SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

DRAFT FINAL REPORT

Inertisation strategies and practices in underground coal mines

J J L du Plessis

D J van Niekerk

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Executive Summary

The purpose of the SIMCOL 701 project was to develop an Inertisation Strategy for use in the in-bye areas of SA underground fiery collieries based on an evaluation of worldwide best practice and an adaptation of these methods (techniques) for use in the current conditions in SA coal mines.

The report alludes to the significant health and safety risks associated with Flammable Gas (FG) ignition / explosions and consequent coal dust ignitions / explosions (see Appendix 1).

The research included an international review of various risk treatment techniques that can be used to eliminate, control or minimize the significant risks associated with FG ignition/explosions and consequent coal dust explosions. These Risk Treatment Techniques (RTTs) are described in detail in Sections 4 to 7 of the report.

The report concludes that any Inertisation Strategy must be based on an efficacious Hazard Identification and Risk Assessment (HIRA), the risk treatment steps prescribed by the relevant articles of the MHSA and be composed of an appropriate selection (portfolio) of RTTs capable of eliminating, controlling and/or minimizing the significant health and safety hazards/risks identified and assessed as part of the mine's HIRA (see Appendix 4).

The report recommends that (a) the RMS set out in Appendix 4 be used for in-bye areas of underground coal mines (b) the RMS be based on a comprehensive health and safety HIRA, and (c) Phase II of the project be commenced without delay.

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Abbreviations

BVS	Bergbau-Versuchsstrecke
DME	Department of Minerals and Energy
HSE	Health and Safety Executive (UK)
LEL	Lower Explosion Limit
LTR	Last Through Road
PS	Polystyrol
PVC	Polyvinyl chloride
TIC	Total Incombustible Content
USA	United States of America
USBM	United States Bureau of Mines
MSHA	Mine Safety and Health Administration

Symbols

%	percentage
ℓ/m^2	litres per square metre
ℓ/m^3	litres per cubic metre
°C	degrees centigrade
CH_4	methane
cm	centimetre
ft	feet
kg	kilogram
kg/ℓ	kilograms per litre
kg/m^2	kilograms per square metre
kPa	kilopascal

lbs	pounds
ℓ	litre
m	metre
m/s	metres per second
m^2	square metre
m^3	cubic metre
m^3/s	cubic metres per second
mm	millimetre

1 Introduction and background

The most significant occupational safety related risks in underground coal mines are flammable gas and consecutive coal dust explosions. For a flammable gas explosion to take place the following independent contributory factors must be present simultaneously namely:

- an explosable gas mixture i.e. fuels such as methane and hydrogen gasses in the correct ratio with oxygen, and
- an ignition source.

Numerous studies in coal mining countries world wide conclude that both contributory factors are most commonly simultaneously present at the coal face (in-bye area) where the coal is broken (excavated). The same applies to the out-bye areas inclusive of the abandoned areas of the mine, albeit at a significantly lower level of risk.

It is therefore appropriate to review the techniques and methods of combating flammable gas and consecutive coal dust explosions that have been developed over the past century, in an attempt to identify all current and possible other feasible risk treatment techniques / methods. What is probably more important is to apply a risk management strategy composed of a portfolio of effective risk treatment techniques / methodology.

With reference to the in-bye area, it is extremely difficult, particularly in room-and-pillar operations to protect the zone since:

- it is the most highly populated area of the underground workings i.e. large proportion of the employees are exposed to these hazards;
- it may consist of numerous headings without effective through ventilation i.e. “blind headings”;
- headings advance intermittently albeit rapidly with time;
- coal fragmentation and the subsequent release of methane is dependant to a large extent on the excavation process e.g. explosive and mechanized routes;
- continual increases in coal production rates to meet market needs;

- roadways are often wet, but not necessarily wet enough to prevent a flammable gas explosion from raising a cloud of coal dust from the surface areas of underground excavations;
- limited space for the installation of explosion protection devices because of the use and movement of relatively large mining equipment in confined underground excavations, and
- accelerated application of mechanized excavation methods, techniques and machinery which increases the likelihood of frictional sparking / heating and results in the production of a larger proportion of fine coal particles.

In an attempt to provide this problematic environment (risk area) with the greatest possible protection against the risks, mining engineers have developed a range (portfolio) of protection methods and devices such as:

- adequate and effective ventilation (dilution or removal / prevention of the accumulation of flammable gas mixtures);
- prevention of frictional and other flammable gas ignitions;
- preventing a flammable gas ignition from propagating the flame and overpressure out of the work headings, and
- preventing coal dust (fuel for a coal dust explosion) from participating in a consecutive coal dust explosion initiated by a flammable gas explosion.

For a coal dust explosion to occur, the following factors (elements of the explosion triangle) need to be present simultaneously:

- an explosive mixture of flammable gas and oxygen and/or ignition of the flammable gas mixture;
- an ignition source for the flammable gas mixture or ignition source for the fuel (finely divided coal dust), and
- adequate fuel in the right (sufficient) concentration and sufficient oxygen to sustain the propagation of the explosion.

It follows that it is of utmost importance to develop an effective strategy to (a) prevent ignitions or explosions from occurring and (b) failing (a) to contain the ignition or explosion as close as is reasonably practical to its point of ignition.

The successful conclusion of this study and the establishment of a set of best practices for use by the mines will enable the employer to reduce the risks that employees are exposed to. The project will also enable the establishment of effective means whereby the actions and control methods that mines use, can be easily audited.

This evaluation was a comprehensive attempt to combine the different disciplines of ventilation, measurement, inertisation and other engineering technologies available to assist the employer to prevent flammable gas and consecutive coal dust explosions from occurring.

2 Objective of work

The Project Proposal for SIMCOL 701 states the Primary Output as follows:

"An Inertisation Strategy for use in the in-bye areas of SA Underground Fiery Collieries based on:

An evaluation of worldwide best practice and an adaptation of these methods (techniques) for use in the conditions in SA Coal Mines"

The main objectives of COL 701 are:

- identification of inertisation technology / techniques / best practice worldwide;
- evaluation of best practice for efficacious inertisation; and
- formulation of an appropriate Risk Management (treatment) Strategy for in-bye areas for underground fiery mines based on appropriate portfolios of Risk Treatment Techniques.

3 Risk management strategy

3.1 Employer's accountability under the MHSA

The objects of the Mine Health and Safety Act 1996, Act Number 29/1996 (MHSA) include the following:

"Article 1 (a)	*to protect the health and safety of persons at mines, and*
Article 1 (b)	*to require employers and employees to identify hazards and eliminate, control and minimize the risks relating to health and safety at mines."*

The employer's accountabilities under the MHSA are captured in the following articles:

"Article 11.1	*Every employer must –*
(a)	*identify the hazards to health or safety to which employees may be exposed while they are at work;*
(b)	*assess the risks to health and safety to which employees may be exposed while they are at work*
(c)	*record the significant hazards identified and risks assessed; and*
(d)	*Make those records available for inspection by employees."*

"Article 11.2	*Every employer, after consulting the health and safety committee at the mine, must determine all measures, including changing the organization of work and the design of safe systems of work, necessary to-*

(a)	*eliminate any recorded risk;*
(b)	*control the risk at source;*
(c)	*minimize the risk, and*
(d)	*In so far as the risk remains –* *(i) provide for personal protective equipment, and* *(ii) institute a programme to monitor the risk to which employees are exposed."*

Article 5	Employer must maintain a healthy and safe environment.
Article 6	Employer must ensure adequate supply of health and safety equipment.
Article 7	Employer must staff the mine with due regard to health and safety.
Article 8	Employer must establish a health and safety policy.
Article 10	Employer must provide health and safety training.

3.2 Hazard Identification and Risk Assessment

Article 11 (1) requires the employer to perform what is commonly known as a Hazard Identification and Risk Assessment (HIRA). The outcome of such HIRA is a list of relevant significant health and safety related hazards / risks e.g.:

- ignition of an explosable mixture of flammable gas (-es);
- ignition of a coal dust explosion; and
- propagation of a coal dust explosion from the point of origin.

3.3 Risk Management Strategy for Explosions

3.3.1 Fault Tree / Causal Mechanisms

Appendices 1 and 2 illustrates the causal mechanisms that could result in either a flammable gas (FG) ignition/explosion or consecutive coal dust explosion (CDE).

3.3.2 Risk Management Strategy for Explosions

It is clear from the diagrams that the Risk Management Strategy (the WHAT) for explosions must succeed in breaking the cause (fault) chain or spiral at the earliest possible stage. This RM- strategy broadly equates to the following two distinct sub-strategies namely:

a)	Prevention (Risk Avertion)	the first line protective measures ("eliminate" and "minimize") such as those required in terms of articles 11 (2) (a) and (c) of the MHSA, and
b)	Containment (Risk Mitigation)	the second line protective measures such as those required in terms of the following articles of the MHSA: ▪ article 11 (2) (b) : "control (containment)" of the risk at source, and ▪ article 11 (2) (c) : "minimize" the risk.

Appendix 3 illustrates the notion of preventative and constructive measures after Michelis 1991.

3.3.3 Risk Treatment Techniques (RTTs)

In an attempt to implement an efficacious RMS for explosions, mining engineers have developed numerous explosion risk treatment (management) techniques (methods) (RTTs) and devices. Although some have been proven to be highly effective, it is wise not to rely too heavily on a single defense mechanism. In practice, modern safely operated mines employers deploy a portfolio of these remedial measures in concentric lines of defense i.e. a

RMS for explosions based on an appropriate portfolio of efficacious risk treatment techniques (RTTs). The following RTTs include but are not limited to:

(a) Adequate Ventilation:

Adequate ventilation which is capable of preventing the accumulation of flammable gas (-es) mixtures ("removal through turbulent flow" and "dilution") is the oldest and most logical effective first line defense against FG- ignitions / explosions.

(b) Ventilating Blind Headings:

Airflow in the last through road is however by no means a guarantee that the face heading, especially the volume surrounding the cutting drum of CMs and long wall faces is free of methane. Machine mounted fans, scrubber systems and high pressure water spray systems are examples of RTTs that are used to ensure that the last 5m of a blind heading is properly ventilated during coal cutting cycles. Occasions will nevertheless arise when these techniques and/or devices fail, either partially or in total, to ventilate the cutting drum adequately and experience has clearly taught us that conditions may occur where the picks can operate in an explosable mixture of FG.

(c) Prevention of Frictional Ignitions:

The prevention of frictional ignitions has been researched extensively and a summary of known facts presented in a previous SIMRAC Report (COL 226). It is known that slow pick speeds, together with the application of water directly behind the pick can very significantly reduce the risk of gas ignitions. A full wet head cutting system is the ultimate example of this form of protection.

(d) Dust Extraction / Removal:

The extraction of dust from the mine air and removal of coal dust deposited on the surface of underground excavations albeit very effective as a RTT, may be logistically and economically onerous for employers to apply.

(e) Prevention of Flame and Overpressure Propagation:

Appendix 1 illustrates clearly that the best post FG- initiation / explosion strategy to follow is to prevent the flame and over pressure from propagating away from the point of ignition. SIMRAC funded work, over the past 6 years has shown that an on-board active suppression system can be designed to effectively prevent a gas ignition from turning into a coal dust explosion. Indeed, these systems can be so effective that, in the event of an ignition, an on board machine operator will be protected from injury.

A very effective defense against the propagation of FG- initiation / explosion is the use of inertisation materials or mediums such as water, stone dust and dust – binding agents.

Stone dust as inertisation medium, when applied throughout the workings, can prevent a coal dust explosion and if applied in concentrations as barriers, it can extinguish a propagating explosion. In recent years a large proportion of SIMRAC funded research has investigated the correct quantities of stone dust necessary to achieve these objectives in SA Collieries and has led to the development of the bagged stone dust barrier.

3.5 Proposed Inertisation Strategy for In-bye Areas

The term inertisation in this context is understood to mean the use of appropriate techniques and / or materials (mediums) to reduce the explosability of airborne coal dust.

Appendix 4 sets out the significant hazards / risks associated with FG- ignitions/explosions and consequent CDEs, proposed appropriate RMSs in accordance with the risk treatment steps prescribed by article 11 (2) of the MHSA as well as the accompanying proposed appropriate RTTs.

4 Preventative measures against methane

The ultimate measure for preventing underground explosions is to prevent the possible ignition of a methane/air mixture. Methane is explosive in methane/air mixtures in the range of 5 to 15 % and the most violent explosions occur at 9,5 %. In all cases, the first line of defence is adequate and well-directed ventilation. If the measures discussed in the following subsections are effectively employed, all the other protective requirements can be regarded as safeguarding or secondary mechanisms.

4.1 Ventilating air

The prime requirement in the face area is the availability of the correct quantity of fresh air to dilute the methane liberated during the excavation process and from freshly mined coal faces.

Guidelines drawn up by the Department of Minerals and Energy (DME) in South Africa require a minimum air velocity of 0,25 m^3/s per cross-sectional face area, with less than 50 % recirculation occurring. They further stipulate a minimum air velocity of 1,0 m/s in the last through road (LTR) and 0,4 m/s over the operator. Strict adherence to these stipulated requirements will effectively dilute methane and give adequate protection against methane accumulation. Within the confines of the cutting drum where methane is most likely to be released, small quantities of methane/air mixtures may, however, still be prone to ignition.

The large cross-sectional face areas in South African underground coal mines result in complex three-dimensional flow patterns (Oberholzer and Meyer, 1995). However, the problem of what is the correct volume of fresh air, correctly directed, has not yet been resolved for high-seam mining.

Ongoing research by the Kloppersbos research team (part of the CSIR's Division of Mining Technology, or Miningtek), utilising its full-scale surface testing facility for ventilation simulations, has resulted in the resolution of some of the complex issues surrounding the dilution of both liberated methane and dust. One of the prime findings of this work (Belle and Du Plessis, 1998) was that correct operation of the water spray system is the ultimate requirement for effective methane dilution. To this end, a new directional water spray system was developed (Du Plessis and Belle, 1998).

Belle and Du Plessis (1998) also made a number of recommendations with regard to good ventilation practices. If the minimum requirements for air ventilating face headings are adhered to, this will prevent the accumulation of any significant explosive methane/air mixture. Prevention of the accumulation of an ignitable mixture is the most effective way of preventing an explosion from occurring.

4.1.1 Application

The operational requirements for this system were well documented in a number of their publications in 1998 and 1999.

The spray system and the spray nozzle configurations were developed at Kloppersbos. A three-dimensional view of the standard spray configuration system without the half-curtain on the CM is shown in Figures 4.1.1a and b. The Kloppersbos spray configuration as installed on the machine consists of a number of water spray blocks, air movers and an on-board scrubber. The system consists of a total of 34 sprays, including three air movers. The detailed descriptions of the individual components as shown on the drawings are as follows:

- <u>On-board scrubber</u>: A wet fan scrubber capable of handling the required air quantity, fitted with an inlet cone.
- <u>Water supply to the spray system</u>: Maintains a water pressure of 2 000 kPa (20 bar) and a water flow rate of at least 120 ℓ/min.
- <u>Type of nozzles</u>: Standard hollow-cone nozzles with single inlet diameter of 1,6 mm and an outlet diameter of 2,0 mm.
- <u>Position A on drawing</u>: Three air movers spraying downwards at an angle greater than 45° from the horizontal onto the conveyor to prevent dust rollback and to wet the coal on the flight conveyor.
- <u>Position B on drawing</u>: Four top spray blocks situated above the cutter drum. A total of 12 directional water sprays is used to move air across the face from right to left towards the scrubber intake.
- <u>Position C on drawing</u>: L-shaped spray block installed on the right-hand side of the machine, approximately 1 m from the hinge of the boom. Three spray blocks, each consisting of two water sprays (a total of six), ensure air movement to the front of the machine.
- <u>Position D on drawing</u>: One spray block consisting of two water sprays installed on the spade, directing air to the left of the machine underneath the boom.
- <u>Position E on drawing</u>: One spray block consisting of two water sprays connected to the bottom of the cutter boom, directing air towards the left of the machine underneath the

boom.

- Position F on drawing: Two bottom directional spray blocks, each consisting of three sprays installed underneath the cutting head on the left and right sides of the head to ventilate under the cutting drum.

