SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

FINAL PROJECT REPORT

Quantification of methane behaviour in continuous miner headings using a controlled environment

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Research Agency	**:**	**CSIR Miningtek (ESH 99—0363)**
Project Number	**:**	**COL 619**
Date	**:**	**June 2000**

Executive Summary

In order to quantitatively assess the effect a ventilation system has on in-heading methane control around a continuous miner, the amount of methane released into the heading needs to be known. This can only be done in the controlled environment of a test gallery.

The aim of this project was to determine the methane control and dilution ability of the retrofitted hood and half-curtain ventilation systems. The two systems were tested in the full-scale ventilation test gallery at CSIR Miningtek's Kloppersbos Test Facility.

The effect of three variables were investigated during the test series, namely the distance of the force column outlet from the face, the pressure of the water supply to the spray fan system, and the rate of methane release into the test section. The tests were conducted for an identified worst-case scenario under static ventilation conditions.

For all the tests, the two ventilation systems complied with the regulatory requirements that have been laid down. The only exception was that for the retrofitted hood system, the air velocity over the operator's cab was insufficient when the outlet of the force column was more than 20 m from the face.

The test results indicate that the half-curtain system has better methane control and dilution abilities than the retrofitted hood system for the scenario tested.

It also came to light that when the force column outlet is moved further than 20 m from the face, its effect on in-heading ventilation conditions is very limited. With a water supply pressure of 15 bar, the face-sweep effect of the water spray system is more pronounced than with a supply pressure of 20 bar.

With regard to the regulatory requirements for underground in-heading ventilation systems, it was found that some air quantities, i.e. recirculation and face air volume required per square metre, are difficult to apply and measure. It is suggested that these quantities should be refined or new ones be developed, using the surface test facility, to assist in the effective application of in-heading underground ventilation systems.

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Glossary of Abbreviations and Symbols

ANOVA	analysis of variance
APTR	as per test requirement
CFD	computational fluid dynamic
CM	Continuous miner
CH_4	methane
CSIR	Counsel for Scientific and Industrial Research
DMEA	Department of Mineral and Energy Affairs
F/C (FC)	force column
GME	government mining engineer
H/C	half curtain
L/F	left front
LTR	Last through road
MS	means squares
N/A	not applicable
P	probability
R/H	retrofitted hood
Ret.	return
SS	sums of squares
SIMRAC	Safety in Mines Research Advisory Committee

Symbols

bar	bar
KPa	kilo Pascal
L/min	liters per minute
m	meter
mm	millimeters
m^3/s	cubic meters per second
m/s	meters per second
%	percentage

1 Aim of Testing

The objective of the ventilation simulation tests done during project COL 619 was to quantify the effectiveness with which the specified ventilation and dust-control systems control and dilute methane gas in a heading, using a controlled environment.

2 Introduction

Ventilation is the primary means of controlling the methane hazard in underground mechanical miner headings. To manage this hazard, it is very important to accurately determine the effectiveness with which a ventilation system clears a heading of methane.

Various methods have been devised for this purpose. In the USA, surface galleries have been used for such determinations. However, owing to the significant differences between the two countries in mining procedures and conditions, ventilation techniques and equipment used, it is difficult to apply these results directly to South African conditions. Some of the indices developed from these tests were adapted and applied locally. However, practical limitations on the placement of methane sensors and the dynamic gas conditions found in our headings resulted in limited success being achieved in applying these indices to determine the effectiveness of a ventilation system in controlling methane (Van Zyl *et al.*, 1997).

In South Africa, the emphasis has been placed on *in situ* methane monitoring. Efforts were directed towards determining whether an applied ventilation system succeeded in keeping methane levels within acceptable limits. In general it was found that the methane levels were below the legal requirement of 1,4 % of methane by volume. Despite this, ignitions still occur. Why? Partly because there are very important questions that have not been answered and cannot be answered using *in situ* monitoring alone. These are questions such as: How effectively does a ventilation system clear a heading of methane? How well will it cope with possible surges? The reason why we have not been able to answer these questions is because there are too many variables that cannot be measured or controlled in a production section. The most important of these variables is the rate at which methane is released into a heading. If this quantity can be determined, the effectiveness with which a particular ventilation set-up clears a heading of methane can be quantitatively assessed.

The only way to accurately quantify the methane release rate is to control it, and this can only be achieved in the controlled environment of a test gallery. The full-scale ventilation tunnel at CSIR Miningtek’s Kloppersbos Test Facility is ideal for performing such tests.

Use of the test gallery allows the methane-clearing ability of various ventilation methods to be quantitatively assessed. The maximum methane-control potential of the systems can be determined to give an indication of how “safe” they are with regard to sudden increases in the rate of methane release. By controlling the environment, the optimum operating parameters relating to methane control for a specific ventilation set-up can also be determined.

3 The Test Gallery

3.1 Simulation Design

Owing to the complex and dynamic ventilation conditions present in an underground production heading, a complete simulation of conditions in the heading is not possible at present.

