

REVIEW PAPER: PREVENTION AND SUPPRESSION OF COAL MINE EXPLOSIONS

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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 indicate 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 ignitions and methods for their control.

INTRODUCTION

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 introduction of rock dusting, adoption of permissible explosives and electrical equipment, improved ventilation and improved methods for detecting hazardous conditions, for example, the methanometer. Although these advances in mine safety are noteworthy, an examination of recent statistics (table 1) indicates that the problem of mine explosion prevention is not completely solved. For example, in recent years major mine explosions have occurred in Turkey (Armutcuk 1983, 102 fatalities); South Africa (Hlobane 1983, 64 fatalities); Japan (Minami Oh Yubari 1985, 61 fatalities); France (Simon 1985, 22 fatalities); and the Federal Republic of Germany (Stolzenbach 1988, 51 fatalities). Other major

mine explosions have recently occurred in Brazil (31 fatalities), Czechoslovakia (65 fatalities), Mexico (43 fatalities), Taiwan (90 fatalities), and Yugoslavia (39 fatalities). The high fatality rates in the United States for the years 1976 and 1981 were associated with the Scotia Mine Disaster in 1976 which claimed a total of 26 lives; the Dutch Creek explosion in April 1981 with 15 fatalities, the Atkins Mine Explosion on December 7, 1981 with 8 fatalities and the Grundy Mine Explosion on the next day which resulted in 13 fatalities (Richmond et al 1983).

Aside from these documented events there is also growing concern over the number of frictional methane ignitions that occur annually. Figure 1 shows the frictional ignition trend for the U.S. World-wide statistics on the frequency of frictional ignitions are not available, but the data presented in figure 1 indicate the magnitude of the problem. Strangely enough, the

high frequency of methane ignitions by friction has not as yet seriously impacted fatal accident statistics, but their potential for disastrous consequences is well known. The mine disaster in Glace Bay, Nova Scotia in 1979, which claimed 12 lives and was attributed to frictional ignition, serves to illustrate this point (Canada 1979).

Table 1: Fatalities From Underground Coal Mine Explosions

Year	Worldwide ¹	United States ²
1976	325	27
1977	342	4
1978	57	0
1979	119	0
1980	51	5
1981	204	36
1982	62	7
1983	291	8
1984	222	3
1985	223	3

¹Michelis et al 1986

²USDOL-MSHA (annual reports)

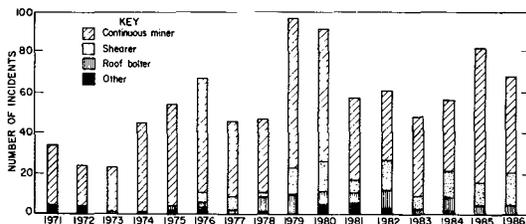


Figure 1. - Fatalities From Underground Coal Mine Explosions

ROCK DUSTING

Rock dusting of coal mines has been in use now for about half a century as a precautionary measure against the dust explosion hazard. It is generally agreed that the effectiveness of rock dust lies in its ability to be simultaneously dispersed with coal dust, and thus prevent flame propagation by serving as a heat sink. In the United States, Rice of the U.S. Bureau of Mines suggested the use of rock

dusting for preventing or limiting coal dust explosions as early as 1911 (Rice 1911); he referenced experiments being conducted in Great Britain. Experiments at the Bureau of Mines confirmed that ignitions could not be obtained with mixtures of Pittsburgh coal dust and rock dust having an incombustible content of 64 percent. In 1927 (Rice 1927) and again in 1937 (Mine Safety Board 1937) the Bureau made recommendations concerning the use of rock dust; the specified level was to produce a total incombustible content of 65 percent. The 1953 Federal Mine Code called for 65 percent incombustible plus an additional 1 percent for each 0.1 percent methane present. This was further revised in the 1969 Health and Safety Act which raised the requirements for returns (U.S. Congress 1969).

The current regulations require that the incombustible content of the combined coal dust, rock dust and other inerts be not less than 65 percent, but the incombustible content in returns where the coal dust is finer shall be not less than 80 percent. Where methane is present, the required incombustible is increased 1.0 and 0.4 percent for each 0.1 percent methane where 65 and 80 percent incombustible, respectively, are required. The effectiveness of rock dusting in preventing mine explosions is illustrated by the decline in fatalities associated with mine explosions which in the U.S. declined from 300/year in the late 1920's to about 20/year in the late 1960's. Since the 1969 Act this number now averages about 8/year. Other safety measures, especially permissible cap lamps, explosives and electrical equipment together with improved ventilation contributed to this decline, but the general use of rock dust played a major role in reducing the frequency of coal dust explosions.

