COAL DUST EXPLOSION BARRIERS

by

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ABSTRACT

The Bureau of Mines is conducting research to develop passive and triggered barriers to be used for protection against coal dust explosions. Commercially available passive water barriers were found adequate for defense against moderate strength explosions, fut failed, however, when the explosion propagated at speeds less than 76 m/sec. To expand the useful range of the passive barrier, the Bureau developed novel barriers for suppressing slow moving explosions traveling at speeds as low as 30 m/sec. A plan was written to install a passive barrier system in a working mine on a trial basis.

Two triggered barrier systems were tested against dust explosions. One uses a Cardox cylinder to discharge the suppressant, and the other uses low-pressure gas to power the disperser. Both systems have been demonstrated to be capable of suppressing coal dust explosions. The relative effectiveness of many extinguishing agents and the optimum conditions for explosion suppression were investigated. It is anticipated that a triggered barrier system will be introduced into a working mine on a trial basis within the near future.

INTRODUCTION

Coal dust explosions are a hazard in underground coal mining operations. The spreading of rock dust on mine surfaces to inert the coal dust has been the traditional means of controlling such hazards in U.S. mines. However, effective rock dusting is not feasible in a number of mine regions. Seven such potentially dangerous areas are (1) conveyor beltways, (2) transfer points, (3) wet roadways, (4) parked mine cars, (5) return airways, (6) longwalls, and (7) isolated sections. To augment current protection against explosions, the Bureau of Mines is conducting research to develop passive and triggered explosion barriers to be used as a supplement to rock dusting in these probable hazardous mine regions.

PASSIVE WATER BARRIERS

The passive water barrier, as tested and used abroad, is made up of numerous water-filled containers mounted in the vicinity of the mine roof. During a coal dust explosion, the dynamic wind pressures induced ahead of the propagating flame tilt or fragment the water containers to release and disperse the water, which acts to suppress the oncoming flame. However, foreign research indicates that the effectiveness of the passive water barrier is limited to moderate-strength explosions; the barrier fails when the explosion is weak

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because the wind forces are insufficient for fracturing or tipping the water containers.[2 3] The studies also show that the barriers are ineffective when positioned at distances closer than about 60 m from the explosion initiation. In recent work conducted at the Bureau of Mines,[4] a German-made water barrier (80-liter capacity, made of polyvinyl chloride [PVC]) was tested against coal dust explosions and found to be efficient in suppressing dust explosions propagating at speeds of 76 to over 300 m/sec. However, weak explosions propagating at less than 76 m/sec were not stopped. To expand the range of effectiveness of the passive water barrier system, the Bureau recently developed water barriers that operate during low-speed explosions and are described in another report.[5] The minimum quantity of water in the passive water barrier necessary to stop explosions in the Bureau's Experimental Mine (5.3 m^2 cross section) was 80 kg (15.1 kg/m^2 of cross section).

On the basis of experience with passive water barriers and the considerable knowledge gained from researchers abroad, a trial passive water barrier installation is being planned in U.S. mines.[6] The initial plan is to install a barrier system on a belt conveyor road just outby a loading station. This would protect the beltway from explosions originating prior to or in the loading zone. The barrier would begin just outby the loading region and consist of at least four rows of tubs. Each row is to be one crosscut apart and located near the center between two crosscuts. The quantity of water in each row of tubs would be equal to at least 26 l/m^2 of roadway cross section. As the section advances, new rows of tubs would be erected and the tub rows farthest outby can be removed.

TRIGGERED BARRIERS

Triggered barriers are a recent innovation. Research efforts are presently in force in the United States and abroad to develop prototypes. The triggered barrier typically consists of three components (1) a flame or explosion sensor, (2) a disperser, and (3) an extinguishing agent. The sensor is an optical, mechanical, or electronic device which activates or triggers the dispersal unit to rapidly expel the extinguishant. The extinguishant can be gas, liquid, or powder and it is contained in the disperser under a stored force. The sensor is located some distance from the dispersal unit to provide sufficient time for the dispersion of the extinguishing agent prior to flame

[2]Fischer, D., and H. Meerbach. New Tests With Water and Stone--Dust Barriers. 12th Internat. Conf. of Mine-Safety Res. Est., Dortmund, Germany, Sept. 11-15, 1967, No. 41, 29 pp.

