

RECOMMENDATIONS FOR THE PREVENTION AND SUPPRESSION
OF COAL DUST EXPLOSIONS AT UNDERGROUND
COAL MINES IN THE UNITED STATES

by

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ABSTRACT

The underground coal industry has recognized the need for better regulations and practices to prevent coal dust explosions in the United States. The catastrophe that occurred at the Upper Big Branch (UBB) Mine in 2010 exposed America to the destructive and violent nature of coal dust explosions.

This research examines rock dusting, mine dust sampling and analysis, rock dust inspection procedures and various types of explosion barriers. The regulatory standards and industry practices in the United States are compared with those in other leading mining countries to outline their effectiveness at preventing or extinguishing a coal dust explosion.

This thesis identifies the development of active barrier technology for continuous miners, along with longwalls, the implementation of hygroscopic salts, and other strategic recommendations of best practices and needed research, will lead to the prevention and suppression of coal dust explosions at underground coal mines in the United States.

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LIST OF COMMON ACRONYMS AND DEFINITIONS

anthracite: a hard, compact variety of mineral coal containing the highest carbon content, the fewest impurities, and the highest calorific content

bituminous coal: a relatively soft coal containing tarlike substances called bitumen; known for releasing dangerous mixtures of gases that can cause underground explosions

bleeder system: a system of ventilation entries surrounding the caved area of a retreat mining panel, including longwall gobs

certified person: a person certified by a regulatory authority overseeing the coal mining industry to perform inspection or maintenance duties prescribed by regulation

coal dust: particles of fine coal that can pass a No. 20 mesh (0.841 mm) sieve

continuous miner: a piece of coal excavating equipment with a large rotating steel drum equipped with tungsten carbide teeth that scrape coal from the seam; also equipped to load the coal into shuttle cars

crosscut: a passageway driven between the entry and its parallel air course for ventilation

development/gate road entries: entries driven for the purpose of launching a longwall system in a panel

DME: Department of Minerals and Energy (South Africa)

explosion barrier (active or passive): equipment or structures erected underground that work to suppress an explosion as it approaches the barrier

face area: active mining area in underground mine where coal is being produced

float coal dust: coal dust consisting of particles that can pass a No. 200 mesh (74 μm) sieve

gob: the caved area of a retreat mining panel, including longwalls

headgate: the conveyor and fresh air side of a longwall panel

IMC: Incombustible Matter Content in mine dust

longwall: underground coal mining method where a shearing machine (shearer) slices coal off a 1,000 to 1,500 ft (330 to 500 m) wide panel of coal

loose coal: coal fragments, larger in size than coal dust

low temperature ashing: the heating of a substance to 120°C (258°F) using activated oxygen that leaves only noncombustible ash

mains: main haulage and transport drifts connected to the portal or shaft of the mine

MHSA: Mine Health and Safety Act of 1996 (South Africa)

MSHA: Mine Safety and Health Administration (United States)

NIOSH: National Institute for Occupational Safety and Health (United States)

parting: a layer of non-coal rock embedded in a coal seam, often mined along with the coal; partings of hard, abrasive sandstone and similar rocks can create sparks and incendive smears when cut

ribs: the side walls of a mine entry

roadheader: a piece of excavating equipment consisting of a boom-mounted cutting head, a loading device usually involving a conveyor, and a crawler travelling track to move the entire machine forward into the rock face

seal: substantial ventilation control cutting off air flow to sealed area of the mine, generally designed to withstand overpressure from a mine explosion

sealed area: an area of a mine that is no longer being ventilated and is inaccessible

shearer: mining machine on a longwall

SMRE: Safety in Mines Research Establishment (United Kingdom)

stone or rock dust: finely crushed rock used to increase the total incombustible content or suppress coal dust underground

submains: haulage and transport drifts connected off the mains drifts

tailgate: the return air side of a longwall panel

TIC: Total Inert Content; see IMC

tube bundle system: a system of tubes collecting atmospheric samples from various locations in a mine, which are analyzed online at a central location

volatile matter: liquid or gaseous substances that evaporate from the coal as it is heated

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CHAPTER 1

BACKGROUND CONTEXT INTO THE NEED FOR THIS RESEARCH

The catastrophe that occurred at the Upper Big Branch (UBB) Mine in 2010 exposed to America the destructive and violent nature of coal dust explosions with the death of 29 miners. This has been heralded as the worst mining accident the U.S. has seen in the past 40 years. The UBB explosion initially started as a small methane gas explosion in the tailgate area of the longwall face at the mine as identified in the investigation report compiled by the U.S. Mine Safety and Health Administration (MSHA; Page, 2011). Investigations have suggested that an initial quantity of methane, roughly 300 ft³ (8.5 m³), mixed with the surrounding air into an explosive mixture and was ignited by the contact between hot incandescence smears created by the contact between the sandstone roof and the cutting bits of the shearer drum.

The methane explosion would most likely have been localized due to its initial size, and its impact restricted to the immediate longwall and tailgate area where only a small number of miners were working. Unfortunately, loose, fine coal dust was stirred up by the methane explosion's pressure wave, which was then ignited into a coal dust explosion. This subsequent explosion was believed to have traveled through 31 million ft³ (880,000 m³) of mine entry. The northwestern production district, where two continuous miners and a longwall were stationed, was completely destroyed.

It was determined that the main causes of the miner fatalities were from exposure to heat, physical trauma, and asphyxiation from high levels of carbon monoxide in excess of 10,000 ppm in different areas throughout the mines. Most of the ventilation controls in the affected area were destroyed by the explosion which caused the ventilation system to become severely compromised.

A series of required preventative measures were ineffective or improperly executed, leading to the explosion:

- The ventilation system at the longwall area was not effective at diluting the methane cloud that accumulated where the cutting drum of the shearer was operating. Insufficient roof support at the tailgate of the longwall may have restricted the quantity of air along the longwall face and jeopardized the longwall ventilation system.
- Several cutting bits on the cutting drum of the shearer were worn away and a number of water sprays had been removed by the operator. The lack of water directed at the cutting surface allowed the cutting bits to become heated and form hot smears. These are believed to have been the source of ignition for the explosive methane-air mixture.

- It was well-known that the areas affected by the explosion, notably the belt entries, were not being sufficiently rock dusted to stop the progression of an explosive wave. The mine examiners employed by UBB identified a number of belts that were outside of compliance on the day the explosion occurred. Sampling conducted by MSHA investigators after the explosion (Page 2011) showed that 90.5% of the samples taken did not pass current regulation requirements.

It is the opinion of this researcher that even though it was the failure of the mine operator to obey mandatory explosion prevention standards that lead to the disaster at UBB, more analysis and research needs to be conducted by the mining industry in the U.S. to prevent and contain explosion events.

A number of other notable mine explosions involving coal dust have occurred over the last 30 years including the Jim Walters #5 Mine in Brookwood, Alabama (13 fatalities, 2001) and the Westray Mine in Nova Scotia, Canada (26 fatalities, 1992).

It is reported that there are still numerous methane ignitions occurring each year in U.S. coal mines. MSHA registered 33 face “ignition or explosion of gas and dust” events in 2010; 34 registered in 2011 (MSHA Accident and Illness Statistics). Each of these ignition events has the potential to start a coal dust explosion similar to what occurred at UBB. In Europe, coal mine operators utilize mounted active suppression systems on their machinery to prevent these ignition events from starting an explosion. This technology could be further utilized in the U.S. and adapted for use on our continuous mining machines.

European mines additionally implement passive suppression barriers to halt the propagation of an explosion. These mines are able to effectively utilize this technology due to their simplified, single-entry designs, which allow for easier implementation compared to the room-and-pillar entry design seen in many U.S. coal mines. However, U.S. mines could examine the use of smaller active barrier designs if enough testing and research was conducted into their implementation in the American mine environment.

This thesis will outline the science of coal dust explosions, assess current regulations and technologies for the prevention and containment of mine explosions in the U.S. and other countries, and extract the techniques, regulations, and additional research that can best be applied to the U.S. underground coal mining industry.

CHAPTER 2 THE SCIENCE OF A COAL DUST EXPLOSION

Coal dust can be produced in a mine from a number of locations including the active face, conveyor belt and transfer points, and the movement of machinery and personnel through entries. Coal dust particles that have a diameter under 74 μm (0.003 in.) are classified as “float” coal. These particles are prone to becoming airborne in airstreams and can be transported long distances into return airways where they settle onto equipment and surfaces of the entry excavation. Float coal dust is more prone to participate in an explosion event, but particles ranging up to 1 mm (0.04 in.) diameter can be involved in an explosion (Nagy, 1965). The process of a coal dust explosion, as described by Edwards (1988), is initiated by a gas explosion, usually methane, or similar event that entrains the coal dust into the atmosphere. The heat from the flame front releases volatile, organic compounds that ignite and burn. The expanding volume of combustible products entrains more coal dust and propagates the explosion.

Coal dust only becomes explosive when it is suspended in air, similar to other organic combustible dusts. The coal dust, when in this suspended state, becomes additional fuel for an explosion to propagate. The explosion can continue to propagate through entries if there is sufficient loose coal dust accumulated in these sections. A coal dust explosion can primarily be prevented in two ways:

- The distribution of a pulverized stone dust, in sufficient quantity in mine entries with deposited coal dust, can inertize the coal dust from propagating an explosion. This stone dust -- or rock dust, as it is commonly referred to -- is typically created using dolomite or limestone. The rock dust particles provide thermal shielding when suspended with the coal dust, which prevents the volatile matter in the coal dust from being cooked off and igniting. It is currently common practice to use rock dust in U.S. coal mines.
- The wetting of coal dust causes the particles to stick to the surfaces of the mine entry more aggressively, which prevents the coal dust from being entrained by an explosion’s pressure wave. Many mines in Europe have shifted to applying hygroscopic salts (MgCl_2 or CaCl_2) to the mine surfaces. These salts create a wetted surface for the coal dust to adhere to until the salt is dry, at which point it cakes into a crust that traps the coal dust particles. These salts must be reapplied as necessary, depending on the air moisture content of the mine, to continue to trap newly settled coal dust in the airways.

Figure 2.1 and Figure 2.2 show a fault tree diagram of the mechanisms that can lead to a coal dust explosion as outlined in South Africa’s Mining Regulatory Advisory Committee (MRAC 2002). The fault tree details an extensive review of potential ignition sources, system and equipment faults, and fault paths that may lead to a coal dust explosion.

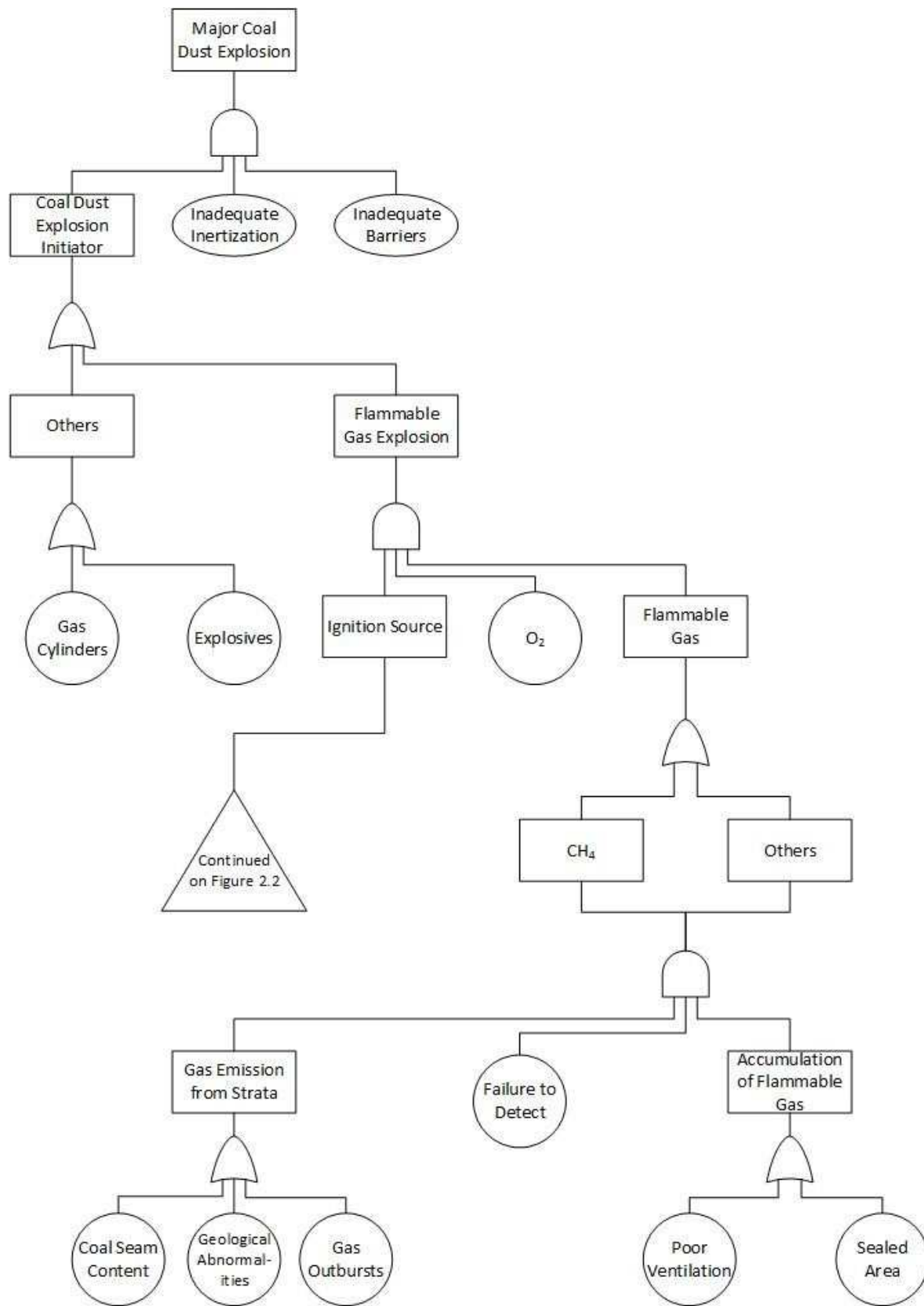


Figure 2.1 Diagram of Fault Tree showing mechanisms of coal dust explosion (MRAC 2002).

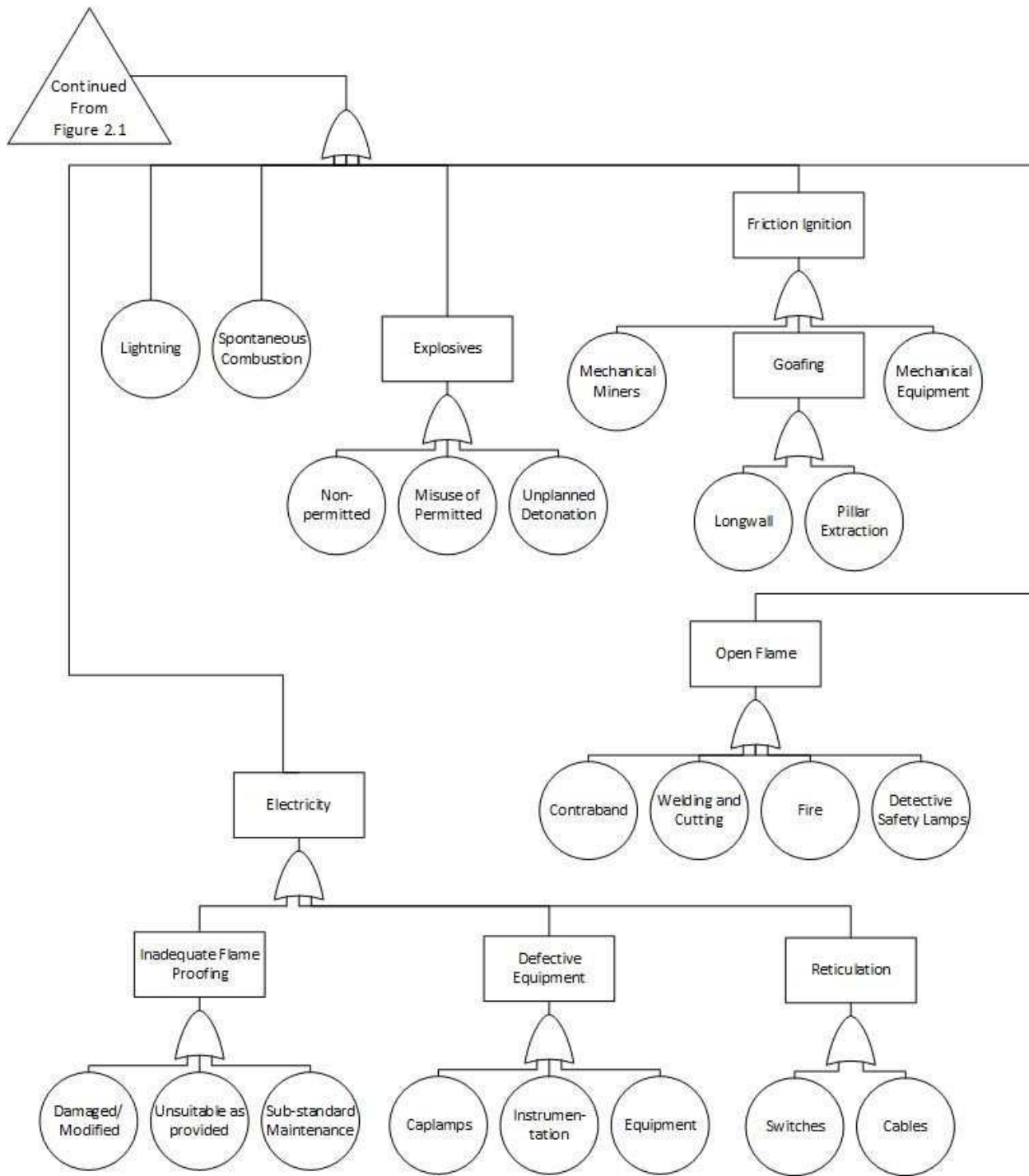


Figure 2.2 Continuation of Fault Tree showing mechanisms of coal dust explosion (MRAC 2002).

