Identifying Improved Control Practices and Regulations to Prevent Methane and Coal Dust Explosions in the United States

By Benjamin Goertz and Jürgen F. Brune

A Research Report

Submitted to:

Wheeling Jesuit University

Charles A Wood, Principal Investigator

Wheeling Jesuit University, Inc.

316 Washington Avenue

Wheeling, WV 26003

Department of Health and Human Services, Centers for Disease Control and Prevention
Grant No. 1H750H009822-01

Subaward No. 0000007708

Submitted by:

Colorado School of Mines, Mining Engineering Department

Dr. Jürgen F. Brune, Principal Investigator

Golden, Colorado, August 15, 2013

Editorial Notes:

This report was prepared for Wheeling Jesuit University, Center for Educational Technologies under Department of Health and Human Services, Centers for Disease Control and Prevention Grant No. 1H750H009822-01; Subaward No. 0000007708.

A Companion Report,

> Lessons Learned from Mine Disasters: New Technologies and Guidelines to Prevent Mine Disasters and Improve Safety

by Jürgen F. Brune and Benjamin Goertz

was prepared under the same Grant.

The authors wish to thank Wheeling Jesuit University, Center for Educational Technologies, for the financial support that made this research possible.

Golden, Colorado, August 2013

Executive Summary

This research study investigates and analyzes methods for the prevention of coal mine explosions in the United States and compares them to those used in other leading coal mining countries. Primary purpose of this research is to identify the best practices for the prevention of methane and coal dust explosions in underground coal mines.

The report is focused on rock dusting, mine dust sampling and analysis, methane and mine ventilation monitoring, rock dust inspection procedures and various types of explosion barriers. It will compare the regulatory standards and industry practices in the United States with those in other leading countries, including Australia, Germany, Great Britain and South Africa.

The report examines the following:

a. Key technical and engineering factors for methane and coal dust explosion prevention

   Researchers have investigated and analyzed which explosion prevention strategies are being employed by mine operators in the U.S. and other leading mining countries. Prevention of methane explosions relies fundamentally on eliminating ignition sources and diluting accumulations of explosive methane with adequate ventilation. Proper ventilation, ventilation engineering and ventilation system monitoring are key components for the prevention of methane accumulations. Prevention of coal dust explosions is done by using sprays to reduce the formation of coal dust, rock dust inertization, trapping of coal dust with hygroscopic salts and explosion barriers.

b. Mine safety regulations pertinent to methane and coal dust explosion prevention

   Researchers have examined the regulatory standards for preventing mine explosions, including equipment standards and general ventilation principles, in the United States and compared them to standards in other countries. In particular, researchers have investigated

   i. Inspection and monitoring procedures with regard to ventilation systems, the presence of gases and the application of rock dust.

   ii. Regulatory structures and requirements pertaining to ventilation procedures for the prevention of methane and coal dust explosions.

c. Methane and coal dust explosion prevention practices deployed around the world.

   Researchers have investigated rock dusting and mine dust sampling procedures, analysis protocols for atmospheric systems and methane controls. Researchers have characterized the current state of the art internationally and to compared it to practices in the USA.

   In U.S. mines, methane is primarily controlled through dilution and methane drainage, while coal dust explosions are controlled by inertizing coal dust with (limestone) rock dust. In addition to these methods, other countries use both passive and active methane and coal dust explosion barriers, hygroscopic pastes to bind coal dust, and mine-wide atmospheric monitoring to control both face ignitions, explosions and fires in sealed areas. European technology on active, triggered explosion barriers is mature and may be applicable, either directly or with adaptations, to US mines.

Researchers also found that, compared to the U.S., the ventilation and atmospheric monitoring practices are more elaborate and monitor ventilation air quantities as well as critical gas concentrations. Also, open-flame and spark generating work such as flame cutting and welding is handled much more restrictive than in the U.S.

Key research work that has been analyzed and documented includes

i. Coal dust inertization with rock dust or hygroscopic pastes (Work by the US Bureau of Mines / NIOSH, German, Polish, British and Australian research institutes etc.);

ii. Passive explosion barriers and their application;

iii. Active explosion barriers and their application;

iv. Rock dust sampling and sample analysis procedures;

v. Methane drainage;

vi. Mine-wide atmospheric monitoring, including in gobs and sealed areas;

d. Suggestions for regulatory improvements and new research

This research study identifies suggestions for improvement of explosion control practices and new research on current rock dusting and rock dust sampling methods that would be applicable to all US coal mines and that would significantly improve coal dust explosion safety. Major improvements can be made through comprehensive air quantity and quality monitoring throughout the mines. Gases monitored should include, at minimum, methane and carbon monoxide. Along with monitoring the ventilation air quantities at all critical points in the mine, malfunctions and inadequacies of the ventilation system can be easily detected and appropriate steps taken to mitigate the explosion hazard. Likewise, rock dust inertization must be monitored more carefully to ensure that coal dust is properly mixed with adequate amounts of inert dust.

Both passive and active explosion barriers are widely used in Europe and South Africa and may also offer opportunities for substantial improvements in explosion prevention in the U.S. mining industry. Research is required to adapt these barrier technologies to U.S. mine geometries and mining equipment used in the U.S.

Table of Contents

Definitions and Acronyms

Anthracite: A hard, compact variety of mineral coal that has the highest carbon content, the fewest impurities, and the highest calorific content of all types of coals

Bituminous coal: A relatively soft coal containing tarlike substances called bitumen and is 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 the authorities overseeing the coal mining industry to perform the duties prescribed by the regulation

Cleat: Natural fracture system in bituminous coalbeds

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. The continuous miner is also equipped to load the coal into shuttle cars.

Crosscut: A passageway driven between the entry and its parallel air course for ventilation purposes

Development or 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 of coal 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) is slicing 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 leave 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, partings are mined along with the coal. Partings of hard, abrasive sandstone and similar rocks can create sparks and incendive smears when they are 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 the mine that is no longer being ventilated and 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. The samples are analyzed online at a central location

Volatile matter: Liquid or gaseous substances that evaporate from the coal as it is heated

1. Introduction

The following report aims to summarize and evaluate coal mine explosion control regulations and practices in the U.S., compare them to those in other leading coal mining nations and develop best practices for mine explosion prevention.

The disaster at the Upper Big Branch (UBB) mine 2010 has demonstrated the destructive violence of a coal dust explosion by killing 29 miners in the worst mining accident the United States had experienced in almost 40 years. According to the investigation report by the U.S. Mine Safety and Health Administration (MSHA; Page, 2011), the UBB explosion started out as a methane gas explosion in the tailgate area of the mine's longwall face, where a cloud of an explosive methane-air mixture was most likely ignited by the cutting action of the shearer that cut into the sandstone roof and created sparks or hot incendive smears through which the methane was ignited. MSHA (Page, 2011) investigators estimated the initial quantity of methane to about 300 ft^3 (8.5 m^3).

Since the size of the initial methane cloud was limited, the methane explosion would have normally been confined to the immediate tailgate area of the longwall and might have only affected a few miners working in this area. However, the pressure wave created by the methane explosion stirred up loose, fine coal dust which was subsequently ignited into a major coal dust explosion that ripped through 31 million ft^3 (880,000 m^3) or about 67 km (42 miles) of mine entries assuming an average cross section of 140 ft^2 (13 m^2). The explosion completely destroyed the entire northwestern production district of the mine with a longwall and two continuous miner production sections.

The miners died from physical trauma, exposure to heat and mostly, from asphyxiation due to levels on carbon monoxide that exceeded 10,000 ppm in some areas of the mine. The mine ventilation system was severely compromised after the explosion, with most ventilation controls destroyed in the area affected by the explosion.

The explosion happened because a number of mandatory prevention measures were not implemented or not effective:

- The longwall ventilation system was ineffective and allowed the initial methane cloud to develop near the cutting drum of the shearer. Ventilation may have been compromised by insufficient roof support installed in the longwall tailgate which reduced the longwall face ventilation quantity.
- The shearer cutting drum had several water sprays missing. Also, several severely worn cutting bits were found on the shearer. This prevented effective control of coal dust produced in the cutting process and also prevented cooling of the cutter bits and the rock, allowing sparks and hot incendive smears to develop that were able to ignite the methane.
- The longwall tailgate and most of the mine workings in the area affected by the explosion, particularly, the belt entries, had been insufficiently treated with rock dust. UBB's own mine examiners found a number of belts out of compliance on the day of the explosion. Post-explosion sampling by MSHA investigators (Page

2011) indicated that 90.5% of the over 1,300 mine dust samples taken were non-compliant.

Although the UBB disaster was primarily caused by a failure of the mine operator to adhere to key, mandatory standards of mine explosion prevention, researchers feel that more can and needs to be done in the U.S. mining industry to prevent mine explosions.

Other recent major mine explosion disasters include the Westray mine explosion in Canada (1992, 26 fatalities), the Moura mine explosions in Australia (No. 4 mine, 1986, 12 fatalities and No. 2 mine, 1994, 11 fatalities), and the Pike River mine explosion in New Zealand (2010, 29 fatalities). These and other explosions are discussed in greater detail in the Companion Report, "Lessons Learned from Mine Disasters: New Technologies and Guidelines to Prevent Mine Disasters and Improve Safety" by Brune and Goertz.

MSHA statistics indicate that, each year, numerous methane ignitions happen in US coal mines. In 2010 MSHA reported 33 face "ignition or explosion of gas and dust" events in 2010; 34 were reported in 2011 (MSHA Accident and Injury Statistics). Each such ignition has the potential to trigger a violent coal dust explosion, just like it happened at UBB. European coal operators use active explosion barriers mounted on their development mining machines – such technology could potentially be adapted to the continuous mining machines used in the U.S.

Furthermore, European mines use passive water barriers to stop propagating coal dust explosions. This technology is enabled by the simplified, single-entry mine development used in European coal and is not immediately applicable to the room-and-pillar style mine geometry used in the U.S. However, smaller active (triggered) barriers could be considered for U.S. mines provided that research and testing could be done to adapt this technology to U.S. mines.

The following sections will outline measures and technologies for the prevention of mine explosions in the U.S. and other countries and distill the best ways and practices from the combined body of research and practice accumulated by the leading mining countries.

2. Science for methane and coal dust explosions

Preventing a methane or coal dust explosion begins with an understanding the mechanical, physical and chemical processes behind the explosion. A large number of studies and physical experiments have been conducted over the past 100 years both in the United States and internationally to understand these processes and to develop regulations and prevention practices to reliably prevent such explosions in underground coal mines. More recent studies also look at the effects of increasing mechanization in mines and the impact of mining deeper, more gassy coal reserves. These effects raise the explosion risk by increasing methane liberation and producing much finer, more explosive coal dust.

2.1 Underlying science of methane explosions

Methane is formed as a byproduct of coal formation. Some of the methane contained in the coal is released continuously, and the rate of release depends on a variety of parameters including methane content, cleat system permeability and degree of fracturing of the coal. More methane is typically released as the coal is mined and broken up into smaller pieces, exposing more of the cleat system that acts as a conduit for the methane. Methane can also migrate into active mine workings from surrounding strata above or below the coal seam (including neighboring coal beds) through pores or fractures created by the coal extraction process. Methane is usually emitted in concentrated form from the cleats and cracks in the coal. Methane flowing from these so-called feeders is then diluted by the ventilation air, as shown in Figure 1:

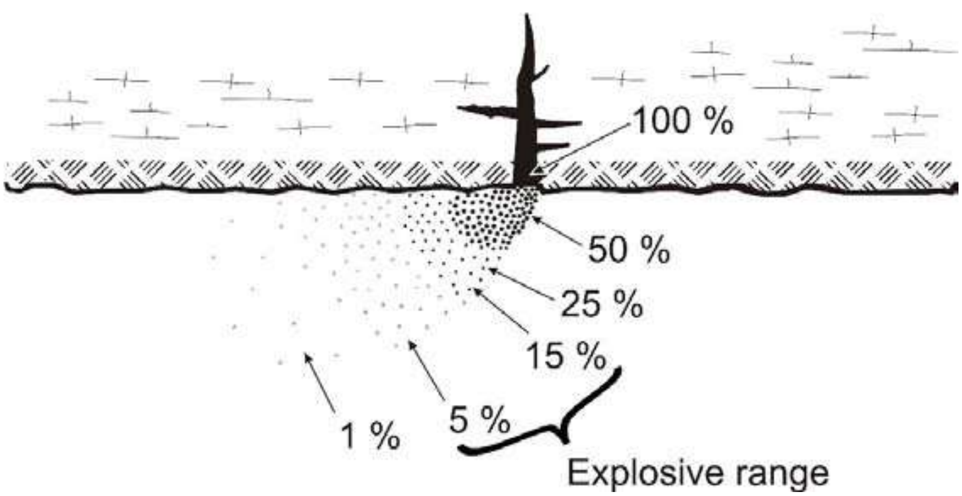

Figure 1: Methane feeder emanating from a crack and being diluted by a moving ventilation air stream (Kissell, 2006)

Methane explosions occur when a buildup of methane gas mixes with air to a flammable concentration and contacts a heat or ignition source. Methane is explosive in air when the concentration ranges from 5% to 16% by volume (Cashdollar et al., 2000). In addition, the oxygen concentration of the air must be at a concentration above 12% in order for the explosion to propagate through the air mixture, otherwise the air is considered oxygen deficient for an explosion to occur. A common tool used for identifying explosive mixtures of oxygen and methane is Coward's Diagram (Coward and Jones, 1952) shown in Figure 2. The abscissa shows the methane concentration while the ordinate shows the oxygen content, both in percent.

The central triangle, also known as “Coward’s Triangle”, marks the explosive range of possible methane-oxygen mixtures. The left edge of the triangle marks the lower explosibility limit (LEL) at approximately 5% methane content. The right corner marks the upper explosibility limit (UEL) at approximately 14% methane content. Note that the more recent studies have demonstrated that the UEL can go up to 16% (Cashdollar et al., 2006). The bottom tip of the triangle marks the minimum required amount of oxygen, about 12%, for an explosive mixture.

Fundamentally, mining engineering practices for the prevention of methane explosions focus on a two-pronged approach:

- prevent accumulations of methane-air-mixtures in the explosive range and
- eliminate all possible ignition sources.

Preventing explosive concentrations is primarily done with mine ventilation by providing sufficient amounts of fresh air to all mine workings so that accumulations and local releases of methane are diluted and rendered harmless. Typically, dilution must be achieved to a concentration of less than 1% by volume in air to provide an adequate safety margin.

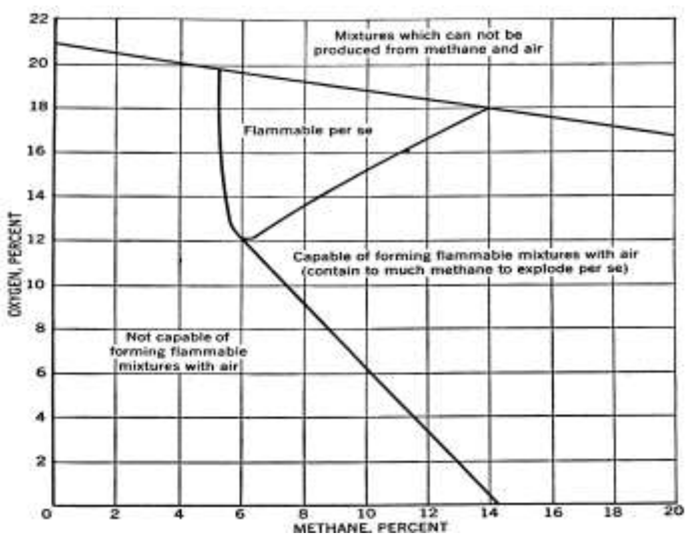

Figure 2: Triangle identifying the explosive zone of methane in air (Coward and Jones 1952).

There are a number of potential ignition sources that could be present in an underground mine and could lead to a methane explosion if not properly managed. All coal mines ban smoking, cigarette lighters, sparkers, other open flame sources and unprotected electrical equipment from use underground as they are potential ignition sources. Electrical equipment for use in explosive atmospheres, also termed “permissible” equipment, must either be encapsulated in an explosion proof housing or designed to use small currents only that are not capable producing sparks with sufficient energy to ignite methane (intrinsically safe electrics). Modern explosives have been designed that can be used in coal mines without the danger of igniting methane or dust explosions. Such explosives are also termed "permissible".

However, several other potential ignition sources exist in mines: Methane can be ignited by a phenomenon known as frictional ignition. When a piece of equipment is mining hard, abrasive rocks such as sandstone, the cutter picks may heat up and leave smears of hot metal on the rock, especially if the picks are worn out. This is one of the more dangerous occurrences as a potential ignition source can be directly next to a methane liberation source.

Nagy and Kawenski (1960) documented that methane can also be ignited through friction between blocks of sandstone and other rock types typically occurring in coal mines. Such frictional ignitions can happen when large blocks of rock collapse and rub against each other in unintended as well as intended roof falls, such as in longwall or retreat mining gobs.

Spontaneous combustion (spon com) of coal in an underground mine is also a potential source of ignition for a methane explosion. Spon com is an exothermic chemical reaction that occurs in some coal bodies between the coal and oxygen in the mine air. Certain coals, for example those found in Australia and Europe, are especially prone to spon com while most U.S. coals are not. The spon com hazard is especially difficult to mitigate when the area of combustion is inaccessible from the active mine workings, for example, in longwall gobs or sealed areas of the mine.

2.2 Underlying science of coal dust explosions

Coal dust is produced at the coal face during mining, along belt conveyors, at conveyor transfer points, and by the normal movement of men and machines in the mine. If fine coal particles, so-called "float" coal dust (typically less than 74 µm or 0.003 in. diameter), become airborne, they may be transported by the ventilating air current over long distances, usually into the return airways where they eventually settle onto mine surfaces. Float coal dust presents a greater explosion hazard than larger coal dust particles, although particles up to about 1 mm (0.04 in.) diameter can participate in dust explosions as expressed in Nagy (1965). The mechanics of a coal dust explosion were characterized by Edwards (1988) as follows: The coal dust explosion is usually initiated by a methane-air explosion. As the heat from the explosion flame expands the air in front of the flame zone, coal dust particles are dispersed from the mine entry surfaces and entrained in the air. As the coal particles heat up in the turbulent mix, they release volatile, flammable organic compounds that are ignited and burn, continuing and propagating the explosion further.

Like other combustible organic dusts, coal dust is only explosive when it is suspended in air. Once airborne, the coal dust provides additional fuel to propagate the explosion. If more loose coal dust is found along the path of the explosion, the propagation can continue for many thousands of feet. According to the MSHA investigation of the 2010 coal dust explosion at the Upper Big Branch (UBB) mine (Page, 2011), a small initial methane-air explosion entrained coal dust which then violently propagated through 80 km (260,000 linear feet) of mine entries with a total flame volume of 880,000 m^3 (31 million ft^3).

Coal dust explosions can fundamentally be prevented in two ways:

- The coal dust that deposits in the mine entries can be inertized by adding finely powdered stone dust. Typically, limestone or dolomite dust is used; this is often referred to as rock dust. When the combined mine dust is scoured up in an explosion, the rock dust particles provide thermal shielding and prevent the coal particles from cooking off volatile matter that could ignite. The method of rock dusting is quite common in the U.S. coal industry.
- The second method of dust explosion prevention is to wet the coal dust and to cause it to adhere to the mine floor and other surfaces so that it cannot be entrained in air and participate in the explosion. European mine operators use hygroscopic salts ($CaCl_2$ or $MgCl_2$) that are sprayed on all mine surfaces. The salts remain wet as long as the hydration process continues, then dry to a crust that permanently arrests the coal dust particles. Salt treatment must be repeated after the crust forms – depending on the amount of moisture in the mine air, this treatment may need to be repeated every few days.

The South African regulation on explosion prevention includes an information fault tree showing the mechanisms of a coal dust explosion. The diagram details a large range of ignition sources, system and equipment faults, and potential paths that lead to a coal dust explosion. This diagram from the Mining Regulatory Advisory Committee (MRAC 2002) is included as Figure 3a and Figure 3b.

2.3 Effects of mechanization on coal dust explosion characteristics

Mining operations continue to become more mechanized every day, and mines are extracting larger amounts of coal at increasingly higher rates. This presents two major problems for mine management, an increase in methane liberation and decrease in coal particle size. The increase in methane liberation means that mines have to increase the air quantity provided underground to continue to dilute the methane. Mine ventilation management becomes a key ensuring proper dilution at all locations in the mine where methane hazards are present.

Cashdollar et al. (2010) found that the higher degree of mechanization in underground coal mining has increased the percentage of fine coal particles in the mine dust. Cashdollar found that the average percentage of float coal dust (<74 µm) in dust samples, taken from 61 U.S. coal mines in all 10 MSHA bituminous coal districts, had increased to 38% as compared to 20% in the 1920's. This increase in float coal dust increases the coal dust explosion potential, as shown by Cybulski (1975). To correct for this, mines must use increased amounts of rock dust to inertize the coal dust. Based on the work by Cashdollar, the United States Mine Safety and Health Administration (MSHA) increased the mandatory inert content for mine dust in fresh air entries from 65% to 80% in 2011 (see 30 CFR §75.403). According to Cybulski, coal dust with 85% of its particles smaller than 200 mesh (74 µm) may, in fact, require 85 to 90% inert dust mixed in to become inert.

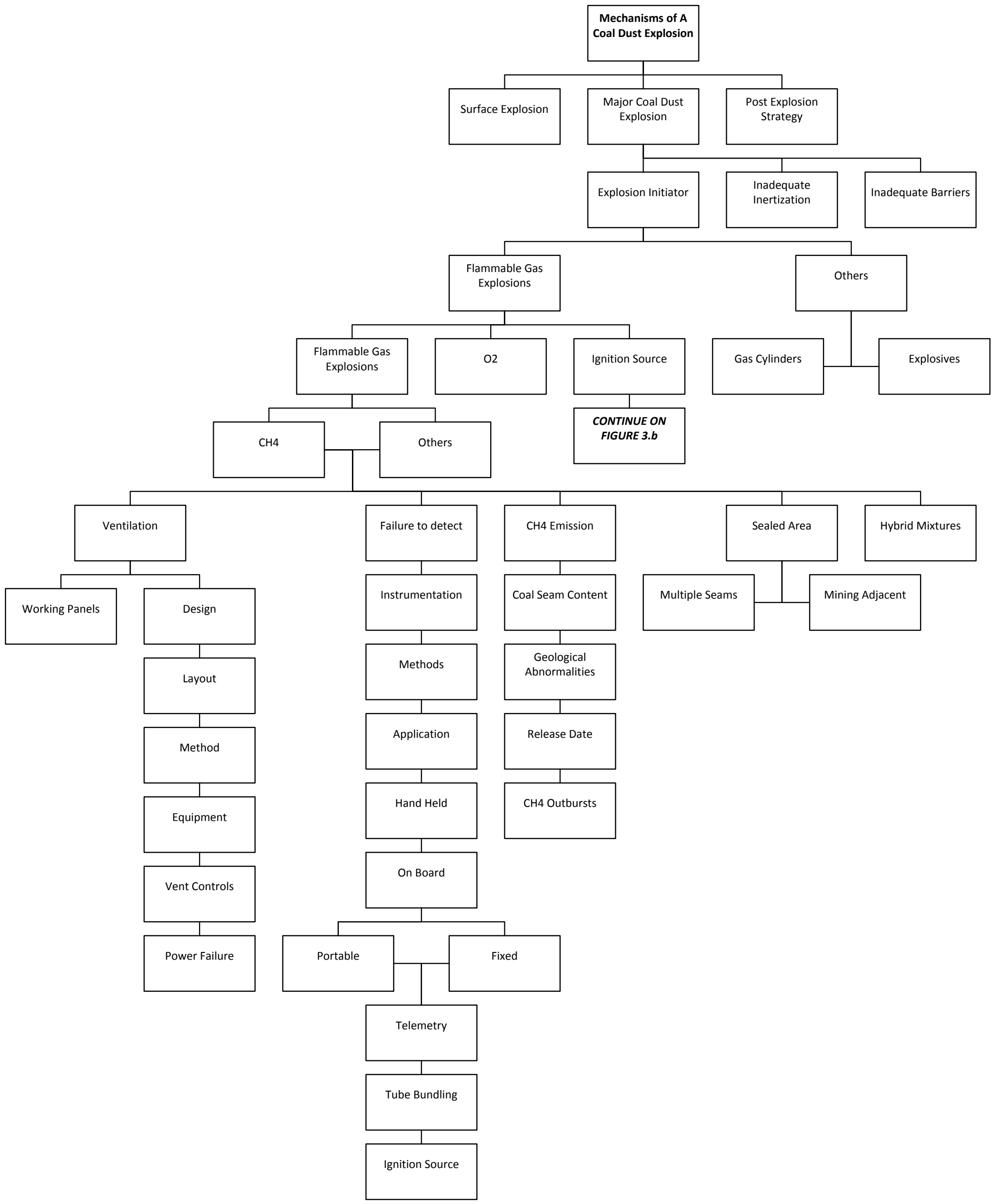

Figure 3a: Diagram of Fault Tree showing mechanisms of coal dust explosion (MRAC 2002).

