25/10/71 and at No 5 c/t the driver stopped the transport when he noticed an unusual smell. Smoke was found issuing from No 1 and 3 c/t's into the belt heading but was too thick to allow entry to locate the source.

Brattice stoppings were erected across the main intakes below No 1 c/t and a hole in the No 3 c/t stopping enlarged to clear the smoke. The smoke was forced back to the second ventilation door at No 1 c/t but was never cleared beyond that point. Fire hoses at this stage were being directed at the smoke.

At 1.00am the concentration at the fan was 10ppm but there was no fire smell. At 2.30am some burning material was seen falling from the roof at the intersection of No 2 Heading and No 1 c/t and it was obvious that a fire was located in the top coal.

At 4.00am the CO level at the fan had risen to 50ppm and the situation was worsening. A rescue team was sent to open a stopping at No 4 c/t to short circuit the ventilation. The team had just left the FAB when a fall occurred outbye flooding the FAB with dense smoke and catching the standby team uncoupled. Both teams eventually retreated in nil visibility across the No 2 c/t to No 5 Heading and fresh air. The fall had occurred in the intersection of No 1 c/t and No 2 Heading and was a mass of flame.

Attempts to fight the fire with water and foam were not successful. During a 40 minute period when foam ran out, results improved. Variations to ventilation made no improvement. There was a sudden increase in black smoke at the fan shaft. The heavy smoke from the fan was soon followed by flames rising to a height of about 15-20 metres. Soon after, the fan stopped and, the fan building collapsed. The mine was then sealed.

Contributing factors to the heating that occurred near the entries of the mine were determined to be:

- General nature of the Liddell seam coal
- Porous nature of the coal, particularly near the outcrop
- Pressure difference between intake and return (approx. 500 pascals)
- Relatively small size of pillars between intake and return (22m)

8.1.3 North Tunnel - 1975

The heating developed in the goaf of a bord and pillar extraction panel.

The Greta seam ranges in thickness from 7m to 10m. The bottom section was mined on development for reasons of coal quality and some top coal recovered during the extraction process. Generally, methane is not detected in the Greta seam up to a depth of cover of about 300m. Methane and other explosive gases are produced by the distillation of coal.

Attempts were made to construct 6 seals to isolate the goaf where the heating took place. During this process three small explosions in the goaf area took place. This caused the sealing of the panel to be abandoned and the mine was sealed at the entries. It was subsequently re-entered and production resumed.

8.1.4 Kianga No.1 - Sep 1975

About 5.10pm on Saturday, September 20th, 1975, an explosion occurred in the Kianga No. 1 underground mine. Thirteen men lost their lives. The men were engaged in sealing a heating in the No. 4 section of the mine at the time of the explosion. The magnitude of the explosion was such that sections of the main conveyor were blown out of the mine. Belt rollers were blown 200m to 300m from the tunnel mouth.

A deputy commencing a pre-shift inspection on 20th September entered the return at 7.30am and noticed a slight haze. He walked inbye for 2 pillars without noticing anything unusual and then returned to the surface to take observations at the fan. He saw no smoke but attributed a fire stink to a fire that had occurred previously in a bolter shunt outbye of the fan shaft. Nevertheless he was still suspicious and immediately reported to the manager.

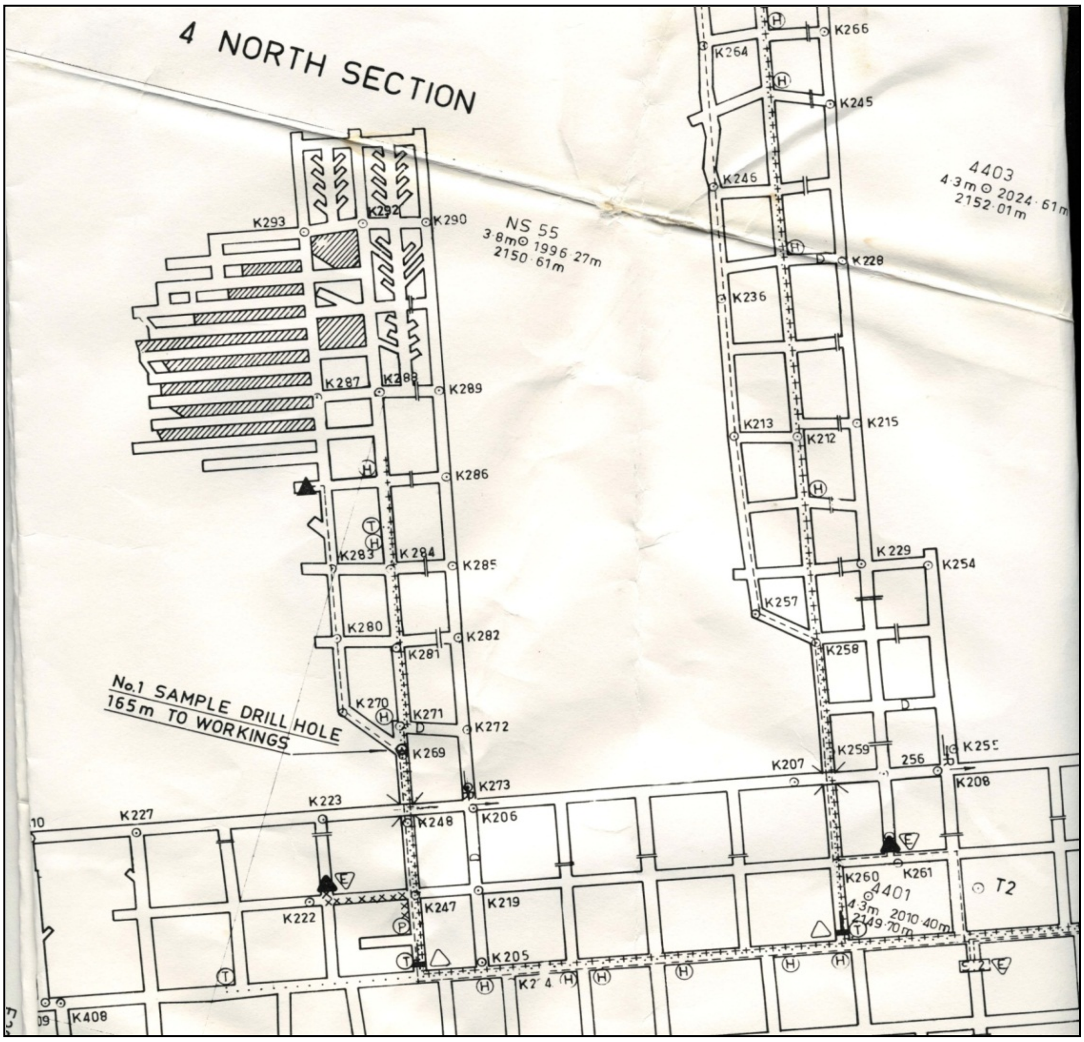
The manager and the deputy went underground to 2 North return and then 4 North where, in the return, smoke was obvious and the fire stink smell more obvious. Gas readings were taken with 25ppm CO being detected.

Construction of the brick seals commenced at 11.30am. Readings of 80ppm CO and 1% CH_4 were noted. At about 5.10pm, a popping sound was heard, lights flickered and an explosion took place.

Approx. 3m of the bottom section of a 4.2m seam was mined by the use of continuous miners. The seam was gassy and liable to spontaneous combustion. The goaf was partially ventilated. Eight (8) rows of pillars had been developed and 3 rows of pillars extracted. This was about 6 months work.

Evidence of a heating had been discovered in the goaf area of 4 North. There appears to have been a large body of methane in the goaf with 3% to 4% found at the edge of the goaf at 7 c/t. Over the 6hr period prior to the explosion, a barometric drop of not less than 5 millibars occurred.

The use at the mine of a Beckman gas analyser was a considerable improvement on methods generally in use in Queensland at the time. The normal signs of sweating, fire stink and haze were not reported in 4 North return prior to the discovery of smoke.



8.1.5 Leichardt Colliery - Dec 1981

Leichardt Colliery is located near Blackwater in Queensland. Mine entries were two vertical shafts equipped with winders. The mine had a history of outbursts and high methane emissions. (CH_4 16m3/ tonne) The 6m thick Gemini seam was mined at a depth of cover of about 400m. Mining in the Gemini seam commenced in 1969 and spontaneous combustions problems were not experienced until 1981.

On 6.20am on 29th December 1981, a Deputy on a pre-shift inspection discovered a smoke haze at the pit bottom of No. 2 Shaft. Further investigation revealed thick smoke coming from the main east return and that 10ppm CO was present in the return shaft.

At 11.30am on 29th December, the IMT group decided no further action would be taken until a detailed analysis of the atmosphere was available. Gas samples were dispatched to Brisbane and ACIRL asked to supply a gas chromatograph.

At about 8.40pm, the first results were obtained from Brisbane. The chromatograph was damaged in transit and failed to function for about 9 hours.

On the basis of the gas results, a rescue team was send underground at 12 noon to establish the source of the heating. The first team entering the mine detected thick smoke and about 800 ppm CO at No 4 c/t on the east belt road. Smoke reduced visibility to an intolerable level and the team retreated to the adjacent track road. The team continued inbye to No 5 c/t and again encountered thick smoke and high temperature.

An exploration across No 5 c/t revealed the source of the heating in a pile of slack coal in a stub end in the right hand rib of the belt road inbye No 5 c/t. Open flame was visible in a number of areas over a distance of about 5m. They determined the fire was poorly ventilated but relatively stable and the gases produced were non-explosive.

Mine rescue teams fought the fire during the remainder of the day. At midnight, the area was declared safe and they continued to hose down the heated zone for the following 12 hours before the slack coal was loaded out. This was completed by 4.30am on 31st December 1981.

8.1.6 Laleham No.1 1982

Laleham Colliery is located about 40km south of Blackwater in Queensland. The 3.7m thick Pollux seam is worked. During 1974 and 1975, serious heatings were experienced in pillars between main intake and return roadways and in July 1975, a serious heating was detected in the goaf of a pillar extraction panel.

