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Active explosion barrier performance against methane and coal dust explosions

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Abstract 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) as well as the Mine Safety Standardisation in the Ministry of Coal Industry, Coal Industrial l Standard of the Peoples Republic of China (MT 694-1997). From the tests conducted, it can be concluded that the ExploSpot System was successful in stopping flame propagation for both methane and methane and coal dust hybrid explosions when ammonium phosphate powder was used as the suppression material. The use of this barrier will 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 throughout a mine.

Keywords Coal · Methane · Explosions · Active barriers

1 Introduction

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 dusts to prevent coal dust from participating in mine explosions (Smith and du Plessis 1998). The final line of defence, however, is the use of barriers(du Plessis et al. 1995) 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 1990's 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 (du Plessis and Vassard 1995; du Plessis 2001).

A coal dust explosion may be defined as the uncontrolled exothermic combustion in air of ultra-fine particles of coal in which the resultant aerodynamic disturbance disperses additional coal dust into the air, thus fuelling the combustion in a self-sustaining process (Kruger et al. 1996). A critical step in determining the severity of an explosion is determining the rate of de-volatilisation of the particulate coal, higher rates are characterised by rapid flame propagation (Cashdollar and Hertzberg 1989). A high-speed, strong explosion is accompanied by a significant and rapid increase in static pressure (Kruger et al. 1996). In low-speed weak explosions, the static pressure does not increase at the same rate or to the same extent as

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in strong explosions. However, weak explosions burn extensively and are therefore very dangerous.

The propagation of a coal mine explosion involving coal dust depends on a conducive environment with respect to the following main factors:

(1) Sufficient heat radiation must be present to ignite unreacted coal particles.
(2) The coal dust must be dispersed to form a dust cloud with an explosive concentration.
(3) The distribution of the particles must be within the explosive range (Knoetze et al. 1993).

In the design of explosion barriers, the suppressant agent should be ideally dispersed as the flame front reaches the barrier (Zou 2001). If the suppressant agent is dispersed prematurely, the suppressant will be driven downstream and its concentration will be diluted by the explosion-induced wind force before being overtaken by the flame. When the suppressant agent is dispersed to late, the suppressant cloud is behind the flame where it has minimal effect in distinguishing the flame. With passive barriers, it is difficult to ensure optimal conditions (Zou 2001). Active barriers with triggering devices are therefore developed to try and meet this need.

For effective operation active barriers detect the arrival of the flame front and then need to effectively disperse the inert materials for suppression. Triggered barriers consist of three main components: the sensor, the dispenser and the suppressant. A sensor device detects the on-coming explosion by a rise in static pressure, temperature or radiation and triggers a mechanism to activate the dispenser for suppression (Zou 2001). The dispenser discharges an inert material by means of a compressed gas, a spring mechanism or explosive materials. Many types of sensor have been developed including (Zou 2001):

(1) Ultraviolet sensor—responds to the ultraviolet radiation emitted by naked flames.
(2) Infrared sensor—reacts to changes in the infrared radiation intensity.
(3) Thermocouple flame sensor—responds to the heat supplied by conduction so that there is no response if the thermocouples are not in the actual flame or products of combustion.
(4) Thermo mechanical sensor—respond to the dynamic pressure of an explosion.
(5) Blast operated sensor—react to the blast of an explosion in much the same way as a passive barrier.

According to Zou (2001), a number of disperser units have been developed. Most of them are based on either a detonating cord or pressurised gas as an energy source. Steel cylinders are used to contain the suppressant and the propellant. A number of agents have been used as suppressants (i.e. extinguishers), these include, Halon1301, water, stone dust (e.g. limestone), sodium bicarbonate, ammonium dihydrogen phosphate, potassium chloride, potassium bicarbonate and sodium chloride.

The main purpose of applying active barrier systems in mines is to suppress methane explosions, prevent methane explosions escalating into coal dust explosions and to suppress coal dust explosions and prevent the explosions from propagating. The use of active explosion-suppression systems remains one of the most underutilised explosion controls in underground coal mines (du Plessis and Späth 2014).