2.1 Effect of mechanization on coal dust explosion characteristics

With the continued mechanization of mining operations, mines have the capability to extract coal at increasingly higher rates. This increased use of mechanization has caused larger amounts of float coal dust to be produced and at smaller average particle sizes, as described in Cashdollar et al. (2010). Cashdollar determined that the average percentage of float coal dust in dust samples, taken from 61 U.S. coal mines in all 10 MSHA bituminous coal districts, had increased from 20% in the 1920's to 38% at the time of his findings. As illustrated by Cybulski (1975), the coal dust explosion potential is higher with increasing amounts of float coal dust. Mines have been correcting for the increase in float coal dust, and coal dust in general, by using larger amounts of rock dust to remain at inert dust levels of combustion. In 2011, MSHA put into regulation the requirement of 80% incombustible content in all airways, compared to the 65% inert content required previously in intakes, based on Cashdollar's (2010) findings (see 30 CFR §75.403). Alternatively, Cybulski has stipulated that coal dust comprised of 85% particle content smaller than 200 mesh (74 μm) may need to be mixed with rock dust to a level of 85-90% inert dust content to ensure that an explosion cannot propagate.

CHAPTER 3

REGULATORY STANDARDS FOR COAL DUST EXPLOSION PREVENTION

Government regulations are constantly adapted to new science and technology to ensure the safety of miners working underground. In the past, mine explosion disasters have been the driving factors for identifying deficiencies in the current standards and implementing new regulations. The adaptation of new excavation techniques and mining methods has also caused agencies to review the effectiveness of current regulations and safety protocols as the industry advances. In this chapter, the regulations pertaining to coal dust explosion prevention in the U.S. and international countries will be examined along with standards that focus on general safety or inspection related to underground coal explosions. When appropriate, comparisons will be made between the various regulatory documents to highlight key advantages over U.S. regulations.

3.1 United States regulations

The Code of Federal Regulations, Title 30, Part 75 (30 CFR Part 75) is the mandatory safety standard enforced for underground coal mines in the U.S. In these regulations are the required criteria for application of rock dust, fire protection and suppression, explosives and blasting, mining equipment, and mine emergencies, that directly facilitate the prevention of coal dust explosions.

3.1.1 Regular mine examinations

Mine operators are required to have qualified persons conduct distinct examinations throughout the working and non-working areas of the mine. The mine is required to conduct 4 different types of examinations: pre-shift, supplementary, on-shift, and weekly. These examinations pinpoint potential deficiencies or violations in the locations being observed. The standards pertinent to coal dust explosion prevention that are checked during these examinations are §75.400, the accumulations of combustible materials, and §75.403, the application of rock dust. Each examination has additional testing criteria that assists with the evaluation of the mines compliance with the designated ventilation and emergency response plan. The sections that regulate these examinations are §75.360, §75.361, §75.362, and §75.364.

3.1.2 Combustible materials and rock dusting

Standard §75.400 and other regulations identified below regulate the accumulation of combustible materials and rock dusting for coal dust explosion prevention. Coal dust deposited on top of rock dust, loose coal found in airways and on equipment, and other combustible materials are not permitted to accumulate in active workings and must be cleaned up. It is the duty of the mine operator to create and follow a clean-up program that will remove or eliminate these accumulations during lifetime of the mine.

Areas within 40 feet of working faces of an underground coal mine, unless unreachable or unsafe to enter, must be rock dusted unless dust in the airway is high in incombustible content or too wet as outlined in §75.402. In addition, crosscuts must also be rock dusted to this same standard. Standard §75.401 states that where operations in active workings produce excessive amounts of coal dust, the mine must use water, water with a wetting agent added to it, or other no less effective methods approved by MSHA to suppress the dust. As with the rock dusting requirements, the area within 40 feet of a working face following §75.401 must also have water applied to coal dust on the ribs, roof and floor. The introduction of both water and rock dust increases the incombustible content of the combined mixture. For the U.S., the total incombustible content for these mixtures are required to be 80% or higher. The presence of methane in the mine atmosphere requires an increase by 0.4% rock dust for each 0.1% methane detected as per §75.403.

The quality criteria for rock dust is defined in §75.2. Based on this definition, the particle size of rock dust must be such that 100% of the rock dust pass a 20 mesh (841 µm) sieve and 70% pass through a 200 mesh (74 µm) sieve. This definition of rock dust also identifies that the rock dust must remain dispersible by a “light blast of air” (§75.2) after it has caked. Rock dust may coagulate or “cake” when it becomes wet which inhibits the rock dust from being entrained by an explosion pressure wave. Based on German regulations (1976), rock dust may coagulate or cake especially if it contains caustic or water-soluble components and/or if the particle size distribution is too fine. 30 CFR Part 75 does not provide a scientific definition for caking, so the application of this requirement is currently up to wide interpretation in the U.S.

3.1.3 Electrical equipment

The 30 CFR Part 75 also specifies requirements for the maintenance and explosion protection of electrical equipment while underground in the mine. MSHA examines, tests and certifies equipment as “permissible” in accordance with §75.506 and other regulations to ensure all electrical equipment used in underground mines will not become an ignition source.

3.1.4 Fire prevention and suppression

U.S. regulations have identified a number of acceptable fire prevention and suppression systems that eliminate ignition sources before they set off an explosion. Section §75.1101 covers deluge-type water sprays, foam generators, dry powder chemical systems, and back-up water systems as applicable to main and secondary belt-conveyor drives. The subsections of this regulation expand on the installation, maintenance, and spacing of these systems and continue into §75.1103 with the inclusion of automatic fire warning devices. These devices use carbon monoxide, radiation, smoke, or other gas sensors alone or

in combination to detect the presence of fire conditions which could be trigger an explosion or be present during an explosion event.

Section §75.1107 contains the regulations for fire suppression device setup and functionality on underground electrical equipment. The most common forms of these devices are dry chemical, high expansion foam, and water sprays. The device must have the proper capacity to extinguish a potential fire within or on the equipment. The setup must also take into account the impact that ventilation flow may have on the dispersion of the extinguishing agent, and be adjusted accordingly.

The requirements for fire suppression systems on diesel-powered equipment are detailed in §75.1907. All diesel-powered equipment must have at least one portable multipurpose dry chemical type (ABC) fire extinguisher within easy reach of the equipment operator, be protected from damage and collisions, and have a manual or automatic fire suppression system separately installed. Section §75.1911 states that the fire suppression system must provide protection for the engine on the diesel equipment, including the hydraulic pumps and tanks, starter, exposed brake units, transmission, air compressors, fuel tanks, and battery areas.

3.2 Australian regulations

The State of Queensland has the most comprehensive and representative regulation standard within the country of Australia. Their governing standard is the Coal Mine Safety and Health Regulation (2001) and is the set of codes that will be examined under this section. The sections of the regulations will be identified using the label S### (Section no. 286 is labeled as S286).

3.2.1 Establishing and regulating explosion risk zones (ERZs)

The most unique difference between the Queensland and U.S. regulations is Queensland's use of Explosion Risk Zones (ERZs) in identifying regulation requirements in the various locations of a coal mine. The ERZ rating that is defined in the regulations provides a strong definition of the explosion hazard and required standards for monitoring and mitigation. The zoning system for the ERZ is divided into three unique categories: ERZ0, ERZ1, and NERZ as defined by S286, S287, and S288. The only zone that is applicable to coal dust is the ERZ1 zone identified by specific locations where coal dust may be generated and the return airways near these locations. Signs must be posted to alert personnel of zone changes from NERZ to ERZ1 and ERZ1 to ERZ0.

The ERZ designation controls the technical requirements for the electrical equipment and installations located within each of the zones. The regulations pertaining to this section are S181 through S183 and require all the intended equipment to be suitable for underground use. ERZ0 equipment must be certified as having explosion protection category "intrinsically safe" (Ex ia based on IEC/EN 60079-25),

“special protection” (Ex s based on IEC/EN 60079-33) or “flameproof encapsulated” (“Ex 1” is mentioned in the regulation but based on IEC/EN 60079-1, it is “Ex d”).

For ERZ1 equipment, the only requirement is that it must be certified as having explosion protection. Similarly, equipment in NERZ (Negligible Explosion Risk Zone) areas must be certified as having explosion protection or having a degree of protection equivalent to at least IP55 under Australian Standard 1939 (apparently equivalent to U.S. National Electrical Manufacturers Association NEMA IP55 enclosure standards). Additionally, the above requirements for ERZ1 and NERZ areas do not apply to electrical equipment associated with flame cutting and welding, or live testing with the explosion proof enclosure opened.

3.2.2 Coal dust explosion prevention and control

Sections S300, S301, and S302 cover the regulations related to coal dust control and explosion prevention. The mine is required to cover the risks of a coal dust explosion and methods of subduing a coal dust explosion while preventing one from reaching other parts of the mine in their Safety and Health Management System. This system must be designed to suppress, collect, and remove airborne dust, limit dust generation and accumulation in airways, and remove coal dust accumulations from roadways and equipment. Additionally, the system is required to outline the stone dust or other inhibitor application rate needed to minimize the potential of a coal dust explosion.

Standard operating procedures for inspections, sample collection and analysis, and scheduling of rock dust application are required in addition to the requirements of the Safety and Health Management System. The frequency of dust sampling and the required Incombustible Material Content (IMC, equivalent to TIC in U.S.) is based on the sample points’ distance from relevant airways or production zones. These location requirements are listed in Table 3.1 and are verified to be in compliance by the underground mine manager. The underground mine manager must also confirm that rock dust, or other permissible dust treatment inhibitor, is applied to all 50m lengths of roadway immediately after and within 24 hours of being excavated. These requirements do not apply to roadways with dust if the mining operation in the area produces enough water to prevent a coal dust explosion from propagating.

Section S303 requires records of the sampling date, location, IMC, and method of analysis to be maintained and updated. The IMC result of a sample is also marked on a mine plan, with the ERZ areas identified, by the underground mine manager as soon as the results are received. If the IMC is below the required level, as identified in Table 1, then the regulations found in S302 are under effect. This section required the area from which the sample was taken to be retreated with rock dust, or other permissible

dust treatment inhibitor, with 7 hours for return and intake airways or 12 hours for roadways in the panel section. These additional treatments must be recorded along with the regularly scheduled treatments.

Table 3.1 Incombustible Material Content (IMC) and mine dust sampling frequency at various locations based on Coal Mine Safety and Health Regulation (2001).

Coal Dust Location	IMC Percentage (by weight)	Sample Type and Frequency
Dust in panel roadway within 200m outby last completed line of cut-throughs in panel	85%	Strip or spot sample – Weekly: Strip sample - Monthly
Dust in 200m section of panel roadway within 400m of longwall face	85%	Strip or spot – Weekly: Strip sample - Monthly
Dust in panel roadway within 200m of the main (if the above do not apply)	80%	Strip sample – Monthly
Dust in return roadway not mentioned above	80%	Strip sample – Monthly
Dust in intake roadway not mentioned above	70%	Strip sample – Every 3 rd Month

3.2.3 Contraband materials in mine

Regulations relating to the restriction and search for contraband material is outlined in S367 and S368. The following are considered contraband: cigarettes, cigars, any device used for smoking tobacco or drugs, any device, including a match or lighter, that may be used to strike or create an open flame, arc or spark, or any articles that have been prohibited from use in surface mine operations. Other items, such as aluminum cans, are also considered contraband due to their potential as a spark source under Queensland regulations. Devices that are used in conjunction with welding or flame-cutting work are not considered contraband items, but strict permitting procedures for their approval underground and risk management practices have been developed to mitigate their potential for initiating an explosion. These sections also provide compliance requirements for a mine’s Safety and Health Management System on how to properly search a person for the above contraband items as related to frequency, randomness, and location.

3.3 South African regulations

The document “Guideline for the Compilation of a Mandatory Code of Practice for the Prevention of Flammable Gas and Coal Dust Explosions in Collieries” (South African Mining Regulation Advisory Committee 2002) is the main reference source for South African mine safety and health regulations. Sections of this code of practice will be labeled with the prefix SA- (Part A Section 2.1 from the document will be referenced as SA-A.2.1). The code of practice is issued by the Mine Health and Safety Inspectorate (MHSI) as part of the Department of Minerals and Energy (DME) under the Republic of South Africa. This document provides regulation for all coal mines in South Africa as based on the MSHI and has been in use since August 1st 2002.

Mine operators in South Africa are also required to implement a Code of Practice (COP) for issues relevant to the safety and health of the miners. These COPs must also obey any additional or relevant guidelines issued by the Chief Inspector of Mines. Section SA-A-2.2 states that failure by the employer to prepare or implement a COP in compliance with this guideline is a breach of the MHSI. COPs are not approved or enforced by the DME. With this said, SA-A-3 states that the objective of the guideline is to support the employer of every coal mine to compile a COP, which, if properly complied, will ensure the inertization of coal dust and prevent the ignition and/or propagation of a coal dust explosion.

The Guideline does not state any mandatory requirements, but rather states that such mandates must be included in the COP. The guideline merely provides a reference of requirements for the mandatory COP and the COP as the actual regulatory document for each mine. The following sections discuss what is required in the COPs as outlined by the guidelines.

3.3.1 Coal dust suppression and inertization

Rock dust is utilized as the primary method of inertizing coal dust in South Africa. The COP must include requirements that limit the accumulation of coal dust at mining faces, conveyor transfer points and tramming routes as stated in SA-C-8.4. Under this, the COP must also outline regular removal of coal dust accumulations in the face areas, transfer point, traveling roads, return airways, conveyor belt roads, and equipment prior to treatment with rock dust. Section SA-C-8.5.1 explicitly states the minimum inertization levels that must be complied with in different areas of the mine. Table 3.2 summarizes these locations and inertization levels. Section SA-C-5.4.4 states that rock dusting must be conducted within 10m of the working faces unless the area is inaccessible, unsafe to enter, or if the coal dust has been washed from the roof, sides, and floor and the floor is too wet to propagate an explosion. It is of interest to note that rock dust is required to be the inertizing agent in areas that are sealed from the rest of the mine.

Provisions under SA-C-8.5.5 cover the frequency of application for rock dust. For face areas, rock dust must be applied, and re-applied, as often as necessary to maintain the required IMC. The rate of application must not be less than once every four production shifts, unless the rate of deposition of float coal or sampling indicates that less frequent application is sufficient. During pillar extraction, rock dust must be applied at the same frequency rate as indicated in SA-C-5.4.4 for a face area, but on a retreat basis. Rock dust must be injected regularly into mined-out areas when total extraction mining is occurring. This must be done before the occurrence of the initial gob fall to inert the dust that will be entrained when it occurs. For both longwall and shortwall mining, rock dust must be introduced into the return airways during production.

Table 3.2 Incombustible Matter Content at Specific Locations in South African Underground Coal Mines.

Location in Mine	Minimum Incombustible Matter Content (IMC; by mass)
Intake airways inby the face area	80%
Intake airways outby the face area	65%
Workshops, sub-stations, battery charging stations and similar places in intake air	80%
Return airways within 1000m of face	80%
Return airways beyond 1000m of face	65%
If barriers installed, face area and outby of barriers	65%
Accessible roads within 250m radius of area being sealed off	80%
Conveyor roads within 180m of face	80%
Conveyor roads beyond 180m of face	65%
Area to be sealed off	80% by rock dusting

The guidelines identify rock dusting and the use of water as possible inertization tools for coal dust. If a mine operator wishes to use water as a dust suppressant, SA-C-8.5.2 states it must specify in the COP the area to be treated in the mine, the technique used to apply the water, the scheduling of water application, the procedure for ensuring sufficient quantity of water has been applied, and the person responsible for ensuring these requirements are followed. The COP must also follow SA-C-8.5.3 which ensures suppliers of rock dust comply with the following minimum quality requirements:

- Rock dust is preferred to be pulverized limestone or dolomite and light in color

- It must contain not less than 95% by mass of incombustible matter, and have a density similar or equal to pulverized limestone
- It must contain no more than 5% by mass of free silica or any other toxic substance in concentrations detrimental to health
- When dry, all rock dust must pass through a sieve of 600 micrometers aperture and at least 50% by mass must pass through a sieve of 75 micrometers aperture
- Unless directly wetted by water, dust must not cake and must readily disperse into the air
- Mine operators must test each batch of rock dust delivered and issue a certification documenting the results
- Should another incombustible dust be used besides limestone or dolomite, compliance with the ability to stop flame propagation of a coal dust explosion must be tested and approved at an accredited institution.