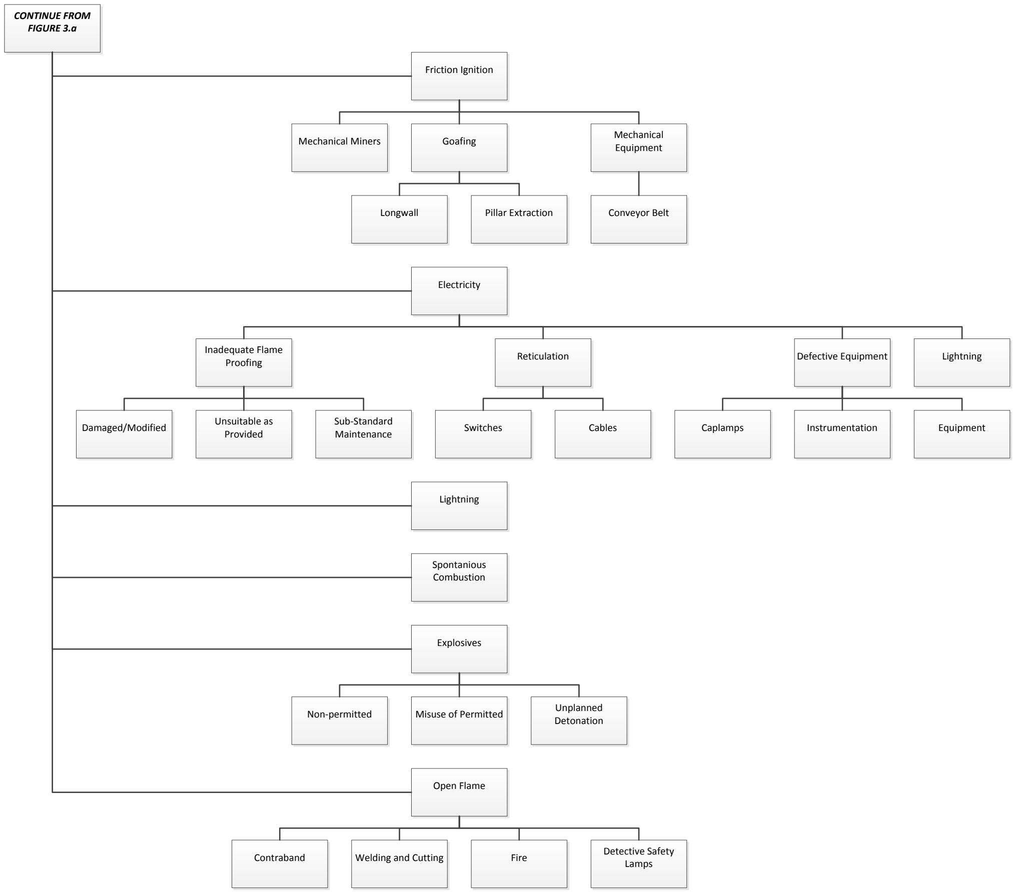

Figure 3b: Diagram of Fault Tree showing mechanisms of coal dust explosion (MRAC 2002).

3. Regulatory standards for methane and coal dust explosion prevention

As scientific understanding about the prevention of coal dust and methane explosions expanded, government regulations for coal mines were adapted to the new science to keep the underground mine environment safe. Historically, new regulations and revisions have been heavily influenced by mine explosion disasters that have exposed weaknesses and insufficiencies in the existing standards. Changing mining methods also play a role in required regulatory improvements as excavation speed, productivity, equipment and mine design can significantly change the effectiveness of various safety protocols and criteria.

This section will outline the regulations that pertain to methane and coal dust explosion prevention and any additional standards that aid in their mitigation such as fire suppression equipment standards.

When applicable, direct comparisons to current U.S. regulation will be used as a baseline when detailing potential advantages and disadvantages for a given regulation.

3.1 United States

The mandatory safety standards for US underground coal mines are found in the Code of Federal Regulations, Title 30, Part 75 (30 CFR Part 75). This document covers a vast range of standards dealing with mine ventilation, application of rock dust, mine seals, fire protection and suppression, explosives and blasting, mining equipment and mine emergencies that directly aid in the prevention of methane and dust explosions. The following outlines the standards relevant to protection from mine explosions.

3.1.1 Mine Fan

30 CFR §75.300 and following regulate mine ventilation and its use as a tool for combustible gas dilution. §75.310 describes installation procedures for the main mine fan that covers a large range of explosion safety features such as the use of incombustible ducts and housing, requirements for pressure recording devices, protection with weak walls or explosion doors, and integration of fan monitoring system. The fan monitoring system records changes in the mine ventilating pressure and provides a designated worker an alert signal if a sudden increase or loss in mine ventilating pressure occurs. §75.312 describes continuous pressure recording along with daily, weekly, and monthly procedures of checking the mine fan and its monitoring equipment as well as record keeping.

3.1.2 Air quality

Sections §75.320 and §75.321 cover the standards for air quality and testing. The air in areas where persons work or travel shall contain at least 19.5 percent oxygen and the volume and velocity of the air current shall be sufficient to dilute, render harmless, and carry away flammable, explosive, noxious, and harmful gases, dusts, smoke, and fumes. Oxygen deficiency tests shall also be made by a qualified person with approved MSHA detectors that can detect oxygen with an accuracy of ± 0.5 percent. Methane must be tested by a qualified person with MSHA-approved detectors that are calibrated at least every 31 days. Methane tests and ventilation system checks must be made:

- Within 3 hours before a new shift comes on (§75.360)
- At the start of and during the ongoing shift, before tramming mining equipment into the face, before energizing and starting up mining equipment in the face, and every 20 minutes while mining equipment is operating (§75.362)
- Before and after blasting (§75.1324, §75.1326)

§75.323 details the steps taken to reduce a methane concentration to less than 1 percent air content. If methane content is higher than 1 percent, electrically powered equipment in the area will be de-energized, mechanized equipment shut off, changes to the ventilation will be made to reduce the concentration to less than 1 percent, and no other work shall be permitted until the concentration is reduced. In addition, if the methane concentration is above 1.5 percent everyone shall be withdrawn from the affected area and electrically powered equipment shall be disconnected at the power source. Similar procedures apply for areas such as the return air split which are not working places or intake air courses.

3.1.3 Minimum air quantity

§75.325 prescribes the required minimum air quantity for different coal types and mine locations. This information is summarized in Table 1. It should be noted that, in order to meet the mandatory methane and dust control standards, it is usually necessary to maintain higher airflow quantities than these minimum values. In addition to the required minimum air quantities, §75.326 mandates that a mean entry air velocity of at least 60 feet per minute must reach each working face where coal is being cut.

Type of Coal Mine	Bituminous/Lignite Mines	Anthracite Mines
Location within the Mine	Minimum Air Quantity (cubic feet per minute)	Minimum Air Quantity (cubic feet per minute)
Working face where coal is being cut	3,000	1,500
Last open crosscut or end of pillar line	9,000	5,000
Longwall or Shortwall mining systems	30,000*	30,000*

Table 1: Comparison of bituminous / lignite and anthracite minimum air quantities

3.1.4 Ventilation control devices

To assist with the dilution of methane at the face of a working area, face Ventilation Control Devices (VCDs) are commonly utilized. Per §75.330, brattice cloth or ventilation tubing shall installed in each working face to a distance no greater than 10 ft from the area of deepest penetration to ensure proper face ventilation and dilution of methane and dust. Auxiliary fans and tubing for face ventilation must be located and operated in a way that avoids the recirculation of air as per §75.331.

Other, usually permanent VCD's include stoppings, overcasts and regulators. §75.333 covers the acceptable uses and restrictions based on intended function. Stoppings separate air courses for different purposes, such as of intake air courses from return air courses, belt conveyor haulageways from return air courses, belt conveyor haulageways from intake air courses, primary intake escapeway entries from belt and trolley haulage entries, and return air courses from adjacent worked-out (gob) areas.

All permanent stoppings and regulators shall be constructed in an accepted method and of materials that have been demonstrated to perform adequately. When timbers are used to create permanent stoppings in heaving or caving areas, the stoppings shall be coated on all accessible surfaces with a flame-retardant material having a flame-spread index of 25 or less. All ventilation controls, including seals, shall be maintained to serve the purpose for which they were built.

It should be noted here that there are no provisions that require permanent ventilation controls to be able to withstand mine explosions or even a certain explosion overpressure. NIOSH testing (Weiss et al., 2002) shows that concrete block stoppings and overcasts can only withstand explosion pressures of 2 to 7 psi (14 to 50 kPa). Experience shows that ventilation controls are frequently damaged even during weak explosions. In most cases, damaged controls compromise the mine ventilation system and render it non-functional following an explosion.

3.1.5 Bleeder systems

§75.334 covers conditions in the mine involving worked-out areas and areas where pillars are being recovered. For a worked-out area, with no pillars recovered, the section must be ventilated to the standards of §75.321 or be sealed off from the remainder of the mine. If an area is currently recovering pillars, then a bleeder system must be used to control the air to the standards of §75.321.

The requirement for bleeder systems is unique to U.S. mining regulations. Bleeders originated in room-and-pillar retreat mining. A set of bleeder entries was maintained around the back end of a set of pillars before retreat mining began. This worked well to route methane and dust away from the mining face directly into the returns. With the arrival of longwall mining technology from Europe in the late 1960s, bleeders were also required to be maintained around longwall gobs.

§75.334 further states that, if it is found a bleeder system is not continuously diluting and moving methane-air mixtures and other gases, dusts, and fumes away from the worked out area the affected area must be sealed from the rest of the mine. If the mine has a history of spontaneous combustion, additional measures such as a pre and post pillar removal gas concentration comparison may be conducted to determine if the section needs to be sealed due to spontaneous combustion.

3.1.6 Seal design and construction

An area of the mine that is no longer ventilated must be sealed. §75.335 outlines seal strengths, designs applications, and installation standards. There are three distinct explosion resistance levels that a seal may be built to. The first level comprises a seal that can withstand at least 50 psi (350 kPa) overpressure for a duration of 4 seconds with either instantaneous pressure rise time or with a rise time of 0.1 seconds. The latter seal is used to seal bleederless gobs. A mine operator choosing seal at this level must monitor and actively maintain an inert atmosphere behind the seal.

The second level comprises seals that can withstand at least 120 psi overpressure for a duration of 4 seconds with either instantaneous pressure rise time. If designing for a seal of this level the area behind the seal must be checked to ensure that there is no likelihood of detonation occurring, the gas mixture will not produce a methane concentration between 4.5 percent and 17.0 percent with oxygen exceeding 17.0 percent throughout the entire area, and no pressure pilling will result in overpressures greater than 120 psi behind the seal area.

The third level comprises a seal that can withstand more than 120 psi overpressure which may be used if the mine operator does not monitor or maintain inert the area behind the seal, and experiences one or more of the stated restrictions for level 2. This seal design would then need to be designed to withstand the calculated overpressures associated with these conditions. It should be noted that a level of explosion resistance is not specified and it is up to the mine operator to demonstrate that the seal design is sufficient for the given hazard.

It should also be noted here that Zipf et al. (2007) documented that explosion overpressures in coal mines can reach 1000 psi (7 MPa) or higher. In fact, a report by the U.S. Army Corps of Engineers (McMahon et al., 2007) documents that pressures in the 2006 explosion inside a sealed area of the Sago Mine may have reached 1,300 psi (9 MPa).

Seal designs from manufacturers or mine operators must address mandatory seal design criteria, be certified by a professional engineer, contain a summary of the installation procedures related to the seals construction, and be submitted for approval by MSHA’s Office of Technical Support. As per §75.337, prior to sealing the mine operator shall remove all potential electric ignition sources from the area to be sealed, remove metallic objects through or across seals, and breach and remove all stoppings in the first crosscut inby the seals immediately prior to sealing the area. A certified person shall directly supervise seal construction and repair in addition to examining the seal site prior to construction, during each working shift, and after seal completion. The certified person must state by initials, date, and time when the examinations were carried out and retain the certification for as long as the seal is needed to serve its purpose.

§75.337 also covers standards for methane sampling pipes and drainage systems built into seals. One non-metallic sampling pipe shall be installed in each seal that shall extend into the center of the first connecting crosscut inby the seal. Each pipe shall be labeled in case of multiple sampling pipes and equipment with a shut-off valve and appropriate fittings for taking gas samples. If a new seal is constructed to replace or reinforce an existing seal with a sampling pipe, the sampling pipe in the existing seal shall extend through the new seal. An additional sampling pipe shall be installed through each new seal to sample the area between seals, as specified in the approved ventilation plan. Additionally, welding, cutting, and soldering with an arc or flame are prohibited within 150 feet of a seal.

The purpose of the sampling pipe through each seal is to monitor the atmosphere in the sealed area with continuous (e.g., using a tube bundle system) or manual sampling. According to §75.336, each sampling pipe shall be sampled at least every 24 hours until the seal has reached its designed strength at which point the operator may request that a sample be taken at each set of seals at least every 7 days. A certified person must record the methane and oxygen concentrations and the direction of leakage from each sample location in order to monitor changes in the sealed area. The mine operator shall also evaluate the atmosphere in the sealed area to determine whether the samples obtained through the sample pipes are representative of the sealed area. MSHA may approve in the ventilation plan the use of a continuous monitoring system in lieu of the above monitoring requirements.

The atmosphere behind the seals is considered inert when the methane concentration is either less than 3% percent or greater than 20% percent and the oxygen concentration is less than 10%. Per §75.336, immediate action shall be taken by the mine operator to restore an inert sealed atmosphere behind seals with strengths less than 120 psi.

3.1.7 Regular mine examinations

Operators are also required to have qualified persons conduct distinct examinations throughout the working and non-working areas of the mine. There are four different examinations the mine is required to conduct: Pre-Shift, Supplementary, On-Shift, and Weekly. The examinations identify potential violations and deficiencies in the various areas being tested. The standards relevant to explosion prevention that are being checked during each of these examinations are listed below:

§75.333(h) and 75.370(a)(1) — ventilation, methane;

§75.400 and 75.403 — accumulations of combustible materials and application of rock dust;

Each examination has additional testing criterion 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. The complete text of these sections can be found in Appendix A.

3.1.8 Atmospheric monitoring systems

An Atmospheric Monitoring System (AMS) is a dedicated system used to automatically and continuously monitor mine air quality in lieu of manual monitoring. AMS usually include alarm functions. §75.351 provides the mandatory standards for installation, signal receiver and display location, operator function, minimum operating requirements, and specified locations of the AMS sensors. Specifically,

1. The mine operator must designate a surface location at the mine where signals from the AMS will be received and two-way voice communication is maintained with each working section.
2. The mine operator must designate an AMS operator to monitor and promptly respond to all AMS signals. The AMS operator must have as a primary duty the responsibility to monitor proper function, alert and alarm signals of the AMS, and to notify appropriate personnel of these signals. In the event of an emergency, the sole responsibility of the AMS operator shall be to respond to the emergency.
3. A map or schematic must be provided at the designated surface location that shows the locations and type of AMS sensor at each location, and the intended air flow direction at these locations. This map or schematic must be updated within 24 hours of any change in this information.
4. The names of the designated AMS operators and other appropriate personnel, including the designated person responsible for initiating an emergency mine evacuation under §75.1501, and the method to contact these persons, must be provided at the designated surface location.

Per §75.351(c) the AMS must identify at the designated surface location the operational status of all sensors and must automatically provide visual and audible signals at the surface and affected underground locations as follows:

1. for any interruption or electrical malfunction of the system,
2. when the carbon monoxide concentration or methane concentration at any sensor reaches the alert level as specified in §75.351(i).
3. when the carbon monoxide, smoke, or methane concentration at any sensor reaches the alarm level as specified in §75.351(i).
4. when the carbon monoxide levels at any two consecutive sensors alert at the same time.

For regulation regarding the general location and installation of AMS sensors, §75.351(d) states the following:

1. All AMS sensors must be located such that measurements are representative of the mine atmosphere in these locations.
2. Carbon monoxide or smoke sensors must be installed near the center in the upper third of the entry, in a location that does not expose personnel working on the system to unsafe conditions.
3. Methane sensors must be installed near the center of the entry, at least 12 inches from the roof, ribs, and floor.

In addition to these requirements, the areas designated as belt air courses, primary escapeways, return air splits, and electrical installation have unique location and installation requirements as outlined in sections 351(e) through 351(f).

§75.351 also provides the examination, testing, and calibration periods for the sensors installed with the AMS. On shifts when belts are operated as part of a production shift, sensors used to detect carbon monoxide or smoke and alarms installed must be visually examined. At least once every seven days, alarms for AMS must be functionally tested for proper operation. At intervals not to exceed 31 days each carbon monoxide and methane sensor must be calibrated and each smoke sensor must be functionally tested. Records must be kept and maintained of all inspections and maintenance of the AMS.

As per §75.352, when a malfunction, alert, or alarm signal is received at the designated surface location, the sensor(s) that are activated must be identified and the AMS operator must promptly notify the appropriate personnel. Upon notification of a malfunction, alert, or alarm signal, appropriate personnel must promptly initiate an investigation to determine the cause of the signal and take the required actions. These actions vary depending on the function the sensor(s) serving as determined by the mine operator.

3.1.9 Mine ventilation plan

One of the keys to maintaining proper ventilation control in a mine is the adherence to an approved mine ventilation plan. The plan is developed by the operator of the mine workings and approved by MSHA. . §75.370 covers the procedures for submitting and approving a mine ventilation plan or revision in regards to posting, district manager denial, and how to outline deficiencies based on input from the district manager, miners, and miner representation.

The contents of the plan are outlined in §75.371 and covers the entire spectrum of ventilation regulations and required approvals. The full text of §75.371 has been provided in Appendix A. In addition to regulation contents, the mine ventilation plan must also contain a mine ventilation map as detailed in §75.372. This map displays the physical layout and workings of the mine, the direction of airflow, location of all VCD's including bleeder system and seals, and the direction and designated quantity of air at key locations in the mine such as last open crosscuts and the intake ends of pillar lines. The ventilation map also must contain projections for air quantity, VCD's, bleeder systems, and return air courses anticipated with future development work at least 12 months from the time of last approval.

3.1.10 Combustible materials and rock dusting

§75.400 and following cover accumulations of combustible materials and rock dusting for coal dust explosion prevention. Coal dust, including float coal dust deposited on rock-dusted surfaces, loose coal, and other combustible materials, shall be cleaned up and not be permitted to accumulate in active workings. The mine must establish a program for regular cleanup and removal of accumulations and maintain it throughout the life of the mine.

The quality criteria for rock dust are defined in §75.2. Based on this regulation, 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 a 200 mesh (74 μm) sieve.

When rock dust gets wet, it may coagulate or cake so that it may no longer be easily dispersed by oncoming explosion pressure. §75.2 requires that the rock dust should be able to be dispersed by a "light blast of air", however, this criterion does not provide a scientific definition so it is currently up to wide interpretation of what “caked” rock dust means. According to 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.

Control of the mine dust underground is an effective way to prevent a coal dust explosion. Where underground mining operations in active workings create or raise excessive amounts of dust, water or water with a wetting agent added to it, or other no less effective methods approved by MSHA shall be used to abate such dust as stated in §75.401. The area within 40 feet of the working face must also have water or water with wetting agent applied to coal dust on the ribs, roof and floor.

§75.402 states that all underground areas of a coal mine, except those areas in which the dust is too wet or too high in incombustible content to propagate an explosion, shall be rock dusted to within 40 feet of all working faces, unless such areas are inaccessible or unsafe to enter. All cross cuts that are less than 40 feet from the working face must also be rock dusted. The application of water or water with wetting agent and rock dust is done to increase the incombustible content of the combined dust and water to at least 80 percent. As per §75.403, if methane is present in the air current, the percent incombustible content must be increased by 0.4 percent for every 0.1 percent methane.

3.1.11 Electrical equipment

A large section of the 30 CFR Part 75 deals with the explosion protection and maintenance of electrical equipment while underground in the mine. MSHA examines, tests and certifies as “permissible” in accordance with §75.506 and other regulations all electrical equipment used in underground mines so that it will not ignite a flammable methane-air mixture.

Additionally, methane monitors must be installed on all face cutting machines, continuous miners, longwall face equipment, loading machines, and other mechanized equipment as per §75.342. These sensors must also have visible warning devices to alert persons to deenergize equipment. If the methane content in the air reaches 1.0% the monitors must emit a warning signal and at 2.0%, the monitor will automatically deenergize the equipment.

3.1.12 Fire prevention and suppression

There is a range of fire prevention and suppression systems and devices that are applicable to the prevention of methane and coal dust explosions. §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 subsets of this regulation expand on the installation, maintenance, and spacing of these systems and continues 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 present during an explosion event.

§75.1107 introduces the regulations for fire suppression devices to be located on underground electrical equipment and their application. The devices must be of adequate size and capacity to extinguish potential fires in or on the equipment. The devices must also take advantage of the ventilation air currents and locate its extinguishant-discharge nozzles accordingly. Fire suppression can be implemented in the form of water sprays, dry chemical devices, and/or high expansion foam devices.

§75.1907 details the requirements for fire suppression systems on diesel-powered equipment in underground mines is outlined. All diesel-powered equipment must have an automatic or manual fire suppression system and at least one portable multipurpose dry chemical type (ABC) fire extinguisher within easy reach of the equipment operator and be protected from damage and collisions. The fire suppression system must provide, as stated in §75.1911, fire suppression and, if automatic, fire detection for the engine including the starter, transmission, hydraulic pumps and tanks, fuel tanks, exposed brake units, air compressors and battery areas on diesel-powered equipment.

3.2 Australia

The regulation standard that has been found to be most representative and thorough of Australian underground coal mining is the Coal Mining Safety and Health Regulation 2001 from the State of Queensland. The other major underground coal mining state in Australia, New South Wales, has similar regulations.

The current Queensland document was last amended on May 31st, 2013 by the "Natural Resources and Mines Legislation Amendment Regulation (No. 2) 2013 SL No. 84 ss 1, 2(2), pt 4" and the last provisions of this amendment went into effect July 1st, 2013. The sections as they are identified for reference in the document are labeled as Snnn below (i.e. Section no. 286 is referenced as S286).

There are two substantial differences between Australian regulation and U.S. regulation: mine-wide, mandatory implementation of atmospheric monitoring systems including the establishment of Trigger Action Response Plans (TARP, see also Section 3.2.2) and the use of Explosion Risk Zones (ERZs). For Queensland, the AMS is a mandatory requirement in place of the manual air quality checks. The U.S. regulations do not have a general AMS mandate but only offer it as an alternative to some of the manual examinations that must be conducted during examinations.

3.2.1 Establishing and regulating explosion risk zones (ERZs)

Queensland regulations introduce a zoning system for use underground in the mine that indicates the risk of mine explosions. 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. An ERZ0 is an area underground where the general body concentration of methane is known to be greater than 2.0%. A location is considered an ERZ1 if the area has a general body concentration of methane between 0.5% and 2.0 percent or is one of the specified places listed as follows: where coal or other material is being mined, where ventilation requirements are not being met, where connections to methane drainage pipe are being conducted, where holes are being drilled in the coal seam, the gob area, and each place on the return air side of the above mentioned areas. The last zone is the NERZ

(Negligible Explosion Risk Zone) in which the general body concentration of methane is less than 0.5%. This can be expanded to include areas where the mine workings are submerged in water and can alternatively be divided into sub-zones to enable tripping and shutting down of electrical equipment when gas detectors in the zone detect a methane concentration of greater than 0.5%. Signs must be posted to alert personnel of zone changes from NERZ to ERZ1 and ERZ1 to ERZ0.

The ERZ designation also 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) “flameproof encapsulated” (“Ex 1” is mentioned in the regulation although based on IEC/EN 60079-1, it is likely “Ex d”).

For ERZ1 equipment the only requirement is it must be certified as having explosion protection. Similarly, equipment in NERZ areas must be certified as having explosion protection or have a degree of protection, or 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 does not apply to electrical equipment associated with flame cutting and welding or live testing with the explosion proof enclosure opened.

3.2.2 Gas monitoring systems (GMS)

The GMS as regulated in the Queensland document are the equivalent of the AMS that is regulated in the 30CFR §75.351. GMS are mandatory for all Queensland underground coal mines and must be adhered to in the mines Safety Health and Management System. As stated in S222, the GMS must have the capability to continuously monitor the mine atmosphere at various locations underground. Sensors are installed to detect methane, carbon monoxide, carbon dioxide and oxygen. The GMS calculate trends for all gas concentrations, the ratio of carbon monoxide and oxygen, the ratio of carbon dioxide and oxygen, and gas explosibility according to the Coward diagram. Along with the GMS, Australian mine operators develop a Trigger Action Response Plan (TARP) with typically four trigger levels ranging from a simple alert to immediate evacuation of the mine. TARPs can also be established for combinations of individual gas concentrations or complex conditions mathematically described with AND or OR operators.

Contrary to U.S. regulations, the TARP levels of the GMS are established in the mine’s Principal Hazard Management Plan and do not adhere to a set standard. S224 requires are additional operating procedures before the alarm levels can be changed.

TARPs generally consider four specific action levels for each condition or combination of conditions monitored:

- Level 0: Conditions within normal range, continue monitoring
- Level 1: Elevated readings, notify ventilation officer and crew foreman

- Level 2: Highly elevated readings. Take immediate action, notify ventilation officer, crew foreman, management officials
- Level 3: Abnormally high readings. Notify senior management; all personnel is to evacuate the mine immediately

In a specific example, a set of simple TARPs for a methane monitor on a continuous miner may be set up as follows:

- Level 0: CH_4 < 0.9%, normal
- Level 1: CH_4 >= 1.0% and <1.5%: Automatic shutdown of face equipment. Notify ventilation officer and crew foreman, and make immediate improvements to face ventilation
- Level 2: CH_4 >= 1.5 and <2.5%: Notification as above, immediately shutdown all section electric power and remove crews from face area except those required to correct local ventilation problems, and
- Level 3: CH_4 >= 2.5%: Notification includes senior management. Immediately evacuate the section and other affected areas of the mine

The TARP levels are established by each mine and based on the conditions considered in the Principal Hazard Management Plan.

S223 provides general monitoring location criteria based upon the Safety and Health Management System created at the mine. The GMS must provide continuous monitoring of the mine atmosphere at the return airway of each ventilation split and continuously detect for products of combustion at the return side of each conveyor belt. The GMS must also provide sampling of the mine atmosphere at the return airway from each unsealed waste, idle workings and gob area, the return of each airway at the upcast shaft, at other places in the mine's Principal Hazard Management Plan that are required to be gas monitored. Should the GMS become non-operational or fail, as stated in S252, the mine must have management procedures in place to ensure that coal mining operations are not carried out until the part of the mine affected is being continuously monitored by portable gas detectors to achieve an equivalent level of safety. The GMS typically require that an authorized individual is at the surface to acknowledge an alarm if it is activated.

3.2.3 Methane detector placement and operation

S241 through S244 detail the methane detector placement based on ERZ type and airway path. This section applies to fixed methane detectors underground that are equipment mounted, located in particular areas and self-contained, or part of the GMS as discussed previously. If the detector malfunctions or fails the unit will automatically shut down any attached equipment it is monitoring and give a visible alarm in response. Table 2 gives a breakdown of the required operations of the methane detectors mounted to different underground equipment. In addition to these machine mounted detector requirements, if a methane detector on the equipment fails, unless stated otherwise, the operator is required to use a portable gas detector as outlined in S227 that gives audible and visual alarms when the identified levels are reached.