[3]Meerbach, H. Investigations of the Development and Control of Coal Dust Explosions in Very Wide, Low Gate Roads. Internat. Conf. of Mine-Safety Res. Est., No. 138; Donetsk, Russia, June 15-18, 1971, 19 pp.; SMRE Trans. No. 5934.

[4]Liebman, I., and J. K. Richmond. Suppression of Coal-Dust Explosions by Passive Water Barriers in a Single-Entry Mine. BuMines RI 7815, 1974, 34 pp.

[5]Liebman, I., J. Corry, and J. K. Richmond. Water Barriers for Suppressing Coal Dust Explosions. BuMines RI 8170, 1976, 26 pp.

[6]Work cited in footnote 5.

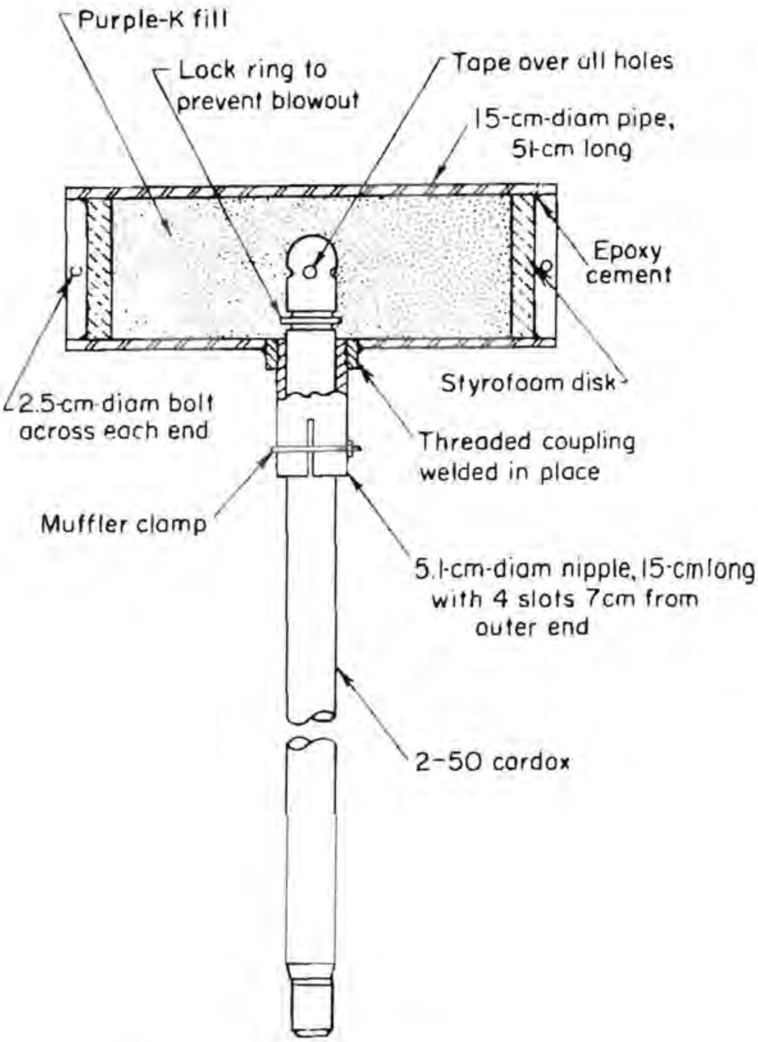

FIGURE 1. - Cardox triggered barrier disperser.

arrival at the barrier site. The triggered barrier is superior to the passive system in that the extinguishant can be discharged at an optimum time, and thereby it can be used more efficiently; dispersion of the material does not depend on the explosion-induced wind forces. Triggered barriers are expected to be most appropriate in low-coal operation where there is insufficient head room for passive barriers. The passive barrier, requiring explosion-induced wind forces for operation, is limited to use in open regions of the roadway and as such would interfere with operations in crowded mine regions. The triggered barrier, however, is not subject to this limitation and can be used in all regions of a mine.