The second-best solution is to identify and simulate the worst-case scenario pertaining to methane control during the development cycle of a heading. If the ventilation system is capable of controlling methane under these conditions, it is reasonable to assume that it will be able to control methane during the whole development cycle of the heading.

3.2 Worst-case Scenario

The worst-case scenario, with regard to methane control, is the point at which the methane levels usually attain a definite maximum during the cutting sequence of a heading.

From available underground methane data, it is known that this point is reached in a continuous miner (CM) section at the end of the first lift during the second cut of a heading (Figure 3.2a). There is definite rise and fall in the methane levels around the cutter head relating to the sumping and shearing actions of the CM. It appears that the peak methane levels occur when the boom is approximately 60 % down into its shear cycle. As the CM boom was static during the tests at Kloppersbos, this was the boom position throughout the test series (Figure 3.2b).

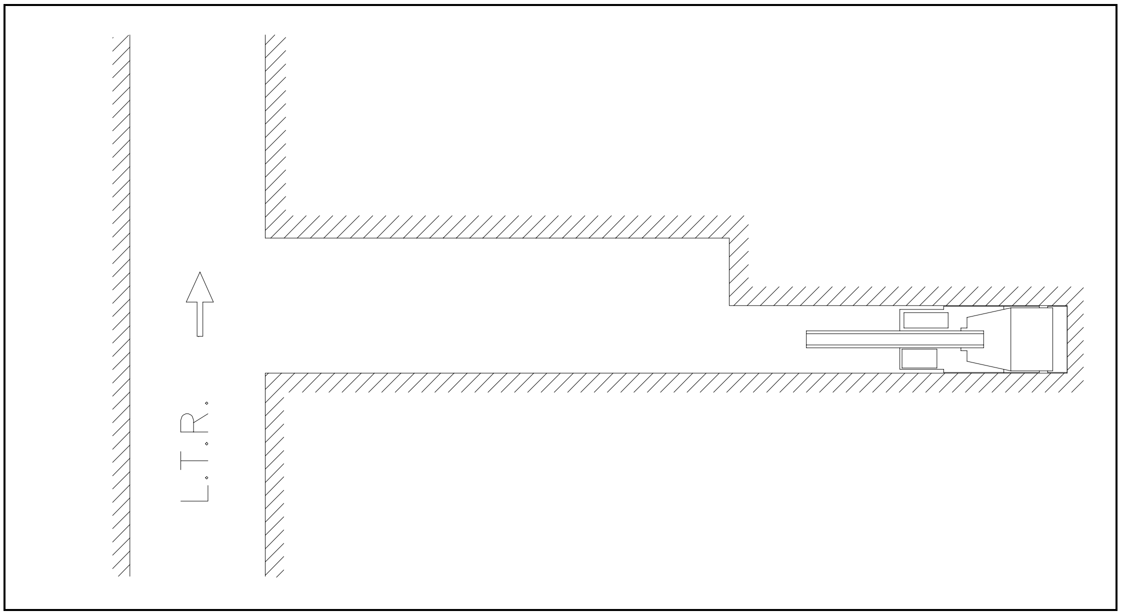

Figure 3.2a: CM position for the worst-case scenario simulated

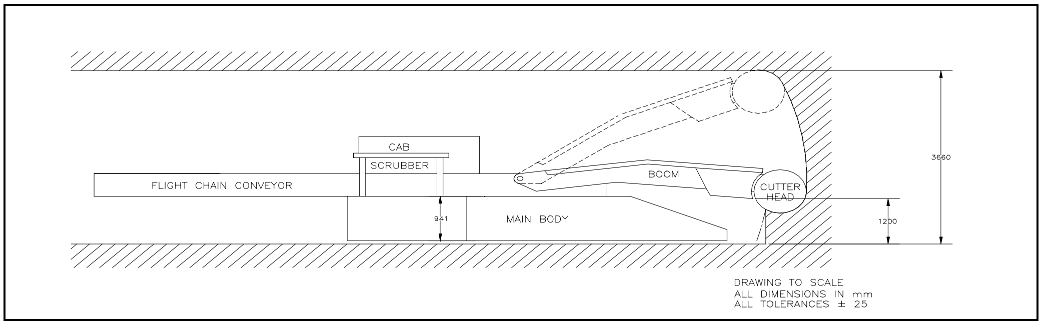

Figure 3.2b: Side profile of the CM model and boom position

Various factors contribute to the worst-case scenario as discussed. With regard to the position of the CM, the main factor is the distance that the secondary ventilation has to penetrate the heading. This is the maximum distance it has to penetrate in order to dilute/control the liberated methane. Secondly, the air volume around the CM is restricted, so methane liberated into the heading has less air by volume to be diluted by, resulting in possible higher concentrations per volume. Thirdly, at this depth the virgin seam gas pressure will be at its “highest” during the cutting of the heading, resulting in the peak methane release rates being experienced (freshly cut coal surrounds the whole cutting head).