Most major coal producing countries have similar requirements, some more stringent and some less stringent

than those enforced in the U.S. A partial listing of these requirements is given in table 2.

Table 2: Summary of Rock Dusting Requirements for Various Countries

Country	TIC pct	VM pct	CH ₄ , pct
Australia ¹	65 75 60 70	--- --- --- ---	>0.1 >0.1 <0.1 <0.1
Belgium ²	75 78 80	≥18	<1 1-1.5 >1.5
Canada (Nova Scotia)	75 80		<1 >1
Czechoslovakia ³	up to 80		
Federal Republic of Germany	80	---	
France ⁴	55 (RD) 65 (RD) 70 (RD) 80 (RD) 50 (RD) 60 (RD) 65 (RD) 70 (RD)	≤18 ≤18 >18 >18 ≤18 ≤18 >18 >18	no gas gas no gas gas no gas gas no gas gas
Japan ⁵	76 (F) 83 (F) 71 (F) 78 (F) . . . 57 (F) 62 (C) 50 (F) 54 (C)	35 35 35 35 . . . ≤15 ≤15 ≤15 ≤15	>1 >1 <1 <1 . . . >1 >1 <1 <1
Poland	70 80	>12 >12	no gas gas
Republic of South Africa	50 55 60 65	>14, 20 >20, 22 >22, 25 >25, 27	no gas no gas no gas no gas no gas

Table 2: Summary of Rock Dusting Requirements for Various Countries Continued

Country	TIC pct	VM pct	CH ₄ , pct
South Africa Continued	68 70 72 75	>27, 30 >32, 32 >32, 35 >35	no gas no gas no gas no gas
United Kingdom	50 55 60 65 68 70 72 75	20 22 25 27 30 32 35 >35	
United States	65 75 80 retn 84 retn	>20 >20 >20 >20	no gas 1 no gas 1
Soviet Union	60 80	>10 >10	no gas gas

¹ High values of TIC apply to face zone; low values apply to zone 200 m beyond face.

² For coals with <18 pct volatile matter (VM) lower values of TIC may be used on approval by authority.

³ TIC set for particular mine based on explosibility of coal dust.

⁴ French requirements are based on rock dust content (RD) not total incombustible content (TIC)

⁵ In Japan the specific requirements depend on the ash, moisture and volatile content of the coal, the gassiness of the seam and the fineness of the rock dust used. Extreme values, see US Coals, are given in Table 3. (F) denotes fine rock dust (85 pct <74 μm) and (C) denotes coarse rock dust (45 to 55 pct 74 μm).

Table 3: Inerting Requirements (TIC) for Different Coals in Two Different Experimental Mines with No Methane Present¹

Coal Type	Volatiles Percent	Total Incombustible Content, pct			
		Pulverized Coal (80% < 200 mesh)		Mine Size Coal (20% < 200 mesh)	
		BEM	LLL	BEM	LLL
Pocahontas	18.0	60	>70	40	55 to 60
Pittsburgh	36.5	78	79 to 82	63	>68
Sunnyside	38.1	80	appr. 80	64	70 to 75

¹Weiss, et al 1989

As will be noted some countries grade rock dust requirements according to the volatile content of the coal. Since rock dusting is the chief defense against dust explosions and probably will remain so in the foreseeable future, it seems appropriate to review the adequacy of the current standards in light of recent research findings. The U.S. regulations on rock dusting were developed on the basis of extensive experimentation in the Bruceton Experimental Mine (BEM) using "mine-sized" Pittsburgh seam coal (20 percent through 200 mesh). The BEM has a cross section of about 5.5 m² (2.9 m wide by 1.9 m high). This represented the typical mine entry size when the BEM was constructed in 1910. With advances in roof support, the width of mine entries gradually increased, and 7 m wide entries are now common in the United States and elsewhere. In order to conduct more meaningful experiments on coal dust explosion prevention the Bureau constructed the Lake Lynn Laboratory (LLL) which has entries that average 12 m² (6 m wide by 2 m high) (Mattes et al 1983). Since becoming fully operational in 1985, a number of important experiments that bear on the adequacy of current rock dusting practices have been conducted. The principal goal of those experiments was to determine the inerting requirements for coals of different particle size and volatility in large entries. The details of these experiments have been presented elsewhere, but the important findings are summarized in table 3.