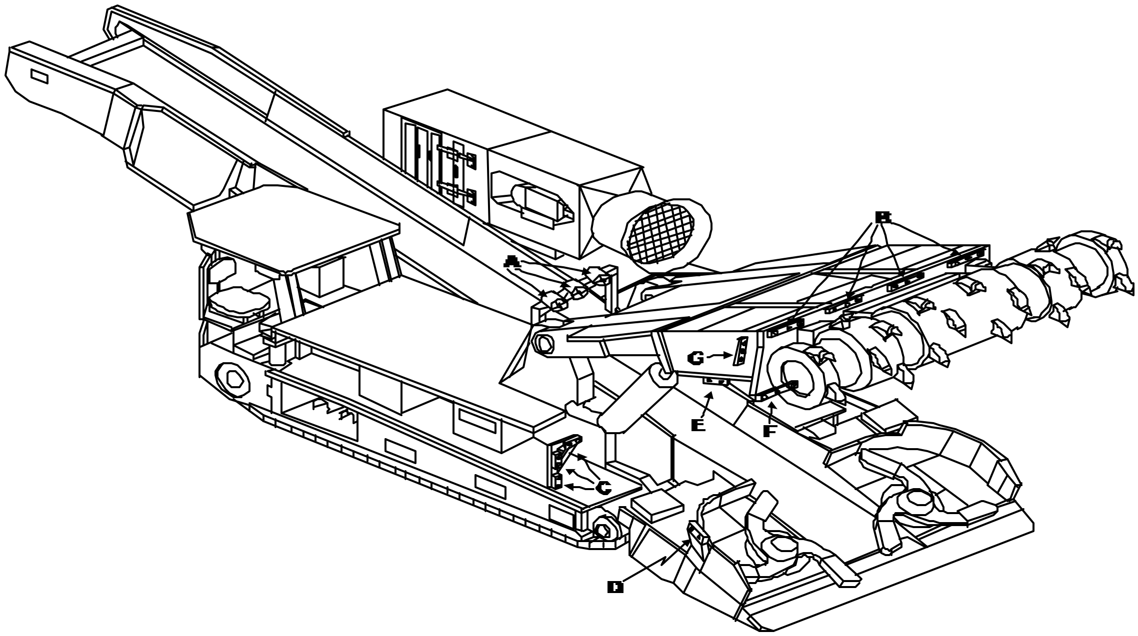


Figure 4.1.1a: Kloppersbos standard spray configuration (driver-side view)

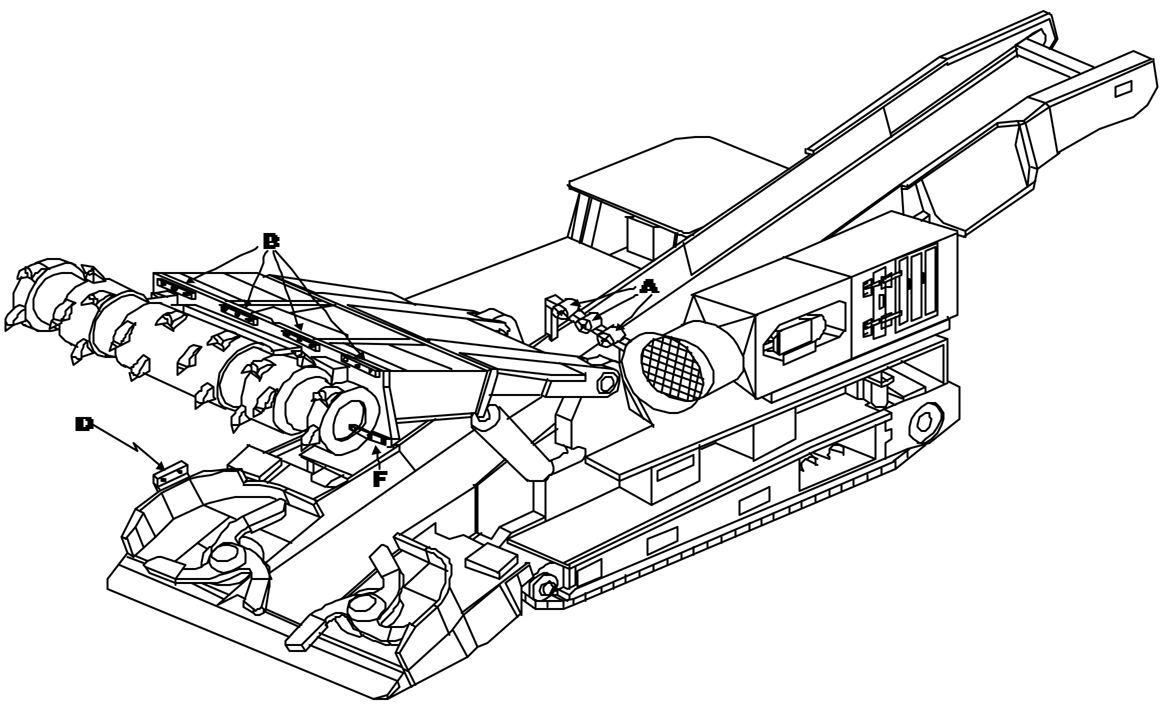


Figure 4.1.1.b: Kloppersbos standard spray configuration (scrubber-side view)

To achieve a dust-concentration level of less than 5 mg/m^3 at the operator's position, the practices to be followed are:

1. Maintenance of machine systems, including the spray system and the dust scrubber.
2. Adherence to system design specifications, e.g. use of optimum spray design, similar to the configurations described in this report.
3. Maintenance of water flow and pressures such as with the Kloppersbos spray system, to optimize air movement and dust-capture effectiveness.
4. The use of the force or jet fan and column within 15 m of the face is not advised as more favourable conditions are observed between 15 m and 20 m from the face. The first right-hand and left-hand cuts should not be force-ventilated. Depending on the section ventilation, beyond 24 m from the LTR, the force ventilation should be such as to ensure that air velocities over the operator do not exceed 1,0 m/s.
5. Adherence to a minimum air velocity of 1 m/s in the LTR to minimize recirculation.
6. Proper training of personnel in the use of dust-suppression and auxiliary ventilation systems.
7. Use of the correct cutting sequence, adhering to the principle of keeping the scrubber against the solid wall at all times.
8. Re-examination of the directive for measurement of coal dust and sampling practices.
9. Training of personnel in the use of dust-monitoring equipment, the objective of sampling, the correct positioning of samplers, information on how to sample, where to sample and the general care and maintenance of the equipment.
10. Educating the workforce with regard to ventilation practices, the aim of ventilation and the advantages to themselves is essential if progress is to be achieved.

The following recommendations are made for future research on the basis of the results obtained from the tests conducted at Matla No.3 Mine:

1. All the systems should be evaluated, independently, so as to ensure compliance with the 5 mg/m^3 sample dust concentration at the operator and less than 1,4 % methane per volume.
2. It is of critical importance to evaluate the systems' performance in high-methane-content seams to ensure methane dilution and ventilation effectiveness across the face.
3. It is equally important to quantify the response of the evaluated systems at high methane-emission rates in the Kloppersbos simulation tunnel.

4. Due to the dynamic nature of mining and the complex interaction between methane, dust and fresh air, the systems should also be tested under low seam mining conditions.
5. The directive on collecting dust samples at the operator position and monitoring be re-examined to incorporate the current findings and the ongoing research at Kloppersbos.

The various elements of the Bank 2000 Road header machine mounted ventilation control system are as follow:

- Hollow cone-single inlet spray nozzles(1,6 mm (inlet) / 2,0 mm (outlet))
- Physical half-curtain: The half-curtain covers an area from the scrubber on the LHS of the machine to the middle of the machine over the flight conveyor. This curtain is made up of a conveyor belt positioned approximately 1m from the scrubber inlet.
- Air movers on flight conveyor and top of computer box (LHS-operator side)
- Jib sprays
- Concave spade plate on LHS and RHS of road header
- Flight conveyor discharge cover (conveyor belt or other suitable material)
- 45 degree scrubber deflector plate
- Water pressure of 15 to 20 bar
- Effective dust scrubber system designed to the required specification

The final configuration of the Bank 2000 RH dust control system is shown in Figure 4.1.1c.

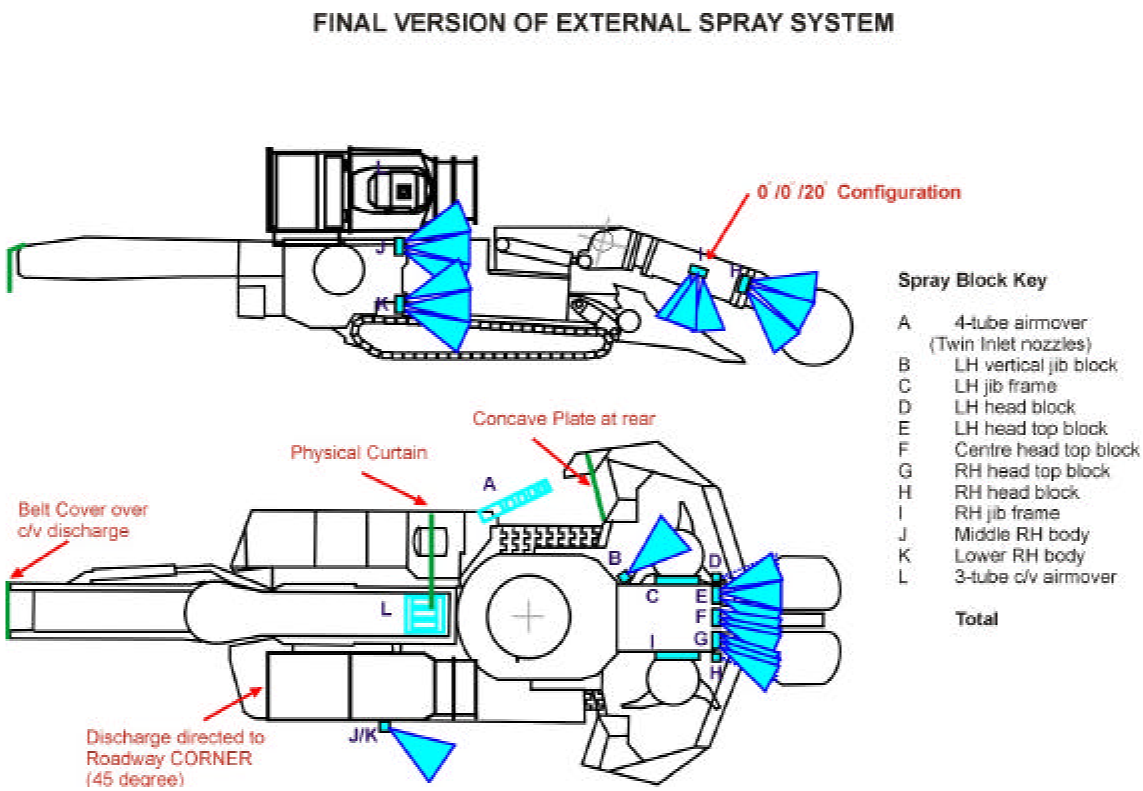


Figure 4.1.1c: The final configuration of Bank 2000 dust control system

To achieve a dust-concentration level of less than 5 mg/m^3 at the operator's position, the practices to be followed are:

1. Maintaining the Bank 2000 road header dust control system design, spray configuration, and individual components of the system is extremely important in order to maintain the dust concentrations below the legal limits.
2. Adherence to system design specifications, e.g. use of optimum spray configuration, similar to the configurations described in this report and maintenance of water flow and pressures to the external spray system, to optimize air movement and dust-capture effectiveness.
3. Adherence to a minimum air velocity of 1 m/s in the LTR to maximize fresh air re-circulation.

4.2 Monitoring

Even in the most well-designed ventilating system, failures can still occur. A further safeguard against ignitions is the use of monitoring instruments (flammable gas warning devices). Their operation can either be continuous or take the form of single measurements. They are also used in a wide range of applications: from continuous monitors on machines, to hand-held instruments and even mine-wide monitoring systems. Continuous monitoring systems are extensively used in mine-wide networks, and the use of on-board interlocked methane-detection systems is also growing.

On-board systems are used as early-warning devices and can trip out the electrical power supply to the machine. The level at which protection is activated is normally set at the legal permissible concentration (1,4 % flammable gas by volume) (Minerals Act, 1991). These systems need to be able to operate effectively in extremely wet and dusty conditions and must have a high vibrational endurance. The decision as to whether these systems need to be used or not is based on the risk profile associated with the seam being mined and the probability of an ignition occurring. Growing pressure from the DME has resulted in an almost uniform requirement for their use throughout the industry.

One of the major problems associated with evaluating the effectiveness of these systems is the position (placement) of the sensor, as well as the calibration of the instrument (Van Zyl, et al. 1997).

Hand-held methanometers and flammable gas warning devices have proved to be valuable tools. Methanometers are extensively used to determine whether work areas are free from methane and to detect accumulations of methane before work is allowed to start.

4.2.1 Application

Numerous well tested and proven systems are commercially avaible. The norm is to mount these on the opposite side of the fresh air ventilation intake on the cutting head as close as practically possible to the face being cut.

It is further recommended to set instruments to 0,7 % CH_4/Vol alarm and 1,0 % CH_4/Vol cut-out.

4.3 Engineering aspects

As South African coals are of a hard and abrasive nature, the machines extracting them require a large power capacity. The presence of sandstone roofs and floors, and either pyrite or sandstone lenses in the coal, further increases the potential for frictional ignitions.

Much research effort has been put into the design of water-spray layouts, picks and cutter heads, and into reducing the rotational speed of the cutter head by means of re-engineering the existing gearboxes.

The objective of these efforts has been to reduce dust generation, power requirements and frictional ignitions.

Research is ongoing through initiatives by individual mining groups, manufacturers and SIMRAC-sponsored projects. The ultimate goal of all this research is to reduce the amount of dust generated and to prevent the possible accumulation of an explosible methane/air mixture in the face area.

4.3.1 Application

The use of wet head technology must be considered in areas shown to have a higher risk of a methane ignition occurring. These will assist in the prevention and dispersion of dust as well as to reduce and eliminate the frictional ignition risk.

5 Measures against coal dust

All preventative measures employed should be situated as close as possible to the potential ignition source. This will either prevent the coal dust from participating in an explosion or prevent any further flame propagation.

5.1 Active on-board ignition-suppression systems

The aim of using active suppression systems is to contain the methane flame in the immediate vicinity of the ignition. This will prevent a methane explosion which, in turn, could be the ignition source of a coal dust explosion.

The major role-players in the development of machine-mounted systems were Germany, the UK and the USA. During the latter part of the 90s, South Africa became a role-player through the adoption of the technology developed by Deutsche Montan Technologie, in Germany. This was achieved through using their BVS system to suit other mining methods and geometries.

Table 5.1 summarises the machine-mounted ignition-suppression systems evaluated in various countries.

Table 5.1: Summary of machine-mounted ignition-suppression systems

Country	Type	Extinguishing Agent	Dispersal method	Vessels		
				No.	Size	Loading (kg)
Federal Republic of Germany	BVS system	Tropolar ammonium phosphate powder	Nitrogen 120 bar detonator. Activated valves	6	12,3 ℓ cylinder	48
UK	Graviner system	Furex 770	N_2 or halon 60 bar	4-6	7 ℓ (app.) cylinder	16-24
USA	PRC system	ABC powder	Linear-shaped charge and halon 13,6 bar	6	Tabular canister 0,76 m 1,2 m 1,8 m 5 cm dia.	17

All three systems used ultraviolet flame detectors that can distinguish between methane and coal flames and are not prone to false triggering from artificial light sources (Furno, et al., 1985).

The BVS machine-mounted system was tested for ignition suppression with longwall operations in the Tremonia Experimental Mine (Michelis, 1983a). Successful suppression was achieved with 5 kg/m^2 of powder at the cutting face.

Further tests on roadheading machines were reported by Scholl and Faber (1979) using 'Tropolar' powder as an extinguishing agent. Ultraviolet sensors were used with response times of 100 to 200 ms for methane only and 250 to 550 ms for methane/coal dust flames. In tests in which the coal dust density exceeded 100 g/m^3, difficulty with detection was observed.