CARDOX SYSTEM: NAVAL SURFACE WEAPONS CENTER STUDY

The Naval Surface Weapons Center (NSWC) at Dahlgren, Va., developed a barrier system based on a Cardox[7] Purple-K ($KHCO_3$) extinguishant device that was used to suppress float coal dust explosions under a variety of conditions.[8] Two facilities were used in the NSWC explosion suppression tests 1.4-m-wide by 97-m-long metal gallery, and a 762-m-long conical shock tube ranging in diameter from 0.4 m at its closed end to 7.3 m at the opening. One of the Cardox disperser units used in this study is shown in figure 1. The high-pressure carbon dioxide gas (about 1,000 atm) developed by the Cardox ejects the suppressant contained in the pipe in opposite directions to reduce recoil. The pipe holds 10 kg of Purple-K.

[7] Reference to specific brands is made for identification only and does not imply endorsement by the Bureau of Mines.

[8] Lull, D. D., L. D. Johnson, T. F. Morris, and J. A. Canfield. Final Report on Development of a System To Suppress and Extinguish Fully Developed Coal Dust Explosions. NSWC Tech. Rept. TR-3151, February 1975, 214 pp.

A number of tests in the 1.4-m-wide gallery, and in the conical shock tube, showed that maximum efficiency of the Purple-K powder was attained when the material was delivered directly onto the flame. The tests also indicated that the amount of Purple-K dust necessary to halt an explosion in a large-scale facility is comparable with the amount of dust needed in rock dust barriers.[9,10]

CARDOX SYSTEM: BUREAU STUDY

The Bureau continued the triggered barrier study using the Cardox system developed by the NSWC. The explosion suppression tests were conducted in the main entry of the Bureau's Experimental Mine at Bruceton, Pa. This is a single 396-m-long entry having an average cross section of about $5.3\ m^2$. The entry is instrumented with optical flame sensors, static pressure transducers, pitot probes, and drag probes. A complete description of the mine and instrumentation is given elsewhere.[11] Explosion initiation was accomplished by igniting a 6.5-pct natural gas-air mixture confined to the first 3 m from the face by a thin plastic diaphragm. In the next 3 m of entry--the booster zone--2.3 kg of pure Pittsburgh pulverized coal (PPC) dust was spread on two roof shelves. The test zone consisted of a PPC coal-rock dust mixture distributed from the end of the booster zone towards the portal with the mixture extending to or past the barrier site. The coal-rock dust test zone contained 65 to 67 pct inert coal rock dust. The weight of coal dust in the mixtures spread in the mine was sufficient to yield a concentration of 300 mg/l if dispersed uniformly throughout the entry cross section. Explosion tests in the mine, without barriers, indicated that the explosion will propagate two to three times the length of the test zone.

The barrier consisted of two to six Cardox units containing either Purple-K or water and placed on opposite ribs of the entry (fig. 2) 1.5 m apart starting 99 m from the face. These Cardox devices were modified versions of those in figure 1 in which the horizontal pipe containing the extinguishant was bent at its center to permit the material to exit at each end at an angle of 12° from the rib. The units were triggered by an infrared optical flame sensor placed upstream of the barrier site (either 84 or 91 m from the face); the flame sensor tripped a relay to fire the Cardox ignitor.[12] The time of extinguishant discharge start was noted by a break wire attached to each Cardox outlet. Preliminary tests showed the Cardox unit began to discharge the

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[9]Grumer, J. Recent Research Concerning Extinguishant of Coal Dust Explosions. 15th Internat. Symp. on Combustion, the Combustion Institute, Pittsburgh, Pa., 1975, pp. 103-114.

[10]Rae, D. Experimental Coal-Dust Explosions in the Buxton Full-Scale Surface Gallery. SMRE Tech. Paper P7, 1973, 71 pp.

[11]Work cited in footnote 4.