For fine (pulverized) high volatile coals (Pittsburgh and Sunnyside) the inerting requirements in terms of total incombustible content and in the absence of methane are about the same in the BEM as at LLL. However for fine, low volatile coal (Pocahontas) significantly more inert is required to prevent propagation in the large entries at LLL than in the smaller BEM entries. For coarser coal dust significantly more inert is required at LLL than in the BEM for both high and low volatile coals, the differences being more pronounced with low volatile coals. In essence, coarse and low volatile coals were shown at LLL to be more reactive and require correspondingly higher inert content to prevent propagation. This effect is presumably associated with longer reaction zones (thermal fields) which apparently scale with entry size and reduced heat losses in the larger entry.

The recent results from LLL although preliminary in nature, point out the possible dangers of extrapolating small-scale laboratory data to full-scale. This is especially true when trying to set a limit for the volatility or on the particle size of coal particles that might enter into explosion reactions in large-scale explosions. The implications of these results regarding the current rock dusting standards in table 2 are obvious.

Inerting requirements for preventing the propagation of coal dust explosions is complicated by factors other than those associated with large entry sizes. The increased

utilization of high production, mechanized mining methods poses additional problems in terms of dust fineness and float dust deposition rates. There is strong evidence that the coal dust now deposited in mine roadways is much finer than the so-called "mine size dust" on which many current rock dusting requirements are based (table 4). For example, a dust survey taken in 1954 (Hartman et al 1954) showed that floor dust averaged 28 percent through 200 mesh; whereas surveys conducted in 1964 (Saltsman 1964) and again in 1982 (Courtney et al 1982) indicated that this value had increased to about 80 percent, roughly equivalent to the pulverized dust listed in table 3.

The explosibility of thin deposits of float coal dust is well documented and in fact, the most severe experimental dust explosion conducted by the Bureau involved float coal dust (Nagy 1981). There is little data regarding the rate of float dust deposition in mechanized mines, but there is no doubt that it correlates with production rates; with the increased utilization of longwall mining methods it represents a problem of growing concern. Recent experiments at the Bureau indicate that only the top layer (2 to 4 mm) of floor dust participates in a weak to moderate float dust explosion (Sapko et al 1987). This results in an enriched cloud of dispersed dust requiring much more inert in the substrate to effectively quench the float dust explosion than would be needed if thicker layers of the floor dust were dispersed. For example, a substrate containing 80 percent total incombustible was shown to be effective only for float dust deposits less than 0.08 mm thick, corresponding to a dispersed concentration of 50 mg/liter.

Heavier deposits of float coal dust required significantly higher values of total incombustible in the substrate to prevent propagation. Current sampling techniques which usually involve relatively thick

layers of floor dust tend to overestimate the degree of protection against float dust explosions. Since rib and roof samples, which represent a small fraction of the total dust, are often combined with floor dust samples, the overall protection against float dust explosions is also overestimated.

Table 4: Dust fineness in the return entries of coal mines.

Year	Pct through 200 mesh	
	Rib-roof	Floor
1954 ¹	49	28
1963 ²	50	40
1964 ³	--	83
1982 ⁴	--	72 - 100

- ¹Hartmann, et al 1954
- ²Kawenski, et al 1963
- ³Saltsman 1964
- ⁴Courtney, et al 1982

Attempts to improve the effectiveness of rock dusting have not met with much success. Full-scale experiments with fluidized rock dust -- to increase dispersibility -- indicated that more fluidized rock dust was required to prevent propagation than ordinary rock dust (NCB 1967 and Greenwald 1948). This was attributed to the higher cohesiveness of ordinary rock dust which more effectively binds the coal dust particles. This is supported by some recent laboratory studies which showed that fluidized limestone dust was less effective than ordinary limestone dust in inerting coal dust. In addition, some large scale studies in the BEM with a phosphate dust, which was intrinsically more fluid than limestone dust, showed it to be less effective than ordinary limestone dust.

Salt encrustation is also utilized to combat float dust deposits and can effectively do so if properly maintained (Berg 1982). This

technique was examined for potential application in the U.S. mining industry (Foreman et al 1981). However, problems involving corrosion and maintaining effectiveness under conditions of low humidity were not resolved, and enthusiasm for the method waned.

The most promising methods for improving the quality of rock dust practice appear to lie in the recent development of practical methods for determining the inert content of mine dust samples, in-situ. The Bureau of Mines has developed an optical rock dust meter that can be used underground to give a direct and rapid read-out of the rock dust content of mine dust samples, thus eliminating the need for laborious and time-consuming laboratory analysis of rock dust content (Sapko et al 1985). The in-situ measurement allows for immediate corrective action and has high potential for improving mine explosion safety. The Bureau device is in the process of being commercialized. A similar device which utilizes nuclear radiation for measuring rock dust content is being developed in Poland and is also believed to be near commercialization (Lebecki 1975 and Krzystolik 1985). The principle of optical reflectance utilized in the Bureau rock dust meter appears to be applicable to the problem of quantitatively determining the build-up of float dust deposits and is being reduced to practice (Sapko et al 1988).