The automatic explosion-extinguishing set-up for continuous miners is based on the same individual components as the multiple-extinguisher system (Faber, 1990a and b) discussed earlier. Each system has to be customised and evaluated for performance. Systems have been developed for the following machines:

- Voest-Alpine, Types AM 85, 100 and 105
- Howden Paurat, Types E 134/504 and 250
- Alpine-Westfalia, Type WAV 300
- Joy continuous miner 14CM5
- Dosco 1300H
- Joy continuous miner 12 HM9.

Installation of these machine-mounted trigger barriers (Provincial Mining Council NRW, 1989) is compulsory in German coal mines where gas emission is suspected. This system is also licensed in South African coal mines to be used on continuous miners (Faber, 1997).

The BVS system has been deployed in operating mines in Germany and France. Ammonium phosphate (in various forms) is used as the extinguishing agent in all three systems. Their effectiveness against methane and coal dust flames was reported by Michelis (1983a) and

Furno (1985). Both nitrogen and halon 1301 have been used to act as the driving agent. However, the subsequent ban on the use of halon disqualifies its use for this purpose in the future. The amount of extinguishing agent required varies widely and is dependent on a number of factors, such as the tunnel geometry, maximum volume of gas needed to suppress an explosion, position of the system and mining method used.

Work at the MRDE in the UK (Browning and Moore, 1985) demonstrated the effectiveness of powder and halon in suppressing quite violent explosions around a drum shearer.

In two separate studies, Liebman (1975, 1979) investigated two systems developed by the USBM. In these tests, infrared sensors were used together with a range of extinguishing agents. In other tests on the Femal system, water proved better than Purple-K.

Neither the Graviner system evaluated in the UK nor the PRC system evaluated in the USA ever went beyond the development and evaluation phase.

The latest developments of these systems have taken place in South Africa where systems have been developed for double-pass machines such as the Joy continuous miners. Du Plessis *et al.* (1997) described the test protocol and the results of the evaluation of an adapted BVS system on a low-seam continuous miner in a specially built surface test gallery (Du Plessis and Oberholzer, 1997). The changes to the machine-mounted system were made by Centrocen, holder (at the time) of the EXPLOSTOP trade name and the international marketing rights to the system. The system successfully suppressed a total of 14 explosions varying in both methane (7,5 to 12 % CH_4/air) and volume concentrations. During the tests, it was proved that the system could detect and suppress stoichiometrically mixed methane ignitions before they reached the operator's position on the machine. It was recommended that the use of the system be considered in areas where the risk of methane ignitions is deemed high.

In a further, more recent, development, a machine-mounted suppression system was designed and evaluated for HBCM of France during 1998. Again the BVS system formed the basis of the machine-mounted system, which was adapted for a Dosco roadheader using a double-pass mining method. A further complication was that the coal seam sloped at an angle of 12 degrees from left to right, resulting in a sloping roof. The surface test gallery at

Kloppersbos was adapted to simulate these adverse mining conditions (Du Plessis, 1998). The system successfully suppressed methane explosions in 24 tests, even at 9 % CH_4/air concentrations with a volume of 188 m^3. This system has been deployed in the HBCM mine in the south of France where mining is undertaken at a depth of 1 400 m below surface.

The research community is in general agreement that the use of these systems will greatly strengthen the strategy for explosion prevention as they are near, or at, the point of ignition and can prevent an explosion from occurring.

During the past years a number of small methane ignitions were reported when mining close to dykes associated with burnt coal. The Department of Minerals and Energy of South Africa issued a circular stipulating that no continuous miner will be allowed to mine into burnt coal unless extra safety precautions are in place. These include the use of wet head systems, machine mounted active suppression systems and water mist curtain systems. Two systems based on the DMT German technology (EXPLOSTOP system) were adapted and tested in South Africa. In the search of developing reliable cost effective alternative systems a South African company (HS Design Engineering) combined forces with the South African Department of Trade and Industry together with Anglo Coal Ltd. to evaluate a system for 3,0m seam heights.

The protocol for testing of the HS Design Engineering system at the Kloppersbos test facility was designed to suit the double pass mining method. This required the suppression of methane explosions resulting from methane/air volumes of 123 m^3 at a 9% concentration per volume. The large volume results from the large cross-sectional area of the tunnel and from the free area in front of the machine when the second cut is taken. In order to mine the second cut the machine is pulled back to mine the web of coal, leaving a pocket in which large volumes of gas can accumulate. Since the system is machine-mounted, it is required to suppress the additional flame volume if a methane ignition occurs.

Active suppression systems have the following main components:

- Detecting sensor/s
- Electronic control and self-checking system
- Dust containers
- Flow nozzles.

These individual components are combined into systems, which are mounted on continuous heading machines. When an ignition occurs, its presence is detected by means of the sensor. These sensors are normally sensitive to the ultraviolet light range. An electronic signal from the sensor triggers the suppression system, creating a barrier of flame-suppressing material and containing the flame in the immediate vicinity of initiation. The flame-suppressing material most frequently used is ammonium phosphate powder, but gases such as NAF S111 may also be considered.

There are two testing facilities for the evaluation of these systems, namely the tunnel at BVS-Derne in Bochum, Germany, and the 20-m tunnel at Kloppersbos, South Africa. A number of systems have been developed by DMT (Faber, 1990b) for roadheaders. These have been in underground use since 1989 and are well proven and trusted.

A test facility capable of testing such systems against a set protocol (Du Plessis *et al.*, 1996) was built and completed during 1995 at the Kloppersbos Research Facility. The facility simulates the various mining configurations encountered in bord-and-pillar mines. To date, two systems have undergone successful evaluations. The first system was developed for low-seam continuous miners (Du Plessis, et al. 1997) and the second for a Dosco 1300H auger-type roadheader (Du Plessis, 1998) capable of excavating a seam height of up to 4,5 m.

The second system is used in mining conditions where the roof slopes at an angle of 12 degrees and a double-pass mining method is employed. For this specific evaluation, the maximum height of the roof was 4,5 m. The system is now deployed at HBCM mine in the south of France.

5.1.1 Application

The application for machine mounted systems is based on a baseline risk assessment. Systems have been developed for the following machines:

- Voest-Alpine, Types AM 85, 100 and 105
- Howden Paurat, Types E 134/504 and 250

- Alpine-Westfalia, Type WAV 300
- Joy continuous miner 14CM5
- Dosco 1300H
- Joy continuous miner 12 HM9.

Double pass continuous mining machines have only been tested to seam heights as high as 3,5 m.

A great need exists for further protocol testing to address seam heights from 3,5 to 6,0 m. No facilities exist to evaluate seam heights greater than 6,0 m.

5.2 Inerting of coal dust

Several materials for inerting coal dust have been identified and tested by numerous researchers and test facilities. The first investigation into the use of stone dust as an inerting material for inhibiting coal dust explosions has been attributed to the French investigator, Taffanel.

Over the years, many studies have been conducted to determine the effectiveness of alternative inerting agents. These tests were conducted at all the major research centres, including Tremonia (Germany), Bruceton (USA), the Barbara Experimental Mine (Poland), Buxton (UK) and the Kloppersbos Research Facility (South Africa).
Most of this work centered on the ability of water, stone dust and clay slate dust to inhibit the propagation of coal dust explosions and on the limits of effective operation. In recent years, various other methods involving the inhibition of coal dust dispersion as an effective means of preventing coal dust explosions have been investigated.

Inert material is applied for two distinctly different purposes in preventing coal dust from participating in an underground explosion, namely as an inerting agent and as an agent to prevent the dispersion of the dust.

Inerting agents include the well-known stone dust, clay slate dust, gypsum and various chemical dusts. Binding and wetting agents are used primarily to bind the coal dust and thus prevent its dispersion into the air. Water acts as a combination agent in that it can both inertise coal dust and also inhibit its dispersion.

Tests conducted world-wide have led to various general conclusions regarding the effectiveness, or lack of effectiveness, of stone dust and other inerting agents. It is widely held that effectiveness is a function of:

- coal dust particle size (Hertzberg and Cashdollar, 1987; Cashdollar and Hertzberg, 1989, Hertzberg *et al.*, 1981)
- the strength of the initiator used (Hertzberg and Cashdollar, 1987)
- the experimental procedure used (Hertzberg and Cashdollar, 1987)
- the presence or absence of a coal dust layer.

The effectiveness is measured in terms of the amount of inert material required to inhibit the propagation of a coal dust explosion. This is normally measured as the % TIC (total inert content), which is calculated as the total percentage of inert material on a per mass basis.

The exact means by which stone dust acts as an inerting agent has not been quantified. However, Cybulski (1975) described it as a combination of the following:

- stone dust acts as heat sink (adsorption of energy)
- stone dust screens radiation from the combustion process in between the coal particles
- the chemical reaction is endothermic, producing carbon dioxide
- stone dust particles obstruct the diffusion of oxygen and combustible gases.

Stone dust requirements are calculated using the equations set out below:

$$\%\,Stone\ dust = \frac{(\%\,TIC - \%\,Ash - \%\,Water)}{\left\{1 - \left[\frac{\%\,Ash + \%\,Water}{100}\right]\right\}}$$ (Michelis *et al*., 1991)

$$\%\,TIC = x$$

where % TIC is the percentage of Total Incombustible Content

The percentages of ash and water inherently present in the coal dust are taken into account when the calculations are made as shown above. An example of the calculation is given below:

$$For\ x = 85\% \quad (\%\,TIC)$$

$$\%\,Stone\ Dust = \frac{(85 - 14{,}1 - 1{,}6)}{\left\{1 - \left[\frac{14{,}1 + 1{,}6}{100}\right]\right\}}$$

$$= 82{,}21$$

$$Total\ Mass = 35\ kg / \left[1 - (\%\,stone\ dust / 100)\right]$$

$$= 35 / (1 - 0{,}08221)$$

$$= 35 / 0{,}1779$$

$$= 196{,}7\,kg$$

Thus the amount of stone dust required to inert 35 kg of coal dust is:

$$Mass\ of\ stone\ dust = Total\ mass - coal\ dust\ mass$$

$$= 196{,}7 - 35$$

$$= 161{,}7\ kg$$

One of the most extensive studies conducted on the effectiveness of inhibiting dusts was done by the United States Bureau of Mines (USBM) (Hertzberg, et al. 1982). In this project, 37 different inhibitors were investigated.

The results of this investigation compared favourably with those of tests done in experimental mines (Gruner, 1975; Richmond, et al. 1979), as shown in Table 5.2a.

Table 5.2a: Inerting requirements for Pittsburgh seam coal

Inhibitor	Weight – percentage required to inert		
	8-ℓ chamber	**2-m-diameter gallery**	**Experimental mine**
$KHCO_3$ (Purple K)	75 – 80	70 – 75	67 – 73
$CaCO_3$ (Rock dust)	~ 60	65 – 70	67 – 70
KCl (Super K)	50 – 55	20 – 30	35 – 40
NaCl (BCD)	45 – 50	18 – 24	35 – 40
$NH_4\ H_2\ PO_4$ (ABC)	18 – 20	10 – 15	18 – 24

In summary, it was suggested that the effectiveness of the inhibiting salts correlated better with their anionic than with their cationic components. The approximate order of anion effectiveness is phosphates> halides> carbonates.

Tests conducted at Lake Lynn Experimental Mine (Greninger *et al.*, 1990) on Pittsburgh coal showed that a coal/stone-dust mixture with a TIC between 80 and 82 % was required to prevent explosion propagation.

Although clay slate dust was used in the past, this material was subsequently abandoned on account of its high free-silica content. British researchers (Mason and Wheeler, 1933 and 1936) carried out investigations to determine the effectiveness of limestone, clay slate and other stone dusts. They found that for coal dust with a volatile matter content of 33,3 %, and tested in a 100-m-long gallery with a diameter of 1,22 m, the following limit percentages (see Table 5.2b) were required to render coal dust incapable of propagating an explosion:

Table 5.2b: Inert limit percentages

Slate	67,5 %
Diatomite	62,5 %
Anhydrite	60,0 %
Limestone	57,5 %
Dolomite	57,5 %
Gypsum	40,0 %

The South African requirements for stone dust are set out in the Minerals Act of 1991. These are shown in Table 5.2c.

Table 5.2c: Specification of stone dust as required by Regulation 10:24 of the Minerals Act of 1991 of the Republic of South Africa

Item	Requirement
Incombustible content	Min. 95 %
Free silica	Max. 5 %
Size distribution	100 % passing 600 µm sieve 50 % passing 75 µm sieve

The requirements for the inerting of coal dust were reviewed by an MRAC task group, which was formed as a result of the recommendations made by the Leon Commission (Leon *et al*., 1995).

The recommendations set out in the *Guidelines for a Mandatory Code of Practice for Explosion Prevention* (1997) with regard to inertisation requirements included the extent of the application as well as the degree of inertisation required.

5.2.1 Extent of application

In order to ensure that the underground workings of a coal mine are adequately protected, all underground areas of a coal mine producing bituminous coal, except those areas extending to the face from and including the last through road, in which the coal dust has been washed from the roof and sides, and the floor is too wet to propagate an explosion, should be stone dusted to within 10 m from all working faces, unless such areas are inaccessible or unsafe to enter. Such areas must be timeously identified by hazard identification and risk assessment and addressed to reduce the hazard.

5.2.2 Degree of inertisation

Any coal mine can be divided into different areas, with significantly different potential for experiencing a coal dust explosion, e.g. intake airways far distant from a working face and return airways in the face area. Considering all available information, the following minimum levels of inertisation by the application of stone dust are required:

a. Intake airways

   i. In the face area, a minimum percentage by mass of incombustible matter content of 80 % must be maintained.

   ii. Outbye the face area, intake airways must be maintained at a minimum of 65 % incombustible matter content. Workshops, substations, battery-charging stations and other similar places where work is done or equipment is maintained, situated in intake air, must nevertheless be maintained at a minimum of 80 % incombustible matter content.

b. Return airways

   i. A minimum percentage by mass of incombustible matter content of 80 % must be maintained up to a minimum distance of 1 000 m from the face. Beyond this distance, a minimum percentage by mass of incombustible matter content of 65 % must be maintained, provided that where approved barriers are installed, the incombustible matter content by mass outbye the face area and outbye the barriers must be maintained at not less than 65 %.

   ii. Return airways in close proximity to sealed areas, or areas in the process of being sealed off, must contain a minimum percentage by mass of incombustible matter content of 80 %, unless the area has been properly sealed off.

c. Conveyor belt roads

A minimum percentage by mass of incombustible matter content of 80 % must be maintained up to a minimum distance of 180 m from the face. Beyond this distance, a minimum percentage by mass of incombustible content of 65 % must be maintained.

It should be recognised that conveyor belt roads constitute a particular hazard. Dust is liberated into the ventilation current at transfer points and during the conveying of coal. Spillage from belts also contributes to the problem. In addition, the conveyor structure itself provides an ideal location for the accumulation of coal dust. Stone dusting alone cannot, therefore, adequately protect conveyor belt roads and use must be made of barriers.

d. Abandoned areas prior to being sealed off

Before any area is sealed off, the roof, sides and floor must, as far as is reasonably practicable, be stone dusted to ensure a minimum percentage by mass of incombustible matter content of 80 %.

The above recommendations were based on mining practices used in Europe, which were in turn based on extensive research. However, research by Cook (1993) has shown that the propagation of a full-scale coal dust explosion can only be stopped if the 80 % TIC requirement is adhered to.

The methods used to place stone dust underground include manually, mechanical and trickle duster. In high seam heights > 6,0 m problems with effective dispersement and placement exists. The use of trickle dusting is also associated with concerns of coal dust layering. These practices are though well used in the USA and Australia, specifically to assist in the longwall return dusting.

6 Passive explosion barriers

The principle of using explosion barriers to safeguard mines was first noted and evaluated by Taffanel (1910) at the turn of the century. He based his principle on the fact that the flame of a coal dust explosion is preceded by a blast wave. It was therefore Taffanel who designed the first shelf-based explosion barrier (Taffanel and Le Floch, 1913). Because he lacked the resources that other researchers had later, the barrier failed to stop an explosion in the Clarence mine. However, the principle developed by him was extensively researched later and formed the basis of a number of shelved stone dust barriers which were developed throughout the world.