Equipment Type	Alarm	Power Trip @ CH_4
Auxiliary Fan	N/A	> 2%
Booster Fan	>1.25%	Manual
Main Exhaust Fan	> Stated Level	Manual
Coal Cutter	>1%	>2%
Continuous Miner	>1%	>2%
Tunnel Boring Machine	>1%	>2%
Road Heading Machine	>1%	>2%
Longwall Shearer	>1%	Cutter >1.25%; Machine >2%
Mobile Roof Bolting Machine	>1%	>2%
Explosion-Protected Electrically-Powered Loader	>1%	>2%
Explosion-protected load-haul dump vehicle powered by battery or internal combustion engine	>1%	Electrical motor >2%; Int. Comb. Engine >1.25%
Other explosion-protected equipment powered by battery or internal combustion engine	>1%	Electrical motor >2%; Int. Comb. Engine >1.25%
Other explosion-protected electrical equipment	N/A	>2%
Non-explosion-protected plant or equipment	>0.25% or if fails in service	>0.5% or within 3 minutes of failure

Table 2: Methane Detector Requirements for Equipment from S231 and S245-248.

For the above listed equipment, there are additional operator requirements that must be followed in the event of methane being detected or if the detector becomes nonoperational. The regulations can be found in S231 and S245 through S248. For an auxiliary fan, the mine manager must ensure that while the fan is operating a person continuously monitors the general body concentration for methane with a portable methane detector. If the methane concentration exceeds 1.25%, the detector must give out a visible and audible alarm and the person monitoring the fan must disconnect the electrical power supply to the fan. For an explosion-protected electrically powered loader, if the general body methane concentration exceeds 1.25% the operator must switch off the electricity supply to the loader’s trailing cable. For an explosion-protected vehicle powered by a battery, or internal combustion engine the operator must immediately withdraw the vehicle if the methane concentration reaches 1% to a place where the methane concentration is below 1%. Additionally, if the methane concentration reaches 1.25%, the operator must immediately switch off the electrical motors or internal combustion engine. For other explosion-protected electrical plants, if the methane concentration reaches 1.25% the person detecting the methane must switch off the electricity supply to the equipment's trailing cable. For all other equipment, if the methane detector(s) become non-operational, the detector may be temporarily overridden to allow the machine to operate only if a portable methane detector is used to continuously monitor the methane concentration and said concentration remains below 1.25% as identified in S251.

Additional methane sensor placement criteria apply to mine locations designated as intake airways, return airways, and longwall faces. For an intake airway, it is mandatory to have at least 1 automatic methane detector at the interface of a NERZ and ERZ1 zone and at the interface of two NERZ zones (if the NERZ is subdivided. Both locations require the automatic activation of a visible alarm when the concentration of methane in the mine atmosphere reaches 0.25% and automatically trip the electrical power supply to the section if the methane content reaches 0.5%. Each of these units must be self-contained or be part of the GMS of the mine. There must also be at least one automatic methane detector in each main return airway and each return airway in a ventilation split that will automatically activate a visible alarm when the concentration of methane for the section reaches the stated level in the mine's Principal Hazard Management Plan. At a longwall face, at least one methane detector must be located at the intersection between the longwall face and an intake airway (usually, the headgate) and at least one at the intersection between the longwall face and the return airway (usually, the tailgate). These units must trip the electrical supply to the longwall equipment if the general body concentration of methane exceeds 2%.

S250 also covers the procedures for if a methane detector becomes non-operational. In this case the detector must be replaced as soon as possible and may be overridden temporarily to allow operations to continue in the zone only if a person with a portable methane detector continuously monitors the location of the failed detector(s). This person must also have the capability to readily trip the electrical supply to the zone, where the detector is located, when the methane concentration exceeds 0.5%.

3.2.4 Ventilation, fans and VCD's

The Queensland regulations do not go into as detail for its requirements of air quantity and quality levels as the U.S. 30 CFR Part 75. There is no explicit requirement for the volume of air needed. The relevant air quality standard calls for an oxygen concentration of at least 19% as stated in S343. The ventilation system must also minimize within acceptable limits the layering and accumulation of noxious and flammable gases in each place a person normally works or travels and, in each working section, on the intake air side and return air side. The minimum air velocity within these sections must be at least 0.3 m/s (60 ft per minute) over the cross-sectional area of the working place. These requirements do not apply to sealed sections of the mine, gob areas, abandoned workings and roadways in which persons are prohibited from working, and places where persons are using self-contained breathing apparatus to carry out work other than normal work as stated in S345. Additionally, the ventilation officer is also tasked with ensuring the proper air quality and flow rate are being maintained and to check designated areas of the mine at least monthly according to S362. He or she must also ensure the barometric pressure on the surface of the mine is continuously measured and recorded.

S355 details the use of auxiliary fans underground. The ventilation officer (as outlined in S341 and 342) must ensure the minimum quantity of air flowing through any panel in the mine is the open circuit capacity of each auxiliary fan in operation in the panel in addition to 30% of the open circuit capacity of the largest auxiliary fan in operation in the panel. The criterion also requires the aux. fan to be capable of switching off automatically if the main ventilation system was to fail totally. The auxiliary fans, booster fans, and main mine fans must also be monitored using an equipment condition monitoring device and device capable of continuously monitoring and recording a fan's static pressure. The monitoring allows for the devices to visibly alarm and then trip the electrical supply to the fan if it begins to operate outside its normal parameters. As stated in S357, the date and time of the anomalies and device actions are recorded as to allow better timeframe reference for when the fan was removed from operation. S358 dictates that persons must not make changes to fans ventilating underground areas unless they have been authorized by the ERZ controller or ventilation officer to make the adjustments.

The Queensland regulation also covers a larger resource for appropriate VCD's for use underground. S350 makes reference to a "Schedule 4" chart which lists approved VCD's and the required design criteria for construction. A tabled version of Schedule 4 has been provided in Appendix B for reference. The Schedule 4 also has design criteria for mine seals which will be covered in the following section. S351 discusses the restrictions on adjusting a designated VCD that significantly alters the mines ventilation system. Adjustments may not be made unless authorized by the underground mine manager or the ventilation officer and prior notice must be given of the intended changes.

3.2.5 Seal design and construction

The Australian designation for seal design is similarly broken down into type based on the expected forces and installation of each seal as stated in S325. Schedule 4 "Ventilation control devices and design criteria" specifies the circumstances and required minimum overpressures, as summarized in Table 3. While this table is current as of July 1, 2013, it should be noted that the State of Queensland has changes to this provision on the 2013 legislative docket.

At least 30 days before an underground mine, or part of it, is sealed, the underground mine manager must give notice of the proposed sealing to a mine inspector and an industry, or site, safety and health representative for the mine as outlined in S236. This notice must contain the proposed sealing procedure, location of the seal in the mine, the area of the mine to be sealed, any evidence of ignition sources in the proposed sealed area, predictions of the rates at which methane and other gases will accumulate, and the gas monitoring procedures to be carried out during and after sealing. As stated in S328, if sealing becomes impracticable in the way previously stated, the mine manager must take reasonable steps to give notice to an inspector and safety and health representative of proposed design changes as soon as possible.

Seal Type	Circumstances for seal type	Seal Minimum Overpressure (kPa or psi)
Type B	Level of naturally occurring flammable gas at mine is insufficient to reach the lower explosive limit for gas under any circumstances	35 or 5.1
Type C	Persons remain underground when an explosive atmosphere exists and there is possibility of spontaneous combustion/incendive spark/ other ignition source	140 or 20.3
Type D	Part of an underground mine not covered by type B or type C seals, not including entrance seals	345 or 50.0
Type E	For sealing the entrance to a mine	70 or 10.2

Table 3: Design Criteria for Mine Seals from Queensland *Coal Mining Safety and Health Regulation 2001;* as of July 1, 2013 (psi conversions added)

A difference in content from the 30 CFR Part 75 is the inclusion of procedures for an emergency sealing scenario. S329 outlines these procedures and S330 details the requirements for evacuating a mine following sealing. In an emergency situation, the underground mine manager must immediately give notice to an inspector and safety and health representative of the proposed sealing, ensure that sealing is carried out in a way that achieves an acceptable level of risk, and as soon as possible after the sealing give an inspector notice of the seals completion. This notice must include the articles previously stated during normal sealing procedures. Additionally, a person must not, without written consent from an inspector, enter or remain in an underground mine after the mine, or part of it, has been sealed.

Emergency sealing of ventilation airlocks is outlined in S156, S157, and S157A. The site senior executive must ensure each entrance from the surface to the underground mine is capable of being sealed at the surface without requiring persons to travel in front of the entrance to seal it and, in the case of a vertical shaft, without requiring persons to travel the roadway at the bottom of the shaft. The site senior executive must also ensure that at least one of the entrances has a mine entry airlock, seal type E, capable of withstanding a pressure pulse of 70kPa passing through the entrance while the airlock is open. When the mine entrance is sealed, the site senior executive must ensure the mine has the capability to allow persons to reenter the mine, large equipment to enter or exit the mine through an airlock, and the facilities to use inertization equipment from a safe distance and monitor the atmosphere behind the seal from a safe distance.

The mine must also have in its Safety and Health Management System conditions on ventilating around sealed areas as described in S346. The system must outline ways of preventing intake air from traveling across the face of a permanent seal at the mine and minimize the risks of inrush and leakage of contaminants into intake airways. This does not apply if the any of the following conditions are present:

- Leakage through the seal is minimized and damage to the seal is prevented
- The seal is as at minimum a type C seal
- A monitoring device is installed in each intake airway on the return side of the seals over which intake air passes and the device triggers an alarm to warn affected persons

A monitoring device of this nature must be capable of detecting the general body concentration of oxygen, carbon dioxide (if present behind the seal in a concentration greater than 3%), and any other gas that is present behind the seal in a quantity or concentration that could create a risk if it entered the intake airway.

3.2.6 Coal dust explosion prevention and control

The Queensland regulation covers the spectrum of coal dust control and explosion prevention in sections S300, S301, and S302. The mine's Safety and Health Management System must provide for minimizing the risk of coal dust explosion and suppressing a coal dust explosion while limiting its propagation to other parts of the mine. The system must also include provisions for limiting coal dust generation, suppressing, collecting and removing airborne dust, limiting and removing coal dust accumulations on roadway and other surfaces in mine roadways, and deciding the stone dust or other explosion inhibitor application rate necessary to minimize the risk of coal dust explosion. The mine must have standard operating procedures for regularly inspecting, sampling and analyzing roadway dust layers and applying stone dust or another explosion inhibitor for suppressing coal dust explosions.

There are subsequent sampling frequencies and incombustible material contents based on the coal dust location to be analyzed. A summary of these locations is presented in Table 4: The underground mine manager must ensure the Incombustible Material Content (IMC, equivalent to TIC in U.S.) in roadway dust at the mine is kept to at or above the stated levels. He must also ensure each 50m length of a roadway that is being driven at the mine is stone dusted or treated with another coal dust explosion inhibitor immediately after and within 24 hours of the length being driven. These procedures do not apply to dust in a roadway where there is sufficient natural make of water associated with the mining operation to prevent coal dust explosion.

Records of roadway dust sampling are required under S303 and must contain the date the sample was taken, the location from which it was taken, the IMC, and the method used for analyzing the sample. The underground mine manager must also ensure the sample's IMC result is marked on a mine plan showing the boundaries of the mine ERZ locations as soon as possible after receiving the results. Section S302 applies if an analysis of a dust sample from an underground mine shows the dust does not comply with the IMC for the dust stated in Table 4. The underground mine manager must ensure the area from which the sample was taken is re-treated with stone dust or another explosion inhibitor within 12 hours for the panel roadway sections and within 7 hours for the other return and intake roadways. A record must be kept of the date and time when the area was retreated. Additionally, the underground mine manager must alert the ERZ controller for the area of the analysis results.

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 3rd Month

Table 4: Incombustible Material Content (IMC) and mine dust sampling frequency at various locations.

3.2.7 Inspections

An underground mine's Safety and Health Management System must provide for inspections. S310 provides the following:

- Who may carry out inspections and their competencies required
- The appointment of a sufficient number of persons to carry out inspections
- Standard operating procedures for the inspection

The procedures must include a risk assessment of the types of activities taking place at the mine along with provisions for the matters relating to safety and health to be covered in each inspection, recording inspection findings, and taking action as a result of the inspection findings. The procedure must also include a schedule of when inspections, including regular periodic inspections, must be carried out. Included in the regulations is "Schedule 5 – Matters to be covered in inspections" which has been provided as Appendix C of this paper. The Schedule 5 lists the items to reviewed by a person conducting an inspection and includes such items as checking for the presence of flammable gases, checking the condition of VCD's and aux. fans, as well as checking the adequacy of the ventilation and coal dust inertization in an inspection area.

As stated in S306, the persons capable of carrying out an inspection must be appointed by the underground mine manager in writing or, in the case of ERZ inspections, must be the ERZ controller for the zone. According to S307, before the ERZ controller carries out a regular inspection he or she must read the record of the latest regular periodic inspection findings and acknowledge in writing he has read the record. The duties of the person carrying out an inspection as outlines in S308 are as follows:

- If practicable, ensure anything that is found to be unsafe is made safe immediately
- If the thing cannot be made safe immediately, take all practicable steps to ensure each person in any part of the mine whose safety may be threatened by the unsafe thing is given immediate notification
- Erect a barrier to prevent persons from unknowingly entering a place where the unsafe condition exists
- As necessary, ensure operations in any part of the mine where a person’s safety is threatened by the unsafe thing are stopped
- If necessary, ensure each person in the part of the mine is withdrawn to a safe location

As soon as practicable after carrying out the inspection, the person must ensure a record is made of any readings taken and observations made during the inspection, the details of any unsafe condition found during the inspection, any action taken to remedy the unsafe condition, and whether the unsafe condition was made safe. If the unsafe condition is not made safe by the end of the shift on which the inspection was made, the person conducting the inspection must tell his or her immediate supervisor and give notice of the matter to persons on the next shift who may enter, travel or work in the area and persons who are required to make similar inspections during the next shift. As required under S311, if for any reason an inspection of part of an underground mine is not carried out when required under the standard operating procedure, the part is to be closed to all persons until the inspection is completed. Immediately after completing an inspection of an inspection district, the ERZ controller who carried out the inspection must ensure a notice of the inspection result is placed on a noticeboard located at the outby boundary of the district as stated in S310. This notice must state the date and time of inspection, the date and time after which the inspection ceases to be effective, and whether or not the inspection district was found to be safe.

An inspection district as outlined in S312 is part of an underground mine that a person may enter, travel or work in or in which a hazardous activity is taking place. For carrying out regular periodic inspections of the part, the underground mine manager must divide the part into districts having regard for the types of activities taking place, the hazards likely to be present, and the appropriate size to allow sufficient time for it to me inspected adequately. As required by S313, the underground mine manager must ensure the boundaries of each inspection district are defined in a way they can be easily recognized by each coal miner in the mine. He or she must also ensure the boundaries are shown on a plan of the mine and a noticeboard located at the outby boundary of the district.

3.2.8 Miscellaneous

Sections S367 and S368 detail the type and procedure for dealing with regulated contraband. Items considered contraband are tobacco used for smoking, cigarettes and cigars, any device used for smoking tobacco or drugs, any device, including a match, that may be used to strike, or could create, an open flame, arc or spark, and any article that is a prohibited article for the surface of the mine. A device used to strike an open flame, arc or spark when it is used for flame cutting or welding work is not a contraband item. An underground mine's Safety and Health Management System must provide for a procedure complying with the above stated regulations for searching a person to ensure the person has not taken, or does not take, contraband underground at the mine. The search procedures must include provisions for routine and random searches, the frequency, time and place for searches, the method of conducting searches including a requirement that the search be conducted by a person of the same sex as the person being searched, and ensuring that in time each of the mine's coal mine workers carrying out tasks underground will be searched.

3.3 South Africa

South African mine safety and health regulations are based on 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 references to sections in this document, the abbreviation of "SA-" will precede each part and section identification (i.e. Part A Section 2.1 from the document will be referenced as SA-A.2.1). The document is published by the Mine Health and Safety Inspectorate (MHSI) as part of the Department of Minerals and Energy (DME) under the Republic of South Africa. The document has been in effect since August 1st 2002 and provides regulation for all coal mines in South Africa as based on the MSHA.

In addition to the Guideline, mine operators must prepare and implement a mandatory Code of Practice (COP) on any matter that affects the health and safety of employees. These COPs must also comply with any additional, relevant guidelines issued by the Chief Inspector of Mines. As stated in SA-A-2.2, failure by the employer to prepare or implement a COP in compliance with this guideline is a breach of the MHSA. The DME does not approve or enforce COPs but only acts to ensure that employers provide healthy and safe working environments at mines. With this said, SA-A-3 states the objective of the guideline as to assist the employer of every coal mine to compile a COP, which, if properly implemented and complied with, would considerably reduce the risk of an ignition of flammable gas and will ensure the inertization of coal dust to 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 the required contents of the COP.

3.3.1 Ventilation, fans and VCDs

AS part of SA-C-8.1 the employer must ensure that a management system in place that prevents the accumulation of an explosive concentration of flammable gas. Layouts for production sections of the mine are required to show elements and parameters of ventilation control including VCDs, air quantities, air velocities, and airflow patterns, mining sequence plans that complement the ventilation flow, and the location of areas where there is the possibility of flammable gas. When using secondary mining (including longwalls), the design must include the same detail as for first mining and introduce a system for the ventilation of the gobs and bleeder roads. Measures must be taken to maintain proper air velocities in intake, return airways and belt roads to prevent dangerous accumulations of flammable gas. Additionally, as per SA-C-8.1.3, the mine must also keep record of the operation, monitoring, maintenance and inspection of main fans and have measures to ensure the health and safety of persons who may be affected due to unplanned stoppages of fans.

3.3.2 Sealing of abandoned areas

SA-C-8.1.8 calls for abandoned areas to either remain ventilated to prevent the buildup of an explosive concentration of flammable gas or be sealed. Measures must be taken to ensure that the planning and maintenance of ventilation, tests for flammable gas and stone dusting are conducted and kept up until the sealing of an area has been completed. The COP must also contain measures to ensure that seals built for the purpose of containing flammable atmospheres are installed with means for monitoring the atmosphere behind the seal after its completion. Per SA-C-8.1.9, seals must be designed to withstand a static pressure of 140 kPa (20 psi). If the area to be sealed is expected to stabilize within or remain in the explosive range for a long period, then explosion proof seals which are designed to withstand a static pressure of 400 kPa (60 psi) must be constructed.

3.3.3 Early detection of flammable gas

SA-C-8.2 covers the guidelines for providing early detection of flammable gases. The COP must contain an appropriate gas testing and gas monitoring strategy including the types of instruments to be used. Management must ensure that employees are competent to test for flammable gases and explosive mixtures of gases. A section on maintenance, calibration and record keeping in respect to the gas monitoring system and instruments must also be part of the COP, along with a section on the frequency, locations, and responsible persons involved with the testing for the presence of flammable gas or explosive mixtures. Procedures must also be established for determining a sufficient number of gas detection instruments and the actions to be taken if flammable gas is detected.

3.3.4 Preventing the ignition of flammable gas

The COP must include measures to prevent frictional ignitions that could lead an explosion. As directed by SA-C-8.3, these actions must include:

- Methods and procedures for the examination and changing of cutter picks

- Measures to ensure a continuous flow rate and pressure of water supply to the mining machines
- Measures to minimize the risk of ignitions during the extraction of gob areas (longwall or retreat pillar mining)
- Systems and procedures to ensure that a mining machine will not ignite flammable gas including pre-use checks, operational checks, maintenance programs, and any other means of preventing ignition
- Measures to ensure the use of electricity or electrical equipment does not create an ignition risk
- Compliance with relevant specifications where electric lighting could ignite flammable gas (permissible lighting equipment)
- Measures for the inspection and monitoring of abandoned areas and their atmospheres if spontaneous combustion could ignite flammable gases
- Measures to ensure the use of explosives does not create a risk of ignition
- Measures to prevent contraband (smoking utensils, lighters) from being taken underground
- Measures to ensure the use power tools or other handheld electrical devices will not create an ignition source
- Measures to prevent ignition if flammable gas could enter the workings under pressure

The South African guidelines provide minimal regulation in terms of specific procedures, parameters and standards but do dictate that these hazards must be addressed in the COP.

3.3.5 Coal dust suppression and inertization

South Africa typically uses stone dust to inertize coal dust for the prevention of dust explosions. SA-C-8.4 requires that the COP must include measures to limit the formation of coal dust at coal mining faces, conveyor transfer points and tramming routes. These measures must also provide for regular clean up and removal of coal accumulations in the face areas, conveyor belt roads, transfer points, traveling roads, return air ways and equipment prior to applications of stone dust. In SA-C-8.5.1, the guideline explicitly states the minimum inertization levels that must be adhered to in different regions of the mine. A summary of these locations and levels can be found in Table 5. It is important to note that for locations that are to be sealed off from the rest of the mine, the IMC must be obtained using stone dust.

As methods of maintaining the minimum IMC of the coal dust, the guideline mentions the use of water and stone dust as inertization tools. SA-C-8.5.2 states for a mine than intends to use water as an inertization method, they must specify the area of the mine to be treated, the method of applying water, the frequency of application, the method for determining that sufficient water has been applied, and the responsible persons who will ensure the requirements are adhered to in the COP. The COP must also contain provisions as outlined in SA-C-8.5.3 that ensure that suppliers of stone dust comply with the following minimum quality requirements:

- Stone dust must preferably 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 not more than 5% by mass of free silica or any other toxic substance in concentrations detrimental to health
- When dry, all stone 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 does not cake and must readily disperse into the air
- Mine operators must test each batch of stone 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.

Location in Mine	Minimum Incombustible Matter Content (IMC; by mass)
Intake airways inby the face area	80%
Intake airways outbye 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 outbye 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 stone dusting

Table 5: Incombustible Matter Content at Specific Locations in South African Underground Coal Mines.

SA-C-5.4.4, requires stone dust application within 10m from the working faces to ensures the underground workings are protected. This does not apply if 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.

The guidelines also have provisions under SA-C-8.5.5 covering the frequency of application for stone dust. For face areas, stone dust must be applied, and re-applied, as often as necessary to maintain the IMC by mass at a minimum of 80%. The frequency rate of application must not be less than once every four production shifts unless the rate of deposition of float coal or other sampling indicates that less frequent application is sufficient. During pillar extraction, stone dust must be applied at the same frequency rate as SA-C-5.4.4 for a face area but on a retreat basis. When total extraction operations are occurring, stone dust must be injected regularly into the mined-out area before the occurrence of the initial gob fall so as to inert the dust cloud that will be raised when it occurs. Additionally, for both longwall and shortwall mining, stone dust must be introduced into the return airway during coal winning.

3.3.6 Stone dust sampling program

Annex 1 of the Guideline is dedicated to the sampling procedures for stone dust applied underground. The first part of Annex 1 describes the sampling locations based on the area for which the sample represents. The second part of the annex details the methods for analyzing each of the dust samples. The two allowed methods are the Colorimetric method that assesses the amount of inert dust by its color and the Laboratory method that is similar to the Low Temperature Ashing analysis used in the U.S. Annex 1 has been provided in Appendix D for reference.

3.4 Germany and Europe

The following section discusses mandatory explosion protection standards in Germany. Many of these standards have been unified throughout the European Union and are therefore applicable for all E.U. mines.

3.4.1 Fundamental regulations in Germany

Mine explosion prevention regulations in the countries of the European Union have largely been standardized. Germany has been a forerunner in developing these standards so it makes sense to discuss the fundamental principles using German regulations as examples. All German states had their own sets of regulations ("Bergverordnung") for different mining applications. In the 1990s these state-specific regulations were unified throughout Germany.

The central mining regulation in Germany is the "Allgemeine Bundesbergverordnung" (ABBergV, 1995 general federal regulation on mining). It prescribes 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 explosions:

- §3: The mine operator must develop a safety and health management plan for the mine prior to commencing mining operations. This document must be made available to all employees.

- §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(7): In gassy mines, the operator must take appropriate steps to prevent explosion hazards as far as possible.
- §15(8): The mine operator must prevent the propagation of coal dust explosions with an appropriate arrangement of explosion barriers
- §16(1)2: The mine operator must ventilate the mine workings with an adequate safety margin in such a way that an atmosphere is maintained that minimizes explosion and respiratory health hazards.
- §16(5): The mine atmosphere must be monitored in all return airways, in airways with auxiliary ventilation and at comparable locations
- §16(6): A mine ventilation plan must be prepared, kept up-to-date and available for inspection.
- §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 explosion prevention.

- The operator must provide appropriate measures to determine and monitor the concentration of flammable gases and provide for alarm systems and automatic shut-off devices for electrical equipment and internal combustion engines. Atmospheric monitoring results must be stored and kept on file for an appropriate time.
- Flammable dusts (coal dust) must be reduced, removed, neutralized or adhesion-bound.
- No smoking, 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 Steinkohlenberg-werke” (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 5 covers roof support and mine seals; section 6 covers mine ventilation, and section 7 covers measures to prevent coal dust explosions. Excerpts from this regulation follow.

- Section 3, §9: Mine operators must provide measures to quickly erect ventilation controls in the mains. Materials to build such controls 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 5, §26: Abandoned areas of the mine must be sealed with explosion-proof seals.
- 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 6, §33(3): Return air from gate road development with auxiliary ventilation may only be used for longwall face ventilation if the methane content does not exceed 0.5 %.
- Section 6, §35: The maximum permissible methane content is 1%. Exceptions may allow up to 1.5%. Maximum air velocity is 6 m/s (1,200 ft/min.) All air splits must be equipped with devices to measure air quantity and climatic data. In all face areas, air quality recorders must be provided that measure CH_4, O_2, CO, CO_2 and H_2S.
- Section 6, §36: All mine officials must carry handheld CH_4 detectors and must make measurements in their areas of responsibility. Excessive methane content must be reported and, if it cannot be mitigated, miners must be withdrawn from the affected areas.
- Section 6, §37: Ventilation conditions determined in the mine must be recorded and record books maintained for inspection for six months.
- 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

It must be stated here that most European mines use single entry gate road development for their longwall operations. These development entries are generally arched and provide cross sections of up to 30 m^2 (320 ft^2) with base widths of up to 6 m (20 ft). 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 norm. 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. Also, the single-entry design improves ventilation system efficiency as it virtually eliminates leakages.

