

Passive and Triggered Explosion Barriers in Underground Coal Mines
- A literature review of recent research

Report to

CANMET
Natural Resources Canada

by

D. H. (Steve) Zou, Ph.D., P.Eng., Mining Engineering Professor

and

S. Panawalage, Graduate Student

Dept. Mining and Metallurgical Engineering
Dal Tech, Dalhousie University
Halifax, Nova Scotia

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During the literature search, many colleagues from around the world responded to our inquiry and some provided valuable information. The authors would like to take this opportunity to thank all of them for their support.

1. INTRODUCTION

Underground coal mining produces methane and coal dust. These two pollutants present a serious hazard to underground safety. Coal dust explosions are usually initiated by methane explosions. The exploding gas creates shock waves that disperse coal dust into the air and the flame ignites the dust. These 'coal dust' explosions are often self-propagating and extremely violent, often affecting large sections of the mine or even the entire mine (such as the case in Westray Mine). The most obvious and practical method to prevent coal dust explosions is to avoid the generation of coal dust and its dispersion throughout the mine workings. However, it is practically impossible to entirely prevent this dispersion. Other measures such as stone dusting and wetting must be undertaken to reduce the hazards.

Explosion barriers are the last lines of defence. Although they can not eliminate the initial explosion, they can prevent the explosion from becoming larger and more violent, and can keep it from propagating into other areas of a mine. Installation of explosion barriers is normally required by mining regulations. Active research was conducted in CANMET prior to 1983 and there was much less research thereafter in Canada. There seems to be a need to update the technology development in this area around the world. There is a particular need for research to develop practical explosion barriers for room and pillar mines and to incorporate current technology in triggered explosion barriers.

An initial proposal to CANMET to conduct research in explosion barriers was submitted by the Nova Scotia Dept. of Natural Resources and the Dept. of Labour as a result of the Nova Scotia Government's response to the Westray Inquiry Report, specifically Recommendation 37. The Nova Scotia government made a request to CANMET to conduct active research into the development and use of passive and triggered stonedust and water barriers. At the time, CANMET had advised that they were not conducting research in this area. However, CANMET and the recently formed Underground Coal Mining Safety Research Collaboration (UCMSRC) agreed to conduct a literature review of the technology development since 1983 as an initial step.

Approval to proceed with the literature review in research of explosion barriers was obtained at the UCMSRC Executive Committee meeting held on May 5, 2000. Final commitment and funding were approved later by CANMET. Both Dalhousie University and the University of British Columbia (UBC) were considered for this contract. Following communications between Dr. S. Zou of Dalhousie University and Dr. A. Hall of UBC it was agreed that Dalhousie University would undertake the study. The study was undertaken by a graduate student under the direct supervision of Dr. S. Zou. The use of a student to undertake this work fulfilled the requirement in the Memorandum of Understanding (MOU) of UCMSRC.

2. OBJECTIVES AND SCOPE OF WORK

The main objective of this project was to undertake a world-wide literature review of research into explosion barrier design and placement for Canadian underground coal mines. This research attempted to identify world-wide technological advances and development over the last 17 years since the last CANMET study which was conducted by Mountford and Associates in 1983. The result of this research could be incorporated into all underground coal mines in Canada, and may provide a basis for the implementation of appropriate legislation and regulation for the use of such barriers. This review may also lead to a ranking of areas in which further research and development are needed.

3. METHODOLOGY OF SEARCH

During the project, a world-wide search for documents on explosion barriers was conducted through the following mechanisms:

- (a) Library search,
- (b) Internet search,
- (c) E-mail inquiry through a mine ventilation mailing list hosted on majordomo@unr.edu,
- (d) Recourses from CANMENT and UCMSRC members.

(a) *Library search*

The library search was mainly carried out through the Dalhousie University library and Nova net. After reviewing the searched article titles, more than 25 of the most relevant publications were identified and the library was able to find 19 of them. They are listed in the Reference section at the end of this report.

(b) *Internet search*

It was found during the search that searching via the Internet was a very effective way in revealing valuable information on relevant publications and organisations. A number of web sites and organisations were thus identified on the Internet. They are listed in the Reference section under 'Relevant Web Sites' at the end of this report.

(c) *E-mail inquiry*

With the assistance of Dr. A Hall, an e-mail message requesting publications and information on explosion barriers was posted on the mine ventilation mailing list, which was distributed to all members. As a result, many responded with valuable information and useful suggestions. Some offered technical information on their own research and some provided information sources (Please see Appendices I to III for detail). In particular, the following persons should be mentioned.

- Dr. Jan J L du Plessis, CSIR, South Africa replied with 98 publications and reports. We have selected 14 of the most relevant publications and were able to locate them all (See Appendix I for more detail).
- Eric S Weiss, NIOSH provided various publications from the former United States Bureau of Mines (USBM). These documents are, however, mostly for the work done in previous years. (See Appendix II for more detail).
- Dr. Darron Dixon-Hardy, University of Leeds indicated his ongoing research on a novel concept of using a permeable explosion door and offered to collaborate with UCMSRC in this research (See Appendix III for more detail).
- In addition to the mailing list, e-mail messages were also sent to a number of individuals and organisations.

(d) Recourses from CANMENT and UCMSRC members

CANMENT provided the report by Mountford (1983) and some information on Canadian Coal mining regulations. Some UCMSRC members supplied data of their own organisations and some made available their own collections (e.g., Dr. Forrester provided a variety of documents including the coal mining regulations of several foreign countries).

This search has found a total of 127 publications and reports (See References and Appendices) related to coal dust explosion barriers, with 36 of them being the most relevant. However, only 25 articles were obtained (Please see “Articles received and reviewed” in the Reference).

4. REVIEW OF TECHNOLOGIES PRIOR TO 1983

In order to identify the new technology development in the past 17 years, it would be useful to first summarise the technology on explosion barriers in previous years. Information sources in this section are from previous publications including those by CANMET (Mountford 1983) and those by USBM. Based on the report by Mountford (1983) and other relevant publications, explosion barriers can be divided into two categories: passive barriers and active barriers, as illustrated below.

Barriers	Passive Barriers	Stone dust barriers (Usually limestone)
		Water barriers
	Active Barriers	Triggered barriers

4.1 PASSIVE BARRIERS AND THEIR OPERATING PRINCIPLES

Passive barriers are sub-divided into stone dust barriers and water barriers depending on the type of inert material (incombustible stone dust or water) used. Compared to stone dust barriers, water barriers are more easily maintained, less expensive and as effective as stone dust barriers.

The barrier utilizes the kinetic energy in the blast wave ahead of the explosion flame. When the explosion flame comes, the preinstalled barriers are overturned by the wave energy thereby dispersing the inert material into the path of the flame. To be effective, water or stone dust should be completely dispersed upon arrival of the flame front. If the barrier is properly situated, the flame will be extinguished. If the barrier is too far from, or too near the explosion source, the flame may not be suppressed effectively. From experience, they should be installed at least 60m away from the coal face. On the other hand, they should be installed as close to the source as possible in order to prevent the flame propagating to a large area.

Both stone and water barriers are further classified as concentrated and distributed barriers because of the method of installation.

Concentrated barriers:

The shelves may be concentrated together in one location with a spacing of about 1m between shelves.

Distributed barriers:

The shelves may be spread out over a considerable length of roadway with a spacing of about 10m between shelves.

4.2 STONE DUST BARRIERS

In the early 1920s, stone dust barriers were introduced in order to suppress coal dust explosions. There were two types of design which were called the 'German ' and the 'Polish ' stone dust barriers. These are still used world-wide today.

The shelves may be 'light' or 'heavy' depending upon the stone dust loading on each shelf. Two similar types of shelves were designed: the German Shelf-long boards & Polish Shelf-short boards. They became the standard for stone dust barriers. Light barriers are used near the face (close to the source of ignition) and heavy barriers are used further away from the source of ignition, such as in conveyor roads and roadways separating major working areas.

4.2.1 German Stone Dust Barriers

The German stone dust barriers could be the 'light' or the 'heavy' types, depending on the location where they are installed and the quantity of stone dust they contain. The light barriers consist of sufficient shelves such that the total load is 80 kg/shelf and each shelf is loaded to a maximum of 30 kg/metre. The heavy barriers consist of sufficient shelves such that the total dust load is 160 kg/shelf and each shelf is loaded to a minimum of 30 kg/metre and a maximum of 60 kg/metre. The total dust loading in both types of barrier must be 400 kg/m² of the roadway cross-section.

The light barrier is designed to be suitable for operation close to the source of ignition. The heavy barrier is designed to protect trunk conveyor roads and roadways that separate major ventilation circuits. Figure 1 illustrates the design of German type barriers.

4.2.2 Polish Stone Dust Barriers

Polish barriers consist of a series of shelves that are known as 'light' or 'heavy' (Figure 2) depending upon the dimensions of the shelf and the weight of dust deposited. For the Light Shelf, the maximum load of stone dust per foot of shelf length is 20 lbs/ft. For the Heavy Shelf, the load of stone dust per foot of shelf length is 20 lbs minimum and 40 lbs/ft maximum.

In view of the previous test work on stone dust barriers, the Polish barrier is considered more effective because the Polish Shelf would be more easily upset in a weak explosion than the German Shelf.

4.2.3 Disadvantages of stone dust barriers

- If the explosion is too weak, the blast waves cannot overturn the shelves and disperse the inert material. This usually happens when the barrier is closer than 60m to the ignition source.
- In roadways with high air velocities, dust may be blown off the shelves and the barrier effectiveness can be reduced.

- The flame speed should be between 100 and 500 m/s if the stone dust barriers are to perform adequately. This may limit their applications considering the various types of flame.
- For fast moving faces, it may be difficult to keep up with the pace in installation.

4.3 PASSIVE WATER BARRIERS

Passive water barriers are set off by the blast wave from an explosion in the same way as stone dust barriers. They are simply water filled containers, such as troughs, tubs and bags. In principle, when an explosion occurs,

- the blast wave upsets or disintegrates the water containers and spills their contents.
- the spilled water is dispersed by air turbulence and forms a barrier of dispersed water droplets across the roadway in the path of the flame.
- the flame is quenched and coal dust in the vicinity of the barrier is wetted so that the flame is suppressed.

4.3.1 TYPES OF WATER BARRIERS

Water barriers consist of troughs, tubs or bags. Although they may come in different sizes and shapes, their designs are similar. In the following, a few major types used in different countries are introduced.

1) (West) Germany Water Barriers

In 1967, the former West German Mines Inspectorate approved the use of both suspended troughs and troughs placed on platforms. Continued research has led to the evolution from the water barrier Types 1 and 2 to barrier Types 3 and 4, which are still in use today. Figure 3 shows the shape and size.

Water Barrier Design

Water trough barriers have generally two types of design: Type 3 for concentrated barriers, and Type 4 for distributed or wide action barriers.

Type 3 Barriers: Troughs (made of PVC) with 80 litre capacity are arranged in groups. A group of troughs is defined as all troughs installed within a 3m interval or section of roadway. Several groups of troughs constitute one concentrated barrier. The quantity of extinguishant for a given roadway area or space is 200 litres/m² roadway cross-section and 5 litres/m³ of space.

Type 4 Barriers: These barriers also consist of groups of troughs as defined in Type 3. The group definition and the spacing between troughs within a group are the same as for Type 3. However the distance between groups may be up to 30 metres with Each trough group must contain a minimum of 1 litres/m³ of roadway space.

2) United States Water Barriers

Four types of passive water barriers have been designed by the USBM and they were found capable of suppressing weak (68.5 m/sec) coal dust explosions. They are

- the Modified ' German ' water trough barrier - Model 1 and Model 2 (Figure 4), and
- the static pressure sensitive barrier - Model 1 (Figure 5) and Model 2 (Figure - 6).

Except for the Model water trough barrier, the other three barriers were found capable of suppressing coal dust explosions with speeds of propagation as low as 30.5 m/sec. The water barriers are operated by the dynamic pressure generated ahead of an explosion. The static pressure barriers are operated by responding to an increase in the static pressure ahead of an explosion.

3) Japan Water Barrier

The water barrier used in Japan is a suspended flexible plastic trough-shaped bag, called a 'flexitrough barrier'. It is suspended from hooks by eyelets on both longitudinal sides of the trough (Figure 7). Suspension alternatives are shown in Figures 8 and 9.

4) Water Barriers used in Other Countries

Water barriers used in other countries are quite similar to those described above, or the modified type. For example,

- in Poland, the barrier trough, with a capacity of 40 liters, is similar in design to the German trough,
- in France, a combination design of Polish and (West) German water barriers is used,
- in United Kingdom, two types of tubs (50 L and 25 L) are used. The loading mass of water must be a minimum of 22 lb/ft² of roadway cross-section and maximum of 40 lb/ft length of shelf,
- in Canada, suspended waterproofed canvas troughs similar to the Japanese 'flexitrough' were used in concentrated barriers at the Sparwood mines of B.C. Coal (no other information available). In Prince Colliery, German type water barriers were used. In Quinsam, Japanese type water barriers were used and in Smoky River Coal, German type water barriers were used (Forrester, 2000).

4.3.2 Comparison with stone dust barriers

1) Advantages of water barriers over stone dust barriers

- They are easier to install and easier to maintain.
- Their contents do not cake and become ineffective with time.
- They occupy less roadway cross-sectional area.
- The four types of passive water barriers developed by USBM were found more responsive to weak explosions.

2) Disadvantage of water barriers

When there is much machinery near the coalface it becomes difficult to install barrier troughs within the regulation distance from the face.

3) Limitations of Passive Barriers (both stone dust and water barriers)

- The more equipment in a roadway, the more difficult it becomes to install a barrier to the required specification.
- The faster a coal face moves, the more difficult it becomes to ensure that the barrier is always at the required distance from the face.
- The barriers can limit the free space in roadways, which is important, for example, when low roof conditions exist.

4.4 ACTIVE (Triggered) BARRIERS

In design of explosion barriers, the suppressant agent should be ideally dispersed as the flame front reaches the barrier. If the suppressant agent is dumped prematurely, the suppressant will be driven downstream and its concentration will be diluted by the explosion-induced wind before being overtaken by the flame. When the suppressant agent is dumped late, the suppressant is dumped behind the flame where it has minimal effect in distinguishing the flame. With the passive barriers, it is difficult to ensure such a condition.

Active barriers with triggering devices are therefore developed to meet the needs. The key is the detection of the arrival of the flame front and timely dumping of inert materials. Triggered barriers consist of three main components: the sensor, the dispenser and the suppressant. A sensor device detects the on-coming explosion by a rise in static pressure, temperature or radiation and triggers a mechanism to activate the dispenser. The dispenser discharges an inert material by means of a compressed gas, a spring or explosive materials.

4.4.1 TRIGGERED BARRIER COMPONENTS

1) Sensors

Several types of sensor have been developed. They include:

- **Ultraviolet Sensor:** It responds to the ultraviolet radiation emitted by naked flames.
- **Infrared Sensor:** It reacts to changes in the infrared radiation intensity.
- **Thermocouple Flame Sensor:** It responds to the heat supplied by conduction so that there is no response if the thermocouples are not in the actual flame or products of combustion.
- **Thermo Mechanical Sensor:** They respond to the dynamic pressure of an explosion.
- **Blast Operated Sensor:** They react to the blast of an explosion in much the same way as a passive barrier.

2) Dispenser

A number of dispenser types have been developed. Most of them are based on either a detonating cord or pressurised gas as an energy source. Steel cylinders or "guns" are the actual containers for both the suppressant and the propellant.

3) Extinguishing Agents

A number of agents have been used as suppressants. They include: Halon1301, water, stone dust (e.g. limestone), sodium bicarbonate, ammonium dihydrogen phosphate, potassium chloride, potassium bicarbonate and sodium chloride.

4.4.2 TRIGGERED BARRIER DESIGN

Several types of triggered barriers have been developed in different countries. The major barrier designs are introduced in the following.

1) Belgium triggered barrier

The Belgians have developed a very sensitive multipoint detection system (Figure 10) that can trigger dispersion throughout the entire zone, regardless of explosion direction and velocity. It consists of a thermomechanical sensor, a dispenser, and water as a suppressant.

Sensor

The Belgian triggered barrier system consists of a thermomechanical sensor that will react to the pressure of the explosion but, if pressures are too low to trigger the system, the sensor will also react to the heat of the flame. The sensing unit consists of three sensors (two acting and one spare) enclosed in a protective steel case (66.5cm high, 30.5cm wide and 46.5cm deep). Both the sensor and triggering system are non-electric.

Dispenser

The dispenser consists of a cylinder of polyurethane foam wrapped in a polyvinyl chloride (PVC) sheet and suspended in a wire mesh cradle. It uses a detonating cord as a means of dispersing the water. The cylinder is 2 metres long, has a diameter of 22.5cm and weighs a total of 10 kg without water. Total water capacity is 90 to 100 litres.

Operation

The dynamic pressure created in the roadway by the blast of an explosion activates a vane inside the sensing unit case. Movement of the vane cuts a nylon cord which in turn releases a hammer which pivots about its axis and strikes a percussion detonator. The hammer is held by the nylon cord against two tension springs. Selective operation is assured by means of a calibrated vane restraining device. If the dynamic pressure fails to trigger the sensing unit, the nylon cord holding the hammer will be melted by the flame, thereby also triggering the system. A removable locking device prevents movement of the vane and hammer during transportation and installation of the system.

