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Active Barrier Performance Preventing Methane Explosion Propagation

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ACTIVE BARRIER PERFORMANCE PREVENTING METHANE EXPLOSION PROPAGATION

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ABSTRACT: Over the past century, the coal mining industry experienced a large number of explosions leading to a considerable loss of life. Research was directed at preventing the accumulation of methane through good ventilation practice, eliminating frictional sparking by the use of water, minimising dust generation and dispersal, and using stone dust to inert coal dust to prevent it from participating in mine explosions. The final line of defence, though, is the use of barriers to prevent a coal dust explosion from propagating. However, the design of passive explosion barrier systems has remained unchanged for many years. The traditional stone dust and water barriers were originally designed and developed as much as 50 years ago. In the 1990s the CSIR of South Africa developed a new type of stone dust explosion barrier, which has been implemented in South Africa and Australia. This barrier is considered to be better suited to modern-day mining practice. It is based on an array of specially manufactured bags holding stone dust and suspended from the mine roof.

Preventing the propagation of methane or coal dust explosions through the use of active explosion-suppression systems remains one of the most underutilised explosion controls in underground coal mines. As part of the effort to develop better technologies to safeguard mines, the use of active barrier systems was investigated at Kloppersbos in South Africa. The system is designed to meet the requirements of the European Standard (EN 14591-4:2007) (European Standard, 2007), as well as the Mine Safety Standardisation in the Ministry of Coal Industry, Coal Industrial Standard (MT 694-1997) of the People's Republic of China.

From the tests conducted, it can be concluded that the HS Suppression System was successful in stopping flame propagation for a methane explosion, as well preventing methane explosions from progressing into methane and coal dust hybrid explosions when ammonium phosphate powder was used as the suppression material. The use of this barrier can provide coal mine management with an additional explosion control close to the point of ignition and may find application within longwall faces, further protecting mines against the risk of an explosion propagating.

INTRODUCTION

Since the 1930s, increased use of mechanised mining machinery exacerbated the risk of frictional ignitions in working headings in which the interaction of cutting tools with quartz bands can result in incendive sparking capable of igniting methane. In recent times the introduction of powerful coal winning machines has further increased the number of frictional ignitions. For example, the mine disaster at Glace Bay, Nova Scotia, in 1979 claimed 12 lives. This explosion was attributed to a frictional ignition and the 1993 explosion at Middelbult Colliery in South Africa was also found to be the result of friction at a continuous miner pick. Many safety measures were researched and developed during the last century. Of these, the following have been instrumental in reducing the frequency and severity of explosions:

- The mixing of inert material with coal dust deposits
- Explosion barriers, both active and passive
- Knowledge and understanding of explosions and their prevention
- Development of permitted explosives
- Flameproofing of electrical apparatus and the use of intrinsically safe electrical circuits
- Improved ventilation practices
- Improved devices for the detection of flammable gases.

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Research conducted by Philips (1995) concluded that in South African mines an explosion starts at the working face where methane accumulations may occur during the coal-cutting activities. Although intense research attention has been paid to the development of preventive and protection measures against coal mine explosions, disasters still occur.

"Of all the risks inherent in coal mining, the one most feared by coal miners is an explosion. Explosions are not the biggest cause of loss of life. On a statistical basis, explosions may be amongst the less frequent events in mining causing loss of life but, apart from fires and flooding, there is no other cause capable of wiping out the entire workforce below ground at the time." These words, written by Joseph Dickson, an Inspector of Mines in the Lancashire coalfield, United Kingdom, in 1850 remain equally valid today.

In this paper a summary of the development and evaluation work done utilising the ExploSpot active suppression system against methane gas explosions developing into coal dust explosions will be described.

BACKGROUND

According to Du Plessis and Späth (2002), the aim of using active suppression systems is to contain the methane flame in the immediate vicinity of the ignition. This will prevent a methane explosion from developing which, in turn, could be the ignition source of a coal dust explosion. Active suppression systems have the following main components:

- Detecting sensor/s
- Electronic control and self-checking system
- Dust containers
- Flow nozzles.