Single-entry development also simplifies the design of the mine ventilation system and its monitoring. It also reduces the opportunities for damaging ventilation controls in a mine explosion, as much fewer controls are necessary.

An important supplementary document governing the prevention of mine explosions is the German and European standard DIN EN 14591. This standard regulates the design and construction of ventilation doors suitable to withstand an explosion pressure of 2 bar (200 kPa or 29 psi), 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, partial face cutting machines used to mine the arch-shaped development entries.

Governing principles of mine explosion prevention in Europe are as follows:

3.4.2 Elimination of all ignition sources

All electrical equipment used in underground coal mines must be designed explosion proof (Ex) or intrinsically safe. This goes for all areas underground with limited exceptions. Trolley wire locomotives are prohibited. Flame cutting and welding as well as electric arc welding are prohibited, again, with limited exceptions, for example, underground central shops ventilated directly to return air. Of course, smoking and any form of open lights are prohibited as well.

3.4.3 Dilution of methane throughout the mine to below 1%.

Methane contents up to 1%, with exception 1.5%, are permitted under certain conditions, as outlined earlier (see BVOSt, 2001).

3.4.4 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 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.

DIN EN 14591-2 prescribes the arrangement and design of passive water trough explosion barriers throughout the mine. Water trough barriers are arrangements of 80-liter (20-gallon) plastic troughs suspended in the upper half of an arched mine entry. Figure 4 shows a typical arrangement of water troughs in an arched entry.

During a mine explosion (both coal dust or methane) these troughs are blown down by the pressure wave that runs in front of the explosion flame and quench the flame, preventing it from propagating further. A full size water trough barrier requires 200 kg of water per square m of entry cross section. A large entry with 30 m^2 would thus require an arrangement of 150 individual, 80-liter containers. A “concentrated” barrier has these water troughs arranged on several rows of shelves. The distance between rows is typically 2 m and the total length of the shelf arrangements must exceed 20 m. The volume of water must be at least 5 liters per m^3 of total entry volume for the entire barrier.

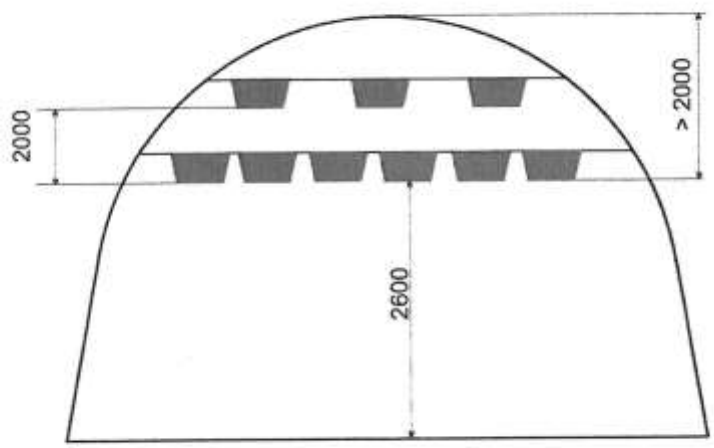

Figure 4: Water troughs suspended on shelves in an arched entry. Dimensions indicated in mm, from DIN EN 14591-2.

Besides the concentrated barriers, DIN EN 14591-2 also provides for groups of explosion barriers that are arranged as "distributed barriers". Troughs are erected on shelves every 3 m (10 ft), and the water amount is at least 1 liter per m^3 of total entry volume for the group. Groups are arranged every 30 m (100 ft)

Barriers can be arranged in a variety of patterns as provided in DIN EN 14591-2. The regulation specifies what type of barriers are required at what distances from identified explosion sources (primarily, mining faces). The following rules apply:

- Concentrated barriers must be erected every 400 m (1,300 ft) along each mine entry. If distributed barriers are used, their first row of troughs must be placed within 30 m (100 ft) of a concentrated barrier or intersection.
- Intersections (3, 4 or more ways) must have a concentrated barrier in each leg within 75 m (250 ft) from the intersection or a distributed barrier where the first row of troughs must be within 30 m (100 ft) from the intersection. Figure 5 shows an example of concentrated and distributed barriers in the legs connecting at a 4-way intersection.

It should be noted here that, in past years, European mines frequently also used stone dust barriers. Similar to the water troughs, stone dust was arranged on shelf boards that would easily topple during an explosion. The dust quantity required was 400 kg/m^2 of entry cross section. The quenching effect of stone dust barriers is usually more effective since the fine dust remains suspended in air much longer than water droplets, making the exact timing of the barrier release less critical. The main disadvantage of using stone dust was that the dust would eventually absorb moisture from the mine air and coagulate, rendering the quenching action ineffective. Also, dust barriers cannot be used in entries with high ventilation airflow velocities. For these reasons, the use of stone dust barriers was discontinued in German Mines starting in the 1980s.

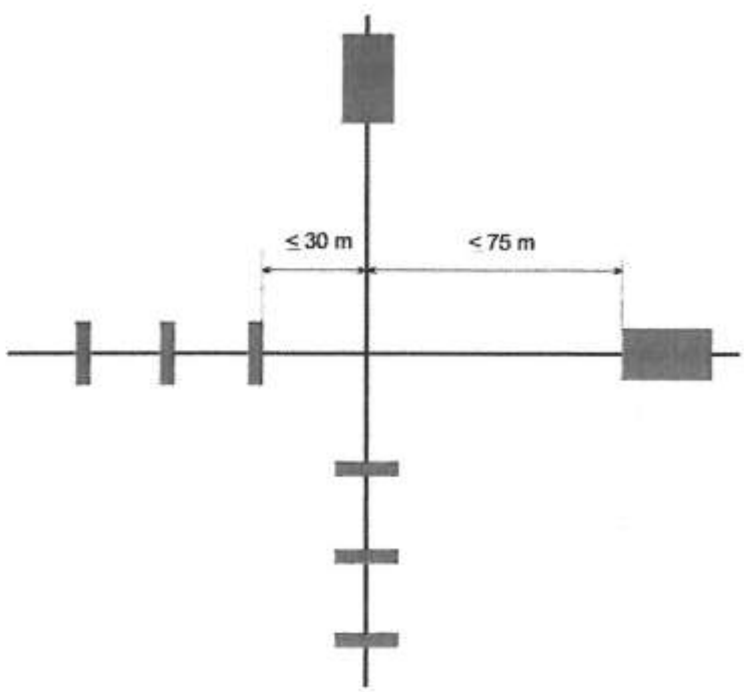

Figure 5: Arrangement of concentrated (large blocks) and distributed (small blocks) water trough explosion barriers around an intersection

3.4.5 Mine-wide atmospheric monitoring and fire management

Mine-wide atmospheric monitoring for standard gases (CH_4, O_2, CO and CO_2; H_2S and other mine gases as necessary) is practiced in all mines. Due to the simplicity of the ventilation system using single entry development, mine engineers can get a good assessment of the mine air quality by monitoring each air split before it combines with another air split. Since leakage is virtually non-existent, this monitoring can be accomplished with a limited number of monitoring stations.

The simplicity of the ventilation system also makes it easier to pinpoint the source location of fire gases, chiefly, CO. In case of a fire, it is simple to install inflatable balloon seals in the mine entries and inject nitrogen to flood the area and extinguish the fire with pinpoint accuracy.

3.4.6 Binding coal dust with hygroscopic salts

The European philosophy of preventing coal dust explosions differs from that used in the U.S. and Australia. Europeans primarily use hygroscopic salt solutions ($CaCl_2$ and $MgCl_2$) to coat all surfaces in the mine where explosive coal dust can settle.

The following information was taken from a variety of internal training documents supplied by Hermülheim (2011) at Deutsche Steinkohle AG.

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. Surfactants can be added to improve the adsorption of coal dust particles since coal dust is hydrophobic. They also increase the spray treatment intervals.

Salts can be applied in liquid, powder or prills form. The amounts of salts required are smaller than the amounts of rock dust required for equivalent protection. Solutions are at concentrations of 30% salt content. Disadvantages of salts are that they are corrosive and can make mine floors slippery.

Both $CaCl_2$ and $MgCl_2$ are frequently used in the food industry and do not constitute significant health hazards. Inhaling, eye or skin contact during application can be irritating and must be avoided. Full PPE (face shield, gloves, rubber apron, rubber boots) should be worn when applying salts in solution, dust or prills form.

When spraying salt solutions with a fine droplet spray (not: fog), the advantage is that all surfaces within the mine entry can be covered. Existing dust should not be washed off during spraying because it provides a support matrix from the salt solution. The solution can be sprayed on at a thickness of 0.4 mm (0.02 in.) using a 60° full cone spray nozzle running at 500 kPa (70 psi) and 16 l/min (4 gpm) flow rate.

Another advantage of the salt spray method is that it can be fully automated with spray nozzles permanently installed and activated by a timer system.

The dust binding capacity of both $CaCl_2$ and $MgCl_2$ solution lies between 100 and 200 g/m^2 and day. Total dust binding capacity is 1.3 kg coal dust per kg of spray solution The dust binding capacity of prills is about 2 kg coal dust per kg prills. For comparison, to achieve 80% total inert content, 1 kg of rock dust can only inertize up to 0.25 kg of coal dust so salts are much more effective.

3.4.7 German regulations for mine dust sampling

Mine dust sampling in German mines is regulated by the regulation "Technische Richtlinien Staubprobenahme" (1980). It should be noted that rock dust is rarely used in German mines anymore; it has been replaced by the application of hygroscopic salt solutions, as described earlier.

Regulations require that mine dust sampling must be done at least monthly by a trained, qualified person. All mine entries in which there is explosible coal dust present which may be entrained in air must be sampled. Samples must be analyzed for combustible content. A maximum of 20% combustible components are permitted which is equivalent to the U.S. rule of minimum 80% incombustible content. All mine dust sampling must be documented in record books.

Sampling locations must be designated based on identified dust sources. Coal dust sources include loading points, conveyor transfers, crushers, working production sections, development sections, longwall move operations, ventilation doors and regulators, ventilation split points, sudden reductions in entry cross section, haulage equipment, and all belt entries, especially those ventilated against the direction of haulage.

Sampling begins downwind from each identified dust source and continues until the effect from this dust source has died down (most dust has settled) or a new dust source has been identified.

Sample locations must be selected as follows: The first samples must be taken 30 to 70 m (100 – 250 ft) downwind from each identified dust source. If the designated sampling area is longer than 400 m (1,300 ft), additional samples must be taken.

If sampling results indicate that additional rock dust needs to be applied in the sampled area, an additional sample must be taken 100 to 150 m (300 to 500 ft) downwind from the freshly dusted area after dusting.

It should be noted here that the sampling locations are chosen based on the run-up characteristics of a propagating coal dust explosion. Based on Cybulski (1975) and other research, coal dust explosions need a so-called run-up distance of 200-400 m (650 – 1,300 ft) before the explosion becomes strong enough so that it can propagate.

The regulation provides for the following exceptions: Longwall production faces, longwall startup entries and surface shafts. Also, belt transfer areas are exempt if they have been treated with dust-binding salts, which is usually done. Areas that are naturally wet so that coal dust cannot be entrained are also exempt. Exempted areas must still be checked to verify that the conditions for exemption remain valid.

The mine dust sampling procedure is prescribed as follows: At each sampling location, samples are taken over an entry length of 2 m. Two samples of >10 cm^3 (0.6 in^3) dust each are taken at every location. One sample is taken from the floor and one from the higher locations. The sample from the higher locations is taken by brush and combined from several areas where dust settles, at knee height, chest height and reach height.

The floor sample should be combined from several points and may be reduced by sieving at 5 mm (approx. 4 mesh or 0.2 in.) Larger pieces of coal, rock or other contaminants may be removed. In areas with high air velocities care must be taken to prevent loss of dust that is blown away. Samples must be stored in suitable, marked containers or bags.

The testing procedure is similar to the low temperature ashing method used in the U.S. A ~10 g (0.35 oz) sample is dried at 106°C (223°F) until its weight no longer changes, then cooled off in a desiccator. After weighing to 1 mg accuracy, it is then heated heat at 500°C (932°F) until weight no longer changes. Again, the sample is cooled off in a desiccator and weighed to 1 mg accuracy. Weight loss equals the combustible content by weight. In difference to U.S. the water loss during initial drying is not determined and is not credited as incombustible content.

Rock dusting and sampling must be conducted based on an approved plan of operations. The mining authorities conduct their own sampling as well.

3.4.8 German regulations on dust quality and testing of rock dust

Although German coal mines no longer use rock dust for explosion barriers, the following regulations 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) are of interest in this context since they ensure that the quality of rock dust is consistent and that the dust does not cake or coagulate if it absorbs moisture from the mine air. Rock dust used in German mines was primarily composed of limestone or dolomite dust.

The first important criterion is the particle size distribution curve of the which must lie within the cross hatched area marked “A” of the RRSB diagram according to DIN 66145 shown in Figure 6: The particle size distribution is determined as follows: >0.5 mm (0.02 in.) by dry sieving, >0.071 mm to <0.5 mm (0.003 to 0.02 in.) by wet sieving and <0.071 mm (0.003 in.) by sedimentation analysis or equivalent methods. Testing follows applicable DIN standards that are typically equivalent to ASTM standards.

If any part of the size distribution curve lies in the simple hatched area “B”, the rock dust is too fine and must be treated with hydrophobizing agents to prevent coagulation. These agents must be chemicals that do not present a health hazard.

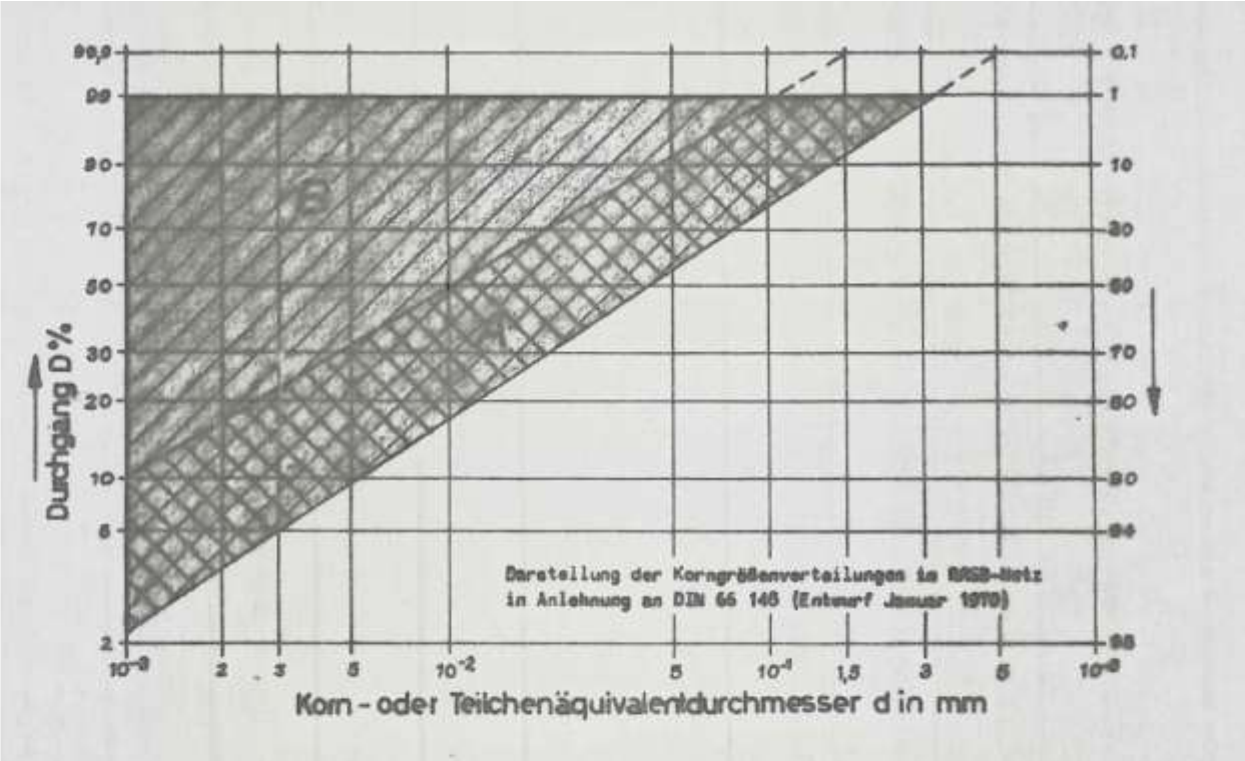

Figure 6: RRSB Diagram for rock dust size distribution based on German regulations. Grain size equivalent diameter is shown in mm on the abscissa while the ordinate shows the percentage passing the sieve.

If the dust passes the size distribution criteria, it must be chemically analyzed for the following quality criteria:

- Maximum 3% by weight components that are insoluble in hydrochloric acid (quartz and other silicates, for example).
- 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) must be determined since it will influence entrainability or caking. Electric conductivity of the electrolyte is determined since it is a sensitive test for water-soluble components. A conductivity of ~200 µS/cm indicates >0.05% soluble salts or >0.15% $Ca(OH)_2$.

If the conductivity is >200 µS/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 in this list, the manufacturer must file an application with the mining authorities that hygienic testing and certification that the rock dust does not present a health hazard. In addition to the full analysis required for initial approval, a simplified chemical analysis is required of every batch of rock dust delivered to the mine.

For this simplified analysis, 1 kg of sample must be analyzed for every 10 tons delivered. For bagged dust, individual samples may be combined to a maximum sample size of 2 kg. Bulk dust must be continuously sampled during unloading. The maximum sample size should not exceed 5 kg.

The following parameters must be determined in the simplified analysis:

- Determine the particle size distribution: Two test points are taken by wet sieving, at 0.071 mm and at 0.025 mm. Hydrophobized dust should first be soaked in acetone to dissolve the chemical coating.
- Determine the components soluble in hydrochloric acid
- Determine the electric conductivity of electrolyte. If the conductivity is >200 µS/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 report must be kept on file by the mine. Remaining samples must be retained for two months.

3.4.9 Seal design requirements in Germany

Seal design follows the “Abdämmungs-Richtlinien” (2013; seal design guidelines) for the State of North-Rhine Westfalia. It should be noted that other German coal mining states have identical requirements.

As a general requirement, seals must be constructed following an approved sealing plan that also regulates the ventilation changes required in conjunction with erecting the seal. All seals must have sampling lines installed so that the sealed atmosphere can be monitored. Often, seals include an access pipe (manhole) with an explosion proof airlock cover so that the sealed area can be accessed by mine rescue teams even after sealing.

Seals must be monitored and the atmosphere sampled following construction and tested for leakages.

Explosion proof mine seals are designed to withstand a static pressure of 500 kPa (72 psi). The structural designs are based on a safety factor of 2.0, therefore requiring a design static load of 1 MPa (144 psi).

The required thickness t for plug-design seals that meet this structural requirement can be calculated as follows (for horizontal and slightly inclined seals):

$$t = 0.7\ a / \sqrt{(\sigma_{bz})}$$

where

t = seal thickness (m)

a = largest entry dimension (width or height; m), and

σ_{bz} = flexural strength of the seal construction material, MPa.

Vertical seals (in shafts) require a coefficient of 0.8 instead of 0.7 in the equation above. The equation implies a safety factor of 2.

4. Methane and coal dust explosion prevention best practices

This section aims at identifying and outlining different explosion prevention and suppression practices used throughout the world and discuss their effectiveness at preventing a methane or coal dust explosion.

4.1 Reduction of methane and coal dust

The first approach towards preventing a coal dust or methane explosion is to reduce the amount of methane and combustible dust from the active mining area. As discussed in the regulations section of this report, ventilation plays a key role in diluting the concentration of methane and dust within the mine. All of the regulations discussed agree in diluting the methane content in the ventilation air below 1%, with exceptions provided to go up to 1.5 or 2%. Most standards require developing formal ventilation to ensure proper air quantities are being supplied to the active mining areas. Besides target quantities, the ventilation plans usually also show all ventilation controls, fans, air quality monitoring equipment, dedication of entries to fresh or return air, and climatic data if temperatures are high.

Reducing the amount of flammable coal dust is not as simple and not as strictly regulated. Coal dust is best managed at the source, i.e., at the mining face where coal is cut, or at conveyor transfers, crushers, longwall shields and loading points where dust is created as the coal is dropped and/or crushed. Point source dust from cutting, crushing and conveyor transfers can usually be effectively controlled by either water sprays, scrubbers or a combination.

Other areas where fine coal dust is produced include conveyor belts and exposed coal ribs. If wet coal dust sticks to the carrying side of a conveyor, it can be carried past the discharge point and remain on the underside of the belt, where it dries and gets ground up into a fine powder by the bottom rollers. Exposed coal along the entry ribs dries and tends to produce fine dust. Deterioration of coal ribs can contribute to this dust creation. Both phenomena create extensive sources of fine dust that are difficult to control at its source.

On equipment such as longwall shearers, conveyors and shield support, continuous miners, loading points, crushers and conveyor transfers, and water sprays act as a first barrier to prevent a coal dust or methane explosion from occurring. Scrubbers can be installed on continuous miners help to reduce the amount of fine coal dust deposited into the return airways by using a wet vacuum fan to trap the coal dust as it passes through the scrubber. Water sprays act in a similar fashion by binding coal dust near its point of creation (cutter picks, crusher bits, transfer points etc.) and preventing the ventilation air from carrying the dust away and depositing it throughout the mine. The water spays also serve the function of cooling the cutter picks on the equipment to reduce the occurrence of hot streaking or sparking when the picks cut into abrasive strata such as sandstone.

4.2 Coal dust inertization with stone or rock dust

Coal dust inertization with stone or rock dust is an effective coal dust explosion prevention technique practiced in most coal mining countries. Regulations in most countries examined agree that mine dust must contain a minimum TIC of 80% inert dust in order to prevent the propagation of a coal dust explosion.

A review of select incombustible matter requirements has been provided in Table 6 using information from Cashdollar et al., 2010, updated with current U.S regulations. Several of these regulations have conditional requirements that require an increased TIC when closer to the active mining face or if methane is found in the ventilation air. Other regulations relax the TIC requirement in areas of the mine where initiating methane explosions are less likely, for example, in fresh air, intake airways.

It should be noted that Cybulski (1975) and other researchers (see also Cashdollar et al., 2010) have found that TICs of 80% may not be sufficient to protect a mine form a coal dust explosion. This applies especially if:

- The initiating explosion is strong or, in case of a propagating dust explosion, the dust explosion has had a long run-up and has developed great momentum
- 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 coal dust size distribution contains a large portion of dust finer than 74 μm (200 mesh). Cybulski tested coal dust where 85% of the dust passed 74 μm (200 mesh). Even though it is unlikely that such dust would be found in typical coal mines, Cashdollar's 2010 study clearly 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.
- The amount of volatile matter in the coal is high: The higher the volatile content, the more explosive is the dust because, as the dust particles are heated by the flame, the volatile matter cooks off and is ignited, propagating the flame. Solid coal particles typically will not combust since their exposure time to heat and flame is too short. This explains that anthracite coal with an extremely low volatile content (typically less than 5%) is unlikely to propagate a coal dust explosion.

The inert material mixed with the coal dust, in the U.S. commonly referred to as "rock dust", is typically limestone or dolomite dust but could be other stone dust as long as it is substantially free of silica (quartz) and it does not coagulate or cake if it absorbs moisture. The inertization mechanism works in two distinct ways:

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

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

Table 6: Summary of Incombustible Matter Contents for Various Nations

Note: After Cashdollar (2010) with changes made to United States where regulation changed in 2011.

Although the entrainment of mine dust is turbulent and mixes the dust particles thoroughly, for best results, the mine dust should ideally be already well mixed in-place.

Figure 7 shows a schematic depiction of a propagating coal dust explosion in 4 phases. Phase 1 shows a flammable methane-air atmosphere and a layer of coal and rock dust on the mine floor. Phase 2 shows the pressure wave (blue arcs) emitted from the methane-air explosion that scour up coal and rock dust in a turbulent cloud. The turbulence mixes coal and rock dust particles. The function of the rock dust particles is to provide thermal shielding and to inhibit the coal particle combustion process. If there are at least 80% by weight rock dust particles floating in the turbulent mix (80% TIC), this will shield the coal particles and quench the explosion.

Phase 3 shows the initial flame development, heating the coal dust and cooking off the volatile matter from the particles. As the coal particles burn, they create heat and increase the rapid expansion of the mine air. This continues the pressure wave that scours up additional dust, which is known as a propagating coal dust explosion.

Phase 4 shows a fully developed, propagating flame that will occur if insufficient amounts of rock dust are scoured up. In the UBB explosion, the flame propagated through 80 km (260,000 linear feet) of mine entries with a total flame volume of 880,000 m^3 (31 million ft^3). The explosion likely lasted for several minutes as the flame speed was probably subsonic based on MSHA's (Page, 2011) investigation and pressure estimates.