3.3.2 Dust sampling program

Annex 1 of the Guideline is dedicated to the sampling procedures for checking IMC. The first part of Annex 1 details the requirements of a mines rock dust sampling program, including the location and frequency of samples along with the type of sample taken at the location. These requirements, as taken directly from Annex 1, are as follows:

SA-Annex 1

1.1. Compliance Sampling

- 1.1.1. samples must be systematically collected from the roads of all accessible workings of a colliery;
- 1.1.2. the workings of a colliery must be divided into the face areas and zoned back areas and these areas must be clearly demarcated on a plan;
- 1.1.3. the sample of the dust on the roof and sides must be taken separately from the sample of dust on the floor;
- 1.1.4. in the case of dust on the roof and sides the sample must be taken to a depth not exceeding 6 mm and in the case of dust on the floor to a depth not exceeding 25 mm;
- 1.1.5. every sample taken must be representative of the whole surface of the roof and sides as well as the floor of the length of road being sampled and must be collected by a method of strip sampling by which the dust is collected from a succession of transverse strips, 100mm wide

and equally spaced not more than 5 m apart. Intersections must be sampled diagonally across to include a sample from at least two pillar corners;

1.1.6. where it appears that the roof and sides or the floor, as the case may be, is wet, the sample must nevertheless be collected. Excess water must be drained off by placing the sample on a 2 mm aperture sieve, for at least one minute; and

1.1.7. areas where water has collected in pools on the floor, need not be sampled but must be recorded as such.

1.2. Sampling of Face and Back Area

1.2.1. Face Area

1.2.1.1. Samples from face areas must be taken at intervals not exceeding 14 working days, or at lesser intervals, if so determined by risk assessment.

1.2.1.2. In the face area, a composite sample must consist of the combined material, collected from 5 equally spaced transverse strips (except where measurements are affected by diagonal sampling at intersections), over a measured distance of 20m. The dust on the roof and sides must be taken separately from the samples of dust on the floor and the two sets of results reported separately.

1.2.1.3. A series of 3 composite samples must be collected from all return airways, the belt road, and at least one intake airway, over a distance not less than 60m length of roadway, commencing at a location approximately 15 m from the face. Similarly, a series of composite samples must be collected over the full length of the last through road.

1.2.1.4. In the case of either longwall or shortwall mining, a series of 5 composite samples must be collected from all gate roads over a distance of not less than 100m length of roadway, commencing at the face.

1.2.2. Back Area Requirements -

1.2.2.1. The workings of a colliery outby of the face area must be divided into zones not exceeding 1200m in length. These zones must further be divided into sub-zones, not exceeding 100m in length, from which representative samples must be taken at intervals not exceeding 30 days.

1.2.2.2. In the back area a composite sample must consist of the combined material collected from 11 equally spaced transverse strips (except where measurements are affected by diagonal sampling at intersections) over a measured distance of 100m. Samples from the roof and sides should be treated separately from those obtained from the floor.

1.2.2.3. Samples from sub-zones must comprise of composite samples taken from at least one return airway, the belt road and one other intake airway.

1.2.2.4. Sampling of zones must be scheduled so that each sub-zone is sampled at least once per year.

The second part of the annex details the methods for analyzing each of the dust samples. The Guideline details the step-by-step process of the Colorimetric method, which assesses the amount of inert dust by its color, and the Laboratory method, which is similar to Low Temperature Ashing analysis used in the U.S. These two methods are the preferred sample analysis tools for determining the IMC.

Annex 1 also requires the mine to keep records the certification of rock dust delivered to the mine for two years and the analysis results a related sample data. It is important to note that if more than 20% of samples in a given area do not meet the IMC requirements, then immediate remediation action must be taken and properly recorded.

3.4 European Union and German regulations

The coal dust explosion prevention standards for the EU and Germany are outlined in the subsections below. Large portions of the German standards have been unified throughout the European Union and are thus applicable for all E.U. underground coal mines. Germany has been a forerunner in developing explosion safety standards, so it is important to discuss some of the general explosion prevention regulation using German documents as examples.

One central supplementary document governing the prevention of mine explosions in Germany and the EU is the DIN EN 14591. This standard regulates the design and construction of ventilation doors suitable to withstand an explosion pressure of 2 bar (200kPa or 29psi), the design of passive water trough barriers to quench mine explosions before they can do major damage and cause injury to miners, and the design of automatic, active explosion barriers mounted on roadheaders used to mine the arch-shaped development entries. This document will be referenced throughout this section of the chapter.

It is important to note that most mines in the EU and Germany utilize a single-entry gate road development for their longwall operations. These development entries are generally arched and provide cross sections of up to 30m² (320ft²) with base widths of up to 6m (20ft). This is a stark contrast to mining operations in the U.S., Australia and South Africa where room-and-pillar-style, multiple-entry development is the standard. Single entries in German mines have 2 to 3 times the cross-sectional areas of typical US mine entries and offer a significant reduction of airway ventilation resistance. The single-entry design almost completely eliminates leakage and provides a significant improvement to ventilation

efficiency. Single-entry development also simplifies the design of the mine ventilation system and significantly reduces the potential for damage to ventilation controls as so few are needed.

3.4.1 Active and passive explosion barriers

Roadheaders cutting development entries under auxiliary ventilation must be equipped with active explosion barriers under DIN EN 14591-4. There, barriers must consist of 6 pressurized containers filled with ammonium-phosphate-based fire extinguishing agent that is rapidly released if an ultraviolet flame sensor detects a methane ignition near the face.

The DIN EN 14591-2 outlines the design of passive water trough explosion barriers for use in underground coal mines. These barriers are arrangements of 80L (20gal) plastic troughs suspended in the upper half of an arched mine entry. Figure 3.1 shows an arched entry with a typical arrangement of water troughs.

These troughs are blown down by a coal dust (or methane) explosion pressure wave and quench the trailing flame front, preventing the explosion from spreading further into the mine workings. A water trough barrier requires 200kg of water per square m of entry cross section if designed to be full sized. Regulations allow for “concentrated” barriers to be installed that have the plastic troughs arranged on rows of shelves instead of suspended. The total length of the shelf arrangements must exceed 20m, the volume of water must be at least 5L per m³ of total entry volume for the entire barrier, and the distance between rows is typically 2m.

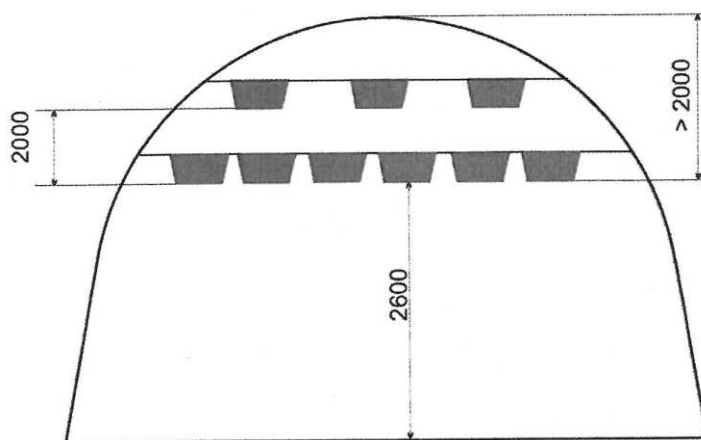


Figure 3.1 Water troughs suspended on shelves in an arched entry. Dimensions indicated in mm, from DIN EN 14591-2.

In addition to the concentrated barriers, DIN EN 14591-2 outlines the use of groups of explosion barriers that are arranged as “distributed barriers”. Water trough groups are arranged every 30m (100ft), are erected on shelves every 3m (10ft), and the water amount needs to cover a minimum of 1 L/m³ of total entry volume for the group.

The DIN EN 14591-2 specifies what type of barriers are required at what distances from identified explosion sources (primarily, mining faces). The following regulations apply:

- Concentrated barriers must be erected every 400m (1,300ft) along each mine entry. If distributed barriers are used, the first row of troughs must be placed within 30m (100ft) of a concentrated barrier or intersection.
- Intersections must have a concentrated barrier in each leg within 75m (250ft), or a distributed barrier where the first row of troughs must be within 30m (100ft) from the intersection. Figure 3.2 shows an example of concentrated and distributed barriers in the legs connecting at a 4-way intersection.

European mines have, in recent years, used rock dust barriers as an alternative to water trough barriers. The rock dust would be arranged on shelves, similar to the water troughs, which would then topple from the pressure wave of an explosion. These shelves would require 400kg of rock dust for every m² of entry cross section. The ability of the rock dust barriers to suppress an explosion is higher due to rock dust staying suspended in the air longer than water droplets. This makes timing of the barriers’ activation a less critical design point. However, the rock dust can, over time, absorb moisture in the air and cake making it ineffective at dispersing and extinguishing an explosion’s flame front. The dust barriers are also restricted to entries with a low enough ventilation airflow to prevent the rock dust from being blown off the shelf. German mines discontinued the use of rock dust barriers in the 1980’s for these reasons.

3.4.2 Binding coal dust with hygroscopic salts

The EU predominantly uses hygroscopic salt solutions (CaCl₂ and MgCl₂) over rock dust in areas where coal dust can accumulate. The information presented in this section was compiled from several training documents supplied by Hermülheim (2011) at Deutsche Steinkohle AG.

Hygroscopic salts absorb moisture from the mine air and remain moist, so they can bind to coal dust particles and ensure they do not participate in an explosion event. Surfactants can be added to improve the adsorption of coal dust particles, as the coal dust is hydrophobic. These surfactants also increase the spray treatment intervals needed to maintain prevention coverage.

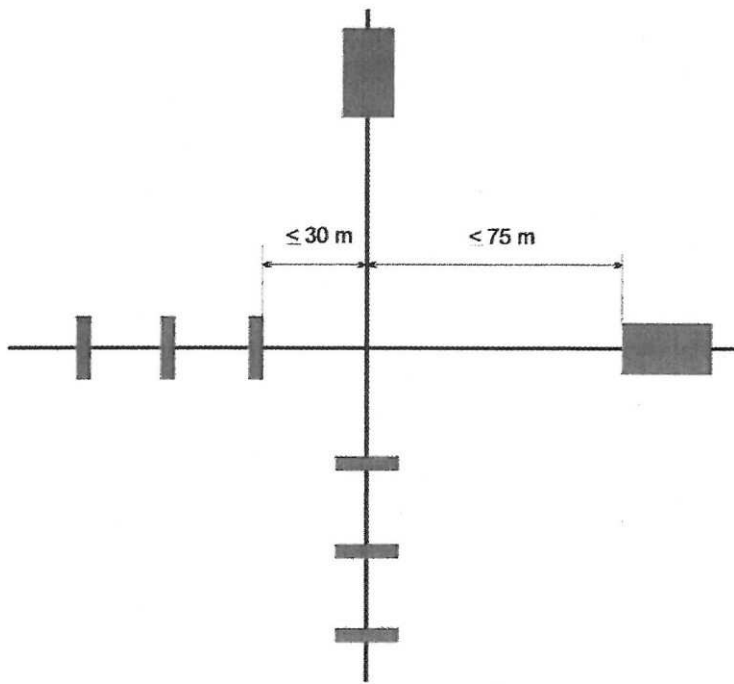


Figure 3.2 Arrangement of concentrated (large blocks) and distributed (small blocks) water trough explosion barriers around an intersection from DIN EN 14591-2.

Salts can be used in the mine in liquid, powder or prill form. The quantity of hygroscopic salt required to suppress coal dust is less than that of rock dust. The salt solutions used underground only have a total salt content of 30%.

CaCl_2 and MgCl_2 have both been proven to pose no significant health hazards and are often used in the food industry. It is still important to avoid eye or skin contact or inhalation as the salts are irritants. Full PPE (gloves, rubber apron, rubber boots, face shield) is recommended when applying the salt solution in any of its forms. Additionally, the salt solution is corrosive to metal and can make the mine floor slippery.

If the salt solution is delivered in liquid form, a fine droplet spray can be utilized for full coverage through an entry cross section. The presence of dust when using this method helps to form a support matrix for the salt solution which better holds the mixture in place. The solution can be sprayed on at a thickness of 0.4mm (0.02in) using a 60° full cone spray nozzle running at 500kPa (70psi) and 16 L/min (4gpm) flow rate. With this spray method, the application of the salt solution can be fully automated by installing permanent infrastructure and a timer system.

The dust binding capacity of both CaCl₂ and MgCl₂ solution lies between 100 and 200 g/m². Total dust binding capacity is 1.3kg coal dust per kg of spray solution. The dust binding capacity of prills is about 2kg coal dust per kg of prills. For comparison, to achieve 80% total inert content, 1kg of rock dust can only inertize up to 0.25kg of coal dust.

3.4.3 Elimination of Ignition Sources

Smoking and any form of open lights are prohibited. The electrical equipment operating in underground coal mines is required to be either explosion proof (Ex) or intrinsically safe and is application for all areas underground with limited exceptions. Flame cutting and welding, as well as electric arc welding, are prohibited with limited exceptions. For example, underground central shops ventilated directly to return air may conduct welding and arc cutting activity.

3.4.4 General explosion prevention in Germany

The central mining regulation in Germany is the “Allgemeine Bundesbergverordnung” (ABBergV, 1995 general federal regulation on mining). These regulations prescribe fundamental requirements pertaining to mine safety and occupational health. The provisions in this regulation are more general and less prescriptive. Fundamentally, it is up to the operator to identify all health and safety hazards present and choose appropriate measures to mitigate and control these hazards. The following outlines relevant content for the prevention of coal dust explosions:

- §11(1)1.: The mine operator must undertake appropriate measures such that mine fires and explosions and toxic atmospheres can be prevented, detected, and mitigated.
- §15(8): The mine operator must prevent the propagation of coal dust explosions with an appropriate arrangement of explosion barriers
- §17(2): Mining equipment and devices to be used in areas where explosion hazards may exist must fulfill the safety requirements for such use.

Appendix 1 of the ABBergV provides more specific regulations for coal dust explosion prevention outlined as follows:

- Flammable dusts (i.e. coal dust) must be reduced, removed, neutralized, or adhesion-bound.
- No smoking or open flame in areas where fire or explosion hazards may be present
- Smoking materials and lighters may not be carried into gassy underground mines
- Flame cutting and welding and similar activities may only be performed on an exception basis while undertaking specific measures for the protection of safety and health of the employees

- The operator must take appropriate measures
 - To prevent the accumulation of explosive gas and dust mixtures with air
 - To prevent the ignition of such mixtures
 - To limit the spread of explosions in a way that minimizes exposure to miners
- The operator must develop an explosion protection plan, keep it updated and make it available for inspection

Underground coal mines are subject to the “Bergverordnung für die Steinkohlenbergwerke” (BVOST, 2001, state mining regulations for underground coal mines), which provides more specific regulations for these mines. Section 3 of this regulation covers fire and explosion prevention, Section 6 covers mine ventilation, and section 7 covers measures to prevent coal dust explosions. Pertinent excerpts of these sections are:

- Section 3, §9: Mine operators must provide measures to quickly erect ventilation controls in the mains. Materials to build such controls, including inflatable, temporary seals, must be kept at the ready at any time.
- Section 3, §19: Responsible, certified persons must be named to monitor and supervise measures for the prevention of fires and explosions.
- Section 6, §32(3): Every main mine fan must be equipped with a spare fan of identical characteristics. Usually, the spare fan is mounted on rails and can be pushed into service immediately if the main fan is destroyed in an explosion.
- Section 7, §41: Coal dust must be adhesion-bound or mixed with rock dust such that the total combustible content is not higher than 20%. Explosion barriers must be erected to prevent the propagation of coal dust explosions.
- Section 7, §42: A responsible, certified person must be named who is in charge of explosion prevention

3.4.5 German regulations for mine dust sampling

Mine dust sampling in German mines is regulated by “Technische Richtlinien Staubprobenahme” (1980). As noted previously, rock dust is rarely used in German mines anymore; it has been replaced by the application of hygroscopic salt solutions. Since rock dusting is still a widely utilized process in non-EU countries, these regulations have been included to provide a direct comparison with the standards followed by the U.S., Australia, and South America.

Regulations require that mine dust sampling be completed monthly by a trained, qualified person. Any entries containing accumulated coal dust that may be suspended in an explosion event are required to be sampled for its combustible content. A maximum of 20% combustible components is permitted, equivalent to the U.S. rule of minimum 80% incombustible content. Record books of all dust sampling are required to be maintained and updated.

A sampling location is selected based on potential dust sources. The sources include loading points, conveyor transfers, ventilation doors and regulators, working production sections, crushers, longwall move operations, development sections, ventilation split points, sudden reductions in entry cross section, haulage equipment, and all belt entries, especially those ventilated against the direction of haulage.