In 4th May 1982, a Deputy on a routine inspection of outbye intake roadways discovered smoke and 150 ppm CO on a Drager tube. Subsequent investigations revealed dense smoke and CO in excess of 3000 ppm issuing from an inaccessible area of intake roadway.

This event resulted in the closure of the mine for about seven days and required a major reorganisation of the ventilation network which was not completed until 25th September 1982.

Monitoring showed that the situation was very serious with the atmosphere in the sealed area either explosive or potentially explosive on number of occasions. The major flammable contribution to the explosive atmosphere was hydrogen which reached a peak of 4.57% on 8th May 1982. This abnormally high concentration may have been due to the injection of water onto the heated zone which may have produced water gas.

Attempts were made to inject water into the barrier pillar between the approx. site of the heating and the main intake roadway. At the same time, attempts were made to gain access to the site by loading out a fall. This was abandoned due to boggy floor, heavy roof and a clear indication the fire area was increasing. It was then decided to seal the area. While this was being done, four long holes were drilled through the barrier pillar and these were connected with hoses for water infusion.

The final sealing was accomplished on 5th May 1982. By this time, the atmosphere coming from the fire area contained thick black smoke a strong tarry odour.

Holes were drilled from the surface to intersect roadways affected by the fire, and to fill the voids with concrete slurry. Despite 1,562 m^3 of concrete slurry being used to affect a seal, high levels of CO were still being produced.

An attempt was made to inject the pillar with bentonite grout and concrete slurry and when this proved unsuccessful, a further six holes were drilled from the surface to fill any remaining voids with fly ash. Although a total of 360 tonnes of fly ash was used, high levels of CO continued to be liberated from cracks in the pillar. These areas were treated by the injection of bentonite and cement grout. The problem was not entirely solved until the pressure differential was removed on 25th September 1982.

8.1.7 Newstan - 1982

The heating took place in a bord and pillar extraction panel that had been completed and sealed for some time. The borehole seam was overlain by the Dudley seam in close proximity. Inter-burden between the borehole and Dudley failed over the seals and allowed air ingress.

Additional stoppings were placed outbye where seals had failed to control the heating

8.1.8 Moura No.2 - Apr 1986

Moura No 2 mine is located in the Moura coalfield in the south eastern part of the Bowen Basin in Queensland. There are five economically exploitable seams, varying from about 2.1m to 7m in thickness. Seam thickness in the "D" seam worked varies from 2.4m to greater than 6m. Extraction panels are driven off main headings and several methods of extraction by continuous miners are employed, including mining of bottom coal and partial extraction.

At 6.40 am on 19th April 1986, a Deputy on a routine inspection of the face area of 5NW pillar extraction unit sampled 13ppm CO and 0.09% CO_2. At the same time, the mine monitoring system recorded 12 ppm CO at a monitoring point about 800m outbye the face of 5NW. Determinations made closer to the goaf edge detected 40 ppm and a slight haze.

At 11.45 am, a "non-typical" gob stink was noted with a definite smoke haze visible in the beam of a cap lamp. By about 2.15pm, 90 ppm CO was detected at the goaf edge, the smoke haze was heavier and a gob stink clearly evident.

Sealing of the area was affected by bricking up the openings in four preparatory seals. This was completed by 5.10am on 19th April 1986. All men were then withdrawn from the mine. During sealing operations, gases were monitored. The highest level of CO detected in the east return was 150 ppm. Monitoring of the atmosphere behind the seals was not possible and the mine was shut down until 5.30am the next day when an inspection revealed the atmosphere has passed through the explosive range.

Monitoring of the atmosphere behind the seals continued over the weeks that followed and indications were that the area was stable. A seal was breached on 10th May 1986 and a rescue team entered via an airlock. After advancing about 200m they reported CO levels in excess of 3,000 ppm. A tube bundle line was advanced to this point and the team retreated. Monitoring of the atmosphere continued during the following weeks and when the CO level dropped to about 1100 ppm, a second attempt was made on 24th May 1986.

Rescue teams constructed brattice stoppings immediately outbye of the goaf edge and the panel was ready for re-ventilation on 2nd June 1986.

After a detailed inspection by rescue teams, the seals were breached on 2nd June 1986. A team of 28 miners, fitters and electricians began a well-executed recovery operation which was completed by 7.15am on 3rd June 1986.

8.1.9 New Hope - Jun 1989

New Hope No.1 mine mined the Bluff seam using bord and pillar methods with the splitting of pillars and the taking of the bottoms on retreat. The seam is around 9.1 metres thick and dips at 1 in 2.8. The seam contains a low level of methane.

The primary indicator of spontaneous combustion was the detection of CO. Background levels in panel returns were typically 1 to 2ppm. The mine had installed a Maihak UNOR 6N analyser with a tube bundle system. This was augmented by hand held monitors.

On Wednesday 31 May 1989, the afternoon shift deputy noticed a reading of 4 ppm of CO in the return for WL1 A section. He established that this was a continuous reading and not due to diesel vehicle emissions. He noted this in his report but took no other action.

On 1 June 1989 the day shift deputy noted the monitor was showing 6 ppm. Further inspection revealed 30 ppm CO immediately after passing through the stoppings. As they went further into the panel they found the O2 content of the air was decreasing evenly across all three roadways and that CO content was rising. This rise was greatest in the belt road and three pillars inbye of the stoppings 45 ppm CO was found. By 10 am the CO content in the supply road had risen to 45 ppm. Men were withdrawn from the panel and Flygty seals placed.

On Monday 5 June, the atmosphere was 89 ppm CO and 17.9 % O_2. The situation seemed stable. Men were detailed to erect permanent brick stoppings directly outbye the flygty stoppings. Falls were occurring in the waste workings which were thought to cause damage to the flygty seals.

On Tuesday 101 ppm CO and 16.6 % O_2, was recorded and on Wednesday, readings were 130 ppm CO and 16.1 % O_2. Mining in the WL1 B section continued and the erection of brick seals progressed.

Samples collected at 7 am on Thursday 8 June indicated 66 ppm H_2. Production in 1B was stopped and all efforts were devoted to completing the brick seals. The stoppings were completed by midday Friday and production recommenced in 1B section. At 4:30 pm the GC results indicated 250 ppm CO and 200 ppm H_2 with 14.4% 02. Because of the rapid rise in H_2 all men were withdrawn from the mine.

By 14 June the oxygen concentration had fallen to 11.5% and the CO was 389 ppm and H_2 was 307 ppm. Men re-entered the mine and brick stoppings were bond-creted to ensure that the seals were air tight. As the fire gas and oxygen concentrations fell the frequency of sampling decreased until gas chromatographic analysis was discontinued on 4 July. No evidence of an activity has since been detected.

8.1.10 Lemington - Jan 1991

A spontaneous combustion event took place in the goaf area of panel 131. There was no seam gas and the working height was between 3 and 4 metres. The 6 heading panel had 3 intakes and 3 returns, with flanking returns.

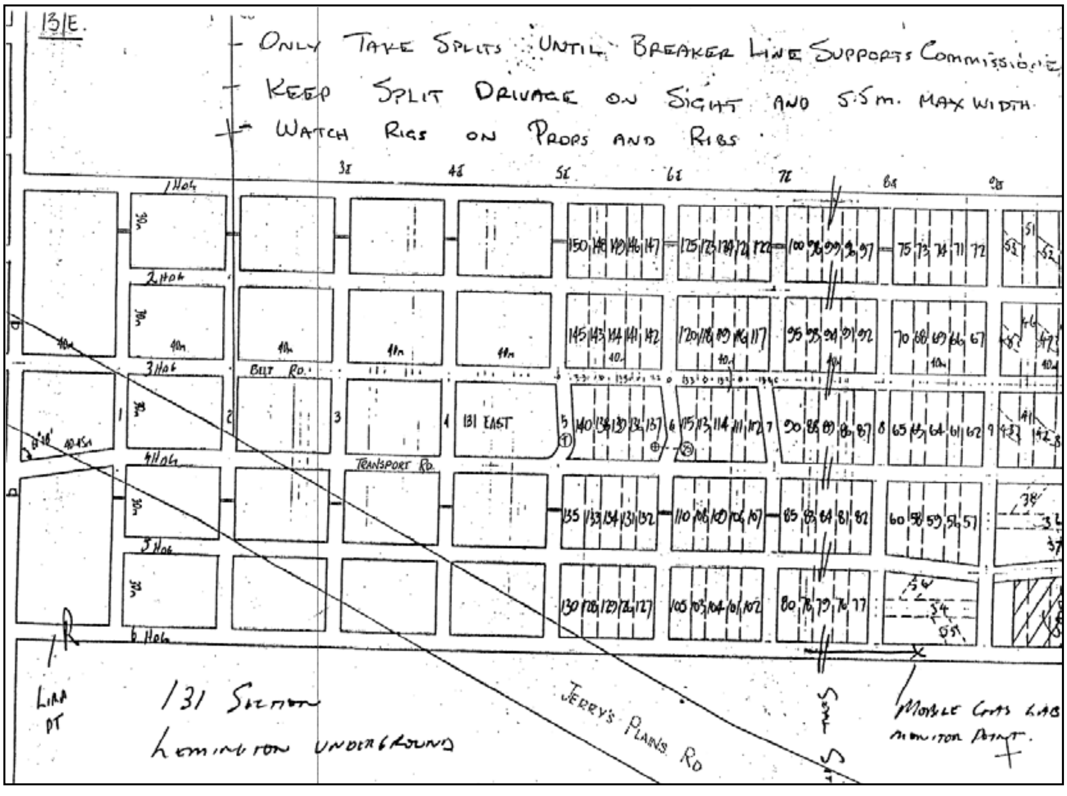
The fire was caused by spontaneous combustion and activated when mining recommenced after a two month break in production. The area was eventually sealed by a line of stoppings a pillar length outbye the goaf edge. An “inert-rich” atmosphere developed within the sealed area which extinguished the fire.

