The effectiveness of on-board suppression systems to prevent the propagation of methane ignitions under simulated coal mining conditions

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Synopsis

After the explosion at Middelbult Colliery, South Africa in May 1993, which claimed 53 lives, the South African Coal Mining Industry and the Safety In Mines Research Advisory Committee (SIMRAC) united forces to establish a surface facility to develop and test on-board flame suppression systems for continuous miners and roadheaders.

The first test that was conducted in this newly constructed test tunnel at the Kloppersbos Research Facility, CSIR was in July 1995. Since then 70 tests have been conducted using the facility and have focused on on-board active ignition suppression systems for continuous miners (CM) and road heading (RH) machines to enhance the safety of South African mine workers in collieries. These suppression systems are mounted on the CM or RH machine and detect the occurrence of an ignition by means of light-sensitive sensors. The electronic signal from the sensor triggers the suppression system, creating a flame-suppression curtain, containing and extinguishing the flame in the immediate vicinity of the ignition.

Forty-three tests have been conducted with an active on-board suppression system present inside the test tunnel. Since flame propagation speed is an extremely important parameter, the CSIR-Miningtek made the results of the test programme available for re-analysis. Flame speed depended on whether a machine was present in the heading or not, the geometry of the heading and the volume and composition of the explosive mixture of gas. Flame speeds of up to 190 m/s were recorded. However, the active suppression systems were almost always successful in containing flame propagation.

Introduction

The G.P. Badenhorst Research Facility, which is owned and operated by the CSIR-Miningtek, is situated 40 km north of Pretoria, where in 1987 a 200-metre long circular explosion gallery was completed[1]. This gallery has so far been used to test different types of barriers for stopping flame propagation in coal dust explosions. In response to the need for enhanced precautionary measures to safeguard mine workers in collieries from the consequences of methane ignitions in a heading, the coal mine industry expressed the desire for the development and testing of an active on-board suppression system[2]. To serve this purpose, a new 20 m long rectangular shape test tunnel was constructed in 1995.

This facility has been used to develop and test on-board, active suppression systems with a particular view to determining the exposure of CM operators close to the coal face to methane flames. In other words, the flame must be extinguished before it reaches the machine operator's position. This work was conducted by CSIR-Miningtek and funded by contracts with SIMRAC, Houilleres de Bassin du Centre at du Midi (France) and Ineris (France) and the system manufacturers, CENTROCEN. The way to determine the effectiveness of the flame suppression system is to note the reduction or increase in the flame speed. The lower the flame speed, the more effective the flame suppression system. Results from this test work have been made available for further analysis[4] and it is this analysis of flame speeds, with and without the application of the suppression system that is reported in this paper.

The type of suppression system used in the tests is of a proprietary nature and, as such, no details can be made available.

Description of the test tunnel

The short test tunnel simulates conditions that could be encountered at the face of a bord-and-pillar heading in an underground coal mine.

The test tunnel is 20 m long, 7 m wide, with a variable height which can be set at heights of between 2 m and 6 m in increments of 0,5 m. It has a rectangular shape closed at one end. The test tunnel is equipped with sensors (pressure, flame and temperature) to measure the pressure generated by the explosion, to detect the rate of the flame travel and to determine temperature increases

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especially in the vicinity of the CM operator's position; a data acquisition system to computerize the test output; a methane-mixing and measuring system as well as an ignition source to ignite the methane/air mixture; and a video camera for the visual recording of the event (Figures 1, 2 and 3).

The tests are carried out on a scale of 1:1 i.e. at full size. Some of the tests were conducted on full-face tunnels while others were conducted with a shoulder in position as shown in Figure 1, to more accurately simulate the underground condition. Earlier tests were done using an actual CM machine, which was on loan from a mine. However, due to production requirements at the mine, this machine was taken back and was replaced by a model of equivalent geometry constructed of steel.

According to the test protocol, provision has been made to simulate the conditions in a heading being mined by a CM after the first lift or part of the first lift has been completed through the addition of a shoulder towards the front of the tunnel as shown in Figure 1. Because the CM is about 3,2 m wide, it cuts the heading in two lifts. This creates the shoulder and this shoulder will be able to simulate a cut of up to a depth of 6 m for all the seam heights. The heading can be simulated at the start or end of the lift and can be done without the shoulder to give a full heading width of 7 m. This is similar to a test being conducted in a full heading as would be the case in the testing of roadheaders.

According to the dimensions of the continuous mining machines, square frames near the closed end of the test tunnel allow the attachment of a plastic membrane thus forming a chamber into which the air-methane mixture is pumped (Figure 2). The position of the membrane varies depending on whether a shoulder is in position or not. If the shoulder is absent, the membrane is located 5 m from the closed end of the tunnel. If the shoulder is present, the distance varies from 7 m to 9 m according to the test to be conducted. A summary of the tests carried out and their results are given in Appendix 1.

The specifications of the sensors, data acquisition system and methane mixing in the test tunnel are given in the protocol for testing procedures in the SIMRAC Project Report[2]. There are 76 flame sensors, one dynamic pressure sensor, one static pressure sensor and one temperature sensor inside the tunnel (Figure 3).

By measuring the time of activation of the individual sensors, the speed of the flame advance can be obtained as well as the profile of the final positions reached by the flame front. It should be noted that the system has a distance sensitivity of one metre. A glass cover is placed over each sensor on the tunnel wall to provide protection. These glass protection covers are cleaned and inspected before every test to ensure that the correct flame intensity will be recorded. When each of the four sensors at 1-metre intervals is activated, a digital output is generated. This will indicate if the flame has passed that point or which side of the tunnel the flame has passed. The positions of the 76 flame sensors inside the test tunnel are shown in Figure 4.

The data are retrieved sequentially from each channel after an explosion. They are stored in binary form and 128 channels are used. A sampling rate of 30 KHz over a period of 2 seconds means that each channel can be sampled 60,000 times in a single explosion test.

Experimental procedure

The tests conducted can be categorized into three different groups:

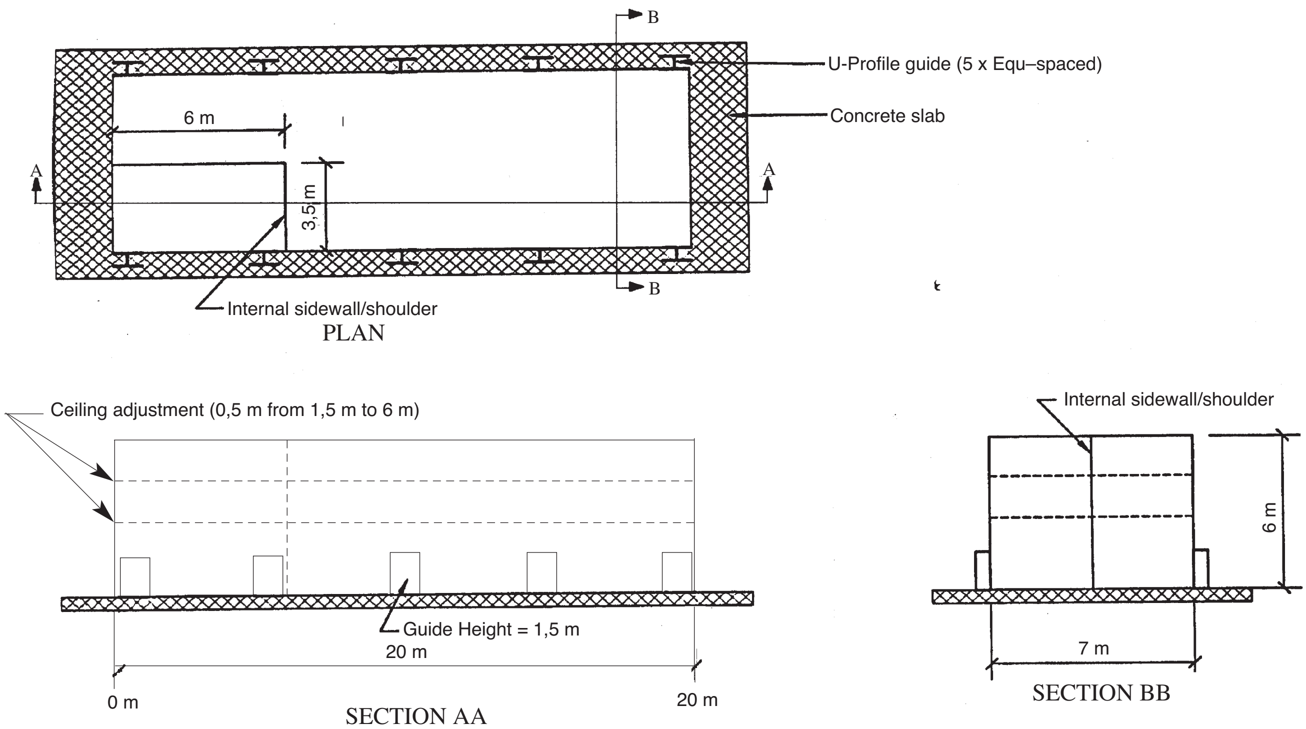

Figure 1—Test tunnel[2]