Concerning the position of the boom (Figure 3.2a), it stands to reason that when the boom is fully lifted, the methane levels will be at the minimum as there is no freshly cut coal under the boom and the volume of air available to dilute the liberated methane is at the maximum. As the CM sumps and shears, freshly cut coal is dropped onto the gathering arms, liberating methane. As the boom lowers during the shearing cycle, the volume of air available to dilute the methane liberated from the cut coal reduces. In conjunction with this, the available air volume is already partially “saturated” with methane liberated form the cut coal gathered and removed by the gathering arms and the methane “drawn” in from in front of the cutting head due to its rotation. It appears that this situation reaches a peak when the boom has lowered approximately 60 % to 70 %.

3.3 General Test Gallery Layout

The test section consists of a last through road (LTR) with a heading leading from it (Figure 3.3a). The structure of the gallery consists of a steel frame covered with corrugated iron. The seam height varies from 3,5 m at the inlet to 3,8 m at the face, with a road width of 6,5 m. The LTR has a length of 50 m and the heading has a maximum depth of 40 m.

The air velocity in the LTR can be varied from 0,5 m/s to 4,0 m/s with the use of the inlet damper control on the twin-inlet centrifugal exhaust fan.

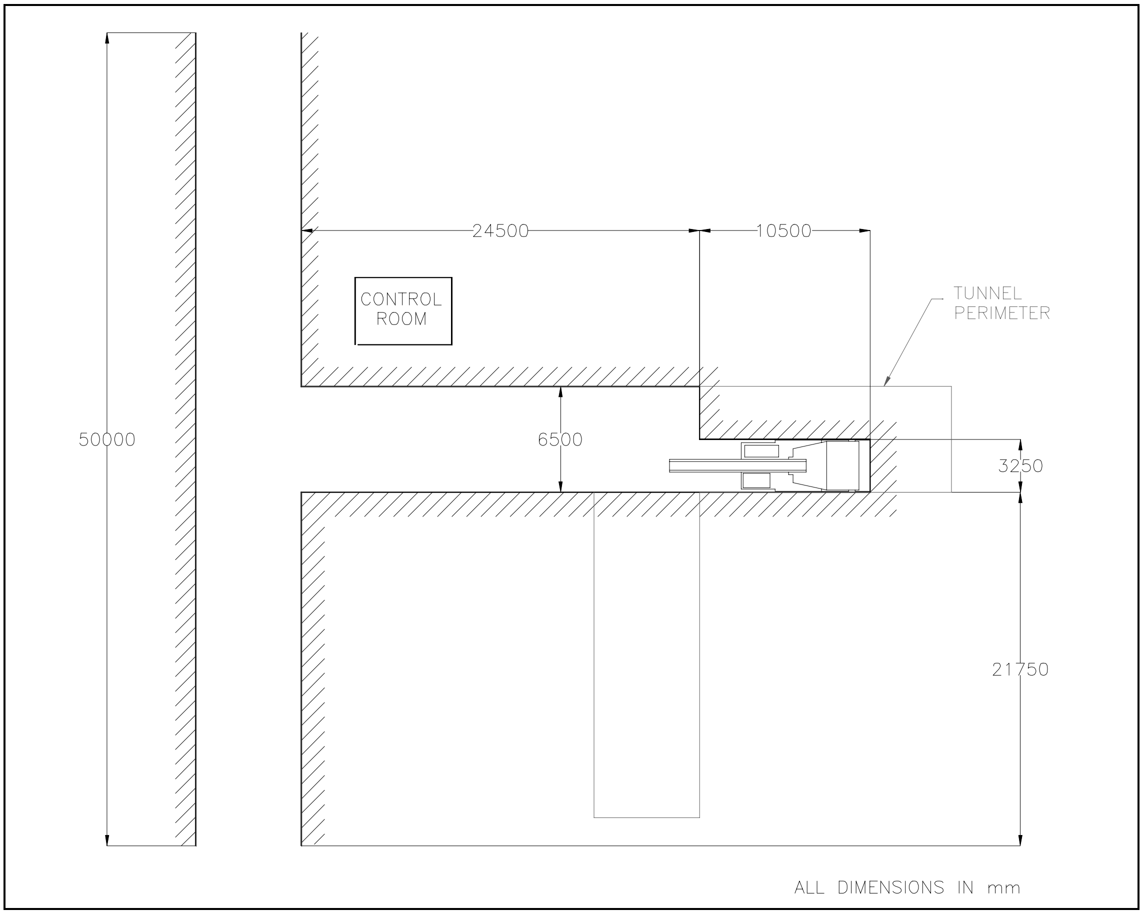

Figure 3.3a: Test gallery layout for the test series

In order to improve the accuracy of the airflow patterns during testing , the profile of the heading was based on that of a cut heading (Figure 3.3b).