[12]The Bureau has also developed a triggering system using a pressure-arming device and a dual infrared optical flame sensor combination. The pressure-sensing element prevents false triggering by switching on battery power when the static pressure rises about $3.5\ kN/m^2$; each flame sensor views a separate narrow vertical field approximately 25" apart and must operate in coincidence to turn on a firing relay.

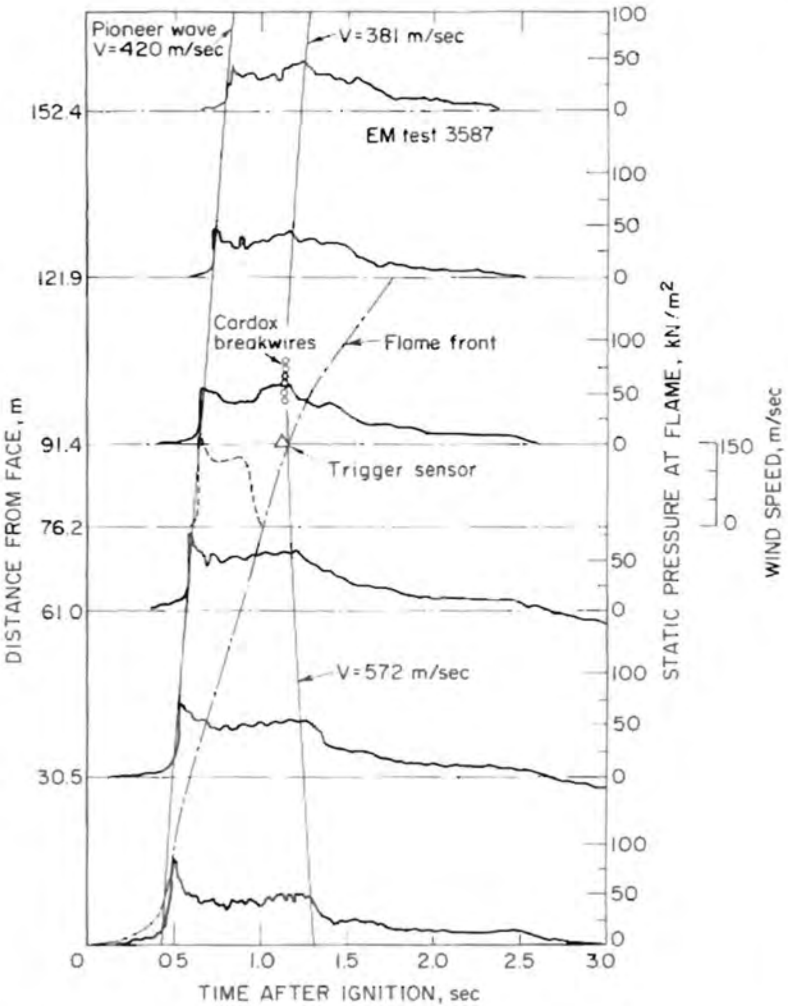

FIGURE 2. - Cardox barrier mounted near rib of Experimental Mine.