Sampling is started downwind from the identified dust source and continues in the downstream direction until the dust generated by the source has visibly settled or a new dust generation source is reached. Sample locations are determined with the following criteria: The first samples must be taken 30-70m (100-250ft) downwind from each identified dust source. If the designated sampling area is longer than 400m (1,300ft), additional samples must be taken. If rock dust needs to be applied due to a failed sample, an additional sample must be taken 100-150m (300- 500ft) downwind from the freshly dusted area after the rock dust has been applied.

Sampling locations are also chosen based on the run-up characteristics of a propagating coal dust explosion. Using the work of Cybulski (1975) and other research, coal dust explosions need a so-called run-up distance of 200-400m (650-1,300ft) before the explosion becomes strong enough so that it can propagate. Regulation provides for the following exceptions: Longwall production faces, longwall startup entries, and surface shafts. Additionally, belt transfer areas are exempt if they have been treated with dust-binding salts, which is usually done. Any area that is naturally wet from ground conditions or mining activity, so that the dust can no longer be entrained, is also exempt. Exempted areas are required to be inspected to verify that the conditions for exemption to remain valid.

The sampling procedure for mine dust is conducted following a set practice. At each sampling location, samples are conducted over an entry length of 2m. Two samples, one from the floor and one from a higher location, of greater than 10cm³ (0.6in³) dust each are taken at every location. The sample from the higher location is taken using a brush to dislodge the particles and combined from several areas where dust settles including knee height, chest height and reach height.

The floor sample should be combined from several points at the sample location and may be reduced by sieving at 5mm (approx. 4 mesh or 0.2in.) to remove larger pieces of coal, rock or other

contaminants that would not be entrained by an explosion's pressure wave. If the sampling location has a high velocity air current, it is important to ensure dust is not lost during the sampling process. While in transit, the samples are required to be stored in marked containers or bags that can be securely closed.

The sample testing procedure is similar to the low temperature ashing method used in the U.S. A roughly 10g (0.35oz) dust sample is dried at 106°C (223°F) until there are no weight fluctuations. The sample is cooled in a desiccator and weighed to a 1mg accuracy. This process is then repeated at a heat of 500°C (932°F). The weight loss measured between the first and second cycle in the process is the combustible content of the sample. Compared to U.S. low temperature ashing reporting, the water loss during initial drying is not determined and is not credited as incombustible content.

Dust sampling and rock dusting must be conducted based on an approved operations plan. The regulation enforcing authorities for the coal mines also conduct their own sampling similar to the MSHA inspections in the U.S.

3.4.6 German regulations on dust quality and testing of rock dust

The regulation for rock dust quality, "Richtlinien des Oberbergamts für das Saarland und das Land Rheinland-Pfalz über die Anforderungen an Gesteinstaub sowie für die Durchführung der Untersuchung von Stäuben" (1976), ensures the consistency of rock dust quality and stipulates that rock dust must not cake or coagulate if it absorbs moisture from the air. Rock dust used in German mines was primarily composed of limestone or dolomite dust. As previously stated, German coal mines no longer use rock dust for explosion barriers.

An important part of ensuring the consistency of the rock dust was the particle size distribution. According to DIN 66145, the particle size distribution curve of the rock dust had to be within the cross hatched area, marked "A", on the RRSB diagram (Figure 3.3). The particle size distribution is determined as follows: >0.5mm (0.02in) by dry sieving, >0.071mm to <0.5mm (0.003-0.02in) by wet sieving, and <0.071mm (0.003in) by sedimentation analysis or equivalent methods. Testing procedures follow applicable DIN standards that are typically equivalent to ASTM standards.

If a portion of the size distribution curve of the rock dust fell in the simple hatched area, marked "B", the rock dust was too fine and was required to be treated with a non-hazardous hydrophobizing agents to prevent coagulation.

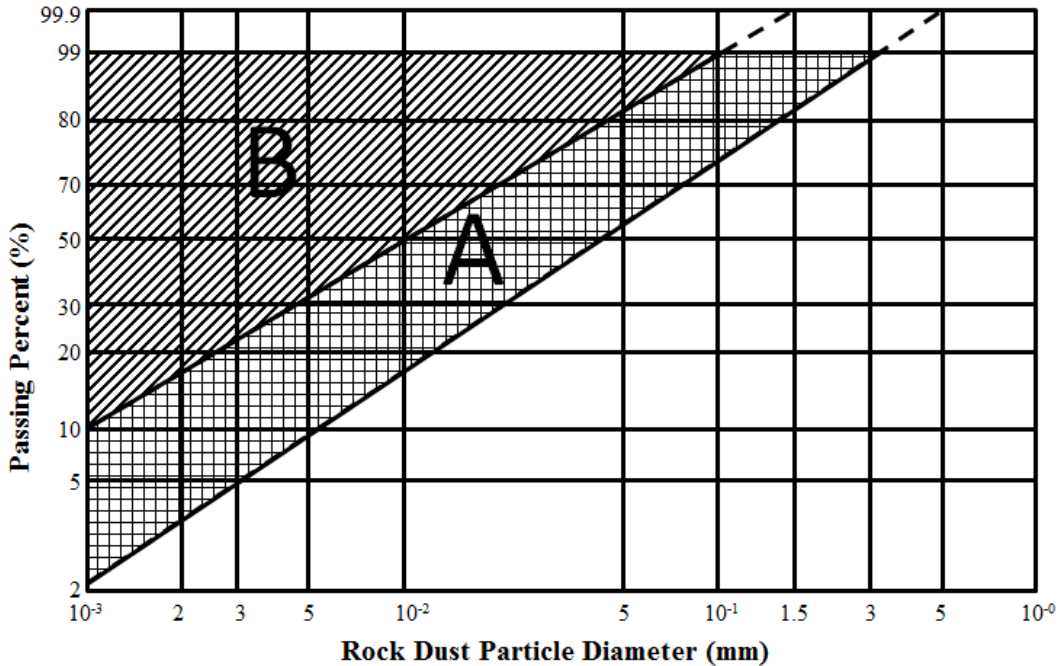


Figure 3.3 RRSB Diagram for rock dust size distribution modified from DIN 66145. Grain size equivalent diameter is shown in mm on the abscissa while the ordinate shows the percentage passing the sieve.

If the rock dust passed the size distribution criteria, it was required to be chemically analyzed for the following quality criteria:

- Maximum 3% by weight components that are insoluble in hydrochloric acid (i.e. quartz and other silicates)
- Maximum 0.3% caustic components (determined as calcium hydroxide equivalent)
- Maximum 0.3% water-soluble components (usually calcium hydroxide and salts)
- Maximum 3% combustible components
- Maximum 0.5% moisture at time of delivery. If in-mine dust is maintained at less than 1.0% moisture by weight, it is considered entrainable

The content of water-soluble components (usually calcium hydroxide) was a required measurement since it influenced the caking and entrainability of the rock dust. The electrical conductivity of the rock dust was the preferred measurement method due to its sensitivity to water-soluble components. A conductivity of $\sim 200\mu\text{S}/\text{cm}$ indicates greater than 0.05% soluble salts or greater than 0.15% $\text{Ca}(\text{OH})_2$.

If the conductivity is greater than 200 μ S/cm, the water-soluble content must be determined by evaporating the filtrate. Water soluble anions and caustic components are determined through standard chemical analysis. This also goes for determination of components that are insoluble in hydrochloric acid.

The German mining authorities have a listing of approved rock dusts and manufacturers. To be included on that list, the manufacturer must have filed an application with the mining authorities certifying that hygienic testing of the rock dust showed no health hazard present. A simplified chemical analysis was also required of every batch of rock dust delivered to the mine in addition to the full analysis required for initial approval. A 1kg sample had to be analyzed using this simplified chemical analysis for every 10 tons of rock dust delivered to the mine. If the rock dust was delivered in bags, samples could be comprised from individual bags to a maximum sample size of 2kg. Bulk dust had to be continuously sampled during unloading with the maximum sample size not exceeding 5kg.

The following parameters had to be determined in the simplified chemical analysis:

- The particle size distribution: Two test points are taken by wet sieving, at 0.071mm and at 0.025mm. Hydrophobized dust should first be soaked in acetone to dissolve the chemical coating.
- The components soluble in hydrochloric acid
- The electric conductivity of electrolyte. If the conductivity is $>200\mu$ S/cm, the soluble components must be determined by evaporating the filtrate. Also, pH shift must be determined. If pH shift is >1 , hydroxides must be determined, usually by titration.
- Moisture content

The laboratory reports from the simplified chemical analyses had to be kept on file at the minesite and unused portions of the sampled had to be stored for two months in case a sample needed to be reanalyzed.

CHAPTER 4

BEST PRACTICES AND TECHNOLOGY FOR THE PREVENTION OF COAL DUST EXPLOSIONS

The aim of this chapter will be to identify the available coal dust explosion prevention and suppression technology and practices while outlining their overall effectiveness and accessibility. The contents of this chapter will meld best practices from around the world to create a comprehensive guide within the industry.

4.1 Reduction of coal dust in mine environment

The first approach towards preventing a coal dust explosion is to reduce the amount of combustible dust from the active mining area. The best location to manage coal dust is at the source of generation, such as the active mining face, belt conveyor transfers points, longwall shields, and crushers. Fine coal dust can also be produced from the exposed coal ribs in entry development sections, or in areas of the mine where equipment creates pinch points. Eliminating spillage on conveyors, particularly when it falls between rollers and conveyor belts where it is crushed to fine consistency, is another area for reduction of coal dust. Water sprays, scrubbers, or combination systems are the most effective methods of controlling coal dust at the source.

On equipment where dust generation is common, such as shearers and continuous miners, water sprays act as a first barrier to prevent a coal dust explosion from initiating. The water binds the coal dust at the point of creation and prevents the dust from being entrained in the ventilation air and transferred to airways throughout the mine. In addition, the water sprays help to lower the temperature of cutter picks, reducing the occurrence of sparking and hot streaking at the active face. For continuous miners, the use of scrubbers has become a common practice. These scrubbers utilize a wet vacuum fan system to remove the coal dust from the ventilation air and keep it from being deposited in return airways as illustrated in Figure 4.1. Scrubber systems have recently been adapted for use at conveyor transfer points and crushing stations to assist in the reduction of coal dust in these less traversed areas.

4.2 Coal dust inertization by mixing with rock dust

The inertization of coal dust with the application of rock dust is an effective solution that is available in most coal mining countries. This material is commonly limestone or dolomite dust but can be any type of stone dust that does not cake if it absorbs moisture and is free of silica (quartz). Other materials that have been utilized clay slate dust, gypsum, and various chemical dusts. Research has been conducted on the effectiveness of inerting materials by Cybulski (1975), Hertzberg and Cashdollar (1987), Sapko et al. (1987) and Cashdollar (2010), among others. The rock dust inerts the coal dust in two primary ways:

- The inert dust particles provide a thermal sink by absorbing heat from the explosion flame through conductive and convective heat transfer
- The inert dust particles shield the coal dust particles from heat transfer by radiation

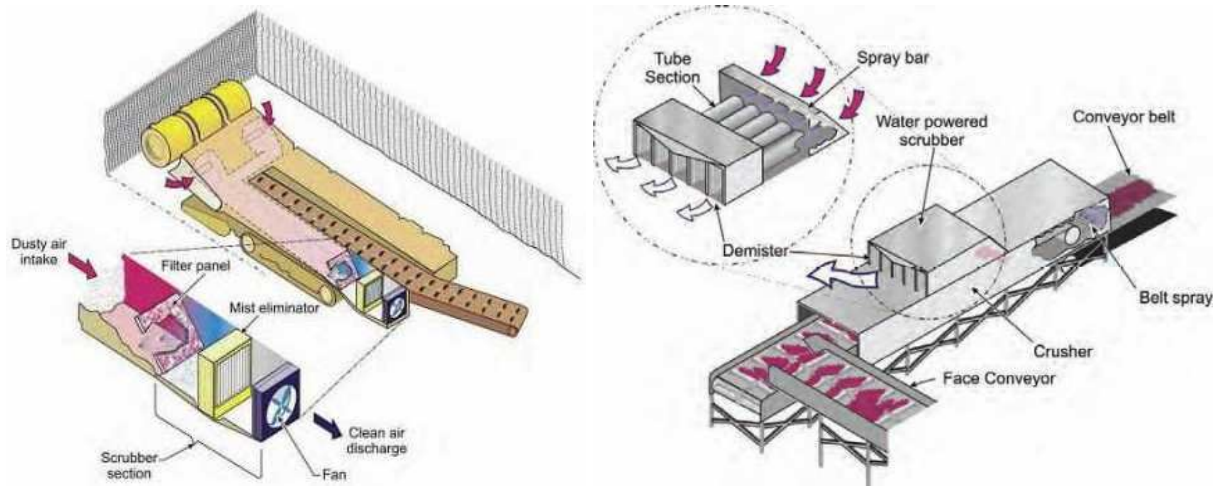


Figure 4.1 Design of a flooded-bed scrubber (left) and high pressure water scrubber installed on top of crusher (right) (“Respirable Dust Control”; <http://www.mirmgate.com>)

Figure 4.2 provides a 4 phase diagram of how a coal dust explosion is initiated and propagated. Phase 1 shows layers of coal and rock dust on the mine floor and an air phase. Phase 2 diagram shows a pressure wave from an initial methane explosion entraining and mixing the coal dust and rock dust in the mine atmosphere. In phase 3, the flame front of the explosion comes into contact with the rock/coal dust mixture. If there is a high enough percentage of rock dust in the entrained mixture, the rock dust will act as a thermal sink and shield the coal dust particles from the radiant energy.

If the percentage of rock dust is insufficient, too much of the coal dust will be heated, allowing the coal particles to de-volatilize and cause a rapid expansion of the mine air. Because of the expansion, the pressure wave continues to scour up additional dust, propagating the explosion. Phase 4 illustrates this propagation through the visible cross-section of the entry. During the UBB explosion, the pressure wave and flame front propagated through 67km (42mi) of mine entries. The explosion is believed to have occurred for several minutes at a subsonic rate based on the investigation findings and pressure estimates produced by MSHA (Page, 2011).

Table 4.1 provides an overview of the TIC requirements of various countries based on Cashdollar et al. (2010) and updated with current U.S regulations. Some of the regulations have higher TIC requirements in locations close to the active mining face, or locations with measureable levels of

methane. Other countries have decreased TIC requirements in areas designated to not have sources of ignition or less prone to methane accumulations.

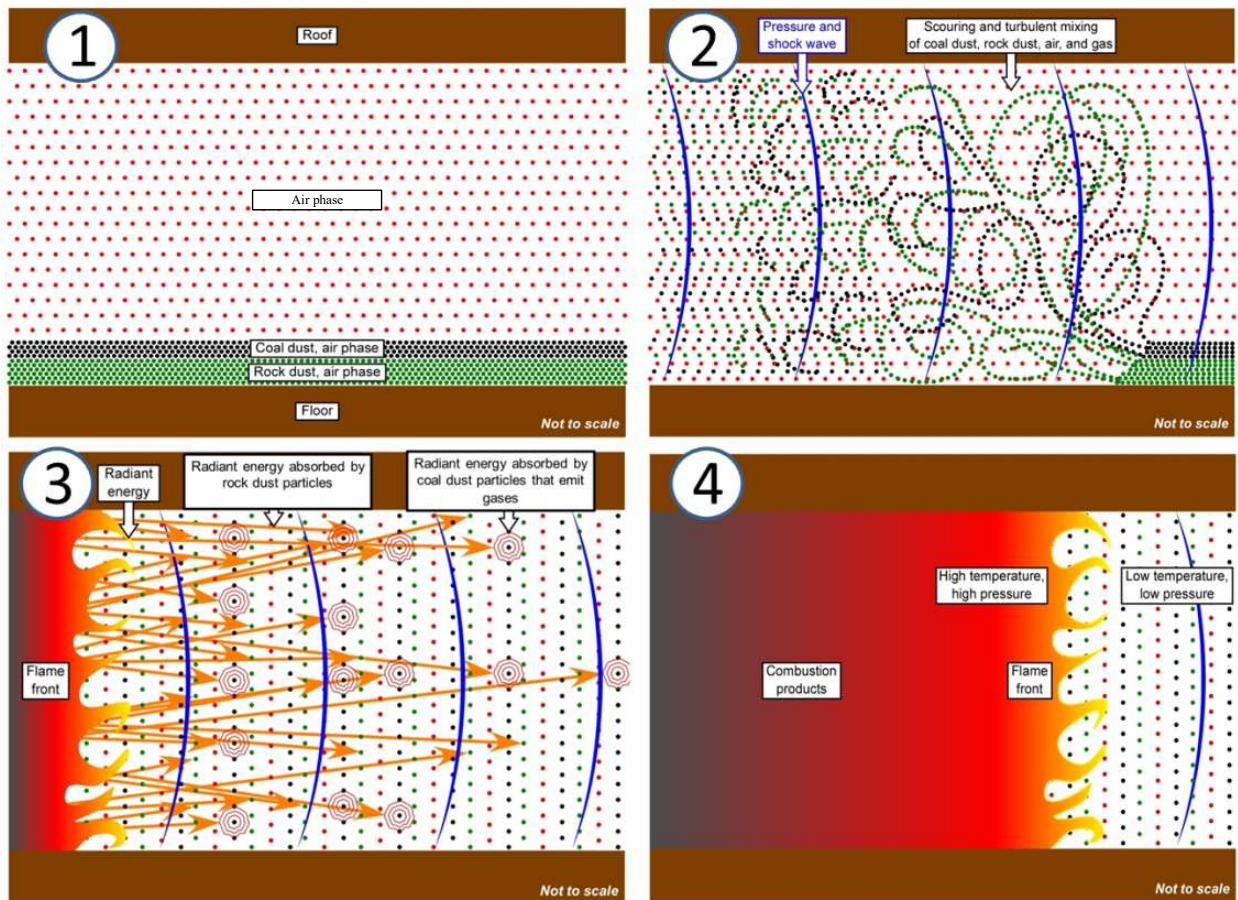


Figure 4.2 Schematic depiction of a coal dust explosion in four phases.