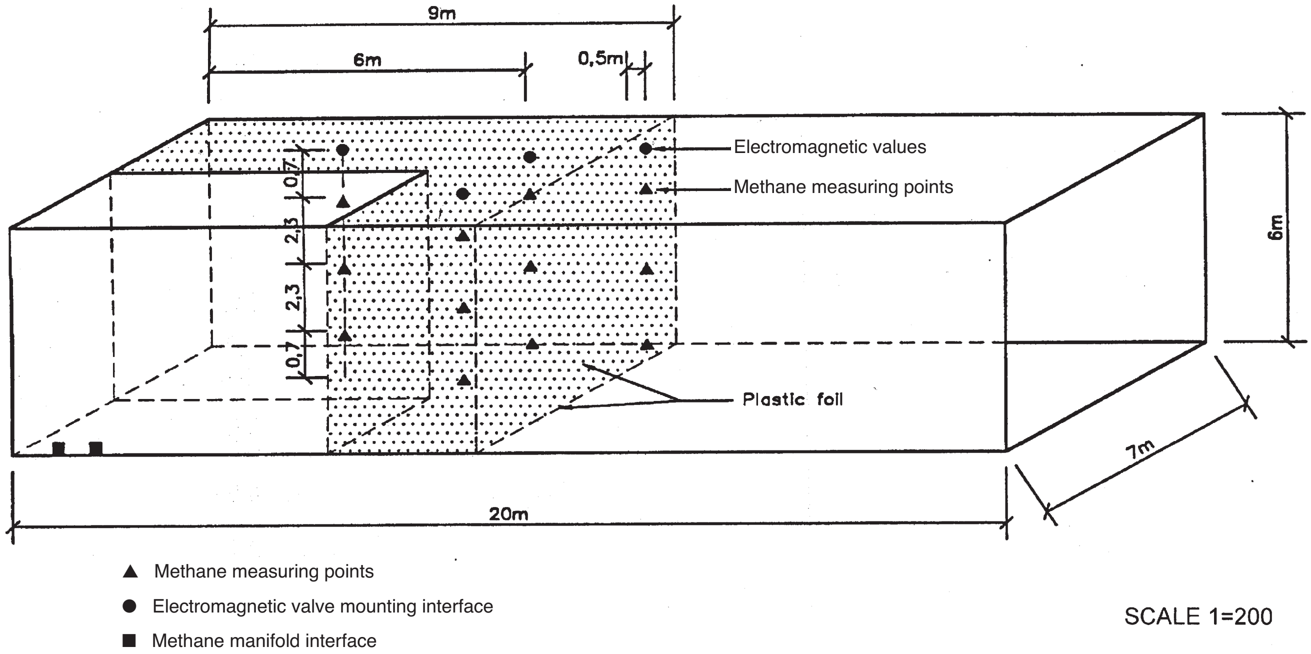

Figure 2—Methane/air mixture measuring points and electromagnetic valve mounting[2]

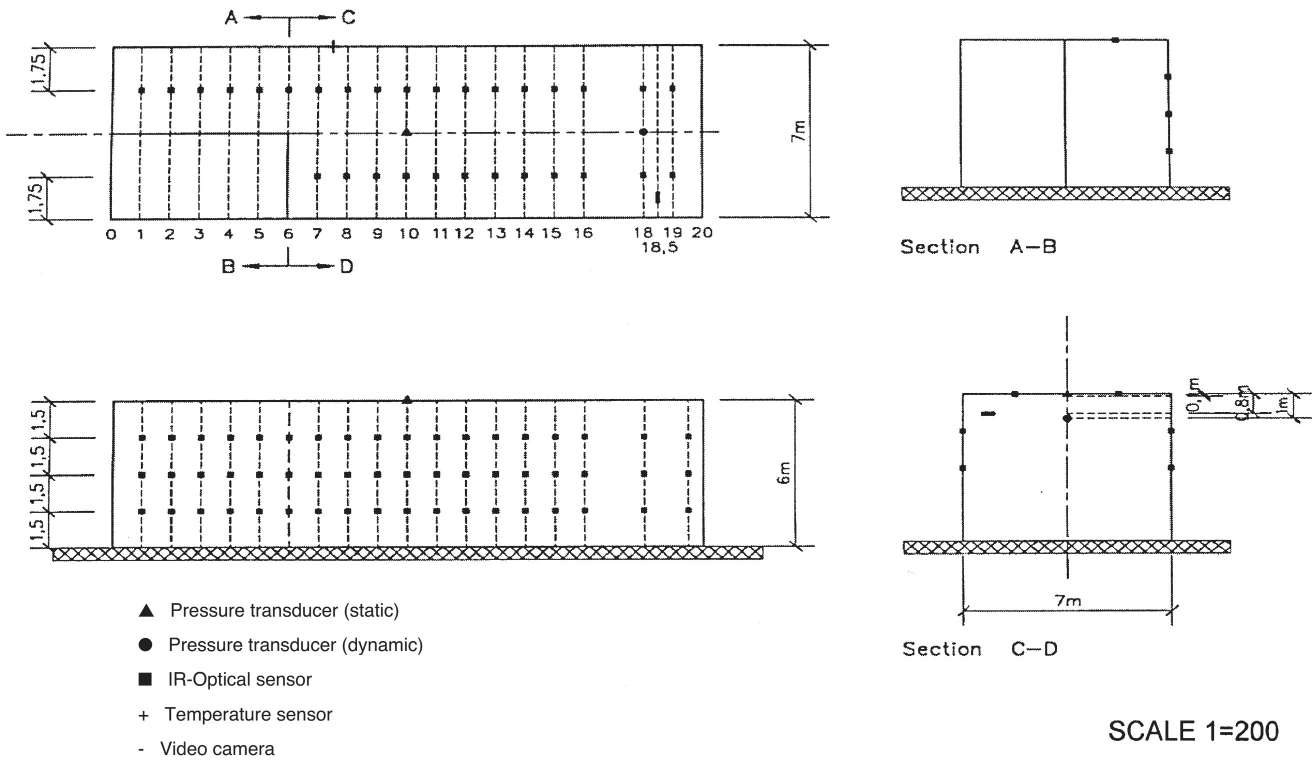

Figure 3—Position of measurement equipment for evaluation of suppression systems[2]

- tests conducted without a suppression system
- tests conducted with a suppression system
- tests conducted with a roadheader model in an inclined gallery.

The tests conducted without a suppression system were aimed not only at determining the extent of the flame, the flame speed and the value of the dynamic pressure and the temperature increase inside the tunnel, but also to calibrate the test tunnel equipment and prepare the tunnel for active suppression system tests.