These individual components are combined into systems, which are mounted on continuous heading machines. When an ignition occurs, its presence is detected by means of the sensor/s. These sensors are normally sensitive to the ultraviolet light range. An electronic signal from the sensor triggers the suppression system, creating a barrier of flame-suppressing material and containing the flame in the immediate vicinity of initiation. The flame-suppressing material most frequently used is ammonium phosphate powder, but gases such as NAF SIII chemical fire extinguishing agent may also be considered.

There are two testing facilities for the evaluation of these systems, namely the tunnel at BVS-Derne in Bochum, Germany, and the 20 m tunnel at Kloppersbos, South Africa. A number of systems have been developed by the Deutsche Montan Technologie (DMT) (Faber, 1990) for roadheaders. These have been in underground use since 1989 and are well proven and trusted. A test facility capable of testing such systems against a set protocol (Du Plessis, 1998) was built and completed during 1995 at the CSIR's Kloppersbos Research Facility. The facility simulates the various mining configurations encountered in bord-and-pillar mines. To date, three systems have undergone successful evaluations. The first system was developed for low-seam continuous miners (Du Plessis, 2001) and the second for a Dosco 1300H auger-type roadheader (Du Plessis, *et al*., 1999) capable of excavating a seam height of up to 4.5 m. The third system was the ExploSpot system (Du Plessis and Späth, 2001) for medium seam conditions and some of the results will be discussed in the paper.

The second system is used in mining conditions where the roof slopes at an angle of 12 degrees and a double-pass mining method is employed. For this specific evaluation, the maximum height of the roof was 4.5 m. The system was deployed at the HBCM mine in the south of France (Du Plessis and Van Dijk, 2001).

Description of system and components

ExploSpot is an intrinsically safe, high-speed flammable gas-ignition detection and suppression system capable of creating an extinguishant barrier within 100 milliseconds.

The ExploSpot system consists of three main components, namely the control electronics, the dual-spectrum sensor units and the discharge assemblies. The control electronics are connected to the peripheral sensor units and discharge assemblies, constantly monitoring the connections so that the system will always be functional when required. The sensor units are placed to monitor the entire tunnel area for any methane ignition or coal dust flame. These units are specially designed to react only to certain light wavelengths specific to burning methane and coal dust, thus reducing the risk of a false ignition. The discharge assemblies are configured for the particular conditions found within a specific mine, the cross-sectional area of the tunnel and the method of coal extraction being applied. They are also configured to ensure the correct powder distribution and concentration for the successful extinguishing of any explosion or ignition.

The system is designed to meet the requirements of the European Standard (EN 14591-4:2007), as well as the Mine Safety Standardisation in the Ministry of Coal Industry, Coal Industrial l Standard of the People's Republic of China (MT 694-1997). It is also designed to comply with the International Standards (IEC) to meet the intrinsically safe and flameproof standards: IEC 60079-11:1999 and IEC 60079-0:2005 for intrinsically safe equipment, and IEC 60079-0:2004 and IEC 60079-1:2004 for flameproof equipment.

The severity of an explosion is directly related to the rate of flame propagation (Cashdollar and Hertzberg, 1989). Figure 1 shows a typical methane gas flame propagation speed and distance plot.

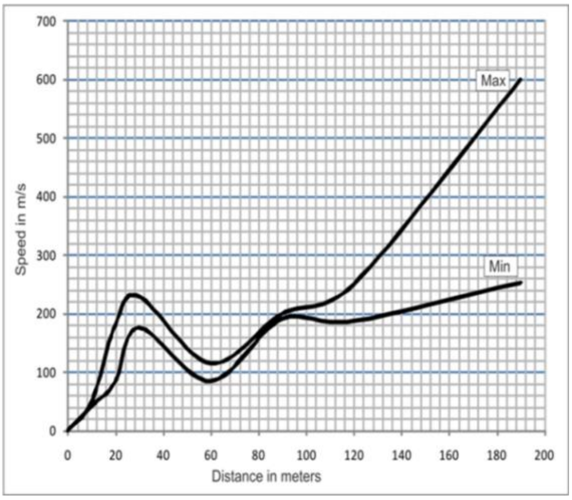

Figure 1 - Typical plot of gas explosion speed versus distance

As such the design of any active barrier system requires rapid and accurate response and distribution of flame suppressant material.