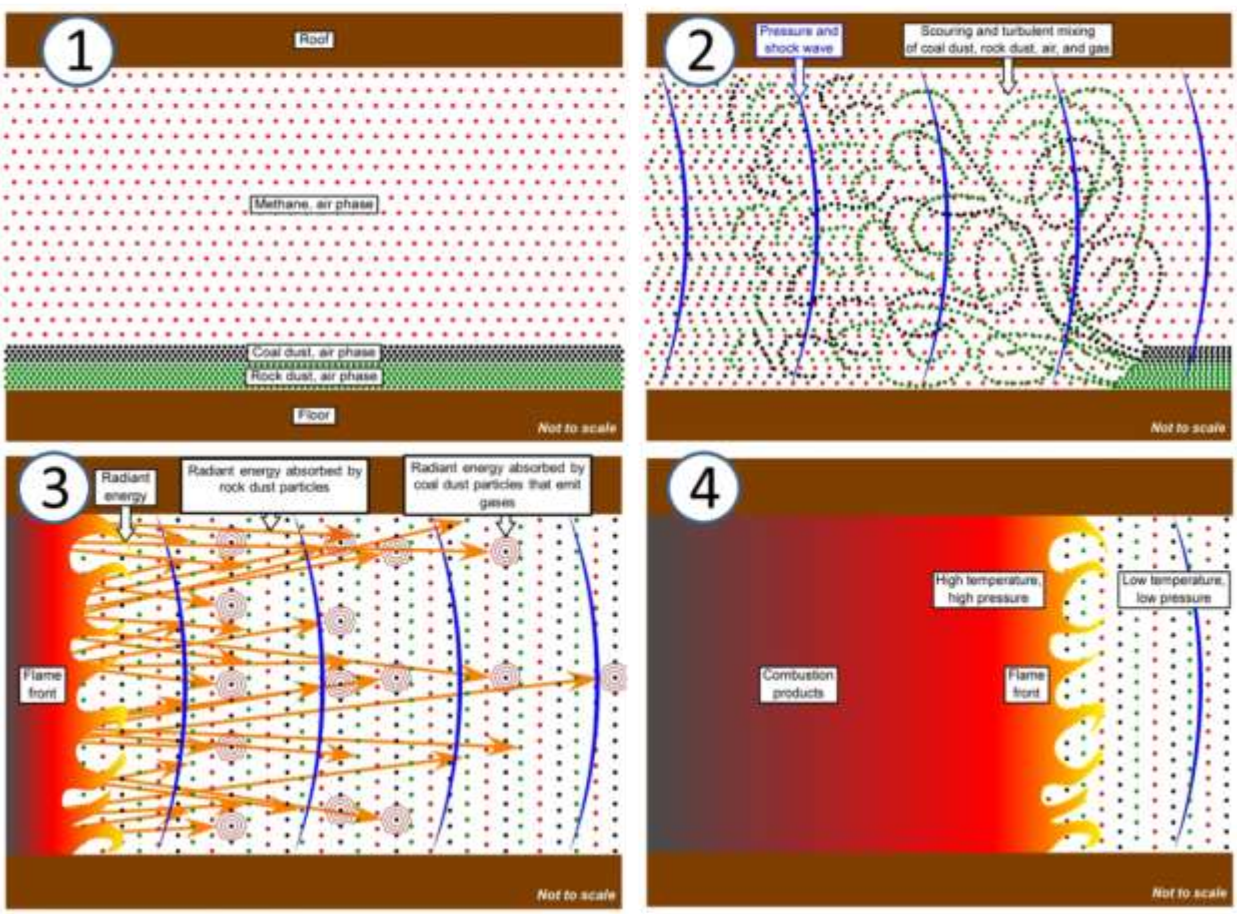

Figure 7: Schematic depiction of a coal dust explosion in four phases

As shown in Phase 2, in order to participate in or extinguish an explosion, mine dust must first be entrained in air. The air blast from an explosion typically scours up only the top 2 – 3 mm (about 0.08 to 0.12 in., Harris et al. 2012), as illustrated in Figure 8.

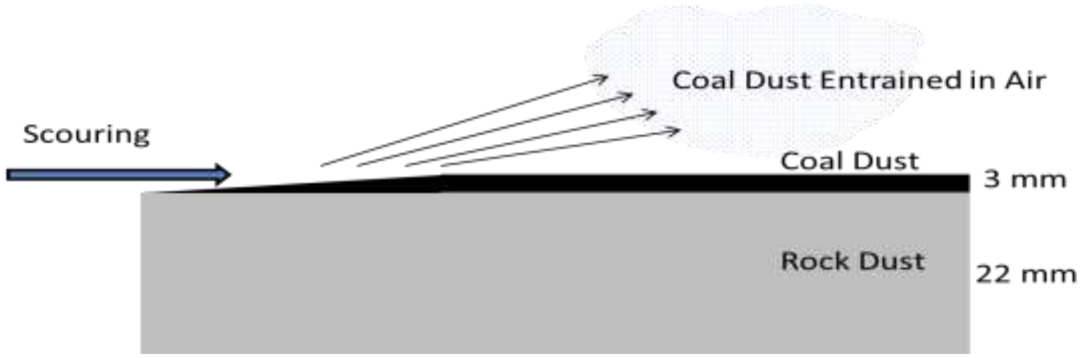

Figure 8: Schematic cross section view of coal dust layered over top of rock dust. An explosion will primarily scour up and entrain the top layer of mine dust.

Therefore, the danger with coal dust explosions is caused by layering. If rock dust is applied in batches every few days, fine coal dust tends to form thin layers of pure coal dust on top of the rock dust. Research by Sapko et al. (1987), Edwards and Ford (1988, p. 8) and other researchers has shown that a 0.12 mm thin top layer (0.005 inch, about the thickness of a single sheet of paper) of coal dust is already sufficient for propagation of a coal dust explosion. Layering also exposes a systemic flaw in the mine dust sampling process currently employed in the U.S. 2013 MSHA inspector guidelines (MSHA, 2013, page 5-12 ff) require mine dust sampling to be conducted with a brush and dust pan, removing the "uppermost 1/8th inch (approximate depth)" of the mine dust layer, as illustrated in Figure 9.

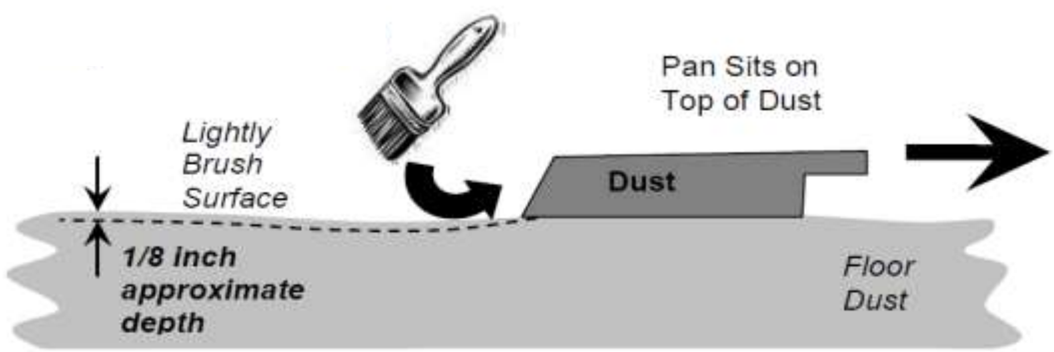

Figure 9: Illustration of Mine Dust Sampling Procedure (modified from MSHA, 2013[15])

While the 2013 guidelines are a significant improvement over the former scoop sampling method to 1-inch depth, the problem of sampling to a given target depth is problematic: Per the findings by Edwards[14], 0.120 in. of rock dust overlaid by a 0.005 in. layer of pure coal dust (thickness of a single sheet of paper) would still be considered explosive even though a 1/8th (0.125) inch deep sample would yield 96% inert content. Furthermore, the brush action is questionable since the bristles may be able to dislodge dust particles with much greater force compared to entrainment in air flow. Yet, only those dust particles entrained in air can participate in and propagate an explosion. Finally, it is difficult to consistently maintain the required sampling depth of 1/8th inch with a scoop and brush.

Finally, a valid method to assess whether wet or coagulated ("caked") mine dust will participate in an explosion does not exist in the U.S. 30 CFR §75.2 requires that the rock dust should be able to be dispersed by a "light blast of air" but this is not a scientific definition so it is currently up to wide interpretation of what "caked" rock dust means. Currently, wet areas may "be bypassed" (MSHA 2013, p. 5-17) from sampling though 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 had had a long-enough run-up path.

Other materials used for coal dust inertization are clay slate dust, gypsum and various chemical dusts. Tests have been conducted by researchers around the world to determine the effectiveness of various inerting materials in preventing coal dust explosions, see Cybulski (1975), Hertzberg and Cashdollar (1987), Sapko et al. (1987) and Cashdollar (2010), among others. The effectiveness or rock dust inertization is usually measured in terms of the amount of the inert material required to inhibit the propagation of the coal dust explosion. This value is then expressed as a % TIC (total inert content) which is the total percentage of inert material on a mass basis.

4.2.1 Application of rock dust

When applying rock dust, it is important that the rock dust is mixed thoroughly with the coal dust. As outlined earlier, any layering of coal dust on top of rock dust may render the inertization ineffective. Only the top 1/8-inch of mine dust is entrained in an explosion and therefore critical in the prevention of dust explosions (Nagy 1965).

To avoid layering, especially downwind from production faces where large amounts of coal dust are being produced, rock dust should be applied continuously rather than in batch applications. If batch application is used, the frequency of rock dust applications must be increased while the quantity may be decreased as long as the mandated TIC is maintained.

In batch applications, rock dust is applied pneumatically using a variety of compressed air-based systems. Mobile bulk rock dusters typically feature a large bulk tank holding up to 4 tons of dust. A screw feed system feeds the dust to a mixing chamber from which it is blown out with compressed air. Air hoses typically are of 2 in. to 3 in. (50 to 75 mm) diameter and the nozzles are controlled by hand, and operating pressures of 40 to 125 psi (280 to 900 kPa). When fed with 100 to 250 cfm (2,800 to 7,000 l/min) of compressed air, bulk dusters can discharge 400 to 600 lb/min (180 to 270 kg/min) dust.

The bulk tanks are track-mounted, suspended on monorails or run on rubber tires. The systems feature on-board compressors and diesel engines. Mines frequently have underground fill stations to load the bulk dust from surface silos connected via a borehole. Figure 10 shows a picture of a wheel mounted bulk tank rock duster that would be moved through the mine.

Some manufacturers also offer fixed, permanently installed bulk dusting systems, often with multiple pressurized bulk tanks installed throughout the mine. These systems can be operated automatically. Figure 11 shows a schematic view of a mine-wide automatic rock dust system offered by A.L. Lee Corporation.

Figure 10: Wheel mounted bulk rock duster (A.L. Lee Corp.; www.alleecorp.com)

Figure 11: Mine-wide automatic rock dust system, (A.L. Lee corporation, www.alleecorp.com)

A disadvantage with bulk dusting is that dust applications in intakes must generally be scheduled during an off-shift since the ventilation air will carry the dust into the face areas where it may cause respiratory or visibility problems. These machines also usually require periodic vessel pressure inspections to ensure proper safety and operation standards. Figure 12 shows a small compressed air duster (left) and large track mounted compressed air duster used commonly in European mines (right).

Smaller batch rock dusters (in the U.S. often referred to as bantam or slinger dusters) are used to spot dust in face areas. These dusters are equipped with a hopper holding about 100 lb of dust, a small rotary compressor with screw feed and are typically loaded with bagged dust from 40-lb (18 kg) bags.

Figure 12: Small (left) and Large (right) Compressed Air Duster Units. Source: RAG Hauptstelle für das Grubenrettungswesen (RAG Mine Rescue Headquarters), Herne, Germany

Continuously running dusters (also called trickle dusters) are used to feed a steady stream of rock dust to the exhaust air from a mining section. The feed must be adjusted so that it delivers at least 4 lb. of rock dust for each lb. of coal dust contained in the exhaust air. In continuous miner development sections trickle dusters are usually installed in the return outby the last open crosscut, often feeding directly into the exhaust of the auxiliary face fan. On longwall sections, trickle dusters are generally installed at the tailgate drive so that they can continuously add rock dust to the exhaust air. Trickle dusters are fed with bagged rock dust. On longwall sections it can be logistically difficult to provide bagged dust at the tailgate and maintain the duster so some operators have gone to feeding dust from the headgate side through a hose along the face. Figure 13 shows a rubber tire mounted trickle duster with standard capacity of 400 lbs produced by A.L. Lee Corporation.

Figure 13: Rubber-tire mounted trickle duster commonly found in US mines (A.L. Lee Corp.; www.alleecorp.com).

4.2.2 Rock dust sampling

Fundamentally, verification of TIC should be done by sampling the mine dust that is entrained in air in front of an explosion. Ideally, a sample would be captured from the air by stirring up the mine dust with a blow of air that simulates the entrainment occurring in an explosion. As outlined above, MSHA guidelines (MSHA, 2013, page 5-12 ff.) require sampling mine dust with a brush and dust pan, removing the “uppermost 1/8th inch (approximate depth).” Other countries have similar regulations, including requiring experienced, trained persons to collect the samples.

Sampling locations must be carefully chosen depending on coal dust source locations. When sampling, 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 much more easily than floor dust so it is potentially more hazardous, as Sapko et al. (1987) have pointed out.

4.3 Binding coal dust with hygroscopic salts or pastes

Besides stone dust inertization, a second, equally effective way to render flammable coal dust harmless is to bind it and trap it on moist surfaces. As outlined in section 3.4.6, 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 prills form. Surfactants can be added to improve the adsorption of coal dust particles since coal dust is hydrophobic. They can also increase the spray treatment intervals.

A major disadvantage of salts are 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.

For more detail on coal dust inertization with salts, please refer to section 3.4.6.

4.4 Passive explosion barriers

Explosion barriers are used to provide explosion suppression for the area of the mine that is outby the active mining area. Passive barriers are installed to provide supplementary protection against coal dust explosions and triggered by the explosion itself. There are two types of passive barrier have been developed and extensively tested at a number of research institutes, the stone dust and the water barriers. These have been deployed in mines throughout Europe, Australia and South Africa.

Passive barriers use a suppressant material that is dispersed by the dynamic pressure wave that precedes a flame. The barriers are classified by the type of extinguishing agent used, commonly rock dust or water, and the manner in which they are deployed. The two deployment methods are concentrated barriers and dispersed barriers. An overview of passive barrier loading requirements is summarized in Table 7 (DuPlessis and VanNiekerk 2002). A large amount of the information in this section is derived from the South African regulations on passive barrier systems with references to changes in different international practice.

Country	Mass Loading			
	Stone Dust (kg/m^2)		Water (l/m^2)	
	Non-gassy	Gassy	Non-gassy	Gassy
Australia	200	200	200	200
Belgium	-	400	-	200
Canada	-	200	-	200
Czech Republic	200	400	-	-
Germany	-	400	-	200
France	-	400	-	200
Japan: *Light* *Heavy* *Extra Heavy*	 0.1 m3/m2 0.3 m3/m2 0.4 m3/m2	-	-	 100 300 400
South Africa	-	200 light 400 heavy		200
Romania	-	400	-	200
United Kingdom		200 light 400 heavy		200 min.
Soviet Union	200	400		

Table 7: Passive Barrier Loading Requirements, in kg per m^2 of entry cross section area (after DuPlessis and VanNiekerk, 2002).

4.4.1 Shelf type stone dust barriers

There are a number of different shelf stone barrier designs based on research work conducted by a number of countries including Germany, Poland, the United Kingdom, and the United States. The most commonly used is the Polish stone dust barrier as tested by Cybulski. More than 1,700 tests were conducted as published in 13 scientific bulletins. The shelves on which the dust is placed are suspended in such a way that they are easily tipped over by the explosion forces, creating a large cloud of stone dust that suppresses the flame. Variations of the Polish stone dust barrier contain multiple, individual boards that aid in the dispersion of the extinguishant. A sample design is shown in Figure 14.

There are three quantities used as a design criterion for 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/m^2); this is normally used as the regulatory requirement for the design of stone dust barriers; typically 400 kg/m^2 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.

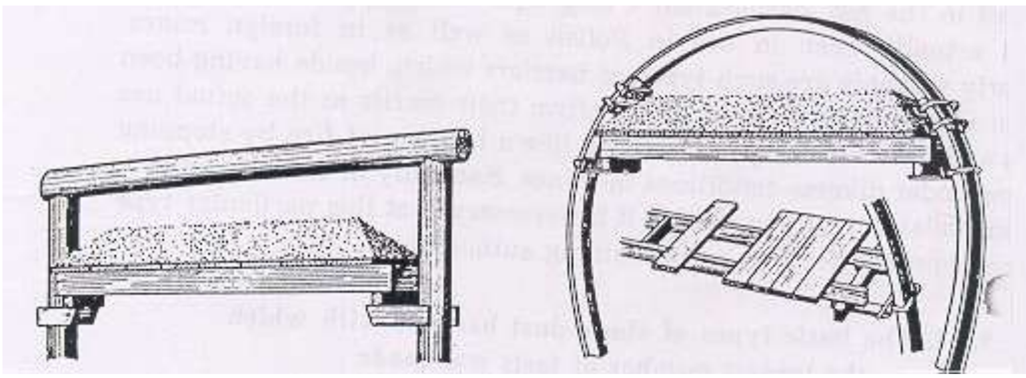

Figure 14: Design of the Polish Stone Dust Barrier from DuPlessis and VanNiekerk (2002, p. 40).

In the design of the concentrated barrier, the stone dust requirement is referenced to the gallery's cross-sectional area. For a concentrated stone dust barrier, dust may be arranged on light or heavy barriers as detailed by DuPlessis and VanNiekerk (2002, p. 43-46). Light barriers are located no further than 180 m and no closer than 80 m from the face and use light shelves 350 mm long by 150 mm wide, loaded with a Q_A of 100 kg/m^2. Heavy stone dust barriers use bigger shelves 450 mm long by 150 mm wide and installed not further than 380 m and no closer than 80 m from the face. The heavy stone dust barrier has a required Q_A of 400 kg/m^2.

It should be noted here that a coal dust explosion gains strength with longer run-up distances. If placed closer to the face, a lighter barrier is sufficient while an greater distances, a heavier barrier is needed. Placing 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 barrier.

When a distributed barrier is to be designed, 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 1kg/m^3
- The value of Q_1 should not be lower than 0.5 kg/m^3."

Distributed stone dust shelf barriers is Australia where the installation requirements for distributed barriers are based on a minimum loading of 200 kg/m^2 (DuPlessis and VanNiekerk 2002).

When using shelf stone dust barriers, it is important that the dust is maintained loose and prevented from coagulating or caking. This may be difficult in mines with high humidity. Also, the stone dust used in the barriers must be carefully selected to maintain non-caking properties, see Section 3.4.8.

4.4.2 Bagged stone dust barriers

In the last 15 years a large amount of research has been expended on developing a bagged stone dust barrier which is better suited to modern mining practices. 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 is not easily suited 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. 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. Figure 15 shows an arrangement of 35 kg dust bags in a concentrated barrier configuration (Michelis 1998). 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 (m^2).

Spacing of bags

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

Distance between bags in a row

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

Distance between rows

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

Distance to sidewall of outer bags

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

Distance to roof

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

Height restrictions

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

- for roads with a height range of less than 3.0 m: a single level of bags suspended below the roof

- for roads in the height range 3.0 m to 3.5 m: a single level of bags suspended at a height of approximately 3.0 m
- for roads in the height range 3.5 m to 4.5 m: a double level of bags suspended at approximately 3.0 m and 4.0 m above floor level
- for roads in the height range of more than 4.5 m but less than 6.0 m: a triple level of bags suspended at approximately 3.0 m, 4.0 m and 5.0 m.

Spacing of barriers

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

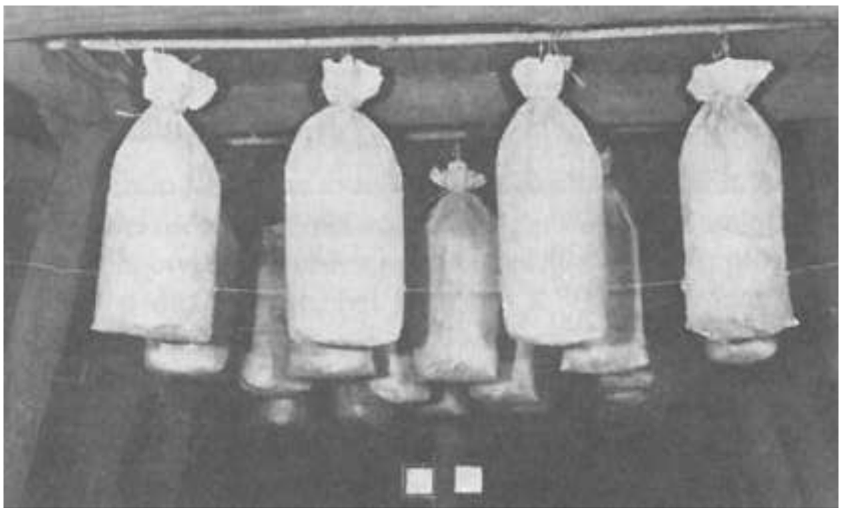

Figure 15: Arrangement of dust bags for an explosion barrier test at the NIOSH Lake Lynn Experimental Mine (Michelis 1998).

The bags themselves are usually suspended from wire mesh or similar steel structures held in place by roof bolts. A common design uses chains as the anchors from the steel to the roof bolts to allow easy height adjustment. The bagged stone dust barriers can also have configurations of a concentrated or distributed design. For a concentrated barrier, the recommended M_A is 100 kg/m^2 and the length of the barrier should be a maximum of 40 m and minimum of 20 m. The concentrated bagged barrier must fulfill the following design criteria (DuPlessis and VanNiekerk 2002):

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

The loading requirements for the distributed barrier are that the M_A must exceed or at least equal 100 kg/m^2 and the M_V must not be less than 1 kg/m^3, where the greater of the two quantities must be used. Distributed barriers are made up of four sub-barriers (MRAC 2002). The placement of the four individual sub-barriers must to conform to the following requirements:

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

A distributed bagged barrier is also suitable for most mining practices but is especially recommended for longwall mining activities. The minimum loading and length of the installed barrier must ensure that M_A is greater than 60 kg/m^2 and the M_V is greater than 0.6 kg/m^3. The first sub-barrier, nearest the face, should not be closer than 60 m to the last through road and not further than 120 m. To ensure a margin of safety, it is recommended that M_A be at least equal to or greater than 100 kg/m^2 (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 0.4 m
- The distance between rows should be between 1.5 and 3 m
- The distance of the closest bags from the roof should not exceed 0.5 m in entry heights over 3.5 m
- The distance from the ribs should be between 0.5 and 1 m
- In entries up to 3.5 m height, a single layer of bags should be used. In heights up to 4.5 m, two levels of bags should be hung, and in heights up to 6 m, three levels should be hung.

4.4.3 Water trough barriers

The use of water trough barriers is an alternative to employing stone dust barriers or bagged stone dust barriers. The concept of a water trough barrier is similar to that of a dust barrier. Cybulski (1975) points out that water, released ahead of an explosion flame, will extinguish the explosion through the following mechanisms:

- The specific heat of water and the high heat of evaporation reduce the flame temperature, and
- A reduction of 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). Typical capacities range from 40 to 80 liters.

As discussed in Section 3.4.4, water trough barrier arrangements for European mines are prescribed by DIN EN 14591-2.

Based on MRAC (2002, p. 22) guidelines and the diagram shown in Figure 16, the following is applicable when troughs are installed in a single layer:

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

- For roadways up to 15 m^2, X+Y+Z must cover at least 50 % of W.
- For roadways in excess of 15 m^2, X+Y+Z must cover at least 65 % of W.
- The distance of A or B or C or D must not exceed 1.2 m.
- The total distance of A+B+C+D, etc. must not exceed 1.5 m.
- The distance V1 must not be less than 0.8 m and must not exceed 2.6 m.
- The distance V2 should not exceed 1.2 m. Whenever this distance is exceeded, additional troughs must be placed above. They may be placed 2.6 m above floor level, but there should not be more than 1.2 m between the base of layers of troughs.

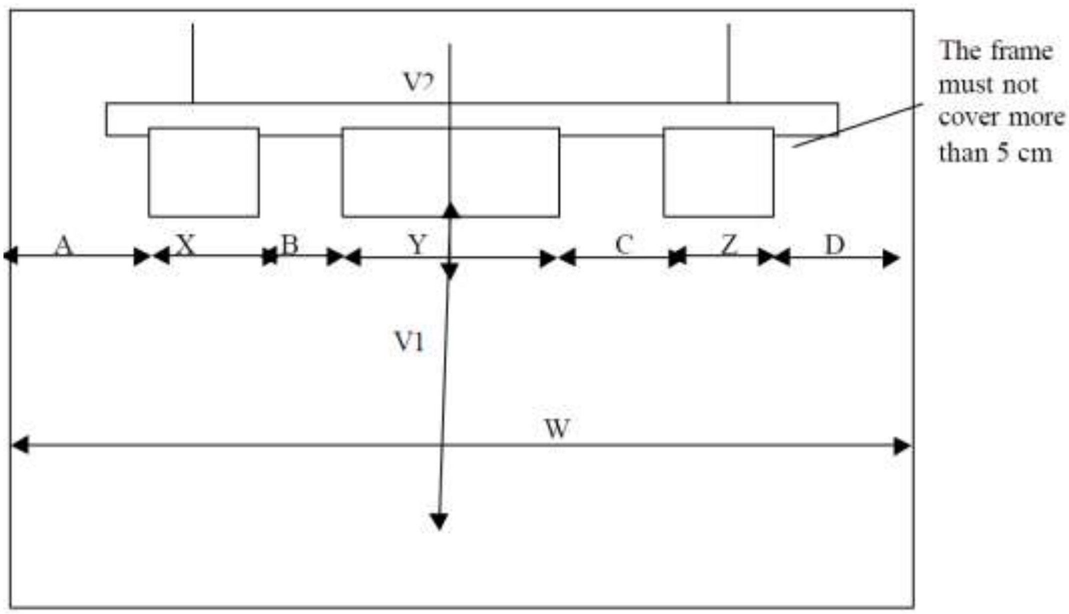

Figure 16: Diagram of South African Water Trough Barrier in Single Layer Configuration (MRAC 2002, p. 22).

If more than one layer of troughs is required, in relation to Figure 17 (MRAC 2002, p.23), the following will apply:

- When troughs are arranged in rows less than 1.2 m 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.
- 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.

The water trough barrier can also be configured as concentrated and distributed designs. For a concentrated barrier, the placement of the barrier must not be closer than 120 m and no further than 360 m from the last through road as recommended by

RMAC(2002). The barrier design also requires either a M_A of 200 l/m^2 or M_V of 5 l/m^3 with a barrier length of 20m to 40 m for both conditions. For a distributed barrier, the placement of the barrier must not be closer than 120 m and no further than 200 m from the face. This barrier has the requirement that am minimum M_V of 1 l/m^3 be maintained with a maximum distance between barriers of 30 m.