2) France triggered barrier

The triggered barrier used in France is comprised of an ultraviolet sensor and triangular section troughs containing suppressant material. The dispenser consists of metal troughs with a triangular configuration and a 25-litre capacity. Suppressant is a mixture of potassium bicarbonate (10kg) and very fine limestone dust which is treated to ensure water repellence.

The system is operated by sensing UV radiation from the flame but is unaffected by the flame of safety lamps and by the light of incandescent mine lamps. The sensor sends an impulse to a detonator in the disperser. The detonator initiates firing of a 3.6m detonating fuse containing 10 grams per metre of penthrite.

3) (West) Germany triggered barrier

(West) German researchers developed two types of active barriers: The System Tremonia and the BVS System.

System Tremonia:

This system consists of a thermoelectric sensor, detonating cord and an 80-litre conventional water trough. The thermoelectric sensor detects the explosion and sends an impulse which triggers the detonating cord to destroy the centrally mounted water trough dispersing the water. The principal advantage of this triggered barrier system as a whole is that in the event that electrical sensing fails, the water troughs will act as a passive barrier when they are destroyed by the blast of the explosion.

BVS System:

The BVS (Bergbau-Versuchsstrecke) triggered barriers are more specialised than the System Tremonia barrier. It consists of an ultraviolet sensor, a disperser powered by compressed nitrogen and ammonium phosphate powder as the suppressant.

The ultraviolet sensor detects the visual flame and triggers the dispersing system via an activator. Then, a detonator blows open the valves of the suppressant containers and the suppressant is expelled by high pressure nitrogen gas.

The disperser system is composed of a flame proof cylinder with a 12.3 litre capacity that contains ammonium phosphate with nitrogen gas at 120 bar pressure. Two valve outlets opened by a detonator allow release of the suppressant. Suppressant quantities of 20 kg/m² of roadway cross-sectional area can extinguish an explosion with flame speeds of up to 500 m/sec.

4) Poland triggered barrier

Two types of sensor units are used to energize the barriers: a thermocouple and an infrared detector. The infrared detectors respond to radiated heat. The thermocouple system responds to both optical and temperature changes.

The disperser consists of a steel cylinder which disperses dry powder by pressurized nitrogen. The cylinder has a capacity of 4 or 8 kg of extinguishing powder pressurized to 120 atm by nitrogen gas.

The cylinder disperser is triggered by one of two mechanisms: detonating cord triggered by an electric detonator and an electric detonator to open a teflon valve head (mushroom valve).

5) United Kingdom triggered barrier

British researchers have developed a triggered system that utilizes a thermocouple flame sensor in conjunction with a compressed nitrogen-powered water disperser. The system is composed of two sensors and two dispersers. The heat sensitive sensor detects arrival of a flame and sends a signal to the disperser which disperses contained water by energy provided from compressed nitrogen.

The nitrogen-powered water disperser is shown in Figure 11. The basic components of the disperser are an 81-litre capacity gas container filled with compressed nitrogen at 7 bars which is clamped to a container that holds 227 kg of water at atmospheric pressure.

6) United States triggered barrier

The former USBM developed two triggered barrier systems. One system, which is called the 'Cardox Triggered Barrier', uses a high pressure cylinder to propel the extinguishant. The second system is called the 'low pressure nitrogen or halon powered barrier' (or FENWAL explosion barrier) and uses pressurized nitrogen or Halon 1301 in a low pressure system to power the disperser. Both the high and low pressure systems were found effective in suppressing coal dust explosions, but the Cardox system is considered hazardous because of the very high pressure involved in expelling the suppressant.

Cardox Triggered Barrier

The Cardox system is based on a Cardox-purple K extinguishant device designed to suppress float coal dust explosions. The actual barrier or disperser system consisted of two to six Cardox units containing either purple K or water and placed on opposite ribs of the entry 1.5 metres apart, at a position starting 99 metres from the face (Figure 12). The general features of the Cardox barrier are illustrated in Figure 13. When a triggering signal is sent to this unit, a fuel-oxygen mixture within the Cardox cylinder is ignited and burns quickly to heat carbon dioxide liquid to a high pressure gas (approximately 1000 atm). At this high pressure the gas ruptures a confining metal diaphragm and expels the suppressant.

The cardox barrier develops considerable pressure in the immediate area of extinguishant dispersion and, because of this, is considered too hazardous to be utilized in mine areas where personnel are working. The system would have to be modified to allow use underground.

Low Pressure Triggered Barrier System

The Low Pressure system operates with much lower pressure. The low pressure gas powered disperser is part of a commercially designed FENWAL barrier (Figure 14). The spherical vessel, approximately 33 cm in diameter, is the 'holding tank' for both suppressant and gas. Satisfactory operation has been found when the unit is filled with 70 percent or 13.6 kg water or completely filled with purple K (20.4 kg) with the void space pressurized with nitrogen gas to a range of 1380 to 2070 KN/m² (13.62 atm to 20.43 atm). Extinguishant and gas are released through a detonator operated, 7.6 cm diameter burst diaphragm at the base of the spherical vessel and dispersed via holes in the multihole nozzle.

The burst diaphragm is scored to prevent fragmenting and/or ejecting during discharge of the suppressant. The detonator, fired by an electrical pulse, is positioned with respect to the diaphragm as a function of the extinguishant used. The detonator is positioned approximately 5 cm back of the diaphragm if water is used, whereas it is positioned directly behind the diaphragm if powder extinguishant is used.

4.5 COMPARISON OF PASSIVE AND ACTIVE BARRIERS

4.5.1 Advantages of active barriers

Active barriers have remarkable advantages over the passive barriers:

- Suppressant is dispersed by an independent, self-contained energy source.
- Active barrier operation does not depend upon the static, dynamic force or pressure generated by an explosion.
- It is good for low height to width ratio roadways where height is less than 80% of the width.
- It is relatively suitable for fast moving face.
- It provides a good safety standard because it responds before the flame develops into a full-scale explosion.
- It can detect the early stage of propagation.
- Little carbon monoxide will be formed.

4.5.2 Disadvantage of active barriers

- It requires external power supply. In most coal mines, it is difficult to provide power to those locations where explosion protection is needed. As a result, it might be difficult to implement it in some mines. This problem may however be overcome by battery-operated internal power supplies.

4.6 SUMMARY OF BARRIERS

TABLE 4.1 SUMMARY OF PASSIVE BARRIERS

TYPE OF BARRIER	APPLICATION	REMARKS
German stone dust barrier (light type)	Close to the source of ignition	Unsuitable for fast moving faces and weak explosions.
German stone dust barrier (heavy type)	Trunk conveyor roads & roadways	Unsuitable for fast moving faces and weak explosions.
Polish stone dust barrier (light type)	Close to the source of ignition	Unsuitable for fast moving faces but relatively effective for weak explosions
Polish stone dust barrier (heavy type)	Trunk conveyor roads & roadways	Unsuitable for fast moving faces but relatively effective for weak explosions
German water barrier (concentrated)	Close to the source of ignition	Unsuitable for fast moving faces and weak explosions. Effectiveness critically depends barrier on location relative to the explosion source.
German water barrier (distributed)	Designed to cover the entire mine	Unsuitable for fast moving faces and weak explosions. Effectiveness does not critically depend on barrier location.
Polish distributed water barrier	May replace stone dust barriers in the first 200 m from the face. 1 st row should be close to the ignition source.	Unsuitable for fast moving faces and weak explosions. Effectiveness does not critically depend on barrier location.
Modified German water trough barrier - Model 1 (USA)	Designed to cover the entire mine	Also capable of suppressing weak (69 m/sec) coal dust explosions
Modified German water trough barrier - Model 2 (USA)	Designed to cover the entire mine	Also capable of suppressing weak (31 m/sec) coal dust explosions
Static pressure sensitive barrier - Model 1 (USA)	Designed to cover the entire mine	Also capable of suppressing weak (31 m/sec) coal dust explosions
Static pressure sensitive barrier - Model 2 (USA)	Designed to cover the entire mine	Also capable of suppressing weak (31 m/sec) coal dust explosions
Japanese water barrier	Designed to cover the entire mine	Little maintenance required

TABLE 4.2 ACTIVE (TRIGGERED) BARRIERS

COUNTRY	SENSOR	REMARKS
United States	Ultraviolet	Researchers consider it as the best and most reliable system. It requires external power supply
Germany	Ultraviolet	Researchers consider it as a good system. It requires external power supply
United Kingdom	Ultraviolet	30% failure due to UV radiation alternation by suspended coal dust (test result). It requires external power supply
France	Ultraviolet	It requires external power supply
Romania	Ultraviolet	Two selective UV sensors are best. It requires external power supply
Poland	Infrared	It uses paired infrared sensors and requires external power supply
USSR	Infrared	It requires external power supply
United Kingdom	Thermocouple	Researchers consider it as the best system. It requires external power supply
Belgium	Thermo-mechanical	An Non-electric system responding to both pressure and flame. It requires external power supply
United Kingdom	Blast Operated	Designed to reproduce as closely as possible triggering conditions of the tipping barrier. Could be an integral part of a wholly mechanical barrier systems. It requires external power supply.

5. REVIEW OF TECHNOLOGY DEVELOPMENT SINCE 1983

Out of the more than 120 publications identified during our search, 36 were closely related to this project and 25 of them were obtained. After review, we found several articles (the first 5 reviewed below) which involved new technology development, particularly in the areas of triggered barriers, stone dust bagged system, flame proof door system and machine mounted barriers. Some articles presented improvement over the previous technology. In the following, ten of the most relevant articles are briefly reviewed.

5.1 "Flame-powered trigger device for activating explosion suppression barrier" by R.A. Cortese & M. J. Sapko, 1991. U.S. Bureau of Mines, Pittsburgh, Pennsylvania.

The former U.S. Bureau of Mines developed a flame-radiation-powered trigger device to explosively activate suppression barriers to quench gas and coal dust explosions. The major component of the device is a silicon solar panel, which converts radiation from the developing explosion into electrical energy to initiate an electrical detonator. This releases an extinguishing agent into the advancing flame front. The solar panels, which are rated to produce 20W of electrical power when exposed to sunlight, produce about 200W when exposed to a full-scale dust explosion.

The solar panel is electrically isolated from the detonator by a pressure-sensitive switch until the arrival of the precursor pressure pulse, which always precedes a deflagration. This combination of pressure arming and flame-powered photogenerator prevents false barrier activation and required no external power supply.

The sensor would be located in the proximity of the suspected explosion source and the extinguishant dispersal unit would be located sufficiently far from the sensor to provide time for the extinguishing agent to be discharged prior to flame arrival. It has been found that maximum effectiveness of the extinguishing agent is attained when it is ejected rapidly and early enough to blanket the entire mine entry cross section prior to flame arrival. If the extinguishing agent is dumped prematurely, the suppressant will be driven downstream and diluted by the explosion-induced wind before being overtaken by the flame. When the trigger signal is late, the suppressant is dumped after the flame where it has minimal effect.

5.2 "Suppression of dust explosions using triggered barriers in wide rectangular entries" by N.B. Greninger, R.A. Cortese and E.S.Weiss, 1995. U.S. Bureau of Mines, Pittsburgh, PA 15236 USA

The former U.S. Bureau of Mine conducted a series of single and multiple-entry tests to evaluate the performance of triggered dual-tube water barriers against dust explosions. A solar panel was used in conjunction with a pressure switch to detect the explosion and activate the dual-tube water units in order to form an inert cloud just ahead of the explosion flame.

This paper presented the full-scale explosion research results on the triggered barrier system. It discussed the effectiveness of the triggered barriers against dust explosions in single and

multiple-entry configuration and the optimal placement of the barrier units in terms of agent dispersion and the spacing interval between the solar panel detector and the barrier units.

The tests conducted in the wide rectangular entries at Lake Lynn Experimental Mines had shown that the solar panel detector in conjunction with the dual-tube water assemblies near the mine roof to be successful in quenching gas and dust explosions in single and multiple-entry configurations. In a single entry, installation of the barrier unit at a distance of 18m from the gas ignition face would provide sufficient time for water dispersion prior to the arrival of the explosion flame. If the distance is less than 18m, the mass density of the water cloud needs to be increased. At an intersection in a multiple-entry configuration, a distance of 23m would provide sufficient time.

Many triggered barrier systems required an external power supply, which could be damaged or interrupted in the event of an explosion. One advantage of the system developed by USBM is that it does not require an external power supply. This new development has rekindled the interest in triggered barrier research in many of the major mining countries.

5.3 "A new method for the arresting of underground tunnel explosions"

by D.W. Dixon, Dept. of Mechanical Engineering, Brunel University, UK, I.G. Ediz, Dept. of Mining Engineering, Dumlupinar University, Kutahya, Turkey, and W.M. Fidler, Dept. of Mechanical Engineering, University of Abertay Dundee, UK, 1995.

This paper proposed a new method for arresting the propagating explosion flame by means of a flame proof door system made of individual perforated steel sandwich packages. The system comprises four main units: the sensor, a release mechanism, the door unit and auxiliary equipment and construction. In the proposed technique, the oncoming explosion is detected by a pressure sensitive device by a pre-determined rise in static pressure. The sensor then triggers a mechanism, which causes the explosion door to be closed in a specially constructed concrete barrier zone. The doors are of a special construction and consist of perforated steel plates that allow part of the blast wave to be transmitted but do not allow the passage of the flame. A number of design parameters have been identified, including: the likely amplitudes of the transmitted/reflected pressure waves that would govern the explosion door pressure loading, the thickness of the perforated steel packages, the perforation dimensions and the heat transfer across the door.

The sensor to be employed to detect the wave (reacting to a rise in static pressure) should be of a simple construction and not requiring a power source to function.

The door unit consists of a flame proof door, a door frame and a locking mechanism. The door is built up of perforated steel packages which are designed to stop the passage of the flame. These packages are positioned onto a steel frame that is designed to resist maximum dynamic pressure. The door is closed against a door frame which is made of four blocks, connected together with bolts and insulating elements. Tunnel fittings such as pipes, cables etc. are placed through these blocks. After closing, the door is securely locked by the locking mechanism on all sides. The complete barrier system is comprised of at least two flame proof doors to ensure the arrest of the flame.

One of the design criteria of the barrier system is that it should not interfere with any mining activity or equipment when open. It is envisaged that with continuing design the system could be used in roadways with overhead monorail, railway and conveyor transportation. However, this system has not been tested in the field yet. The inventor has expressed interest in collaboration with Canadian partners in a field trial. Figure 16 illustrates in more detail the proposed flame proof door system.

5.4 "Performance of distributed bagged stone dust barrier in combating coal-dust explosions" by Jan J L du Plessis and Pierre S Vassard, CSIR - Miningtek, Kloppersbos, South Africa, 1999

This article presented a new method of building stone dust barriers developed by the CSIR's Division of Mining Technology. The new barrier makes use of the concept of stone dust bags (Figure 15) and a new method of rupturing the bags. This was achieved by adapting the closing mechanism and by balancing the stone dust content with the void in the bag.

The bagged stone dust barrier was extensively tested in a 200m test gallery. During these tests, it became evident that these bags could be made to rupture and spread stone dust when they are subjected to smaller forces than those required for the most commonly used passive barrier, the polish light barrier.

The barrier was evaluated against numerous methane-initiated coal dust explosions. The barrier has been proven successful for static pressures of 44 to 82 kPa, dynamic pressures of 12 to 36 kPa and for flame speed as low as 23 m/s. This barrier is now accepted by the South African government and has been implemented in numerous South African collieries.

5.5 "Special types of concentrated and mobile water-trough explosion barriers" by Dr.-Ing. Jurgen Michelis and Wolfgang Marth, Experimental Mine Co, Dortmund, West Ger, 1985.

When the water-trough explosion barriers were arranged in or behind the pantechnicon in such a way that they could be moved along with the heading machine, they are known as "mobile water-trough explosion barriers". The operation method of mobile water-trough explosion barriers is dependent on specific criteria, including whether the explosion barrier is to be mounted in the pantechnicon of a boom-type tunnelling machine (or of a full-face tunneller) or at the end of a road heading machine. The individual design must yet be approved.

The utilisation of mobile explosion barriers can be effected with both passive and active water-troughs. When passive water-troughs are used in the barriers, the spatial conditions must be examined in depth to see whether the necessary explosion protection will be guaranteed. When active water-troughs are used, the barriers disperse their suppressant automatically using external power, independently of the strength of the blast. The use of these explosion barriers is also advisable in gateroads and especially in the adjacent area of the face/gate junction, where the available space is often limited.

5.6 "Explosion barriers and British mines" by G.A. Lunn and D.E. Brookes, 1992.

Synopsis: The installation in coal mines of passive water trough barriers to extinguishing flame is described. The difficulties associated with headings that contain machinery and in which the cross-sectional area is obstructed are discussed. Experiments have been performed in the Health and Safety Executive's (HSE) explosion gallery at Buxton with a view to overcoming these difficulties; these experiments, on a number of barriers, are described.