According to the testing protocol, when suppression tests were conducted, the ignition source was positioned between the drum and the face so that it was in the sighting shadow of the sensors of the suppression system. The methane/air

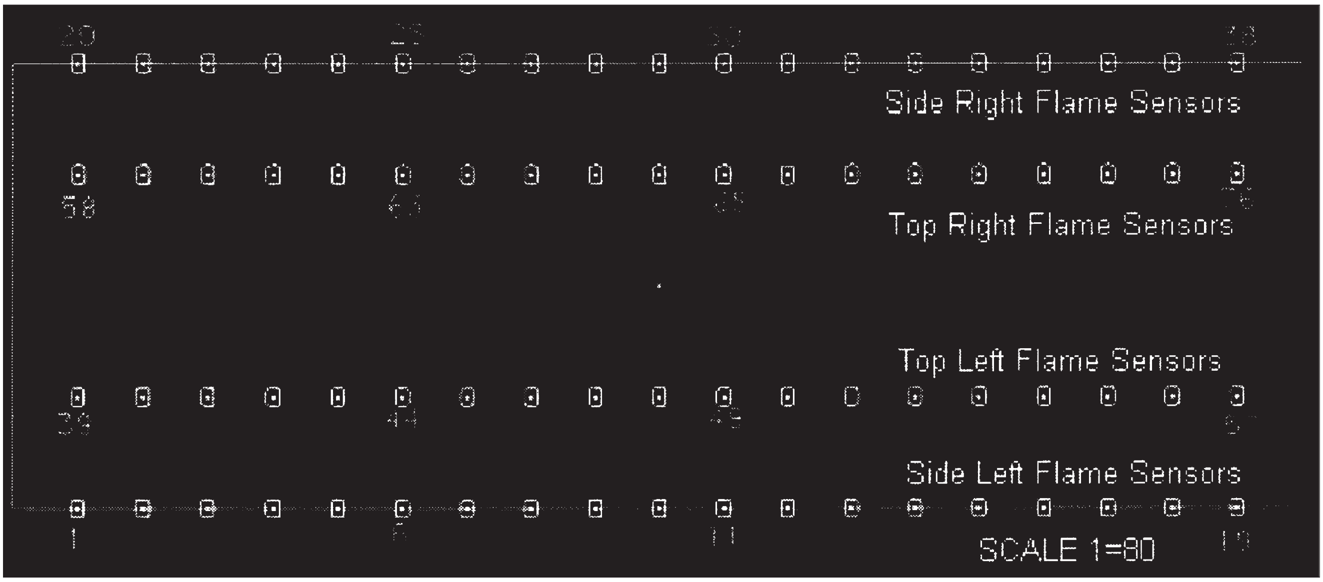

Figure 4—Position of the flame sensors

mixture was ignited by means of a fuse cap (200 joule) or a chemical detonator. The ignition source and the data acquisition system were activated simultaneously, thereby allowing the controlled capture of the explosion data. An in-tunnel video camera captured the visual material. The visual material and the data acquisition system output were used to determine the extent of the flame, the values recorded by the dynamic and static pressure sensors as well as the temperature sensor.

Different methane/air volumes and concentrations for a CM, CM model and finally CM mounted on-board suppression systems were used. During the first 43 tests conducted, the roof height of the test tunnel was set at 2,5 m and during the shoulder tests, the depth of shoulder was 2 m and its width 3,5 m.

For the tests conducted for Houilleres de Bassin du Centre at du Midi (France) and Ineris (France), the test tunnel was modified according to French coal mine conditions[3]. A model of a Dosco 1300H type roadheader model was used. Roof height was changed to a sloping roof (2,45 m high to 4,20 m) inclined at an angle of 30° and during the shoulder tests, the depth was 4 m and the width 2,5 m (Figure 5 and Figure 6). Plastic membranes were used to create an explosive methane/air mixture in a chamber covering the head of the machine. Methane/air concentrations of 7,5 to 12% were used. The volume of the mixture depends on the height of the seam being simulated, the position of the membrane and the required methane/air concentration.

Experimental results

There were 76 (4 × 19) flame sensors inside the test tunnel. Two sets of flame sensors in linear array (19 each) were located on the sides of the tunnel, while the other two sets were on the roof (total of 4 sets of flame sensors, Figure 4). Figure 7 shows how the flame arrival time at a specific flame sensor was determined. The channel numbers from 1 to 76 correspond with the number of the flame sensors, e.g. channel 24 corresponds with flame sensor number 24. Similar readings were obtained for the 76 flame sensors to obtain the exact flame arrival time. Figure 8 combines all flame sensor-reading results for one test and demonstrates the flame propagation in seconds. The maximum time for which data can be recorded is 2 seconds.

From a research point of view, one of the most important parameters to study is flame speed. However, depending on the method of calculation, different results may be obtained. From an initial study of the data, it was apparent that the early stages of ignition, where the interaction between the initiator and the methane/air mixture takes place, contribute to the degree of experimental error. While it was important to calculate the flame speeds and arrival time from a fixed datum ($t_0=0$), the results were also calculated from the time the flame passes through the membrane position (t_6). The equations used for these four calculations are:

- Flame speed$_1$ = $V_1 = [(1/(t_1-t_0) + 1/(t_2-t_1) + \ldots 1/(t_{19}-t_{18})) / 19]$ (m/s)
- Flame speed$_2$ = $V_2 = [19 / (t_{19} - t_0)]$ (m/s)
- Flame speed$_3$ = $V_3 = [(1/(t_6-t_0) + 1/(t_7-t_6) + \ldots 1/(t_{19}-t_{18})) / 14]$ (m/s)
- Flame speed$_4$ = $V_4 = [13 / (t_{19}-t_6)]$ (m/s)

In the first method of calculating the flame speed (V_1), the distance between two consecutive flame sensors, which is 1 m, is divided by the difference between the two consecutive flame sensor readings. The sum of these values is then divided by 19 where 19 was the distance between the first sensor (t_1) and the last sensor (t_{19}). This formula was applied to all 4 sets of flame sensors (as described above). The average results obtained from the four linear arrays of flame sensors were then added together and divided by 4 to calculate the total average flame speed through the test tunnel. In the same way, the average results obtained for each set of flame sensors when calculating with the second, third and fourth formulae were also added together and divided by four to obtain the total average flame speed.