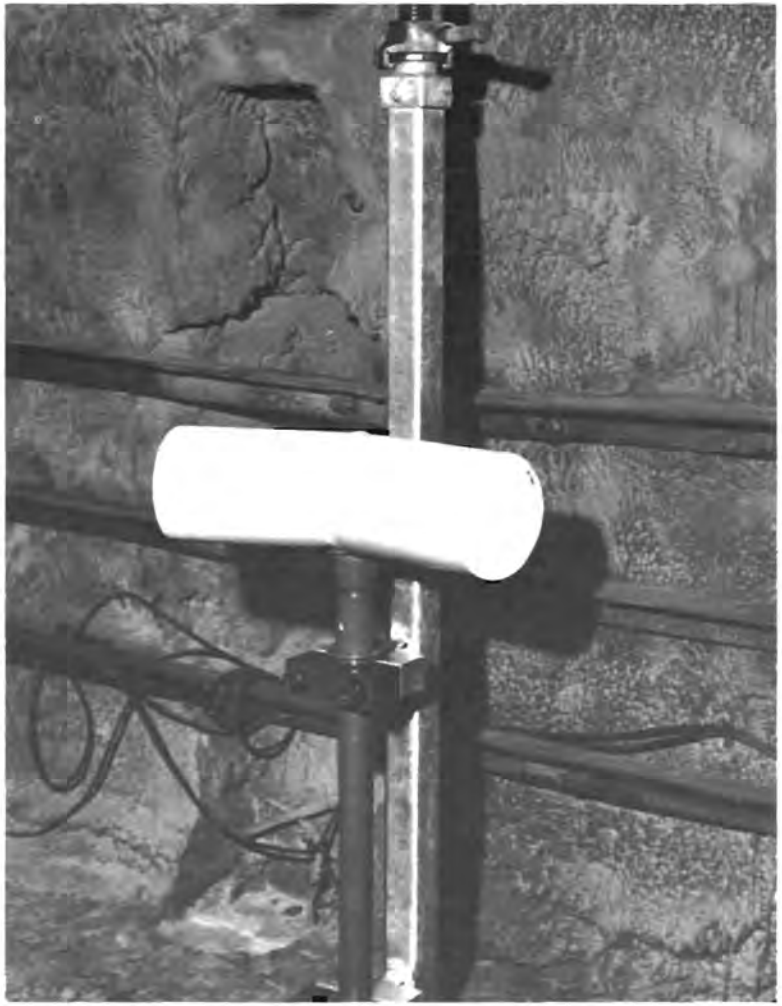

FIGURE 3. - Wave diagram of coal-dust explosion and suppression by six Cardox dispersers placed 99 to 107 m from mine face. EM test 3587.

extinguishant about 25 msec following the triggering pulse, and the extinguishant cloud filled the mine cross section in an additional 30 to 50 msec. Time for most of the material to be expelled from the barrier was estimated to be less than 50 msec.

The objective of the tests were to determine the effectiveness of the Cardox system against dust explosions, the relative effectiveness of Purple-K against water, the minimum quantity of extinguishant required for suppression, and the optimum time for extinguishant discharge. Test variables were the type and quantity of extinguishant, and the time interval between extinguishant discharge and flame arrival at the barrier.

A wave diagram illustrating explosion extinguishment and its effect on flame and pressure development is shown in figure 3; particular attention should be given to the strong compression waves driven in both directions from the vicinity of the barrier site generated by the sudden deceleration and suppression of the flame. Test conditions and results for all the tests are summarized in table 1. For similar test conditions, without a barrier, the flame was always observed to go beyond the last optical flame sensor located 198 m from the face. In the remarks section of table 1, "no suppression" is indicative of a test in which the flame propagates beyond this point. In the tests interpreted as "explosion suppressed" the flame was not observed to propagate past a flame sensor located 122 m from the face (18 m beyond the barrier), whereas tests in which the flame was stopped past the 122-m location but before 198 m were arbitrarily chosen to be "marginal suppression." In test 3587, 60 kg of Purple-K was necessary to suppress the explosion rapidly. In tests 3585 and 3588, 40 kg of material resulted in a marginal suppression, and in test 3589, 20 kg had little effect on the explosion. The optimum time to discharge the powder is about 50 to 100 msec prior to flame arrival (tests 3587 and 3588); this agrees with the NSWC study that the dust should be injected onto the flame for maximum efficiency. When the dust is released prematurely (tests 3585-3586), the flame must propagate some distance past the barrier to reach the extinguishant cloud. The short discharge time (less than 50 msec) inherent to the Cardox seems to be the principal reason for the brief time requirements between extinguishant release and flame arrival. Since exact timing would be impossible to achieve for a wide range of explosion speeds, an effective Cardox barrier must be redundant and consist of many units to cover a considerable length of entry. Table 1 shows that water is at least as effective as Purple-K.