The introduction of chain-supports for water trough as replacement for the rigid supports previously used has lessened the difficulties of installing troughs in an obstructed cross-section. Chain-supports allow installation of troughs with greater adaptability to the available area.

When there is much machinery near the coal face it becomes difficult to install passive water trough barriers within the regulation 35 m of the face. If an approved triggered barrier can be used between the face and the first row of troughs, the passive barrier can be moved further from the face. The experimental work on new designs of triggered barriers is described and discussed. These are a triggered stone-dust barrier and a triggered water barrier which utilise the Belgian water disperser and the HSE's Safety in Mines Research Establishment (SMRE) thermocouple sensor. The latter barrier, especially, shows great potential for solving what is a difficult problem of explosion protection in modern, fast moving headings.

Introduction: Since the early 1960's a familiar sight in British collieries has been the stonedust explosion barrier, a group of wooden shelves high in the mine roadway, a short distance from the face and loaded with stone-dust to a specified amount. Along with general stone dusting these barriers have been a legal requirement in coal conveyor roadways.

In its three forms--- the light stonedust barrier near the face and intermediate and heavy barriers further back in the mine---the stonedust explosion barrier has provided a reliable means of protection. However, as the years have passed changes in both the practice and speed of mining have made the installation of these barriers increasingly difficult. The more a roadway contains equipment, the more difficult it becomes to install a barrier to the required specification; the faster a coalface moves the more difficult it becomes to ensure that the barrier is always at the required distance from the face.

Over the last few years, HM Inspectorate of Mines, the Safety in Mines Research Establishment at Buxton (SMRE, now part of the HSE's Research and Laboratory Services Division) and British Coal have considered a number of replacements for the stonedust barrier system. Some of these replacements are being introduced into British collieries

This paper discusses these new barriers, describes some of the research work carried out on them in the Buxton surface explosion gallery, and assesses their importance for use in British mines.

Conclusions: The installation of passive water trough barriers in UK mines has been improved by the use of chain supports in roadways containing obstructed cross-sectional areas. The installation of triggered water barriers comprising Belgian dispersers and the SMRE (the Safety in Mines Research Establishment at Buxton) thermocouple sensor in the roadway between the

face and a passive barrier are improvements. This installation made it easier to protect roadways containing machinery and other equipment near the face.

5.7 "The design and performance of underground explosion barriers - A review" by B Jensen and T O'Beirne, 1997.

The following is extracted from the cited paper and the full detail is available for review by anyone who is interested.

Abstract: The paper focuses on explosibility conditions in underground coal mines, the behaviour of explosions from initiating gas ignitions to violent dust explosions and the effectiveness and limits of operation of current designs of passive explosion barriers in suppressing the flame front. Areas of particular emphasis include:

- Passive explosion barriers are not designed to protect personnel in the flame initiation zone and its immediate surroundings;
- Passive dust and water barriers are generally considered ineffective against methane ignitions of the magnitude that can occur at the working face;
- Dispersal of suppressant from passive barriers is adversely influenced by equipment, including conveyor belts, located in the barrier zone;
- Current regulations in Australia do not specify the installation of barriers in all roadways leading to the face, so their use has a limited capacity to contain explosions;
- A manifest design limitation is that passive barriers are restricted to just one event and are therefore ineffective against repetitive fire gases explosions; and
- The practice of stone dusting in roadways inbye the barrier zone could conceivably adversely affect the operation of passive barriers.

The paper discusses performance evaluation made in full-scale explosion galleries and the use of alternatives to passive barriers, including the installation of active barriers under some circumstances.

5.8 "Assessment of explosion barriers" by JL du Plessis, M P Brandt, and PS Vassard, CSIR, 1995.

Synopsis: This report summarises the test work that has been completed on the comparison of different types of barriers for stopping flame propagation of coal dust explosions in a 200-m gallery. The tests were conducted at the Kloppersbos Research Facility.

A standard test explosion was developed with enough wind pressure and flame propagation at 80m from the closed end of the gallery to activate passive water barriers, stone dust barriers, active water barriers and automatic belt roadway suppression systems. The barriers were evaluated on their effectiveness at preventing further flame propagation.

At present the passive barriers which have been tested include water trough barriers, stone dust barriers and dispersed barriers, and the active barriers include gas and a mixture of gas and water.

The different passive barriers: water, stone dust and dispersed barriers all proved successful in stopping flame propagation within 20m from the barrier end point. The active roadway barrier needs further investigation.

The effectiveness of the dispersed barriers must be determined at low dynamic pressures as these might be the systems of the future.

The various explosion barriers tested at the Kloppersbos facility are briefly described in this paper.

Recommendations: The effectiveness of the dispersed explosion barriers must be determined at low dynamic pressure as this system might be the easiest to implement. The tests conducted on the active suppression barrier are not conclusive as the system has not been optimised. More work should be done in close co-operation with the manufacturer.

5.9 "Recent result of dust explosion studies at the Lake Lynn experimental mine"

by E.S. Weiss, N.B. Greninger, and M.J. Sapko, USBM, 1989.

Abstract: The former U.S. Bureau of Mines, as part of its continuing research program for evaluating coal dust explosion hazards, has recently completed a series of tests in the Lake Lynn Experimental Mines (LLEM) to study the effect of entry size on the flammability limits of pure coal and coal/rock dust mixtures. Data will be presented that compare measurements from explosions of mixtures of coal dust, methane, and rock dust. There are significant differences in dust explosion propagation characteristics between the LLEM and the smaller entry Buxton experimental mine (BEM). The larger entry (LLEM) results indicate a larger rock dust percentage is required to prevent flame propagation than in the BEM. Lower flammable limits of coarse and fine Pittsburgh seam coal dusts were obtained in the LLEM. A lower volatile mine size coal required about 40 pct total incombustible content (TIC) to prevent propagation in previous BEM experiments, whereas, recent tests with a similar volatile (18 pct) Pocahontas seam mine-size coal required 60 pct TIC in the larger entry of the LLEM to prevent flame propagation.

As one means of preventing these coal dust explosions, 80-L water tub barrier units were tested in the larger entry of the LLEM. The relative efficiencies of roof-mounted and rib-stacked barriers were determined for suppressing fully developed coal dust explosions in a single entry. Barrier sets were evaluated at various locations (40 to 160 m from the face) and configurations in the entry. Units were suspended near the roof and triply stacked at the ribs. Stacked barrier units which are portable, simple to install, and inexpensive to erect provided protection against coal dust explosions in the LLEM. In wide mine entries, they pose less of an impedance problem for men and equipment than do roof-mounted barriers. For some mines having high dust deposition rates, stacked barriers would offer additional protection beyond that afforded by generalized rock dusting.

5.10 " Prevention and Suppression of coal mine explosions" by Sapko, MJ, Greninger, NB, and Watson, RW, 1991. Bureau of Mines, Pittsburgh Research Center, USA.

Abstract: There has been a notable decline in the frequency and severity of mine explosions since the turn of the century. Among the major safety measures responsible for this decline are the use of rock dusting, development of permissible explosives and electrical equipment, improved ventilation and improved methods for detecting hazardous conditions. While these advances in mine safety are noteworthy, an examination of recent statistics indicates that the problem of mine explosion prevention is not completely solved. There is also growing concern over the number of frictional methane ignitions that occur annually; the frequency of methane ignitions has not as yet seriously impacted fatal accident statistics, but their potential for disastrous consequences is well known.

This paper reviews recent research aimed at explosion prevention. Particular emphasis is given to the present practice of rock dusting and the implications of recent experimental evidence on the overall effectiveness of rock dust standards. Developments in supplemental explosion protection including devices for monitoring the explosibility of mine dust and passive and triggered explosion barriers are also discussed. The paper concludes with a section on frictional face ignition and methods for their control.

5.11 Summary of some suppression practices in various countries

Table 5.1 Summary of machine-mounted ignition suppression practices in three countries

Country/ Type	Detector Type	Extinguish- ing Agent	Expulsion Mode	Vessels Number	Vessels shape	Vessels Loading
Germany BVS-system	UV	Tropolar- Powder (ammonium phosphate)	Nitrogen at 120 bar + detonator activated valves	6	12.3 liter cyl.	48 kg
UK Graviner System	UV	Furex 770 ammonium phosphate	60 bar Nitrogen or Halon 1301	4 - 6	App. 7 liter Cyl.	16-24 kg
USA PRC- System	UV	ABC- powder (ammonium phosphate)	Linear- shaped charge and Halon 1301 13.6 bar	6	Tubular-cann. 0.76, 1.2, 1.8 m long, 5 cm dia.	17 kg

Table 5.2 Summary of fixed-location triggered barrier practices for various countries

Country/ type	Detection type	Extinguishing agent	Expulsion mode	Vessels shape	Vessels loading L/m²
Belgium	thermo-mechanical	Water 90-100 liters / unit	detonating cord	2 m long 25 cm dia. Open-pore polyurethane form	10
Germany	thermocouple	Water 80 liters / unit	detonating cord	PVC water tub	80
France	thermo-mechanical	Water 90 - 100 liters / unit	detonating cord	2 m long, 25 cm dia, open pore polyurethane form	10
UK	thermocouple	Water 227 liters / unit	compressed nitrogen	long cylinder	45
USA	Pressure and UV (solar panel)	water or mono-ammonium phosphate 40 liters / unit	sheet explosive	Ridged polystyrene container	80

6. DISCUSSIONS

Underground gas and coal dust explosions are the most devastating events that can occur in coal mines. As per past experience, mitigation measures could not entirely stop initiation of coal dust explosions completely. Barriers were therefore introduced to stop the propagation of the explosions. Barriers are, however, not designed to protect personnel in the flame initiation zone and its immediate surrounding.

Barriers are only intended as the final solution if all other preventative measures fail. Various sources showed a greater proportion of barrier failure than confirmed successes. However, most of the failures were due to improper location, improper design, poor installation, and inadequate maintenance. A properly designed, located and maintained barrier can arrest propagation of a coal dust explosion.

6.1 PAST EXPERIENCE WITH PASSIVE BARRIERS

1) Important Findings

After the Mountford report (1983), there is little report on further development in stone dust barrier systems except the stone dust bagged system (CSIR). Previous publications indicated that stone dust barriers failed mainly because of these two reasons:

- If the explosion was too weak, the blast waves couldn't disperse the shelves and the inert material because passive barriers required a certain minimum pressure to activate them. This failure usually occurred when the barrier was closer than 60m to the ignition point or when the source is weak.
- If the flame speed exceeded 500 m/s then the delay between the pressure front and the flame front was very short and the flame may have passed before the dispersion of inert material was completed. (Dixon et al 1995)

In locations where high-speed equipment is used, or in low roadways, the stone dust barrier may be inappropriate and water barriers or triggered barriers may be more suitable.

Although the stone dust barrier is increasingly being replaced by the water trough barrier, there is still a great deal of interest in the stone dust barrier. For example, experiments have shown that with lighter, more easily destructible shelves, stone dust may become effective against weak explosions (Mountford 1983).

Passive barriers should generally be installed 60 m away from the face to be effective because of the time required to disperse the suppressant.

Also, there is no reported information available on significant new developments on passive water barrier systems after the Mountford report.

2) **Disadvantages of passive Barriers**

Although the maintenance and installation of passive barriers is quite simple, their use in modern roadways containing large amounts of mining equipment is difficult. Passive barriers are limited to locations where there is adequate space for installation. They do not allow the easy use of an overhead monorail and other modes of transportation. Installation problems can occur in tunnels containing a large amount of mining equipment such as overhead rail conveyors, compressed air pipes, etc. and airway resistance is also increased. Their main disadvantage is that the flame speed should be between 100 m/s and 500m/s if they are to perform adequately (Dixon et al 1995).

3) **Stone Dust Bagged Barrier**

The test results on the stone dust bagged system have confirmed that it can successfully overcome most of the above mentioned disadvantages of the passive barriers. The bagged stone dust barrier has been proven successful for static pressures of 44 to 82 kPa, dynamic pressures of 12 to 36 kPa and flame speeds as low as 23 m/s (Plessis & Vassard 1999).

6.2 **PAST EXPERIENCE WITH ACTIVE BARRIERS**

There is an indication that at distance of less than 60m from the ignition point, the triggered barrier was more successful in extinguishing flame than the passive shelf barriers. This is due to the reliance for operation of the triggered barrier on static pressure rise rather than on the dynamic pressure. The static pressure rises faster than the dynamic pressure during an explosion.

The passive barriers were found to be ineffective in arresting weak dust explosions and covering fast moving faces. Active barriers have been considered as partial replacement for passive barriers between the face and the passive barriers.

Disadvantages of Active Barriers :

Active barriers are relatively expensive and complicated devices. Their major disadvantage is that they have to provide precise juxtaposition of an explosion flame and the inert material cloud. If the cloud is formed too soon it will be carried along by the blast of the explosion and if formed too late the flame front will have passed and the barrier will be ineffective. Therefore active barriers should not be considered as a complete replacement for passive barriers but as enhancement. They are recommended for protecting the roadway between the face and the passive barrier (Dixon et al 1995).

6.3 **PROTECTION IN ROOM AND PILLAR OPERATIONS**

Explosion prevention and suppression in room and pillar mines is much more difficult than in longwall operations. The difficulty arises from the complex configuration of the workings, the relatively large number of operations being undertaken simultaneously and the rapid rate of advance of the faces (MOUNTFORD 1983). The new concept of stone dust bagged barrier systems developed by CSIR was considered the best at present for room and pillar mining layout.

6.4 NEW TECHNOLOGICAL DEVELOPMENTS

Since 1983, there has been remarkable technological development in active barrier systems, particularly in the following areas:

- Triggered barriers (See articles in section 5.1 and 5.2)
- Flame proof door system (See article in 5.3)
- Stone dust bagged system (See article in 5.4)
- Machine mounted barriers (see article in 5.5)

The details of these technologies can be found in the quoted relevant articles. A summary of these new developments is given in Table 6.1.

TABLE 6.1 NEW TECHNOLOGY DEVELOPMENTS AFTER 1983

METHOD	TECHNOLOGY & REMARKS
Distributed Bagged Stone Dust Barrier by J L du Plessis and P S Vassard, CSIR	Coal dust explosions were effectively arrested for a dynamic pressure range from 12 to 36 kPa and flame speeds as low as 23 m/s. The distributed-bagged barrier is the best-suited barrier for room-&-pillar mining layouts.
Flame-radiation-powered trigger device by R A Cortese and M J Sapko, USBM	Silicon solar panel converts radiation from the developing explosion into electrical energy to initiate an electrical detonator, which releases an extinguishing agent into the advancing flame front. It requires no external power supply. Until now, all rapidly activated triggering system requires an external power source that is difficult to provide in most coal mines.
Active Flame Proof Door System by D W Dixon, I G Ediz & W.M. Fidler, UK	A pressure sensitive device detects the oncoming explosion by a pre-determined rise in static pressure. The sensor then triggers a mechanism that causes the explosion door to be closed in a specially constructed concrete barrier zone. Not tested in field yet.
Mobile explosion barriers with passive / active water-troughs by I J Michelis and W Marth,	Suitable for use in gateroads and especially in the adjacent area of the face/gate junction, where long and often bulky installations in reduced roadway cross sections frequently mean that the installation of conventional passive water-trough explosion barriers is not possible.
Japan- flexible water bags system By M J Sapko, N B Greninger and R W Watson, 1991)	No information available
Machine mounted triggered barrier - German	Suitable to target at point of ignitions
Machine mounted triggered barrier - UK	Suitable to target at point of ignitions
Machine mounted triggered barrier - USA	Suitable to target at point of ignitions

7 CURRENT PRACTICE AND REGULATIONS

7.1 Regulations and current practice in Canadian mines

From the available materials (see Appendix IV), the regulations regarding explosion barriers in the three provinces (Alberta, BC and Nova Scotia) of Canada are quite simple and not much technical detail is given. In general, the technical details are left for the mine inspector and the mine manager. However the regulations provided certain guidelines. Table 7.1 gives a brief summary of the relevant regulations and the practices in some mines.

Current practices of explosion barriers in Canadian underground coal mines are summarized in Appendix V from feedback of the three then operating mines: CBDC, Smoky River and Quinsam.

Table 7.1 Summary of recommended and typically used barrier systems in Canada

Mines	Barrier system recommended	Typically used
Westray, NS (Richard, 1997)	<ul style="list-style-type: none"> - Stone dusting: All underground areas of coal mine should be stonedusted to within 12m of the working face; all cross-cuts less than 12m distant from the face should be stone dusted, except for areas within the mine containing sufficient moisture to render the coal dust incombustible or for which the regulator has granted exemption. - Barriers systems were an additional (not alternative) methods to combat the potential coal-dust explosion and were the fourth and last line of defence. - (Those used in CBDC were suggested as typical ones.) 	<ul style="list-style-type: none"> - Discrepancy between the legislative requirements and the actual practice occurred and persisted. - Did not have any stonedust or water barriers. (no other detail available)
CBDC, NS (CBDC, 1984 and Richard, 1997)	<ul style="list-style-type: none"> - Water spraying: Coal dust is not allowed to accumulate in any place. Dry areas producing coal dust shall be wetted down with water. - Stone dusting: Every roadway shall be treated with stone dust or other non-combustible materials. The dust on the floor, roof and sides of roadways should contain at least 75% such materials, which should be increased by 5% for every 1% flammable gas in the air. 	<ul style="list-style-type: none"> - Water spraying is used on shearers, DRCLs and at conveyor spill and transfer points, and used within 15m of the face. - Stone dust is made of non-combustible materials: limestone, gypsum or shale, with 70% passing # 200 and all passing # 20. It must be relied on beyond 15m of the face. Sampling and testing of mine dust must be not less than once a month.