Cybulski (1975) and other researchers (see also Cashdollar et al., 2010) have indicated that the common TIC requirement of 80% may be insufficient to prevent a coal dust explosion from occurring if:

- The initiating explosion is strong, or, in the case of a propagating dust explosion, the dust explosion has a long run-up and develops great momentum.
- The coal dust size distribution contains a large portion of dust finer than 74 μ m (200 mesh).
Cybulski tested coal dust where 85% of the dust passed 74 μ m (200 mesh). Even though it is unlikely that such dust would be found in typical coal mines, Cashdollar's 2010 study shows that higher mechanization in mines, including mechanical cutting vs. blasting and belt conveyors vs. track haulage, have significantly increased the amount of fine dust contained in the mine dust samples tested.

Table 4.1 Summary of Incombustible Matter Contents for Various Nations. Note: Modified from Cashdollar (2010), with changes made to United States to reflect the most recent regulation changes.

Country	TIC %	Volatile matter %	Methane %	Comments
<i>Australia</i>	85-80 (return)	-		85% TIC ≤ 200m from the face
<i>Queensland</i>	85-70 (intake)	-		80% TIC > 200 m from the face 85% TIC ≤ 200 m from the face 70% TIC > 200 m from the face Supplemental protection-barriers
<i>Australia</i>	85-70 (return)			85% TIC ≤ 200m from the face
<i>NSW</i>	80-70 (intake)			70% TIC > 200 m from the face 80% TIC ≤ 200 m from the face 70% TIC > 200 m from the face Supplemental protection-barriers
<i>Canada</i>	75 (intake)	-	< 1	
<i>(Nova Scotia)</i>	80 (return)	-	> 1	
<i>Czech Republic</i>	80 (intake/return)	-	< 1	Supplemental protection-barriers
	85 (intake/return)	-	> 1	
<i>Slovakia</i>	80 (intake/return)	-	< 1	Supplemental protection-barriers
	85 (intake/return)	-	> 1	
<i>Germany</i>	80 (intake/return)	-		Supplemental protection-barriers
<i>Japan</i>	78 (intake/return)	35	< 1	Specific requirements depend on as, moisture and volatile content, the gassiness of the seam, and the fineness of the rock dust used.
	83 (intake/return)	35	> 1	
<i>Poland</i>	70 (intake/return)	> 10 > 10		70% in "non-gassy" roadways 80% in "gassy" roadways Supplemental protection-barriers
<i>South Africa</i>	80 (intake)	-		80% TIC < 200 m from the face
	80 (return)	-		65% TIC > 200 m from the face 80% TIC for 100 m from the face Supplemental protection-barriers
<i>United Kingdom</i>	50 (intake/return)	20		Supplemental protection-barriers
	65 (intake/return)	27		
	72 (intake/return)	35		
	75 (intake/return)	> 35		
<i>United States</i>	80 (intake/return)	-		Add 0.4% TIC / 0.1% methane

- The ventilation air contains methane or other flammable gases (note that the U.S. regulation 30 CFR §75.403 requires a TIC increase of 0.4% for every 0.1% methane). If the entry carries 1% methane, the minimum TIC is therefore 84%.
- The amount of volatile matter in the coal is high. As dust particles are heated by the flame, the volatile matter is ignited, propagating the flame. Solid coal particles typically will not combust since their exposure time to heat and flame is too short. This indicates that anthracite coal with an extremely low volatile content (typically less than 5%) is unlikely to propagate a coal dust explosion.

As illustrated in phase 2 of Figure 4.2, dust must be entrained in the air to participate in an explosion. It has been measured that the air blast from an explosion typically entrains only the top 2-3mm (0.08-0.12in) of dust (Harris et al. 2012). This creates a hazard due to dust layering from the method/frequency of rock dust application. If the rock dust is not applied continuously, fine coal dust that is still settling in the mine air can accumulate as the top layer. Studies conducted by Sapko et al. (1987), Edwards and Ford (1988, p. 8) and other researchers, have proven a 0.12mm thin top layer (0.005in, about the thickness of a single sheet of paper) of coal dust, on top of any depth of rock dust, is sufficient to propagate a coal dust explosion.

This layering issue highlights a deficit of the current MSHA inspector guidelines (MSHA 2013) for dust sampling. These guidelines require the mine to take a band sample using a bristle brush and flat metal pan to remove the top 1/8th inch of the dust layer. Before 2013, the inspector guidelines required a sample be taken to a depth of 1 inch. Figure 4.3 shows an illustration of this technique as provided by the 2013 Guidelines. Other countries have similar regulations, including the requirement of experienced, trained persons to collect the samples. Given that a 0.12mm layer of pure coal dust can propagate a coal dust explosion, the current guidelines to sample to a depth of 0.125in would yield 96% TIC, even with a pure rock dust layer underneath.

There is also concern over the ability of an inspector to consistently sample to a depth of 0.125 in, along with the possibility that the brush-pan collection method may physically dislodge particles that would not be entrained during an explosion. The impact of deviations from a flat, horizontal surface and variations in dust density have not been researched to understand their effect on explosion propagation. Additionally, wet areas may be bypassed by inspectors conducting dust samples (MSHA 2013). Research has shown that wet coal dust can be entrained in air and propagate a coal dust explosion (Cybulski 1975) if the initiating explosion is strong and has had a long run-up path. Fundamentally, verification of TIC should be done by sampling the mine dust that is entrained in the air in front of an explosion. A sample

could be captured from the air by stirring up the mine dust with a puff of air that simulates the entrainment of the explosion process.

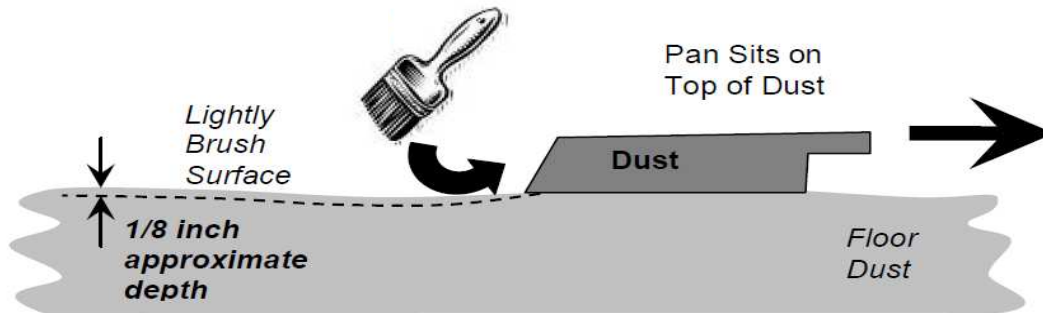


Figure 4.3 Illustration of Mine Dust Sampling Procedure (modified from MSHA, 2013¹⁵)

Sampling locations must be carefully chosen depending on coal dust source locations. Care must be taken to sample the mine dust deposited not only on the floor, but on the ribs, conveyor belt structure, pipelines, cables, roof meshing, etc. Dust released from these elevated locations and entrained by an explosion participates in the explosion more readily than floor dust, making it more hazardous, depending on the thoroughness of rock dust application, as Sapko et al. (1987) have pointed out.

4.3 Equipment to apply rock dust in underground environment

Rock dust is typically applied underground in two methods: continuous application or batch application. In continuous application, a steady stream of rock dust is supplied to the airway and settles with the coal dust, preventing separated layering. With batch applications, the rock dust is applied in intervals, and thus leads to the layering outlined in the previous section. To mitigate this, the frequency of batch applications can be increased and the quantity in each batch decreased to meet the minimum TIC and reduce the likelihood of coal dust being the top layer.

Batch applications consist of rock dust being pneumatically supplied using a compressed air system. Mobile bulk rock dusters typically feature a large bulk tank capable of holding up to 4 tons of dust. These systems usually have on-board compressors and diesel engines to allow application in any airways accessible to the unit. A screw feed system moves the dust from the tanks to a mixing chamber where it is then supplied to the operator using a series of compressed air hoses. The hoses are typically 2-3 in in diameter and have a nozzle on the end for easy control of application. Depending on the system, between 40 and 125psi pressure is needed for the compressed air system to operate. When fed with 100-250cfm (2,800-7,000 L/min) of compressed air, bulk dusters can discharge 400- 600lb/min (180-270kg/min) of dust.

The bulk rock dusters can be mounted on rubber tires or locomotive tracks, or suspended on a monorail system. The mines will usually have underground fill stations that are fed from bulk silos on the surface connected via borehole. Figure 4.4 shows a rubber tire mounted batch application bulk duster system.



Figure 4.4 Wheel mounted bulk rock duster (A.L. Lee Corp.; www.alleecorp.com).

Some manufacturers also offer fixed, permanently installed bulk dusting systems, often with multiple pressurized bulk tanks installed throughout the mine. These batch systems can be operated automatically. Figure 4.5 shows a schematic view of a mine-wide automatic rock dust system offered by A.L. Lee Corporation.

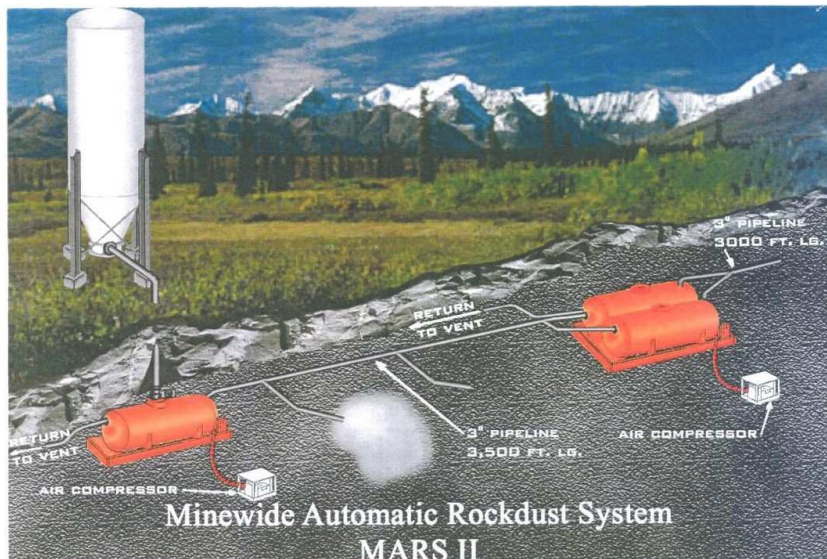


Figure 4.5 Mine-wide automatic rock dust system, (A.L. Lee corporation, www.alleecorp.com).

One issue with the bulk dusting system is the scheduling of rock dust application in intake airways. These applications are usually scheduled during an off-shift due to the visibility and respiratory

concerns for miners in downwind areas. These systems also usually require periodic vessel pressure inspections to ensure proper safety and operation standards.

Smaller batch rock dusters, often referred to as bantam or slinger dusters in the U.S., are used to spot dust in face areas. These slinger dusters are equipped with a hopper holding about 100lb of dust and are typically loaded with bagged dust from 40lb (18kg) bags. Figure 4.6 shows a small compressed air duster and large track mounted compressed air duster used commonly in European mines.



Figure 4.6 Small (left) and Large (right) Compressed Air Duster Units. Source: RAG Hauptstelle für das Grubenrettungswesen (RAG Mine Rescue Headquarters), Herne, Germany.

Continuous application systems, commonly called trickle dusters, are used to feed a steady stream of rock dust to the return air of a production section. The feed on these systems must be set so at least 4lb of rock dust is applied for each 1lb of coal dust in the exhaust air. In development areas with continuous miners, trickle dusters are usually installed in the return outby the last open crosscut, usually feeding into the exhaust of the auxiliary face fan.

In production areas with longwalls, trickle dusters are generally installed at the tailgate to add rock dust to the exhaust air. On longwall sections, it can be logistically difficult to store and transport the 40lb bags of rock dust to the trickle duster at the tailgate. Due to this, some operators have begun feeding dust from the headgate side of the longwall through a long hose that runs the length of the production face. Figure 4.7 shows a rubber tire mounted trickle duster, with standard capacity of 400lb, produced by A.L. Lee Corporation.

4.4 Binding coal dust with hygroscopic salts or pastes

Another effective way to inertize coal dust is to bind it and trap it on moist surfaces. As stated in Chapter 3, hygroscopic salts absorb moisture from the mine air and remain moist so that they can bind coal dust particles and prevent them from becoming entrained in air by a mine explosion.

The salts most frequently used are calcium chloride or magnesium chloride. Each can be applied as an approximately 30% solution or in dry powder or prill form. Surfactants can be added to improve the adsorption of the hydrophobic coal dust particles, and to increase the time between spray treatment intervals.

A major disadvantage of salts is that they are corrosive and can make mine floors slippery. Corrosion may become a problem with mining equipment and roof support, so corrosion-proof support elements (bolts, wire mesh) may be required.



Figure 4.7 Rubber-tire mounted trickle duster commonly found in US mines (A.L. Lee Corp.; www.alleecorp.com).

4.5 Passive explosion barriers

Explosion barriers provide explosion suppression in the outby areas of active mining sections. Passive barriers use a suppressant material that is dispersed by the dynamic pressure wave to extinguish the trailing flame front. The two most common types of passive explosion barriers are water barriers and stone dust barriers. These two types have been extensively researched and tested and have been successfully deployed in mines throughout South Africa, Europe, and Australia.

The two deployment methods for the extinguishing materials are concentrated barriers and dispersed barriers. An overview of passive barrier loading requirements is summarized in Table 4.2 (DuPlessis and VanNiekerk 2002). A large amount of the information in this section will be derived from the South African regulations on passive barrier systems with references to variances in differing international practices.

Table 4.2 Passive barrier loading requirements, in kg per m² of entry cross section area (after DuPlessis and VanNiekerk, 2002).

<i>Country</i>	Mass Loading			
	Stone Dust (kg/m²)		Water (l/m²)	
	Non-gassy	Gassy	Non-gassy	Gassy
<i>Australia</i>	200	200	200	200
<i>Belgium</i>	-	400	-	200
<i>Canada</i>	-	200	-	200
<i>Czech Republic</i>	200	400	-	-
<i>Germany</i>	-	400	-	200
<i>France</i>	-	400	-	200
<i>Japan:</i>				
<i>Light</i>	0.1 m ³ /m ²	-	-	100
<i>Heavy</i>	0.3 m ³ /m ²	-	-	300
<i>Extra Heavy</i>	0.4 m ³ /m ²	-	-	400
<i>South Africa</i>	-	200 light 400 heavy		200
<i>Romania</i>	-	400	-	200
<i>United Kingdom</i>		200 light 400 heavy		200 min.
<i>Soviet Union</i>	200	400		

4.5.1 Shelf type stone dust barriers

There are several different shelf stone barrier designs based on research work conducted by countries including Germany, Poland, the United Kingdom, and the United States. The most commonly used design is the Polish Stone Dust Barrier as tested by Cybulski. More than 1,700 tests were conducted and results published in 13 scientific bulletins. The dust is placed on a shelf that is suspended in a manner which allows for it to be easily knocked over by explosion forces. This creates a large cloud of rock dust that extinguishes the flame front. Variations of the Polish Stone Dust Barrier contain multiple, individual boards on the shelf that aid in the rock dust dispersion. Figure 4.8 illustrates both of these barriers.

There are three quantities used as a design criterion for shelf-type stone dust passive explosion barriers, as described by Cybulski (1975), which 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 meter of the gallery's cross-section (kg/m²). This is normally used as the regulatory requirement for the design of stone dust barriers; typically 400 kg/m² for a concentrated barrier.

- Q_1 : The quantity of stone dust on each single shelf per square meter of the gallery's cross-section (kg/m^2).
- Q_V : The concentration of stone dust in the zone in which a barrier is positioned; i.e. the quantity of stone dust on the whole barrier in relation to the volume of the working area that is occupied by the flame (kg/m^3). This last parameter is important in the design of distributed barriers.