Tests were conducted in the 200 m explosion test tunnel at the Kloppersbos Research Facility of the Council of Scientific and Industrial Research in South Africa (CSIR) to determine the effectiveness of an active explosion protection barrier (ExploSpot) system in preventing the propagation of methane coal dust explosions. The employees of HS Design Engineering undertook the set-up of the ExploSpot system in the 200 m tunnel while the CSIR employees prepared the tunnel and conducted testing. The suppressant material used to suppress a coal dust explosion in the test tunnel was ammonium phosphate powder.

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 200 m tunnel provides a means of conducting large-scale evaluations, and assessments of barrier performance and other requirements that cannot be economically done by other means.

The active suppression system tested had the following main components (du Plessis and Späth 2014), detecting sensors, electronic control and self-checking system, dust containers and flow nozzles. The electronic control and self-checking system are connected to the detecting sensor units and discharge assemblies, constantly monitoring the connections so that the system will always be functional when required. The sensor units are so placed as 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 can be 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 for successfully extinguishing an explosion is achieved.

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. Figure 1 shows the respective active barrier system components.

2 Coal sample preparation

2.1 Coal dust properties

In Table 1 the properties of the standard coal dust used for creating coal dust explosions and for testing the effectiveness of passive or active barrier systems is shown. The coal dust was prepared in accordance with the guidelines given by Cook (1993) for coal dust tests at Kloppersbos. The properties are determined by means of proximate analysis done by the Coal Analysis Laboratory of the South African Bureau of Standards (SABS) and through ultrasonic sieve analysis done in the Kloppersbos laboratories.

Table 1 Typical Properties of the coal dust used for testing

Description	**Coal**
Ash (%)	16.0
Moisture (%)	2.4
Volatiles (%)	25.2
Fixed carbon (%)	56.4
Particle size (microns)	20.0

2.2 Description of test tunnel

The 200 m test gallery was used to conduct the various tests. A comprehensive description of the gallery was given by Cook (1993). A photograph of the test gallery is shown in Fig. 2. The purpose of testing gallery was instrumented with flame sensors and a data acquisition system.

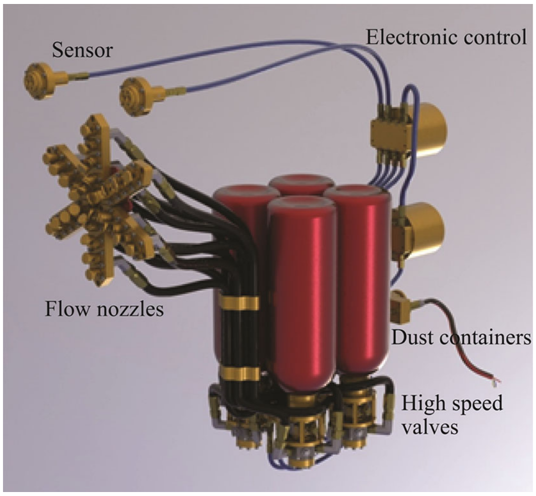


Fig. 1 Graphical representation of the active barrier system components

Fig. 2 Photograph of the 200 m test tunnel barrel and mouth

A diagrammatic representation of the gallery showing the instrument positions is shown in Fig. 3.

3 Test procedure

3.1 Ignition source

In all the tests the methane/air mixture were ignited using a standard fuse cap. The fuse was chosen simply because it produces a very small flame that would not be seen or recognised by the sensor triggering the active barrier suppression system.