	<p>- Stonedust barriers: Stone dust barrier shall be placed in every roadway leading to a working face within 300 m of the face and at every transfer point on the main conveyor road.</p> <p>- Water barriers: (not the major suppression methods, but used)</p>	<p>- Stonedust barriers consisting of shelf of boards hung on the roof are installed in all longwall roads within 180 – 320 m of the nearest face. Typical design: Board length: 3m and distance to floor: 2m. One third of the shelves (closest to the face) are constructed of boards no more than 0.35m wide and loaded by no more than 4.5kg of stone dust per foot of shelf length. The remaining two thirds of the shelves are constructed of boards up to 0.5m wide and loaded with up to 18kg of stone dust per 0.3m of shelf length.</p> <p>- Water barriers were also used in main conveyor roads. They were made of lightweight, easily fractured, rectangular plastic tubs over-hung on the roof. Typical design: distance to roof: 0.3 ~ 2m, distance to floor: 0.8 ~ 2.6m.</p>
BC mines (BC, 1997)	<p>- In any underground coal mine which is dry and dusty, rock dust or water barriers (of authorized type) shall be installed at designated places. The condition and position of the barriers shall be inspected by a (certified) person at intervals of not more 4 weeks.</p>	- N/A.
Alberta mines (Alberta, 1995)	<p>- Rock dusting: (All) accessible roads shall be treated with incombustible dust. The total dust on the floor, roof and sides of each road should always contain not less than 65% such dust, which must be increased by 1% for each 0.1% flammable gas in the air. (with more detail)</p> <p>- Explosion barrier: shall be established at every entrance to:</p> <ul style="list-style-type: none"> - every production section, - every development district as soon as it advanced 200 m, - every ventilation split intake and return. 	- N/A

7.2 Regulations in other countries

Regulations from other countries are summarized in Table 7.2 from the available sources (Forrester, 2000).

Table 7.2 Summary of barrier systems used in other countries

Mines	Barrier system recommended	Typically used
Japan (Japan, 1994)	<ul style="list-style-type: none"> - Explosion barriers shall be installed at the entrance and exit of the working area, and in other necessary area. - Rock dust barrier or water trough barrier shall have a capacity of 0.1 m³ or more dust or water per m² of the gallery cross section. - Special type barriers to prevent explosion propagation with a capacity of 0.4 m³ or more per m² of gallery cross section shall be installed at the entrance and exit of working area. - Rock dust or water trough barriers shall be at equal intervals along the gallery from 1 to 30m. 	- N/A.
Australia (Australia, 1984)	<p>Approved types of barriers are to be installed at these locations:</p> <ul style="list-style-type: none"> - in a Class A seam in a mine – near each ventilation district, - in roadways where coal is carried by means of a conveyor – within specified distance of working faces. 	- N/A.
UK (UK, 1984)	<ul style="list-style-type: none"> - Stone dust is to be applied in every length of road in a coal mine (with some exception and with specific restrictions on particle size and sampling and testing). - Stone dust barriers are to be installed in every area of a coal mine (where coal is carried by conveyors and where flame may be caused by an ignition of inflammable gas or dust). - The manager shall prepare a scheme in respect of each such area specifying the position and type of each such barrier. 	- N/A.
USA (USA, 1983)	<ul style="list-style-type: none"> - Rock dusting: All underground areas of a coal mine, except 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 ft of all working faces. All crosscuts in this zone shall also be rock dusted. 	- Barriers: N/A.

8 AREAS FOR FURTHER RESEARCH

From the review of the selected articles on explosion barriers and the new development and from the reported past experience with them, a number of areas where further research is needed have been identified in this project as follows:

- 1) Until now, most rapidly activated triggering systems consist of an external power source that is difficult to provide in most coal mines. However, the Silicon Solar Panel, flame-radiation-powered trigger barrier developed by USBM does not require external power supply. Field research is required to test the performance of the solar panel system and its suitability in Canadian mines. Further research is also required to overcome the power supply problems for other triggered systems.
- 2) Before the distributed bagged barrier system was introduced by CSIR, all other barrier systems were found not very effective in arresting dust explosions in room-and-pillar sections. The distributed bagged barrier is said to be best suited to bord-and-pillar mining layout. Field research is needed to confirm the efficiency of this new technology in Canadian mines.
- 3) Greater proportions of passive barrier failures were reported due to improper location, improper design, poor installation, and inadequate maintenance. Further research should be carried out to establish a practical guideline for installation and maintenance in various conditions.
- 4) Research is needed to formalise the Terms Of Reference (TOR) for explosion impact assessment report or barrier viability report.
- 5) Field research is needed to test the machine mounted (passive and active) barrier systems for use in Canadian mines.
- 6) Further research and field trials in mine scale are needed to complete the development of the flame proof door system for consideration in Canadian mines. This may be in partnership with the inventor.

9. RECOMMENDATIONS

Based on the technology development and research results world wide discovered from this literature review, the following recommendations are suggested:

- 1) The regulations in Canadian provinces vary. It will be beneficial to have uniform regulations in all provinces regarding explosion barriers. Further discussion and research are needed whether to amend or not the existing regulations.
- 2) Existing regulations pertaining to explosion barriers should be updated to include the past experience and the new technical knowledge.
- 3) Further research be initiated in all areas where further research is needed as identified in section 7.
- 4) In regard to the installation and maintenance of passive stone dust barriers, the light barrier should be used in areas close to the source of ignition and the heavy barrier should be used to protect trunk conveyor roads and roadways that separate major ventilation circuits.
- 5) In regard to the installation and maintenance of passive water barriers, concentrated barriers should be used for the protection of the main roadway, with the distance between adjacent barriers not exceeding 400m. When water containers are selected, suspended tubs should be tried first because they are more favoured than supported tubs.
- 6) Triggered barrier systems should be used to cover fast moving faces and to protect against “weak” explosions.
- 7) Triggered barriers may be combined with passive barriers to increase the overall effectiveness, particularly within 60 m from the face.
- 8) All barriers should be inspected and maintained regularly, and each barrier should be logged in detail with the following information:
 - (a) date of construction
 - (b) cross-sectional area of the roadway
 - (c) total rock dust loading of the barrier
 - (d) number and loading of shelves
 - (e) date of last rock dust change
 - (f) reference number of the barrier
 - (g) date of last inspection

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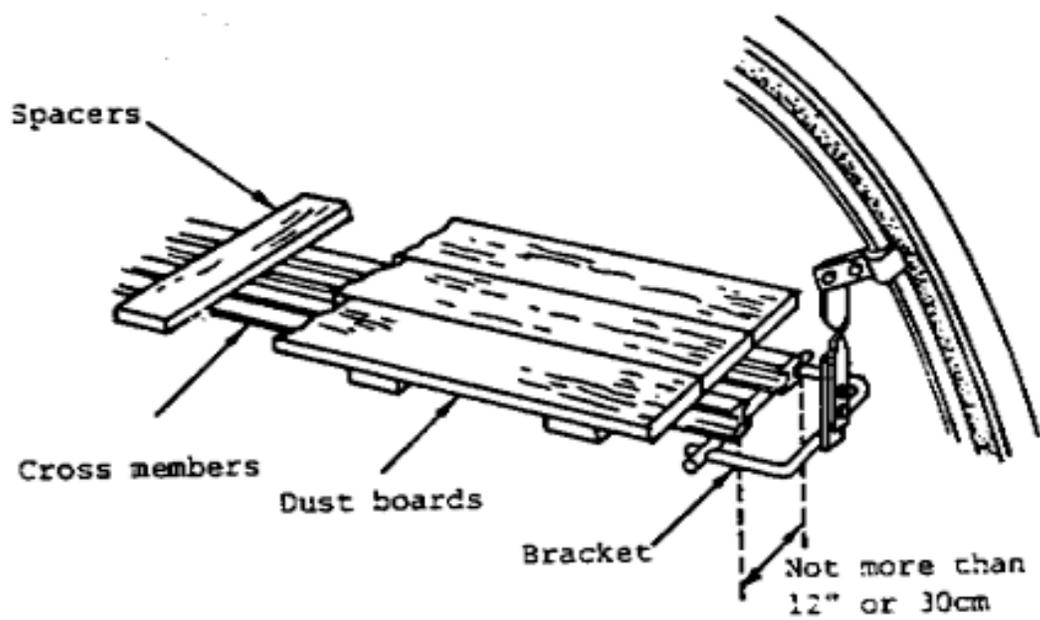
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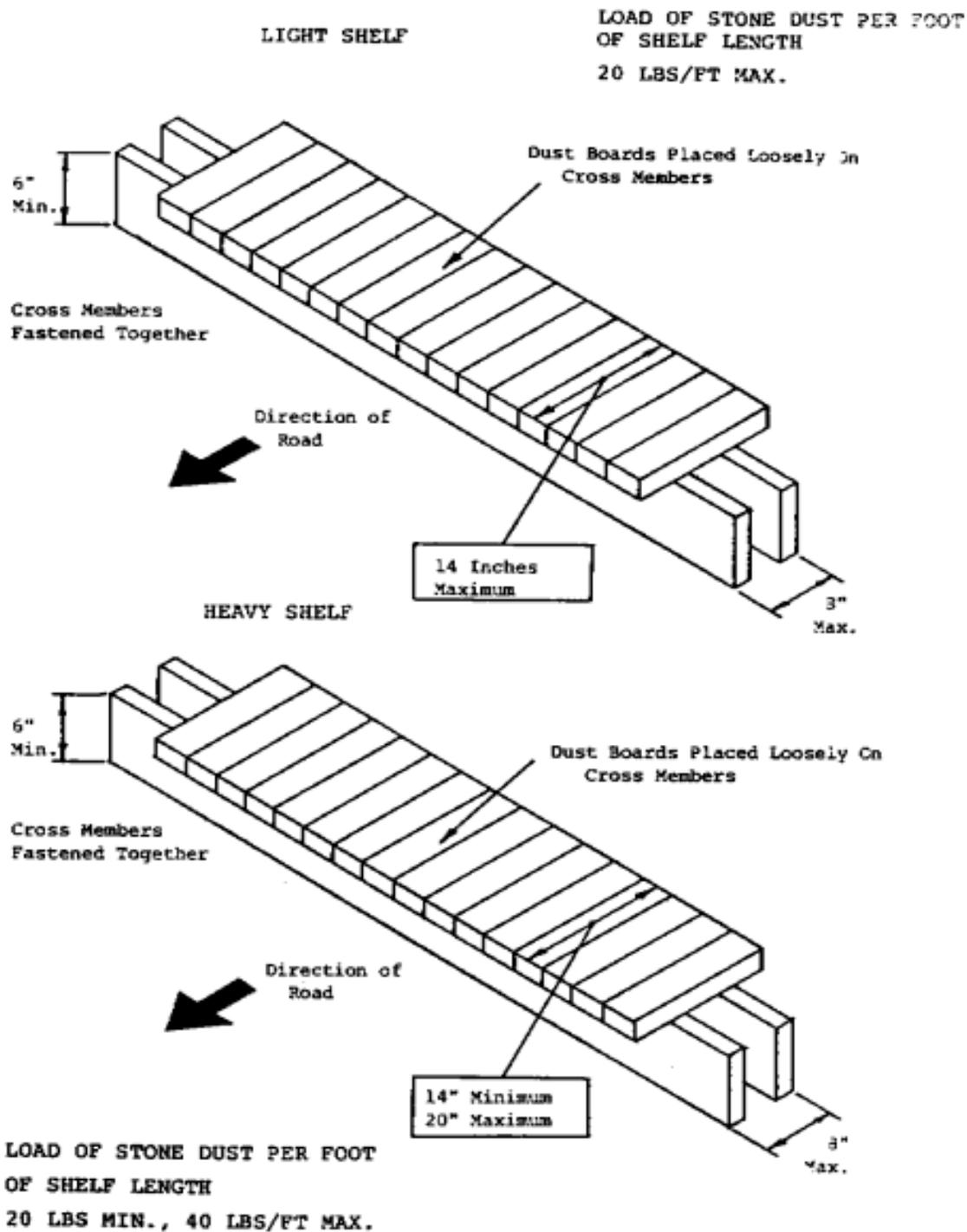
C. Relevant Web sites:

CDC	http://outside.cdc.gov
CISTI	http://cat.cisti.nrc.cza
CROWSNEST	www.crowsnest.bc.ca
CSIR	http://minelib.csir.za
DIALOGWEB	www.dialogweb.com
III	www.iii.co.za
MSHA	http://library.msha.gov
NIOSH	www.cdc.gov/niosh
TH ON LINE	www.thonline.com
VIRGINIA TECH	www.eng.vt.edu/eng/mining/ugrndlab.html