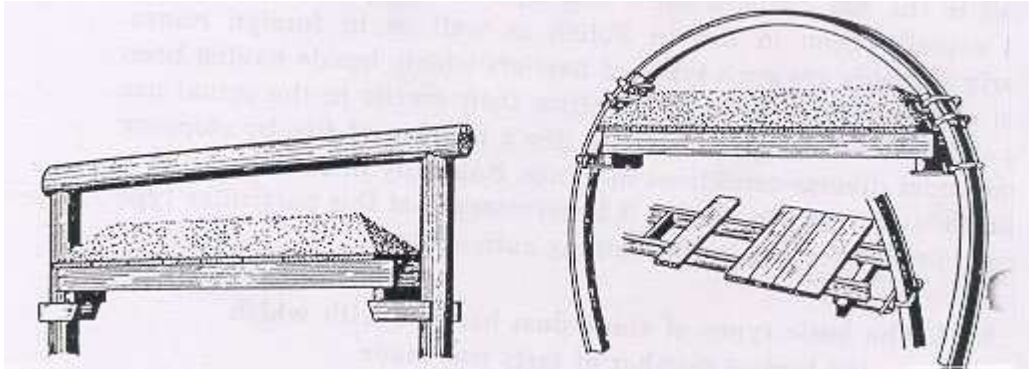


Figure 4.8 Design of the Polish Stone Dust Barrier (left) and multi-board variation (right) from DuPlessis and VanNiekerk (2002, p. 40).

When examining the designs of concentrated barrier of this type, the requirements of the stone dust quantity reference the gallery's cross-sectional area. For the concentrated barriers, rock dust may be arranged as light or heavy barriers as detailed by DuPlessis and VanNiekerk (2002, p. 43-46). Light barriers are required to be no further than 180m and no closer than 80m from the face and use light shelves measuring 350x150mm. The light barrier must have a Q_A of $100\text{kg}/\text{m}^2$. Heavy stone dust barriers are required to use larger shelves 450x150mm wide and installed at a distance between 80m and 380m from the face. The heavy stone dust barrier must have a Q_A of $400\text{ kg}/\text{m}^2$.

As previously identified, a propagating coal dust explosion gains strength with a longer run-up distance. If placed closer to the face, a lighter barrier is sufficient to suppress an explosion, while at greater distances a heavy barrier is needed. Placing either of the barriers too close to a potential explosion source is not effective since the shorter run-up will not develop sufficient pressure to trigger the barriers.

For the design of a distributed barrier system, the amount of stone dust required is based on the mass per unit volume. Cybulski (1975) states that: "Distributed barriers are barriers in which the shelves are placed at such distances as to satisfy the following basic condition:

- Q_V should not amount to less than $1\text{kg}/\text{m}^3$
- The value of Q_1 should not be lower than $0.5\text{ kg}/\text{m}^3$."

Distributed stone dust shelf barriers designed in Australia are based on a minimum loading of 200kg/m² based on the cross-section area (DuPlessis and VanNiekerk 2002).

4.5.2 Bagged stone dust barriers

Over the last 20 years, research has been conducted into the development of bagged passive stone dust barriers. This was done with the intention of updating the passive stone dust barrier to modern mining practices, and attempting to eliminate the humidity and ventilation issues associated with the shelf-type barriers. The design of the shelved stone dust barriers and water barriers have remained relatively unchanged for the past 60 years and were developed for long single-entry mining practices and are not easily adaptable for room and pillar mining layouts. In bagged dust barriers, the stone dust is contained in sealed, thin-walled plastic bags that break easily as the explosion pressure wave arrives. Figure 4.9 shows an arrangement of 35kg dust bags in a concentrated barrier configuration (Michelis 1998).

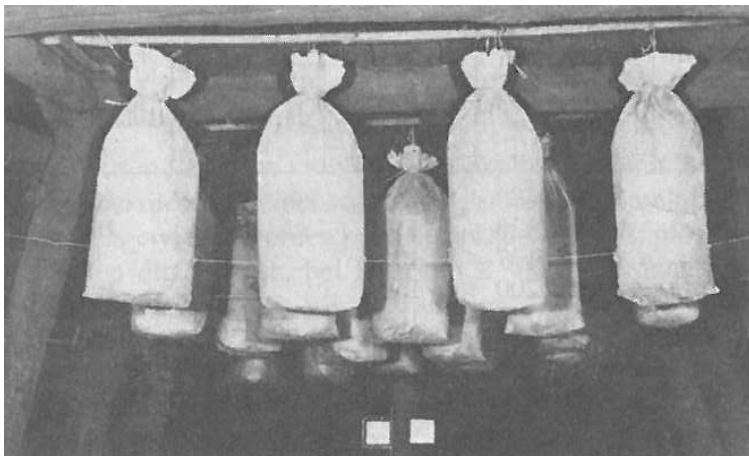


Figure 4.9 Arrangement of dust bags for an explosion barrier test at the NIOSH Lake Lynn Experimental Mine (Michelis 1998).

The bagged design was proven effective at suppressing explosions in test galleries at Kloppersbos, South Africa, the experimental mine at Tremonia in Germany, and a simulated room-and-pillar mine at the NIOSH Lake Lynn Experimental mine. From these tests, the following requirements for bagged stone dust barriers were determined (DuPlessis and VanNiekerk 2002):

Loading

The recommended quantity of stone dust, MA, is expressed as a mass (kg) loading per roadway cross-sectional area (m²).

Spacing of bags

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

Distance between bags in a row

- not closer than 0.4m
- not further than 1.0m

Distance between rows

- not closer than 1.5m
- not further than 3.0m

Distance to sidewall of outer bags

- not nearer than 0.5m
- not further than 1.0m

Distance to roof

- not nearer than 0.5m for seam heights greater than 3.5m

Height restrictions

The following are minimum requirements; 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 3.0m: a single level of bags suspended below the roof
- for roads in the height range 3.0-3.5m: a single level of bags suspended at a height of approximately 3.0m
- for roads in the height range 3.5-4.5m: a double level of bags suspended at approximately 3.0 and 4.0m above floor level
- for roads in the height range of more than 4.5m but less than 6.0m: a triple level of bags suspended at approximately 3.0, 4.0, and 5.0m.

Spacing of barriers

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

The bags are usually suspended from wire mesh or similar steel structures held in place by roof bolts. Another common design uses chains as the anchors from the steel to the roof bolts to allow for the height of the barrier to be adjusted as needed. The bagged stone dust barriers can be configured to be either concentrated or distributed in design.

For a concentrated bagged rock dust barrier, the recommended Q_A is 100kg/m^2 and the length of the barrier should be a maximum of 40m and minimum of 20m. The concentrated bagged barrier must fulfill the following design criteria (DuPlessis and VanNiekerk 2002):

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

For a distributed bagged stone dust barrier, the loading requirements for Q_A must exceed or at least equal 100kg/m^2 and the Q_V must not be less than 1kg/m^3 , where the greater of the two quantities must be used. These distributed barriers are made up of four sub-barriers (MRAC 2002) and the placement of the individual sub-barriers must conform to the following requirements:

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

A distributed bagged rock dust barrier is recommended for use with longwall mining sections, though it is suitable in most mining layouts. The minimum loading and length of the installed barrier must ensure that Q_A is greater than 60kg/m^2 and the Q_V is greater than 0.6kg/m^3 . The first sub-barrier, nearest the face, should not be closer than 60m to the last through road and not further than 120m. To ensure a margin of safety, it is recommended that Q_A be equal to or greater than 100kg/m^2 (MRAC 2002, p. 25).

Individual bags in concentrated or distributed bagged dust barriers should be arranged as follows:

- The distance between bags in each row should be between 0.1 and 0.4m.
- The distance between rows should be between 1.5 and 3m.
- The distance of the closest bags from the roof should not exceed 0.5m in entry heights over 3.5m.
- The distance from the ribs should be between 0.5 and 1m.

- In entries up to 3.5m height, a single layer of bags should be used. In heights up to 4.5m, two levels of bags should be hung, and in heights up to 6 m, three levels should be hung.

4.5.3 Water trough barriers

The use of water trough barriers is an alternative to the shelf and bagged rock dust barriers. Cybulski (1975) points out that water, released ahead of an explosion flame, will extinguish the explosion by reducing the flame temperature, due to the specific heat of water and the high heat of evaporation, and by reducing oxygen where water vapor is formed. The water trough barrier consists of individual water troughs made predominantly of polyvinyl chloride (PVC) or polystyrol (PS; Michelis 1998) with typical capacities ranging from 40 to 80 liters.

The timing of the water trough barriers is more critical than with the stone dust barriers. The stone dust will remain suspended in the cross-section longer than the water, requiring the water troughs to be released with a higher level of accuracy to be effective in quenching the explosion.

As discussed in the previous chapter, water trough barrier arrangements for European mines are prescribed by DIN EN 14591-2. Figure 4.10, Figure 4.11 and the following sets of guidelines come from MRAC (2002, p. 22) and detail the specific design criteria for single layer and multi-layer water trough barriers.

When water troughs are installed in a single layer for a barrier, the following apply (referenced from Figure 4.10):

- For roadways up to 10m², X+Y+Z must cover at least 35% of W.
- For roadways up to 15m², X+Y+Z must cover at least 50% of W.
- For roadways in excess of 15m², X+Y+Z must cover at least 65% of W.
- The distance of A or B or C or D must not exceed 1.2m.
- The total distance of A+B+C+D, etc. must not exceed 1.5m.
- The distance V1 must not be less than 0.8m and must not exceed 2.6m.
- The distance V2 should not exceed 1.2m. Whenever this distance is exceeded, additional troughs must be placed above. They may be placed 2.6m above floor level, but there should not be more than 1.2m between the base of layers of troughs.

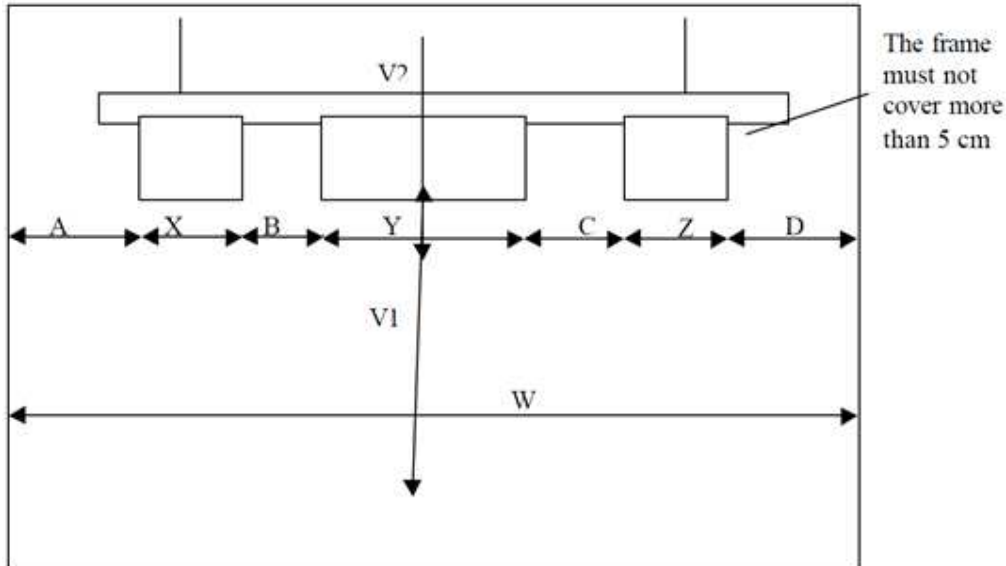


Figure 4.10 Diagram of South African Water Trough Barrier in Single Layer Configuration (MRAC 2002, p. 22).

If more than one layer of troughs is required, as illustrated in Figure 4.11, the following apply:

- When troughs are arranged in rows less than 1.2m apart, measured along the roadway, troughs in one row must not conceal troughs in the adjacent row from the blast effect.
- No trough must have any part sheltered from the effect of a blast wave by a rigid installation in the roadway.

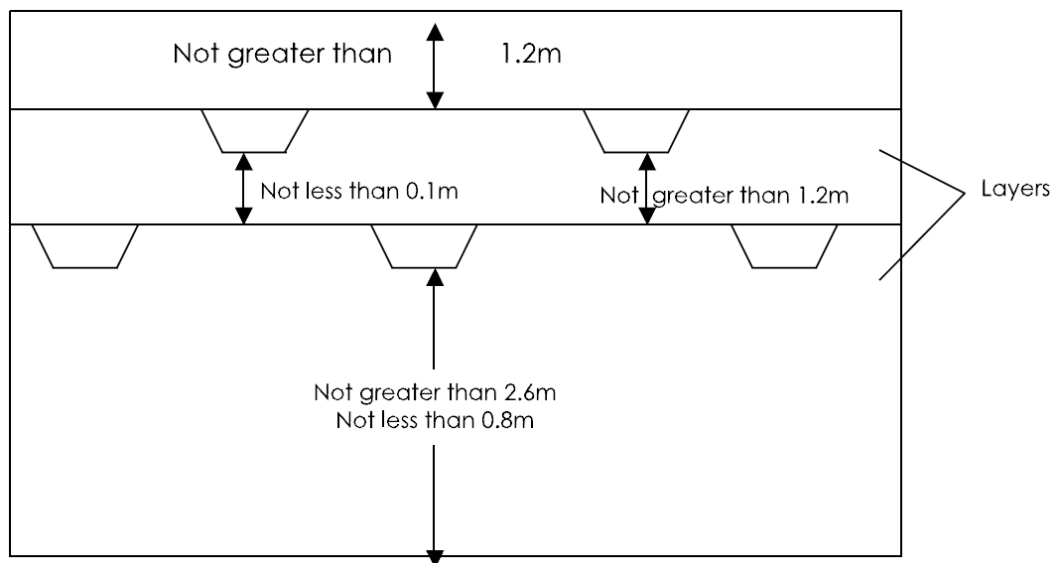


Figure 4.11 Diagram of South African Water Trough Barrier with Multiple Layer Configuration (MRAC 2002).

In circumstances where the dispersion of water over the cross sectional area of the roadway might be obstructed by equipment, additional troughs must be installed to improve distribution.

Water trough barriers can be designed as concentrated or distributed barriers, like its stone dust counterparts. For a concentrated barrier, the placement of the barrier must not be closer than 120m and no further than 360m from the last through road as recommended by RMAC (2002). The concentrated barrier design also requires either a Q_A of 200L/m² or Q_V of 5L/m³ with a barrier length of 20-40m for both conditions. For a distributed barrier, the placement of the barrier must not be closer than 120m and no further than 200m from the face. The distributed barriers have the requirement that a minimum Q_V of 1L/m³ must be maintained with a maximum distance between barriers of 30m.

4.6 Active (triggered) explosion barriers

With the advent of technology capable of sensing an explosion front, active barrier systems, interchangeably called triggered barriers, have been developed that utilize electric signals processed from flame, pressure, or other sensors to “trigger” the release of extinguishing agent to halt the propagation of a coal dust explosion. These barriers consist of a cluster of pressurized containers (usually 6-8) that are charged with nitrogen and filled with an extinguishant composed of rock dust, water or other extinguishing agent. The two forms of active barrier systems are machine mounted and fixed location. These containers are usually the size of a handheld fire extinguisher and disperse the extinguishant with a rapid discharge nozzle triggered by a small explosive charge initiated by the sensor. Lunn (1988) describes the various parts and triggering procedure of the active barrier as follows:

- a) A sensor detects the presence of an approaching explosion. Sensors fitted to triggered barriers include blast pressure sensors, thermocouples, and ultraviolet or infrared flame detectors.
- b) A disperser rapidly ejects the flame suppressant once the flame is detected. Triggered barriers may use water, stone dust or fire extinguishing agent (diammoniumphosphate or similar). Extinguishing agents are typically more effective than water or stone dust. Dispersers can be small explosive charges or compressed gas with a quick-release valve arrangement.
- c) Trigger delay timing must be carefully chosen between the detection of the flame and the release of the suppressant upon arrival of the flame at the barrier. Timing must be chosen so that the suppressant is fully ejected across the roadway to form a well-distributed cloud as the flame arrives. If the delay is too long, the flame has passed by before the suppressant is dispersed; if the delay is too short, the suppressant cloud may become diluted before the flame arrives.

Figure 4.12 diagrams the function of an active barrier in relation to an explosion front. The sensor of the system identifies the presence of the explosion and triggers the release of the extinguishing agent based on the configuration of the sensors to the flame front.