PASSIVE BARRIER

To provide supplemental protection against coal dust explosions, passive barriers have been deployed in most major coal producing countries. Conveyor roadways have received emphasis (NCB 1961). There are two approaches to the deployment of passive barriers --- concentrated and distributed. Concentrated barriers are placed at strategic locations within a mine and are designed to quench an explosion immediately on arrival at the

location. Distributed barriers are placed throughout the length of an entry and are designed to moderate or quench an explosion over much longer distances. Table 5 summarizes requirements for various countries utilizing either concentrated rock dust or water barriers. The current trend is toward increased utilization of water barriers in lieu of rock dust barriers. Almost all countries that deploy water barriers use frangible plastic tubs which typically hold either 40 or 80 liters of water. A notable exception is Japan where flexible water bags are used (Ng et al 1986). For concentrated water barriers many countries have adopted a 200 liter/m² loading. However, for gassy mines some countries (Australia and Poland) (NSW 1984 and Ministry of Mining & Energy 1984) require a loading of 400 liter/m². In countries where distributed barriers are deployed a loading of 1 liter/m³ has been adopted. Where water barriers are deployed they are in most situations suspended from the roof which in the case of roadways using yieldable steel arches does not significantly impede ground transport. The impact of the use of barriers for supplemental explosion protection on the local total incombustible or rock dust requirements varies from country to country. In the United Kingdom (The Coal Mine Regulations 1977) and in many other countries the level of rock dusting near barriers cannot be diminished. On the other hand, in France (Cerchar 1988) the rock dusting requirement is reduced by 5 percent in the zones where barriers are deployed.

Because sizeable pressure forces are required to activate passive barriers, they must be located at some distance from the probable ignition point (working face). At intersections, which provide considerable pressure relief, passive barriers can be easily defeated. This ease of defeat is the chief reason that passive barriers have not been adopted in the United States which still

Table 5: Summary of Passive Barrier Requirements in Various Countries

Country	Loading			
	Rock dust nongassy	(kg/m ²) gassy	Water (liters/m ²) nongassy	gassy
Australia ¹	200	400	200	400
Belgium ²	---	400	---	200
Canada ³	---	200	---	200
Czechoslovakia ⁴	200	400	---	---
Federal Republic of Germany ⁵	---	400	---	200
France ⁴	---	400	---	200
Japan ⁶	0.1m ³ /m ² 0.3m ³ /m ² 0.4m ³ /m ²	light heavy ext hvy	---	100 light 300 heavy 400 ext hvy
Poland ⁷	200	400	200	400
South Africa ⁸	200	400	---	---
Romania ⁴	---	400	---	200
United Kingdom ⁹	---	200 light 400 heavy	---	200 minimum
Soviet Union ⁴	200	400	---	---

¹ MSW 1984

² Ministrere des Affaires Economiques 1982

³ Canada Labour Code 1979

⁴ Cybulski 1976

⁵ Michelis 1987

⁶ Ministry of International Trade and Industry

⁷ Ministry of Mining and Energy 1984

⁸ Republic of South Africa

⁹ The Coal Mine Regulations 1977

produces a significant fraction of its total coal in room-and-pillar mines.

The problem of erecting passive barriers to keep up with the changing location of the active face poses another problem. Erecting frames to support barriers suspended from the roof is a labor intensive operation. For wide entries,

experimental studies on the deployment of barriers along the ribs have been conducted in several countries. Recent results at the LLL indicate (Sapko et al 1988) that stacked rib barriers are fairly effective and may have direct application in longwall mining.

There are several important examples of mine explosions where the value

of passive barriers in reducing the extent of propagation was convincingly demonstrated. At the Fenton Colliery (UK, 1963) (Eisner et al 1964) a methane explosion occurred at the face of an entry. The first shelf of the barrier installation was located 80 m from the face of the heading. There was clear evidence that the flames had actually reached the barrier. A transfer point was located just outbye the barrier where there were ample deposits of coal dust, and there was little doubt that without the operation of the barrier the explosion would have increased in intensity and travelled much further. In another incident at the Mainsforth Colliery in Durham (UK, 1963) an explosion occurred (Eisner et al 1964). A rock dust barrier on the mine intake airway 218 m from the face of the heading was completely discharged and without doubt arrested the spread of flame.