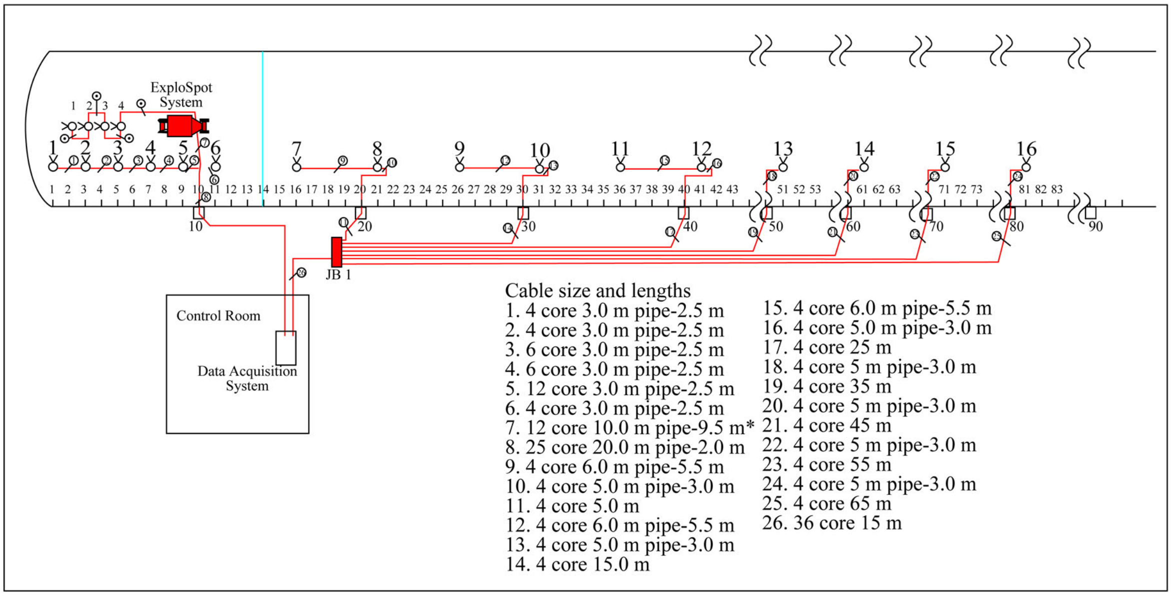
3.2 Methane initiator

The initiation of coal dust explosions for evaluating the active explosion barrier was achieved by igniting a methane/air mixture. A chamber with a methane/air volume of 75 m^3 was created by placing a plastic membrane 14 m from the closed end of the gallery and introducing pure methane into the chamber. The methane/air mixture is mixed and allowed to stabilise at a methane/air mixture of

9 % per volume. The methane explosion resulting from the ignited methane/air mixture is adequate to produce enough dynamic (wind) pressure to lift the coal dust particles into the air and to supply sufficient heat to the coal dust particles for flame propagation and the associated coal dust explosion to propagate.

The installation of the plastic membrane, containing the methane chamber is shown in Fig. 4.

A data-collection system automatically retrieves the data from the individual measuring stations and combines them into a report showing pressure and flame data. These data are then analysed to evaluate both the explosion characteristics and the barrier performance. The pressure and flame trace data captured are plotted on graphs, with time, distance and maximum readings on the other axes.



Cable size and lengths

1. 4 core 3.0 m pipe-2.5 m
2. 4 core 3.0 m pipe-2.5 m
3. 6 core 3.0 m pipe-2.5 m
4. 6 core 3.0 m pipe-2.5 m
5. 12 core 3.0 m pipe-2.5 m
6. 4 core 3.0 m pipe-2.5 m
7. 12 core 10.0 m pipe-9.5 m*
8. 25 core 20.0 m pipe-2.0 m
9. 4 core 6.0 m pipe-5.5 m
10. 4 core 5.0 m pipe-3.0 m
11. 4 core 5.0 m
12. 4 core 6.0 m pipe-5.5 m
13. 4 core 5.0 m pipe-3.0 m
14. 4 core 15.0 m
15. 4 core 6.0 m pipe-5.5 m
16. 4 core 5.0 m pipe-3.0 m
17. 4 core 25 m
18. 4 core 5 m pipe-3.0 m
19. 4 core 35 m
20. 4 core 5 m pipe-3.0 m
21. 4 core 45 m
22. 4 core 5 m pipe-3.0 m
23. 4 core 55 m
24. 4 core 5 m pipe-3.0 m
25. 4 core 65 m
26. 36 core 15 m

Fig. 3 Diagrammatic representation of the 200 m test gallery

Fig. 4 Photograph showing the plastic membrane enclosing the methane chamber (du Plessis 2001)

4 Description of explosions

The tests were conducted with and without coal dust present. The different explosions were:

1. Baseline 1: (75 ± 1) m^3 methane/air mixture ignition without coal dust.
2. Baseline 2: (75 ± 1) m^3 methane/air mixture with coal dust.