The mine was evacuated during the crucial phase when remote tube monitoring indicated that the sealed area atmosphere passed through the explosive range.

Events reported were:

- Sep 3rd 1990 Pillar extraction in 131 east panel ceased when the continuous miner was buried in a goaf fall
- Sep 17th 1990 A continuous miner was set up in the section. Mine. Ventilation was increased to levels required by statutory limits. 50ppm CO was detected in the return at the goaf edge. The Lira tube bundle system showed no cause for alarm.
- Jan 18th 1991 Production recommenced on afternoon shift splitting pillars. Low levels of CO were detected at the goaf edge, peaking at 80ppm
- Jan 21st 1991 Production on 3 shifts. Low levels of CO (70ppm) were detected in the return at the goaf edge.
  Jan 22nd 1991 Production on 3 shifts.
- Low levels of CO. (70ppm) detected in the return at the goaf edge. At 4.00am, the Lira detected CO above the background level (22ppm)

- Jan 23rd 1991 Production on 3 shifts. Low levels of CO (70ppm) were detected in the return at the goaf edge. CO incursion on afternoon shift, increase by a significant fall in the barometer.
- Jan 24th 1991 At midnight, heavy smoke was detected in 6 heading return. Production did not recommence. Men were withdrawn to a fresh air area. At 7.00am they decided to seal the area. Seal construction commenced at 11.00am and was completed by 9.25pm.Continuous monitoring within the sealed area by the mobile lab commenced at 5.00pm. All men out of the mine by 10.05pm.
- Jan 26th 1991 Monitoring indicated the area had passed through the explosive range.
- Jan 28th 1991 Pre-shift inspection of the mine with a view to restoring power. Bag samples were taken from the sealed area. Maintenance work commenced to resume production.



8.1.11 Ulan – Aug 1991

There was a heating in the longwall block at Ulan in December 1990 that had reappeared in a minor form on several occasions. Management were in the process of trying to control that heating through improved sealing of the bleeder roadways when another major event occurred.

On 9th July 1991, a rise in oxygen was noted behind seal 23 and a rise in CO. The rate of seal repairs increased. On 4th August, H2 was first detected.

On 7th August, 2250ppm CO was detected in the goaf and H_2 increased to 0.25%.

On 8th August 1991, at approximately 6.15pm smoke was noticed on longwall 5 face and a red glow reflecting on the coal rib-side was observe> 3000ppm, 2% CO & 2% CH_4 in Longwall 6 tailgate at 21 c/t. At 6.25pm, Drager readings at L2 6 were 7000ppm CO and 4% H_2. At 6.30pm there was an alarm at the fan. Evacuation of employees commenced at 6.40pm. At 7.55pm, Drager readings at the fan were CO > 3000ppm, 2%CO_2 & 2% CH_4.

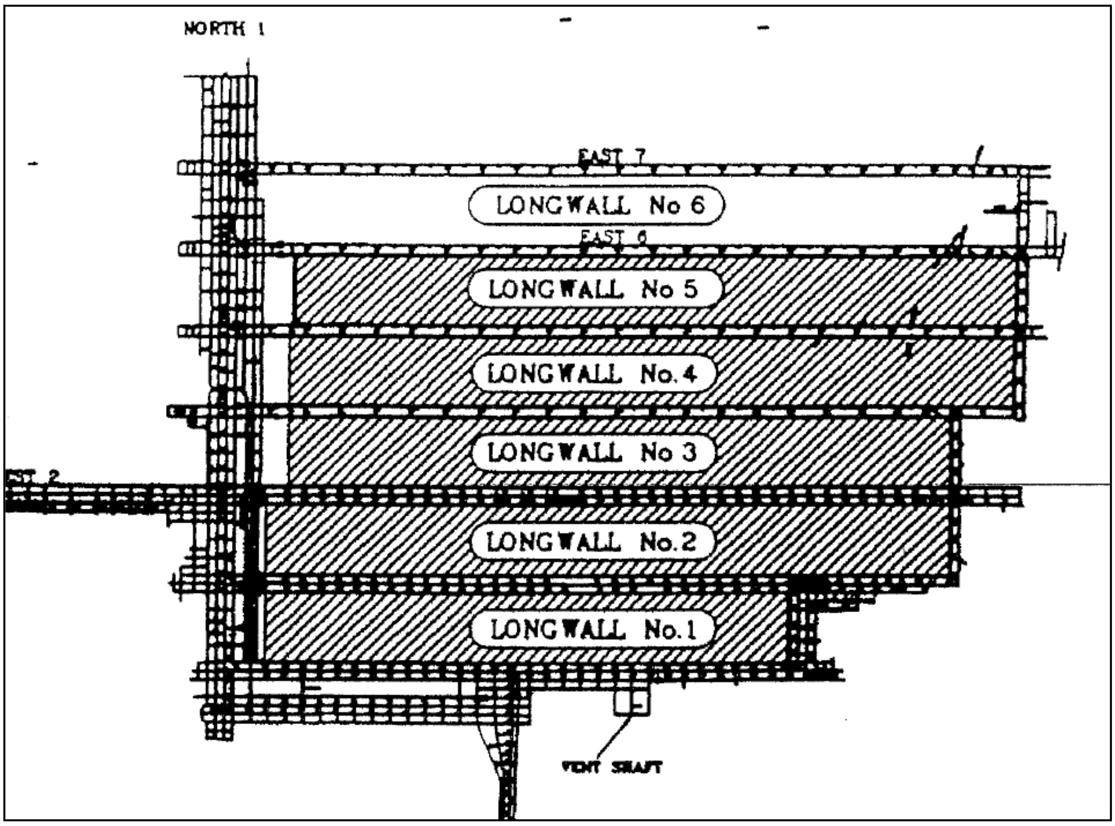
The mine was then sealed. Subsequently, the area suspected of heating was flooded and the atmosphere inertised by the introduction of gaseous nitrogen.

The Ulan seam was believed to have a low liability to spontaneous combustion. There was no seam gas. The bottom 3m section of the 10 to 14m thick seam was worked. Gate road stoppings were constructed from plasterboard.

The main contributing factors to the heating were considered to be:

- Lack of appreciation of the liability of the seam to spontaneous combustion
- Inappropriate ventilation layout
- Lack of understanding of spontaneous combustion initiation
- Incorrect interpretation/ analysis of monitoring results
- Insufficient monitoring information
- Inadequate ventilation standards
- Lack of pre-determined action plan
- Unclear definition of responsibilities

The mine resumed operations in March 1992.



8.1.12 Huntly West, New Zealand – Sep. 1992

Huntly West is a State owned mine developed in the Waikato region of New Zealand. The Kupakupa seam is mined and is a sub-bituminous coal with a very high propensity to spontaneous combustion. R70 = 10 to 16.5.

Depth of cover is approx. 300m. The seam is up to 6m thick with an undulating pavement and a number of structures. The coal deposit has varying thickness and roof and floor gradients. The roof and floor lithology is weaker than the coal and the optimum roadway stability is achieved with a coal roof and floor. Methane drainage is practiced and the returns contain 0.4% CH_4

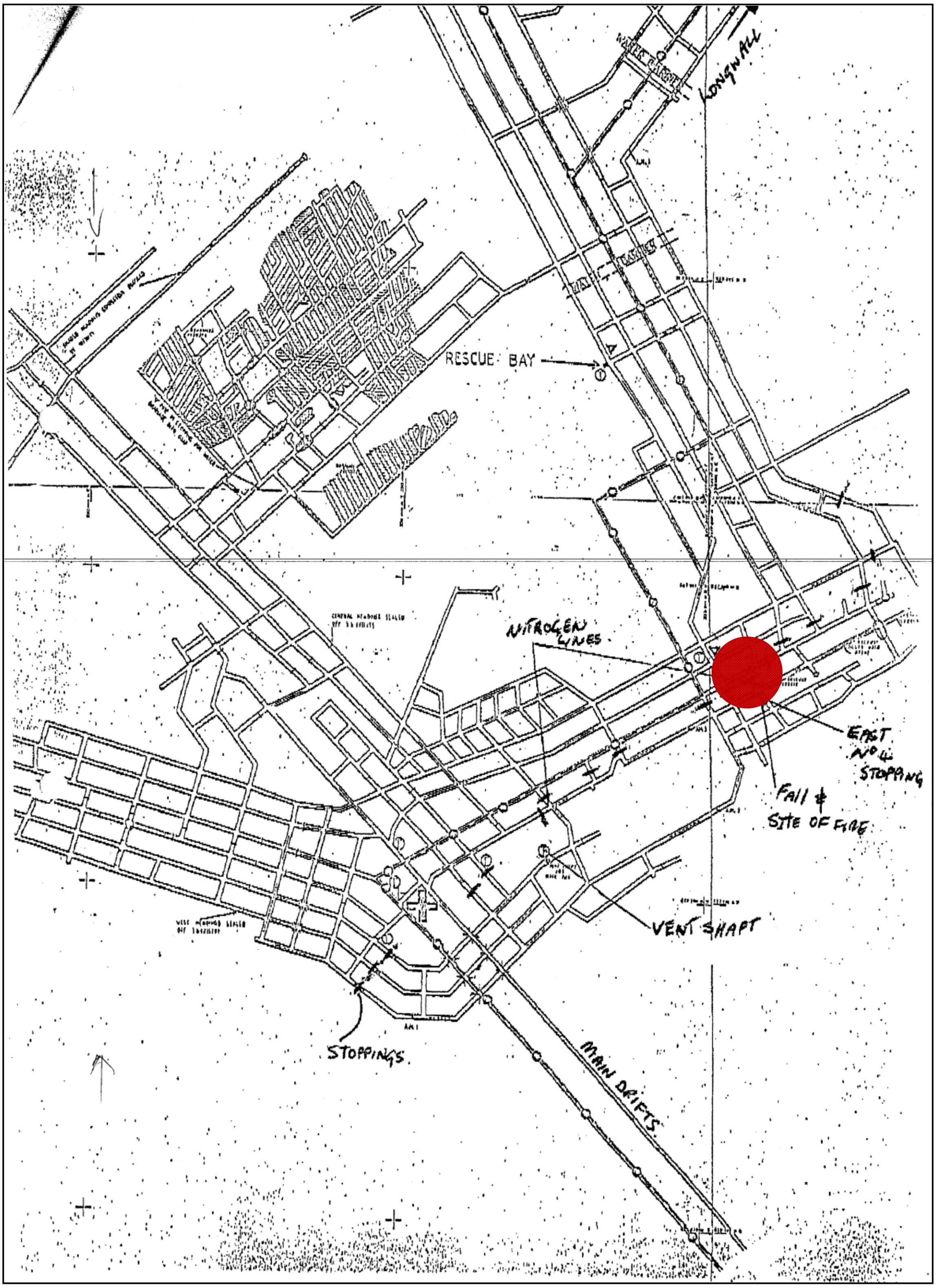
Initially coal was won on development only. Trials on total extraction and hydraulic mining failed. There was a history of spontaneous combustion in roadway sides and junctions. Longwall equipment was purchased in 1986 and the longwall commenced in September 1991. There were problems with face guttering and frequent spontaneous combustion issues in the longwall goaf.