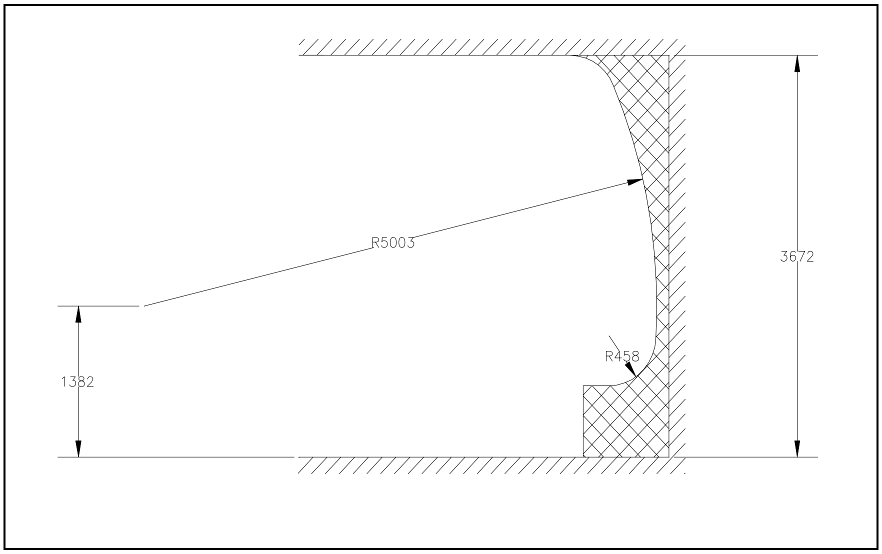

Figure 3.3b: Cut section of the heading profile

3.4 The CM Model

A full-scale model of a CM, without moving parts and based on the dimensions of a JOY HM9 CM, was used for the test series.

The CM model was fitted with the water spray system developed by Kloppersbos, consisting of 31 sprays (Belle and Du Plessis, 1998). The sprays are distributed around the CM as follows:

- four directional spray blocks on top of the boom (three sprays per spray block)
- two directional spray blocks at the bottom of the boom (three sprays per spray block)
- one fan spray block to the right of the cutter head (three sprays)
- one horizontal spray block at the bottom of the boom on the right, facing left (two sprays)
- one horizontal spray block on the spade, directing to the right (two sprays)
- one L-shaped block on the right of the model (total six sprays: four vertical and two horizontal).

All the sprays are hollow-cone sprays with a single 1,6 mm inlet and a 2 mm outlet. A D35 Meyers piston pump with a maximum capacity of 3 000 kPa (140 L/min) supplies water to the spray system.

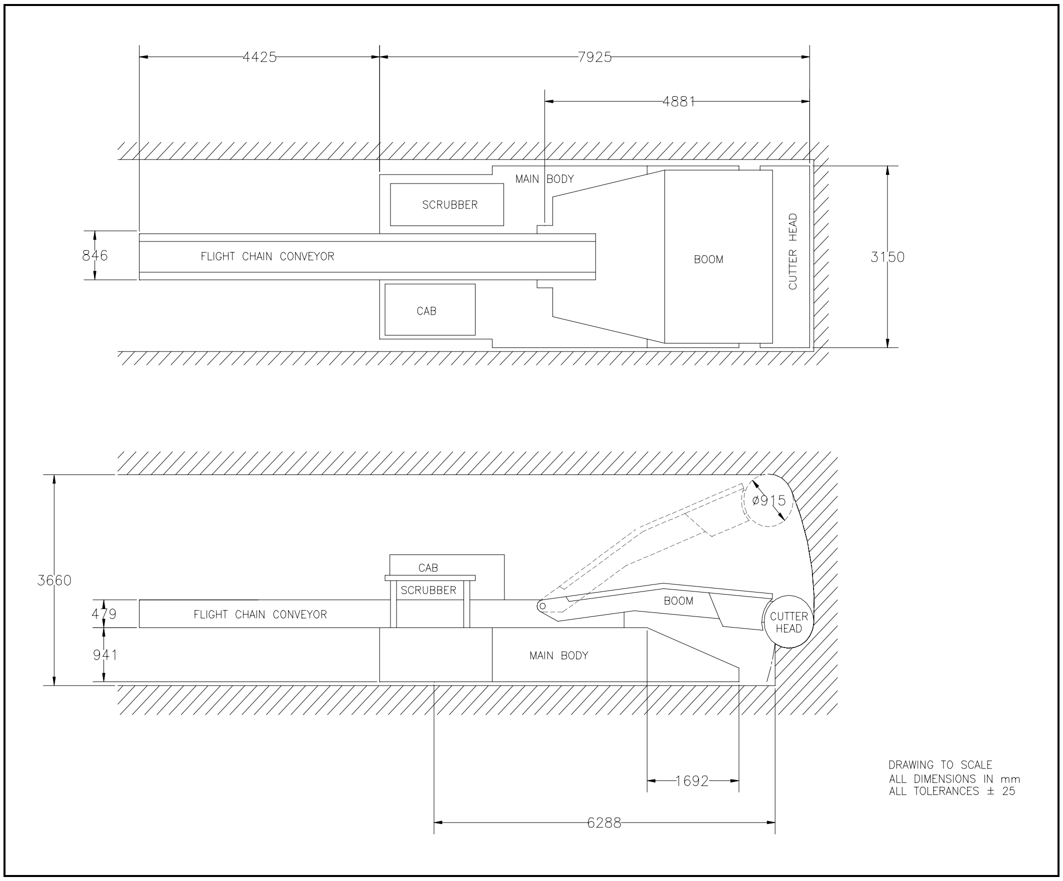

Figure 3.4: Details of the CM model

4 Instrumentation

4.1 Basis of Instrumentation Layout

The instrumentation layout of the ventilation tunnel is based on three main considerations:

- The instrumentation must be able to determine whether the ventilation system complies with the statutory requirements.

- It must be verified that the ventilation system is operating within its design specifications.
- The methane conditions in the test section must be quantifiable.

4.2 Statutory Requirements

There are five quantities that must be determined to ensure that a ventilation system complies with the statutory regulations (DMEA, 1995):

1. The LTR velocity must be 1,0 m/s, but no lower than 0,6 m/s.
2. A minimum airflow of 0,4 m/s needs to pass over the operator, in the direction of the face.
3. Methane levels in the heading must not exceed 1,4 % by volume.
4. A minimum fresh air quantity of 0,2 $m^3/s/m^2$ of face area is required in the heading.
5. Recirculation is not allowed to exceed 50 % for on-board scrubbers.

Requirements 4 and 5 are difficult quantities to measure physically in an active heading. These quantities are mainly used as guidelines when a ventilation system is designed. Both the ventilation systems tested were designed to comply with these requirements (Belle and Du Plessis, 1998).

Taking this into account, only requirements 1 to 3 were monitored during the test series, i.e. velocities and methane levels. These three quantities were used to determine whether the ventilation systems complied with the regulatory requirements (Figure 4.21).

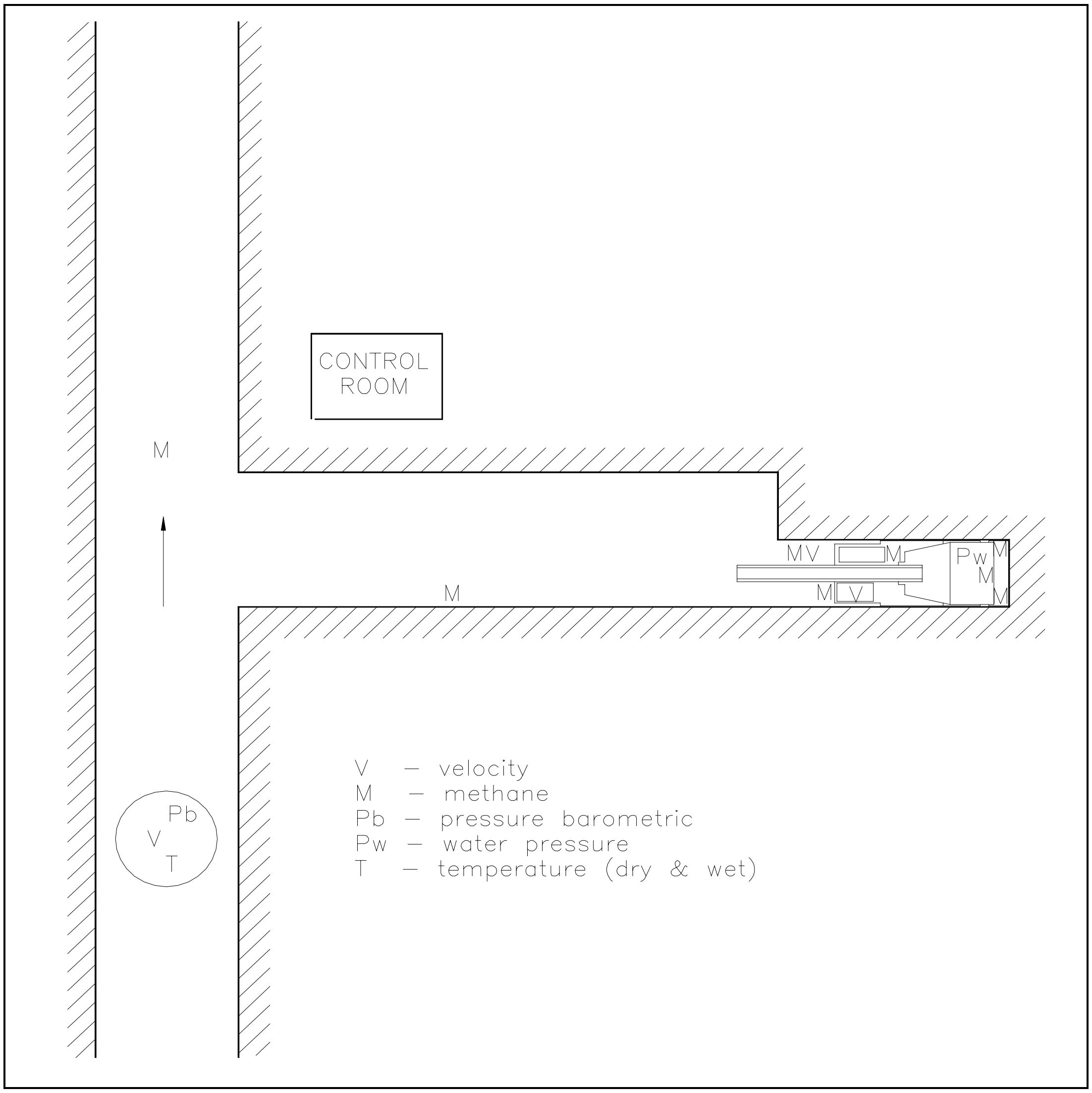

Figure 4.2: Instrumentation layout in the test section

4.3 Ventilation System and Test Section Operating Parameters

To ensure that the ventilation system being tested is operating within its design parameters, it is critical to monitor the vital operating parameters (Section 7). As the intention of the ventilation system is to move air, all the factors influencing air movement need to be monitored. These include:

- the force column (F/C) volumetric flow rate (m^3/s)

- the scrubber volumetric flow rate (m^3/s)
- the water pressure of the water spray fan system (kPa).

It is also important to monitor the two operating parameters of the test section, namely the methane in-flow rate and the methane distribution at the face (Section 5). The methane in-flow rate is monitored at the main inlet valve using an in-line Ventcaptor flow meter. The flow is recorded electronically every two seconds on the same real-time clock as the methane data. The methane distribution is controlled via three needle valves in the control room using in-line Rotameter flow meters. The distribution setting was kept constant for the duration of the test series.

4.4 Methane Monitoring

To quantify the methane behaviour in a test section, several quantities are investigated:

- The maximum methane level recorded during a test and its location are important. This information is used to identify whether ‘problem’ areas exist and where they are located in the heading.
- It is important to determine whether the general methane distribution in the heading exhibits the expected trends, based on the general design philosophy of the ventilation system.