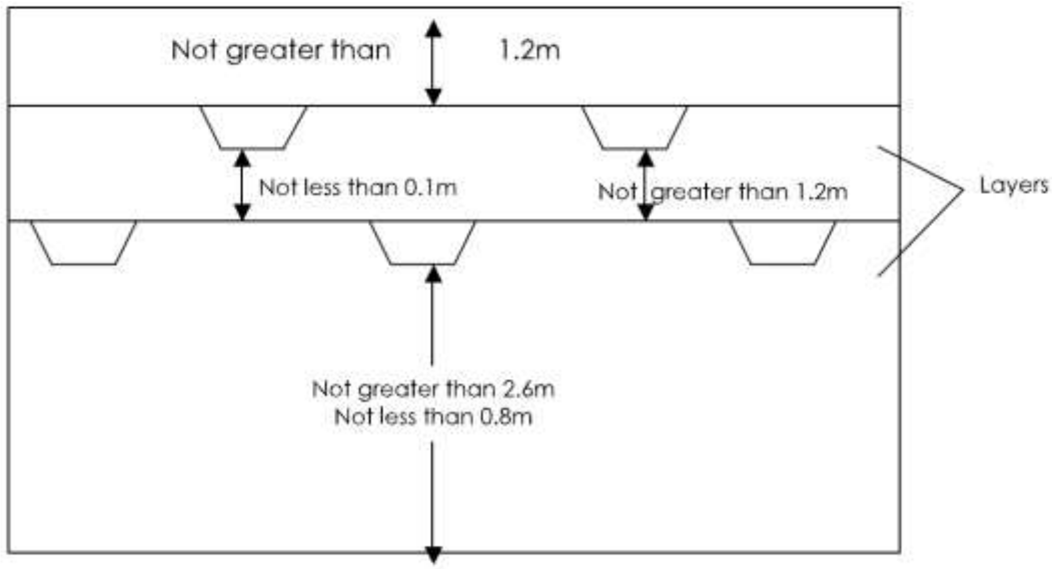

Figure 17: Diagram of South African Water Trough Barrier with Multiple Layer Configuration (MRAC 2002).

It should be noted that barrier positioning is much more critical for water troughs compared to dust shelves. Dust remains suspended in the air for a much longer time than water. Therefore, water must be released at the correct moment to be effective in quenching the explosion.

4.5 Active, triggered explosion barriers

Active explosion barriers are a more recent development as compared to the passive explosion barriers mentioned above. The two types, machine mounted and fixed location, are triggered by an electronic signal from an explosion flame and/or pressure sensor. The barriers typically consist of a cluster of 6 to 8 pressurized containers filled with fire extinguishant powder , rock dust or water and charged with nitrogen. Each container has the size of a handheld fire extinguisher and is equipped with a rapid discharge nozzle, activated by a small explosive charge. The charge is triggered by a signal from the flame sensor.

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

a) A sensor detects the presence of an approaching explosion. Sensors fitted to triggered barriers include blast pressure sensors, thermocouples, 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 18 illustrates the function of a triggered barrier. Sensors indicate the presence of an oncoming explosion, and the trigger mechanism releases the suppressant just as the flame arrives.

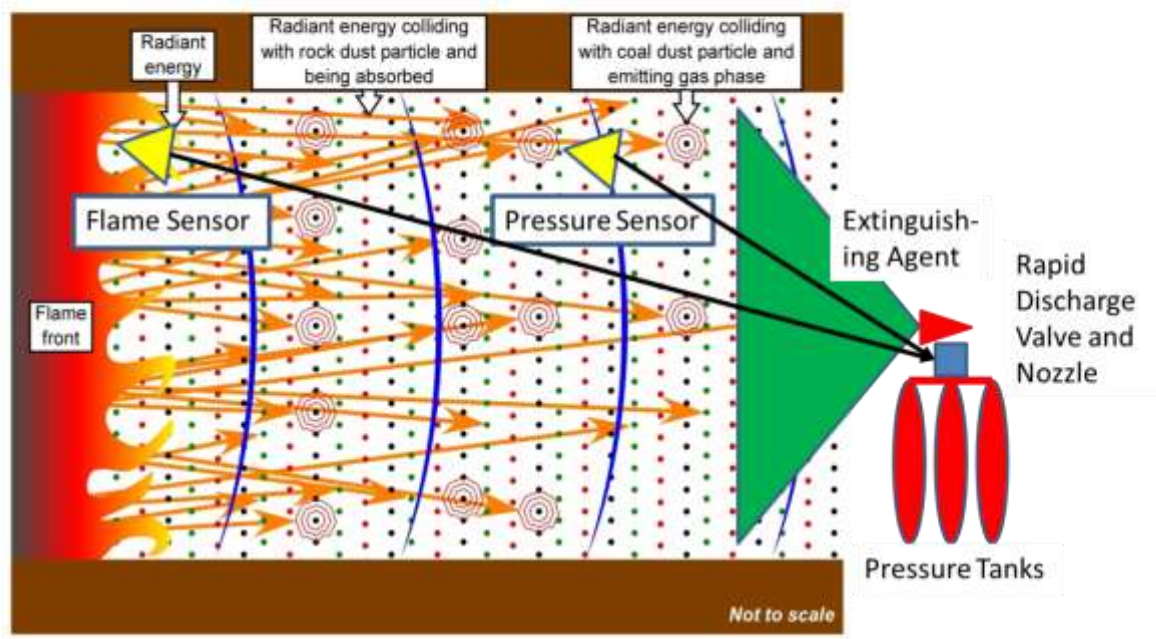

Figure 18: Principle of a Triggered Barrier

An overview of the types of sensors used in active explosion barriers and the characteristics measured are provided in Table 8 (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	Radiant energy in flame
Thermo-mechanical	Heat from flam and dynamic pressure

Table 8: Sensors Used in Active Explosion Barriers (pg.58, DuPlessis and VanNiekerk 2002).

The solar cell detector is of particular interest since it may allow a trigger design that does not require batteries or an external electric power supply. For sensors that are reliant on radiation or light from an explosion flame the sensor surface must be kept free of dust or the signal produced by the sensor may be too weak to activate the dispenser. This is usually achieved by air or water sprayed across or parallel to the sensing surface (DuPlessis and VanNiekerk 2002).

4.5.1 Machine mounted active suppression systems

Country	Type	Extinguishing Agent	Dispersal Method	Vessels		
				No.	Size	Loading (kg)
Federal Republic of Germany	BVS system	Tropolar ammonium phosphate powder	Nitrogen 120 bar detonator. Activated valves	6	12.3 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

Table 9: Summary of Machine Mounted Ignition-Suppression Systems (DuPlessis and VanNiekerk 2002, p. 25).

The above Table 9 (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 machine mounted systems are composed of detecting sensor(s), electronic control and self-checking system, dust containers and flow nozzles. When ignition occurs, it is detected by the sensors and an electronic signal is sent to the suppression system. When the suppression system is triggered a barrier of flame-suppressing material stops the propagation of the flame and contains it to the immediate area of origin. 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. Figure 19 shows the arrangement of a machine mounted triggered barrier on a roadheader. It should be noted here that these triggered barriers have been used on European roadheaders for the past 20 or more years. The technology is proven and well established in the industry. Still, it cannot be easily adapted to continuous miners because the larger cutting boom and drum require a more elaborate arrangement of flame sensors and release nozzles. Likewise, adaptation to a longwall shearer has been experimentally tested in the U.S. and Europe but was viewed as too complex because there are too many possible directions of flame arrival that complicate sensor arrangement.

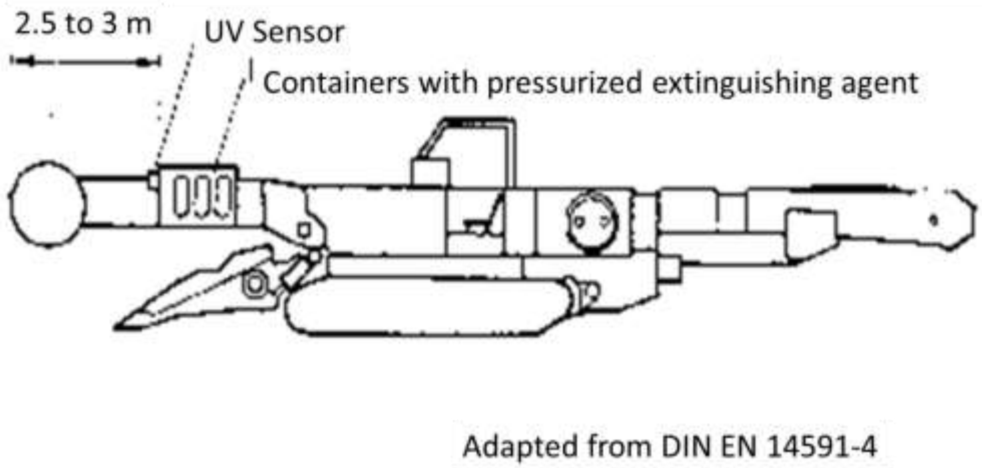

Figure 19: Machine mounted triggered barrier system on a roadheader, based on DIN EN 14591-4.

4.5.2 Fixed location active suppression systems

Table10 (DuPlessis and VanNiekerk 2002) provides a summary of a number of fixed active barrier systems that have been developed or deployed. Unlike the machine mounted active barriers whose purpose was 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 stimulated by the need for systems that were not dependent on the pressure build-up required for the passive barrier systems (DuPlessis and VanNiekerk 2002).

The Belgian system utilizes 2-m-long by 0.25 m polyethene sleeves and flame-resistant polyurethane foam for rigidity. Each suspended container holds 90 to 100 l of water. Embedded in the foam is a waterproof channel holding a detonating cord used to disperse the water. The barrier is triggered by a thermo – mechanical device that is sensitive to both pressure and flame. This system was also used in France. A similar system developed in Germany (Michelis et al., 1987) also uses 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. The barrier found application in or at:

- 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.

A water trough with built in ignition system is shown in Figure 20 (DuPlessis and VanNiekerk 2002).

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

Table 10: Summary of characteristics of fixed active barriers Systems (DuPlessis and VanNiekerk 2002, p. 59)

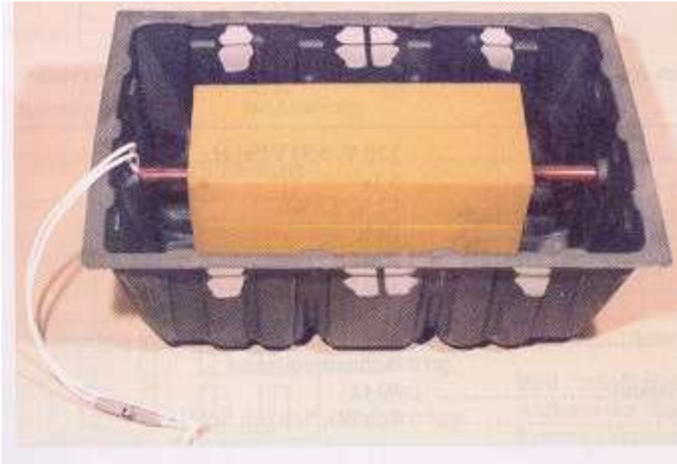

Figure 20: Water Trough with Built-in Ignition System (DuPlessis and VanNiekerk 2002).

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/m^2 instead of 200 l/m^2 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.

Michelis listed their disadvantages as follows:

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

Because of the pressure on German coal mines to control operating costs, the barrier did not find considerable application (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. Two systems were developed:

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

- An automatic explosion-extinguishing installation, Type TSM, for roadheaders, as discussed in Section 4.5.1.

The main aim 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 triggered 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 12.3 l and the capacity to hold 8 kg of ammonium phosphate extinguishant powder. Nitrogen is used as the driving agent and is pressurized to an overpressure of 12 MPa. Release of the ammonium phosphate from the cylinders starts 5 to 10 ms after the sensor has been triggered and lasts between 600 and 900 ms. Figure 21 (DuPlessis and VanNiekerk, 2002) shows the components of the BVS system and Figure 22 (DuPlessis and VanNiekerk, 2002). depicts a diagram of the mobile automatic multiple extinguisher system. Tests showed that the system was effective against explosions reaching 500 m/s when ammonium phosphate was used (Scholl, 1967).

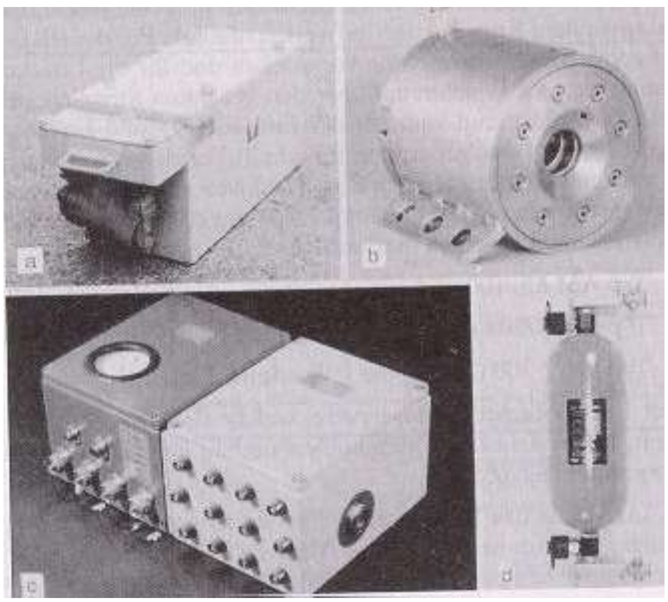

Figure 21: Components of the BVS Triggered Barrier System (DuPlessis and VanNiekerk 2002). a = complete unit, b = UV flame sensor, c = triggered electronics and d = HRD suppressant container

Up 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 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 being costly and unproven.

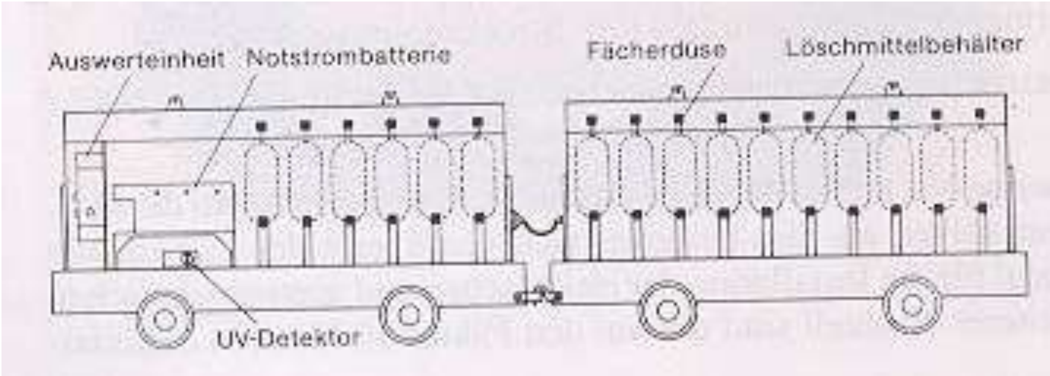

Figure 22: Mobile Automatic Multiple-Extinguisher System (BVS) (DuPlessis and VanNiekerk 2002).

4.6 Monitoring of the mine atmosphere and other conditions

There are a number of different techniques for monitoring the mine atmosphere and underground. Most detectors underground are used either in conjunction with a mine-wide monitoring system or locally as a trigger to initiate an equipment shutoff procedure or localized warning systems. Advanced mine monitoring systems are capable of measuring pressure, humidity, air density, oxygen, explosive and toxic gas concentrations, vibration, temperature, DPM and airflow quantities.

Most mine monitoring systems rely on external power and communication lines connected to the surface. The disadvantage is that if an explosion, fire, inundation or rock fall disables power or communication to the surface, emergency managers can no longer obtain data from the underground sensors which can impact a rescue operation. The issue of equipment damage and maintenance underground also poses a unique dilemma if the stations and detectors are located near an active mining face.

One method used extensively in Australia is the Tube Bundle atmospheric monitoring System (TBS) which allows for mine gas monitoring to be conducted on the surface. A TBS is often used in conjunction with electronic methane detectors and warning systems underground.

Figure 23 (Zipf et al., 2007) shows different components of a deployed tube-bundle system used for continuous gas monitoring. The top left of Figure 23 shows a typical monitoring shed located with gas analyzers, pumps and control valves located on the surface above a mine. The bundled monitoring tubes (top right) enter the mine via a borehole near the shed. Typical tube-bundle systems will monitor from 20 to 40 points or more. Each tube goes from the shed to a distinct sampling location underground from which atmospheric samples are drawn. Sampling locations are often behind mine seals, but they are also used to monitor the atmosphere at ventilation check points in the active areas of the mine. The top right of Figure 23 shows a close-up of a seven-tube bundle. Vacuum pumps shown in the bottom right of Figure 23 draw air samples continuously from each monitoring tube. The bottom left of Figure 23 shows where the sample tubes enter the monitoring shed for analysis. Inside the monitoring shed is a solenoid-valve-manifold system that controls the gas flow from the sampling tubes to the on-line analyzer. The solenoid valves are activated by a programmable logic controller. Samples are sequentially directed to an on-line gas analyzer and analyzed for carbon monoxide, carbon dioxide, methane, and oxygen. Depending on the length of each tube, there is a delay (typically 15 minutes to 1 hr) between the analysis and the time the sample was drawn into the tube. The delay is normally not problematic as mine management looks primarily at trends of change in the data. A typical TBS provides a gas analysis at each monitoring point every 1–3 hr. Data are displayed at the mine's control center, where trained operators can respond as necessary.

The outside data analyzers also compute a variety of gas mixture ratios and determine where each atmosphere lies in the Coward explosibility diagram. The geometric representation in the Coward diagram is important as it allows mine management to determine if a gas composition is trending toward the explosive range.

Figure 23: Continuous atmospheric gas monitoring system in Australia (Zipf et al. 2007). *Top Left*: Monitoring shed over mine showing borehole and sample tubes. *Top Right*: Clop-up of sample tube bundle. *Bottom Right*: Vacuum pumps. *Bottom Left*: Inside monitoring shed showing manifold system and gas analyzer.

A distinct advantage of TBS is that are not reliant on electric power and data communications. This permits installation in sealed areas or in potentially explosive atmospheres. A further advantage is that there is only a single calibration point located at the surface, simplifying maintenance. Sampling tubes must be kept from drawing in water and debris, and tubes need to be routed so that condensation will not plug the tubes. Tubes are sensitive to destruction by fire, explosions, roof falls and inundations yet often, a part of the tube remains functional and, in some situations, the tube itself can be used to locate the point of damage by injecting pure nitrogen and reversing the flow in the tube. After filling the entire tube, flow is returned back to normal and the time to detecting mine gases can be used to calculate the remaining tube length.

4.7 Mine seal design and inertization

Mines seals serve to isolate abandoned areas of a mine. Continuing to ventilate these areas is expensive and often impossible because the ventilation controls and check points can no longer be accessed due to deterioration. The function of a seal is twofold:

- To lock-in the atmosphere inside the sealed area and to prevent the movement of harmful or explosive gases from entering the active mine area.
- If the sealed atmosphere is or may become explosive, seals must prevent an explosion from propagating into the active mine workings.

Seal designs vary on their application within a mine and the extent the seal is being monitored. A comparison of worldwide seal design, construction and related practices is provided in Table 11 (modified after Zipf et al., 2007). Further explanation of seal design that has not been covered in the regulations section is described below.

From theoretical considerations, Zipf et al. (2007) determined that explosive pressures exerted on mine seals could reach 1,000 psi (7 MPa). Higher pressures can occur if reflections of pressure waves pile up and amplify, and yet higher pressures are created if the gas mixture reaches detonation. In the case of the 2006 Sago Mine explosion, the maximum pressure that had likely developed in the sealed area was estimated to 1,300 psi (9 MPa) based on explosion modeling by McMahon et al. (2007). Sawyer (1992) analyzed and back-calculated that “extremely high internal pressures” of 1,000 psi or more caused bursting and destroyed the concrete collar and cap at the Blacksville #1 mine shaft in the 1992 explosion.

4.7.1 Seal design practices in the United Kingdom

With reference to explosion testing at the former U.K. Buxton facility, the Sealing Off Fires Underground report (Hornsby et al. 1985) recommended an explosion design pressure of 524 kPa (76 psig) and a formula for calculating the required thickness of an explosion-proof seal, given as

$$t = \frac{H + W}{2} + 0.6$$

where t = the required seal thickness, m,
H = roadway height, m,
and W = roadway width, m.

In any case, minimum seal thickness is 3 m (10 ft). This formula assumes the use of “Hardstop” for the seal, which is a gypsum product with a compressive strength of about 4 MPa (600 psi) after 2 hr and 12–14 MPa (1,700–2,000 psi) after 24 hr. Recent explosion tests on full-scale seals validated this design formula and showed that the formula contained an implicit safety factor of at least 2.

Country	Mining Method	Design Standard	Year	Problems	Formula	Typical width x height	Typical thickness	Material	Inert?	Monitoring?
United Kingdom	Single-entry longwall	0.5 Mpa (73 psig) x 2	Pre-1960	No seals destroyed	$t = \frac{H+W}{2} + 0.6$	6 x 3 m (20 x 10 ft)	4-5 m (13-16 ft)	Gypsum	Set up to inertize	Tube bundle
Germany	Single-entry longwall	0.5 Mpa (73 psig) x 2	Pre-1960	No seals destroyed	$t = \frac{0.7a}{\sqrt{\sigma_{bz}}}$	6 x 5 m (20 x 16 ft)	3-6 m (10-20 ft)	2/3 fly ash 1/3 cement	No	Initially, as nedded
Poland	Single-entry longwall	0.5 Mpa (73 psig) x 2	Pre-1960	No seals destroyed	Full-scale test	6 x 5 m (20 x 16 ft)	3-6 m (10-20 ft)	Varies	GAG jet engine	As needed
Australia	Two-entry longwall	345 kPa (50 psig) x 1 or 140 kPa (20 psig) x 1 or 35 kPa (5 psig) x 1	1999	Moura No. 2 (1994)	Structural analysis	6 x 3 m (20 x 10 ft)	Rarely used: 0.3-1.5 m (1-5 ft)	Varies	Many mines	Tube Bundle
United States	Longwall and room-and-pillar	4.4 Mpa (640 psig) x 1 or 800 kPa (120 psig) x 1 or 345 kPa (50 psig) x 1	2010	No seals destroyed	Full-scale test	6 x 2 m (20 x 7 ft)	0.5-1 m (1.5-3.5 ft)	Varies	Dependant on seal design	Dependant on seal design
South Africa	Longwall and room-and-pillar	400 kPa (60 psig) x 1 or 140 kPa (20 psig) x 1	2002	No seals destroyed				Varies		

Table11: Comparison of worldwide seal designs: construction and related practices (modified after Zipf et al., 2007).

4.7.2 Seal design practices in Germany

Seal design practices in Germany have been extensively discussed in Section 3.4.9. Seals are typically designed as plug seals constructed from lightweight pumpable concrete. The fundamental design requirement for explosion pressure resistance is 700 kPa (100 psi) with a safety factor of 2.0. Seals are equipped with the usual gas sampling tubes and water drainage pipes. They often have a built-in man tunnel capped with an explosion proof door to allow post-construction inspections of the sealed area.

4.7.3 Seal design practices in Poland

Cybulski et al. (1967) discussed a series of test explosions conducted in the No. 1 Maja Mine, which generated pressure greater than 3 MPa (450 psi) and caused great damage to a test seal. Cybulski and his researchers believed it difficult or impractical to construct a seal robust enough to withstand these observed pressures. They reasoned that in practice only small volumes of explosive methane-air could accumulate in the face area of an active longwall operation and therefore the maximum explosion pressure at a seal would not exceed 500 kPa (72 psi). This design standard seems to correlate with those of Germany and the United Kingdom. Examination of the Polish technical literature did not identify a design formula for seal thickness. Full-scale testing at Experimental Mine Barbara is used to validate various seal designs. Lebecki et al. (1999) describe several such validation tests. These tests will apply a pressure of about 1 MPa (145 psi) to a candidate seal in order to ensure that the design has a safety factor of about 2.

4.7.4 Seal practices in Australia

In addition to monitoring to ensure that the sealed area does not contain any explosive atmosphere, as mentioned by the regulatory standards in section 3.2.5, most Australian coal mines artificially inertize sealed areas. Artificial inertization is mainly employed at mines with high risk of spontaneous combustion. Two methods are in use: nitrogen injection and Tomlinson boiler gas injection. Nitrogen injection systems may use molecular membranes or cryogenic processes to separate nitrogen from the atmosphere. While these systems are adequate for routine nitrogen injection at low flow rates, they may lack sufficient capacity for bulk injection during an emergency, such as a fully developed spontaneous combustion event. The Tomlinson boiler, shown in Figure 24 (Zipf et al., 2007), burns diesel fuel and air in a combustion chamber, and the resulting exhaust gases are cooled and compressed for injection into a sealed area. The inert gas is mainly nitrogen and carbon dioxide with trace amounts of carbon monoxide and 1%–2% oxygen.

Mine seal strength requirements range from 35 to 345 kPa (5 to 50 psi) in Australia have been discussed in Section 3.2.5

Figure 24: Tomlinson Boiler at an Australian coal mine (Zipf et al., 2007).

4.7.5 Seal design practices in the United States

Zipf et al. (2007) provides a flow flowchart for selecting the design pressure-time curve for a new seal as provided in Figure 25. The seal design criteria are selected based on whether the atmosphere inside the sealed area is being monitored and based on the potential run-up length for a mine explosion inside the sealed area.

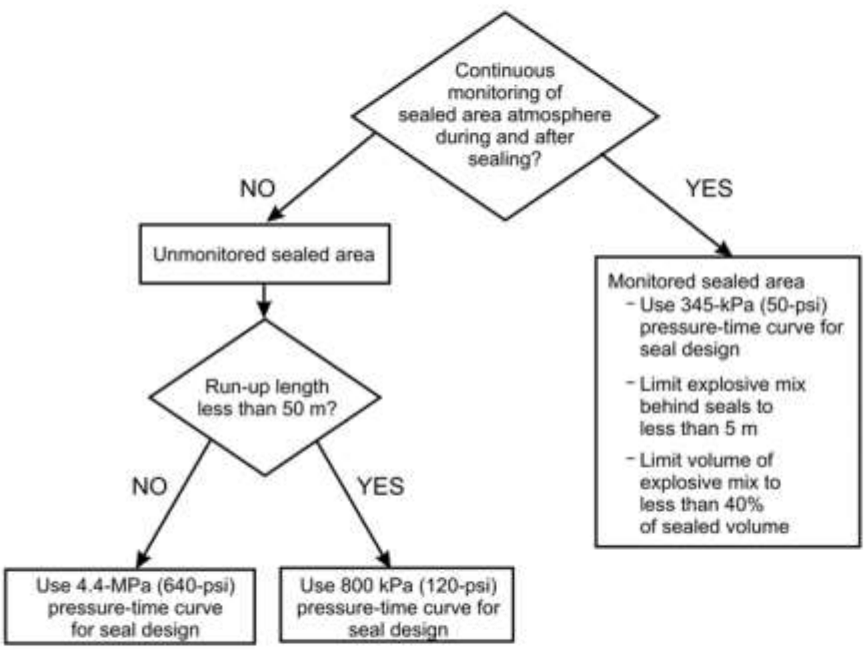

Figure 25: Flowchart for design pressure-time curves for new seals (Zipf et al., 2007).