However, there have been other instances when the effectiveness of passive barriers was not so clearly demonstrated. In Belgium in March 1984 the efficacy of water barriers was proven to some extent during the explosion at the Eisdan Mine in which seven men were killed (Jones 1988). The bottom gate to a face in an inclined seam was protected by distributed water barriers of four shelves, each containing a single 80-liter water trough, positioned 100 m behind the face, and then repeated outbye at 40 m intervals. The investigation indicated that the first five sets of distributed barriers operated, between 100 and 270 m from the face, and arrested the explosion. This was suggested as the reason why men who were located some 290 m from the face were not injured.

More recently, an explosion occurred at the Moura Mine in Australia which on July 16, 1986 killed 13 miners (Jones 1988). The inquiry report shows that a water barrier was installed in the belt heading as required by law and was in good working condition prior to the

event. The report concludes that the explosion was quenched by the presence of the water barrier in the conveyor road, and by substantial quantities of water present in swills in other roadways.

TRIGGERED BARRIERS

Triggered explosion barriers are a relatively recent development as compared to passive barriers, and there is considerable research effort in the United States and elsewhere to develop and implement this technology.

There are two general types of triggered barriers: machine mounted devices for the rapid detection and extinguishment of face ignitions and fixed triggered barriers for quenching more or less fully developed methane or coal dust flames.

Table 6 summarizes the machine mounted technology for three countries. The Federal Republic of Germany has been using their BVS system in operating mines, and the United Kingdom has conducted tests with a Graviner system under conditions which simulate the mine environment. All three systems utilize ultraviolet flame detectors (1800 Å) which can distinguish methane or coal dust flames and are not prone to false triggering by artificial light sources (Furno 1985). Ammonium phosphate in its mono or dibasic form is the extinguishing agent of choice and has been demonstrated to be particularly effective against methane and coal dust flames (Michelis 1983 and Furno et al 1985). Expulsion of the extinguishing agent, which must occur in as short a time as possible, is affected with pressurized nitrogen or Halon 1301 (CF₃Br). The quantity of extinguishing agent varies with the application but typically runs from 16 to 48 kg depending on machine and entry geometry.

Table 6: Summary of Machine Mounted Ignition Suppression Practices in Various Countries

Country/ Type	Detector Type	Extinguishing Agent	Expulsion Mode	Vessels		
				Number	Shape	Loading, kg
Federal Republic of Germany ¹ BVS System	UV	Tropolar Powder (ammonium phosphate)	Nitrogen at 120 bar + detonator activated valves	6	12.3 liter cyl.	48
United Kingdom Graviner System ²	UV	Furex 770 ammonium phosphate	60 bar N ₂ or Halon 1301	4-6 (seven diff pos)	app. 7 liter cyl.	16-24
United States PRC System ³	UV	ABC Powder ammonium phosphate	linear shaped charge and Halon 1301 13.6 bar 13.6 bar	6	tubular cann. 0.76, 1.2, 1.8 m long x 5 cm dia	17

¹ Michelis 1983, Fabor 1987

² Browning et al 1985

³ Furno et al 1985

There is general agreement that the use of machine mounted ignition suppression systems would greatly strengthen the strategy for mine explosion prevention since these systems are targeted at combating methane ignitions near their point of ignition. However, the systems are severely taxed in detecting and suppressing fast flames associated with near stoichiometric methane-air mixtures, and their effectiveness against turbulent flame has not been demonstrated. In addition, the systems are difficult to retrofit to existing mining machines in a way that would guarantee protection against all possible points of ignition. Components of machine mounted ignition suppression systems, especially the flame detectors, are rather delicate and will require dedicated maintenance in order to function properly. Noise associated with explosively activated systems (US) and material toxicity problems with Halon 1301 (US and UK) are also problems that have not been completely resolved.

Table 7 summarizes the characteristics of fixed location triggered barriers being developed or deployed in various countries. The Belgium system, which utilizes a length of detonating cord to expel water from a 2-m long by 0.25 m diameter cylinder of open pore polyurethane, is triggered by a thermo-mechanical device that is sensitive to both pressure and flame. This system is also used in France. The system utilized in the Federal Republic of Germany also used detonating cord for dispersion, but the extinguishing agent (water) is contained in a PVC tub similar to that used for passive barriers; sensitive thermocouples are used to trigger the device. The system deployed in the United Kingdom consists of a steel cylinder containing 227 liters of water and a pressurized reservoir of nitrogen which is used to drive a piston to expel the water. The system is activated with a sensitive thermocouple coupled to a fast acting valve which releases the stored nitrogen. The system

Table 7: Summary of Fixed Location Triggered Barrier Practices for Various Countries