For the two ventilation systems tested, the general in-heading methane-removal design was as follows: Fresh air is blown over the operator’s cab towards the face. On reaching the face, it must sweep the released methane across the cutting face towards the scrubber inlets. The scrubber then discards the ‘methane-polluted’ air in the direction of the LTR, with a possible 40 % air recirculation allowed. To be able to evaluate the general methane distribution, methane sensors are placed on both sides of the cutter head, and at the operator’s cab (Figure 4.1). By monitoring the methane levels at these locations, a quantitative indication of the sweeping of the face and of recirculation is obtained (Section 8.4).

4.5 Data Logging System

To be able to quantify the methane behaviour in the test section, it is necessary to record the methane levels during the test. To optimise the data, the methane levels are continuously monitored throughout a test. The methane levels (and the methane in-flow rate) are recorded every two seconds.

5 Methane Release Simulation

5.1 Location of Gas Release in the Heading

Three main areas of significant methane release can be identified in an active CM heading (Cook, 1994):

- the freshly cut coal face exposed directly above the cutting head as it shears down
- the coal face area directly in contact with the cutting drum
- the freshly cut coal accumulated at the gathering arms.

The gas release rate of these three methane-liberating areas can be expected to vary owing to the different characteristics of the exposed coal.

Above the cutting head, the coal is still intact with limited surface area exposed. The driving factor for methane release is the in-seam gas pressure equalising with the barometric pressure.

In front of the cutter head, the coal face exposed can be expected to have the highest difference between the barometric pressure and the in-seam gas pressure, resulting in a higher methane-liberation rate than above the cutter head where the face has been exposed for a “longer” time. In addition, the cutter head fractures the coal face to break coal from it, increasing the exposed surface area and resulting in increased gas-liberation rates.

As not all the gas is liberated immediately from the broken coal, gas liberation continues as the coal gathers on the floor of the heading. Although this quantity can be expected to be lower, the decreasing air volume under the boom as the boom shears down, and the possible restrictions on ventilation in this area, make it an important quantity to simulate.

Quantifying a value for each of these areas is very difficult. As a point of departure, the methane distribution was based on the Computational Fluid Dynamic (CFD) simulation work carried out by CSIR Miningtek in 1994 (Cook, 1994). The trends observed from the simulations showed good correlation with the *in situ* data gathered (Van Zyl, 1994). The methane distribution shown in Table 5.1 was used for the entire test series.

The conditions described above were simulated with the use of a gas distributor. The distributor consists of three pipes located at the face, each having a number of holes. The pipes are covered with foam and the outlets are pointed towards the face, allowing an even distribution of gas at the face. The ratio of gas release between the three pipes, each representing an identified methane-liberation area, is achieved through the use of needle valves. The methane gas is supplied to the test section from four commercially available gas cylinders (99,5 % methane by volume) operated in parallel.