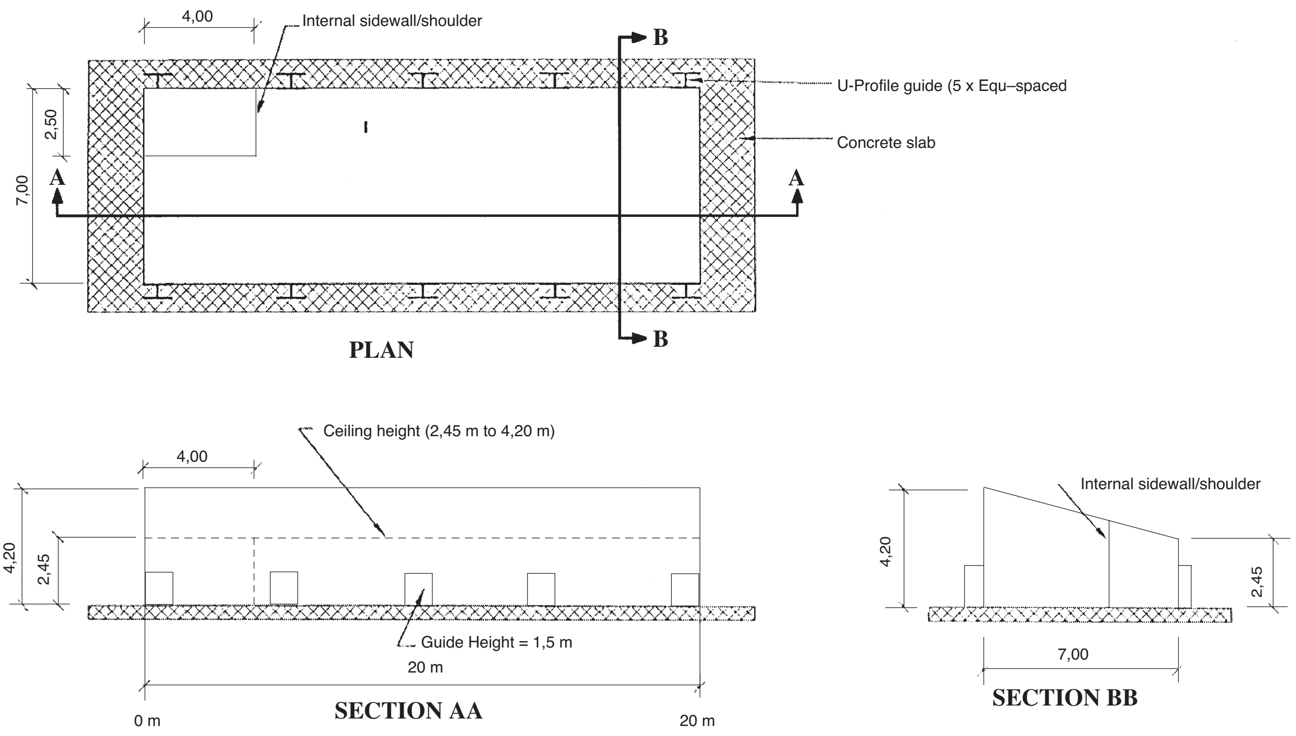

Figure 5—Test tunnel[3]

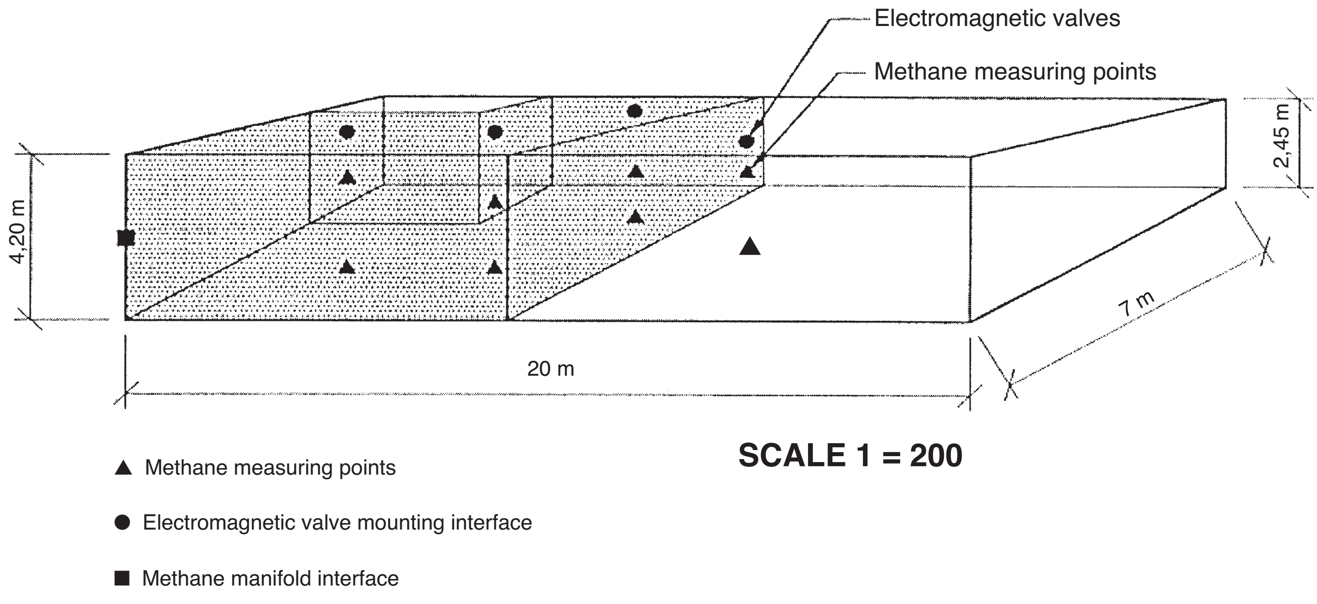

Figure 6—Methane/air mixture measuring points and electromagnetic valve mountings[3]

In the second method, the flame speed (V_2) was calculated by dividing 19 into the flame arrival time at the last flame sensor. In the third and fourth methods, the distance between the face of the tunnel and the membrane position was ignored. Depending on the test conducted, the membrane was positioned at 5 m, 7 m, and 9 m respectively from the face. The flame speed calculation formulae (V_3 and V_4) were used accordingly. When the membrane was positioned 5 m from the face, the formula for the flame speed (V_3) was $[(1/(t_6\text{-}t_0) + 1/(t_7\text{-}t_6) + ...1/(t_{19}\text{-}t_{18})) / 14]$ and when the membrane was positioned 7 m from the face, the formula for the flame speed (V_3) was $[(1/(t_8\text{-}t_0) + 1/(t_9\text{-}t_8) + ...1/(t_{19}\text{-}t_{18})) / 12]$ where 12 was the distance between the first sensor (t_8) and the last sensor (t_{19}).

When comparing the flame speed results, it can be seen from the flame sensor readings, explosion videos and the test graphs (Figure 3) that it takes up to 200 milliseconds for an explosion to develop. During this time, the explosion

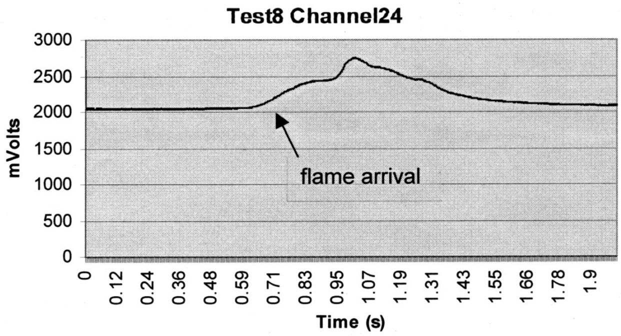

Figure 7—Flame arrival time

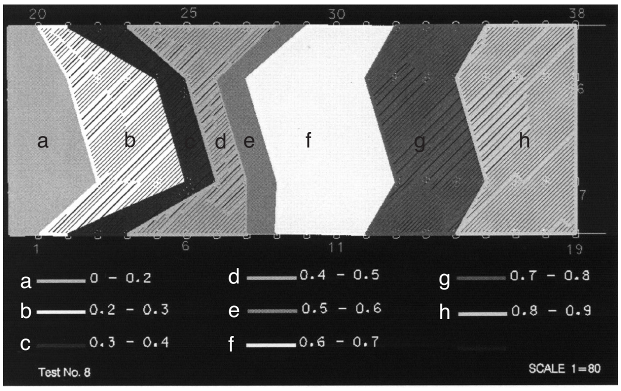

Figure 8—Flame propagation inside the test tunnel in seconds. The shading denotes the arrival of the flame

develops inside the membrane, the methane/air mixture burns, and thereafter the methane explosion starts propagating from the membrane position onwards. From this point of view, the flame speed $V_4 = [13 / (t_{19}\text{-}t_6)]$ would be the most realistic approach to calculate the flame speed. When using V_4, the distance between the face of the tunnel and the membrane position was ignored and in some tests, the active suppression system successfully stopped flame propagation, within the membrane. As a result, some of the results show no flame speed inside the test tunnel. In this case, the formula V_2 was used instead to calculate the flame speeds where applicable, even though the accuracy of the result is in doubt. In the Tables of results that follow, the flame speed quoted has been calculated by method 4, i.e. (V4).

As discussed earlier, the 70 tests that were conducted between July 1995 and January 1999 in the 20 m tunnel at the Kloppersbos Research Facility can be categorized in three different ways:

- tests conducted without a suppression system
- tests conducted with a suppression system
- tests conducted with a roadheader model in an inclined gallery.

Tests conducted without a suppression system

There were four ways to conduct tests without a suppression system, namely:

- empty tunnel tests
- tests with a CM in place
- tests with a CM model in place
- tests with a CM model in place and with the shoulder in position.