In essence, explosion barriers are used to safeguard the rest of the mine outbye the normal production area. Passive barriers are installed to provide supplementary protection against coal dust explosions. To this end, two types of passive barrier have been developed and extensively tested at a number of research institutes. These barriers - the stone dust barrier and the water trough barrier - have been deployed in mines throughout Europe, Australia and South Africa.

Although tests have indicated certain shortcomings, especially against weak and very strong coal dust explosions, the reduction in the risk of a coal dust explosion propagating throughout a mine when barriers are systematically deployed is well understood and accepted.

Passive explosion barriers use the dynamic pressure from the windblast that precedes the flame front to activate and disperse the suppressant material. In the event of an explosion, the following sequence of events occurs:

- The methane ignites and there is a slow growth in the flame and the size of the fireball, with almost no pressure increase.
- Deflection of the methane fireball and pressure from the sides of the gallery create turbulence. At this point, there is almost no time delay between the flame front and the pressure wave.

- Coal dust particles start to participate with the methane fireball and become the incendive driver. The dispersion characteristics of the coal dust cloud will determine the initial time delay between the pressure pulse and the flame of the coal dust progression.
- From here onwards, the explosion is self-generating and only governed by the amount of fuel readily available.

The time delay between the flame front and the pressure wave is the time available for the passive barrier to disperse enough flame-suppressant material at the correct concentration. Thus, passive barriers require a minimum dynamic pressure for activation and a minimum period of time for the dispersal of suppressant material to operate effectively.

The use of inerting agents to prevent coal dust explosions from occurring leads to a paradox when considering the effective operation of barriers. This was explained by Goffart (1983) as follows: “The use of preventative measures such as stone dust or hygroscopic salts may result in favouring explosions with low speeds of propagation, or the so-called mild explosions which can result in barrier failure”.

In most countries, the mining regulations do not allow the amount of stone dust to be reduced in the area of the barrier, except in France where the stone dusting requirement is reduced by five per cent in zones where barriers are deployed.

Passive barriers are classified according to the type of extinguishing agent used, as either water or stone dust barriers. They are further classified according to the manner in which they are normally deployed, namely as either concentrated or distributed barriers. Concentrated barriers are strategically deployed in a mine and are designed to stop flame propagation immediately on arrival of the flame. Distributed barriers can be deployed over extended distances in a mine and will allow longer flame extension, but with a greater certainty of successful suppression.

6.1 Shelf Stone dust barriers

Up and until the early 1960s, most of the research on passive barriers focused on investigating the effectiveness of stone dust barriers. Extensive research work was conducted in the United Kingdom, Poland, Germany and the USA to refine the design of this barrier. In the following sections various developments with regard to stone dust barriers in individual countries are explained.

6.1.1 United Kingdom stone dust barriers

As early as 1961, British mines (National Coal Board, 1961) were required to install stone dust barriers in their conveyor roadways. In 1963, the barriers prevented two potentially major coal dust explosions at the Fenton and Mainsforth Collieries (Eisner and Hartwell, 1964).

The barriers used in the United Kingdom follow the design of the Polish stone dust barriers. The design of the barrier is described in the law relating to safety and health in mines and quarries. There are three types of United Kingdom stone dust barriers in use. They were described by Lunn (1988):

6.1.1.1 The light stone dust barrier

This barrier is designed to arrest explosions in the early stages of development, within 64 to 119 m of the point of ignition (assumed to be the coal face). The barrier consists of a set of "light" shelves (i.e. up to a maximum of 29,8 kg of dust per metre of shelf). Sufficient dust is used to provide 107,4 kg of stone dust for each square metre of roadway cross-section.

6.1.1.2 The intermediate stone dust barrier

This barrier is designed to arrest explosions that have developed beyond the initial stage and have accelerated over a distance of about 230 m from the source of ignition. The barrier consists of a mixture of "light" shelves (< 29,8 kg of dust per metre) and "heavy" shelves (29,8 to 59,9 kg of dust per metre), with not more than one-third of the shelves heavily loaded. Sufficient dust is used to provide 195 kg of stone dust for each square metre of roadway cross-section.

6.1.1.3 The heavy stone dust barrier

This barrier is designed to arrest highly developed explosions, within 183 to 320 m from the source of ignition, with not more than two-thirds of the shelves heavily loaded. Sufficient dust is used to provide 390,7 kg of stone dust for each square metre of roadway cross-section. Heavy barriers are always used in conjunction with light barriers.

Lunn (1988) explained the effectiveness of the barriers in accordance with the work done by Cybulski (1966). The limits of the barriers were such that he postulated that the different barriers would be able to give adequate protection for explosion run-up distances to the start positions of barriers as shown below:

- Light barrier: approximately 180 m
- Intermediate barrier: approximately 230 m
- Heavy barrier: greater than 280 m with no upper limit set.

6.1.2 Polish shelf barriers

The most extensively documented work on the evaluation of stone dust barriers was done by Cybulski (1975). More than 1 700 tests were conducted at the Barbara Experimental Mine. The Polish stone dust barrier consists of a number of smaller units, suspended on a shelf. These aid in the easier dispersal of stone dust. The barrier design is shown in Figure 6.1.2a.

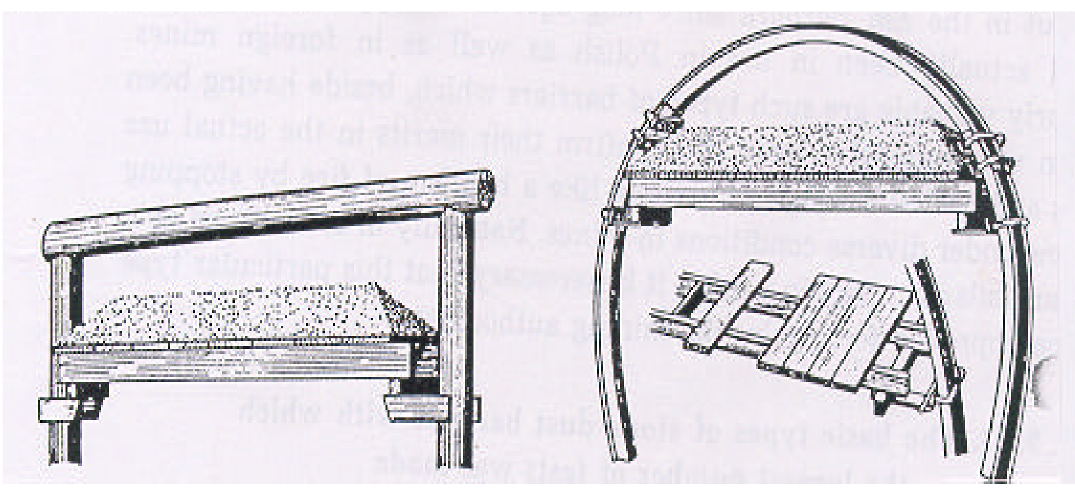


Figure 6.1.2a: Design of the Polish stone dust barrier

The results of these 1 700 tests were published in 13 scientific bulletins by Cybulski (1950, 1954, 1960, 1965a, 1965b, 1968a, 1968b, 1969a, 1969b, 1969c and 1971).

The barrier consists of support props, brackets on props, the frame and the platform (shelf or loose boards). The boards are either 35 or 50 cm long and the frame should be more than 20 cm high. It is further recommended that water-resistant stone dust be used to improve dust dispersion characteristics, even in humid conditions.

Of all the barriers developed, the Polish stone dust barrier and the German water trough barrier are the most widely used internationally. Table 6.1.2 summarises the requirements of the various countries that use explosion barriers.

Table 6.1.2: Passive barrier loading requirements (after Sapko *et al.*, revised 1989)

Country	**Mass loading**			
	Stone dust (kg/m^2)		**Water (ℓ/m^2)**	
	Non-gassy	**Gassy**	**Non-gassy**	**Gassy**
Australia	200	200	200	200
Belgium	-	400	-	200
Canada	-	200	-	200
Czechoslovakia	200	400	-	-
Federal Republic of Germany	-	400	-	200
France	-	400	-	200
Japan: Light Heavy Extra heavy	 0,1 m^3/m^2 0,3 m^3/m^2 0,4 m^3/m^2	 -	 -	 100 300 400
South Africa	-	100 light 400 heavy		200
Romania	-	400	-	200
United Kingdom		200 light 400 heavy		200 min.
Soviet Union	200	400		

Note: After Sapko (1989) with changes made for South Africa and Australia where the mining regulations changed in 1997 and 1999 respectively.

All the water barriers referred to in the above table use destructible water troughs, except the Japanese barriers in which flexible water bags are used (Nagy, 1986).

Cybulski (1975) defined three quantities that are used as the design criteria for passive explosion barriers. All of these will affect the mass of stone dust as well as its distribution in a barrier. The criteria are:

- Q_A - the total quantity of stone dust in the barrier per square metre of the gallery's cross-section (kg/m^2); this is normally used as the regulatory requirement for the design of stone dust barriers.

- Q_1 - the quantity of stone dust on a single shelf per square metre of the gallery's cross-section (kg/m^2).

- Q_V - the concentration of stone dust in the zone in which the barrier is positioned, i.e. the quantity of stone dust on the whole barrier in relation to the volume of the working area that it occupies (kg/m^3).

The way in which Cybulski defines the Q_V value is different from that suggested for the water trough barrier (free volume between barriers). As all of the concentration criteria are based on mass concentrations and not volume, the notation used in this report was changed to reflect this: M_A, M_1 and M_V respectively.

In each of the barrier designs, the mass of stone dust or water required inside the barrier is calculated on the basis of the type of barrier that is to be used. In the design of the concentrated barrier, the stone dust requirement is referenced to the gallery's cross-sectional area. When a distributed barrier is to be designed, the amount of stone dust required is based on the mass per unit volume.

Stone dust barriers have been extensively used as concentrated barriers. The design requirements for the concentrated barrier are based on the mass of stone dust required per unit of roadway area. Two main types of barrier are used: either light (100 kg/m^2) or heavy (400 kg/m^2) design criteria.

Furthermore, in the respective barriers, two types of shelf are used to construct the barrier. They are described below:

Light shelf

The lightly loaded shelves consist of masonite boards, 350 mm long by 150 mm wide. Stone dust is loaded onto these shelves at a rate of 30 kg per metre of shelf width. The average height of the pyramidally shaped stone dust load on top of the shelves is 140 mm.

Heavy shelf

The heavily loaded shelves consist of lightweight wood, such as masonite boards, 450 mm long by 150 mm wide. Stone dust is loaded onto these shelves at a rate of 60 kg per metre of shelf length. The average height of the "pyramid" of stone dust is 220 mm.

The design specifications for the construction and placement of both the light and heavy stone dust barriers are described in the following paragraphs.

6.1.2.1 Light stone dust barrier

The placement requirements for this barrier are as follows:

- not closer than 80 m from the face
- not further than 180 m from the face.

All the shelves used are light shelves spaced 1,5 m apart and the minimum design requirement for the barrier is 100 kg of stone dust per unit area of the roadway. To illustrate the design requirement, an example of a calculation for a mine with a seam height of 4,0 m and a road width of 6,5 m is shown:

Area of roadway	=	4 x 6,5	= 26 m^2
Mass of stone dust required	=	26 x 100	= 2 600 kg

If the shelves are 6,0 m wide, their loading capacity is:

Mass per shelf	=	30 x 6	= 180 kg
Number of shelves required	=	2 600/180	= 14, 4 shelves

The barrier thus consists of 15 shelves, spaced 1,5 m apart. The total barrier length is 21 m.

6.1.2.2 Heavy stone dust barrier

The placement requirements for this barrier are as follows:

- not closer than 80 m from the face
- not further than 380 m from the face.

A combination of light and heavy shelves is used in a ratio of 1:2. The shelves are spaced 1,5 m apart. The light shelves are placed in front of the heavy shelves in the most probable direction of the explosion. The minimum design requirement for the heavy barrier is 400 kg of stone dust per unit area of the roadway. To illustrate the design requirement, an example of a calculation for a mine with a seam height of 4,0 m and a road width of 6,5 m is shown:

Area of roadway	=	4 x 6,5	= 26 m^2
Mass of stone dust required	=	26 x 400	= 10 400 kg

If the shelves are 6,0 m wide, their loading capacity is:

Mass per light shelf	=	30 x 6	= 180 kg
Mass per heavy shelf	=	60 x 6	= 360 kg
Mass of 1:2 ratio	=	180 + 720	= 900 kg
Number of shelf units	=	10 400/900	= 11,6 units

The barrier consists of 12 light shelves and 24 heavy shelves, spaced 1,5 m apart. The total barrier length is 52,5 m, with a total barrier mass of 10 800 kg.

6.1.2.3 Distributed stone dust barrier

Success in suppressing the propagation of coal dust flames through the use of distributed barriers with a stone dust concentration of 0,25 kg/m^3 was reported by Cybulski (1975). He further recommended that a concentration of 1 kg/m^3 should be used for this type of stone dust barrier.

Cybulski (1975) also stated that: "Distributed barriers are barriers in which the shelves are placed at such distances as to satisfy the following basic conditions:

- Q_V should not amount to less than 1 kg/m^3
- The value of Q_1 should not be lower than 0,5 kg/m^2."

The only country using distributed stone dust shelf barriers is Australia where the installation requirements for distributed barriers are based on a minimum loading of 200 kg/m^2.

6.2 Water trough barriers

Water trough barriers have a long history. In 1910 Pardour was the first to recommend the use of water troughs. The first use of water barriers (according to Cybulski, 1975) was attributed to Taffanel, the principle of operation being simply that if water were distributed ahead of the explosion flame, the flame could be extinguished through:

- the high specific heat of water reducing the temperature of the flame
- the heat required to evaporate the water
- the reduction of oxygen where water vapour is formed.

The minimum requirements for water trough barriers for use in German mines were based on the extensive research carried out at Tremonia. The material used for a plastic (composite) water trough had to fulfil various criteria to satisfy both the demands of the mining industry and technical explosion requirements. Various products were tested with specific reference to the following properties:

- combustibility (inflammability)
- consistency
- ageing
- mould stability
- chemical composition.

Polyethylene, polystyrol and polyvinyl chloride all fulfilled the criteria for suitable material. Figure 6.2a shows water troughs made out of different materials.

Figure 6.2a: Water troughs made out of different materials

Left - Styropor, Centre - Polyvinyl chloride, Right - Polystyrol

Only polyvinyl chloride (PVC) and polystyrol (PS) are now used for manufacturing barriers (Michelis, 1998).

The water trough barrier consists of individual PVC water troughs, each able to hold between 40 and 80 ℓ of water. The dimensions of a water trough are: 56 cm wide, 81 cm long and 28 cm high. Two different barrier designs are used, either concentrated or distributed.

Referring to Figures 6.5.2a and b, the following must apply with regard to troughs when installed in a single layer, if they are to be effective:

- For roadways up to 10 m^2, X+Y+Z must cover at least 35 % of W.
- For roadways up to 15 m^2, X+Y+Z must cover at least 50 % of W.

- For roadways in excess of 15 m^2, X+Y+Z must cover at least 65 % of W.
- The distance of A or B or C or D must not exceed 1,2 m.
- The total distance of A+B+C+D, etc. must not exceed 1,5 m.
- The distance V1 must not be less than 0,8 m and must not exceed 2,6 m.
- The distance V2 should not exceed 1,2 m. Whenever this distance is exceeded, additional troughs must be placed above. They may be placed 2,6 m above floor level, but there should not be more than 1,2 m between the base of layers of troughs.