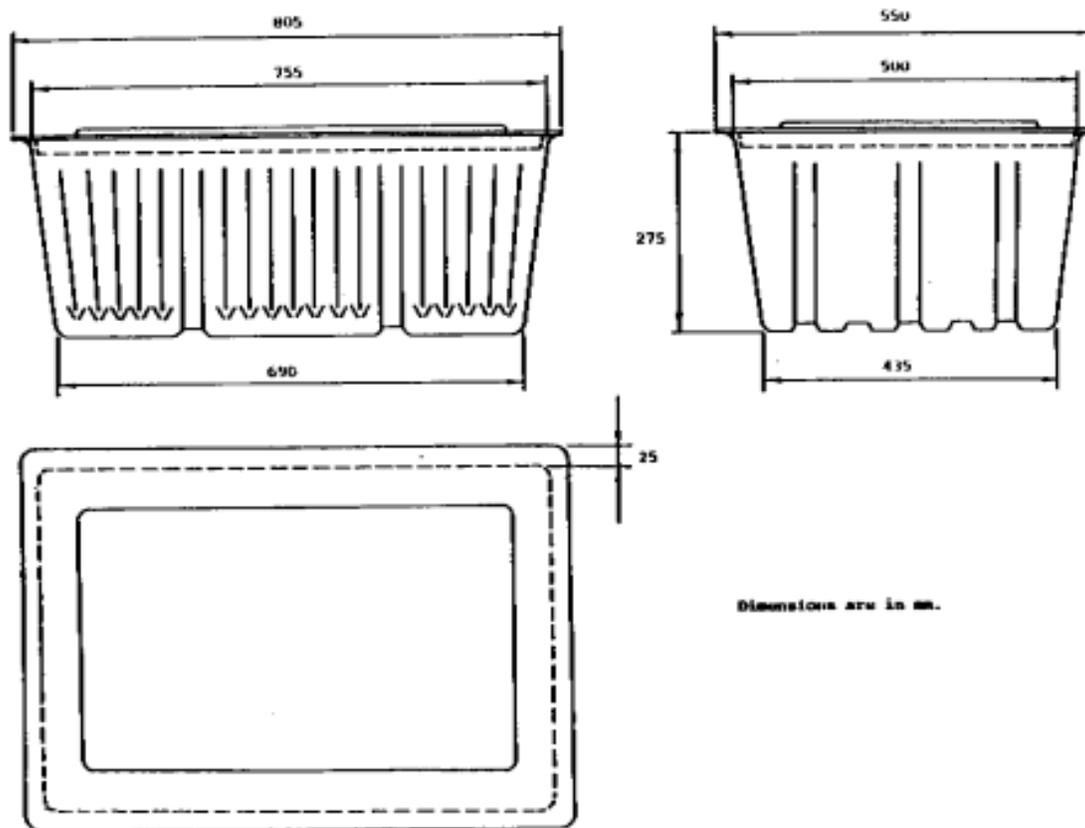
GERMAN TYPE BARRIER

FIGURE 1



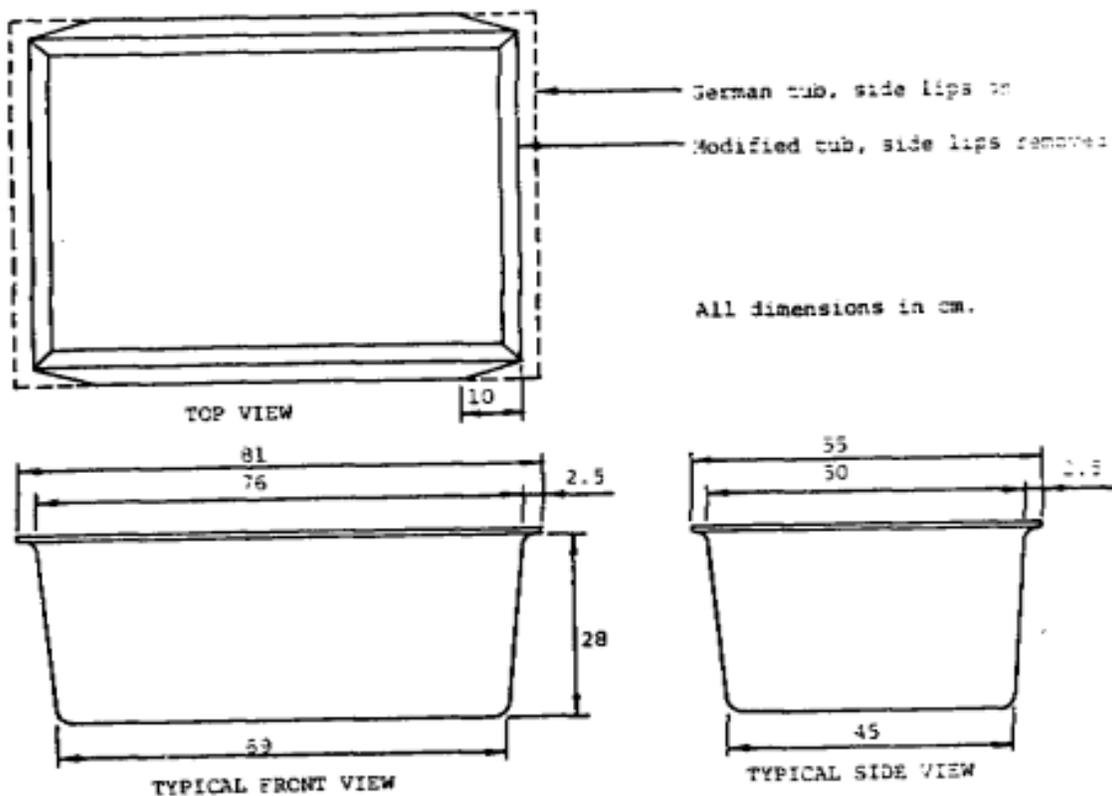
POLISH SHELF TYPES

FIGURE 2



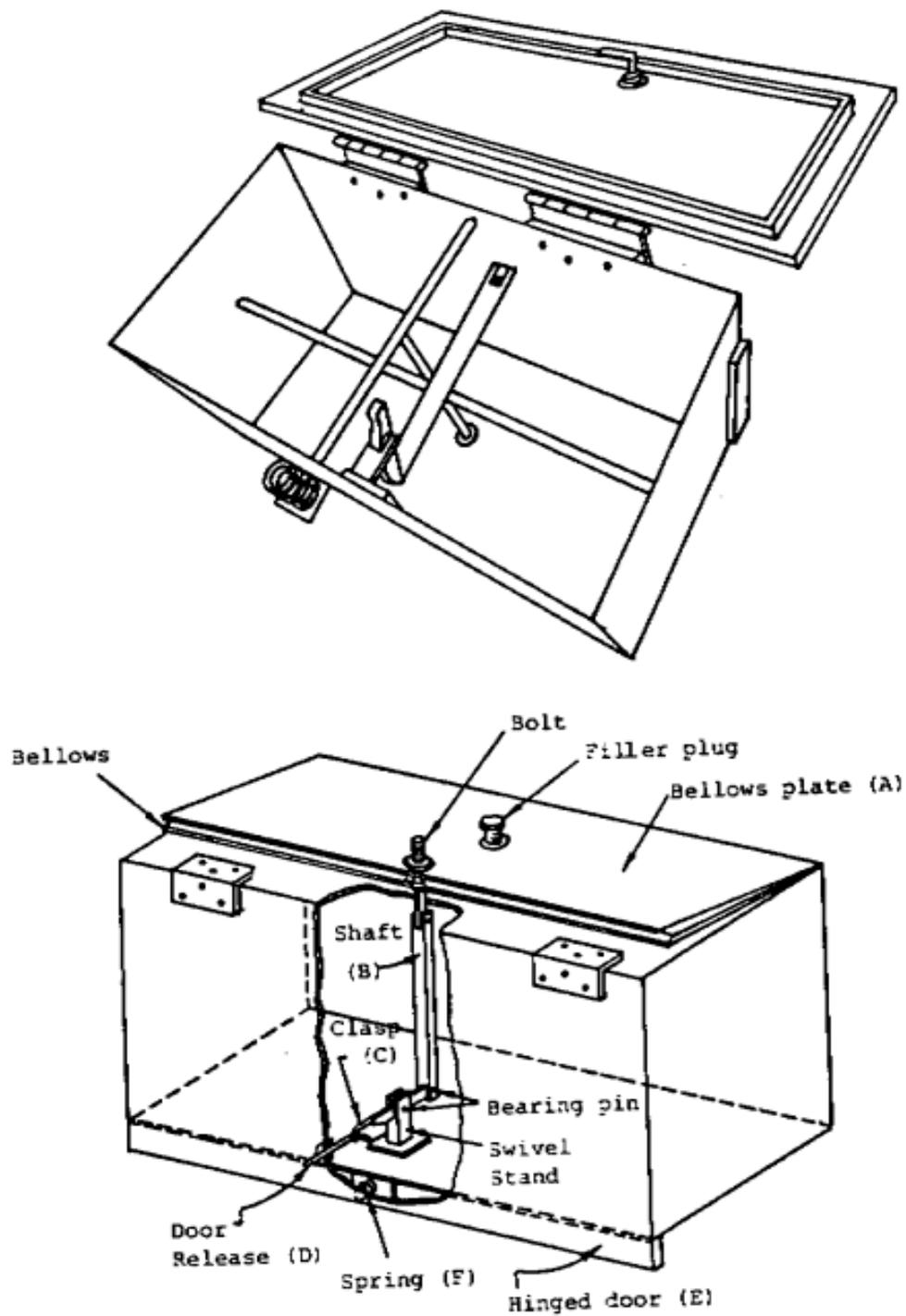
GERMAN DESIGN WATER TROUGH

FIGURE 3



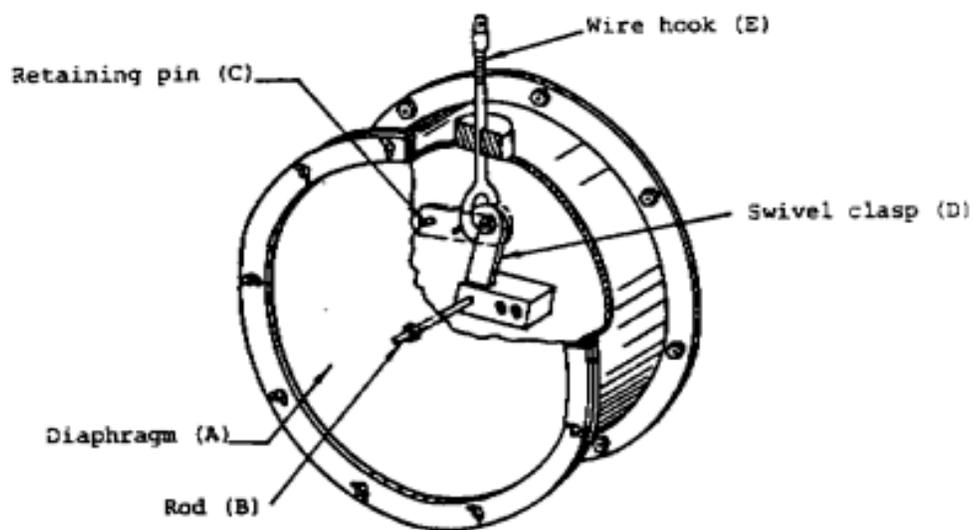
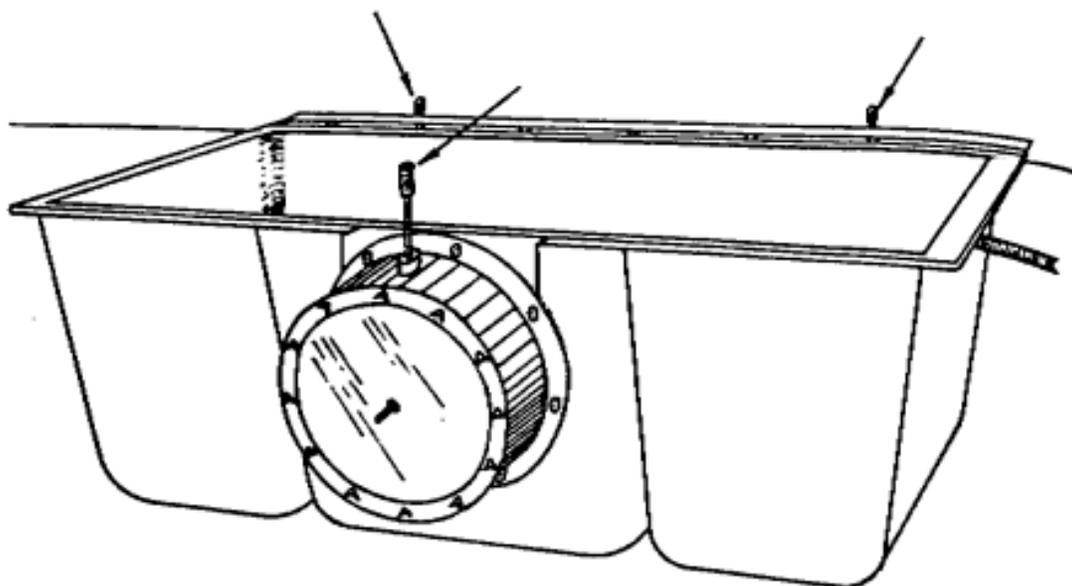
MODIFIED GERMAN WATER TROUGH (MODEL 1)

FIGURE 4



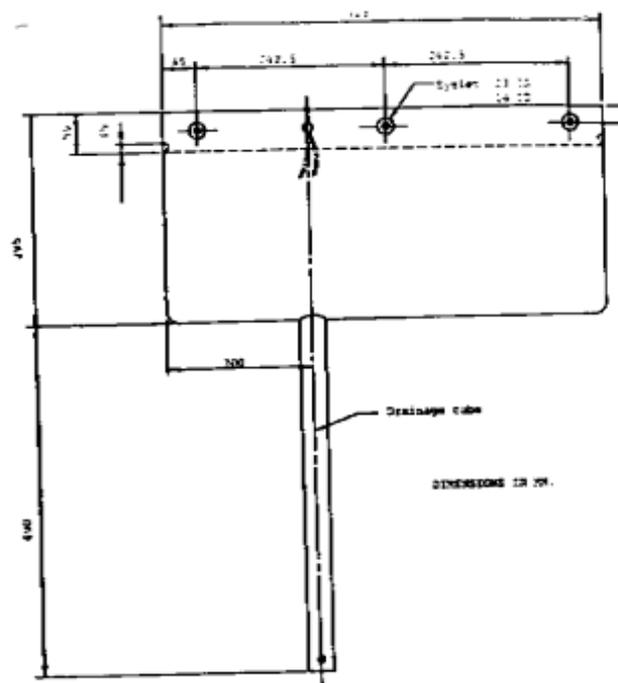
STATIC PRESSURE SENSITIVE BARRIER (MODEL 1)

FIGURE 5

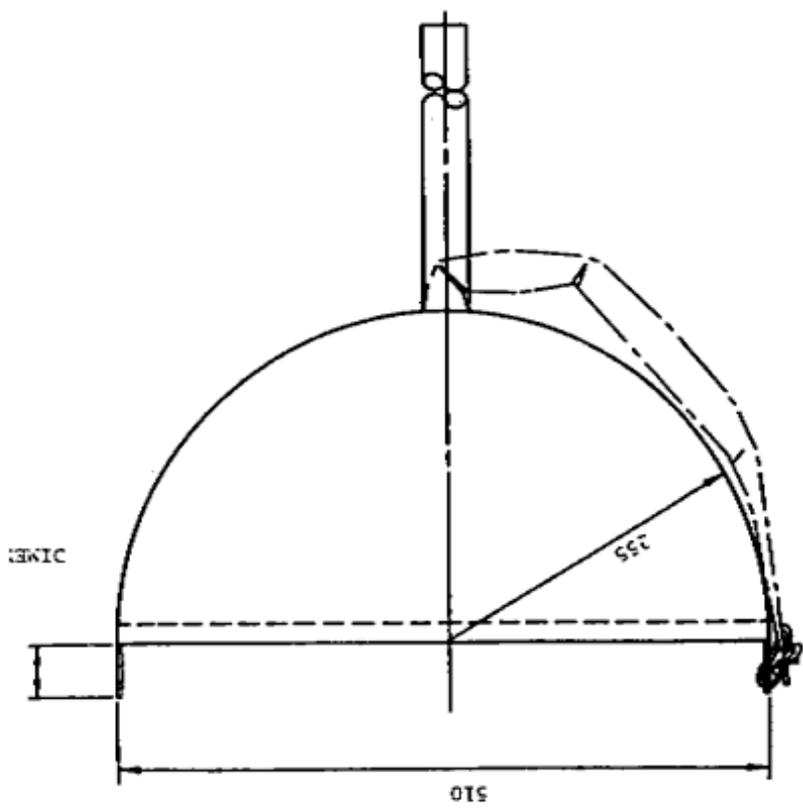


STATIC PRESSURE SENSITIVE BARRIER (MODEL 2)

FIGURE 6

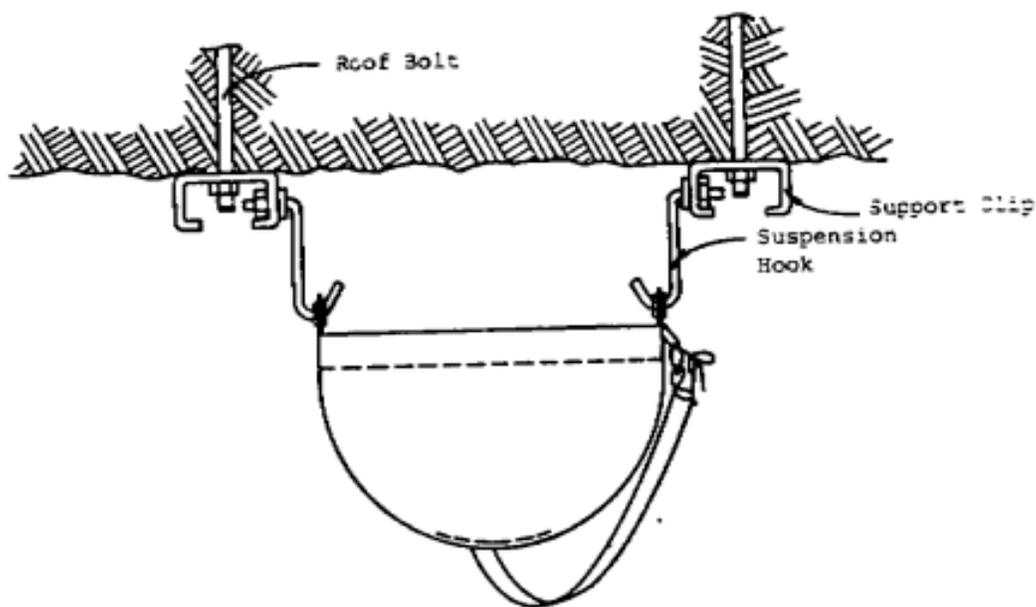
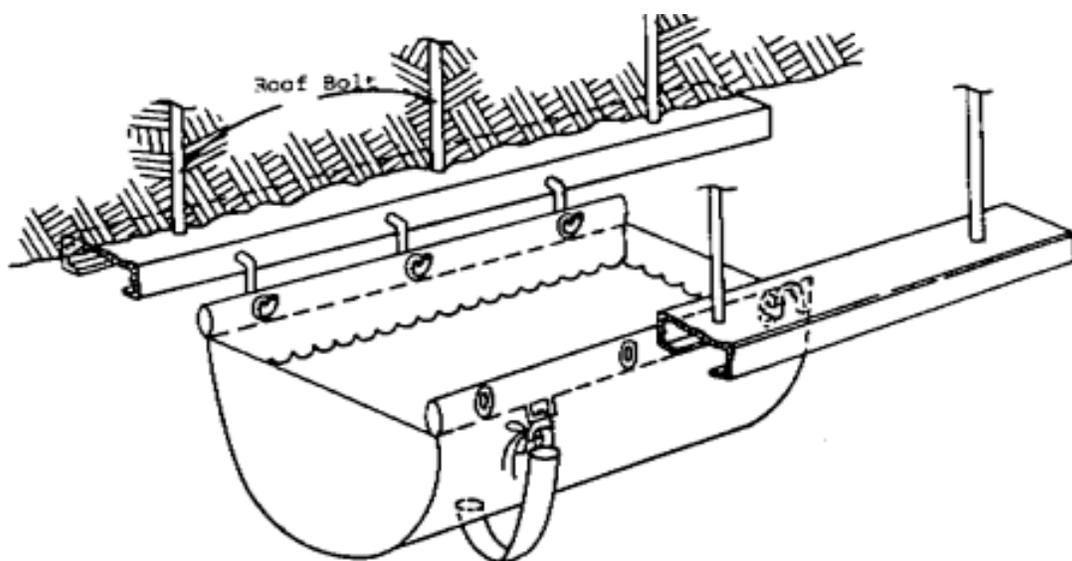