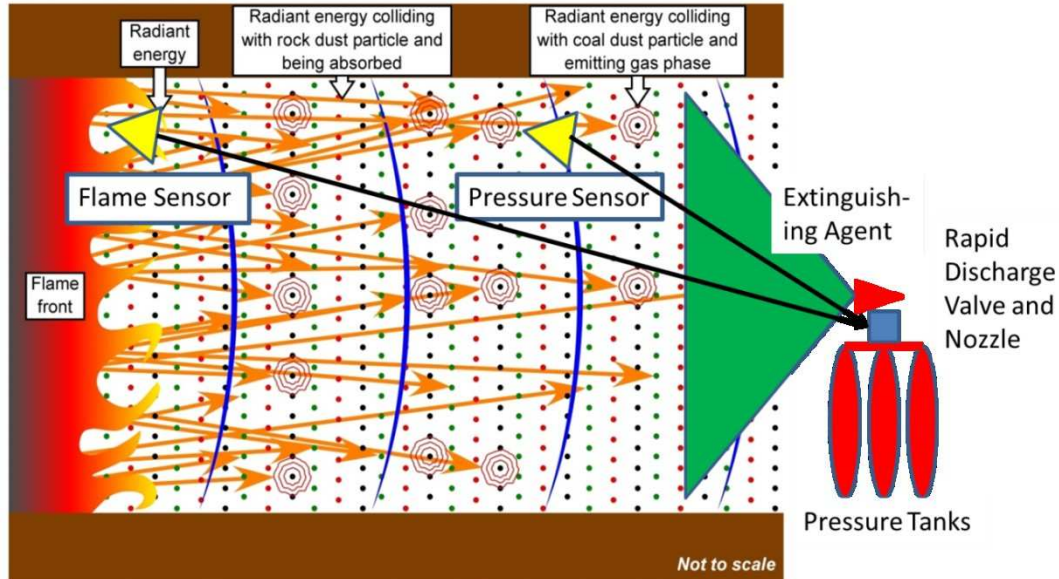


Figure 4.12 Principle of an Active Barrier.

Table 4.3 provides a short overview of the types of sensors used with active barriers and the characteristic being measured as identified by DuPlessis and VanNiekerk (2002, pg. 58).

For sensors that are reliant on radiation or light from an explosion flame, the sensing surface must be kept free of dust. If the sensor is dirty, the signal quality can be compromised and lead to the system not being triggered. To mitigate the dust issue, air or water are sprayed across or parallel to the sensing surface to keep it clean (DuPlessis and VanNiekerk 2002). The solar cell detector indicated above is of interest since it may allow a trigger design that does not require batteries or an external electric power supply.

4.6.1 Machine mounted active barrier systems

Table 4.4 (DuPlessis and VanNiekerk 2002, p. 25) summarizes the major machine mounted active barrier systems from the Federal Republic of Germany, UK, and USA. All three of these systems use ultraviolet flame detectors that are capable of distinguishing between methane and coal dust flames and are not sensitive to false triggering from artificial light sources (Furno et al., 1985). These systems have been adapted primarily for roadheaders, but some research has been done on longwall machines, continuous miners, and other mining equipment that is in proximity to the mining face.

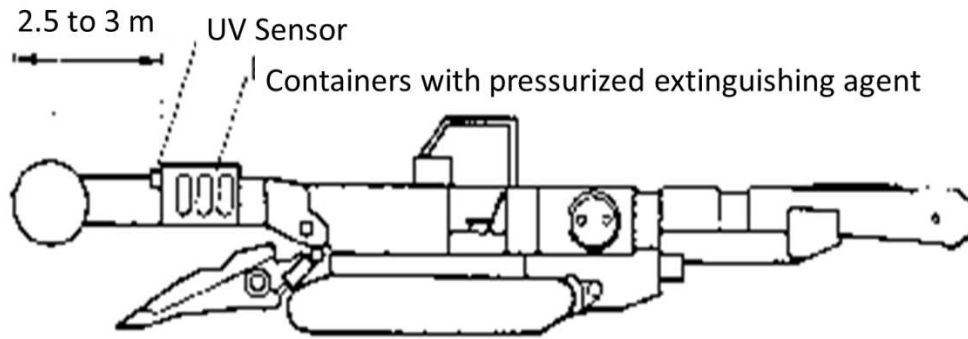
Table 4.3 Sensors Used in Active Explosion Barriers (pg.58, DuPlessis and VanNiekerk 2002).

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

Table 4.4 Summary of Machine Mounted Ignition-Suppression Systems (DuPlessis and VanNiekerk 2002, p. 25).

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 liter cylinder	48
UK	Graviner system	Furex 770	N ₂ or halon 60 bar	4-6	7 liter (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

Figure 4.13 shows the arrangement of a machine mounted active barrier on a roadheader. It should be noted here that these active barriers have been used on European roadheaders for the past 20 or more years. The technology is proven and well established in the industry. This system, though, cannot be directly installed to continuous miners due to the larger cutting boom and drum. These would require a more elaborate arrangement of flame sensors and release nozzles to provide sufficient coverage of the continuous miner face. Likewise, adaptation to a longwall shearer has been experimentally tested in the U.S. and Europe and is viewed as too complex for this arrangement, since there are too many possible directions of flame arrival that complicate sensor arrangement.



Adapted from DIN EN 14591-4

Figure 4.13 Machine mounted active barrier system on a roadheader, based on DIN EN 14591-4.

4.6.2 Fixed location active suppression systems

Table 4.5 (DuPlessis and VanNiekerk 2002) provides a summary of the fixed active barrier systems that have been developed or deployed throughout the world. Unlike the machine mounted active barriers, whose purpose is to isolate the flame at the source, the fixed mounted systems are designed to stop a fully developed methane or coal dust explosion. The development of these systems was stipulated by the need for systems that were triggered independent from the pressure build-up required to initiate the passive barrier systems (DuPlessis and VanNiekerk 2002).

The Belgian system, which is also used in France, is notable as it utilizes 2m long by 0.25m diameter polyethylene sleeves and flame-resistant polyurethane foam for rigidity. Each of the sleeves holds 90-100L of water and embedded in the foam is a waterproof channel that contains a detonating cord used to disperse the water during activation. The barrier is triggered by a thermo-mechanical device that is sensitive to both pressure and flame.

A similar system developed in Germany (Michelis et al., 1987) also utilizes a detonating cord to disperse the water from a PVC trough. A sensitive thermo-electrical sensor, based on the SMRE thermocouple sensor, is used as a triggering device in the German system. Figure 4.14 shows the water trough and ignition system used on this type of fixed barrier (DuPlessis and VanNiekerk 2002). This version of the barrier found application in:

- Conventional roadway developments where high methane emissions occurred
- Development entries mined with tunneling machines or continuous miners
- Change-overs of longwall faces/roadways

- Deadheaded entries ventilated with auxiliary ventilation.

Table 4.5 Summary of characteristics of fixed active barriers Systems (DuPlessis and VanNiekerk 2002, p. 59).

Country	Detector Type	Extinguishing 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., open-pore polyurethane foam	10
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: 40l/unit	Sheet explosive	Ridged polystyrene container	80

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

- They extinguish propagating low-pressure ignitions that might be too weak to trigger passive barriers.

- Their water-distributing ability is twice as high as that of passive water trough barriers and they are therefore more flexible.
- They are more compact, requiring less space than passive troughs.
- They have a reduced water quantity requirement of 80 L/m² instead of 200 L/m² of cross section because the water release is timed more precisely by the trigger mechanism.
- Even if the electrical triggering fails, they still operate as passive water trough barriers.

However, the active water trough barriers do have disadvantages, as Michelis (1998) noted:

- The initial installation of the triggered barrier is labor-intensive, though not significantly more so than 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).

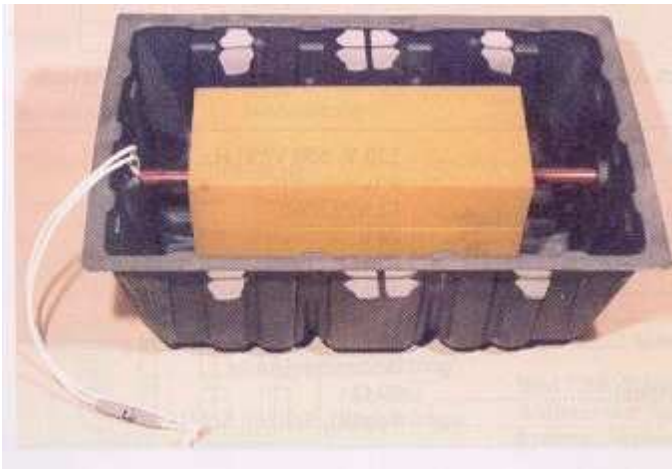


Figure 4.14 Water Trough with Built-in Ignition System (DuPlessis and VanNiekerk 2002).

Because of the pressure on German coal mines to control operating costs, the barrier did not find considerable application in the nation (DuPlessis and VanNiekerk, 2002). 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 High-pressure, Rapid Discharge (HRD) extinguishant containers. From this research, two systems were developed:

- A mobile BVS active barrier for the protection of mine workers constructing seals

- An automatic explosion-extinguishing installation, type TSM, for roadheaders, as discussed in the previous section.

The main purpose of the system is to detect an explosion by means of ultraviolet flame sensors and to activate the extinguishing installation by means of an electronic control system. The mobile BVS active barrier was developed as a multiple extinguisher system to protect mine rescue teams constructing mine seals to close off a section of the mine following a fire or explosion (Faber, 1984; 1990a and 1990b).

There are 32 HRD extinguishant containers, each with a volume of 12.3L and the capacity to hold 8kg of ammonium phosphate extinguishant powder. Nitrogen, pressurized to an overpressure of 12MPa, is used as the driving agent. Tests showed that the systems are effective against explosions reaching 500m/s when ammonium phosphate was used (Scholl, 1967). Release of the ammonium phosphate from the cylinders starts 5-10ms after the sensor has been triggered and lasts between 600 and 900ms. Figure 4.15 shows the components of the BVS system and Figure 4.16 depicts a diagram of the mobile automatic multiple extinguisher system as taken from DuPlessis and VanNiekerk (2002).

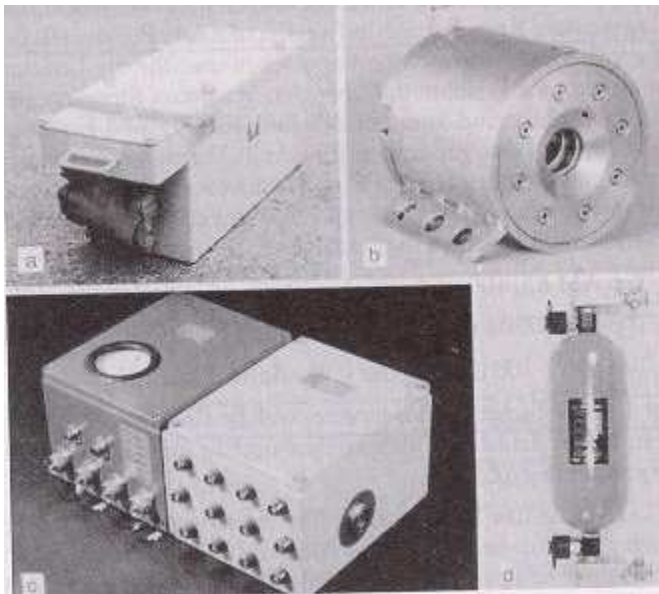


Figure 4.15 Components of the BVS Triggered Barrier System (DuPlessis and VanNiekerk 2002). a = complete unit, b = UV flame sensor, c = triggered electronics and d = HRD suppressant container.

Until 1995 there was an effort to combine the most suitable components of the active barrier systems 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 the Tremonia Experimental Mine to compare all the detectors (Michelis and Margenburg, 1995). Although these

systems have been under development for more than 40 years, they have found limited application as they are perceived as costly and unproven.

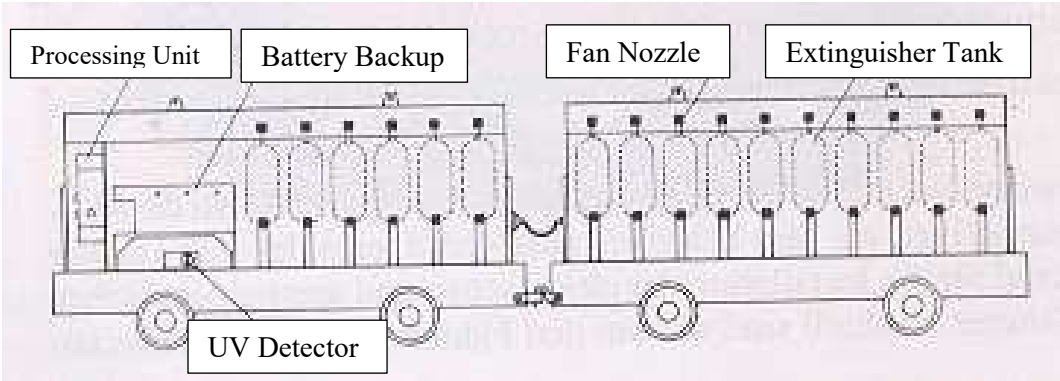


Figure 4.16 Mobile Automatic Multiple-Extinguisher System (BVS) (DuPlessis and VanNiekerk 2002).

CHAPTER 5
RECOMMENDATIONS FOR REGULATORY IMPROVEMENTS
AND INDUSTRY RESEARCH FOR U.S. COAL MINING

Below is a summary of recommendations for regulatory improvements and further industry research into key coal dust explosion prevention techniques as is applicable to the current state of U.S. coal mining. These recommendations are based off the best practices and regulations as highlighted in Chapter 3 and Chapter 4.

5.1 Recommendation for the use of hygroscopic salts

Researchers believe that it is worthwhile to examine alternatives to rock dust inertization, specifically, the use of hygroscopic salts that bind and immobilize the coal dust. The German mining industry has been using this method successfully for many years. It should be noted that there are several distinct advantages of using salts over rock dust:

- Salts can be applied in batches every few days. They retain their ability to bind coal dust and there is no layering problem as there is with rock dust.
- Salts can be applied effectively to vertical and inverted surfaces and structures such as wire mesh roof support and cables.
- Salts can be applied on-shift without affecting workers downwind.
- Salts are more efficient than rock dust, with smaller quantities needed.
- In belt conveyors, transfer areas etc., salt application can be automated with an installation of spray nozzles.

A major disadvantage is that salts are corrosive and application requires personal protective equipment to be worn. However, the potential health hazards are manageable.

The U.S. coal industry should take into the consideration the wider use of hygroscopic salts as a substitution for rock dusting. Some U.S. mines have already adapted the salts using sprays, powders, and prills to be dispersed through mine entries with effective results. It is recommended that a cost and risk analysis comparing rock dust and hygroscopic salts be conducted to identify the financial impacts of the corrosive properties of the salt versus the decreased material costs and improved coal dust binding.

5.2 Recommendation for further development of active explosion barriers for use on continuous miners, longwalls and as mobile barriers outby face areas

Passive or active explosion barriers are being used in many countries except in the U.S. They are most widely used in Europe (Germany, Poland), as the single-entry ventilation systems with large cross sections used in these countries lend themselves to easy installation. Cybulski (1975) makes clear that explosion protection with rock dust alone may not be sufficient and that barriers are needed in addition to rock dust or salts.

The typical, multiple-entry, room-and-pillar, in-seam layout used in U.S. coal mine development does not lend itself to installation of passive explosion barriers for the two reasons: The entry height is usually the same as the thickness of the coal bed and does not provide sufficient headroom for barriers, and the complex room-and pillar pattern would require multiple barriers because of the possible explosion paths.

Since the 1970's, the technology for active explosion barriers has existed for mounting on road headers. It is possible that similar barriers could be implemented and designed for longwalls, continuous miners or as a portable, installation-free mobile barrier to be used in crosscuts and entries outby the production faces.

As has been discussed in the previous chapter, the technology of active barriers is straightforward. These barriers should be easy to adapt to various types of equipment due to their transposable design. The installation requirements should be similar between a road header and a continuous miner. However, this adaptation will require additional research to guarantee that ignition flames can be detected reliably despite the larger boom of the continuous miner. This adaptation will most likely require the addition of multiple flame sensors to ensure a full range of detection around the equipment. The barrier system will most likely also require the addition of a wider distribution nozzle system for the extinguishant and/or the inclusion of larger tanks. Computer modeling of the extinguishant distribution and sensor system against a variety of ignition points would allow for pre-verification of a system before final certification with a full-scale ignition event.

The adaption of active barrier technology for longwall systems could be achieved by mounting the system under the canopy of the support shields or directly on the shearer. DMT in Germany has successfully tested shearer mounted systems against full scale explosions with success. The downside of a shearer mounted system is that the source of ignition cannot accurately be predicted. A more pro-active option would be to mount a flame sensor and active barrier system, tied into a fire control computer, on the underside of each shield. The fire control computer could then activate the shield mounted systems

directly adjacent on both sides of the ignition source to improve the efficiency of the system. Computer modeling would help with this design process, similar to the continuous miner design to assist in bringing the system to fruition in a cost-effective manner.

It is also believed that a portable, installation-free mobile barrier unit can be designed for use in mine entries outby the production faces, as indicated by the work conducted by Humphreys (2003). This kind of barrier should be capable of extinguishing both methane and coal dust explosions with the use of diammoniumphosphate or similar agents. Computer modeling combined with limited full scale explosion testing would provide the framework to bring this technology and relevant regulations to the industry.

5.3 Recommendation of comprehensive rock dust testing and sample management program

Inertization of coal dust with rock dust is common in the coal industry worldwide. As discussed throughout this report, rock dust inertization is a simple yet effective way to prevent coal dust explosion. Most regulations, including those in the U.S., agree that a minimum of 80% inert dust is required to reliably prevent a coal dust explosion. Some countries permit lower inert content in areas where the explosion risk is lower. It should be noted that Cybulski (1975) reported that more than 80% inert content would be required in cases where the initiating explosion was strong.