TYPES OF SYSTEM

Machine-mounted systems

The objective of suppressing methane ignitions within the face area where frictional ignition caused by the mining of coal occurs can be achieved by using machine-mounted systems. These systems detect the ignition of methane caused by the continuous miner or roadheader picks. They will also detect any other ignition sources (e.g. electrical) and will prevent the methane ignition from propagating within the face area. Modern continuous miners utilise a combination of systems to prevent a methane gas ignition from occurring: the use of flameproof equipment, ventilation of methane gas from the face and around the continuous miner (CM), a wet cutter head and active suppression barriers. Figure 2 shows the components of a CM ExploSpot system.

Roadway systems

The use of an active barrier system for inbye protection, close to the face area, has the additional advantage that it is capable of protecting outbye areas by preventing methane explosions from developing into coal dust explosions. Furthermore, it does not require any dynamic pressure build-up for activation as activation is dependent on flame detection. Figure 3 shows a graphical representation of all the system components. This includes the complete unpacked system of detectors, controllers, high-pressure bottles and spray bar and nozzles.

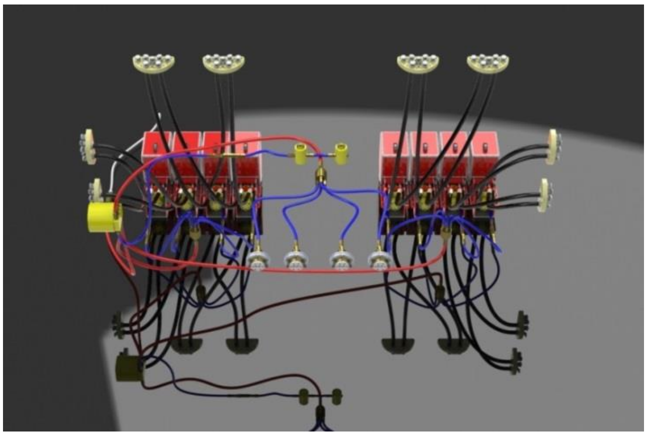

Figure 2 - Typical continuous miner layout for the ExploSpot system

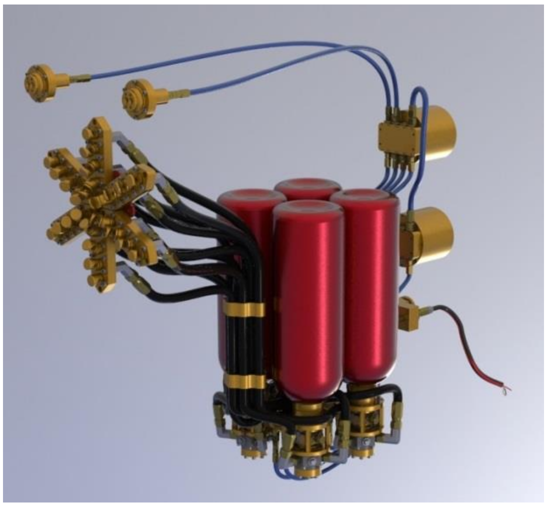

Figure 3 - Graphical representation of the active barrier system components Testing facilities and Evaluations

10 m test tunnel results

The objective of the test work was to investigate the operational effectiveness of the triggered barrier system in stopping the methane/coal-related explosions that can occur during typical auger mining operations and to demonstrate its effectiveness to Auger mining of South Africa AMSA, DME and the coal mining industry (Moolman, *et al*., 2006). Tests were conducted in the 10 m explosion test tunnel to determine the effectiveness of the triggered barrier system in stopping propagating methane explosions, simulating flame exiting from the opening of a production hole. Employees of HS Design Engineering undertook the set-up of the suppression system 1.5 m outside the 10 m tunnel, while CSIR employees prepared the tunnel for testing. Only ammonium phosphate powder was used as the suppression agent.

The evaluation simulated a typical auger operation set-up as far as practically possible. In order to test the system under the most severe conditions, no auger flights were placed in the 10 m tunnel. In the auger mining application, the active suppression system can only be mounted on the auger outside the production hole, thus far away from the cutter head. As the cutter head is most likely to be the only ignition source and the auger hole the only roadway for the ignition to propagate in, it can be expected that the explosion would exit the auger hole in due course. This is, however, dependent on the amount of fuel and oxygen available and on the amount of confinement achieved by the number of auger flights trailing the cutter head.