TABLE 1. - Summary of explosion suppression tests in EM with Cardox dispersers

Test No.	Length of test zone, m from face	Extinguishant	No. of Cardox units[1]	Distance of barrier from face, m	Distance of trigger sensor from face, m	Interval,[a] sec	Flame speed at barrier site, m/sec	Remarks
3585	107	Purple-K	4	99 to 104	84	0.36	101	Marginal suppression, flame to 152 m.
3586	107	...do...	6	99 to 107	84	.18	152	Marginal suppression, flame to 162 m.
3587	107	...do...	6	99 to 107	91	.10	140	Explosion suppressed, flame to 122 m.
3588	107	...do...	4	99 to 104	91	.05	149	Marginal suppression, flame to 137 m.
3589	107	...do...	2	99 to 102	91	.10	156	No suppression, flame past 198 m.
3590	107	Water...	4	99 to 104	91	-	-	Explosion suppressed, flame to 122 m.
3591	107	...do...	2	99 to 102	91	.10	110	Marginal suppression, flame to 137 m.
3594	107	...do...	2	99 to 102	91	.10	110	Do.
3595	107	Purple-K	2	99 to 102	91	.08	158	No suppression, flame past 198 m.

[1] Each Cardox is filled with 10 Kg of extinguishant.

[a] Time from the beginning of extinguishant discharge to flame arrival at barrier site, measured at the front of the barrier.

LOW-PRESSURE-POWERED DISPERSER

The Cardox develops considerable pressure forces and would be hazardous to mine personnel in its immediate vicinity if triggered inadvertently. Therefore, this device cannot be considered for use in underground mines without modification. Prior to making this effort, it was convenient to conduct experiments with a low-pressure-powered disperser. This disperser (fig. 4) is part of a Fenwal explosion protection system and is readily controlled to yield low external forces and longer discharge times than the Cardox system. The spherical vessel is approximately 33 cm in diameter and was found to operate satisfactorily when 70 pct filled with water or completely filled with Purple-K with the void space pressurized with a gas. The material was released at the base of the vessel through a 7.6-cm-wide burst diaphragm (detonator operated) and then exited through a multihole nozzle or a 7.6-cm-wide pipe. Peak pressures averaged over the spray cross section and measured

FIGURE 4. - Low-pressure-powered disperser.

90 cm in front of the nozzle during discharge of water from a Fenwal vessel pressurized to 1,380 kN/m² did not exceed 2 kN/m²; such pressures could be tolerated by personnel if the disperser were accidentally fired. Tests indicated that discharge began about 15 msec following an electrical pulse to the detonator, and the majority of water or dust was released in about 0.2 sec for the nozzle and less than 0.15 sec for the 7.6-cm-wide pipe exit.

In explosion suppression trials in the main entry of the Experimental Mine, two spherical vessels were positioned on opposite ribs at 99 and 101 m from the face with the trigger (flame) sensor located upstream at either 72 or 87 m. Preparations for the explosions were similar to those in previously described Cardox tests--the test zone now being PPC mixed with 65 pct rock dust spread along the entry to 107 m from the face. Table 2 shows the test results. In test 3617, less than half of the water was injected in front of the flame and the explosion was stopped; whereas in test 3618 using Purple-K and about the same initial conditions, the explosion was not suppressed. For tests 3624 to 3626, an attempt was made to increase the Purple-K concentration in the entry by increasing the quantity of dust in the vessels and decreasing the discharge time (outlet changed from nozzle to pipe). Practically all the dust was released immediately behind the flame front (test 3625), and the explosion continued to propagate past 198 m. In test 3626, all of the dust was injected immediately prior to the flame front, and suppression was still not attained. The barrier was accidentally triggered (not caused by any reaction within the mine) after completing preparations of the entry for explosion test 3624; the extinguishant powder was carried along the entry to form a layer on the coal-rock dust mixture spread on the mine floor and rib-roof and it extended from 77 to 107 m from the face. The dust explosion, initiated an hour later, propagated past the last flame sensor at 198 m without any appearance of being influenced by the extinguishant powder. Suppression of explosion was again obtained with only 27 kg of water (test 3627), whereas for similar test conditions (nozzle and discharge time) and for 41 kg of Purple-K (test 3629), suppression was not achieved.