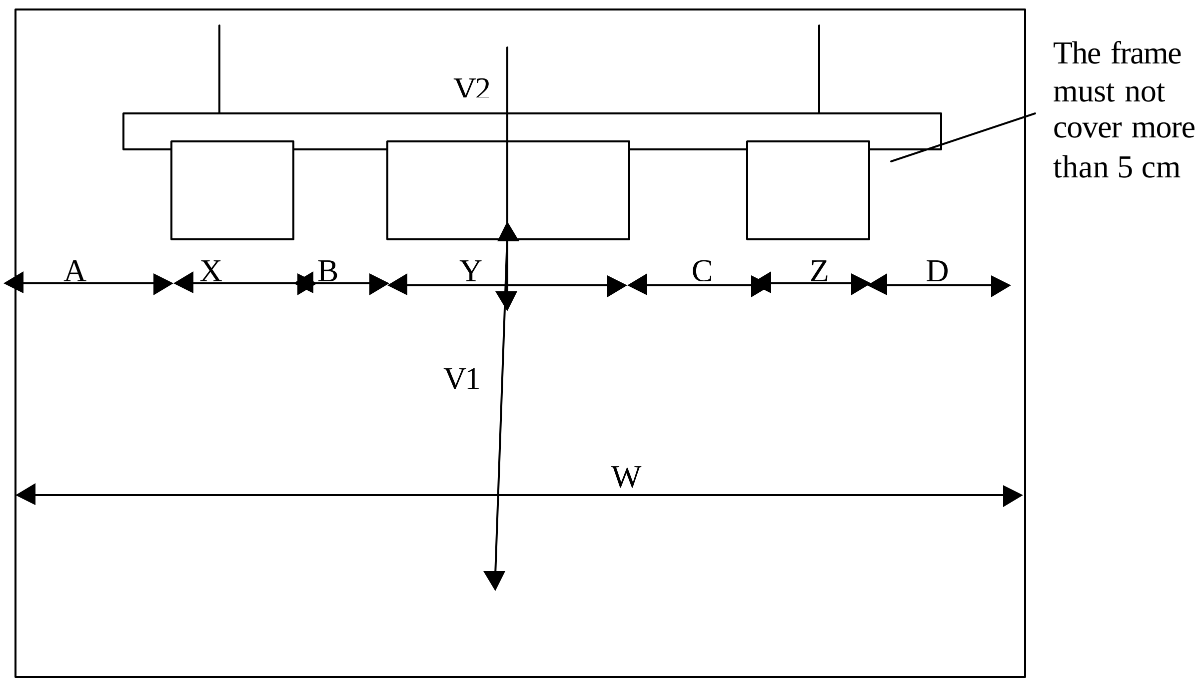
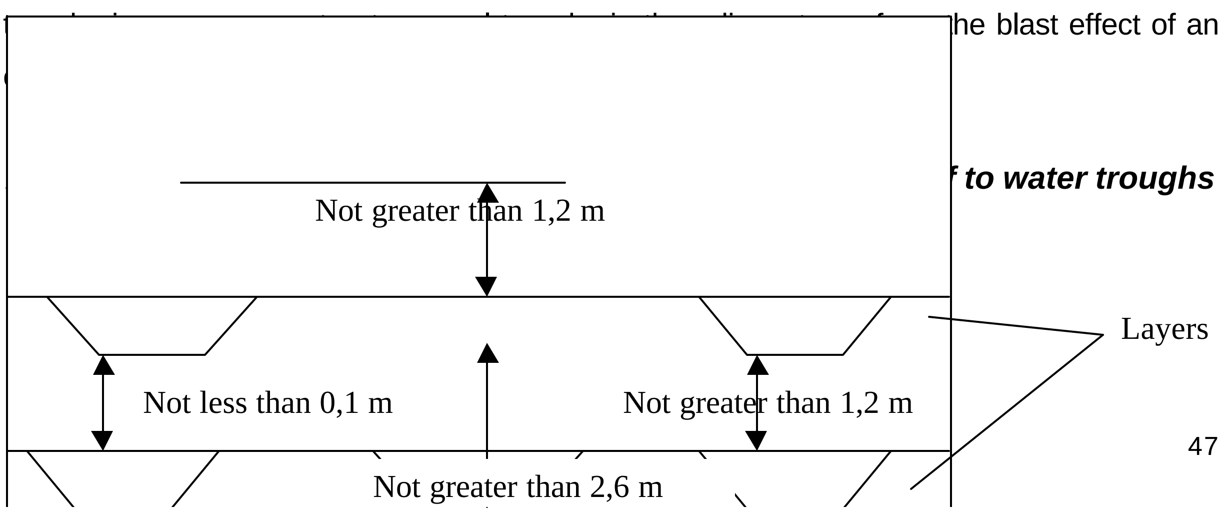


Figure 6.2b: Water trough barrier area coverage

Where more than one layer of troughs is required, the following will apply:

When troughs are arranged in rows less than 1,2 m apart, measured along the roadway,

he blast effect of an



f to water troughs

6.2.1 Concentrated water barrier

The placement requirements for this barrier are as follows:

- not closer than 120 m from the last through road
- not further than 360 m from the last through road.

The concentrated barrier design requires the minimum of either 200 ℓ/m^2 of the roadway cross-sectional area or 5 ℓ/m^3 of the volumetric area inside the barrier, with a minimum barrier length of 20 m, but not greater than 40 m.

To illustrate the design requirement, an example of a calculation for a mine with a seam height of 4,0 m and a road width of 6,5 m is shown:

Area of roadway	=	4 x 6,5	= 26 m^2
Water required (area based)	=	26 x 200	= 5 200 ℓ
Number of troughs required	=	5 200/80	= 65

Check:

Water required (volume-based)	=	26 x 20 x 5	= 2 600 ℓ
Max. barrier length allowed	=	5 200/(26 x 5)	= 40 m

The barriers are placed in a double layer of 65 troughs. There are five troughs per row, with the top row being 1 m below the roof and the second row 2 m above the floor. The troughs are spaced 3 m apart. The total length of the barrier is 30 m.

6.2.2 Distributed water barrier

The placement requirements for this barrier are as follows:

- not closer than 120 m from the face
- not further than 200 m from the face.

The distributed barrier design requirements state a minimum requirement of 1 ℓ/m^3 of the volumetric area between individual barriers, with a maximum distance of 30 m between them.

To illustrate the design requirements, an example of a calculation for a mine with a seam height of 4,0 m and a roadway width of 6,5 m is shown:

Area of roadway	=	4 x 6,5	= 26 m^2
Acceptable max. distance	=	30 m	
Water required	=	26 x 30 x 1	= 780 ℓ
Number of troughs required	=	780/80	= 9,8

Each sub-barrier consists of ten water troughs, five per row spaced not closer than 1,5 and not further than 3,0 m apart. The length of the sub-barrier is therefore 3 m.

6.3 Bagged stone dust barrier

From the early 1970s onwards, the South African coal mining industry has experienced a significant number of underground explosions, leading to a considerable loss of life. Since the formation of the Safety in Mines Research Advisory Committee (SIMRAC) in 1993, one of the strategic thrusts of South African mining research has been towards reducing the explosion risk in collieries. This research has focused on preventing the accumulation of methane by diluting it through good ventilation practice, reducing frictional sparking through the use of water, minimising dust generation and dispersion, and using stone dust to prevent coal dust explosions. The final line of defence is, however, the use of barriers to prevent coal dust explosion flames from propagating.

During the testing and evaluation of the available passive barrier systems, a number of shortcomings were identified. It was also recognised that the design of the passive explosion barrier systems currently in use has remained unchanged for many years. Stone dust and water barriers were originally designed and developed as much as 50 years ago. These systems were developed and tested for long single-entry mining practices and are now often regarded as an impediment to modern mining practices. They are also costly, as well as being difficult to install and maintain. Furthermore, none of these systems was ever evaluated in multiple bord and entry mining layouts.

In the last six years, a great deal of research effort has been expended on developing a bagged stone dust barrier which is considered to be better suited to modern mining practices. The work initially concentrated on the selection and development of suitable material for the bags. Once this had been accomplished, the holder arrangement for the bags was developed. This holder aids the dispersion of the stone dust in the bags and is also cost-effective. The final bagged barrier design consists of an array of these specially manufactured holders and plastic bags containing stone dust, suspended from suitable structures or the mine roof.

The new bagged barrier proved effective in suppressing explosions in the test gallery at Kloppersbos (5-m^2 cross-sectional area) and in the experimental mine at Tremonia in Germany (20 and 22-m^2 cross-sectional areas). This showed that the concept of a bagged stone dust barrier could be used with considerable confidence in protecting long single entries. In South African coal mines, however, multiple-entry mining methods are invariably used but little was known about how explosions propagate under these conditions and whether the bagged barriers would be able to inhibit flame propagation in these circumstances.

The different barrier configurations evaluated were: single bags (to test their operation), bags used as a stone dust supplement, and bags in the formats of concentrated, distributed and classic distributed barriers. After the development of the bagged barrier concept and the initiation of the evaluation programme at Kloppersbos, the question arose as to the operational effectiveness of stone dust bags in larger cross-sectional galleries. To answer this, a project was formulated under the auspices of SIMRAC and Deutsche Montan Technologie (DMT) in Germany was contacted to assist in the evaluation of the stone dust bags under these conditions.

The initial test work at DMT focused on the performance of single bags in a small surface gallery when subjected to various low-pressure explosion pulses. This work was followed by extensive evaluation in the 20-m^2 gallery at the Tremonia Experimental Mine. From the tests conducted in the large cross-sectional test gallery (BVS elliptical tunnel) at this facility, it was shown that the bag would rupture under low dynamic pressure loading.

Some of the work done in the experimental mine was aimed at determining the correct placement and distribution of the bags in relation to the cross-sectional dimensions of the gallery. This was necessary to ensure optimum operational effectiveness of the bags when subjected to explosions of weak dynamic pressure. The last set of tests at Tremonia was aimed at proving the effectiveness of the bagged stone dust barriers, both concentrated and distributed, in inhibiting flame propagation when subjected to a weak coal dust explosion in a large cross-sectional gallery.

The final evaluation of the bagged barrier was conducted in a simulated bord-and-pillar mine at Lake Lynn, USA. As the effect of intersections on explosion propagation was unknown and the simultaneous arrival of pressure waves from different directions might render the bag breakage mechanism ineffective, it was felt important that the ultimate series of tests for these barriers should be conducted in a bord-and-pillar section. In particular, it was essential to determine whether or not bagged stone dust barriers could effectively suppress coal dust explosions in bord-and-pillar mines.

The operation of individual bags positioned in the various roadways and in the cross-cuts showed that the bags operated at dynamic pressures as low as 4 kPa. Furthermore, it was concluded that the individual bags operated effectively when suspended close to the mine roof in a low-seam (~2 m) multiple-entry mine configuration. The effective distribution of the stone dust contained within the bags was dependent on the distance of the bag from the explosion source, as well as on its placement, i.e. whether the bag was suspended in a roadway or in a cross-cut.

From the development and test work done at Kloppersbos, Tremonia and Lake Lynn, general requirements for the bagged barriers were determined. They are summarised in Section 6.3.1.

6.3.1 General barrier requirements

6.3.1.1 Loading

The recommended quantity of stone dust, M_A, is expressed as a mass (kg) loading per roadway cross-sectional area (m^2).

6.3.1.2 Spacing

Spacing of bags

The spacing of the bags should conform to the following minimum standards:

Distance between bags in a row

- not closer than 0,4 m
- not further than 1,0 m

Distance between rows

- not closer than 1,5 m
- not further than 3,0 m

Distance to sidewall of outer bags

- not nearer than 0,5 m
- not further than 1,0 m

Distance to roof

- not nearer than 0,5 m for seam heights greater than 3,5 m

Height restrictions

The following are minimum requirements, i.e. if the mine wishes to install more levels of bags within the other specified requirements, it may do so.

- for roads with a height range of less than 3,0 m: a single level of bags suspended below the roof
- for roads in the height range 3,0 m to 3,5 m: a single level of bags suspended at a height of approximately 3,0 m

- for roads in the height range 3,5 m to 4,5 m: a double level of bags suspended at approximately 3,0 m and 4,0 m above floor level
- for roads in the height range of more than 4,5 m but less than 6,0 m: a triple level of bags suspended at approximately 3,0 m, 4,0 m and 5,0 m.

Spacing of barriers

The spacing of the barriers should conform to the minimum standards prescribed for each individual design.

6.3.2 Means of suspension

The use of steel structures suspended from the roof bolts by any suitable means is recommended. A suggested example is the use of a chain-and-angle-iron configuration suspended from the roof bolts, allowing height adjustment as necessary. Any other possible suspension method can be investigated.

The closing mechanism and plastic bag must conform to the requirement that no bag may be used unless it has been tested and found to be of adequate quality, strength and thickness, and also tested to ensure that it has the correct operating characteristics (it should work effectively for a dynamic pressure of 5 kPa).

In the following sections a recommended design for each of these individual barriers is given.

6.3.3 Concentrated barrier

The concentrated barrier was designed for use as an alternative passive barrier system especially for areas where high-speed flame development can occur, for example in longwall sections. The recommended stone dust quantity, M_A, is 100 kg/m^2.

The placement of the barrier should conform to the following design criteria:

- The first row of bags must be not nearer than 70 m to the last through road and not further than 120 m.

- The first row of bags of the second barrier must be not further than 120 m from the last row of bags of the first barrier.

The length of the barrier should be a minimum of 20 m and a maximum of 40 m. Furthermore, it is required that at least one fully constructed barrier should be in position at all times, implying leap-frogging from the second barrier.

6.3.4 Distributed barrier

The design of the distributed stone dust barrier is based on the principle of lower stone dust concentrations, distributed over extended areas, protecting against explosions. The idea is that by safeguarding a greater area, greater protection should be afforded against the propagation of coal dust explosions in bord-and-pillar mines. The loading requirements for the distributed barrier are that M_A must exceed or at least equal 100 kg/m^2 of roadway area and that M_V must not be less than 1 kg/m^3, where the greater of the two quantities must be used. Distributed barriers are made up of four sub-barriers.

The placement of the four individual sub-barriers must to conform to the following requirements:

- The sub-barrier nearest the face should be not closer than 60 m to the last through road and not further than 120 m.
- The fourth sub-barrier, the one furthest from the face area, should be installed not more than 120 m from the first row of bags in the first sub-barrier.
- There should be two intermediate sub-barriers in between.

At least three fully constructed sub-barriers are required to be in position at all times, implying leap-frogging from the fourth sub-barrier.

6.3.5 Classic distributed barrier

The classic distributed barrier is based on the same design principles as the distributed barrier and also provides extended area coverage. This barrier is suitable for most mining practices and is recommended for longwall mining. From the test work, the requirements are as follows: the minimum loading and length of the installed barrier must be such as to ensure that M_A is greater than 60 kg/m^2 and that M_V is greater than 0,6 kg/m^3. The first sub-barrier, nearest the face, should not be closer than 60 m to the last through road and not further than 120 m. To ensure a margin of safety, it is recommended that M_A be at least equal to or greater than 100 kg/m^2.

All the sub-barriers must be in position, i.e. more units must be deployed, before the units at the back of the barrier are recovered. Thus at least one fully constructed barrier must be in position at all times, prior to allowing leap-frogging from the sub-barriers at the back.

6.3.6 Stone dust supplement

This unique concept was also only evaluated at the Kloppersbos research facility. In this configuration the bags inhibited flame propagation in simulated worst-case scenarios, i.e. they successfully inhibited flame propagation in coal dust explosions propagating through 40-m and 60-m pure coal dust zones prior to reaching the start position of the bags.

6.3.6.1 Stone dust supplement design

The minimum user requirements cannot be stipulated *per se*. Each application should be specifically designed according to the minimum requirements for that application. In this design it is assumed that an explosion will already be in progress and that the function of the supplementary stone dust is to ensure a greater percentage TIC than the minimum requirement as stipulated in the DME Guidelines. The minimum requirement for this design is that the number of bags installed must exceed the distance required to ensure the minimum stone dust requirements of M_A greater than 50 kg/m^2 and M_V greater than 0,5 kg/m^3. The first row of bags, nearest the face, must be not closer than 40 m to the last through road and not further than 60 m. It is also advisable for the bags to be deployed as close as possible to, or better still in, the area that requires safeguarding.

6.4 Passive barrier application shortcomings

Difficulty with barrier installation in low seams exists. Careful design of access routes can though assist in eliminating this shortcoming. The shelf stone dust barriers were never evaluated. There is thus no change in their design criteria for different seam heights. This might lead to a sense of false security.

Both the water trough barriers and the dust bag barrier system design requirements only refer to seam heights up and to 6 m. The use of these in higher seam heights might require a higher factor of safety (increase in suppressant).

Only the bagged stone dust barriers were evaluated in bord and pillar mines.