Vaporised liquid Nitrogen was routinely injected into the Longwall goaf from pipes through trailing longwall supports at the rate of 100 – 100 m^3/hr. It was common for CO to exceed 1000ppm after sealing the longwall

Events were:

- Nov 11th 1991 longwall sealed due to heating
- Feb 13th 1992 longwall re-ventilated
- Mar 24th 1992 fall on face and heating in goaf

- Apr 18th 1992 longwall re-ventilated
- May 5th 1992 longwall sealed due to heating
- May14th 1992 longwall re-ventilated and re-sealed 5 hr. later
- June 30 1992 longwall re-ventilated then re-sealed 30 hr. Later
- June 29 1992 - longwall re-ventilated
- July 15 1992 - longwall sealed
- Sept 16 1992 - fire observed at No. 4 seal (see plan for location)
- Sept 18 1992 - fire out, minor smoke cleared, 48 hr. evacuation
- Sep 19 1992 - inspection determined all okay
- Sept 20 1992 - High CO in East Returns
- Sept 20 1992 - fighting fire with water and foam failed. Roof fall at No.4 seal. In seam sealing attempts failed. It was sealed at the surface with tarpaulins and Nitrogen pumped into the mine. The main fan was stopped.
- Sept 23 1992 4:45 pm - atmosphere explosive 9.5 % CH_4


LONGWALL
RESCUE BAY
NITROGEN LINES
EAST No 4 STOPPING
FALL & SITE OF FIRE
VENT SHAFT
STOPPINGS
MAIN DRIFTS

The following photograph shows the resulting damage to the mine transport portal.

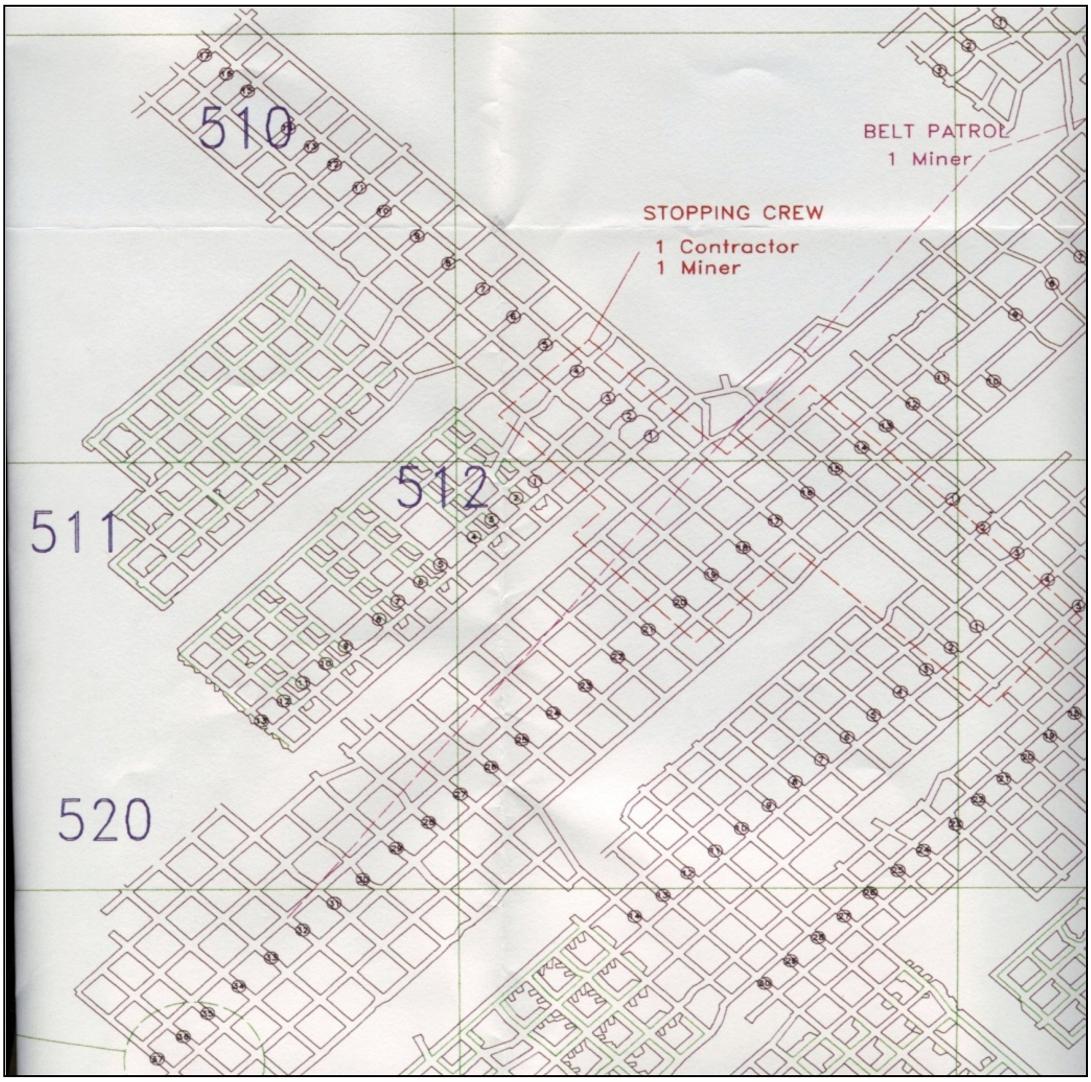
8.1.13 Moura No.2 – Aug 1994 – 11 Fatalities

The sealing of a bord and pillar extraction panel, 512 section, commenced on Saturday 6th August 1994. Sealing was completed at about 1am the following day.

Eleven (11) mineworkers were killed by an explosion that took place at 11.40pm. Ten (10) men were working in the 5 south production panel, which is located in another air split some three kilometres inbye and they self-escaped. It is believed the first explosion originated in 512 panel when a heating ignited flammable gas.

No.2 coal mine seam had inseam methane drainage. Seam gas content was $15m^3/t$ before drainage. The 5 South panel had been drained of methane and the panel was on development. The amount of methane being released out of the coal at the time of cutting was not high, less than one-half per cent in the section return.

The seam was 4.5m in thickness and the gradient 1 in 8. The top 3m was mined on development and bottoms mined on extraction. It was a partial extraction system.



8.1.14 North Goonyella – 1997

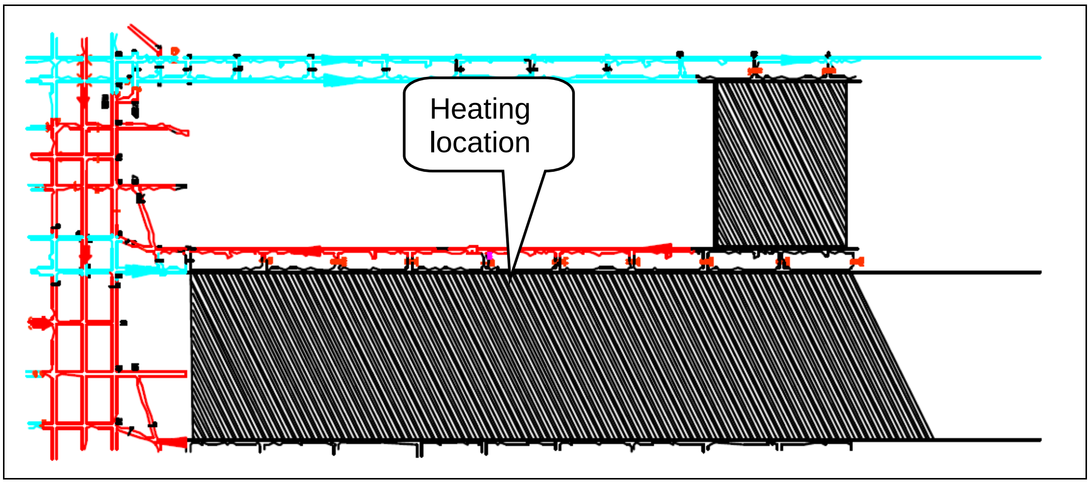
North Goonyella is a large longwall operation mining the Goonyella Middle Seam. Due to the seam thickness significant quantities of roof coal are left in the goaf. At the time of this incident, at the end of 1997, the mine operated two longwalls, numbers 3 and 4 South concurrently.

Three South longwall was only 9 metres from the take-off line whist four south face was just outbye 9 cut-through. An advanced heating was detected in the goaf of LW3.