TABLE 2. - Summary of explosion suppression tests in EM with nitrogen gas-powered disperser

Test No.	Length of test zone, m from face	Extinguishant,[1] total quantity	Discharge outlet[2]	Distance of barrier from face, m	Distance of trigger sensor from face, m	Interval,[3] sec	Flame speed at barrier site, m/sec	Remarks
3617	107	Water 27 kg.	Nozzle.	99 to 101	87	0.06	169	Explosion suppressed, flame to 122 m.
3618	107	Purple-K, 27 kg.	...do..	99 to 101	87	.06	183	No suppression, flame past 198 m.
3624[4]	107	Purple-K, 41 kg.	Pipe...	99 to 101	-	-	-	Do.
3625	107	Purple-K, 41 kg.	...do..	99 to 101	87	.02	165	Do.
3626	107	Purple-K, 41 kg.	...do..	99 to 101	72	.14	189	Do.
3627	107	Water, 27 kg.	Nozzle.	99 to 101	72	.21	189	Explosion suppressed, flame to 122 m.
3629	107	Purple-K, 41 kg.	...do..	99 to 101	72	.27	122	No suppression, flame past 198 m.

[1] Two barrier units mounted on opposite ribs, each containing equal quantity of extinguishant.

[2] Extinguishant discharged through a 10-cm-wide multihole nozzle or a 7.6-cm-wide pipe outlet.

[3] Time from beginning of extinguishant discharge to flame arrival at barrier site.

[4] Extinguishant accidentally discharged prior to initiating explosion in test 3624.

Table 2 shows that the time interval between barrier discharge and flame arrival is not a critical factor for the case of water; it is observed to range from 0.06 to 0.21 sec without a loss in barrier efficiency. Also, water seemed to be significantly superior to Purple-K in this trial series. The excellent success obtained in test 3617 may indicate that optimal conditions are obtained when a portion of the water is injected after flame arrival. Comparing tables 1 and 2, it seems that Purple-K has a higher degree of effectiveness when used in the Cardox system. This may be attributed to the increased Cardox barrier length, the increased quantity of powder (test 3587), and probably of greater importance, the extremely high discharge rate of the Cardox system. The last factor would decrease the time to fill the entry cross section with a higher concentration of extinguishant. Why water performed better than Purple-K in these trials is not clear.

Pure PPC was used in the test zone for the next series of explosion suppression experiments. This was expected to increase the flame temperature over that obtained with the previous coal-rock test zone and in turn increase the efficiency of the Purple-K suppressant. The relative effect of water, Halon 1301 (CF_3BR), and hybrid extinguishing agents (aqueous foam solution or water combined with Halon 1301) was also examined. These hybrid mixtures had previously been shown to be excellent suppressants against gas flames. Preparation for the explosions were similar to previous trials except for the substitution of pure PPC in the test zone using a nominal dust concentration of 75 mg/l. Two Fenwal vessels containing the suppressants were again positioned on opposing ribs of the mine entry, and the infrared trigger sensor was placed 11 to 21 m inby; table 3 summarizes the results. The Fenwall vessels were pressurized with either nitrogen (1,400 to 2,000 kN/m^2) or Halon 1301 (vapor pressure 1,350 to 1,450 kN/m^2). A pipe discharge outlet was used in the trials with Purple-K to obtain high discharge rates shown to be an important factor in suppressant effectiveness in the Cardox trials. Results of the first three trials of table 3 (two marginal and one successful suppression) is a much better record for Purple-K than noted in the trials of table 2. However, the following test 3727 shows that less than half of the weight of water has an equal or greater suppressant effect. This confirms previous observations that Purple-K is inferior to water as a suppressant of coal dust explosions. Decreasing the water quantity in test 3694 of table 2 resulted in a marginal suppression indicating this to be a minimal amount of water. The failure of test 3723 is attributed to an electronic error resulting in a zero time interval. The two hybrid combinations (tests 3724 and 3725) and pure Halon (test 3728) stopped the flame at 122 m versus 107 m for water (test 3727). Since equal weights of extinguishants were used in all four tests, it would appear that the hybrids and pure Halon are no better than just water.