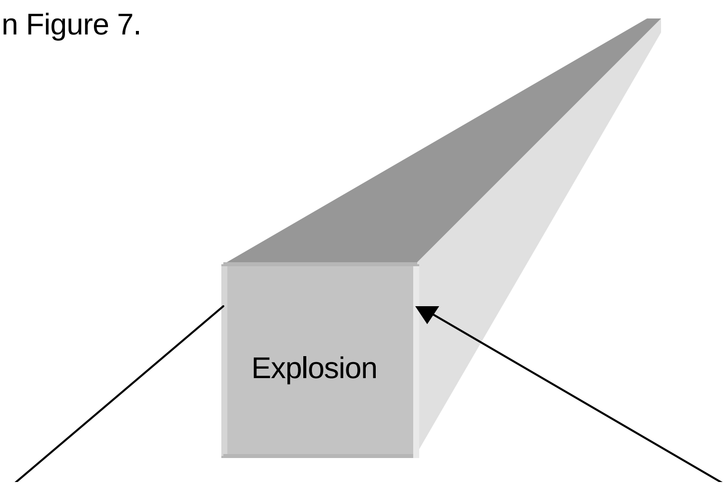
In the application problems are encountered in very high seam mining conditions. These conditions >5 m normally result from top or bottom coaling operations. Technology to address these do not exist.

In the return airway of a longwall section the amount of float dust generalised results in high requirement levels of stone dust. The reliability of trickle dusters is still a problem.

7 Active explosion barriers

Active explosion barriers (also known as triggered barriers) are a more recent development compared with the development history of passive explosion barriers. There are two types of active barrier: machine-mounted systems and fixed active barriers.

The operation of these barriers can be triggered by an electronic signal from a sensor (e.g. temperature, pressure or flame) or by a mechanical sensing device. Michelis (1991) combined active barrier units into a simple schematic layout, a diagrammatic representation of which is shown in Figure 7.



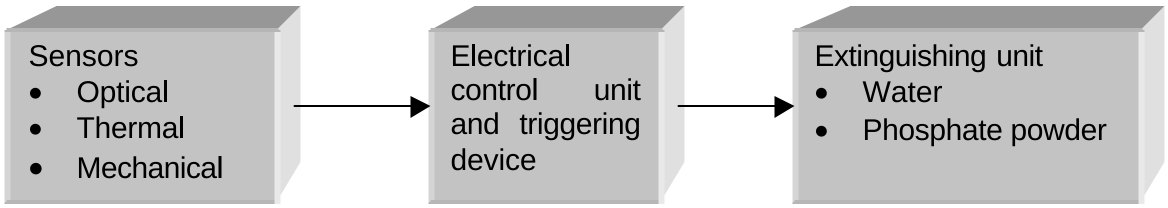


Figure 7: Schematic layout of an active explosion barrier (after Michelis, 1991)

Lunn (1988) defined the various parts of the triggered barrier as follows:

(a) *The sensor*: The sensor is a device that detects the presence of an approaching explosion. Sensors fitted to triggered barriers include blast sensors, thermocouple sensors, ultraviolet detectors and infrared sensors.

(b) *The disperser*: The disperser is the part of the triggered barrier that contains the suppressant and from which the suppressant must be ejected quickly once the flame is detected.

(c) *The interval*: The interval is the time between the detection of the flame and the arrival of the flame at the disperser and it therefore represents the time available for the suppressant to be ejected across the roadway to form a well-distributed cloud. For a given dispersal time, the interval determines the effectiveness of the barrier; if it is too long, the flame has passed by before the suppressant is dispersed; if the interval is too short, the suppressant cloud becomes diluted before the flame arrives.

The sensors used over the years and the characteristics measured are shown in Table 7 below.

Table 7: Sensors used in triggered barriers

Type of sensor	Explosion characteristic measured
Thermocouple	Heat from combustion reaction
Infrared	Infrared radiation in flame
Ultraviolet	Ultraviolet radiation in flame
Solar cell	Radiant energy in flame
Thermo-mechanical	Heat from flame and dynamic pressure

In the thermocouple sensor, the heat from the explosion combustion reaction is detected by the thermocouple and an electrical signal is produced. There is insufficient energy in the signal to operate the disperser and a separate power supply is needed to provide the necessary amplification and power.

Work at *Bergbau versuchstrecke* (BVS) (Faber, 1982) showed that infrared sensors detect flames quickly, but also respond to certain mine lighting. A modified improved detector incorporating a pressure trigger was designed at the USBM (Liebman, et al., 1976b).

The ultraviolet sensor is designed to respond to radiation in that range of the energy spectrum and responds to open flames from an explosion or a fire, but not to the radiation from any type of mine lighting (ultraviolet sensors generally detect methane flames later than the infrared sensors) (Faber, 1982). As in the previous example, a separate power circuit is needed to operate the disperser.

With the solar cell sensor, sufficient power is generated by the solar cell array to directly activate the disperser. The need for a separate power supply is therefore avoided.

The thermo-mechanical sensor responds to the effects of heat or dynamic pressure. A synthetic filament is melted by heat from the explosion and releases a striking pin, which in turn causes a detonator to explode. The mechanical element of the sensor incorporates a mobile flap, which responds to dynamic pressure and operates the same striking pin.

In sensing systems reliant on radiation from the explosion flame, the exposed surface must be kept free of dust, otherwise the signal produced by the sensor may be too weak to activate the disperser. The surface is kept clean by a mixture of air and water that is sprayed across and parallel to the sensing surface.

7.1 Fixed triggered barriers

Fixed triggered barriers were intended to quench fully developed methane and coal dust explosions. The development of such systems was also stimulated by the need for systems that are not dependent on the pressure build-up required for passive barrier systems.

In 1969, Demelenne and Poivre described the following triggering device:

- A strong, flame-sensitive cord connected to an extinguisher, which activates when the flame arrives.
- A shutter installed perpendicular to the gallery axis, rotating around an axis, with fitted knives to cut the ribbon when the dynamic pressure pulse reaches the triggering device (Goffart, 1983).

Table 7.1 gives a summary of the characteristics of a number of fixed barriers that have been developed or deployed.

Table 7.1: Summary of characteristics of fixed triggered barriers

Country	Detector type	Extin-guishing Agent	Dispersal method	Vessels	
				Shape	Loading (ℓ/m^2)
Belgium	Thermo-mechanical	Water: 90-100 ℓ/unit	Detonating cord	2-m-long, 25-cm-diam.,	10

				open-pore polyurethane foam	
Federal Republic of Germany	BVS UV	Tropolar ammonium phosphate powder	Nitrogen 120 bar detonator-activated valves	12,3 ℓ cylinder	48
Federal Republic of Germany	Thermo-couple	Water: 80 ℓ/unit	Detonating cord	PVC trough	80
France	Thermo-mechanical	Water: 90-100 ℓ/unit	Detonating cord	2-m-long, 25-cm-diam., open-pore polyurethane foam	10
UK	Thermo-couple	Water: 227 ℓ/unit	Compressed N_2	Long cylinder	45
USA	Pressure and ultraviolet radiation	Water or mono-ammonium phosphate: 40 ℓ/unit	Sheet explosive	Ridged polystyrene container	80

Goffart (1983) claimed that the Belgian triggered water barrier (Goffart and Browayes, 1982) is designed to be effective where normal passive barriers may fail. The Belgium system (*Ministrere des Affairs Economiques*, 1982) utilises 2-m-long by 0,25 m polythene sleeves and flame-resistant polyurethane foam for rigidity. Each suspended container holds 90 to 100 ℓ of water. Along the axis of the foam is a waterproof channel in which a detonating cord is placed. This cord is used to disperse the water. The barrier is triggered by a thermo–mechanical device that is sensitive to both pressure and flame. This system was also used in France (Cerchar, 1988). Tests at Cerchar showed that this barrier was capable of extinguishing explosions with low flame speeds (Goffart, 1973).

The system used in the Federal Republic of Germany (Michelis *et al.*, 1987) also uses a detonating cord to disperse the water from a PVC trough. A very sensitive thermo-electrical sensor, based on the SMRE thermocouple sensor, is used as a triggering device. Due to the possibility of varying operating conditions, different triggered barrier systems were developed. All of them were tested at Tremonia with regard to their effectiveness (Meerbach *et al.*, 1980a and b and Michelis, 1985).

The objective of the development of the *Versuchsgrube Tremonia* water trough triggered barrier system was to construct a barrier that would be effective against any type of explosion. The triggered barriers should be inexpensive, reliable and universally applicable. Michelis emphasised that the intention of introducing triggered barriers in the West German coal mining industry was not to replace conventional barrier systems but to supplement the current passive barrier systems, and to use triggered barriers in critical locations.

The sensor is a sensitive thermocouple (working on a thermo-electrical principle). Figure 7.1a shows a thermocouple of the type TFK 80. A battery serves as a standby power unit.

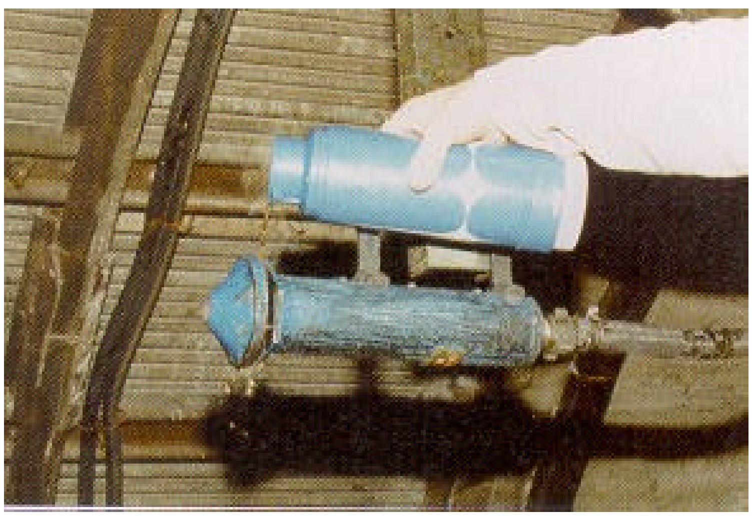


Figure 7.1a: Thermofühlerkopf TFK 80 sensor

The Tremonia triggered barrier system consists of 80-ℓ water troughs with an igniter system in each trough. The igniter consists of 0,6 m of detonating cord inserted into and sealed in the middle of the trough.

The distance from the sensor to the disperser is typically 35 to 50 mm, which ensures adequate water dispersal (200 to 300 ms).

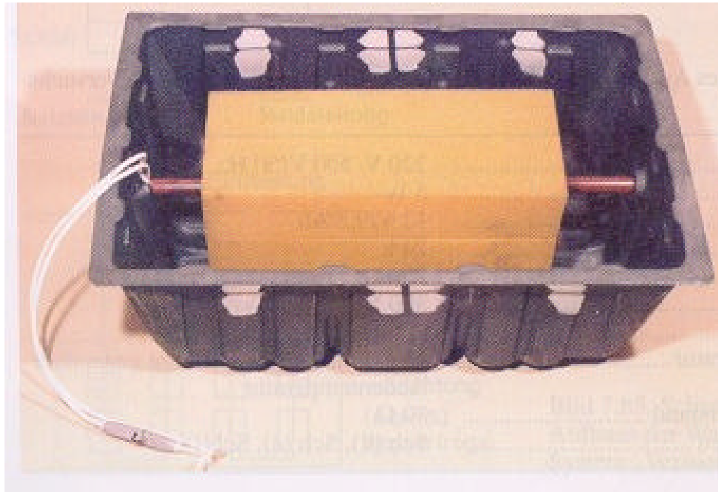


Figure 7.1b: Water trough with built-in ignition system

This arrangement disperses water over a radius of approximately 2 m compared with conventional passive water troughs.

The water trough triggered barrier was endorsed by the mining authorities as Design 6 in 1985. The design description covers the maintenance and use of the barrier. The barrier found application in or at:

- conventional roadway developments where high methane emissions occurred
- mechanisation of development ends with tunneling machines or continuous miners
- change-overs of longwall faces/roadways
- ventilation end-points.

Michelis (1998) listed the advantages of using active water trough barriers as follows:

- They extinguish propagating low-pressure ignitions.
- Their water-distributing ability is twice as high as that of passive water trough barriers and they are therefore more flexible (see Figure 7.1c).
- They are compact, thus saving space.
- They have a reduced water quantity requirement of 80 ℓ/m^2 instead of 200 ℓ/m^2 of cross-section.
- Even if the electrical triggering fails, they still operate as passive water trough barriers.

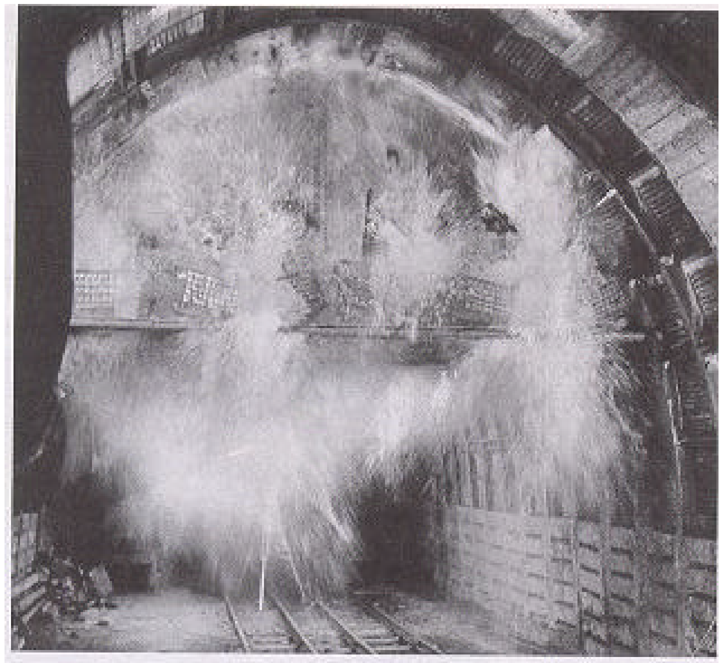


Figure 7.1c: Water distribution of an active water trough barrier

He listed their disadvantages as follows:

- The initial installation of the triggered barrier is labour-intensive, as is the case with a passive barrier.
- They require qualified personnel for the installation of the electrical and blasting components.
- They have a high capital investment cost (10 times higher than the passive barrier systems).

Because of the pressure on German coal mines to save costs between 1974 and 1996, the barrier did not find considerable application. Furthermore, it was always difficult to find manufacturers, especially for the electrical instrumentation. Permission for this design (Design 6) was withdrawn in 1996.

Using the information given by Bartknecht and Scholl (1969), the *Bergbau-Versuchsstrecke* (BVS) in Dortmund-Derne developed a triggered barrier that differs from the water trough triggered barrier system by using extinguishant power and HRD extinguishant containers. Two systems were developed:

- A mobile BVS triggered barrier for the protection of mine workers constructing seals
- An automatic explosion-extinguishing installation, Type TSM, for continuous miners.

The main aim of the system is to detect an explosion by means of ultraviolet sensors and to activate the extinguishing installation by means of an electronic control system. The system continuously monitors the functioning ability of the installation.

The mobile triggered barrier was developed as a multiple extinguisher system to protect the mine seal construction team (Faber, 1984 and 1990a and b). The barrier consists of two parts (Figure 7.1d). There are 32 HRD extinguishant containers, each with a volume of 12,3 ℓ and the capacity to hold 8 kg of ammonium phosphate extinguishant powder.

Nitrogen is used as the driving agent and is pressurised to an overpressure of 12 MPa. The distance from the sensor to the disperser is 40 m. Spraying of the ammonium phosphate from the cylinders starts 5 to 10 ms after the sensor has been triggered and lasts between 600 and 900 ms. Most of the powder is actually dispersed long before the vessel is empty. Figure 7.1d shows the components of the system.