Researchers recommend analyzing the rock dust for its caking potential following the German standards discussed in Chapter 3. This is a crucial point of information since rock dust is the principal defense used against coal dust explosions in U.S. mines.

It is also important to establish a dust sample management plan for each mine which contains a thorough sampling strategy and tracks all applications of rock dust. Lack of such a management plan at UBB may have contributed to the disaster. Sampling strategies should focus on the dust source locations to ensure that all coal dust produced is immediately inertized. Measurements of actual coal dust production can be used to determine how much rock dust is required. Each mine should have its own sampling program, in addition to that carried out by MSHA, which should be managed by the Ventilation Officer.

5.4 Recommendation into additional research addressing the entrainment of dust from non-traditional surfaces and compactions

USBM and NIOSH research of dust entrainment during coal dust explosions has focused on flat, horizontal, non-compacted dust surfaces. It is important to note that these testing scenarios do not represent the conditions in actual underground coal mines, where the dust surface is undulating, similar to sand on a beach. The MSHA (2013) Coal Mine Safety and Health General Inspection Procedures

Handbook requirement for dust sample collection to a depth of 1/8th inch was established based on USBM and NIOSH research. The actual depth of dust entrained by an explosion from an undulating dust surface covering the mine floor may actually be deeper along the peaks and shallower in the valleys. It is proposed that computational fluid dynamic modeling be conducted to examine a dust surface with an undulating profile paired with laboratory and scaled explosion testing.

Dust compaction and density are also not considered in the MSHA (2013) Inspection Procedures Handbook. It was found that compaction of the dust surface may likely affect dust entrainment in an explosion. It is recommended that further investigations to improve the scientific understanding of the mine dust entrainment process on various types of surfaces and dusts during coal dust explosions be examined. This would lead to a greater understanding of the interaction between the dust surface and explosion pressure wave and produce recommendations for more representative mine dust sampling for the industry.

5.5 Additional recommendations for the reduction of methane ignitions and explosions

In addition to the recommendations listed above, it is critical to recognize the significant impact methane explosion prevention practices and regulations have on preventing the initiation and propagation of coal dust explosions. Research to reduce methane ignitions at the production face in U.S. mines can lead directly to decreases in coal dust explosions. Previously recommended changes, such as explosion barriers, provide coverage of both methane and coal dust explosion. Based on outside research, the following recommendations have been included to provide a comprehensive outlook towards explosion prevention in U.S. coal mines.

5.5.1 Prevention of methane face ignitions

Methane face ignitions are still common in U.S. coal mines because explosive concentrations near exposed methane feeders can be ignited before the on-board methane sensor responds and shuts down the cutter. These face ignitions remain an unsolved problem in the U.S. mining industry. The 2010 UBB explosion originated from such a face ignition.

Good ventilation around the cutter head, a system of water sprays, and proper maintenance of the cutter bits are effective in preventing face ignitions. Ventilation helps dilute methane feeders quickly. Water sprays keep cutter bits cool and assist in diluting methane. Finally, dull or broken bits must be replaced during regular maintenance breaks, especially if the machine must cut sandstone or other abrasive rocks that occur in the roof, floor, or partings.

5.5.2 Comprehensive mine atmospheric monitoring

Researchers recommend that all underground coal mines be equipped with atmospheric monitoring systems (AMS) to monitor, at minimum, CH₄, CO, and O₂. Other gases, such as CO₂ and H₂S, should be monitored where needed. AMS sensors must also be installed to monitor the ventilation airflow velocity.

AMS sensors should be located in all areas and evaluation points that currently require periodic air quality and quantity readings by certified mine examiners, including, but not limited to: all return splits, fans, regulators, belt entries, production faces, bleeder entries, gob ventilation boreholes, seals and seal ventilation controls, and shops.

The technology for these AMS is well proven, and there are numerous vendors providing suitable products. In return and bleeder locations where electrical installations may not be desirable, the use of tube bundle systems may be a suitable alternative. It is important that the AMS data is tracked and that appropriate alarm levels are set to provide early warning of harmful gas accumulations or ventilation system malfunctions.

5.5.3 Comprehensive computational fluid dynamic modeling of U.S. bleeder systems

Bleeder systems are unique to U.S. longwall mining. European and Australian mines exclusively operate with progressively sealed longwall gobs. Sealing the gobs is necessary, especially if the coal tends to spontaneously combust, which is often the case in Europe and Australia. Sealing the gob keeps out oxygen and allows mine operators to inject nitrogen or Tomlinson boiler gas into the gob to completely inertize the gob atmosphere.

As Brune (2013) points out, evidence from many mine explosion investigations, including that of the UBB explosion, suggests that explosive methane air mixtures had accumulated in the bleeder ventilated longwall gob. In the cases studied, the methane either exploded within the gob or in the active longwall face area, casting doubt on the proper function of the bleeder systems. Due to the lack of physical access to a mine gob, it is difficult to assess whether a large bleeder system ventilating a longwall gob fulfills the requirements of 30 CFR §75.334. A gob can only be monitored in certain, accessible locations along its outer fringes, so it is impossible to track methane concentrations deep inside the gob unless boreholes are drilled for this purpose.

Further research is recommended to provide a thorough understanding of the function of bleeder systems around longwall gobs. Mine operators and regulators must be fully aware of the function of bleeder systems and recognize any explosion hazards relating to bleeders.

5.6 Recommendation for major hazard risk analysis and management throughout mine

To prevent not only mine explosions but all major operational hazards, a mine operator should employ major hazard risk analysis (MHRA) and management practices for all mines. MHRA is also useful to address exposures to operational, market and financial risk.

To put the term “major risk” into perspective, the UBB mine explosion killed 29 miners and had an immeasurable impact on their families. In addition, the explosion resulted in the permanent closure of the UBB mine and in the sale of the parent company, Massey Energy, for a reported \$7.1 billion (Erman and Saphir, 2011). Massey was the sixth largest U.S. coal producer with an annual production of about 40 million tons (2009: 37.1 million; DOE-EIA 2009) and almost 6,000 employees (Crocodyl 2013). The buyer eventually settled criminal liabilities for \$209 million (Tavernise and Krauss, 2011) but settlement of civil liabilities is still continuing at the time of this writing.

MHRA is widely used in Australia and incorporates a broad palette of analytical tools and quantitative methods to assess the magnitude and likelihood of occurrence for major hazards. The techniques are also well established in other industries, including nuclear power generation, aviation and automobile manufacturing.

Risk analysis and management techniques start with the identification of major hazards and potential consequences of failures. Risk managers then assess the likelihood that an event will happen and the probabilities for each of the consequences. Often MHRA is done with involvement from all levels of personnel in an operation. Following identification and assessment of risks, management must determine how each risk can be avoided, eliminated or mitigated to a level “as low as reasonably possible” (ALARP).

CHAPTER 6

CONCLUSIONS

Researchers have analyzed current mandatory safety standards and practices in leading mining countries worldwide, including Australia, South Africa, Germany and the United States. In comparing these standards, researchers observed that regulations for the protection against mine explosions are more rigorous in other countries compared to the U.S. The following safety measures were recommended in this report:

- Utilization of Hygroscopic Salts in place of Rock Dust as Coal Dust Inerting Agent
- Development of Active Explosion Barriers for Use on Continuous Miners, Longwalls and as Mobile Barriers Outby Face Areas
- Implementation of Comprehensive Rock Dust Testing and Sample Management Program
- Additional Research Addressing the Entrainment of Dust from Non-traditional Surfaces and Compactions
- Additional Recommendations for the Reduction of Methane Ignitions and Explosions
- Major Hazard Risk Analysis and Management throughout Mine

Researchers believe that significant improvements can be made to explosion safety in U.S. underground coal mines. Many useful technologies are available on the market while others require additional research before they can be adapted for use in U.S. mines. Research in the field of explosion barriers is crucial step in reducing and working to eliminate explosion fatalities and disasters in the future.

REFERENCES

30 CFR Part 75: Title 30 Code of Federal Regulations, Part 75

Abdämmungs-Richtlinien [2013]: Richtlinien der Bezirksregierung Arnsberg über das explosionsfeste Abdämmen von aufgegebenen Grubenbauen (Abdämmungs-Richtlinien; Guidelines of the Arnsberg District Government for the Construction of Mine Seals), www.esb.bezreg-arnsberg.nrw.de, last accessed July 31, 2013

Allgemeine Bundesbergverordnung (ABBergV), October 23, 1995 (German Federal Register BGBl. I p. 1466)

Bartknecht W and Scholl E W [1969]: Automatische Löschung von Grubenexplosionen in Rohren mit grossen Querschnitten. Proceedings of the International Conference of Safety in Mines Research Institutes, Tokyo, Paper No. 38.

Bergverordnung für die Steinkohlenbergwerke (BVOST), version May 1, 2001

Brune JF [2013]: The Methane-Air Explosion Hazard Within Coal Mine Gobs, SME Transactions 2013, accepted for publication, October 2013.

Cashdollar et al [2010]: Recommendations for a New Rock Dusting Standard to Prevent Coal Dust Explosions in Intake Airways, CDC NIOSH RI no. 9679, Pittsburgh 2010, 12 p.

Cashdollar KL, Zlochower IA, Green GM, Thomas RA, Hertzberg M [2000]: Flammability of methane, propane, and hydrogen gases. J Loss Prev Process Ind 13:327–340.

Cybulski et al. [1967]: Research on firedamp explosions in sealed-off roadways (abstract in English and German; complete paper in German only). In: Proceedings of the 12th International Conference of Mine-Safety Research Establishments (Dortmund, Germany, September 11–15, 1967). Vol. I, paper No. 22.

Cybulski, W [1975]: Coal Explosions and their Suppression, Report No. TT 7354001+, translated from Polish, US Bureau of Mines, Washington, DC 1975, 586 p.

Department of Natural Resources and Mines [2013]: Coal Mining Safety and Health Regulation 2001, The State of Queensland, Australia, current as of 1 July 2013.

DIN EN 14591-1:2004-12; Explosion prevention and protection in underground mines - Protective systems - Part 1: 2-bar-explosion proof ventilation structure; German version EN 14591-1:2004;

DIN EN 14591-2; Explosion prevention and protection in underground mines - Protective systems - Part 2: Passive water trough barriers; German version EN 14591-2:2007, and

DIN EN 14591-4; Explosion prevention and protection in underground mines - Protective systems - Part 4: Automatic extinguishing systems for road headers; German version EN 14591-4:2007

Du Plessis JJJ, Van Niekerk DJ [2002]: Inertisation Strategies and Practices in Underground Coal Mines, CSIR Miningtek, Project No. COL 701 (EC 01-0157), 2002.

- Edwards JC and Ford KM [1988]: Model of Coal Dust Explosion Suppression by Rock Dust Entrainment, Report of Investigations no. 9206, U.S. Bureau of Mines, Pittsburgh PA, 22 p.
- Erman M and Saphir A, [2011]: Alpha agrees to buy Massey Energy for about \$7.1 billion, Reuters Jan. 30, 2011, <http://www.reuters.com/article/2011/01/30/us-alpha-massey-idUSTRE70S0PC20110130>, last accessed 12-08-16
- Faber M [1984]: Mobile triggered barrier BVS for the protection against mine explosions. Glückauf Research Journal 45, No. 4, pp 177-180.
- Faber M [1990a]: Automatic multiple extinguishing system for the suppression of mine explosions. Glückauf Research Journal 57, No. 1, pp 26-29.
- Faber M [1990b]: Development of automatic extinguishing systems for road tunnelling using continuous miners. Bochum: DMT Publication, Journal 5.
- Furno A L et al. [1985]: An Ignition Suppression Device for coal cutting Equipment. Paper presented at the 21st International Conference of Safety in Mines Research Institutes, Australia.
- Hermülheim W [2011], Deutsche Steinkohle AG, personal communication, 2011
- Hopkins A [1999]: Managing Major Hazards: The Lessons of the Moura Mine Disaster, Allen and Unwin, St. Leonards, NSW, Australia, 1999, 160 p.
- Humphreys D. [2003]: Demonstration of Active Explosion Barrier Technology, Final Report, ACARP Project no. C9008, April 2003, 23 p.
- International Electrotechnical Commission – European Norm IEC/EN 60079 Parts 1 through 34: Explosive atmospheres
- Lunn G A [1988]: The Suppression of Dust Explosions in Coal Mines. Mining Technology, 1988, pp 35-43.
- McMahon G W, Britt J R, O’Daniel J L, Davis L K and Walker R E [2007]: CFD Study and Structural Analysis of the Sago Mine Accident, U.S. Army Corps of Engineers contract report ERDC/GSL TR-06-X, Vicksburg MS, 150 p.
- Michelis et al. [1987]: Large Scale Tests with Coal Explosions in a 700m Long Underground Gallery, Archivum Combustionis, Vol. 7.
- Michelis J [1998]: Explosionschute im Bergbau untertage. Glückauf-Betriebsbücher, Volume 38, DME, Essen, Germany.
- Michelis J and Margenburg B [1995]: Development of an operational-ready European trigger barrier from available testing building elements. Final report of DMT organization for research and testing mbH, Institute for Fire and Explosion Protection – Experimental Mine Tremonia for EGKS – Research – Agreement No. 7262-03-312-01.
- Mining Regulation Advisory Committee (MRAC) [2002]: Guideline for the Compilation of a Mandatory Code of Practice for the Prevention of Flammable Gas and Coal Dust Explosions in Collieries, Mine Health and Safety Inspectorate, Arcadia, Pretoria, South Africa, 34p.

- MSHA [2013]: Coal Mine Safety and Health General Inspection Procedures Handbook, Mine Safety and Health Administration, Handbook Number: PH13-V-1, February 2013, 276 p.
- “MSHA Accident and Illness Statistics”, www.msha.gov, last accessed December 10, 2017.
- Nagy et al. [1965]: Float Coal Hazard in Mines: A Progress Report, U.S. Bureau of Mines RI No. 6581, Pittsburgh, 1965, 2 p.
- Nagy J, Kawenski EM [1960]: Frictional Ignition of Gas During a Roof Fall, U.S. Bureau of Mines RI No. 5548, Pittsburgh, 1960, 15 p.
- Page NG et al. [2011]: Report of Investigation, Fatal Underground Mine Explosion, April 5, 2010, Upper Big Branch Mine-South, Performance Coal Company, Montcoal, Raleigh County, West Virginia, ID No. 46-08436, Mine Safety and Health Administration, Arlington, Virginia, 2011, 965 p.
- Regulations of the Mining Authority for the German States of Saarland and Rhineland-Palatinate on Quality of Rock Dust and on Laboratory Testing of Rock Dust, 12-30-1976. Note that this regulation is no longer relevant since German mines do no longer use rock dust.
- "Respirable Dust Control", www.mirmgate.com, last accessed April 10, 2017.
- Richtlinien des Oberbergamts für das Saarland und das Land Rheinland-Pfalz über die Anforderungen an Gesteinstaub sowie für die Durchführung der Untersuchung von Stäuben, Dec. 30, 1976, and Prüfbestimmungen des Landesoberbergamts Nordrhein-Westfalen für Gesteinstaub gem. § 224 BVOSt February 28, 1970
- Sapko, M J, Weiss E and Watson R W [1987]: Explosibility of float coal dust distributed over a coal-rock dust substratum. In Proc. 22nd International Conference of Safety in Mines Research Institutes 1987, pp. 459-468 (Beijing, China: China Coal Industry Publishing House)
- Sawyer S G [1992]: An elementary structural failure analysis of the reinforced concrete shaft at the Blacksville No. 1 mine, Appendix M in: Rutherford JW et al. [1992]: Report of investigation, underground coal mine explosion, Blacksville No. 1 mine – I.D. No. 46-01867, Consolidation Coal Company, Blacksville West Virginia, March 19, 1992; Mine safety and Health Administration, Arlington VA 1992
- Scholl E W [1967]: Extinguisher explosion barrier for the prevention of the propagation of mine gas (methane) explosions and coal dust explosions. Dissertation, Technische Hochschule Clausthal, Germany.
- South African Mining Regulation Advisory Committee [2002]: Guideline for the Compilation of a Mandatory Code of Practice for the Prevention of Flammable Gas and Coal Dust Explosions in Collieries, Mine Health and Safety Inspectorate, Arcadia, Pretoria, South Africa.
- Tavernise S and Krauss C [2011]: Mine Owner Will Pay \$209 Million in Blast That Killed 29 Workers, The New York Times Dec. 6, 2011, http://www.nytimes.com/2011/12/07/us/mine-owner-to-pay-200-million-in-west-virginia-explosion.html?pagewanted=all&_r=0 last accessed 08-05-13
- Technische Richtlinien Staubprobenahme [1980]: Grundsätze für die Entnahme und Untersuchung von Staubproben unter Tage 18.42.1-1-22, October 13, 1980

U.S. Dept of Energy, Energy Information Administration, 2009 Annual Coal Report, DOE/EIA-0584 (2009), 79 p.

U.S. National Electrical Manufacturers Association (NEMA), Ingress Protection (IP) standards, 55 means dust and water jet protected