For the ExploSpot active barrier tests conducted in the 200 m test tunnel both explosions were used to evaluate the performance of the system. For the Baseline 2 explosion coal dust (35 kg) is distributed on the floor and shelves of the tunnel (for 60 m from the end position of the membrane). This results in a methane initiated coal dust explosion.

The test sequence included the installation of the active barrier system at the following positions:

1. Some 5 m from the closed end, i.e. within the methane chamber.
2. Some 7 m from the closed end, i.e. within the methane chamber.
3. Some 12 m from the closed end, i.e. within the methane chamber.
4. One test with a split system with bottles installed at 7 (2 bottles) and 12 m (4 bottles) respectively.

In Fig. 5 the physical installation of the mobile active barrier as installed inside the 200 m test tunnel is shown prior to the evaluation testing.

The pass criterion was specifically defined to indicate whether the flame propagation was, stopped inside the barrier (referred to as "stopped inside"), stopped at the barrier (referred to as "stopped on the spot") and "stopped" (du Plessis and Späth 2002). An explosion would be considered to have been "stopped on the spot" if the flame did not exceed a distance of 30 m beyond the end position of the barrier. Furthermore, the barrier was considered to have "stopped" an explosion if the flame propagation (i.e. flame distance) was less than what it would have been without a barrier installed.

5 Description of results

The results of the methane only explosion tests are shown in Table 2. The position of the flame distance is indicated where no flame was detected by the flame sensors. This means that the flame had stopped before the flame sensor position, i.e. in-between the previous sensor and the one reported with no flame visible.

Test 2 was the baseline test in which no suppression system was placed in the tunnel during testing. This explosion propagated beyond the 71 m sensor position. The flame speed for the baseline methane explosion and for the flame inhibition by the system when installed at 5, 7 and 12 m are shown in Fig. 6.

Table 3 shows the flame speeds at respectively 3, 5, 7, 9 and 11 m in front of the active barrier system position. In Test 12 the flame progressed beyond the barrier position but no flame was observed at the flame sensor position at 36 m. This again re-iterated the importance of being as close as possible to the ignition source and initial methane explosion.

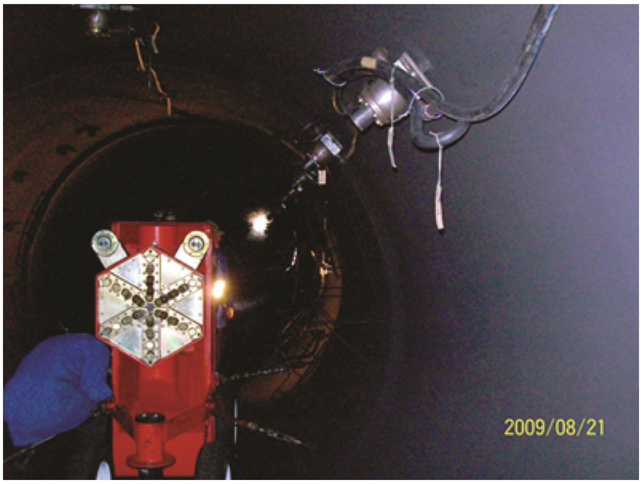


Fig. 5 Photograph of the active barrier system installed inside the 200 m test tunnel

Table 2 Results of the performance of the ExploSpot system against propagating methane explosion flames

Test No.	System position (m)	Number of bottles	Flame distance (m)	Flame speed at 41 (m)	Max flame speed (m/s)
Test 2	None		70–80	216	249
Test 3	5	4	7	No	14.9
Test 4	7	4	9	No	53.2
Test 6	7	4	9	No	30.7
Test 5	12	6	36	No	55.0

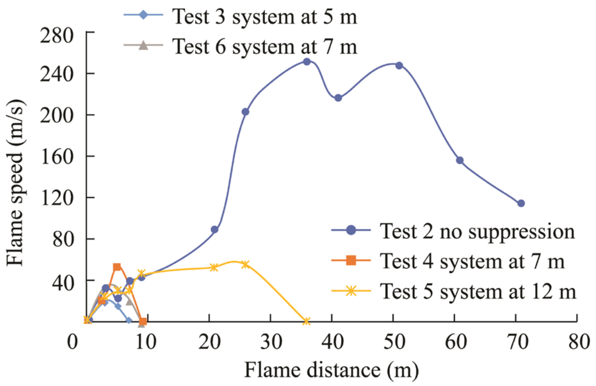


Fig. 6 Maximum flame length and speeds for baseline (test 2) and active barrier tests