On the afternoon of the 28/12/97 a deputy detected 25ppm of Carbon Monoxide (CO) in the general body of 6 c/t in Longwall 4 Tailgate. This reading was followed up with bag samples from the Longwall 3 goaf out of the 5 and 7 cut-through seals. The 6 c/t seal sample pipes were blocked with mud and water. The manager ordered the evacuation of the mine at 5.55pm on the 29/12/97 following the confirmation of the results of these bag samples. The bag sample results were as follows:

	H_2	CO_2	C_2H_6	O_2	CO	CH_4
7 c/t	0.4%	14.0%	0.08%	3.15%	0.13%	2.09%
5 c/t	0.43%	4.6%	0.05%	14.86%	0.12%	0.90%

This event is generally recognised as the most serious spontaneous combustion event to have occurred in Queensland since the Moura No. 4 explosion. Following as it did only a few months after the trials of the Tomlinson Boiler it was to be a crucial event in proving the ability of low flow inertisation techniques to treat serious goaf heatings. A heating which would have historically resulted in the loss of at least the section and possibly the mine's ability to produce for many weeks was controlled over a period of five days.



Plan of longwall 3 and 4 South Panels North Goonyella

8.1.15 Newlands - 1998

The Upper Newlands seam varies in thickness from 6 to 7 metres, with the lower 3m being mined. The predominant seam gas is methane in concentrations of above 95% Early tests on the Upper Newlands seam classified it as having a 'moderate to high propensity' for spontaneous combustion

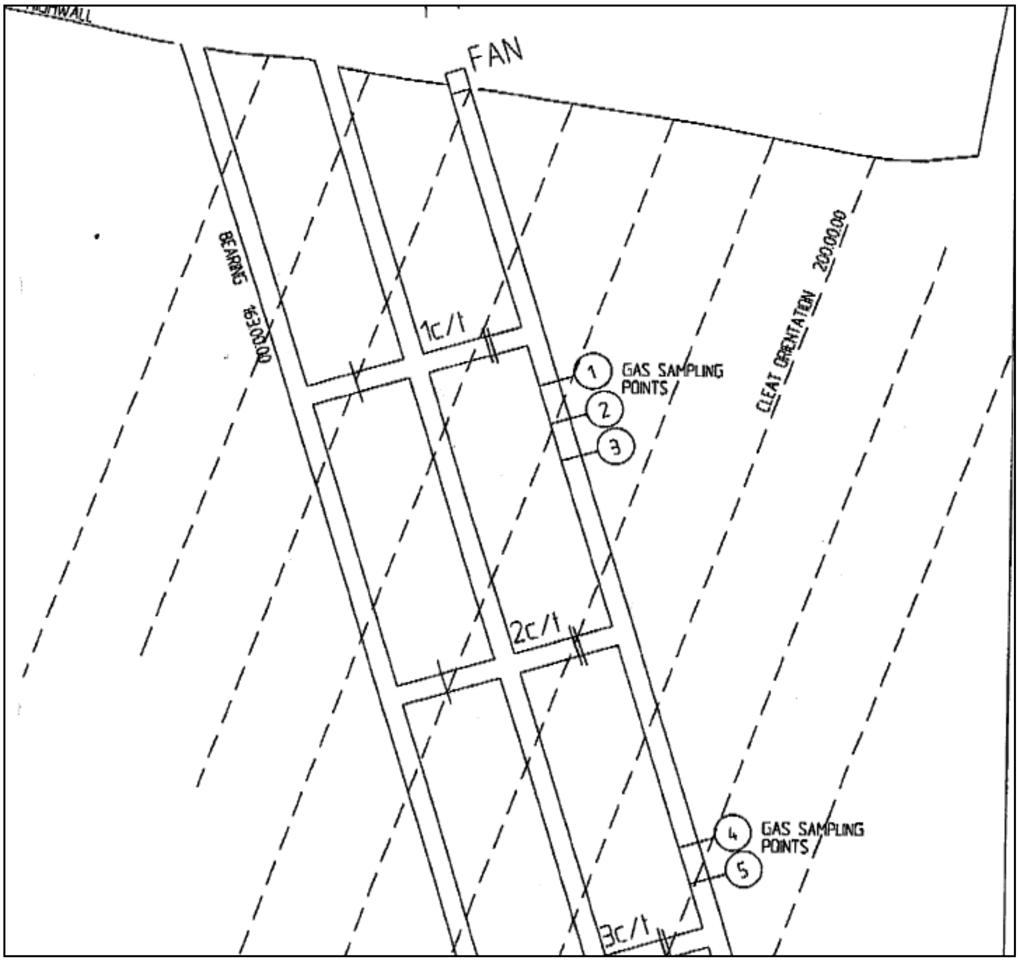
A number of small heatings took place near the portal entries in April and May of 1998 prior to longwall mining commencement. Newlands now classes the seam as having a high propensity.

Contributing factors to the heatings were considered to be:

- A sustained pressure differential of 400Pa across coal pillars that contained a large amount of open fractures
- Air migration through the fractures.
- High ventilation quantities concealing any products of the heating from monitoring devices located outbye.

The heatings were first contained by water injection and later by injection of both silicate resin and strata seal products. Injection varied in depth and direction in relation to the cleat direction for maximum results.

Temperature monitoring of roof and rib surfaces along with in seam measurements showed that a surface temperature of 30 to 35 degrees was an indicator of higher heat below the surface. Temperatures below the surface ranged up to 300 degrees. The 30 degree trigger was a valuable tool for the identification of further hot spots. Atmospheric monitoring, including minigas readings and bag samples was also used in the system for detection.



Plan of Newland entries

8.1.16 Blair Athol - 1999

Blair Athol Coal (BAC) is an open cut coal mine producing 11mtpa of export quality steaming coal from the 30m thick Number 3 Seam. The No.3 Seam is overlaid by an average of 40m of overburden. The 1-2m thick No.2 Seam, is spoiled with the overburden.

Underground coal mining commenced at Blair Athol in the 1890's. Four (4) underground mines have affected approx. 50% of the coal deposit. The No 3 Colliery closed in the 1950's. It had three levels of workings and a history of heatings.

The most significant intersection of the open-cut and underground workings was when strip 16 east intersected the Blair Athol No 3 Colliery in 1999. A significant fire started in exposed coal at the end of the strip. This fire was successfully smothered with overburden and it was assumed that any heating in the old workings could be treated this way.

However, as the dragline began to uncover the coal a number of openings on top of coal and in the new highwall began to emit smoke and steam. BAC were alerted to two major hazards. Firstly, concentrations of CO up to 1.2% (1200ppm) were present in the smoke venting from the workings. Secondly, there was a risk that an explosive mixture of distilled gases from the fires could be present in the workings. The area of the mine was evacuated until the composition of the atmosphere within the workings could be determined.

After some discussion, the DME recommended CO exposure limits of:

- Time Weighted Average (8 hours) 30ppm
- Short Term Exposure Limit (15 minutes) 200ppm
- Absolute Limit 400ppm

Exceedance of any these limits resulted in withdrawal of persons for the remainder of their shift. Research indicated that these limits were appropriate to ensure blood carboxyhaemoglobin levels were maintained at acceptable levels.

Monitoring boreholes were drilled into the workings from the surface, and a bundle tube system set up to sample gas from the holes. A typical analysis from the holes was 10% Carbon Monoxide, 12% Hydrogen, 4% Methane and less than 1% Oxygen; a very fuel rich, but inert, atmosphere. Such an atmosphere was somewhat outside that normally experienced in Australian mines.

Flooding the colliery with water was attempted to treat the fires. Water was pumped down 2 x 150mm boreholes into the workings for several weeks. The water had limited success, only marginally reducing the level of combustible gases.

By this stage, the uncovered strip of coal was burning strongly. The roof of a number of roadways had burnt through to the surface, exposing glowing hot ashes and a number were also burning with a blue flame. Water was diverted straight over the highwall onto the top of coal and mud and water were washed over the coal surface, smothering many of the more active fires. However, the atmosphere within the colliery remained rich with combustibles.

To control the explosion risk and continue mining operations it was decided to isolate the main section of the colliery from the current strip, inertise the atmosphere in the underground openings and smother the burning top of coal with a thin layer of overburden.

A GAG unit, Tomlinson boiler and Floxal units were used to flush and inertise the underground atmosphere.

To access the underground workings for use of the GAG, a 900mm hole was drilled into the workings. The GAG typically generated output of around 17.5m^3/s of inert gas at less than 0.1% Oxygen, and this has been adequate to generate an inert atmosphere within the workings in between 1 and 4 hours. In total 5 GAG campaigns have been run at BAC. QMRS recommend a minimum of 6 operators

8.1.17 **Wallarah – Aug 2001**

A heating took place in the Great Northern seam in August 2001. The seam was not considered to be a spontaneous combustion risk in underground mining, and this was the first recorded event despite the seam being mined for many years.

The exact site of the heating was not determined but considered to be in an area of old waste workings influenced by a ventilation connection between Wallarah and Moonie Collieries near Lake Macquarie NSW.