Country/ Type	Detector Type	Extinguishing Agent	Expulsion Mode	Vessels	
				Shape	Loading L/m ²
Belgium ¹	thermo- mechanical	water 90-100 liters/ unit	detonating cord	2 m long 25 cm dia open pore polyurethane foam	10
Federal Republic of Germany ²	thermocouple	water 80 liters/unit	detonating cord	PVC water tub	80
France ³	thermo- mechanical	water 90-100 liters/ unit	detonating cord	2 m long 25 cm dia open pore polyurethane foam	10
United Kingdom ⁴	thermocouple	water 227 liters/unit	compressed N ₂	long cylinder	45
United States new	pressure and UV (solar panel)	water or mono-ammonium phosphate 40 liters/unit	sheet explosive	ridged polystyrene container	80

¹ Ministrere des Affaires Economiques 1982

² Michelis et al 1987

³ Cerchar 1988

⁴ HSE 1977

currently being examined in the United States uses a formed sheet of explosive to expel water (or monoammonium phosphate) from a 40-liter reinforced polystyrene container. The unit is activated with a novel flame sensor, an ultraviolet solar panel, which provides enough electrical energy to fire any reasonable number of electric detonators and is in a sense "explosion-powered".

All of these systems have successfully functioned with water loadings varying from 10 to 80 liters of extinguishing agent per square meter of entry in experimental mines. Total discharge volumes vary from 227 liters (UK) to 1600 liters (FRG) depending on entry

size. Experiments in the U.S. center around total discharge volumes of 720 liters.

Triggered barriers for fixed locations offer significant advantage over machine mounted devices. First and foremost they do not have to withstand the rigors of the coal cutting environment at the face. In addition, they do not have to respond in the very short time frame necessary for effectively quenching face ignitions and as a consequence are far simpler in design. Furthermore, they do not appear to suffer from the noise and potential toxicity hazards that are associated with some of the machine mounted systems. They also offer advantages over passive barriers

inasmuch as they would appear to be applicable in low coal seams and in the room-and-pillar mine configurations.

FRICITIONAL IGNITION

In the U.S. the ignition of methane by coal cutting machinery outweighs ignitions by other sources, electrical, open flame, etc., by a wide margin, usually by three or four to one. Since there is no reason to believe that the U.S. is unique in this regard, a brief summary of the current efforts to mitigate this hazard is in order.

There has been a large amount of research on the subject of frictional ignition in general and the frictional ignition of methane by mining machines in particular; several excellent survey papers on the subject have been published (Hartman 1955, Powell et al 1975, Lobegko 1978, Watson 1981, and Browning 1988). The important findings are:

1. Most ignitions are caused by cutter bits striking rock in mines; siliceous or quartz bearing sandstones present the greatest hazard followed by pyrite inclusions.
2. The ignitions invariably start in methane air mixtures and not in coal dust. (There have been two or three reported instances of coal dust ignitions in allegedly "non-gassy" mines; however, they have not been verified.)
3. The principal source of ignition is hot or molten rock created through friction -- not the elevated temperature of the bits or flying sparks.
4. All bit materials can cause ignitions, but some materials are more incendive than others.

5. The tendency for ignition to occur greatly increases with bit wear. (This is due to an increase in the contact area associated with bit wear and the subsequent exposure of the steel shank material which is more incendive than the tungsten carbide cutting tips.)
6. Reducing the cutting speed appears to reduce the tendency for ignitions to occur. (Recent research at the Bureau indicates that the benefit of machine speed reduction is marginal at best.)

These observations suggest practical ways of reducing the frequency or severity of ignition, i.e., improved ventilation, a rigid bit inspection program with frequent bit changes, improved cutter bits, and the use of water to cool the hot spots responsible for ignitions.

Observations on the relative incendivity of various metals used in the construction of coal cutting bits indicate that there is some room for improvement in the design of bits to reduce their tendency to ignite methane. For example, Blickensderfer's early work showed (Blickensderfer et al 1974) that the steel used in the construction of bit shanks was significantly more incendive than the tungsten carbide cutting tip.

This suggested that any modification in bit design that would prevent early exposure of the shank material to frictional abrasion would serve to moderate the tendency for bits to cause ignitions. On this basis, a considerable amount of experimental work was conducted with conical bits used on continuous miners (Cheng et al 1983). One experimental design having a "mushroom" tip or capped carbide, as it is referred to in the bit industry, was particularly effective in protecting the steel shank from early exposure during the cutting operations. Laboratory testing of a commercial version of