If the atmosphere is monitored, the mine operator can limit the explosion hazard by reducing the explosive gas mixture through inertization. If the atmosphere is not being monitored or unknown, the seal strength must be 120 psi or higher depending on run-up length. These criteria have been reflected in 30 CFR §75.335 Seal strengths, design applications, and installation, as discussed in Section 3.1.6.

5. Best industry regulations and practices for the prevention of mine explosions

This section summarizes and compares explosion prevention practices for underground coal mines in different major coal mining countries. The goal is to identify the best practices and alternatives to improve explosion safety.

5.1 Mine atmospheric and ventilation system monitoring, ventilation officer

All countries examined rely on dilution of methane gas as the primary defense against methane-air explosions. While standards in the countries examined, the U.S., Australia, Germany and South Africa, differ slightly in the maximum concentration of methane gas permitted in mining faces and other areas in the mine, the fundamental concept is to maintain a sufficient margin of safety in relation to the lower explosibility limit (LEL) of methane in air (5%). Most standards and practices, including those in the U.S., allow a maximum methane concentration of 1% in active mining faces. In Germany, under certain conditions, it may be permissible to operate mining equipment in concentrations of 1.5% methane. In the U.S., a maximum concentration of 2% is permitted in certain return and bleeder airways.

5.1.1 Prevention of face ignitions

As discussed in Section 2.1, a major hazard with methane results from feeders that are exposed in the cutting process, both during development with continuous miners or roadheaders, and during longwall mining. Methane sensors mounted on typical mining machines are at least 5 to 10 ft (1.5 to 3 m) away from the cutter picks that expose feeders. As mentioned in Section 1, methane face ignitions are still fairly 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 maintaining the cutter bits in optimum condition are effective in preventing face ignitions. Ventilation helps dilute methane feeders quickly. Water sprays keep cutter bits cool and also 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 roof, floor or partings.

German and European operators use machine-mounted, active triggered explosion barriers on their roadheaders that are operating in potentially explosive atmospheres. The barrier technology has been in use for over 20 years and is mature; however, it is currently only available for roadheaders. The barriers are capable to extinguish methane face ignitions without harming the operator and crew. In the past, US Bureau of Mines researchers have attempted to adapt the barriers to continuous miners and longwalls but thus far, this research has been unsuccessful. Due to their wide cutter head and boom, continuous miners require a more complex arrangement of flame sensors and discharge nozzles, which would have required a large number of full scale explosion tests.

Testing on longwall shearers has been conducted by DMT in Germany in the 1980s and was successful under laboratory conditions. In an operating longwall setting there are many different scenarios, locations and directions for an ignition to develop. Consequently, the arrangement of flame sensors and extinguisher nozzles will become significantly more complex compared to the roadheader mounted barriers.

Researchers feel that, with today's advanced computer modeling capabilities, it should be possible to test a great number of sensor and nozzle arrangements in numerical models rather than requiring expensive, full-scale physical explosion tests. In any case, more research is required to understand the role of machine-mounted active explosion barriers to extinguish face ignitions before they turn into mine explosions.

5.1.2 Bleeder systems

As discussed in Section 3.1.5, bleeder systems are unique to U.S. longwall mining. European and Australian mines exclusively operate with progressively sealed longwall gobs. Sealing of 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 a number of mine explosion investigations, including that of the UBB explosion, suggests that explosive methane air mixtures had accumulated in the bleedered 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 is fulfilling 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.

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. Various researchers have conducted computational fluid dynamics (CFD) studies to analyze gas concentrations and flows inside longwall gobs. These studies are still in their infancy by researchers believe that they hold the key to mitigating explosion hazards stemming from bleeder ventilated longwall gobs.

5.1.3 Mine atmospheric and ventilation monitoring

All mine operators monitor atmospheric conditions and airflow quantities through their certified mine examiners and foremen. Examiners maintain written records of their examinations that are shared with the oncoming shift, mine managers and all interested employees. The problem with individual examinations is that they may not be comparable as the readings are not always taken at identical locations, rely on individual instruments with varying biases and rely on additional measurements, for example, those of the cross section area.

In addition to manual ventilation readings, Australian, German and South African mining regulations mandate extensive, continuous monitoring of the mine atmosphere and ventilation conditions. Continuous monitoring permits the mine operator to analyze trends, daily and longer-term fluctuations and to set automatic alarm levels. Stationary monitors maintained properly calibrated will provide consistent and reliable reading results that are not subject to errors of human measurement. Technologies for such monitoring systems are proven and widely available on the market. While many U.S. mines already use automatic atmospheric monitoring systems, the use of these systems should be mandatory and expanded. In particular, researchers suggest continuous monitoring of air quantities, methane and carbon monoxide content in all mining face areas (both continuous miner development and longwalls), all return air splits, bleeder systems, sealed areas and all belt conveyors. In the case of the UBB explosion, it remains unclear whether the longwall ventilation system had been compromised prior to the explosion. Witness testimony indicates that the longwall face quantity may have been lower than required by the ventilation plan while mine examiner readings indicate that there was sufficient airflow at the face. Continuous monitoring would have not only given clear indication of a compromised ventilation system, it would have also enabled mine operators to recognize the hazard early and make appropriate management decisions.

An advanced decision making tool for mine atmospheric monitoring is the Principal Hazard Management Plan (PHMP) in conjunction with the Trigger Action Response Plan (TARP) required in Australia (see Section 3.2.2). TARPs contain specific action levels prescribed in detail for four alarm conditions that are evaluated by the computer that controls the atmospheric monitoring system. TARPs are quite flexible as they do not follow prescriptive standards but require the mine operator to establish the PHMP with specific actions required at each trigger point. Another advantage of TARPs is that actions can be defined that must be taken if a combination of trigger conditions is met. For example, in analyzing if the atmosphere in a sealed presents can explosion hazard, one must not only evaluate if the methane content lies within the explosive range but also if there is sufficient oxygen available.

As best practice, researchers recommend that mine operators establish a PHMP along with TARPs for comprehensive monitoring of mine ventilation and atmospheric conditions along with clear communication of required action when trigger level are exceeded.

As discussed in Section 3.4.1, German regulations also require climatic data to be collected by the mine AMS. This is important since German coal mines are typically deeper that 1,000 m (3,300 ft) and due to the geothermal gradient, temperatures can exceed physiological limits for workplaces. Capturing climatic data is a useful best practice in warm mines where physiological limits mist be observed.

5.1.4 Ventilation officers, ventilation management

A common characteristic in all countries examined in this research is the position of a dedicated ventilation officer (VO) at each mine. For large mines, the VO heads a staff of ventilation specialists tasked with managing and monitoring the mine ventilation system. The VO typically reports directly to senior mine management.

In comparison, U.S. mines do not have a dedicated VO. Ventilation responsibility typically lies with the General Mine Foreman but this individual is also responsible for production, supplies, safety and sometimes other areas.

Germany, South Africa and Australia all require VOs to have formal training and to have passed qualifying examinations. VOs are sometimes college-educated engineers but are often experienced mine ventilation practitioners. In larger mines, they are assisted by a staff of skilled technicians and junior ventilation engineers familiar with taking ventilation measurements, adjusting ventilation controls, numerical modeling and maintaining AMS components.

The VO typically maintains a working numerical model of the mine ventilation system, along with up-to-date ventilation maps and databases for the monitoring system. There are numerous, PC-based software packages for mine ventilation numerical modeling and this skill is taught in all mining engineering university curricula.

In contrast, U.S. regulations require that the mine operator submit a mine ventilation plan to MSHA for approval every six months. However, there is no requirement for a numerical model as a basis for the ventilation plan. While most larger mining companies maintain such models, examination of the UBB mine ventilation plan (see also the companion report, “Lessons Learned from Mine Disasters: New Technologies and Guidelines to Prevent Mine Disasters and Improve Safety” by Brune and Goertz) revealed that it was inconsistent and appeared not to be based on a recently updated numerical model.

Best recommended practice is that each mine keep on staff or retain on a consultancy basis a named Ventilation Officer responsible for all aspects of mine ventilation. Also, researchers recommend that each mine maintain a comprehensive numerical model of the mine ventilation system updated at intervals no greater than three months.

Finally, each mine should be required to file a comprehensive, major hazard management plan along with the semi-annual update of the mine ventilation plan. The major hazard management plan should cover explosion and fire hazards and should include a formal assessment of the risks posed by these hazards. The plan document should set mandatory performance standards to which the mine operator is held liable.

5.2 Coal dust inertization with rock dust, explosion barriers

5.2.1 Rock dust management

Inertization of coal dust with rock dust is common throughout 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 in the U.S., agree that a minimum of 80% of 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.

When rock dust is applied, mine operators must be careful to avoid layers of coal dust that deposit on rock dusted surfaces. Ideally, this can be accomplished by continuously adding rock dust to the mine return air that is loaded with fine coal dust. To be effective in preventing explosions, rock dust must be well mixed with the coal particles and must be dry and entrainable in air. If the rock dust coagulates or cakes, it loses its effectiveness. As best practice, researchers recommend to analyze the rock dust for its caking potential by following the German standards discussed in Section 3.4.8. This is important because in U.S. mines, rock dust is the principal defense used against coal dust explosions.

It is also important to establish a rock dust management plan for each mine that 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 key 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. Section 3.4.7 provides guidance in establishing a sampling program. The program should be managed by the VO.

5.2.2 Use of salts to prevent coal dust explosions

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. Details are discussed in Section 4.3. 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 as smaller quantities are 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. Application requires personal protective equipment to be worn but the potential health hazards are manageable.

5.2.3 Explosion barriers

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 of passive barriers. 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.

Passive barriers today are built using water troughs; rarely shelves of rock dust. South African mines use barriers constructed of bagged rock dust. Specific regulations govern the locations where barriers are installed and the geometric parameters of the installation. With all passive barrier types there are concentrated and distributed barriers. Installation locations typically begin 100 to 200 m outby all mining faces and continue at regular intervals from there on.

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 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.

European mines also make effective use of active, triggered barriers mounted on roadheaders used in mine development. Researchers believe that this technology would be adaptable to continuous miners and possibly even to longwalls. More research, particularly on numerical modeling of the extinguishing action, sensor and nozzle positioning is needed to adapt the triggered barriers to continuous miners. Modeling is expected to be far less expensive than full scale laboratory tests. Researchers believe that it will be possible to design active barriers for longwalls and compact, stand-alone, movable active barriers for mine geometries used in the U.S. The research and development to design such barriers will require significant funding.

5.3 Explosion-resistant ventilation controls and seals

European mine standards require a minimum of 200 kPa (29 psi) explosion resistance for all ventilation controls (see Section 3.4.2), i.e. more than what was required in the U.S. for mine seals prior to the 2006 Sago mine explosion (140 kPa or 20 psi.). There are no explicit requirements in U.S. regulations concerning the explosion resistance of common ventilation controls such as stoppings, overcasts and regulators. As documented in the investigation reports, these controls are easily destroyed in mine explosions. In the case of the UBB explosion (Page, 2011), compromised ventilation controls cut off all ventilation to the headgate 22 development section and allowed over 10,000 ppm CO to accumulate. If the miners in this section were not killed instantly by heat or pressure trauma, they would have been asphyxiated by CO poisoning after a few minutes. Researchers recommend additional research to determine if more substantial designs for stoppings, overcasts and regulators could improve survivability in cases of smaller mine explosions. Also, maintaining an intact ventilation system can prevent secondary explosions and allow rescuers to enter the mine much quicker.

Mine seals in German mines must withstand 700 kPa (102 psi) overpressure with a design safety factor of 2. The U.S. requirements for mine seals as outlined in Sections 3.1.6 and 4.7.5 are considered a best practice, however, in line with international best practices, all sealed atmospheres should be continuously monitored from the time of sealing until it is well established that the atmosphere behind the seal is sufficiently inert and there is no longer a risk of explosion. Sealing an area of a mine without monitoring the sealed atmosphere will expose mine workers to unnecessary risks. Miners should not enter or work in a mine while a sealed area atmosphere is in or near the explosive range. While researchers were unable to find specific regulations, Australian companies have adopted this best practice (Hopkins, 1999).

Mines should also be equipped to rapidly inertize sealed atmospheres by injecting nitrogen, carbon dioxide or other suitable inert gases, including Tomlinson boiler exhaust. This best practice is common in European and Australia but only a few U.S. mines have adopted it.

5.4 Major hazard risk analysis and management

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

To put the term “major risk” into perspective, the UBB disaster is a good example. The mine explosion killed 29 miners and, first and foremost, had an immeasurable impact on their families and livelihoods. In addition, the explosion not only resulted in the permanent closure of the UBB mine but also 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 goes on.

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).

6. Summary of suggestions for new research and regulatory improvements

Review limitations of the selected regulations and standards as applicable to US coal mines

What practices are not proven yet but could become a viable with more research

6.1 Comprehensive mine atmospheric monitoring, including mine gobs

Researchers believe that all underground coal mines should be equipped with atmospheric monitoring systems (AMS) to monitor, at minimum, CH_4, CO, and O_2. Other gases, including CO_2 and H_2S 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 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 are tracked and that appropriate alarm levels are set to provide early warning of harmful gas accumulations or ventilation system malfunctions. The Australian TARP system (see Section 3.2.2) should be used as guidance.

No further research is required to equip mines with comprehensive AMS coverage.

6.2 Naming of a mine ventilation officer, ventilation numerical model

U.S. mine operators should be required to formally name a competent (qualified, perhaps certified) Ventilation Officer (VO) to provide expert advice to mine management on all mine ventilation related matters. The ventilation officer would also take responsibility for mine planning and be required to maintain an up-to-date numerical ventilation model of the mine.

Smaller mines may not have the need for a full-time ventilation officer. These mines should retain the services of a competent consultancy to fulfill the function of the VO.

6.3 Consideration of hygroscopic salts in addition to rock dusting

The use of hygroscopic salts to bind coal dust and render it inert should be considered more widely in the U.S. Salt sprays or other forms of salts (powder, prills) have been proven effective and are already being used in some U.S. mines.

More research is recommended to compare the costs of using salts to those of rock dusting, and to better assess the impact of the corrosive properties on mining equipment and roof support.

6.4 Use of passive explosion barriers

As discussed in Sections 3.4.4 and 4.4.3, the technology for passive explosion barriers consisting of water troughs is well established and proved to provide effective protection from propagating coal dust explosions. The biggest obstacle for their implementation and use in U.S. coal mines is that the low entry height makes it difficult to accommodate these barriers. Another complexity is added by the room-and-pillar layout typically used in U.S. mines. If European regulations for the placement of water trough barriers were applied in the U.S., a large number of distributed barriers would be needed. Due to the short run-up distances between barriers, concentrated barriers would likely not be applicable.

Passive barriers can be installed if the entry height is 10 ft (3 m) or higher, but only few U.S. mines have such high entries.

6.5 Development of active explosion barriers for use on continuous miners, longwalls and as mobile barriers outby face areas

As discussed in Section 4.5 and subsections, the technology for active explosion barriers mounted on roadheaders exists and has been proven effective since the 1970s. It is conceivable that similar barriers can be designed and implemented on

- Continuous Miners,
- Longwalls, and
- As compact, movable stand-alone barriers to be used in entries and crosscuts outby the production faces.

As discussed earlier, the technology of active barriers is simple. The modular design should facilitate adaptation of the barriers to a variety of equipment types. Installation on a continuous miner is quite similar to that on a roadheader. However, additional research is required to ensure that methane ignition flames can be reliably detected despite the larger boom. Multiple flame sensors will likely be required because the boom shades possible flame locations from some of the sensors. Likewise, the boom will inhibit distribution of the extinguishant so that more containers and/or a wider distribution of discharge nozzles will be necessary. Simulations covering a large variety of ignition locations can be simplified by computer modeling. The final sensor and nozzle arrangement would then be verified in a few full-scale explosion tests.

Barriers for longwalls can be mounted on the shearer or under the canopies of the support shields. Arrangements mounted on a shearer have been successfully tested in full scale explosions by DMT, Germany. The shearer-mounted design is complicated, though, since it is not known where the initial ignition will develop. Researchers believe that it may be easier to mount a barrier and flame sensor under each shield and have a firing control computer activate a group of barriers to either side of the flame location. Again, numerical modeling research would be required to bring this barrier design to maturity.

Finally, researchers believe that it should be possible to design compact, movable barrier units along with sensor and nozzle arrangements that can be placed in mine entries outby the production faces. The work by Humphreys (2003) indicates that this barrier technology is fundamentally feasible. Barriers filled with diammoniumphosphate or similar agents are capable of extinguishing both methane and coal dust explosions. Numerical modeling and limited full scale explosion testing would be required to develop these barriers to maturity.

7. Summary and conclusions

This report examines the regulations and best engineering practices to prevent methane gas and coal dust explosions in underground coal mines. 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 bullets provide the highlights:

- Foreign mines use comprehensive mine atmospheric monitoring systems (AMS) to continuously watch for signs of fires, accumulations of methane and other gases and proper function of the mine ventilation system. AMS alert the mine operator if an abnormal condition is detected and can even be programmed to instruct system operators in specific response actions. AMS technology is widely available on the market and can be easily installed in all U.S. mines.
- Foreign mines assign a certified ventilation officer (VO) the responsibility for the mine ventilation system and the protection from major explosion hazards. In large mines, the VO has dedicated engineering and technical staff to maintain the ventilation and monitoring systems. A VO is recommended in all U.S. mines as well.
- Passive coal dust explosion barriers are widely used in European and South African mines in addition to rock dust or salt inertization of coal dust. The barrier technology using shelf-mounted water troughs is not easily adaptable to typical U.S. mine layouts. Still, it has been widely recognized that the U.S. practice of using rock dust to inertize coal dust may not be sufficient to reliably prevent coal dust explosions. Binding the coal dust with hygroscopic salts may be a simple and effective way to complement rock dust inertization.
- European mines also use active, triggered barriers to quench face ignitions in development faces. This technology is applied on roadheaders and has matured over several decades. Considering that U.S. mines experience 30 to 40 face ignitions each year, research should be undertaken to adapt active barrier technology to continuous miners and longwall faces.

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 all [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.

Coward HF, Jones GW [1952]: Limits of flammability of gases and vapors. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, Bulletin 503.

Crocodyl Company Profile [2013]: http://www.crocodyl.org/wiki/massey_energy last accessed 08-05-13

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 JJL, 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 08-05-13

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.

Hornesby C D et al. [1985]: Sealing off fires underground. Memorandum from the Committee of the Institution of Mining Engineers, U.K.

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

Kissell FN [2006]: Handbook for Methane Control in Mining, CDC NIOSH IC no. 9486, Pittsburgh 2006, 191 p.

Lebecki K, Kajdasz Z, Napieracz T, Cybulski K [1999]: Tests on bulkheads resistance to methane explosion. In: Proceedings of the 28th International Conference of Safety in Mines Research Institutes (Sinaia, Romania, June 7–11, 1999). Vol. III. Petroşani, Romania: National Institute for Mining Safety and Explosion Proof Protection, pp. 5–19.

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 700 m 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 August 20, 2013

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.

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

Weiss ES, Cashdollar KL and Sapko MJ [2002]: Evaluation of Explosion-Resistant Seals, Stoppings, and Overcast for Ventilation Control in Underground Coal Mining, CDC NIOSH RI no. 9659, Pittsburgh 2002, 57 p.

Zipf RK, Sapko MJ and Brune JF [2007]: Explosion Pressure Design Criteria for New Seals in U.S. Coal Mines, CDC NOISH RI No. 9500, Pittsburgh, 2007, 76 p.

Appendix A – United States Code of Federal Regulations, Title 30, Part 75, (selected sections)

30 CFR §75.360 Preshift examination.

(a)(1) Except as provided in paragraph (a)(2) of this section, a certified person designated by the operator must make a preshift examination within 3 hours preceding the beginning of any 8-hour interval during which any person is scheduled to work or travel underground. No person other than certified examiners may enter or remain in any underground area unless a preshift examination has been completed for the established 8-hour interval. The operator must establish 8-hour intervals of time subject to the required preshift examinations.
(2) Preshift examinations of areas where pumpers are scheduled to work or travel shall not be required prior to the pumper entering the areas if the pumper is a certified person and the pumper conducts an examination for hazardous conditions and violations of the mandatory health or safety standards referenced in paragraph (b)(11) of this section, tests for methane and oxygen deficiency, and determines if the air is moving in its proper direction in the area where the pumper works or travels. The examination of the area must be completed before the pumper performs any other work. A record of all hazardous conditions and violations of the mandatory health or safety standards found by the pumper shall be made and retained in accordance with §75.363 of this part.

(b) The person conducting the preshift examination shall examine for hazardous conditions and violations of the mandatory health or safety standards referenced in paragraph (b)(11) of this section, test for methane and oxygen deficiency, and determine if the air is moving in its proper direction at the following locations:
(1) Roadways, travelways and track haulageways where persons are scheduled, prior to the beginning of the preshift examination, to work or travel during the oncoming shift.
(2) Belt conveyors that will be used to transport persons during the oncoming shift and the entries in which these belt conveyors are located.
(3) Working sections and areas where mechanized mining equipment is being installed or removed, if anyone is scheduled to work on the section or in the area during the oncoming shift. The scope of the examination shall include the working places, approaches to worked-out areas and ventilation controls on these sections and in these areas, and the examination shall include tests of the roof, face and rib conditions on these sections and in these areas.
(4) Approaches to worked-out areas along intake air courses and at the entries used to carry air into worked-out areas if the intake air passing the approaches is used to ventilate working sections where anyone is scheduled to work during the oncoming shift. The examination of the approaches to the worked-out areas shall be made in the intake air course immediately inby and outby each entry used to carry air into the worked-out area. An examination of the entries used to carry air into the worked-out areas shall be conducted at a point immediately inby the intersection of each entry with the intake air course.
(5) Seals along intake air courses where intake air passes by a seal to ventilate working sections where anyone is scheduled to work during the oncoming shift.
(6)(i) Entries and rooms developed after November 15, 1992, and developed more than 2 crosscuts off an intake air course without permanent ventilation controls where intake

air passes through or by these entries or rooms to reach a working section where anyone is scheduled to work during the oncoming shift; and,
(ii) Entries and rooms developed after November 15, 1992, and driven more than 20 feet off an intake air course without a crosscut and without permanent ventilation controls where intake air passes through or by these entries or rooms to reach a working section where anyone is scheduled to work during the oncoming shift.
(7) Areas where trolley wires or trolley feeder wires are to be or will remain energized during the oncoming shift.
(8) High spots along intake air courses where methane is likely to accumulate, if equipment will be operated in the area during the shift.
(9) Underground electrical installations referred to in §75.340(a), except those pumps listed in §75.340(b)(2) through (b)(6), and areas where compressors subject to §75.344 are installed if the electrical installation or compressor is or will be energized during the shift.
(10) Other areas where work or travel during the oncoming shift is scheduled prior to the beginning of the preshift examination.
(11) Preshift examinations shall include examinations to identify violations of the standards listed below:
(i) § §75.202(a) and 75.220(a)(1) — roof control;
(ii) § §75.333(h) and 75.370(a)(1) — ventilation, methane;
(iii) § §75.400 and 75.403 — accumulations of combustible materials and application of rock dust;
(iv) §75.1403 — other safeguards, limited to maintenance of travelways along belt conveyors, off track haulage roadways, and track haulage, track switches, and other components for haulage;
(v) §75.1722(a) — guarding moving machine parts; and
(vi) §75.1731(a) — maintenance of belt conveyor components.

(c) The person conducting the preshift examination shall determine the volume of air entering each of the following areas if anyone is scheduled to work in the areas during the oncoming shift:
(1) In the last open crosscut of each set of entries or rooms on each working section and areas where mechanized mining equipment is being installed or removed. The last open crosscut is the crosscut in the line of pillars containing the permanent stoppings that separate the intake air courses and the return air courses.
(2) On each longwall or shortwall in the intake entry or entries at the intake end of the longwall or shortwall face immediately outby the face and the velocity of air at each end of the face at the locations specified in the approved ventilation plan.
(3) At the intake end of any pillar line--
(i) If a single split of air is used, in the intake entry furthest from the return air course, immediately outby the first open crosscut outby the line of pillars being mined; or
(ii) If a split system is used, in the intake entries of each split immediately inby the split point.

(d) The person conducting the preshift examination shall check the refuge alternative for damage, the integrity of the tamper-evident seal and the mechanisms required to deploy the refuge alternative, and the ready availability of compressed oxygen and air.

(e) The district manager may require the operator to examine other areas of the mine or examine for other hazards and violations of other mandatory health or safety standards found during the preshift examination.

(f) *Certification.* At each working place examined, the person doing the preshift examination shall certify by initials, date, and the time, that the examination was made. In areas required to be examined outby a working section, the certified person shall certify by initials, date, and the time at enough locations to show that the entire area has been examined.

(g) *Recordkeeping.* A record of the results of each preshift examination, including a record of hazardous conditions and violations of the nine mandatory health or safety standards and their locations found by the examiner during each examination, and of the results and locations of air and methane measurements, shall be made on the surface before any persons, other than certified persons conducting examinations required by this subpart, enter any underground area of the mine. The results of methane tests shall be recorded as the percentage of methane measured by the examiner. The record shall be made by the certified person who made the examination or by a person designated by the operator. If the record is made by someone other than the examiner, the examiner shall verify the record by initials and date by or at the end of the shift for which the examination was made. A record shall also be made by a certified person of the action taken to correct hazardous conditions and violations of mandatory health or safety standards found during the preshift examination. All preshift and corrective action records shall be countersigned by the mine foreman or equivalent mine official by the end of the mine foreman's or equivalent mine official's next regularly scheduled working shift. The records required by this section shall be made in a secure book that is not susceptible to alteration or electronically in a computer system so as to be secure and not susceptible to alteration.

(h) *Retention period.* Records shall be retained at a surface location at the mine for at least 1 year and shall be made available for inspection by authorized representatives of the Secretary and the representative of miners.