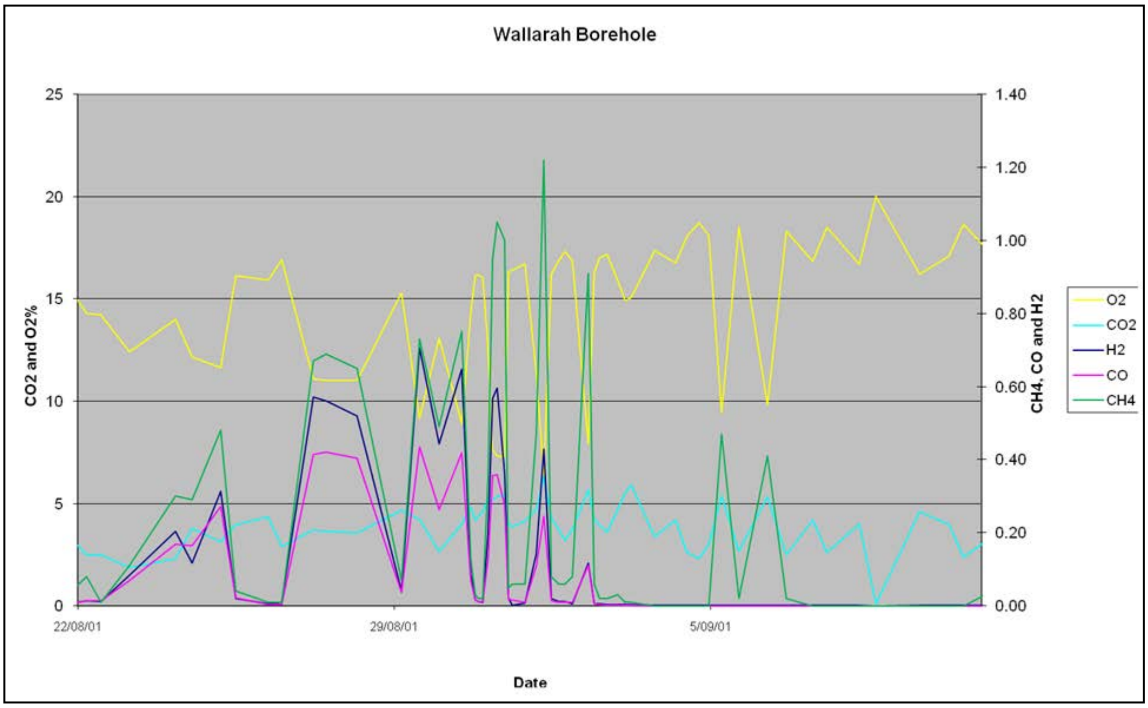
Increased readings of CO had been detected in Moonie Colliery dating back to March 2001. In the period leading up to the increased readings, two changes occurred that may have had an influence on the detection of gases and these were

- Improvements to ventilation at Moonie resulting in an increase in airflow through the connection from $4m^3/s$ to $20m^3/s$.
- Reduction in water flow into the Wallarah goaf from Moonie Colliery.

Checks on the Wallarah goaf showed no signs of heating.

The estimated size and shape of the void and the inability to successfully seal or isolate from the Wallarah seam (40m above) led to the decision to deviate from the normal process of nitrogen inertisation and instead, use the Mineshield unit to deliver carbon dioxide. Pumping of carbon dioxide ceased on 2 September. Since then, gas readings have been safe and stable.

The following diagram shows the influence of variations in the barometer on the atmosphere in the area.



Results of sampling of the atmosphere in the mine via a borehole

8.1.18 Beltana - Dec. 2002

Beltana mine is located in the Hunter Valley district of NSW. Mine entries are from the highwall of an open cut. The return highwall entry had an axial primary ventilation fan installation.

On 15th December 2002 physical indications (smell) and products of combustion from a heating (high CO) were detected in the first pillar between intake & return highwall entries of the Longwall 1 Panel Tailgate. The maximum differential pressure experienced during the life of the pillar was 250Pa, and pillar dimensions were 30m by 90m.

The heating had developed from airflow through open joints in the coal pillar and roof, and via blast induced fracturing from the highwall. These entries were also immediately adjacent to the endwall & therefore subjected to stress concentrations.

Over several weeks the heating was brought under control by sealing off the air paths using 6m drill holes and microfine cement grout injection. Also applied to the ribs and areas of roof in and adjacent to the fractured zones was a flexible surface sealant (cement in a latex binder).

Five meter long temperature probes & gas sampling holes were also installed during these remediation measures. Temperature monitors recorded peaks of 67^0C, whereas comparison of gas samples with gas evolution test results indicated the gas resulted from coal temperatures of 350^0C. Thermographic camera imaging was unable to detect any heat source or warm gas release.

Following Christmas 2002, the gas sampling indicated no detectable products of combustion other than small CO values. These fluctuated with barometric pressure and air temperature (night vs. day).

Temperature probes continued to show elevated temperatures, so in May 2003 seven 47mm diameter inseam boreholes were drilled at lengths between 20 & 40m into the pillar along different axis's in an attempt to locate the heat source. This was unsuccessful & water was injected for 1½ days to remove remnant heat, followed by microfine cement injection to seal any further potential leakage paths.

Further remnant fire gases could not be found & temperatures remained at normal background levels until the area was sealed & access lost in March 2005.

8.1.19 Beltana - Mar 2003

On 31st March 2003, off scale values of CO were detected using handheld gas instruments from open cleat cracks in two pillars each side of the overcast structures separating intake and return airways of Longwall 1 Maingate Panel.

These pillars were the third & fourth pillars inbye from the highwall entries, had dimensions of 17m by 30m, and were subjected to a pressure differential of 115Pa at the time of heating discovery (this was also the maximum pressure differential during the pillars life to-date).

Gas sampling indicated approximately 150oC heating temperatures. Thermographic camera imaging was capable of identifying hot/warm gas release from the open cleat.

A 20m long 47mm diameter hole was drilled in each pillar and water injected for 1½ days. These holes were then microfine cement injected. Leakage paths were identified through each pillar using smoke tubes and visual inspection and then targeted for drilling with short holes and grout injection.

The pillars continued to remain benign, and access was lost for inspection when the area was sealed in March 2005.

8.1.20 Southland – Dec 2003

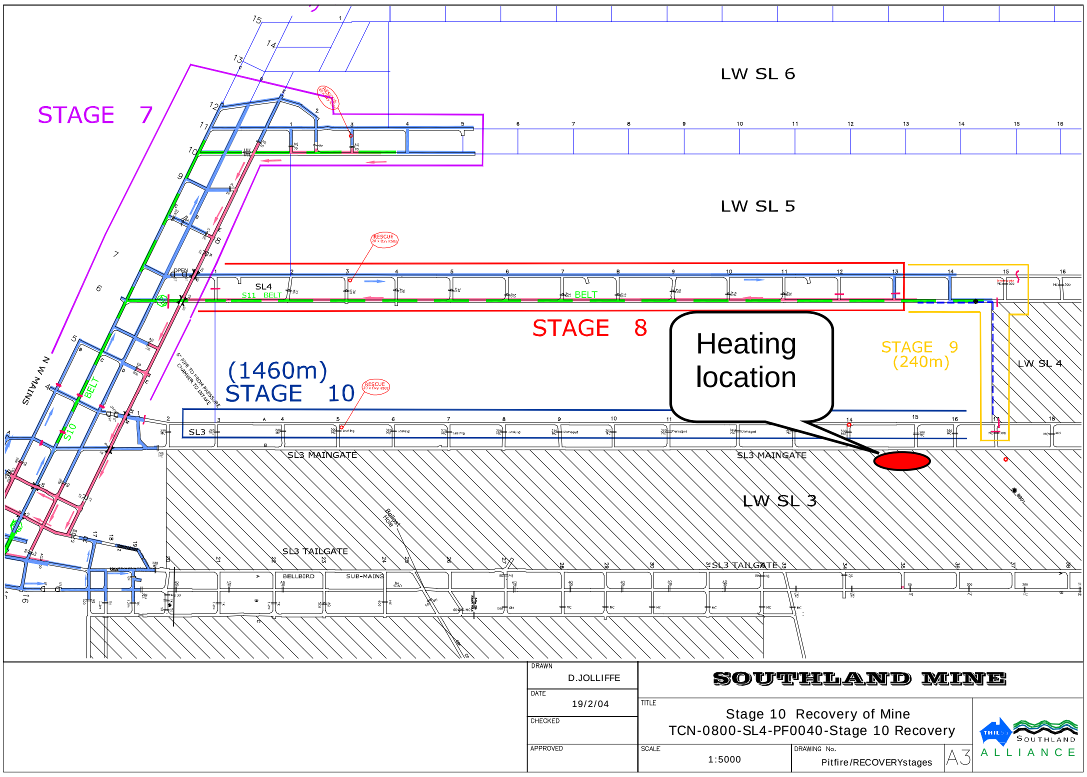
The heating took place in the longwall panel adjacent to the active panel. On 23rd December, a high CO alarm caused the mine to be evacuated. The goaf stopping adjacent to the longwall face crushed and air was entering the adjacent goaf.

On 24th December, black smoke issued from the upcast shaft. On 25th December, the colour of the smoke changed to light grey and it was believed the fire had broken out of the goaf into the longwall tailgate.

The GAG jet engine was used in an attempt to inertise the mine on 27th and 28th December. This was abandoned when the mine fan failed on 29th December. The mine was then sealed to extinguish the fire.

The bottom 3m of a 3 to 7m thick Greta seam was mined for reasons of coal quality.

A Tomlinson boiler was used to assist in the re-entry of the mine.



LW SL 6
STAGE 7
LW SL 5
SL4
STAGE 8
Heating location
STAGE 9
(240m)
LW SL 4
(1460m)
STAGE 10
N W MAINS
SL3
SL3 MAINGATE
LW SL 3
SL3 TAILGATE
DRAWN
D.JOLLIFFE
DATE
19/2/04
CHECKED
APPROVED
SOUTHLAND MINE
TITLE
Stage 10 Recovery of Mine
TCN-0800-SL4-PF0040-Stage 10 Recovery
SCALE
1:5000
DRAWING No.
Pitfire/RECOVERYstages
A3
SOUTHLAND
ALLIANCE

8.1.21 Newstan - 2005

A heating took place in a sealed longwall goaf that was remote from current operations. The ventilation circuit was such that the main returns were adjacent to the seals of the current longwall goaves.

Normally, the goaf of each longwall block would become inert because of the liberation of seam gas. On this occasion, loss of inertisation was caused by interconnection from the goaf to surface cracks. The depth of cover was approx. 110m.

The location of the heating was derived from extensive surface drilling and associated monitoring and was adjacent to a fault system. At the time of mining with the longwall the fault had resulted in a large fall and a resultant cavity on the face.

The Mineshield was used to inject nitrogen into the goaf and stabilise the heating. However, oxygen from the surface was being continually drawn into the underground workings via the interconnection of the subsidence and goaf cracks by the negative pressure generated from the main mine fan.