" FLEXITROUGH " SIDE ELEVATION



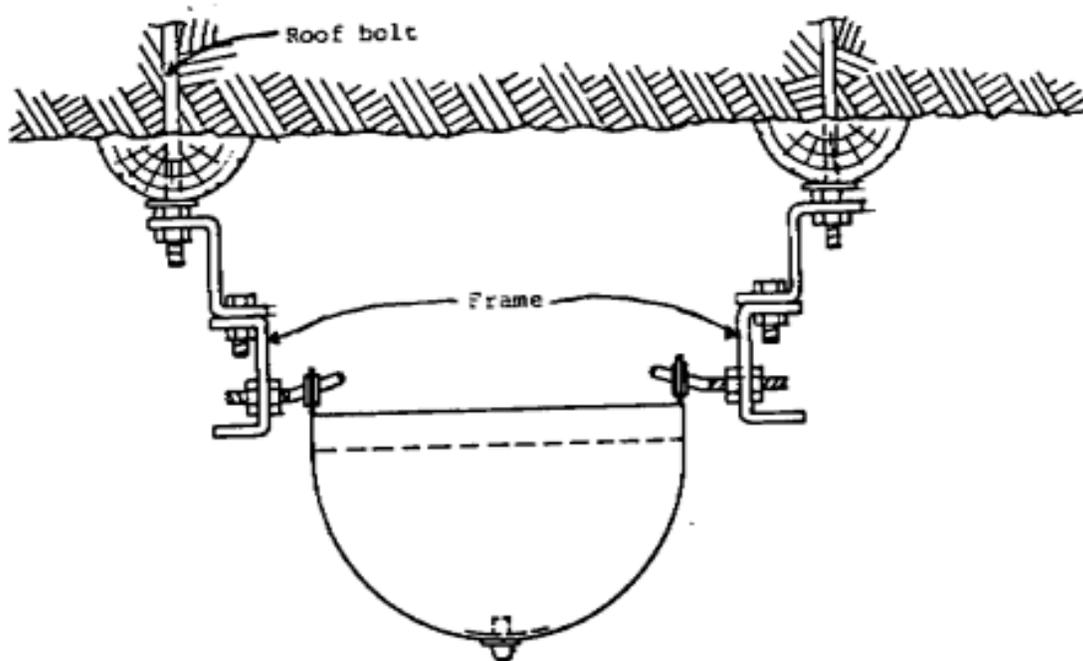
" FLEXITROUGH " END ELEVATION

FIGURE 7

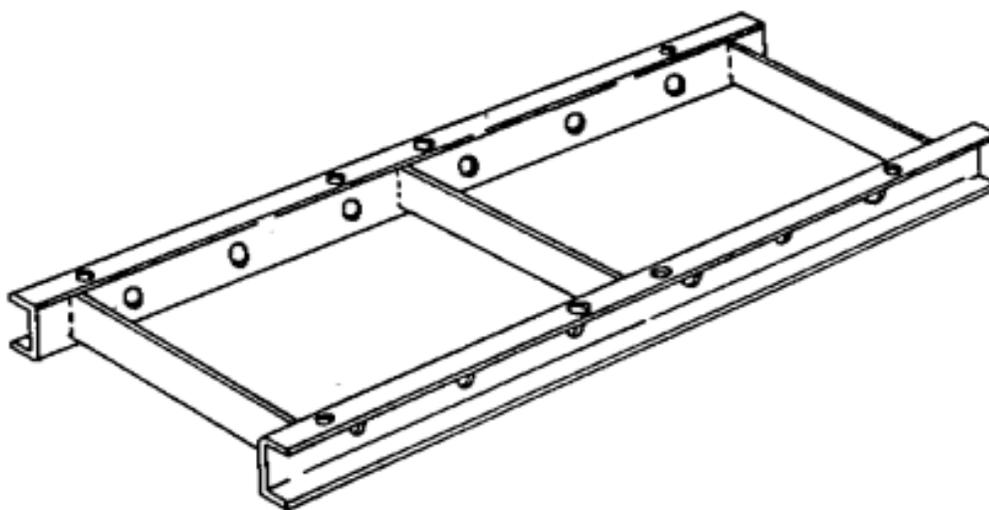


" FLEXITROUGH " SUPPORT MODES

FIGURE 8

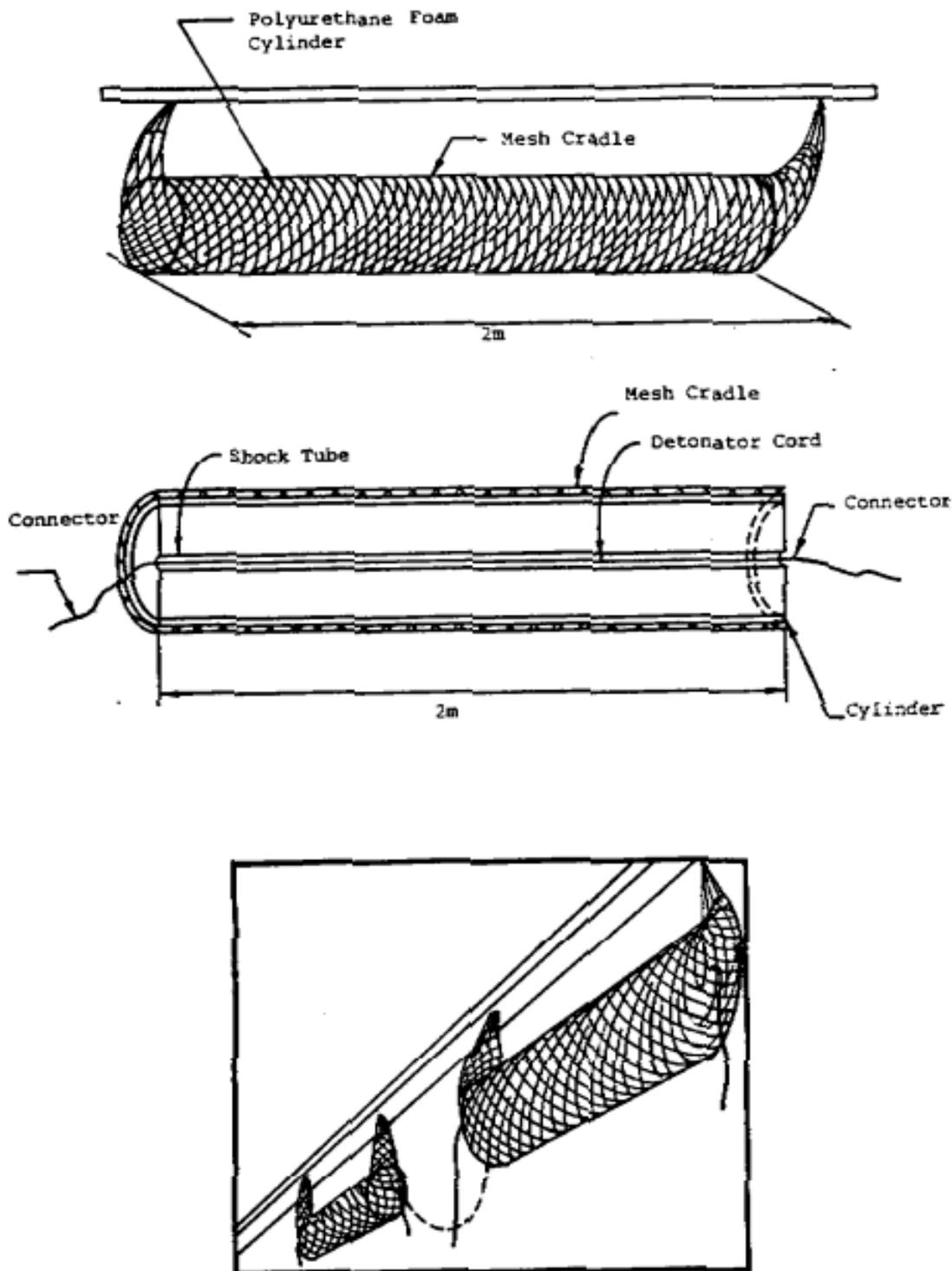


" FLEXITROUGH " SUPPORT FROM A FRAME



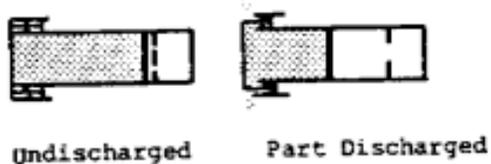
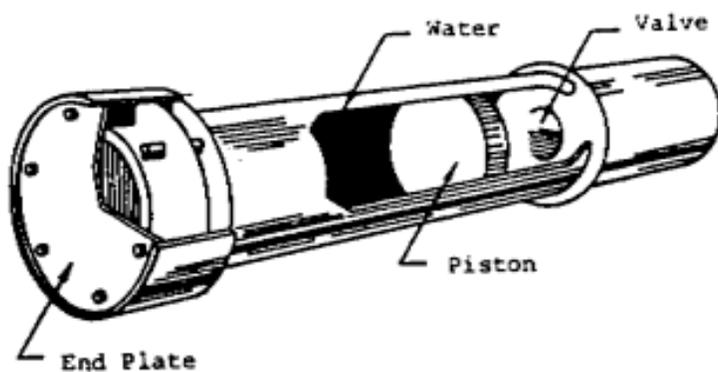
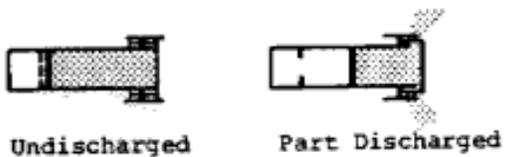
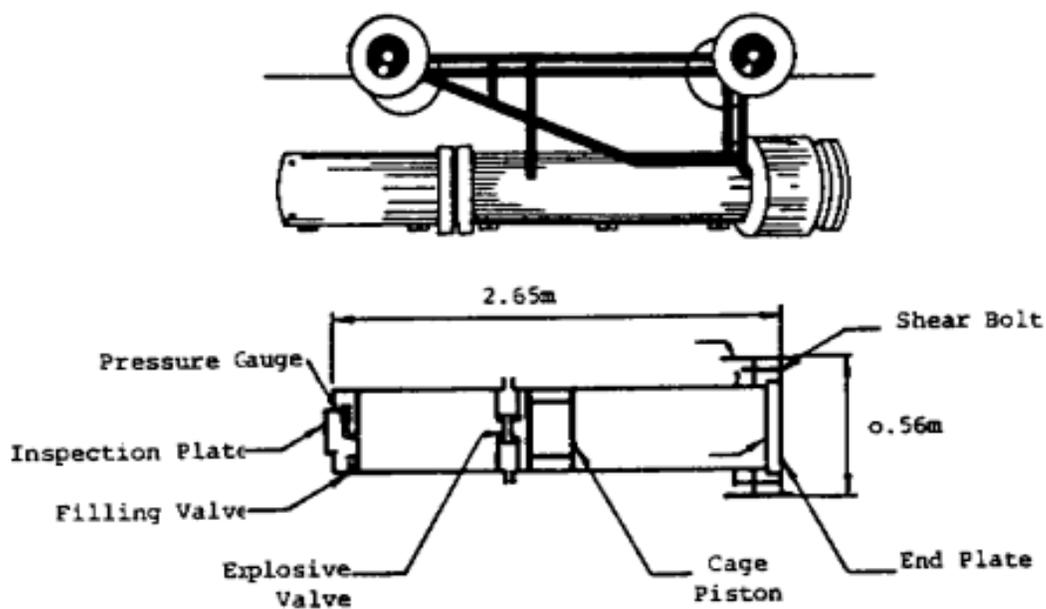
" FLEXITROUGH " SUSPENSION FRAME