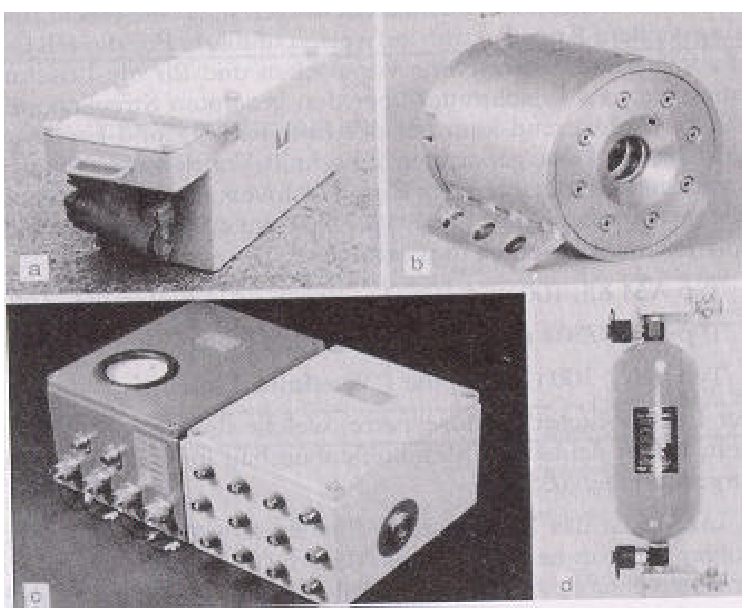


Figure 7.1d: Components of the BVS triggered barrier system

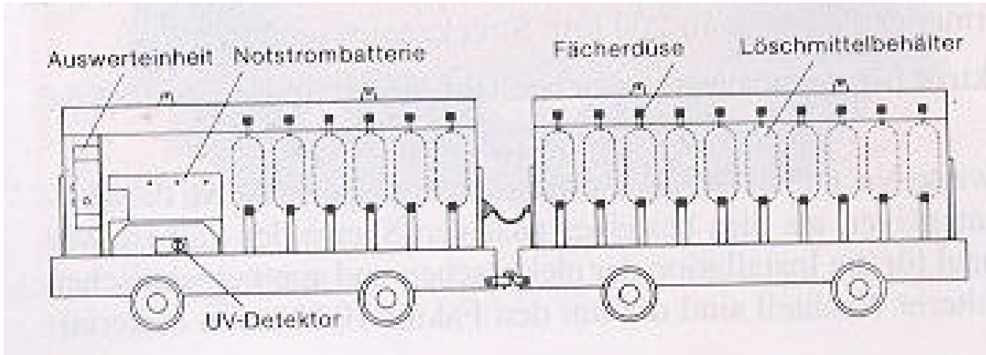


Figure 7.1e: Mobile automatic multiple-extinguisher system (BVS)

Tests showed that the system was effective against explosions reaching 500 m/s when ammonium phosphate was used (Scholl, 1967). The triggered barriers proved their effectiveness during extensive tests, but were never used in real operational situations.

In a study reported by the HSE (1977), the work conducted on an active water barrier at Buxton is explained. The triggering device used was a thermocouple flame sensor. Water was contained in a dispersal unit, pressurised using nitrogen (to 630 kPa) and contained by a retaining plate. The signal activated a fast-acting valve, releasing the nitrogen to pressurise the water and force open the retaining plate. Altogether 227 ℓ of water were then discharged (starting 40 to 60 ms after triggering) across the gallery within 180 ms.

In later work, the SMRE Mk II is explained. In these guidelines (NCB, 1982), the use of two units for areas greater than 7,5 m^2 is recommended. The barrier covers the cross-sectional area for 200 ms. Experiments by Rae (1982) and Roebuck and Rooker (1982) suggested that this barrier should be effective for explosions with flame speeds between 20 and 300 m/s.

In recent research conducted at DMT Tremonia (Michelis and Margenburg, 1995), a number of triggering devices (UK, Belgium, USA and Germany) were evaluated. This was an attempt to develop a more cost-effective system, referred to as the ‘European triggered barrier’.

The objective was to combine the most suitable components of the triggered barriers from Belgium, France, the UK and Germany to market a collective European system. Extinguishing tests were performed in 1993 and 1995 in the R4 explosion gallery at Tremonia to compare all the detectors (Michelis and Margenburg, 1995). The detectors were evaluated against weak coal dust explosions as well as methane roof-layer explosions (<5 kPa) (Figure 7.1e). All the detectors proved their capability in a wide variety of different explosions. The 'European triggered barrier' (Figure 7.1f) was, however, not realised due to cost constraints and the subsequent closure of Tremonia.

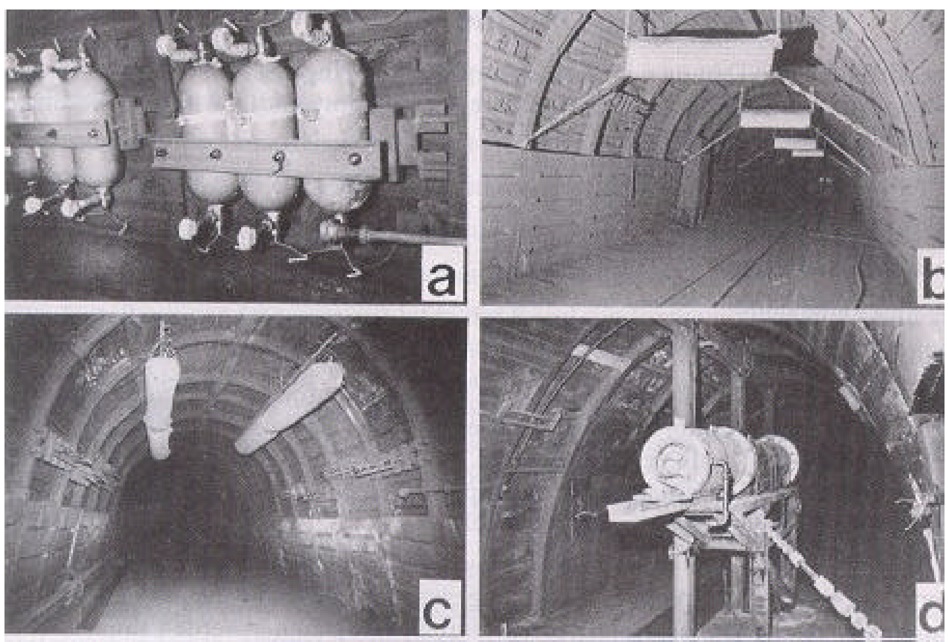


Figure 7.1f: Sensors evaluated for the development of a 'European triggered barrier'

Although these systems have been under development for more than 30 years, they have found limited application as they are perceived as being costly and unproven.

8 Conclusions

The process of managing the risk of underground explosions, even though it is familiar, is not as simple as it is generally believed to be. Apart from the engineering controls, aspects such as the human factor and management influence play a significant role. At present, there are very few processes that incorporate the human role or the management role into the risk assessment and management process.

Apart from a fundamentally well-designed engineering control process, there should also be methods for auditing implementation and using the controls. As the probability of a hazard occurring is directly proportional to the period of time that the control system cannot cope, auditing systems should also encompass changing conditions, trends and rates.

These auditing processes should become an integral part of the overall risk management system. The necessary actions, as indicated by changes in the system, should be implemented in terms of both the resources that are allocated and the way in which these resources are applied. This means that risk management is a dynamic process and not simply a set of guidelines or a checklist for solving risk-related issues. As knowledge is gained, and newer and better methods and technologies are developed for use as engineering controls, so the process must be reviewed and adapted by management in order to remain relevant and effective.

The best practices in the world cannot alone eliminate the explosion risk since the occurrence of an explosion is ultimately determined by how man has influenced his environment. Man, being both the strong and the weak link in the chain of occurrences, ultimately controls the safety of his environment. A process of management that reduces the negative influence of man, supports and advances his positive contributions, and at the same time increases the effectiveness of the preventative controls, should be the ultimate aim of a risk management strategy.

The inevitable explosion danger associated with the underground mining of coal will always be present. Experience shows that preventative measures may fail and that remedial or protective measures are indispensable in protecting against the consequences of the spread of an explosion through mine workings.

Cybulski (1975) stated: “It becomes an absolute and unquestionable necessity to have at one’s disposal some means to be used as the last line of defence of the highest possible dependability for checking the range of an explosion”. In this part of the publication, he was referring to barriers as the means of doing this. In a more recent work, Michelis (1998) reiterated the above opinion when he stated that the measures for preventing explosions are building blocks and that each of them forms part of a whole prevention system. He also stated that the residual risk of an explosion would always be there. He further suggested that the function of constructive explosion protection measures is to reduce any explosion and its effect to a minimum.

As one of the most successful constructive measures achieved has been passive and active explosion barriers, the development and testing of such barriers has been the focus of extensive research effort for almost a century. In Section 3 the history and development of explosion barriers are described in greater detail.

The approach through the years of the various countries reviewed can be summarised in the following flow diagram:

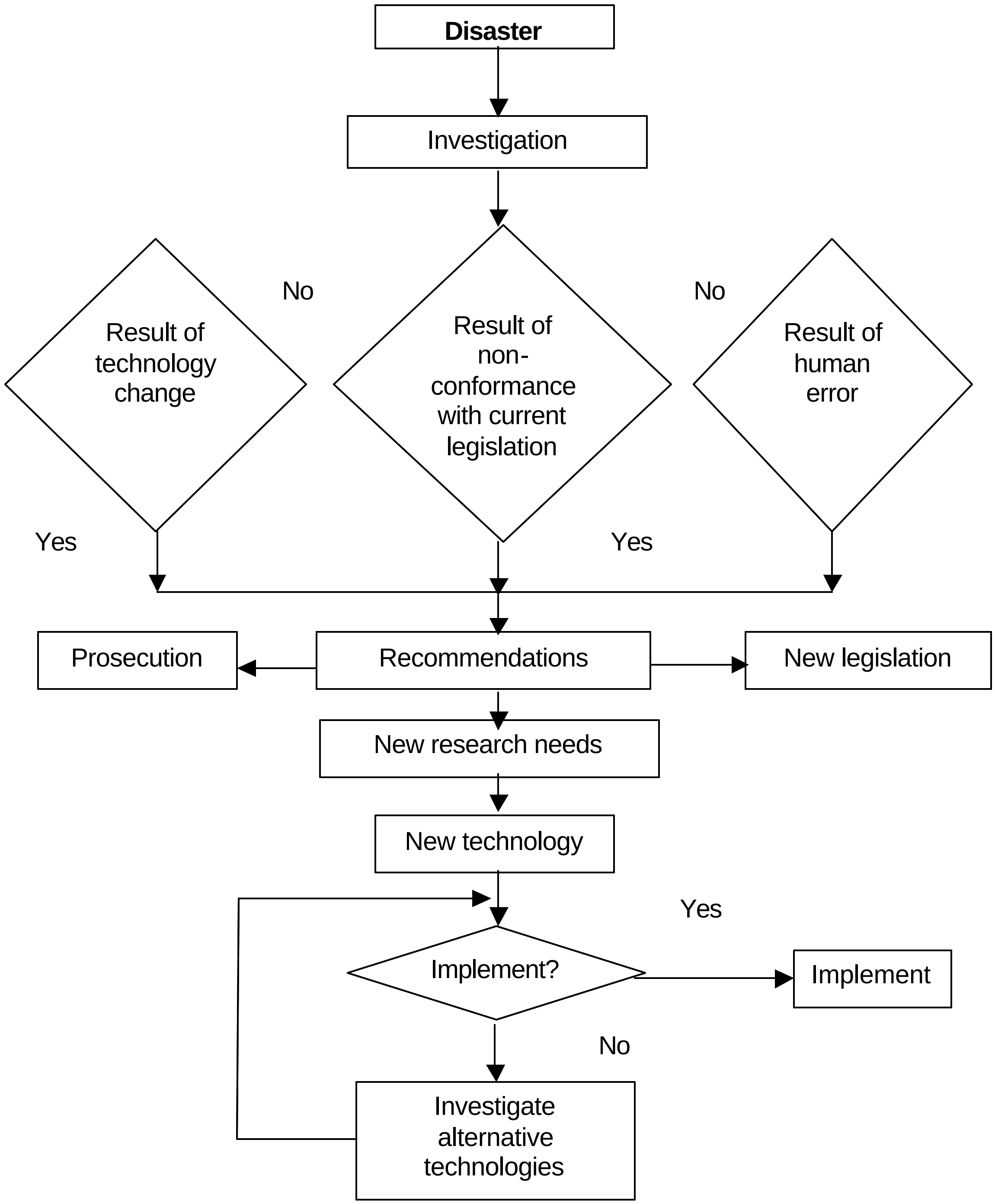


Figure 8: Flow diagram driving disaster prevention

Throughout the study it was clear that technology that can be implemented to prevent explosions does exist. The differences in the enforced or actual legislation are in most countries a function of the mining methods employed together with the inherent risks associated with mining.

These inherent risks, one of which is the presence of methane, are mostly a function of the country and also of the region. This specific leads to the paradigm that some of the inertisation controls implemented are country-specific and cannot simply be transferred to other countries.

In practice, therefore, dynamic management of mining risks is required through a well-formulated risk management process and later through a corporate governance function, thus moving the onus of liability from the state to the mining industry. In short, the responsibility for developing 'best practice' (Codes of Practice) is now removed from the legislator to the employer.

In investigating the international trends, it was found that the latest changes in legislation in Australia (Queensland) point to a totally new responsibility. The emphasis is on enforcing the *duty* to care for the employees.

It was also clear that a total integrative approach to explosion prevention and protection is needed and that this cannot be implemented in isolation from an operation's other mining practices.

The major basic methods of explosion control in the face area remain:

1. Effective ventilation practices to dilute methane
2. Monitoring of flammable gas concentrations
3. Inertisation of coal dust
4. Use of explosion barriers.

These controls are often generically described in the legislation, with the final responsibility lying with management to implement an effective Code of Practice.

The use of active barrier technology, both on machines and to replace passive barriers, has so far been limited to France and Germany and no reference to these systems is found in most countries' regulations.

The specified inertisation requirements do not differentiate on the basis of seam heights. Indeed, seam heights are only taken into account in deciding on the most suitable ventilation practices to adopt and in the physical implementation of explosion barriers.

The recommended process to be followed for effective explosion prevention is thus:

a) Identify the generic hazards.
b) Assess the inherent risks.
c) Develop and implement appropriate procedures.
d) Monitor the effectiveness of these procedures.
e) Monitor changes in the hazards.

This process is a loop in which, when changes occur, the whole process needs to be repeated.

In the second part of the study, this ‘loop’ process will be followed in order to develop and evaluate the inherent and residual risks associated with various mining practices.

In summary:

- any Inertisation Strategy must be based on an efficacious HIRA and risk treatment steps prescribed by relevant articles of the MHSA;
- any Inertisation Strategy should be composed of an appropriate portfolio of Risk Treatment Techniques described in Sections 4 to 7 of this report, capable of eliminating, controlling or minimizing the significant health and safety hazards / risks identified and assessed as part of the mine’s HIRA; and
- an appropriate comprehensive and integrated RMS which includes inter alia out-bye areas need to be developed.

9 Recommendations

The researchers submit the following recommendations relating to an appropriate Inertisation Strategy for in-bye areas:

- the report proposes an appropriate Inertisation Strategy for FG- ignitions/explosions and consequent coal dust explosions based on the risk treatment steps prescribed by article 11 (2) of the MHSA;
- the report proposes that the mine/site – specific Inertisation Strategy be based on the significant health and safety hazards/risks associated with FG- ignitions/ explosions and consequent CDEs in the in-bye area as determined by a HIRA;
- the report proposes that the mine/site- specific Inertisation Strategy be composed of a selection of an adequate portfolio of Risk Treatment Techniques described in Sections 4 to 7 of the report. This introduces the notion of selecting appropriate RTTs from a venue of internationally benchmarked and proven RTTs; and
- since the project has delivered on its project outcomes, the report proposes that Phase II of the project be commenced without delay. The main outcome of the extention project is to produce a comprehensive and integrated RMS for all areas of underground coal mines based on the concepts identified by SIMCOL 701.

Phase II of the project should investigate the appropriateness of the different RTTs in relation to aspects as coal excavation processes/layouts, seam thickness/mining height and in-bye vs. out-bye areas of underground coal mines.