Table 5.1

Methane distribution in the test section heading

Area of Release	**% of Liberated Methane**
Above the cutter drum	12
Cutter drum area	80
Gathering arm area	8

5.2 Gas Release Rate into the Heading

The quantity of methane to be released into the test heading was derived from similar work done in test galleries in the USA (Taylor, 1999) and from local values for coal gas content and release rates (Cook, 1999; Van Zyl, 1998). In the test protocol it was specified that the ventilation systems had to be tested for coals with high, medium and low methane release rates. From the gas content data available and an estimation of how long broken coal is present in a heading during the filling of a shuttle car, the methane release rates for the three scenarios were calculated. The values given in Table 5.2 were calculated and used throughout the test series.

Table 5.2

Methane release rate values

Release Rate Condition	**Release Rate (L/min)**
Low	80
Medium	200
High	600

6 Test Procedure

All ventilation systems are switched on and allowed to run for five minutes.

Before the start of each test, the following environmental conditions in the heading are monitored:

1. LTR velocity
2. Ambient temperature
3. Velocity at the operator's cab
4. Volumetric flow rate of the scrubber
5. Volumetric flow rate of the force column
6. Water pressure supplied to the water sprays.

To determine the pre-test methane conditions in the heading, the methane levels are monitored for 120 seconds. This is to establish the zero conditions of the test. Methane gas is then released into the test section at the required rate and continued until one of two conditions are met. Firstly, if steady state methane conditions are present in the heading for a period of 75 seconds, the test is terminated. Secondly, if after 180 seconds a steady state condition has still not been achieved, the test is also terminated; this is done because of practical and cost implications. The 180-second period was chosen as a cut-off as this represents three minutes of continuous shearing of the CM, which is an overestimation of the worst-case scenario.

7 Ventilation Systems Tested

Two ventilation systems were tested, namely:

- a forced secondary ventilation system with a half-curtain system placed on the CM (Belle and Du Plessis, 1998)
- a forced secondary ventilation system with a retrofitted hood system in place (Belle & Du Plessis, 1998).

For each of these systems, the effect of three operating parameters on the system's ability to control methane was investigated:

i. the effect of water pressure variations on the operation of the on-board spray system
ii. the effect of the position of the forced ventilation column outlet, with regard to the face, on methane behaviour
iii. the ability of the secondary ventilation system to cope with various methane-liberation rates.

To determine the reliability of the test results, each test was repeated three times.

Table 7

Schedule of tests conducted

Test Parameters				
Test No.	**Water Pressure (bar)**	**Outlet Distance from the Face (m)**	**Methane Emission Rate (L/min)**	**Reliability Determination (no. of tests)**
1	15	15	80	3
2	15	15	200	3
3	15	15	600	3
4	15	20	80	3
5	15	20	200	3
6	15	20	600	3
7	15	25	80	3
8	15	25	200	3
9	15	25	600	3
10	20	15	80	3
11	20	15	200	3
12	20	15	600	3
13	20	20	80	3
14	20	20	200	3
15	20	20	600	3
16	20	25	80	3
17	20	25	200	3
18	20	25	600	3
Total no. of tests per ventilation system				**54**

8 Data Analysis

8.1 Aim of Data Analysis

The aim of the data analysis is to verify the compliance of a ventilation system with the regulatory requirements as set out in Section 4. To achieve this, a number of parameters are monitored or calculated for each test. From the data set obtained, the effectiveness of the ventilation system is evaluated.

To ensure the reliability of the test data, all tests were conducted three times. In the evaluation of the required parameters, the average of the three test values was taken as a test value.

8.2 Statutory Requirements

The statutory requirements that were investigated in this test series are given in Table 8.1 (see Section 4.2).

Table 8.2

Statutory requirements

No.	Quantity	Requirement
1	Last through road (LTR) velocity	1,0 m/s
2	Airflow past operator’s cab	> 0,4 m/s
3	Peak methane levels	< 1,4 % by volume

LTR Velocity

The LTR velocity is measured downwind from the test heading with a vane anemometer in accordance with current underground monitoring practices. The LTR is measured and adjusted before a test session commences. The LTR velocity is checked randomly throughout the duration of a test session.

Airflow Past Operator’s Cab

The airflow across the operator’s cab is measured before a test commences when the ventilation set-up is changed. The velocity at the cab is measured with a vane anemometer in the region of the head of the CM operator.

Peak Methane Levels

The methane levels are measured at four points at two-second intervals throughout a test (Figure 4.2). The maximum of the steady state average methane levels recorded during a test is taken as the peak methane level for that test.

8.3 Operating Parameters of the Ventilation System and Test Section

The quantities monitored to verify that the ventilation system and test section are operating within specifications are tabled below.