the "mushroom" bit also showed a strong relationship between ignition probability and bit attack (and clearance) angle. The optimum attack angle corresponding to minimum ignition probability, was found to be near 57° for the particular bit used (Cheng et al 1987). On the basis of this research an extensive field evaluation was conducted under a joint cooperative effort between the Bureau and Jim Walter Resources Incorporated (JWR), Brookwood, Alabama together with Hughes Mining Tools, a Division of Hughes Tool Company, Bristol, Virginia (McNider et al 1987). An experimental cutter head laced to accommodate a capped carbide bit operating at a 57° attack angle was constructed and tested in JWR's Blue Creek #3 Mine in an area prone to ignitions. The machine mined over 50,000 tons in an ignition prone area without incident. When it was removed for internal rebuilding, a miner with a 50° attack angle replaced it. Before 10,000 tons were mined, two ignitions had occurred. Consequently, all miner heads scheduled for rebuilding were equipped with the capped carbide bits fixed to operate at a 57° attack angle. In the past four years over ten mining machines have been modified in this manner resulting in a dramatic reduction in the number of ignitions at Jim Walter Resources. In fact, there has not been a single ignition traceable to a modified machine that was within specifications.

Another promising method for controlling frictional ignitions would appear to be the use of machine mounted water sprays to cool the hot spots responsible for ignition. There is overwhelming laboratory evidence that properly designed water sprays are effective for this purpose (Watson 1981 and Browning 1988). All of these studies agree that water sprays in back of the bit are much more effective than sprays in front of the bit. Our experience is that front sprays are almost totally

ineffective in preventing ignition although Browning (Browning 1988) indicates that front sprays do have some effect. This is probably associated with bit tip cooling and the lubricating effect of water in reducing frictional forces. Browning also cites work that indicates that bits with water through the body, with the water released immediately behind the carbide tip, were ineffective in eliminating ignition. However, other work indicates (Morris et al 1984) reasonable effectiveness of "through-the-bit" water sprays.

Although there is no disagreement that back sprays can be used to control frictional ignitions, there is no consensus on the optimum spray configuration. Courtney found that a 30° full cone spray nozzle operating at 6.9 bar and 1.9 lpm helped when used with a relatively small chisel bit (Courtney 1987). Browning recommends (Browning 1988) a 65° hollow cone spray delivering about 2.3 lpm. A recent bulletin from the British Coal Board recommends (British Coal - Pvt comm) a 25° full cone spray operating at between 1.9 and 2.3 lpm. Recent work at the Bureau showed (Cecala et al 1988) that jet sprays operating at 6.9 bar and 6.1 lpm were effective in preventing ignition with a large chisel bit. However, lower flow rates were ineffective in quenching the hot spot responsible for ignition. This indicates that the water flow requirements are probably sensitive to bit tip size and geometry which seems reasonable. Other factors complicate the identification of optimum spray parameters for behind-the-bit spray systems. For example, besides hot spot cooling, the water spray may serve as an inerting agent for the methane containing air volume in the vicinity of the pick, thus reducing the possibility of an ignition. Aerodynamic effects which would sweep the methane-air mixture from around the cutting tip may also be important. In any case, the back sprays should be carefully oriented

to sweep the area immediately behind the carbide cutting tip.

It should be pointed out that there is little documentation of the effectiveness of machine mounted back sprays under actual mining conditions. Most laboratory research does not involve the actual cutting of coal, and the effect of the production of large amounts of cuttings in the vicinity of the back spray is not known. Recent field experiments indicate (Cecala et al 1988) that the effectiveness of back sprays demonstrated in the laboratory experiments are indeed carried over to real mining conditions.

CONCLUSIONS

Notwithstanding the effort devoted to their prevention, coal mine ignitions and explosions continue to occur with unsettling frequency. The increased utilization of high production, mechanized mining methods in deeper and gassier coal seams will place additional demands on those responsible for mine safety particularly in explosion prevention. Rock dusting is still the chief defense against coal dust explosions and probably will remain so in the foreseeable future. Research has raised some question regarding the overall effectiveness of present rock dust practice. Recent experiments in a large entry indicate that coarser and less volatile coal dusts participate in explosion reactions more readily than in smaller entries and require more rock dust for inerting than anticipated under current regulations. In addition, high production mining methods lead to the generation of larger quantities of fine dust which is difficult to inert especially in the form of float dust deposits. Except for the development of techniques for monitoring the quality of rock dusting, in-situ, there is little on the research horizon.

Passive explosion barriers have proven to be effective for

supplemental explosion protection in arched roadways with few intersections but are difficult to apply in low coal and the room-and-pillar mining configuration. Triggered explosion suppression systems for entry protection are being developed and may have wider application than passive barriers if problems of reliability, maintenance, noise, and potential health hazards (in some cases) can be overcome. Triggered ignition suppression systems are also being developed for use on continuous miners and longwall shearers for controlling frictional ignitions, but these too suffer from the same problems associated with triggered explosion barriers. In addition, they are difficult to retrofit to existing mining machines and will be difficult to maintain in operating condition. Results of field studies on the effectiveness of improved bit designs and cutting geometries in reducing the frequency of frictional ignitions are encouraging; the same is true for "water sprays" mounted behind the cutting bits for the purpose of cooling the hot spots responsible for ignition.