The 10 m test tunnel had previously been erected at the CSIR's Kloppersbos Research Facility for the purpose of testing machine-mounted active suppression systems. This tunnel was used to simulate the dimensions of an auger hole, and a full-scale model of the triggered barrier system was constructed 1.5 m in front of the tunnel opening for test purposes. The Kloppersbos explosion tunnel is 10 m long, with a diameter of 2 m. It is raised 700 mm above a cement floor with one side is sealed off by a steel plate. During a suppressed explosion, the steel plate acts as an emergency pressure-release mechanism in the event of very high pressures building up in the tunnel (see Figure 4 which shows the 10 m test tunnel with an explosion-stopping wall built over it). During normal tests, the pressure wave and the flame exit the mouth of the tunnel unhindered.

Figure 4 - 10 m test tunnel at Kloppersbos

In one test a fuse cap was used to ignite the methane/air mixture. In all the other tests a shielded detonator was used to ignite the flammable gas mixture. The fuse cap was initially chosen for use as it produced a flame that would not be seen or recognised by the triggering mechanism of the suppression system. The detonator was shielded from the triggering system; the reason for using it was to create a more violent methane explosion. The chamber containing 23 m^3 of methane/air mixture was obtained by placing a plastic membrane 7 m from the closed end of the tunnel. This amount of methane/air mixture will produce enough wind pressure to lift the coal dust into the air, supply sufficient heat to the coal dust particles for flame propagation to take place and be sufficient to ensure flame growth up to 5 m beyond the tunnel mouth.

For most of the active suppression system tests conducted in the 10 m test tunnel, an explosion mixture of 9% methane/air per volume was used. This was done to test the triggered barrier system under simulated worst-case scenarios. A small amount of coal dust was placed on racks at the open end of the 10 m tunnel. The main reason for adding this dust was to change the colour of the methane flame to assist in the visual evaluation of the system's success or failure. The amount of coal dust used did not change the characteristics of the explosion.

The measure of success was defined to indicate whether the flame propagation was stopped inside the tunnel opening (referred to as "stopped inside"). The results of the methane explosion tests are shown in Table 1:

In every test the flame was stopped at the tunnel opening, with no flame visible from the front and perpendicular to the tunnel. Each explosion was further captured on camera, and a record of the photos and the video material was used to evaluate the success of the flame suppression.

The ExploSpot system registered a methane ignition and opened the extinguishing cylinders within 20 ms. The suppressing agent sealed off the tunnel opening completely within 30 ms, preventing the flame from penetrating the suppressant material. During these tests the suppressing agent was initially dispersed at high pressure (stored at 60 MPa in the cylinder) and velocity into the propagating flame front. From the tests conducted, it was concluded that the machine-mounted ExploSpot system was successful in stopping a methane flame in the tunnel opening.

Table 1 - Results of the performance of the ExploSpot system

Test No.	Methane concentration	Initiator used	Visible flame	Comments
1	7.5%	Detonator	None	One cylinder failed, flame stopped successfully
2	9%	Detonator	None	Flame stopped successfully
3	9%	Detonator	None	Flame stopped successfully
4	9%	Fuse cap	None	Flame stopped successfully
5	12%	Detonator	None	Flame stopped successfully
6	9%	Detonator	None	Flame stopped successfully. Small flame could be seen at the back of the tunnel.

20 m test tunnel: Facility for testing machine-mounted systems

A 20-m test tunnel was erected at the Kloppersbos Research Facility to suit the double-pass mining method associated with the use a continuous miner. The protocol for testing the ExploSpot system was developed by a forum including representatives from industry, government and labour organisations. The tests were carried in accordance with a protocol developed by the CSIR for such testing (Du Plessis, 2001). This protocol drew on experience with a similar protocol which had been accepted by the South African Safety in Mines Research Advisory Committee (Du Plessis, *et al.,* 1999) for previous tests, as well as a protocol accepted by INERIS of France (Du Plessis, 1998).