Empty tunnel tests

The empty tunnel tests results are shown in Table I. Tests 8 to 12 fall into this category. Flammable gas mixtures were generated using the mixing and monitoring procedures described by du Plessis and Bryden[2]. Two concentrations were used; 9% and 12% and the volume of the mixture was kept at 87,5 m^3 throughout this series of tests. Flame speed was found to be independent of the change in the methane concentration from 9% to 12%. The flame propagated throughout the test tunnel, which can be seen in Figure 8. The average flame speed was 45,2 m/s when 9% methane/air concentration was used and it was 44,9 m/s when 12% methane/air concentration was used. The highest flame speed was 53,4 m/s, which was recorded in test 12.

Tests with a continuous miner in place

Only two tests were conducted with a Joy 14 CM 6 present inside the test tunnel: These were tests 5 and 6. Flame speeds of 118,9 m/s and 69,2 m/s were recorded respectively. The results of the tests conducted with the presence of a CM are shown in Table I. While using the same volume of mixture that was used in the empty tunnel tests, only 9% methane/air concentration was used. Because the presence of the CM inside the test tunnel created an obstruction and reduced the cross-sectional area of the tunnel, the flame propagated more quickly. The 70% difference between the flame speeds could have been caused by experimental error, however, compared to empty tunnel tests, the flame speed increased by more than 100%. The average flame speed was 94,1 m/s.

Tests with a continuous miner model in place

Eight tests were conducted with the presence of a CM model inside the test tunnel, the results of which are given in Table I. Even though two methane/air concentrations were used, 7,5% and 9% respectively, the volume of the mixture was

Table I

Flame speed without suppression system

Empty tunnel			Test with a CM			Test with a CM model			CM model with a shoulder		
No.	(%)	S (m/s)	No.	(%)	S (m/s)	No.	(%)	S (m/s)	No.	(%)	S (m/s)
8	9	30.3	5	9	118.9	13	9	68.4	28	7.7	55.1
9	9	51.9	6	9	69.2	15	7.5	28.1	37	7.8	117.5
10	12	41.7				16	9	70.1	38	7.8	101.9
11	12	48.1				17	7.5	35.8	39	7.8	118.2
12	9	53.4				18	7.5	33.9	40	7.8	109.4
						19	9	78.2	41	7.8	106.8
						20	9	79.2	42	7.8	109.6
						21	9	68.5			

No.: Test No., (%): CH_4 / Air %, S: Flame Speed, Volume CH_4/Air = 87,5 m^3

again kept at 87,5 m^3, the same as for the two previous series of tests conducted.

In this category, the cutting head of the CM model was positioned at one of three positions: on the floor, in the middle of the tunnel or at the ceiling (roof position). In tests 13, 19, 20 and 21, as detailed in Appendix 1, the cutter was on the floor. In tests 15 and 16, the cutter was in the middle of the tunnel, while in tests 17 and 18; the cutter was at the roof. The position of the cutter did not influence the flame speed.

One significant result from the tests conducted was that when comparing the results of tests conducted with 7,5% methane/air concentration and 9% methane/air concentration, it can be seen that the flame speed more than doubled. The reason for this was the change of the methane/air concentration from 7,5% to 9%. The average flame speed was 32,6 m/s when 7,5% methane/air concentration was used and it was 72,9 m/s when 9% methane/air concentration was used.

When comparing the results of tests conducted with the presence of a CM and CM model inside the test tunnel using a methane-air concentration of 9%, the average flame speed was 94,1 m/s when the CM was present inside the test tunnel, and 72,9 m/s when the CM model was present. Despite the fact that the average flame speed was 94,1 m/s when the CM was present inside the tunnel (with considerable variation in the results of the two tests), the flame speed of test 6 was 69,2 m/s. This comparison shows that the CM model can be used as a replacement for the CM.

Tests with a CM model with shoulder in position

Seven tests were conducted with both the CM model and shoulder in position as illustrated in Table I. Two methane/air concentrations were used; 7,7% and 7,8% and the volume of the mixture was increased to 105 m^3 throughout this series of tests. In this category, the cutter of the CM model was positioned in the middle of the tunnel (see Appendix 1).

Adding a shoulder inside the tunnel and increasing the methane/air volume from 87,5 m^3 to 105 m^3 affected the flame speed. 7,8% methane/air concentration was used for tests 37 to 42 and the average flame speed was 110,6 m/s. Only one test (test 28) was conducted with a 7,7% methane/air concentration which resulted in a 55,1 m/s flame speed. This difference in flame speed of more than 100% between test 28 and the average flame speed of the rest of the tests in this category was probably due to an experimental error.

Discussion of results of the tests conducted without a suppression system

A summary of the results of the tests conducted without a suppression system can be seen in Table II. When comparing the average flame speed between tests with a CM model inside the test tunnel (9% methane/air concentration) and tests with a CM model with shoulder in position (7,8% methane/air concentration), the flame speed increased from 72,9 m/s to 110,6 m/s. This is almost a 52% increase in the average flame speed. The reason for this difference was as a result of the decrease in the cross-sectional area caused by the presence of the shoulder.

Although the flame speeds with a 7,8% methane/air concentration (CM model with a shoulder) was 40% faster than those at 9% (CM model without a shoulder), it can still be reasonably concluded that the tests conducted without a suppression system resulted in the most violent explosions when the methane/air concentration was 9% while weak explosions occurred when the methane/air concentration was 7.5%. The reasoning behind this conclusion is because of the absence of the shoulder in the tests conducted with a 9% methane/air concentration, thus the 40% difference in flame speed. Unfortunately no test with a 9% methane/air concentration with the shoulder in position were conducted to make a more accurate comparison.

Tests conducted with the suppression system

Forty-three tests have been conducted with an active on-board suppression system present inside the test tunnel. Test 0 was the first and only test conducted using a local on-board suppression system. For the other forty-two tests, an international system (Centrocen / DMT Explo-Stop System) was used. The Centrocen / DMT Explo-Stop System is a German based system which proved to be very effective in suppressing flame propagation.

The tests conducted with the suppression system can be categorized in three different areas:

- on-board suppression tests with a CM
- on-board suppression tests with a CM model (full face)
- on-board suppression tests with a CM model with the shoulder in position.

According to the test protocol for tests conducted under this category, the machine operator's position was 8 m from the face of the test tunnel.

On-board suppression tests with a CM

Only three tests were conducted with a CM (Joy 14 CM 6). Test 0 was the first test conducted using the local on-board suppression system with the shoulder in position. A 9% methane/air concentration was used and the volume of the mixture was kept at 87,5 m^3 for this test. This test caused severe damage to the test tunnel with a failure of the suppression system to stop the flame propagation. The fastest flame speed recorded was 189,9 m/s (Table III). The flame propagated throughout the test tunnel. This vast disparity in the flame speed was caused by two factors: the 9% methane/air concentration and the presence of the shoulder.

Table II

Average flame speed without suppression system

Empty tunnel		Test with a CM		Test with a CM model		CM Model with a shoulder	
(%)	S (m/s)	(%)	S (m/s)	(%)	S (m/s)	(%)	S (m/s)
9 12	45.2 44.9	9	94.1	7.5 9	32.6 72.9	7.7 7.8	55.1 110.6

Table III

On-board suppression tests with a CM and a CM model (full-face tests) results

Test with a CM					Test with a CM model (Full face test)				
No.	(%)	S (m/s)	L	P	No.	(%)	S (m/s)	L	P
0	9	189.9	>19	Roofs & Sides	22	9	11.9	4	TLF
3	7.5	19.6	2	TLF	23	9	9.1	4	TLF
4	9	7.6	3	TLF	24	9	13.9	4	TLF and TRF
					25	9	17.7	4	TLF
					26	9	14.5	4	TLF
					27	9	14.4	4	TLF

TLF: Top left flame, TRF: Top right flame, SLF: Side left flame, SRF: Side right flame, L: Flame length, P: Flame position
Volume CH_4/Air = 87,5 m^3

The other two tests (test 3 and 4) in this category were full-face tests and the international system (Centrocen / DMT Explo-Stop System) was used. Two methane/air concentrations were used, 7,5% and 9% and the volume of the mixture was again kept at 87,5 m^3 throughout the tests. Both tests were successful and the flame stopped propagating at 2 m and 3 m respectively long before it could reach the operator's position. The highest flame speed was 19,6 m/s or about 10% of that in Test 0. The results of the on-board active suppression system tests with a CM machine are shown in Table III. In Table III, flame positions e.g. TLF (Top Left Flame), TRF (Top Right Flame), SLF (Side Left Flame) and SRF (Side Right Flame) indicates whether the flame has been detected on the sides and/or the roof of the tunnel.