The overall direction in research on mine explosion prevention seems to be headed in the right direction, but it is disappointing that quantum improvements in the practice of rock dusting do not appear imminent.

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Les méthodes de sécurité utilisées : le poudrage minéral, les explosifs autorisés, les équipements électriques intrinsèquement sûrs, l'amélioration de la ventilation et l'amélioration des méthodes de détection des risques sont en grande partie responsables de la diminution remarquable du nombre des explosions minières. Toutefois, selon de récentes statistiques, le problème de la prévention des explosions minières subsiste toujours. Il y a également une préoccupation croissante concernant le nombre d'inflammations par an provoquées par la friction du méthane. Les recherches récentes sur la prévention des explosions portent tout particulièrement sur le poudrage minéral dont l'efficacité générale a été récemment mise en évidence. D'autres méthodes de protection contre les explosions comprennent la surveillance de l'explosibilité des poussières minières, ainsi que les protections anti-déflagrantes passives et actives. Nous examinons les inflammations par friction des fronts de taille ainsi que les moyens de les contrôler.

VERHÜTUNG UND UNTERDRÜCKUNG VON EXPLOSIONEN IN KOHLEGRUBEN

M. Sapko, N. Greninger, R. Watson

Zu den wichtigsten Sicherheitsfaktoren, die für den bemerkenswerten Rückgang der Explosionen in Kohlenzechen verantwortlich sind, gehören solche Maßnahmen wie das Einstauben mit Steinstaub, Verwendung von zugelassenen Sprengstoffen, eigensichere Elektroanlagen, verbesserte Bewetterung und eine Verbesserung in der Erkennung von Gefahrensituationen. Trotzdem zeigen neuere Statistiken, daß die Explosionsverhütung immer noch ein Problem ist. Auch wächst die Besorgnis wegen der jährlichen Anzahl von durch Reibung verursachten Methanentzündungen. Bei einer Betrachtung der neuesten Explosionsverhütungs-Forschung wird besonders auf das Einstauben und die kürzlich erhaltenen Beweise der Effektivität von Einstaubungs-Normen geachtet. Zusätzliche Explosions-Verhütungsmittel bestehen in Einrichtungen zur Überwachung der Explosivität des Grubenstaubes und passiv sowie aktiv ausgelöste Explosionssperren. Entzündungen durch Oberflächenreibung und ihre Beherrschung werden diskutiert.

ОБЗОРНЫЙ ДОКЛАД: ПРЕДОТВРАЩЕНИЕ И УМЕНЬШЕНИЕ СИЛЫ ВЗРЫВОВ В УГОЛЬНЫХ ШАХТАХ

М. Сапко, Н. Гренингер и Р. Вотсон

Среди главных факторов, способствующих значительному сокращению взрывов в шахтах, можно отметить запыление каменной пылью, применение рекомендованных взрывчатых веществ, взрывобезопасное электрическое оборудование, усовершенствованную вентиляцию и улучшенные методы слежения за возникновением опасных условий. Однако, согласно последним статистическим данным, предотвращение взрывов попрежнему остается проблемой. Все большее опасение внушает ежегодное количество воспламенений метана, вызванных трением. Особое значение во всех рассмотренных авторами исследованиях придается способу каменного запыления и недавно полученным экспериментальным доказательствам эффективности стандартов каменного запыления. Дополнительная защита от взрывов включает приспособления для слежения за взрывоопасностью пыли в шахтах, а также пассивные и быстродействующие противовзрывные барьеры. Обсуждается проблема воспламенения при трении и способы контроля.

评论文：煤矿爆炸的预防和抑止

М. 沙不柯， N. 葛兰宁格 及 R. 华特生

减少煤矿爆炸主要的安全因素为：撒石粉，使用准许用的炸药，本质上安全的电力设备，改进的通风设备，及改进的测定危险情况方法。但从最近的统计数字来看，煤矿爆炸仍是一个问题。而且美年甲烷摩擦引燃的事件也为数不少。最近防止爆炸的研究多着重在撒石粉和石粉标准与防止有效性的关系。另外爆炸的保护方法包括侦察煤尘的爆炸性，及无源和触发的爆炸栅栏。摩擦的表面引燃和它的控制亦在本文里讨论。



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OFR 27-89

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第23届采矿安全研究学院国际会议

**Washington, DC
September 11-15, 1989**

Organized by the U.S. Department of the Interior, Bureau of Mines