The protocol defines acceptance criteria in accordance with which the results of the tests would be either accepted or rejected, and the tests themselves either passed or failed (Du Plessis, 2001). The protocol stipulates the following acceptance criteria:

- The flame should not propagate along the tunnel in line with the operator's position – so that the operator is not exposed to any direct flame.
- The temperature increase at the operator's position should not exceed human tolerance levels (in this case 100 ^{o}C for less than half a second).
- Both the dynamic and static pressures measured should be within human tolerance limits.
- There must be no false triggering of the system due to other equipment being used underground.
- The system should be up and running again within eight hours of a detonation.

This tunnel was modified to simulate the dimensions of mine workings of medium seam height, and a full-scale model of the Joy 12HM9 continuous miner was used for test purposes. The test tunnel is 20 m long and 7 m wide, with a variable height of 2 to 6 m. It has a cement floor and springs along both sides, on the outside, supporting and guiding it. For the case of an unsuppressed explosion, the tunnel is able to lift up to 140 mm off its base to provide an alternative escape route for the expanding gases. For the full-face conditions, the cross-sectional area was approximately 21 m^2. Later, after the full-face tests had been completed, a shoulder was built into the left front of the test tunnel to simulate the out-shoulder conditions. A 4 m-long shoulder was built into the right-hand front corner of the tunnel to simulate the two-cut scenario where the machine was mining next to the shoulder.

In accordance with the protocol (Du Plessis, 1998), the test sequence was carried out in order of ascending difficulty. Three main placements of the machine inside the tunnel were tested, as well as sub-conditions for the placements of the boom (and thus ignition) for these machine positions, and, of course, the various methane concentrations. The testing began with the 9% methane/air explosion for full-face conditions (see Table 2). This was successful, with no flame being detected along the right-hand wall of the tunnel (the operator's cab position is on the right-hand side of the machine). Some flame was, however, detected at the roof and along the left-hand wall of the tunnel.

The pressure rises caused by the explosion were so small that they were almost zero. For these tests, the highest temperature rise at the operator's position was approximately 93 ^{o}C. The operator and the rest of the crew working at the face would be safe under the worst possible conditions.

Once the full-face tests were complete, a 4-m shoulder was put in place against the front right-hand wall of the tunnel, simulating the second cut. The machine was moved in adjacent to this wall for the in-shoulder tests. The results of these tests are shown in Table 3.

Table 2 - Full-face active suppression test results

Test	CH_4/air (%)	Flame length (m)	Temp. increase (°C)
77	9.0	6	80
78	9.0	6	NR*
79	9.0	6	93
80	9.0	6	70
81	9.0	6	NR*
82	12.0	5	58

* NR = no temperature rise

Table 3 - In-shoulder active suppression test results

Test	CH_4/air (%)	Flame length (m)	Temp. increase (°C)
92	9.0	6	33
93	9.0	3	33
94	9,0	4	33
95	9.0	5	33
96	12.0	5	33
97	9.0	5	33

For the in-shoulder testing, all tests complied with the protocol, with the system successfully suppressing all the explosions for the different ignition (and machine-boom) positions. For this series of tests, the highest temperature rise measured at the operator's cab was approximately 33 ^{o}C, and once again the pressure sensors detected almost no pressure variations due to the explosion. In none of the cases was any flame detected at the operator's cab position.

For the final series of tests, the machine was pulled out from next to the shoulder, and the boom moved to simulate cutting the shoulder. The results of these tests are shown in Table 4.

Table 4 - Out-shoulder active suppression test results

Test	CH_4/air (%)	Flame length (m)	Temp. increase (°C)
85	9.0	8	100
86	9.0	7	96
87	9.0	8	100
88	12.0	8	81
89	9.0	8	98
90	12.0	8	32
91	7.5	6	32

The tests were completed uneventfully for all the given positions and different concentrations for the out-shoulder machine conditions. The maximum length of the flame extension was 8 m (the operator's position was now at 9 m for the out-shoulder tests). Once again, the pressure sensors detected almost no pressure changes.

The system proved itself to be effective in detecting and suppressing explosions when configured and mounted on a Joy 12HM9 model for a cross-section with an area of approximately 21 m^2. To test the system for South African medium-seam mining conditions, a second mining cut was simulated, resulting in a potential increase in the explosive volume of methane. The ExploSpot system complied effectively with all the requirements of the test protocol.