The long term solution was to inject fly ash to seal the cracks to the surface and to reverse the ventilation underground. This involved placing the longwall seals on intake ventilation. The result of these two actions was to reduce the pressure differential across the seals of the longwall that was allowing oxygen access to the heating. This allowed seam gases to build up and naturally inert the goaf.

8.1.22 Dartbrook 2005

Operations re-located from Wynn seam to Kayuga seam in 2004. The Kayuga seam is overlain by the Mt Arthur seam. The heating took place in the first longwall block mined in the Kayuga seam.

Both seams were considered to have a medium to high propensity for spontaneous combustion. Goaf drainage & Perimeter road established for gas management. Systematic goaf inertisation, thermal imaging of seals and tube bundle monitoring of seals used as precautionary measures against spontaneous combustion.

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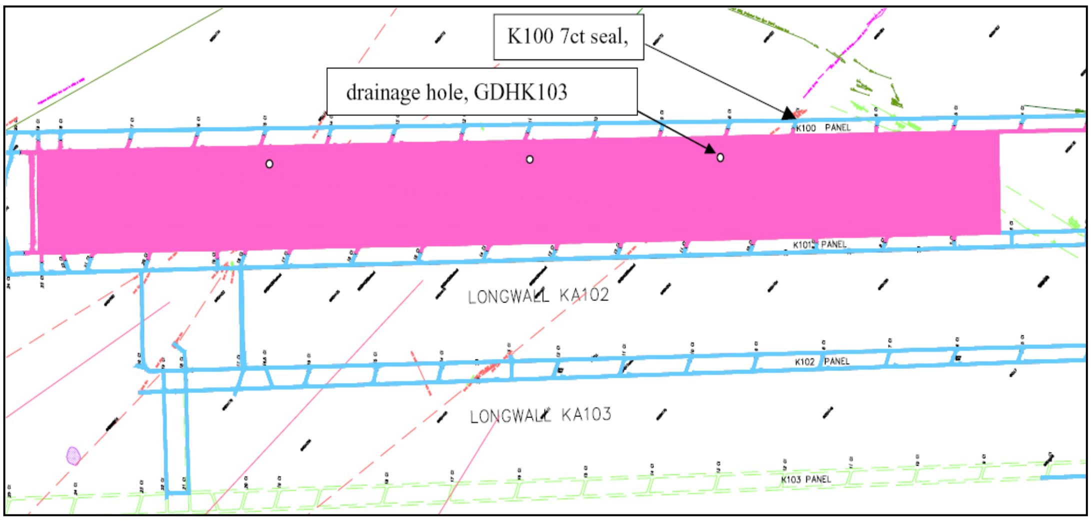
The Mineshield was used to inject Nitrogen into the area through a goaf drainage borehole and the mine fan was slowed to reduce longwall quantity from 80m^3/s to 60m^3/sec. When the heating was controlled, mining recommenced with two Floxal units replacing the Mineshield.



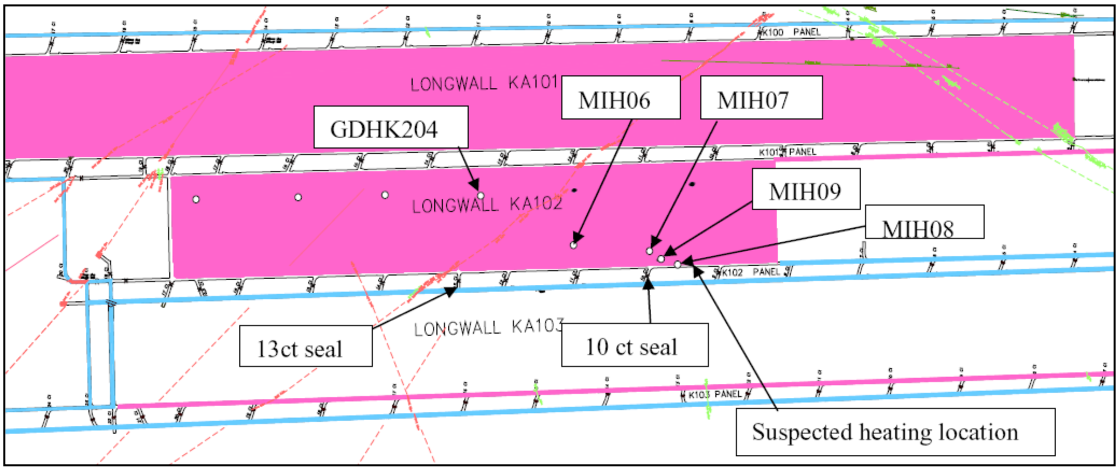
8.1.23 Dartbrook - 2006

The heating took place in the second active longwall block in the Kayuga seam. Bag samples from 13c/t and 10 c/t stoppings indicated unusual hydrogen levels. Subsequent samples indicated the presence of ethylene. The mine was evacuated on 19th January and tube bundle locations established into the goaf at 10, 11 and 13 c/t stoppings. Subsequent samples indicated ethylene

The mine was re-entered on 21st January with limited activities. The mine was again evacuated and further inertisation took place with a reduced mine fan speed.

The mine was re-entered on 18th February 2006 with limited activities taking place.

In the circumstances at the mine with high seam gas content, the ratio of Hydrogen to Carbon monoxide is considered a very useful indicator.



8.2 USEFUL FORMULAE

8.2.1 CO Make

CO Make is the volume of Carbon Monoxide flowing past a fixed point per unit time. This indicator removes the effect of dilution by general body air.

$$CO\ Make = K \times CO \times Q$$

Where: CO Make is measured in litres/minute.
Q is airflow measured in m3/second.
CO is the measured concentration of carbon monoxide in the air.
K is a factor as determined as follows:
If CO is measured in ppm then K = 0.06
If CO is measured in % then K = 600

As the equation requires air quantity, CO Make is only valid for roadways with airflow and cannot be used behind seals or closed boreholes. But because this indicator does make full allowance for changes in airflow to a heating it is suitable for monitoring the effects of oxygen deprivation on a heating.

8.2.2 Graham's Ratio

The equation is commonly expressed as:

$$GR = \frac{CO}{O_2\ Deficiency} = \frac{100 \times CO}{0.265 \times N_2 - O_2}$$

Where: GR is the Graham's Ratio calculated percentage depletion of oxygen in normal air.

CO is the measured percentage concentration of carbon monoxide.
N_2 is the measured percentage concentration of nitrogen.
O_2 is the measured percentage concentration of oxygen.

The CO/O2 deficiency ratio may underestimate the state of progression of a heating, but combined with other monitoring and analysis methods it provides an extremely useful indication of the state of a heating. The main application of Graham's Ratio is in the detection of heatings or fires that may otherwise be disguised by changes in ventilation and for monitoring their progress. The trend of the readings is more important than absolute values, with an increasing trend indicating increasing temperature within the fire.

8.2.3 Young's Ratio

Young's Ratio is the same as Graham's Ratio except that CO is replaced by CO2 as the indicator of oxidation of the coal. Because of the size of the CO2 concentration it is not usually multiplied by 100 and thus is a fraction not a percentage as is Graham's Ratio:

$$YR = \frac{CO_2}{O_2\ Deficiency} = \frac{CO_2}{0.265 \times N_2 - O_2}$$

There are no universally acceptable trigger levels because carbon dioxide generation as a function of temperature is very coal dependent. The ratio trend is more important than absolute ratio values.

The limitations of this ratio include other sources of CO_2 from seam gas or vehicle exhaust, the potential loss of CO_2 as it readily dissolves in water, and the same problems with oxygen deficiency as Graham's Ratio. Decaying timber can be a source of CO_2 than could unbalance the use of this ratio.

8.2.4 CO/CO_2 Ratio

This ratio is independent of oxygen deficiency and so overcomes a lot of the problems associated with other ratios that are dependent of that deficiency. It is based on the change in ratio of carbon monoxide produced to carbon dioxide produced as a function of the coal temperature during the initial development of a heating. It therefore defines typical coal temperature values. Obviously this index can be used only where no carbon dioxide occurs naturally in the strata.
The index increases rapidly during the early stages of a heating, but the rate of increase slows at high temperatures. However, the rate of change at higher temperatures is sufficient to provide a very useful indicator of the progress of a well-established fire.

8.2.5 Morris Ratio

This ratio is essentially the inverse of Graham's and Young's Ratios. It is a measure of the amount of oxygen absorbed/destroyed (as determined by the excess of nitrogen over that required to balance the amount of oxygen present) by the coal to the amount of oxidation produced by the coal. Where the inlet is fresh air the ratio is expressed as:

$$MR = \frac{N_2\ Excess}{CO + CO_2} = \frac{N_2 - 3.774 \times O_2}{CO + CO_2}$$

An unusual feature of this ratio is that the ratio increases to a maximum at approximately 120^{0}C then decreases, and the size of the peak is very coal dependent. Because of this peaked behaviour, it cannot be used alone to indicate temperature of a coal heating as one cannot estimate on which side of the maximum a data point lies. Therefore valid in early stages of heating when increasing trend indicates increasing heating activity.

8.2.6 Jones-Trickett Ratio

Not suitable for sealed areas. This ratio is based on the measurement of the amount of oxygen required to be consumed to produce the oxidation products observed compared to the amount of oxygen actually removed from the inlet gas stream. Increasing ratio indicates intensifying heating / temp increase.

$$JTR = \frac{CO_2 + 0.75 \times CO - 0.25 \times H_2}{O_2\ Deficiency} = \frac{CO_2 + 0.75 \times CO - 0.25 \times H_2}{0.265 \times N_2 - O_2}$$

Research has shown that the type of fire or heating that has occurred can be determined from the product gas mix using the Jones-Trickett Ratio. Literature based indicator levels for the ratio are:

- < 0.4 Normal
- < 0.5 Methane Fire possible

- < 1.0 Coal Fire possible
- > 1.6 Impossible

Note that the Jones-Trickett Ratio is invalid if the intake air is oxygen deficient through the injection of nitrogen or carbon dioxide or through a high methane make. In addition the dilution with fresh air of the combustion products has no effect on the ratio.