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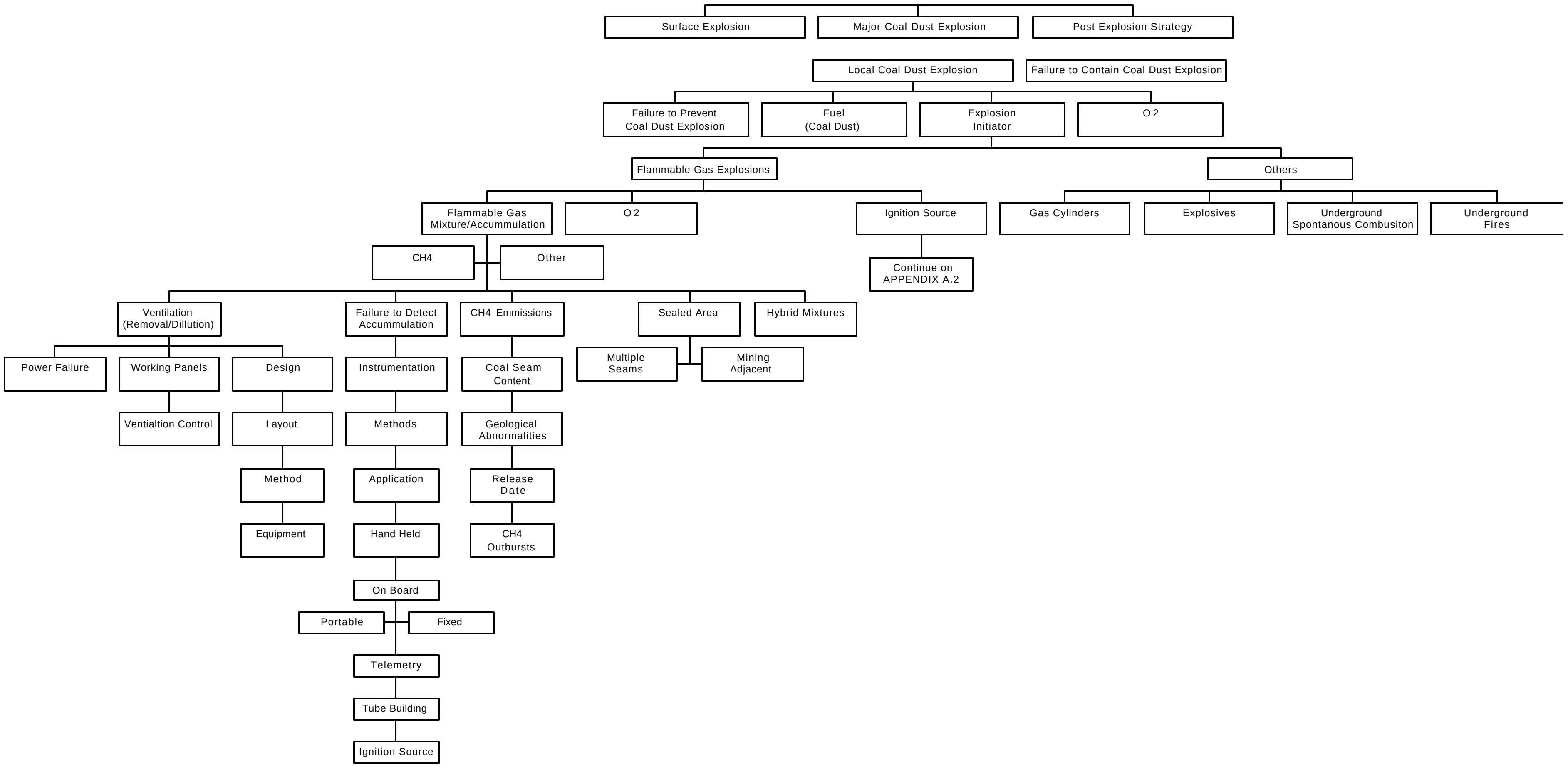
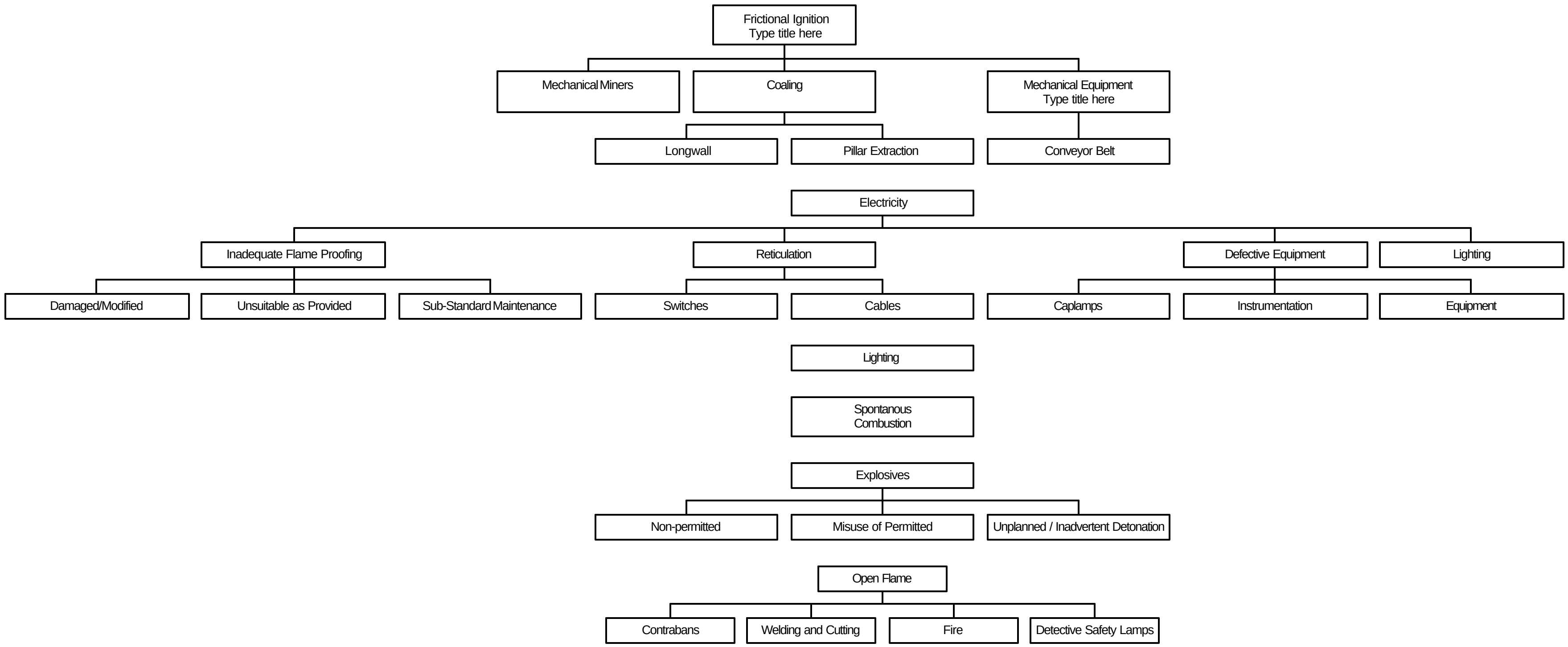
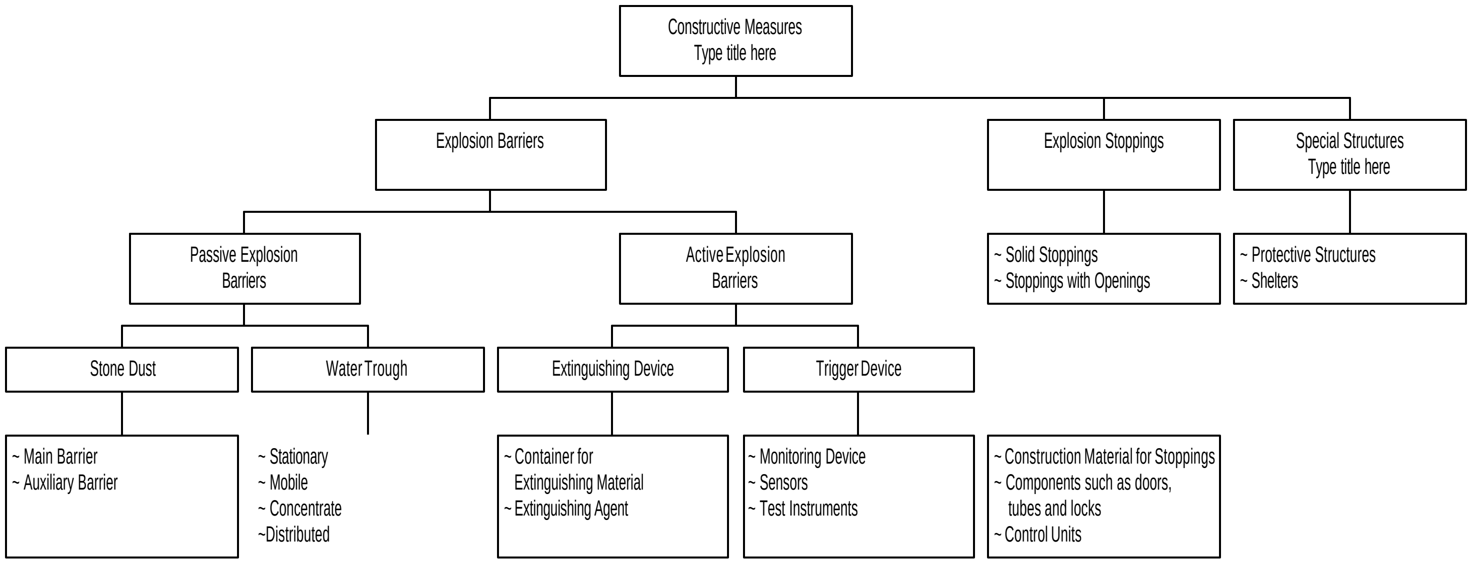
Appendix 1: Fault tree showing casual mechanisms for flammable gas and coal dust explosions



Appendix 2: Fault tree showing causal mechanism for flammable gas and coal dust explosions



Appendix 3: Explosion protective measure: Underground coal mines after Michelis, 1991



Appendix 4: Inertisation strategies and practices in underground coal mines

Description of the significant hazard or risk	Proposed risk management strategy	Proposed appropriate risk treatment techniques (RTTs)
Flammable Gas Ignition / Explosion in a Working Heading	(a) Eliminate the risk	1. Reduce the coal seam gas content e.g. gas drainage systems.
	(b) Control the risk at source	1. Prevent accumulation/layering of FG liberated from the face area to below 1% per volume. The design of the ventilation system must provide sufficient air to the face so as to effectively dilute and/or remove the maximum methane emission rate. 2. Design the water spray system as a spray fan to dilute liberated methane. This RTT is the most effective methane dilution element of the RMS. 3. An engineering control that is a mandatory RTT is the flame proofing of electrical equipment and machinery. It is critical that audits be performed to ensure that the prescribed flame proofing requirements are met. 4. In areas of higher risk, engineering controls aimed and minimizing the frictional ignition hazard should be utilized. These TTTs include: slower rotational speed on cutters, wet cutter heads, pick spacing and lacing and new pick design.

Description of the significant hazard or risk	Proposed risk management strategy	Proposed appropriate risk treatment techniques (RTTs)
FG ignition/explosion in a Working Heading (continued)	(c) Minimize the risk	1. Special attention should be given to the competence of employees exposed to this significant hazard especially in respect of hazard awareness and their ability to respond appropriately to the hazard. 2. Competence of employees responsible for the testing for/monitoring of flammable gas. 3. Equipping of CMs with onboard methane detection/monitoring systems which are designed to give early warning and which must be capable of isolating the electricity supply to the machine at 1% per volume of FG. The system should be checked for functionality and calibrated prior to commencement of coal mining operations. Should the system's functionality fail, additional measures should be put in place to prevent the possible accumulation/layering of FG in the Working Heading. 4. In areas where a history of face ignitions exists, coal mining machinery must be fitted with active suppression systems.
Hybrid ignitions/explosions in Working Headings	(a) Eliminate the risk (b) Control the risk at source	1. Reduce the coal seam gas content e.g. gas drainage systems. 1. Prevent accumulation/layering of FG liberated from the face area to below 1% per volume. The design of the ventilation system must provide sufficient air to the face so as to effectively dilute and/or remove the maximum methane emission rate.

Description of the significant hazard or risk	Proposed risk management strategy	Proposed appropriate risk treatment techniques (RTTs)
Hybrid ignitions/explosions in Working Headings (continue)		2. Design the water spray system as a spray fan to dilute liberated methane. This RTT is the most effective methane dilution element of the RMS. 3. An engineering control that is a mandatory RTT is the flame proofing of electrical equipment and machinery. It is critical that audits be performed to ensure that the prescribed flame proofing requirements are met. 4. In areas of higher risk, engineering controls aimed and minimizing the frictional ignition hazard should be utilized. These TTTs include: slower rotational speed on cutters, wet cutter heads, pick spacing and lacing and new pick design.
	(c) Minimize the risk	1. Special attention should be given to the competence of employees exposed to this significant hazard especially in respect of hazard awareness and their ability to respond appropriately to the hazard. 2. Competence of employees responsible for the testing for/monitoring of flammable gas.

Description of the significant hazard or risk	Proposed risk management strategy	Proposed appropriate risk treatment techniques (RTTs)
Hybrid ignitions/explosions in Working Headings (continue)		3. Equipping of CMs with onboard methane detection/monitoring systems which are designed to give early warning and which must be capable of isolating the electricity supply to the machine at 1% per volume of FG. The system should be checked for functionality and calibrated prior to commencement of coal mining operations. Should the system's functionality fail, additional measures should be put in place to prevent the possible accumulation/layering of FG in the Working Heading. 4. All working faces must be adequately wetted down or stone dust must be applied in accordance with prescribed requirements to ensure effective inertisation of coal dust in the working heading. 5. In areas where a history of face ignitions exists, coal mining machines must be fitted with active suppression systems.
Coal Dust Explosions initiated by FG ignitions/explosions	(a) Eliminate the risk	1. Eliminate, control or minimize the risk of a FG ignition/explosion or CDEs. 2. Eliminate, control or minimize the risk of a hybrid ignitions/explosions.
	(b) Control the risk	1. Prevent accumulation/layering of FG liberated from the face area to below 1% per volume. The design of the ventilation system must provide sufficient air to the face so as to effectively dilute and/or remove the maximum methane emission rate.

Description of the significant hazard or risk	Proposed risk management strategy		Proposed appropriate risk treatment techniques (RTTs)
Coal Dust Explosions initiated by FG ignitions/explosions (continue)	(b) Control the risk (continued)	2.	An engineering control that is a mandatory RTT is the flam proofing of electrical equipment and machinery. It is critical that audits be performed to ensure that the prescribed flame proofing requirements are met.
	(c) Minimize the risk	1.	Special attention should be given to the competence of employees exposed to this significant hazard especially in respect of hazard awareness and their ability to respond appropriately to the hazard.
		2.	Competence of employees responsible for the testing for/monitoring of flammable gas.
		3.	In areas where a history of face ignitions exists, coal mining machinery must be fitted with active suppression systems.
		4.	Ensure the correct use and application of stone dusting in the immediate area of the Working Heading.
		5.	Implement an efficacious stone dusting and monitoring strategy and appropriate sampling on testing protocol to ensure that stone dusting in accordance with prescribed requirements.
		6.	Equip all belt roads with efficacious passive explosion arresting barriers which must be of an approved design and one or more of the following: • bagged stone dust barrier; • polish stone dust barrier; or • German trough barrier.

Description of the significant hazard or risk	Proposed risk management strategy	Proposed appropriate risk treatment techniques (RTTs)
Coal Dust Explosions initiated by FG ignitions/explosions (continue)	(c) Minimize the risk (continued)	7. Protect return airways with efficacious explosion arresting barriers (see point 6). The use of such barriers is not a requirement when a 100 metre stretch of return airway is protected by stone dusting of 80% T.I.C. 8. Issue all personnel with an efficacious self-contained-self-rescue. 9. Personnel must be competent in the Emergency Preparedness and Response procedure for the mine, inclusive of Escape and Rescue strategies. 10. The design and availability of Refuge Bays must be in accordance with acceptable design specifications, maintained and used in accordance with approved site specific codes of practice.