200 m test tunnel: Facility for testing roadway barriers

The 200-m test tunnel was used to conduct various tests. A comprehensive description of the tunnel was given by Cook (1993). The test tunnel was instrumented with flame sensors and a data acquisition system for the evaluation. The tests were conducted with and without coal dust present. The different baseline explosions were:

- Baseline 1: 75 ± 1 m^3 methane/air mixture without coal dust
- Baseline 2: 75 ± 1 m^3 methane/air mixture with coal dust

For the ExploSpot system evaluation in the 200 m test tunnel both explosions were used to evaluate the performance of the system. For the Baseline 2 explosion, coal dust is distributed on the floor and shelves of the tunnel (for 60 m after the membrane position). This results in a methane-initiated coal dust explosion. The test sequence included the placement of the HS Design Suppression System at the following positions within the 200-m test tunnel:

- some 5 m from the closed end, i.e. within the methane chamber
- some 7 m from the closed end, i.e. within the methane chamber
- some 12 m from the closed end, i.e. within the methane chamber

The purpose of the tests was to attempt to simulate explosion scenarios and to relate the results obtained in the test tunnel to those likely to be obtained in a mine. The Measure of success was defined to indicate whether the flame propagation was:

- stopped inside the barrier (referred to as "stopped inside" in tables)
- stopped at the barrier (referred to as “stopped on the spot”)
- "stopped".

An explosion is considered to have been "stopped on the spot" if the flame does not exceed a distance of 30 m beyond the end position of the barrier. Furthermore, the barrier is considered to have "stopped" an explosion if the flame propagation (i.e. flame distance) is less than what it would have been without a barrier installed.

Test 2 was the baseline test in which no suppression system was placed in the tunnel. In this test the methane explosion propagated beyond the 71-m sensor position with an average calculated flame speed of 216 m/s at the 41-m sensor position, reaching a maximum calculated flame speed of 249 m/s. Figure 5 shows the flame speeds for the baseline methane explosion and for the tests with the active system in place for the installation positions at 5, 7 and 12 m.

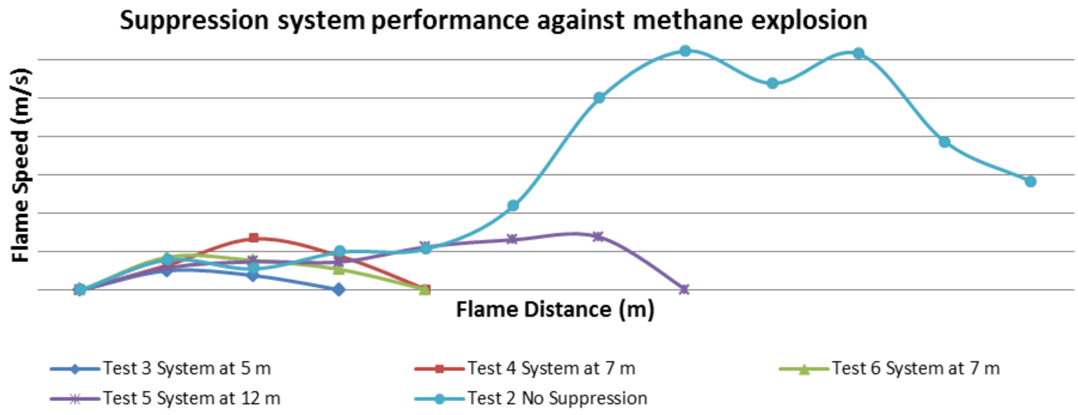

Figure 5 - Test 2 (baseline) flame and performance of the active barrier

The active barrier successfully suppressed the propagating methane flames approaching the barrier at flame speeds varying from 13.4 m/s during test 3 to 53.2 m/s during test 4. In test 5 the flame stop position was at 21 m and only in this test did the flame progress beyond the barrier position, although the flame is still considered to have been “stopped on the spot”.

Tests 1 and 7 were baseline explosion tests with coal dust placed outbye of the methane chamber. In these tests no suppression system was placed in the tunnel; they were done to determine flame propagation speeds and maximum flame travel. In these tests the coal dust explosion flames propagated beyond the final sensor positions at 81 m and reached maximum speeds of between 306.8 and 366.3 m/s at the 41 m sensor position.

In the tests with a single suppression system installed at 5 and 7 m and a double system at 7 and 12 m respectively, it was clear that the methane ignition was inhibited to such an extent that no coal dust participated outbye of the barrier position.