30 CFR §75.361
Supplemental examination.

(a)(1) Except for certified persons conducting examinations required by this subpart, within 3 hours before anyone enters an area in which a preshift examination has not been made for that shift, a certified person shall examine the area for hazardous conditions and violations of the mandatory health or safety standards referenced in paragraph (a)(2) of this section, determine whether the air is traveling in its proper direction and at its normal volume, and test for methane and oxygen deficiency.
(2) Supplemental examinations shall include examinations to identify violations of the standards listed below:
(i) § §75.202(a) and 75.220(a)(1) — roof control;
(ii) § §75.333(h) and 75.370(a)(1) — ventilation, methane;
(iii) § §75.400 and 75.403 — accumulations of combustible materials and application of rock dust;
(iv) §75.1403 — other safeguards, limited to maintenance of travelways along belt

conveyors, off track haulage roadways, and track haulage, track switches, and other components for haulage;

(v) §75.1722(a) — guarding moving machine parts; and

(vi) §75.1731(a) — maintenance of belt conveyor components.

(b) *Certification.* At each working place examined, the person making the supplemental examination shall certify by initials, date, and the time, that the examination was made. In areas required to be examined outby a working section, the certified person shall certify by initials, date, and the time at enough locations to show that the entire area has been examined.

30 CFR §75.362
On-shift examination.

(a)(1) At least once during each shift, or more often if necessary for safety, a certified person designated by the operator shall conduct an on-shift examination of each section where anyone is assigned to work during the shift and any area where mechanized mining equipment is being installed or removed during the shift. The certified person shall check for hazardous conditions and violations of the mandatory health or safety standards referenced in paragraph (a)(3) of this section, test for methane and oxygen deficiency, and determine if the air is moving in its proper direction.

(2) A person designated by the operator shall conduct an examination to assure compliance with the respirable dust control parameters specified in the mine ventilation plan. In those instances when a shift change is accomplished without an interruption in production on a section, the examination shall be made anytime within 1 hour of the shift change. In those instances when there is an interruption in production during the shift change, the examination shall be made before production begins on a section. Deficiencies in dust controls shall be corrected before production begins or resumes. The examination shall include air quantities and velocities, water pressures and flow rates, excessive leakage in the water delivery system, water spray numbers and orientations, section ventilation and control device placement, and any other dust suppression measures required by the ventilation plan. Measurements of the air velocity and quantity, water pressure and flow rates are not required if continuous monitoring of these controls is used and indicates that the dust controls are functioning properly.

(a)(3) On-shift examinations shall include examinations to identify violations of the standards listed below:

(i) § §75.202(a) and 75.220(a)(1) — roof control;

(ii) § §75.333(h) and 75.370(a)(1) — ventilation, methane;

(iii) § §75.400 and 75.403 — accumulations of combustible materials and application of rock dust;

(iv) §75.1403 — other safeguards, limited to maintenance of travelways along belt conveyors, off track haulage roadways, and track haulage, track switches, and other components for haulage;

(v) §75.1722(a) — guarding moving machine parts; and

(vi) §75.1731(a) — maintenance of belt conveyor components.

(b) During each shift that coal is produced, a certified person shall examine for hazardous conditions and violations of the mandatory health or safety standards referenced in paragraph (a)(3) of this section along each belt conveyor haulageway where a belt conveyor is operated. This examination may be conducted at the same time as the preshift examination of belt conveyors and belt conveyor haulageways, if the examination is conducted within 3 hours before the oncoming shift.

(c) Persons conducting the on-shift examination shall determine at the following locations:
(1) The volume of air in the last open crosscut of each set of entries or rooms on each section and areas where mechanized mining equipment is being installed or removed. The last open crosscut is the crosscut in the line of pillars containing the permanent stoppings that separate the intake air courses and the return air courses.
(2) The volume of air on a longwall or shortwall, including areas where longwall or shortwall equipment is being installed or removed, in the intake entry or entries at the intake end of the longwall or shortwall.
(3) The velocity of air at each end of the longwall or shortwall face at the locations specified in the approved ventilation plan.
(4) The volume of air at the intake end of any pillar line--
(i) Where a single split of air is used in the intake entry furthest from the return air course immediately outby the first open crosscut outby the line of pillars being mined; or
(ii) Where a split system is used in the intake entries of each split immediately inby the split point.

(d)(1) A qualified person shall make tests for methane--
(i) At the start of each shift at each working place before electrically operated equipment is energized; and
(ii) Immediately before equipment is energized, taken into, or operated in a working place; and
(iii) At 20-minute intervals, or more often if required in the approved ventilation plan at specific locations, during the operation of equipment in the working place.
(2) These methane tests shall be made at the face from under permanent roof support, using extendable probes or other acceptable means. When longwall or shortwall mining systems are used, these methane tests shall be made at the shearer, the plow, or the cutting head. When mining has been stopped for more than 20 minutes, methane tests shall be conducted prior to the start up of equipment.
(3) As an alternative method of compliance with paragraph (d)(2) of this section during roof bolting, methane tests may be made by sweeping an area not less than 16 feet inby the last area of permanently supported roof, using a probe or other acceptable means. This method of testing is conditioned on meeting the following requirements:
(i) The roof bolting machine must be equipped with an integral automated temporary roof support (ATRS) system that meets the requirements of 30 CFR 75.209.
(ii) The roof bolting machine must have a permanently mounted, MSHA-approved methane monitor which meets the maintenance and calibration requirements of 30 CFR 75.342(a)(4), the warning signal requirements of 30 CFR 75.342(b), and the automatic de-energization requirements of 30 CFR 75.342(c).
(iii) The methane monitor sensor must be mounted near the inby end and within 18 inches of the longitudinal center of the ATRS support, and positioned at least 12 inches from the roof when the ATRS is fully deployed.
(iv) Manual methane tests must be made at intervals not exceeding 20 minutes. The test may be made either from under permanent roof support or from the roof bolter's

work position protected by the deployed ATRS.
(v) Once a methane test is made at the face, all subsequent methane tests in the same area of unsupported roof must also be made at the face, from under permanent roof support, using extendable probes or other acceptable means at intervals not exceeding 20 minutes.
(vi) The district manager may require that the ventilation plan include the minimum air quantity and the position and placement of ventilation controls to be maintained during roof bolting.

(e) If auxiliary fans and tubing are used, they shall be inspected frequently.

(f) During each shift that coal is produced and at intervals not exceeding 4 hours, tests for methane shall be made by a certified person or by an atmospheric monitoring system (AMS) in each return split of air from each working section between the last working place, or longwall or shortwall face, ventilated by that split of air and the junction of the return air split with another air split, seal, or worked-out area. If auxiliary fans and tubing are used, the tests shall be made at a location outby the auxiliary fan discharge.

(g) *Certification.* (1) The person conducting the on-shift examination in belt haulage entries shall certify by initials, date, and time that the examination was made. The certified person shall certify by initials, date, and the time at enough locations to show that the entire area has been examined.
(2) The certified person directing the on-shift examination to assure compliance with the respirable dust control parameters specified in the mine ventilation plan shall certify by initials, date, and time that the examination was made.

30 CFR §75.364
Weekly examination.

(a)*Worked-out areas.*(1) At least every 7 days, a certified person shall examine unsealed worked-out areas where no pillars have been recovered by traveling to the area of deepest penetration; measuring methane and oxygen concentrations and air quantities and making tests to determine if the air is moving in the proper direction in the area. The locations of measurement points where tests and measurements will be performed shall be included in the mine ventilation plan and shall be adequate in number and location to assure ventilation and air quality in the area. Air quantity measurements shall also be made where the air enters and leaves the worked-out area. An alternative method of evaluating the ventilation of the area may be approved in the ventilation plan.
(2) At least every 7 days, a certified person shall evaluate the effectiveness of bleeder systems required by §75.334 as follows:
(i) Measurements of methane and oxygen concentrations and air quantity and a test to determine if the air is moving in its proper direction shall be made where air enters the worked-out area.
(ii) Measurements of methane and oxygen concentrations and air quantity and a test to determine if the air is moving in the proper direction shall be made immediately before the air enters a return split of air.
(iii) At least one entry of each set of bleeder entries used as part of a bleeder system

under §75.334 shall be traveled in its entirety. Measurements of methane and oxygen concentrations and air quantities and a test to determine if the air is moving in the proper direction shall be made at the measurement point locations specified in the mine ventilation plan to determine the effectiveness of the bleeder system.

(iv) In lieu of the requirements of paragraphs (a)(2)(i) and (iii) of this section, an alternative method of evaluation may be specified in the ventilation plan provided the alternative method results in proper evaluation of the effectiveness of the bleeder system.

(b) *Hazardous conditions and violations of mandatory health or safety standards.* At least every 7 days, an examination for hazardous conditions and violations of the mandatory health or safety standards referenced in paragraph (b)(8) of this section shall be made by a certified person designated by the operator at the following locations:

(1) In at least one entry of each intake air course, in its entirety, so that the entire air course is traveled.

(2) In at least one entry of each return air course, in its entirety, so that the entire air course is traveled.

(3) In each longwall or shortwall travelway in its entirety, so that the entire travelway is traveled.

(4) At each seal along return and bleeder air courses and at each seal along intake air courses not examined under §75.360(b)(5).

(5) In each escapeway so that the entire escapeway is traveled.

(6) On each working section not examined under §75.360(b)(3) during the previous 7 days.

(7) At each water pump not examined during a preshift examination conducted during the previous 7 days.

(8) Weekly examinations shall include examinations to identify violations of the standards listed below:

(i) § §75.202(a) and 75.220(a)(1) — roof control;

(ii) § §75.333(h) and 75.370(a)(1) — ventilation, methane;

(iii) § §75.400 and 75.403 — accumulations of combustible materials and application of rock dust; and

(iv) §75.1403 — maintenance of off track haulage roadways, and track haulage, track switches, and other components for haulage;

(v) §75.1722(a) — guarding moving machine parts; and

(vi) §75.1731(a) — maintenance of belt conveyor components.

(c) *Measurements and tests.* At least every 7 days, a certified person shall--

(1) Determine the volume of air entering the main intakes and in each intake split;

(2) Determine the volume of air and test for methane in the last open crosscut in any pair or set of developing entries or rooms, in the return of each split of air immediately before it enters the main returns, and where the air leaves the main returns; and

(3) Test for methane in the return entry nearest each set of seals immediately after the air passes the seals.

(d) Hazardous conditions shall be corrected immediately. If the condition creates an imminent danger, everyone except those persons referred to in §75.104(c) of the Act shall be withdrawn from the area affected to a safe area until the hazardous condition is corrected. Any violation of the nine mandatory health or safety standards found during a weekly examination shall be corrected.

(e) The weekly examination may be conducted at the same time as the preshift or on-shift examinations.

(f)(1) The weekly examination is not required during any 7 day period in which no one enters any underground area of the mine.
(2) Except for certified persons required to make examinations, no one shall enter any underground area of the mine if a weekly examination has not been completed within the previous 7 days.

(g) *Certification.* The person making the weekly examinations shall certify by initials, date, and the time that the examination was made. Certifications and times shall appear at enough locations to show that the entire area has been examined.

(h) *Recordkeeping.* At the completion of any shift during which a portion of a weekly examination is conducted, a record of the results of each weekly examination, including a record of hazardous conditions and violations of the nine mandatory health or safety standards found during each examination and their locations, the corrective action taken, and the results and location of air and methane measurements, shall be made. The results of methane tests shall be recorded as the percentage of methane measured by the examiner. The record shall be made by the person making the examination or a person designated by the operator. If made by a person other than the examiner, the examiner shall verify the record by initials and date by or at the end of the shift for which the examination was made. The record shall be countersigned by the mine foreman or equivalent mine official by the end of the mine foreman's or equivalent mine official's next regularly scheduled working shift. The records required by this section shall be made in a secure book that is not susceptible to alteration or electronically in a computer system so as to be secure and not susceptible to alteration.

(i) *Retention period.* Records shall be retained at a surface location at the mine for at least 1 year and shall be made available for inspection by authorized representatives of the Secretary and the representative of miners.

30 CFR §75.371
Mine ventilation plan; contents.

The mine ventilation plan shall contain the information described below and any additional provisions required by the district manager:
(a) The mine name, company name, mine identification number, and the name of the individual submitting the plan information.
(b) Planned main mine fan stoppages, other than those scheduled for testing, maintenance or adjustment, including procedures to be followed during these stoppages and subsequent restarts (see §75.311(a)) and the type of device to be used for monitoring main mine fan pressure, if other than a pressure recording device (see 75.310(a)(4)).
(c) Methods of protecting main mine fans and associated components from the forces of an underground explosion if a 15-foot offset from the nearest side of the mine opening is not provided (see §75.310(a)(6)); and the methods of protecting main mine fans and

intake air openings if combustible material will be within 100 feet of the area surrounding the fan or these openings (see §75.311(f)).
(d) Persons that will be permitted to enter the mine, the work these persons will do while in the mine, and electric power circuits that will be energized when a back-up fan system is used that does not provide the ventilating quantity provided by the main mine fan (see §75.311(c)).
(e) The locations and operating conditions of booster fans installed in anthracite mines (see §75.302).
(f) Section and face ventilation systems used, including drawings illustrating how each system is used, and a description of each different dust suppression system used on equipment on working sections.
(g) Locations where the air quantities must be greater than 3,000 cubic feet per minute (see (h) In anthracite mines, locations where the air quantities must be greater than 1,500 cubic feet per minute (see §75.325(e)(1)).
(i) Working places and working faces other than those where coal is being cut, mined, drilled for blasting or loaded, where a minimum air quantity will be maintained, and the air quantity at those locations (see §75.325(a)(1)).
(j) The operating volume of machine mounted dust collectors or diffuser fans, if used (see §75.325(a)(3)).
(k) The minimum mean entry air velocity in exhausting face ventilation systems where coal is being cut, mined, drilled for blasting, or loaded, if the velocity will be less than 60 feet per minute. Other working places where coal is not being cut, mined, drilled for blasting or loaded, where at least 60 feet per minute or some other minimum mean entry air velocity will be maintained (see §75.326).
(l) The maximum distance if greater than 10 feet from each working face at which face ventilation control devices will be installed (see §75.330(b)(2)). The working places other than those where coal is being cut, mined, drilled for blasting or loaded, where face ventilation control devices will be used (see §75.330(b)(1)(ii).
(m) The volume of air required in the last open crosscut or the quantity of air reaching the pillar line if greater than 9,000 cubic feet per minute (see §75.325(b)).
(n) In anthracite mines, the volume of air required in the last open crosscut or the quantity of air reaching the pillar line if greater than 5,000 cubic feet per minute (see §75.325(e)(2)).
(o) Locations where separations of intake and return air courses will be built and maintained to other than the third connecting crosscut outby each working face (see §75.333(b)(1)).
(p) The volume of air required at the intake to the longwall sections, if different than 30,000 cubic feet per minute (see §75.325(c)).
(q) The velocities of air on a longwall or shortwall face, and the locations where the velocities must be measured (see §75.325(c)(2)).
(r) The minimum quantity of air that will be provided during the installation and removal of mechanized mining equipment, the location where this quantity will be provided, and the ventilation controls that will be used (see §75.325(d), *(g), and (i))*.
(s) The locations and frequency of the methane tests if required more often by §75.362(d)(1)(iii) (see §75.362(d)(1)(iii).
(t) The locations where samples for "designated areas" will be collected, including the

specific location of each sampling device, and the respirable dust control measures used at the dust generating sources for these locations (see §70.208 of this chapter).
(u) The methane and dust control systems at underground dumps, crushers, transfer points, and haulageways.
(v) Areas in trolley haulage entries where the air velocity will be greater than 250 feet per minute and the velocity in these areas (see §75.327(b)).
(w) Locations where entries will be advanced less than 20 feet from the inby rib without a crosscut being provided where a line brattice will be required. (see §75.333(g)).
(x) A description of the bleeder system to be used, including its design (see §75.334).
(y) The means for determining the effectiveness of bleeder systems (see §75.334(c)(2)).
(z) The locations where measurements of methane and oxygen concentrations and air quantities and tests to determine whether the air is moving in the proper direction will be made to evaluate the ventilation of nonpillared worked-out areas (see §75.364(a)(1)) and the effectiveness of bleeder systems (see §75.364(a)(2)(iii). Alternative methods of evaluation of the effectiveness of bleeder systems (§75.364(a)(2)(iv)).
(aa) The means for adequately maintaining bleeder entries free of obstructions such as roof falls and standing water (see §75.334(c)(3)).
(bb) The location of ventilation devices such as regulators, stoppings and bleeder connectors used to control air movement through worked-out areas (see §75.334(c)(4)). The location and sequence of construction of proposed seals for each worked-out area. (see §75.334(e)).
(cc) In mines with a demonstrated history of spontaneous combustion: a description of the measures that will be used to detect methane, carbon monoxide, and oxygen concentration during and after pillar recovery and in worked-out areas where no pillars have been recovered (see §75.334(f)(1); and, the actions which will be taken to protect miners from the hazards associated with spontaneous combustion (see §75.334(f)(2). If a bleeder system will not be used, the methods that will be used to control spontaneous combustion, accumulations of methane-air mixtures, and other gases, dusts, and fumes in the worked-out area (see §75.334(f)(3)).
(dd) The location of all horizontal degasification holes that are longer than 1,000 feet and the location of all vertical degasification holes.
(ee) If methane drainage systems are used, a detailed sketch of each system, including a description of safety precautions used with the systems.
(ff) Seal installation requirements provided by § 75.335 and the sampling provisions provided by § 75.336.
(gg) The alternative location for the additional sensing device if the device will not be installed on the longwall shearing machine (see §75.342(a)(2)).
(hh) The ambient level in parts per million of carbon monoxide, and the method for determining the ambient level, in all areas where carbon monoxide sensors are installed.
(ii) The locations (designated areas) where dust measurements would be made in the belt entry when belt air is used to ventilate working sections or areas where mechanized mining equipment is being installed or removed, in accordance with § 75.350(b)(3).
(jj) The locations and approved velocities at those locations where air velocities in the belt entry are above or below the limits set forth in Sec. 75.350(a)(2) or Sec. Sec. 75.350(b)(7) and 75.350(b)(8).

(kk) The locations where air quantities are measured as set forth in § 75.350(b)(6).
(ll) The locations and use of point-feed regulators, in accordance with § § 75.350(c) and 75.350(d)(5).
(mm) The location of any diesel-discriminating sensor, and additional carbon monoxide or smoke sensors installed in the belt air course.
(nn) The length of the time delay or any other method used to reduce the number of non-fire related alert and alarm signals from carbon monoxide sensors.
(oo) The reduced alert and alarm settings for carbon monoxide sensors, in accordance with § 75.351(i)(2).
(pp) The alternate detector and the alert and alarm levels associated with the detector, in accordance with § 75.352(e)(7).
(qq) The distance that separation between the primary escapeway and the belt or track haulage entries will be maintained if other than to the first connecting crosscut outby the section loading point (see §75.380(g)).
(rr) In anthracite mines, the dimensions of escapeways where the pitch of the coal seam does not permit escapeways to be maintained 4 feet by 5 feet and the locations where these dimensions must be maintained (see §75.381(c)(4)).
(ss) Areas designated by the district manager where measurements of CO and NO^2 concentrations will be made (see § 70.1900(a)(4)).
(tt) Location where the air quantity will be maintained at the section loading point (see §75.325(f)(2)).
(uu) Any additional location(s) required by the district manager where a minimum air quantity must be maintained for an individual unit of diesel-powered equipment. (see §75.325(f)(5)).
(vv) The minimum air quantities that will be provided where multiple units of diesel-powered equipment are operated (see §75.325(g) (1)-(3) and (i)).
(ww) The diesel-powered mining equipment excluded from the calculation under §75.325(g). (see §75.325(h)).
(xx) Action levels higher than the 50 percent level specified by § 70.1900(c). (see §75.325(j)).
(yy) The locations where the pressure differential cannot be maintained from the primary escapeway to the belt entry.

Appendix B – Schedule 4 from Queensland, Australia, Coal Mining Safety and Health Regulation 2001

Schedule 4 **Ventilation control devices and design criteria**

Column 1 Ventilation control devices	Column 2 Design criteria
brattice line or temporary stopping	antistatic and fire resistant
mine entry airlock	capable of withstanding an overpressure of 70kPa while it is open
separation stoppings for a primary escapeway	antistatic, fire resistant and of substantial construction providing for minimal leakage
stopping, overcast or regulator installed as part of the main ventilation system	capable of withstanding an overpressure of 35kPa
stopping, overcast or regulator installed as part of the ventilation system for a panel	capable of withstanding an overpressure of 14kPa during life of the panel
type B seal	capable of withstanding an overpressure of 35kPa
type C seal	capable of withstanding an overpressure of 140kPa
type D seal	capable of withstanding an overpressure of 345kPa
type E seal	capable of withstanding an overpressure of 70kPa
ventilation ducting	antistatic and fire resistant

Appendix C – Schedule 5 from Queensland, Australia, Coal Mining Safety and Health Regulation 2001

Schedule 5 Matters to be covered in inspections

1) The presence of flammable gases or contaminants in the atmosphere
2) The adequacy of the following-
    a) Ventilation;
    b) Coal dust inertization;
    c) Emergency, first aid and fire fighting equipment
3) The condition of the following-
    a) Ventilation control devices;
    b) Auxiliary fans;
    c) Surfaces over which persons may travel or vehicles may be driven;
    d) The support for roof and sides of the workings
4) The stability of roadways in the workings
5) Indications of heating or fire
6) Abnormal water inflow
7) Plant malfunction
8) The proper functioning of communication and monitoring systems
9) Excessive accumulation of mud, water or coal
10) Thermal environmental conditions

Appendix D: Annex 1 of South African Regulations for the Prevention of Flammable Gas and Coal Dust Explosions in Collieries

1. STONE DUST SAMPLING PROGRAMS

A sampling program that will ensure compliance with the requirements of incombustible matter content and the taking of samples must be set out as follows:

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, 100 mm 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 20 m. 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 60 m 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 outbye of the face area must be divided into zones not exceeding 1200 m in length. These zones must further be divided into sub-zones, not exceeding 100 m 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 100 m. 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.

2. Analysis Samples

2.1 Samples must be analysed by either the colourimetric method or by a laboratory determination of mass of incombustible matter, or by both methods. Samples may also be analysed using a portable stonedust analyser. Only laboratories accredited by SANAS and analysers approved by a certification body accredited by SANAS may be used for these purposes.

2.2 Dust collected at a mine must without delay be processed and the incombustible matter content of the samples determined. Descriptions of the two methods are set out in 2.2.1 and 2.2.4 below -

2.2.1 Colourimetric Method

(a) analysing of samples by using the colourimetric method can be done on surface or underground. In both cases the method described remains the same. For the underground option drying facilities and adequate lighting must be provided. This option evaluates the degree of inertisation in the shortest possible time, permitting immediate remedial action. (Moisture correction is not considered in this option);

(b) the colour of a sample of dust must be compared with that of a scientifically prepared standard colour sample, known to contain eighty percent, or sixty five percent as the case may be, of incombustible matter content. When on such comparison, the colour of the sample is found to be the same colour or lighter than that of the standard sample, the incombustible matter content in the dust must be taken to comply with the prescribed percentage of the total incombustible matter content;

(c) any sample that appears to be below the prescribed percentage of incombustible matter content must be analysed using the laboratory method described below; and

(d) in addition to (c) above, at least ten percent of the remaining samples must be analysed using the laboratory method.

2.2.2 A separate standard colour sample must be prepared for each geographical/working area of a mine in the following manner -

(a) grind some dry coal dust from the seam in each area for which the standard colour sample is being prepared so that it passes through a 250 micrometers sieve;

(b) determine the ash content of the sieved coal dust. The ash content must not exceed 20 percent by mass on a dry basis;

(c) pass through a 250 micrometers sieve some dry stone dust of the type used in the mine;

(d) weigh quantities of the sieved coal dust and sieved stone dust in proportions that will give the desired incombustible matter content i.e. 65% and 80%;

(e) mix the dust thoroughly by stirring, shaking or rolling but do not grind the mixture;

(f) using the approved laboratory method, determine the incombustible matter content of the mixture and verify that it is not less than the required;

(g) whenever there is change in the colour/reflectivity of the stone dust supplied to the mine, and whenever the colour of the coal seam changes distinctly, new standard samples must be prepared; and

(h) at intervals of not more than 3 months, re-test the standard and keep a record of the results of these tests. If the standard has an incombustible matter content which is less than that required, replace the standard with a new one.

2.2.3 The procedure for the preparation and evaluation of collected dust samples is as follows -

2.2.3.1 split the sample and retain one half of the sample, if required, for laboratory analysis. Air-dry the portion to be compared if necessary. Sieve the sample through a 250 micrometers sieve and mix the sample thoroughly but do not grind it.

2.2.3.2 compare the colour of the mixed sieved sample with that of the standard colour sample. The comparison must be made under good and even illumination. When conditions permit, and if by choice, this comparison is done underground, it must take place at a designated site. The comparison must be done in a suitably designed light box. The person performing this duty must be trained to prepare the samples and to conduct the colourimetric test. Furthermore, his ability to distinguish between the colour ranges, must have been determined.

2.2.3.3 if any sample fails the comparison test, this must be reported without delay to the employer who must ensure that the area concerned is properly inertised timeously.

2.2.4 Laboratory Method

Analysis of samples in a laboratory must be carried out by the following method or by other methods approved by the laboratory concerned -

2.2.4.1 the residue of a weighed quantity of dust, after that quantity has been dried at a temperature not exceeding 140°C, and the loss of mass attributable to moisture ascertained, must be heated in an open vessel to a temperature not less than 480°C, and not more than 520°C, until the coal is completely burnt away. The incinerated residue must be weighed;

2.2.4.2 the sum of the masses of moisture and incinerated residue must be recorded as incombustible matter and be expressed as a percentage of the total mass of the dust; and

2.2.4.3 where samples were air dried before analysis by the laboratory method, a correction may be made to the incombustible matter content of the dust sample analysed by laboratory method. The corrected total incombustible content is equal to M+I (100-M/100) where M is the percentage loss of mass during air-drying and I is the percentage of total incombustible matter in the dust as determined by the method described in the preceding paragraph.

3. Keeping of Records

3.1 the certificates showing the quality of stone dust supplied to the mine must be retained for two years; and

3.2 a record must be kept of the date, places sampled and results of the analysis of the mine dust sampling program. Failure of more than 20% of the number of samples of a given area is unacceptable and requires immediate remedial action, which must be reflected in the record referred to in 3.1.