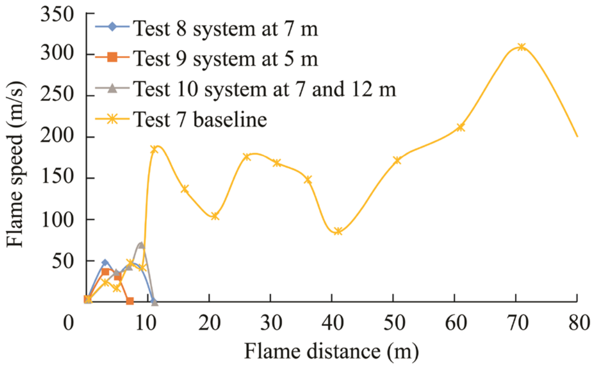


Fig. 7 Maximum flame length and speeds for baseline (average test 1 and 7) and active barrier tests

The active barrier successfully suppressed propagating methane flames approaching the barrier at flame speeds varying from 13.4 to 53.2 m/s.

The results of the methane and coal dust explosion tests and suppressions tests are shown in Table 4.

Test 1 and 7 was a baseline explosion in which no system was placed in the tunnel and the measured flame length and calculated flame speeds is used as measurement criteria. Both baseline explosions propagated beyond the final sensor positions at 81 m. The baseline explosions thus

Table 3 Flame speeds in front of the active barrier position

Test No.	System position (m)	Flame speed in front of system (m/s)				
		3 m	5 m	7 m	9 m	11 m
Test 3	5	13.4	14.9			
Test 4	7	17.2	53.2	35.1		
Test 6	7	22.8	30.7	21.2		
Test 5	12	15.4	29.4	29.3	44.9	52.4

Table 4 Performance results of the active barrier against propagating coal dust explosions

Test No.	System position (m)	Number of bottles	Flame distance (m)	Flame speed at 41 (m)	Max flame speed (m/s)
Test 1	None		>80	366.3	366.3
Test 7	None		>80	306.8	306.8
Test 9	5	4	7	No	29.4
Test 8	7	6	11	No	45.5
Test 10	7 and 12	2 and 4	11	No	69.2

Table 6 Flame speeds in front of the active barrier position

Test No.	System position (m)	Flame speed in front of system (m/s)				
		3 m	5 m	7 m	9 m	11 m
Test 9	5	24.4	29.4			
Test 8	7	31.6	28.5	45.5		
Test 10	7 and 12	15.9	36.0	42.3	62.2	

show the propagation of a methane initiated coal dust explosion in which no inertant or suppression system is used. The average flame speeds for the baseline explosion and for the flame inhibition by the active barrier system when installed at 5 m, 7 m and 7 and 12 m are shown in Fig. 7.

In all the tests the active barrier system charged with ammonium phosphate powder as suppression agent, it 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. Table 6 shows the flame speeds at respectively 3, 5, 7, 9 and 11 m in front of the active barrier system position. In none of the tests did the flame progress beyond the barrier position.

The active barrier successfully suppressed propagating methane flames approaching the barrier at flame speeds varying from 24.4 to 62.2 m/s. The maximum flame distance measured was 11 m when compared to more than 80 m without the barrier being in place. As the flame did not progress beyond the barrier position, start of the coal dust, it can be concluded that no coal dust participated in the explosion.

6 Conclusions

In protecting a mine against methane and or coal dust explosions many different controls are implemented. Many of these controls remain in 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.

All the results obtained in the 200 m test tunnel at Kloppersbos need to be evaluated and interpreted in terms of and against the physical size constraints of this tunnel. From the tests conducted, it can be concluded that the active barrier system tested (ExploSpot) was successful in stopping flame propagation when ammonium phosphate powder was used as the suppression material.

In the methane only explosions the active explosion barrier stopped the methane flame spread successfully. In the methane initiated explosions with coal dust present the active explosion barrier effectively prevented the methane explosion progressing into a coal dust explosion with the resulting flame inhibition.

The use of this active explosion barrier will 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 throughout a mine.

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