8.2.7 Litton Ratio

$$LR = \frac{1}{3} CO_s \, (\%R_g)^{-1.5} \, (\%O_2)^{-0.5}$$

Where:

COs -	carbon monoxide concentration in ppm		
O2 -	oxygen concentration in percent		
%Rg -	percentage residual gas -	originally specified as	= 100 - 4.774 O_2 - CH_4
		but more generally	= 100 - 4.774 O_2 - seam gases

This ratio is a measure of the oxidation efficiency and has mainly been applied in evaluating the level of activity of fires, with low temperature oxidation having a low conversion efficiency of oxygen to carbon monoxide. The situation is unsafe if the ratio is greater than 1, and can only be defined as safe if the ratio is less than 1 and stabilised. Decreasing values for the ratio even if less than 1 indicates that equilibrium (i.e. normal temperature oxidation) has not been reached.

This ratio is able to detect actual combustion, but is not sensitive enough to identify the preliminary phase of heating.

8.2.8 Willett Ratio

$$Willett\ Ratio = \frac{CO_2\ produced}{Blackdamp + Combustibles} \%$$

Blackdamp is a term generally applied to carbon dioxide, but also includes nitrogen. Combustibles include all combustible gases present (methane, carbon monoxide, hydrogen and any higher hydrocarbons).

Level of activity is indicated by the value obtained, with a falling trend indicating decreasing activity. Stable values may indicate no activity. This ratio has been found to be more effective than Graham's Ratio in determining the state of spontaneous combustion activity behind sealed areas.

8.2.9 H_2/CO Ratio

This ratio indicates temperature of a heating. An increasing ratio indicates intensifying heating or temperature increase. The ratio is independent of dilution with fresh air or seam gas or oxygen deficiency.

Limitations of this ratio include: CO depleted by bacteria, vehicle emissions, ratio rate of change slowed in sealed areas resulting in 'averaged' values, inaccurate for low H2 values due to analysis limitations.

8.2.10 Air Free Analysis

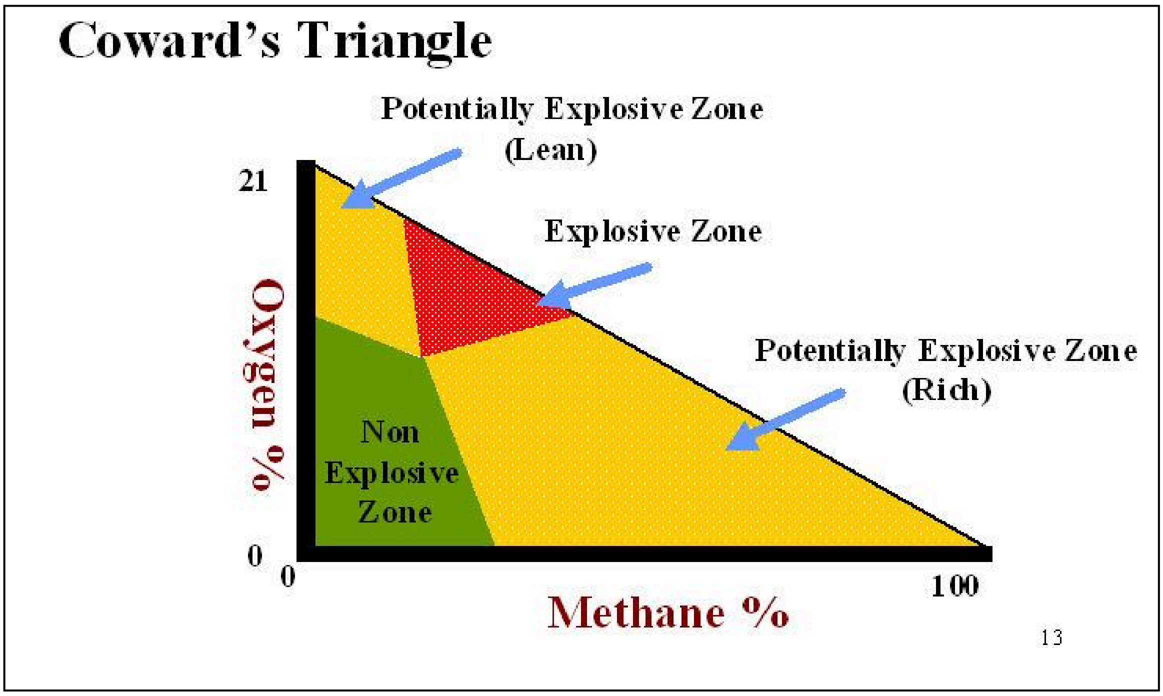
Air free calculation:

$$\frac{100 \text{ gas component\%}}{100 - 4.778 \times O_2 \text{ (as analysed)}}$$

Seam gas free calculation:

$$\frac{100 \text{ gas component\%}}{100 - \% \text{ total seam gas (as analysed)}}$$

8.2.11 Coward Triangle



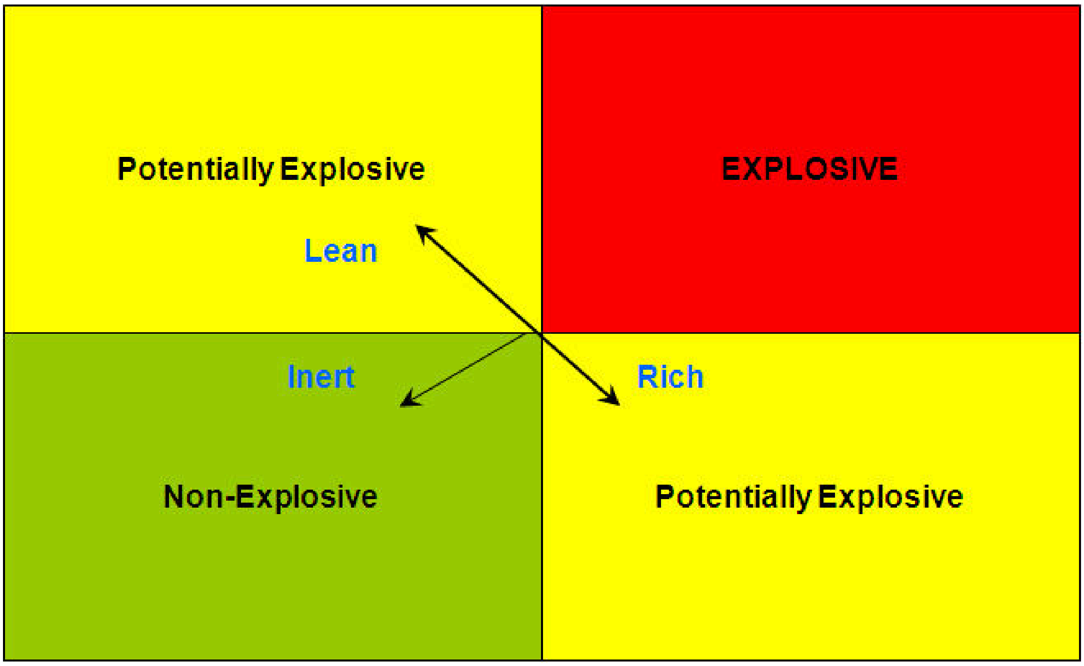
The Coward Triangle plots the percentage oxygen against the total percentage of methane gas in the gas sample. In addition, the barriers between the explosive, potentially explosive and non-explosive gas concentration zones are defined. The position of these barriers is calculated from the combination of the upper and lower explosive limits of the flammable gases present weighted by their concentration. The position of the datum point then indicates the potential for explosion. In addition the expected behaviour of the gas mixture under various scenarios can be predicted.

- Adding fresh air makes the datum point move toward the top left corner of the triangle.
- Adding inert gases makes the datum point move toward the bottom left corner.
- Adding more combustible gases makes the datum point move toward the bottom right corner.

The triangle limits are fresh air, inert gas and 100% flammable gas. The calculations are complex and are usually conducted using computer software.

Due to the changing size of the explosive zone with different explosive gas concentrations, it is not possible to use the Coward Triangle for trending a sample point over time.

8.2.12 Ellicott Diagram



The Ellicott Diagram is a modification of the Coward Triangle that allows trend analysis. The triangle is changed into a rectangle, with the centre of the diagram being the nose point and the axes radiating from there being defined by the upper explosive limit barrier (+X axis), the lower explosive limit barrier (+Y axis), the line from the fresh air limit on the Y axis to the nose point (- X axis), and the continuation of this line to intersect the Y axis of the Coward Triangle (-Y axis).

- Adding fresh air makes the datum point move toward the left end of the horizontal axis.
- Adding inert gases makes the datum point move toward the bottom left corner.
- Adding more combustible gases makes datum point move toward the bottom right corner.

One major advantage that the Ellicott Diagrams has over the Coward Diagram is the ability to plot a number of samples on the same graph and establish trends over time.

Care needs to be taken in comparing Ellicott Diagrams, as some of the information available in Coward Triangles is lost. In particular the size of the various sectors on the Coward Triangle may vary between analyses as the mixture varies, yet the Ellicott Diagram always allocates each segment the same size. The information conveyed through the relative sizes of the zones is lost as they are set to a fixed size on an Ellicott Diagram, with the non-explosive zone forming twice the size of the other zones.

8.3 REFERENCE MATERIAL

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- "Ignitions, Explosions and Fires", Editor A J Hargraves, AusIMM.
- Department of Mineral resources, NSW, Spontaneous Combustion Seminar, Mudgee, 6th to 8th November 1995.

Feedback sheet

Your comments on **MDG1006 Spontaneous Combustion Management Guideline** and **MDG 1006 Technical Reference** will be very helpful in reviewing and improving these documents.

Please copy and complete the feedback sheet and return it to:

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Phone: (02) 4931 6658 Fax: (02) 4931 6790
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How did you use, or intend to use, these guidelines?

What do you find most useful about these guidelines?

What do you find least useful?

Do you have any suggested changes to these guidelines?

Thank you for completing and returning this feedback sheet