On-board suppression tests with a CM model (full-face tests)

Six tests were conducted with a CM model (simulation of a Joy 14 CM 9). While using the same volume mixture that was used in the on-board suppression tests with a CM, only 9% methane/air concentration was used. A Centrocen / DMT Explo-Stop System successfully stopped flame propagation at 4 m in all six tests. The average flame speed was 14,2 m/s. The on-board suppression tests with a CM model (full-face tests) results are shown in Table III.

On-board suppression tests with a CM model with the shoulder in position

Seven tests were conducted with a suppression system on board the CM model and shoulder in position, the results of which are shown in Table IV. Two methane/air concentrations were used; 9% and 12%, and the volume of the mixture was increased to 105 m^3 throughout this series of tests. In all the tests, the flame propagated beyond the operator's position as prescribed by the test protocol except test 36.

Tests 29 to 32 where 9% methane/air concentrations was used were partially successful and the flame propagated up to 3 m beyond the operator's position with an average flame speed of 23,8 m/s. In test 33 the flame propagated up to 19 m with a flame speed of 33,1 m/s while in test 34 the on-board suppression system failed to operate and the flame propagated throughout the test tunnel with a speed of 38,1 m/s. The overall average flame speed with 9% methane/air concentrations was 25,7 m/s. Test 36 was a repeat of test 34 where the flame propagation stopped within 8 m.

Discussion of results of the tests conducted with the suppression system

Both the on-board suppression tests with a CM and with a CM model were successful and the flame propagation ceased before reaching the operator's position, except in test 0 which was a failure. All the tests that succeeded were full-face tests while the failure was a shoulder test.

The results of the on-board suppression tests with a CM model with the shoulder in position were all unsuccessful except for test 36. The reason for the failure was the presence of the shoulder in position as well as an increase of the methane/air volume from 87,5 m^3 to 105 m^3. Therefore we can once again conclude that the most violent explosions occurred when shoulder tests were conducted.

When we compare the average flame speeds of the shoulder tests conducted with a suppression system and without a suppression system, the average flame speed of the tests with the suppression system where 9% methane/air concentrations was used was 25,7 m/s while tests conducted without a suppression system with 7,8% methane/air concentrations was 110,6 m/s, the results of which are given in Table V. From these results we can conclude that even though there were failures with the shoulder tests, the suppression system still reduced the flame speed by up to 76,8%.

Tests conducted with a roadheader model in an inclined gallery

Twenty-seven tests, the results of which were compiled by

Table IV

On-board suppression tests results with a CM model with the shoulder in position

Test No.	CH_4/Air (%)	Flame speed (m/s)	Flame length (m)	Flame position
29	9	22.8	10	TRF
30	9	23.8	10	TRF
31	9	26.8	9	TRF and SRF
32	9	21.8	11	TRF
33	9	33.1	19	TRF
34	12	38.1	> 19	Roof and sides
36	12	4.6	8	TRF

Volume CH_4/Air = 105.0 m^3

Table V

Average flame speed with suppression system

Test with a CM		Test with a CM model		CM model with a shoulder	
(%)	S (m/s)	(%)	S (m/s)	(%)	S (m/s)
7.5	19.6	9	14.2	9	25.7
9	7.6			12	21.4

Van Dijk[3], were conducted for Houilleres de Bassin du Centre at du Midi (France) and Ineris (France). A Dosco 1300H type roadheader (RH) model was used. There were three ways to conduct tests with a RH model in an inclined gallery, namely:

- on-board suppression tests with a RH model (full face tests)
- on-board suppression tests with a RH model inside the shoulder
- on-board suppression tests with a RH model outside the shoulder.

On-board suppression tests with a RH model (full-face)

Eight full-face tests have been conducted with a RH model, the results of which are shown in Table VI. Three methane/air concentrations were used, 7,5%, 9% and 12%, but the volume of the mixture was kept at 116 m^3 throughout this series of tests. According to the protocol for tests conducted under this category, the machine operator's position was at 7 m from the face of the test tunnel. In tests 44, 49 and 69 the suppression system failed to stop flame propagation before the flame reached the operator's position. The flame propagated beyond the operator's position for a distance of 3 m, 1 m and 2 m respectively. The average flame speed for the full-face RH model tests using a methane-air mixture of 116 m^3 with a 9% methane/air concentration was 29,7 m/s.

On-board suppression tests with a RH model inside the shoulder

Eight tests were conducted with a RH model inside the shoulder. While using the same concentrations that were used in the on-board suppression tests with a RH model (full-face), the volume of the mixture was kept at 90 m^3 throughout this series of tests. According to the protocol for tests conducted under this category, the machine operator's position was again at 7 m from the face of the test tunnel. Results of the on-board suppression tests with a RH model inside the shoulder are shown in Table VI.

In tests 52 and 53 the suppression system failed again to stop flame propagation before the flame reached the operator's position. The flame propagated beyond the operator's position at 3 m and 1 m respectively. The average flame speed for the RH model inside the shoulder tests using a methane-air mixture of 90 m^3 with a 9% methane/air concentration was 37,9 m/s.

On-board suppression tests with a RH model outside the shoulder

Eleven tests were conducted with a RH model outside the shoulder. The same as for the two previous series of tests conducted, three concentrations were used; 7,5%, 9% and 12% but the volume of the mixture was increased to 180 m^3 throughout this series of tests. In this category, the volume of the methane/air mixture was doubled (180 m^3 instead of 90 m^3) compared to that used in the test with the on-board suppression for a RH model inside the shoulder. According to the test protocol for tests conducted under this category, the machine operator's position was at 11 m from the face of the test tunnel. Results of the on-board suppression tests with a RH model outside the shoulder are shown in Table VII.

In test 57, despite the fact that 7,5% of the methane/air mixture was used, the flame propagated 19 m to the top left side (roof side) of the test tunnel with a 17,3 m/s flame speed. In test 58, the on-board suppression system failed to operate and the flame propagated throughout the test tunnel with a speed of 21,2 m/s. In tests 61, 62, 63 and 65 the flame propagated 1 m or 2 m beyond the operator's position. The average flame speed for the RH model outside the shoulder tests using a methane-air mixture of 180 m^3 with a 9% methane/air concentration was 36,6 m/s.

Discussion of results of the tests conducted with a RH model in an inclined gallery

Under this category, three methane/air concentrations were used, 7,5%, 9% and 12%, and three different volumes of mixture were used, 90 m^3, 116 m^3 and 180 m^3.