FIGURE 9



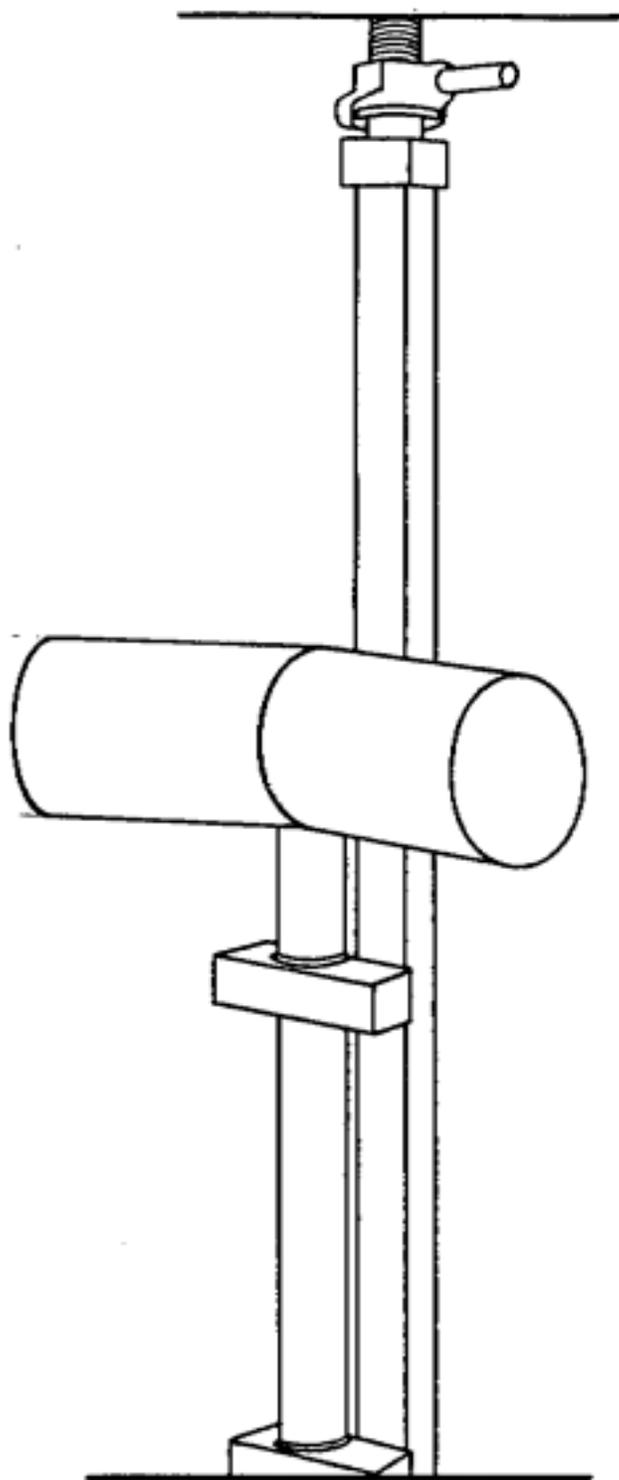
BELGIAN TRIGGERED BARRIER DETAILS

FIGURE 10



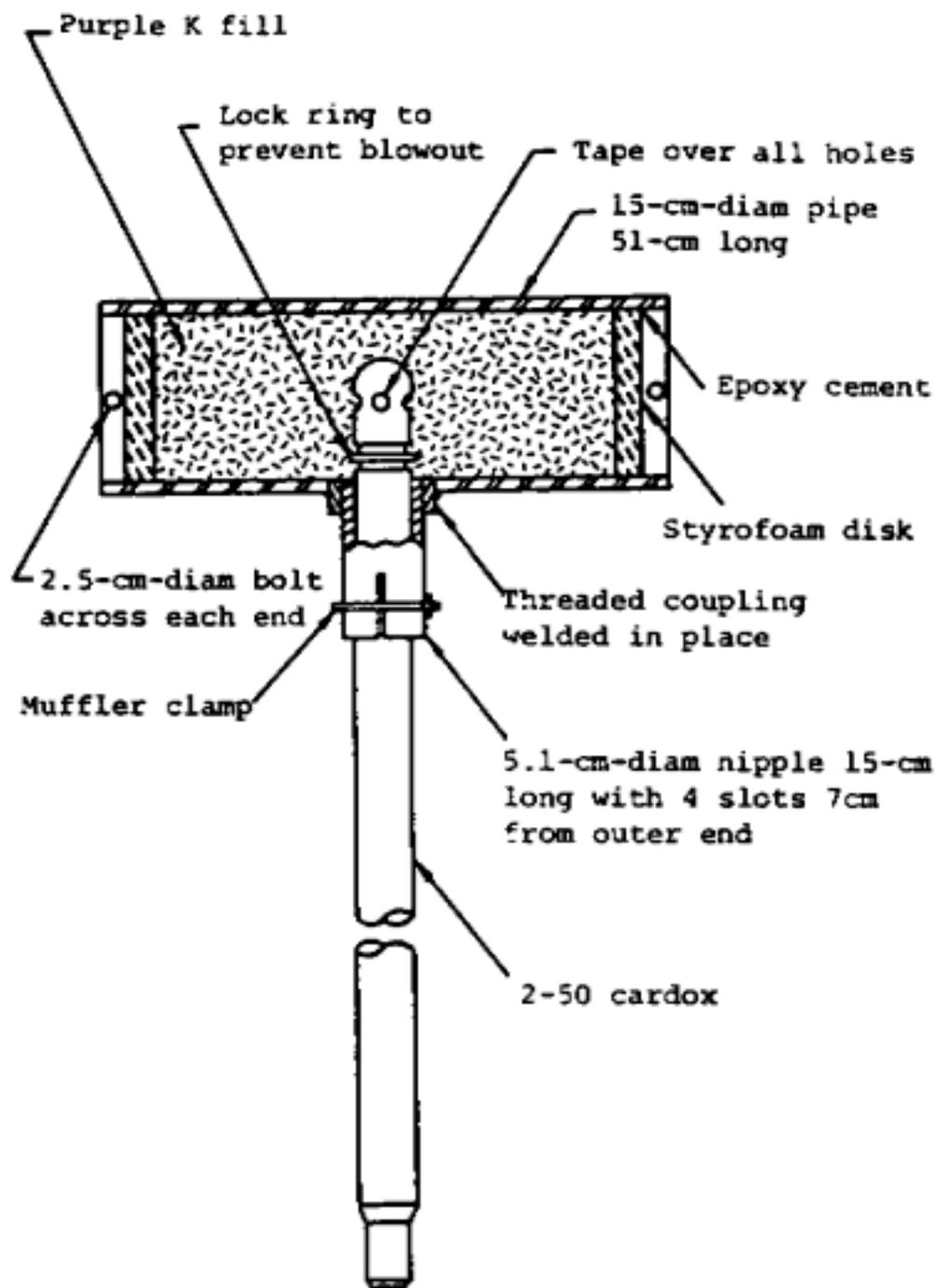
MARK II DISPERSER

FIGURE 11



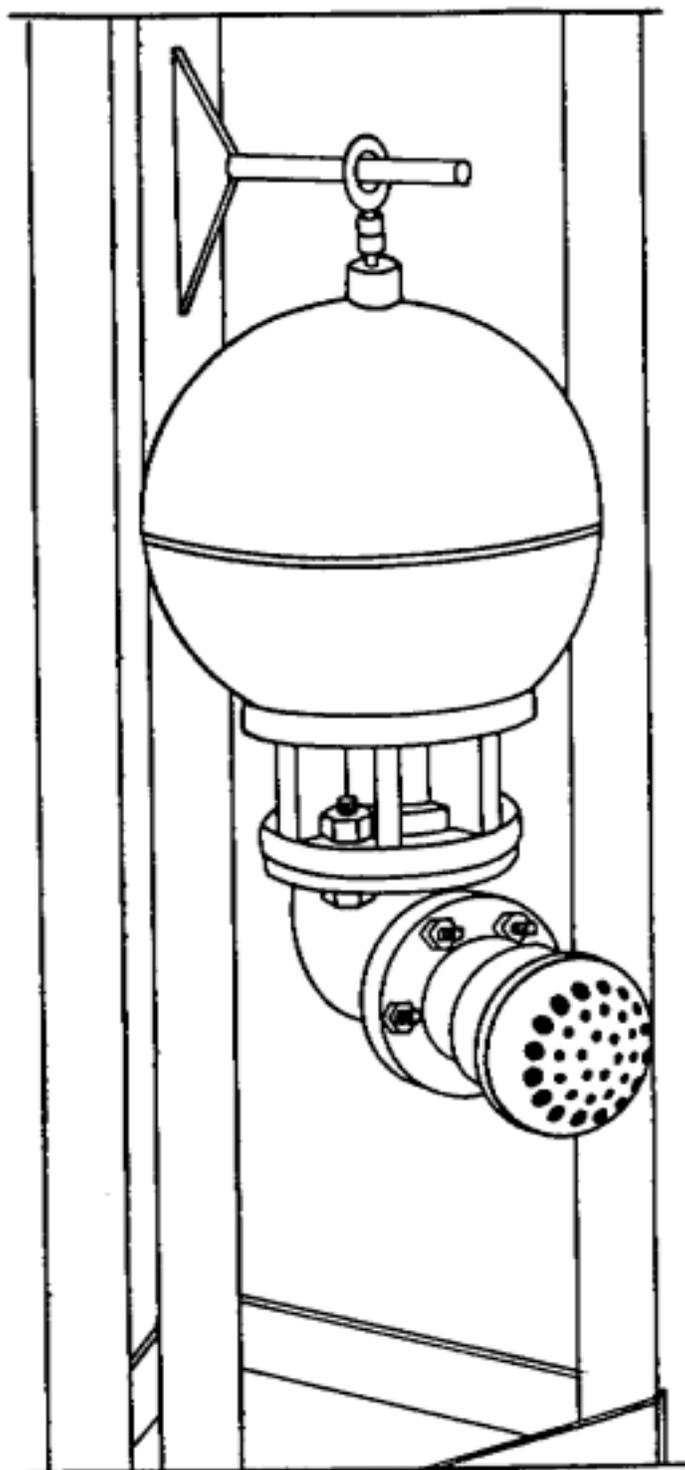
TYPICAL CARDOX INSTALLATION

FIGURE 12



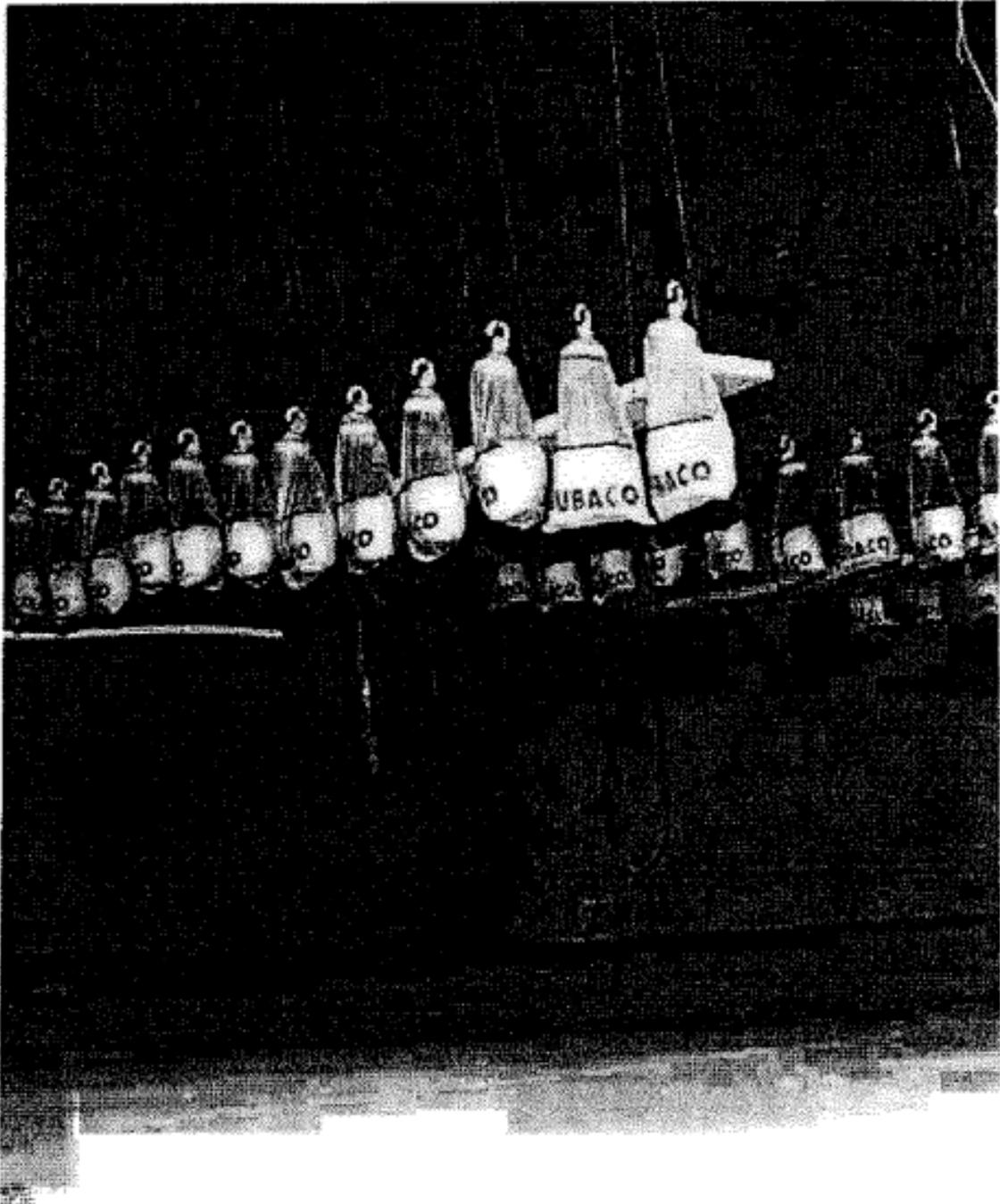
CARDOX BARRIER DETAILS

FIGURE 13



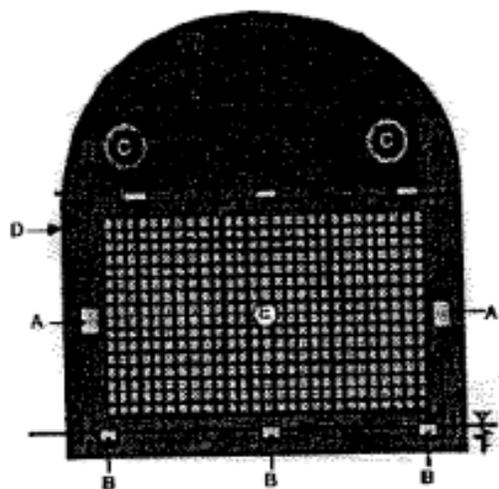
FENWAL BARRIER

FIGURE 14



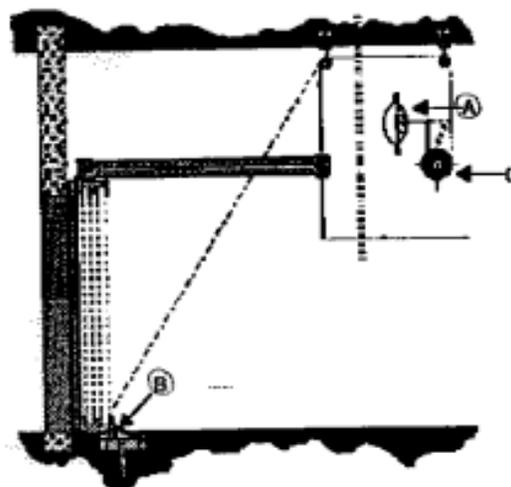
BAGGED STONE DUST BARRIER

FIGURE 15



- A & B - locking mechanism
- C - services (pipes etc.)
- D - door frame
- E - individual door flame proof components

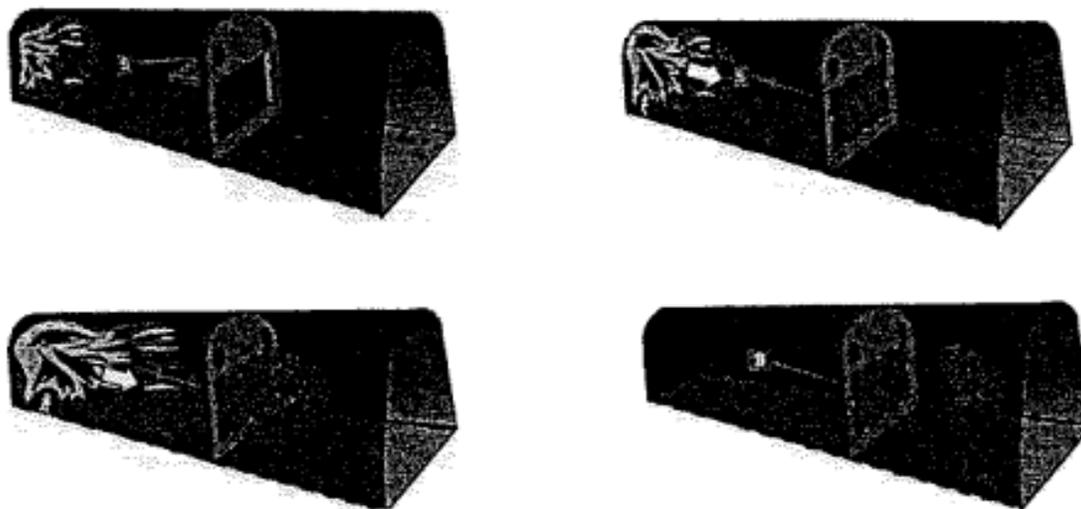
Front Elevation of the Explosion Door



- A - sensor
- B - locking mechanism
- C - pulley and wire for door release

Side Elevation of the Explosion Door

NEW METHOD FOR ARRESTING OF UNDERGROUND TUNNEL EXPLOSIONS



FIRE DOOR
FIGURE 16

APPENDIX I

From: "Jan Du Plessis" <jdupless@csir.co.za>
 To: <Steve.Zou@Dal.Ca>
 Subject: RE: explosion barriers in coal mines

Dear Steve

Find attached some relevant publications.

Jan

Jan Du Plessis wrote:

>
 > Dear Professor
 >
 > We at the CSIR Miningteks kloppersbos research station have been involved in the development of the bagged stone dust barrier that has been in use in South African mines since 1997.
 > Furthermore we have evaluated active suppression systems that is machine mounted on continuous miners as well as on a Dosco Roadheader for a Mining company in France.
 >
 > We have also done extensive testing on stone dusting, fly ash and other inert materials.
 >
 > I will gladly assist you if you can provide me with a little more information as I am also currently involved in evaluating a similar set of work in my research program.
 >
 > As such I belief we can assist each other greatly.
 >
 > Regards
 >
 > Jan du Plessis

----- Forwarded Message -----

From: "Jan Du Plessis" To: Subject: RE: publications in explosion barriers
 Dear Kazimierz

A large number of tests in SA as well as in Germany and the USA have been done. I attached a list of publications and some photos. I will also be interested if you could forward some photos on the water bag as presented at the conference last year in a paper. The stone dust bags is used in South Africa by more than 90% of the mines and the popularity in Australia is increasing rapidly. Let me know if you require anything else
 Regards Jan



[LISTOFRE.doc](#), [barrier photos.mlm](#), [DMTconveyor.jpg](#)

APPENDIX II

From: "**Weiss, Eric S.**" edw9@cdc.gov
To: zoudh zoudh@IS.Dal.Ca
Subject: barrier research at USBM/NIOSH

Dear Professor Zou,

I am sending you this message in regard to your request for information on previous barrier research. The U. S. Bureau of Mines (USBM) has conducted numerous projects to evaluate the performance of various types of passive and triggered barrier systems (water and chemical) in suppressing full-scale explosions at both the Bruceton Experimental Mine near Pittsburgh, PA and at the Lake Lynn Laboratory experimental mine located near Uniontown (Fairchance), PA. The health and safety programs of the now abolished USBM are being continued by the Pittsburgh Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH).

I can send you various publications summarizing the USBM barrier studies if you provide me with an address. Please call me at 412-386-5050 or email if you need any additional information.

Thanks,

Eric Weiss
Supervisory Mining Engineer
NIOSH/Lake Lynn Laboratory

APPENDIX III

From: "D.W.Dixon-Hardy@leeds.ac.uk" <D.W.Dixon-Hardy@leeds.ac.uk>
To: zoudh <zoudh@is.dal.ca>
Subject: Explosion barriers

Dear Prof Zou

I've been conducting research into a novel method for explosion arresting in underground mines and tunnels using a permeable explosion door concept. I proposed the idea with some Turkish Colleagues back in 1993 and it's been a long haul, with both computational and fairly simple experimental studies so far. I've attempted to get funding from the UK Mines Inspectorate for full scale testing but mining is in the doldrums here so I've had no luck.

I've been concentrating on CFD work on the concept for the last couple of years so I may be behind the times a bit but I don't think that anyone is doing any research into passive or active barriers so I'd be surprised if there has been a lot of technical advancement, though now I've said it, perhaps there has been?

My own feelings are that both passive and conventional active barriers that use a dust or water spray are unreliable in that they have to cope with a wide range of flame speeds and pressures. My idea of the explosion door is one that would act as a failsafe device.

My publications on the topic are listed at the end of this message and I can e-mail you a paper if your e-mail can cope with 2 x 2MB files.

I'd be very interested in any research collaboration, especially if it might lead to getting a full-scale version of my explosion door tested.

Hope to hear from you soon.

Regards

EDIZ, I.G., GORGULU, A. and DIXON D.W., " A New Approach for Arresting the Propagation of Coal Dust Explosions - AGE.1 Active Flame Door ", Proceedings of the 13th Mining Congress of Turkey, Istanbul, May 1993.

DIXON, D.W., FIDLER, W.M. and EDIZ, I.G., " The Preliminary Analysis of the Pressure Wave Transmission/Reflection Characteristics of Explosion Doors using One-Dimensional Finite Isentropic Wave Theory ", Proceedings of the 9th Coal Congress of Turkey, Zonguldak, May 1994. ISBN 975-395-118-3.

DIXON, D.W., EDIZ, I.G. and FIDLER, W.M., " A New Method for the Arresting of Underground Tunnel Explosions ", Proceedings of the 7th US Mine Ventilation Symposium, Lexington, Kentucky, June 1995. ISBN 0-87335-133-9.