TABLE 3. - Summary of explosion suppression tests with nitrogen or halon powered disperser

Test No.	Length of test zone,[1] m from face	Extinguishant and pressure agent[2]	Discharge outlet	Distance of barrier from face, m	Distance of trigger sensor from face, m	Interval, sec	Flame speed at barrier site, m/sec	Remarks
3679	49	Purple-K, 36 kg--N_2	Pipe.....	32 to 34	21	0.09	138	Marginal suppressed, flame to 61 m.
3681	95	Purple-K, 36 kg--N_2	...do....	32 to 34	21	.10	112	.....do.......
3682	95	Purple-K, 36 kg--N_2	...do....	32 to 34	21	.12	64	Suppression, flame to 33 m.
3727	104	Water, 15 kg--N_2...	Nozzle...	99 to 101	76	.13	143	Suppression, flame to 107 m
3694	95	Water, 13 kg--N_2...	...do....	99 to 101	76	.08	183	Marginal suppressed, flame to 152 m.
3723	105	Foam, 10 kg; Halon, 5 kg.	...do....	99 to 101	79	.0	168	No suppression, flame beyond 198 m.
3724	104	Foam, 10 kg; Halon, 5 kg.	...do....	99 to 101	76	.15	91	Suppression, flame to 122 m
3725	104	Water, 10 kg; Halon, 5 kg.	...do....	99 to 101	76	.16	137	Do.
3728	104	Halon, 15 kg.......	...do....	99 to 101	76	.14	107	Do.

[1] Test zone--pure PPC, 75 mg/l nominal loading.

[2] Two barrier units on opposite mine ribs. Total quantity of extinguishant listed. N_2 pressure 1,400 to 2,000 kN/m^2. Halon vapor pressure 1,350 to 1,450 kN/m^2.

SUMMARY AND CONCLUSIONS

Commercial passive water barriers were tested and found effective in stopping moderate strength coal dust explosions; they failed, however, for explosions propagating at less than 76 m/sec. To extend the range of effectiveness of the passive barrier, novel barriers were developed and shown to be efficient in suppressing weak explosions propagating at speeds as low as 30 m/sec.

Two triggered barrier systems were investigated. One barrier uses a Cardox cylinder to propel the extinguishant, and the second system used pressurized nitrogen gas or Halon 1301 to power the disperser. With the former barrier, 40 kg of water or 60 kg of Purple-K ($KHCO_3$) was sufficient to suppress coal dust explosions propagating in a mine entry of 5.3 m^2 cross section. In the nitrogen powered barrier, as little as 15 kg of water or 36 kg of Purple-K was required to stop an explosion. The time interval between barrier discharge of the extinguishant and the flame arrival at the barrier site is not a critical factor for water as it is for Purple-K; the latter effectiveness is maximized when the powder is injected onto the flame. Relative to weight of extinguishant required for explosion suppression, the tests indicated water is more than twice as effective as Purple-K and at least as effective as hybrid mixtures (aqueous foam solution combined with Halon 1301) or pure Halon.

Low cost is the principle advantage of the passive barrier over the triggered system. However, the passive barrier is restricted to use in open regions of the mine because it depends wholly on wind forces for the operation and dispersion of the extinguishant. In addition, it is not effective when positioned too close or too far from the explosion initiation; therefore, the system must be redundant using many units to protect an entry. The triggered barrier is superior to the passive in that the extinguishant can be discharged at an optimum time and thereby be used more efficiently. Therefore, this barrier can be smaller and use fewer units. Since wind forces are not essential for operation, the triggered barrier is applicable throughout the mine and can be placed in crowded mine regions without interfering with mining operations.

Because of the hazards associated with the Cardox barrier and the good results obtained with the low-pressure nitrogen powered dispersal unit, the latter system is the most attractive prototype. There is little doubt from the present study that water is superior to Purple-K as an extinguishant. A recent but still incomplete study of additional powder extinguishing agents indicate that materials such as NaCl, KCl, and $NH_4H_2PO_4$ may be equal or better than water in suppressing coal dust explosion. However, the corrosive nature of these materials and the increased costs would prohibit their use over water.

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