The presence of a RH model with the shoulder in position resulted in a very significant reduction in the tunnel cross-section and a consequent increase in flame speed. We can

Table VI

On-board suppression tests with a RH model (full-face tests) and RH model inside the shoulder results

Test with a RH model (Full face test)					Test with a RH model inside the shoulder				
No.	(%)	S (m/s)	L	P	No.	(%)	S (m/s)	L	P
43	7,5	13,4	5	TLF	50	9	35,7	7	TLF and TRF
44	9	51,4	10	TLF	51	9	26,3	7	TRF
45	9	20,9	7	TRF	52	9	89,3	10	TRF
46	9	20,1	6	TRF and TLF	53	9	35,8	8	TRF
47	9	29,4	7	TRF and TLF	54	9	22,7	6	TRF and SLF
48	9	36,6	7	TRF	55	12	13,7	4	TLF
49	12	18,9	8	TRF	56	7,5	97,7	> 19	Roof and sides
69	9	19,9	9	TLF	68	9	17,7	7	TLF

Volume CH_4/Air = 116 m^3 Volume CH_4/Air = 90 m^3

Table VII

On-board suppression tests with a RH model outside the shoulder results

Test no.	CH_4/Air (%)	Flame speed (m/s)	Flame length (m)	Flame position
57	7.5	17.3	19	TLF
58	9	21.2	> 19	Roof and sides
59	9	37.4	11	SRF
60	9	46.8	8	TRF
61	9	44.2	13	TRF
62	9	42.7	12	TRF
63	9	40.3	12	TRF
64	9	32.8	9	Roof and sides
65	12	28.6	13	TRF
66	9	34.4	9	TRF and TLF
67	9	29.3	8	TRF

Volume CH4/Air = 180 m^3

once again conclude from the tests conducted that the highest flame speed was recorded when the shoulder was present inside the test tunnel as it can be seen in Table VIII.

Test 56 was conducted without a suppression system so as to compare with the flame speeds of tests with the suppression system. In test 56, the fastest flame speed was recorded at 97,7 m/s under 7,5% methane/air concentration. The reason for this was the installation of the shoulder in position. In test 56, the flame propagated throughout the test tunnel. The flame speed of the full-face RH model test with a 7,5% methane/air concentration was 13,4 m/s while the test with the RH model outside the shoulder was 17,3 m/s. These results indicate that the on-board suppression system reduced the flame speed by more than 82%.

Out of the 27 tests conducted, 21 used 9% methane/air concentration. The average flame speed was 29,7 m/s with the full-face RH model and 37,9 m/s with the RH model inside the shoulder. This results in a 27,6% increase in the flame speed. The average flame speed was 36,6 m/s with the RH model outside the shoulder.

The other three tests were conducted with a 12% methane/air concentration, namely, test with a RH model full-face test, test with a RH model inside the shoulder and test with the RH model outside the shoulder. The results of these tests were 18,9 m/s, 13,7 m/s and 28,6 m/s respectively.

It can be concluded from these tests results that the position of the RH model either inside the shoulder or outside the shoulder is what affects the flame speed compared to full-face tests.

Table VIII

Average flame speed with a RH model in an inclined gallery

Test with a RH model (Full face test)		Test with a RH model inside the shoulder		Test with a RH model outside the shoulder	
(%)	S (m/s)	(%)	S (m/s)	(%)	S (m/s)
7.5	13.4	9	37.9	7.5	17.3
9	29.7	12	13.7	9	36.6
12	18.9			12	34.4

Conclusions

It can be concluded from the tests conducted with an on-board suppression system that the Centrocen / DMT Explo-Stop System successfully stopped flame propagation inside the test tunnel. Despite a few failures, this system has a potential of significantly reducing the risk of harm to CM and RH operators involved in underground methane ignitions.

As expected, the most violent explosions occurred when the methane/air concentration was 9%. This was, in general, also the concentration that resulted in the highest flame speed. The presence of an actual CM or full-size models of a RH or a CM resulted in a very significant reduction in the tunnel cross-section and a consequent increase in flame speed. In fact, on the occasion of the first test, the failure of the suppression system on a Joy 14 CM 6 resulted in massive damage to the test tunnel when 87,5 m^3 of 9% methane/air mixture was ignited.

In South Africa, the coal mining operations are highly mechanized with more than 175 continuous miner machines in use. Even though the risk of a coal mine explosion can never be reduced to zero by a single line of defence, the Centrocen / DMT Explo-Stop System active on-board suppression system has the potential of stopping explosions and could be deployed in high risk areas to reduce the possibility of a coal mine explosion.

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Appendix 1

Test No	Date of test	Membrane position	Volume m³	Ch_4/Air %	Continuous miner	Shoulder	Suppression system	Comments	Flame position
Test 0	14 Jul. 1995	5 metres	87,5	9,0	CM	Yes	HS Design Engineering	Cutter on the floor	>19 meters
Test 1	23 Aug. 1995	3 metres	26,5	9,0	Empty	No	No		>19 meters
Test 2	25 Aug. 1995	3 metres	52,5	9,0	Empty	No	No		>19 meters
Test 3	6 Sep. 1995	5 metres	87,5	7,5	CM	No	Centrocen	Cutter on the floor	TLF - 2 m
Test 4	8 Sep. 1996	5 metres	87,5	9,0	CM	No	Centrocen	Cutter on the floor	>TLF - 3 m
Test 5	13 Sep. 1995	5 metres	87,5	9,0	CM	No	No	Cutter on the floor	>19 meters
Test 6	14 Sep. 1995	5 metres	87,5	9,0	CM	No	No	Cutter on the floor	>19 meters
Test 7	22 Oct. 1995	5 metres	87,5	9,0	Empty	No	No	Data acquisition system failed.	
Test 8	11 Dec. 1995	5 metres	87,5	9,0	Empty	No	No		>19 meters
Test 9	29 Apr. 1996	5 metres	87,5	9,0	Empty	No	No		>19 meters
Test 10	30 Apr. 1996	5 metres	87,5	12,0	Empty	No	No		>19 meters
Test 11	2 May 1996	5 metres	87,5	12,0	Empty	No	No		>19 meter
Test 12	21 May 1996	5 metres	87,5	9,0	Empty	No	No		>19 meters
Test 13	24 May 1996	5 metres	87,5	9,0	Model	No	No	Cutter on the floor	>19 meters
Test 14	31 May 1996	5 metres	87,5	9,0	Model	No	No	Cutter on the floor	
Test 15	16 Jul. 1996	5 metres	87,5	7,5	Model	No	No	Cutter in the middle of the tunnel	>19 meters
Test 16	18 Jul. 1996	5 metres	87,5	9,0	Model	No	No	Cutter at 1,5 meter. Igniter at floor level	>19 meters
Test 17	23 Jul. 1996	5 metres	87,5	7,5	Model	No	No	Cutter at 1,5 meter. Igniter at 1,5 meter	>19 metres
Test 18	24 Jul. 1996	5 metres	87,5	7,5	Model	No	No	Cutter at ceiling	>19 metres
Test 19	13 Aug. 1996	5 metres	87,5	9,0	Model	No	No	Cutter on the floor	>19 metres
Test 20	12 Sep. 1996	5 metres	87,5	9,0	Model	No	No	Cutter on the floor	>19 metres
Test 21	2 Oct. 1996	5 metres	87,5	9,0	Model	No	No	Cutter on the floor	>19 metres
Test 22	26 Nov. 1996	5 metres	87,5	9,0	New Model	No	Centrocen	Cutter on the floor, stationary. Igniter was on the left side of the cutter	TLF -4m
Test 23	29 Nov. 1996	5 metres	87,5	9,0	New Model	No	Centrocen	Cutter on the floor, rotating. Igniter was on the left side of the cutter	TLF -4m
Test 24	3 Dec. 1996	5 metres	87,5	9,0	New Model	No	Centrocen	Cutter on the floor, rotating. Igniter was on the right side of the cutter	TLF and TRF -4m
Test 25	4 Dec. 1996	5 metres	87,5	9,0	New Model	No	Centrocen	Cutter at the middle position, rotating. Igniter was on the centre of the cutter	TLF -4m
Test 26	6 Dec. 1996	5 metres	87,5	9,0	New Model	No	Centrocen	Cutter at the ceiling, rotating. Igniter was on the left side of the cutter	TLF -4m
Test 27	9 Dec. 1996	5 metres	87,5	9,0	New Model	No	Centrocen	Cutter at the ceiling, rotating. Igniter was on the right side of the cutter	TLF -4m
Test 28	13 Dec. 1996	7 metres	105,0	7,7	New Model	Yes	No	Cutter on the floor, rotating. Igniter was on the right side of the cutter	>19 meters
Test 29	19 Dec. 1996	7 metres	105,0	9,0	New Model	Yes	Centrocen	Cutter on the floor, rotating. Igniter was on the left side of the cutter	TRF -10m
Test 30	15 Jan. 1997	7 metres	105,0	9,0	New Model	Yes	Centrocen	Cutter on the floor, rotating. Igniter was on the left side of the cutter	TRF -10m
Test 31	21 Jan. 1997	7 metres	105,0	9,0	New Model	Yes	Centrocen	Cutter on the floor, rotating. Igniter was on the right side of the cutter	TRF SRF -9m
Test 32	22 Jan. 1997	7 metres	105,0	9,0	New Model	Yes	Centrocen	Cutter at the ceiling, rotating. Igniter was on the left side of the cutter	TRF -11m
Test 33	24 Jan. 1997	7 metres	105,0	9,0	New Model	Yes	Centrocen	Cutter at the ceiling, rotating. Igniter was on the right side of the cutter	TRF -19m
Test 34	28 Jan. 1997	7 metres	105,0	12,0	New Model	Yes	Centrocen	Cutter at the ceiling, rotating. Igniters were on the left side of the cutter	>19 meters
Test 35	28 Jan. 1997	n/a	n/a	n/a	New Model	Yes	Centrocen		
Test 36	31 Jan. 1997	7 metres	105,0	12,0	New Model	Yes	Centrocen	Cutter at the ceiling, rotating. Igniters were on the left side of the cutter	TRF -8m
Test 37	11 Apr. 1997	7 metres	105,0	7,8	New Model	Yes	No	Cutter at the middle position, rotating. Igniter was on the left side of the cutter	>19 meters
Test 38	15 Apr. 1997	7 metres	105,0	7,8	New Model	Yes	No	Cutter at the middle position, rotating. Igniter was on the left side of the cutter	>19 meters