The average flame speed for the baseline and for the flame inhibition by the active barrier system when installed at 5 m, 7 m and at 7 and12 m is shown in Figure 6.

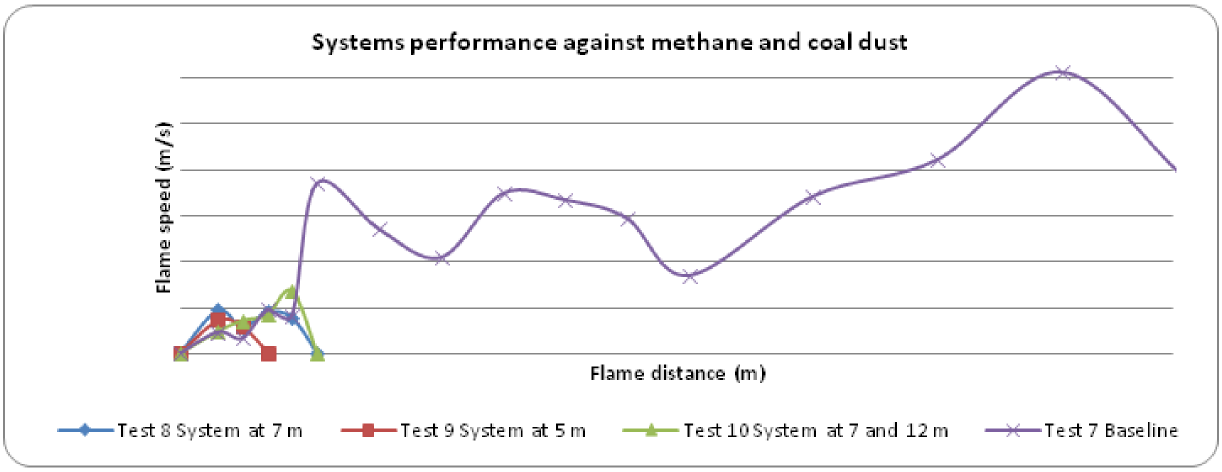

Figure 6 - Tests 8, 9, 10 and 7 average (baseline) flame speed and active barrier performance

In all the tests the system was successful in suppressing flame propagation. In each case the performance of the system can be classified as "stopped on the spot", i.e. the flame was stopped at the position at which the system was placed. The active barrier successfully suppressed propagating coal dust flames approaching the barrier at flame speeds varying from 24.4 to 62.2 m/s.

In the unsuppressed explosion, the flame front reaches a distance of 180 m within 750 milliseconds, while the flame front, with the system installed at 30 m from the end of the tunnel, does not reach 50 m.

The test results in the 200-m Kloppersbos tunnel were extrapolated to design the active suppression protection system for longwall mining. The 200-m tunnel provides a means of conducting large-scale evaluations and assessments of barrier performance and other requirements that cannot be done economically by other means.

DEPLOYMENT OF SYSTEMS

A total of 17 machine-mounted systems have been deployed in South Africa at Sasol mines and Anglo Thermal Coal operations. The system has successfully suppressed methane gas ignitions on five separate occasions.

In China more than 400 systems have been deployed. The system is utilised within longwall operations to protect against ignitions associated with shearer frictional events. It is also deployed as a roadway barrier within 30 m of the tailgate position. Recent legislative changes in China have resulted in it being made mandatory to install ExploSpot systems on roadheaders and to install roadway barriers in all returns in Shanxi Province and Liaoning Province.

CONCLUSIONS

In protecting a mine against methane and/or coal dust explosions many different controls are implemented. However, many of these controls remain under the control of man. In this context the use of active barrier systems can assist mine management in the prevention and control of the risk associated with mine explosions.

The results obtained in the 10 m, 20-m and 200-m test tunnels at Kloppersbos still need to be considered in terms of the constraints of the different tunnels and different evaluation protocols. Nevertheless, from the tests conducted it can be concluded that the ExploSpot system was successful in stopping methane explosions and the associated flame propagation when ammonium phosphate powder was used as the suppression material.

In all the tests conducted, both methane explosions and methane and coal dust hybrid explosions, the ExploSpot system stopped the flame spread, thus successfully preventing coal dust from participating in the methane ignition.

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