DWOMOH, M., DIXON, D.W., and EDIZ, I.G., " The Passage of Shock Waves Through a Perforated Explosion Door - A Computational Study ", Proceedings of the 15th Mining Congress of Turkey, Ankara, May 1997. ISBN 975-395-216-3.

EDIZ, I.G., SEYFETTINOGLU, M.A., and DIXON-HARDY, D.W., " Suppression of Coal Dusts using Surfactants in Combating Coal Dust Explosions ", Proceedings of the 5th International Symposium on Environmental Issues and Waste Management in Energy and Mineral Production, Ankara, May 1998.

DIXON-HARDY, D.W., and DWOMOH, M., " Arresting Underground Explosions - A Computational Fluid Dynamics Study ", submitted to the International Mining & Minerals and under review.

Dr Darron W Dixon-Hardy
School of Process, Environmental & Materials Engineering
University of Leeds
Leeds, LS2 9JT
Tel: 0113 233 2800, Fax: 0113 246 7310
D.W.Dixon-Hardy@leeds.ac.uk

APPENDIX IV

Coal mine explosion barrier regulations BC , 1997

Type	6.30.1 (1) In any underground coal mine which is dry and dusty, rock dust or water barriers of a type authorized by the chief mine inspector shall be installed at places designated in a scheme prepared by the manager and authorized by the district inspector.
Order	(2) The district inspector may order the manager to prepare a similar, authorized scheme at any mine where the district inspector believes that a hazard may exist from the ignition of flammable gas or dust.
Inspection	(3) Where the explosion barriers are required in an underground coal mine, the manager shall appoint a person who holds an Underground coal mine shiftboss certificate to examine the Condition and position of the barriers.
Frequency	(4) The person appointed under subsection (3) shall examine the barriers at intervals of not more than 4 weeks and shall report the results of the examination in writing in a book to be kept at the mine.

Coal mine explosion barrier regulations Alberta , 1995 (292/95)

Certified Barriers	251 The employer shall ensure that the scheme for design, erection, location and maintenance of explosion barriers is certified by a professional engineer.
Explosion barrier placement	252 Unless issued an acceptance by the Director, the employer shall ensure that explosion barriers are established at <ul style="list-style-type: none"> (a) every entrance to every production section, (b) every entrance to every development district as soon as the development district has advanced 200 metres, and (c) every entrance to every ventilation split intake and return.

Coal mine explosion barrier regulations NS , 1989 (ch.73)

Stone dust

(5) Not less than twenty bags of stone dust shall be stored in every working section for emergency within a reasonable distance of the working face and in room and pillar sections, a suitable amount of stone dust shall be kept within easy access of the working faces.

No mention of explosion barriers.

APPENDIX V

Current Practice of Explosion Barriers in Canadian Underground Coal Mines

The following information on practice of explosion barriers used in Canadian underground coal mines is extracted from feedback of mine personnel from the then three operating mines: CBDC, Smoky River and Quinsam.

1. Explosion Barriers Used at Prince Colliery, CBDC, Nova Scotia

Information in this section is provided by Joe Shea, Manager, Engineering, Prince Colliery.

The Canada Labour Code makes provision for the installation of explosion barriers at the Cape Breton Development Corporation in Section 137 (1),(2),(3) of the Coal Mines (CBDC) Occupational Safety and Health Regulations.

137 (1) In each intake airway leading to a working face, a stone-dust or a water barrier shall be placed within 300m of the working face.

137 (2) A stone-dust barrier referred to in subsection (1) shall hold not less than 100 kg of stone-dust per square meter of area of the roadway that it serves.

137 (3) A water barrier referred to in subsection (1) shall contain not less than 200 L of water per square meter of area of the roadway that it serves.

Both types of barriers have been used in the CBDC Mines. However, problems with keeping sufficient stone-dust on the barrier trays (air velocity), and with stone-dust caking (air moisture), have led to the elimination of stone-dust barriers in favor of the current practice of water barriers at Prince Colliery.

Detailed Specification

The water barriers used at Prince Colliery are of the German design using Ruhrkohle Standard 735900 as a basis. They were approved for use underground within the CBDC Mines in 1987 by the Chief Inspector of Mines. The water barrier troughs or containers are of 80 L capacity and constructed to standard DIN21 576.

Approved manufacturer for Polystyrene water barrier troughs : Montanplastik GmbH
– Certification Number : LOBA NW. 18.42.5-9-1

Approved manufacturer for PVC water barrier troughs : VKG Wilhelm Leppak GmbH – Certification Number : LOBA NW. 18.42.5-111-16

Installation Standards

A water barrier must be located within 300m of the working face of an intake air roadway.

In addition, at Prince Colliery it is our standard to install a water barrier within 300m of the working face on the return side of a longwall.

Each water barrier must contain 200 L of water per square meter of area of roadway it serves.

Each water barrier must contain 5 L of water per cubic meter of roadway volume that the water barrier serves.

Water barrier troughs of the German design with a capacity of 80 L shall be used and are installed with the long side of the trough across the roadway.

The water barrier troughs must be kept full of water at all times.

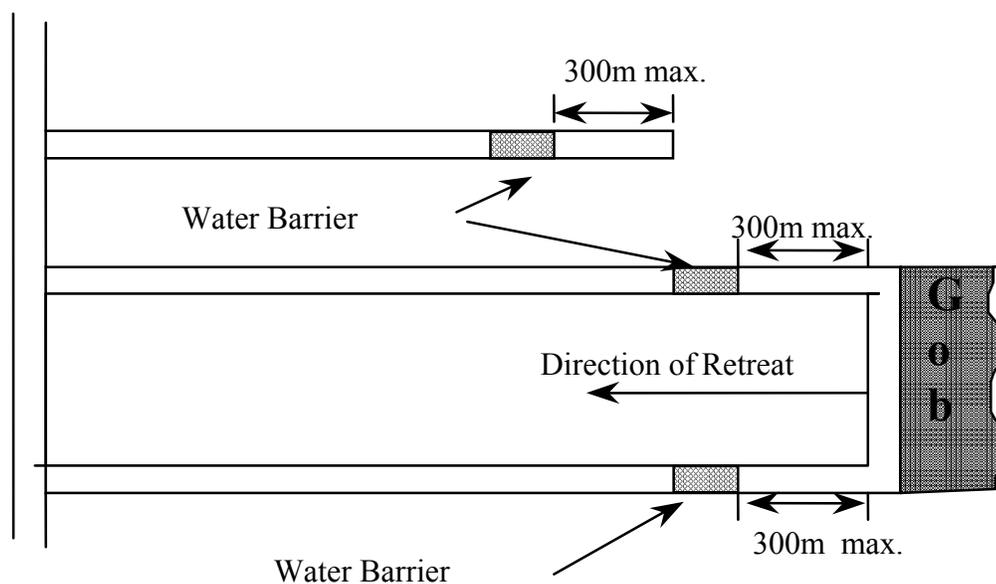
The water barrier troughs must be supported with a framework that is of robust design capable of supporting the designed number of troughs, typically steel angle is used.

Where the cross-section area of the roadway is greater than 10 square meters, the barrier must cover at least 35% of the roadway width.

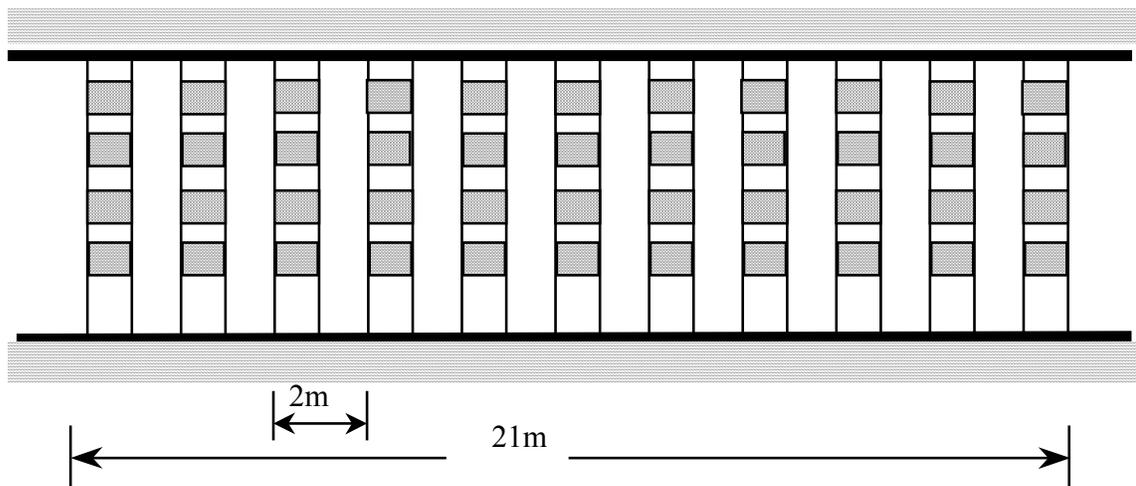
Where the cross-section area of the roadway is 10 – 15 square meters, the barrier must cover at least 50% of the roadway width.

Where the cross-section area of the roadway is greater than 15 square meters, the barrier must cover at least 65% of the roadway width.

At Prince Colliery the roadway drivages are typically inseam (9.6 square meters) or arched (16.8 square meters). Two typical plan views of water barrier installations for the inseam roadway drivages and the arched roadway drivages are attached in the following. Other arrangements are possible for various situations. The design spacing and use of any alternative water barrier arrangements are the responsibility of the Mine Engineer. Prince Colliery has settled on the PVC type construction for water barrier troughs used underground. The PVC trough construction is more durable, and can be more easily moved as the section advances, with less damage. The current supplier of water barrier troughs is Kunststoff Technik Gerthe, Germany.

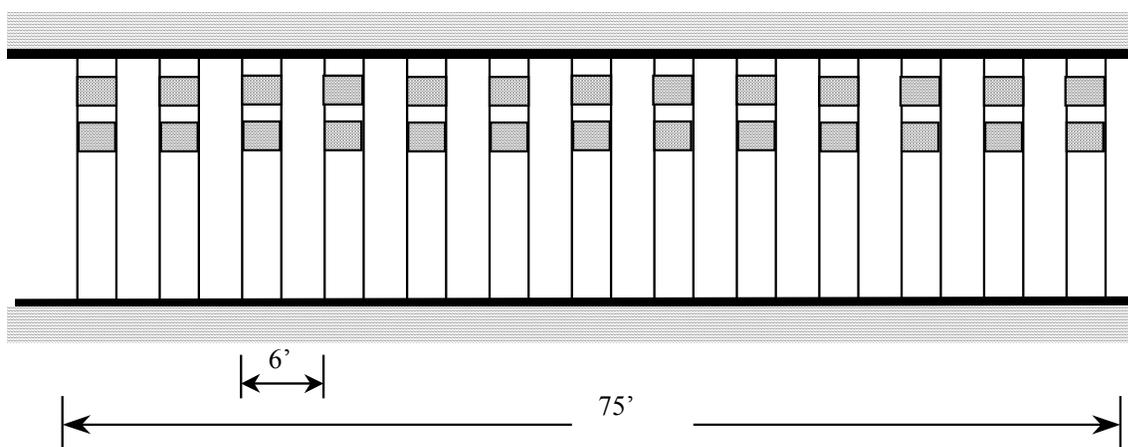


Water Barriers - West Mains (18' wide- 2 piece Arch)



- 4 Troughs / Shelf
- 11 Shelves
- 1m Gap between Shelves
- 44 Troughs required

Water Barriers - Inseam (14' wide x 6' 8" Legs)



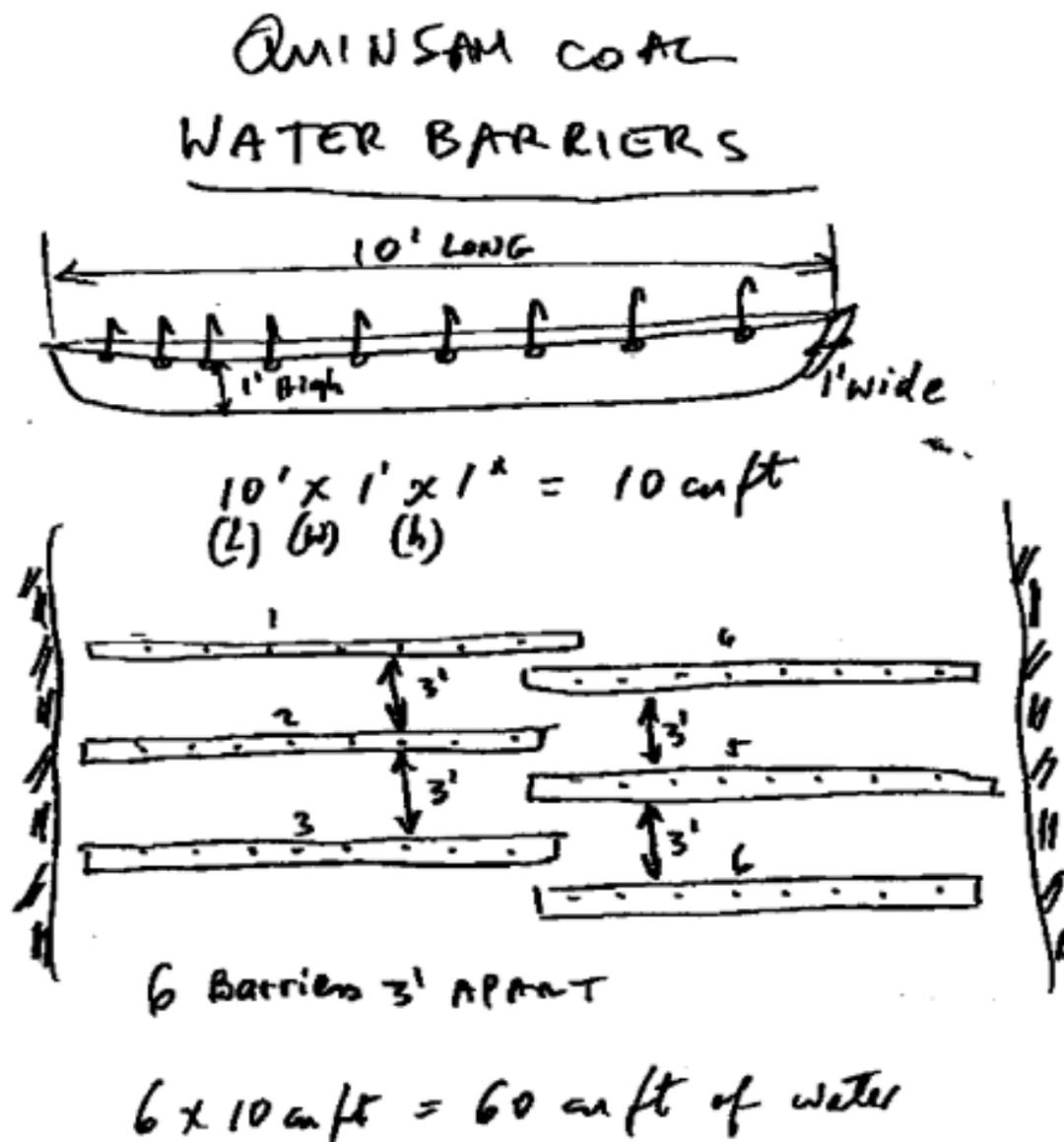
- 2 Troughs / Shelf
- 13 Shelves
- 3' Gap between Shelves
- 26 Troughs required

2. Water Barriers used in Quinsam Coal, British Columbia

Information in this section is made available by Kresho Galovich, Quinsam, BC, through Gary Bonnel, CANMET.

The sketch shows arrangement and size. The containers are made of collapsible yellow plastic that is also used for brattice in the coal mines.

It is available from National Mine Service. All technical details and studies academic papers, reports on water barriers should be available from NIOSH. This is Japanese invention.



3. Practice in Smoky River Coal, Alberta

Information in this section is provided by Peter Cain, Smoky River Coal, Alberta.

Current practice in the Smoky Coalfield is, as would be expected, not to install explosion barriers, but some time next year (2002) when we get the mine going, we will meet the requirements of the Alberta Regulations, i.e:

- barriers at every entrance to every production section
- every entrance to every development district once the district has advanced more than 200 m, and
- every entrance to every ventilation split intake and return.

We currently plan to use water barriers, 85L troughs, with 200L/sq. metre of roadway cross section plus 10% at every barrier. Barriers made up of shelves rigidly attached or on chains (the latter has a lower activation pressure) between 1.5 and 3 m apart.

APPENDIX VI

Most relevant articles

1. Flame-powered trigger device for activating explosion suppression barrier by R.A. Cortese and M.J Sapko
2. A new method for the arresting of underground tunnel explosions by D.W. Dixon, L.G. Ediz and W.M. Fidler
3. Performance of distributed bagged stone dust barrier in combating coal-dust explosions by J.L. du Plessis and P.S. Vassard
4. Special types of concentrated and mobile water-trough explosion barriers by J. Michells and W. Marth
5. Recent result of dust explosion studies at the Lake Lynn experimental mine by E.S. Weiss, N.B. Greninger and M.J. Sapko