Appendix 1 (Continued)

Test No	Date of test	Membrane position	Volume m^3	Ch_4/Air %	Continuous miner	Shoulder	Suppression system	Comments	Flame position
Test 39	18 Sep. 1997	7 metres	105,0	7,8	New model	Yes	No	Cutter at the middle position, stationary. Igniter was on the left side of the cutter	>19 meters
Test 40		7 metres	105,0	7,8	New model	Yes	No	Cutter at the middle position, stationary. Igniter was on the left side of the cutter	>19 meters
Test 41	11 Dec. 1997	7 metres	105,0	7,8	New model	Yes	No	Cutter at the middle position, stationary. Igniter was on the left side of the cutter	>19 meters
Test 42		7 metres	105,0	7,8	New model	Yes	No	Cutter at the middle position, rotating. Igniter was on the left side of the cutter	>19 meters
Test 43	6 Jul. 1998	5 metres	116,0	7,5	RH model	No	Centrocen	Cutter at the bottom left position, stationary. Igniter was on the bottom side of the cutter	>TLF - 5 m
Test 44	8 Jul. 1998	5 metres	116,0	9,0	RH model	No	Centrocen	Cutter at the bottom left position, rotating. Igniter was on the bottom side of the cutter	>TLF - 5 m
Test 45	10 Jul. 1998	5 metres	116,0	9,0	RH model	No	Centrocen	Cutter at the bottom lright position, rotating. Igniter was on the right side of the cutter	>TRF - 7 m
Test 46	14 Jul. 1998	5 metres	116,0	9,0	RH model	No	Centrocen	Cutter at the centre of the face, rotating. Igniter was on the centre of the cutter	>TRF and TLF - 6 m
Test 47	15 Jul. 1998	5 metres	116,0	9,0	RH model	No	Centrocen	Cutter at the top left position, rotating. Igniter was on the bottom side of the cutter	>TRF -and TLF - 7 m
Test 48	16 Jul. 1998	5 metres	116,0	9,0	RH model	No	Centrocen	Cutter at the top right position, rotating. Igniter was on the right side of the cutter	>TRF - 7 m
Test 49	20 Jul. 1998	5 metres	116,0	12,0	RH model	No	Centrocen	Cutter at the bottom left position, rotating. Igniter was on the left side of the cutter	>TRF - 8 m
Test 50	4 Aug. 1998	5 metres	90,0	9,0	RH model	Yes	Centrocen	Cutter at the bottom left position. Igniter was on the left side of the cutter	>TRF and TLF - 7 m
Test 51	5 Aug. 1998	5 metres	90,0	9,0	RH model	Yes	Centrocen	Cutter at the bottom right position. Igniter was on the right side of the cutter	>TRF - 7 m
Test 52	11 Aug. 1998	5 metres	90,0	9,0	RH model	Yes	Centrocen	Cutter at the centre of the face position. Igniter was on the centre of the cutter	>TRF- 10 m
Test 53	12 Aug. 1998	5 metres	90,0	9,0	RH model	Yes	Centrocen	Cutter at the top left position. Igniter was on the left side of the cutter	>TRF - 8 m
Test 54	13 Aug. 1998	5 metres	90,0	9,0	RH model	Yes	Centrocen	Cutter at the top righy position. Igniter was on the right side of the cutter	>TLF and SLF - 6 m
Test 55	18 Aug. 1998	5 metres	90,0	12,0	RH model	Yes	Centrocen	Cutter at the bottom left position. Igniter was on the left side of the cutter	>TLF - 4 m
Test 56	19 Aug. 1998	5 metres	90,0	7,5	RH model	Yes	No	Cutter at the bottom left position. Igniter was on the left side of the cutter	>19 metres
Test 57	24 Aug. 1998	9 metres	180,0	7,5	RH model	Yes	Centrocen	Cutter at the bottom left position. Igniter was on the left side of the cutter	>TLF - 19 m
Test 58	25 Aug. 1998	9 metres	180,0	9,0	RH model	Yes	Centrocen	Cutter at the bottom left position. Igniter was on the left side of the cutter	>19 metres
Test 59	31 Aug. 1998	9 metres	180,0	9,0	RH model	Yes	Centrocen	Cutter at the bottom right position. Igniter was on the right side of the cutter	>STLF - 11m
Test 60	2 Aug. 1998	9 metres	180,0	9,0	RH model	Yes	Centrocen	Cutter at the top right position. Igniter was on the bottom side of the cutter	>TRF - 13 m
Test 61	4 Sep. 1998	9 metres	180,0	9,0	RH model	Yes	Centrocen	Cutter at the centre of the shoulder's face.. Igniter was on the centre of the cutter	>TRF - 13 m
Test 62	10 Sep. 1998	9 metres	180,0	9,0	RH model	Yes	Centrocen	Cutter at the center of the shoulder's face. Igniter was on the centre of the cutter	>TRF - 12 m
Test 63	14 Sep. 1998	9 metres	180,0	9,0	RH model	Yes	Centrocen	Cutter at the bottom left position. Igniter was on the left side of the cutter	>TRF - 12 m
Test 64	23 Sep. 1998	9 metres	180,0	9,0	RH model	Yes	Centrocen	Cutter at the top left position. Igniter was on the left side of the cutter	>9 metres
Test 65	29 Sep. 1998	9 metres	180,0	12,0	RH model	Yes	Centrocen	Cutter at the top left position. Igniter was on the left side of the cutter	>TRF - 13 m
Test 66	20 Jan. 1999	9 metres	180,0	9,0	RH model	Yes	Centrocen	Cutter at the bottom right position. Igniter was on the right side of the cutter	>TRF - 13 m TLF - 9 m
Test 67	21 Jan. 1999	9 metres	180,0	9,0	RH model	Yes	Centrocen	Cutter at the top right position. Igniter was on the right side of the cutter	>TRF - 8 m
Test 68	25 Jan. 1999	5 metres	90,0	9,0	RH model	Yes	Centrocen	Cutter at the bottom left position. Igniter was on the right side of the cutter	>TLF - 7 m
Test 69	29 Jan. 1999	5 metres	116,0	9,0	RH model	No	Centrocen	Cutter at the bottom left position. Igniter was on the left side of the cutter	>TLF - 9 m