Table 8.3

Operating parameters of the ventilation system and test section

No.	Operating Parameter	Requirement
Ventilation System		
1	Water pressure of the spray system	15 and 20 bar
2	Volumetric flow rate of the scrubber	10 m^3/s
3	Volumetric flow rate of the force column	6 m^3/s
Test Section		
4	Methane release rate	80, 200 and 600 L/min

Volumetric Flow Rate of the Scrubber

Before each test, the volumetric flow rate of the scrubber is measured at the inlet of the scrubber by measuring the inlet velocity.

Volumetric Flow Rate of the Force Column

The volumetric flow rate of the force column is measured at the start of each test. The velocity is measured at the outlet and the volumetric flow rate is calculated.

Water Pressure of the Spray System

The water pressure to the spray system is measured at the right front spray block. The pressure is checked and adjusted at the start of each test session. The pressure is also checked sporadically during the course of testing.

Methane Release Rate

The methane release rate is measured and recorded in the control room every two seconds at the main gas inlet. The flow rate is adjusted via a needle valve to achieve the desired flow rate (Section 4.3).

8.4 Quantification of Methane Behaviour

To quantify the methane behaviour in the test heading, the quantities shown in Table 8.3 are determined or calculated (Section 4.4):

Table 8.3

Methane behavioural investigation quantities

No.	Quantity	Measurement
1	Peak methane level	Level (%) and location
2	Face sweep index	The closer to 0, the better
3	% Methane recirculation	The lower, the better (< 50 %)

Peak Methane Level

The peak methane value is the maximum average steady state methane level recorded during a test. It is the same value used to verify statutory compliance. In addition to the maximum level, the location of the maximum level is also recorded. This allows the methane ‘hot spots’ to be determined, allowing for proper sensor placement in underground headings.

Face Sweep Index

An inherent operating principle of both the ventilation systems tested is the sweeping of released methane across the face towards the scrubber inlet/s. Care has to be taken to quantify this effect sensibly. To obtain a quantitative indication of the effectiveness of this action, a 'Face Sweep Index' is used.

The Face Sweep Index is simply the ratio between the methane concentrations at the air intake side of the cutter head and those at the return air side.

$$FSI = \frac{\%CH_4 Intake}{\%CH_4 \mathrm{Re}turn} \tag{8.1}$$

The closer this index is to zero, the 'more effectively' methane is swept across the face of the heading. This is because the more effectively methane is swept across the face, the higher the methane level recorded on the return air side should be, and hence the Face Sweep Index will reduce in value.

When a ventilation system is set up, the amount of air moved across the face is independent of the methane release rate at the face. As there is some concern about the accuracy of pellistor-based methane sensors at low methane levels (< 0,4 % by volume), only the methane levels recorded during the high release rate tests are used for this analysis. By doing this, a more accurate estimation of the face-sweeping action is obtained.

% Methane Recirculation

The percentage methane recirculation is used as an indicator to determine how much 'methane-contaminated' air is being reintroduced (recirculated) back into the heading. It is assumed that the fresh air from the force column contains no methane. As the airflow is in the direction of the face over the operator's cab (Section 8.2), it stands to reason that if any methane is measured at the operator's cab, it is most likely to have come from the 'contaminated' air recirculating from the scrubber exhaust and/or the air passing by the scrubber. To quantitatively assess this amount of 'recirculation', the methane recorded at the operator's cab is related to the maximum methane level recorded at the cutter head, as a percentage value.

$$\%\mathrm{Re}circ. = \frac{\%Cab_{CH4}}{\%DrumPeak_{CH4}} * 100 \tag{8.2}$$

The lower the percentage methane recirculation, the 'better' a ventilation system is performing, as the amount of 'contaminated' air reintroduced into the heading is reduced, allowing more fresh air to enter the heading and increasing the availability of fresh air for methane dilution.

Using the argument put forward for the Face Sweep Index, only the percentage methane recirculation for the high methane release rate tests is calculated (Section 8.4).

9 Results

Table 9a

Test results for the half-curtain ventilation system

		Test No.																	
Parameter	**Rqr.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Operating Parameters																			
CH_4 release rate (m^3/s)	APTR**	88	203	571	90	200	568	94	201	567	88	204	563	91	202	567	95	205	565
Scrub. vol. flow rate (m^3/s)	10	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6	8,6
FC* vol. flow rate (m^3/s)	6	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3	4,3
FC outlet from face (m)	APTR	15	15	15	20	20	20	25	25	25	15	15	15	20	20	20	25	25	25
Spray syst. pressure (bar)	APTR	15	15	15	15	15	15	15	15	15	20	20	20	20	20	20	20	20	20

*FC – Force column

** APTR – As per test requirement

Table 9b

Test results for the half-curtain ventilation system

		Test No.																	
Parameter	**Rqr.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Statutory Requirements																			
LTR velocity (m/s)	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Cab velocity (m/s)	> 0,4	1,5	0,9	0,7	1,5	0,9	0,7	1,5	0,9	0,7	1,3	1,2	0,8	1,3	1,2	0,8	1,3	1,2	0,8
Peak CH_4 level (%)	< 1,4	0,1	0,3	0,8	0,1	0,3	0,9	0,1	0,3	0,8	0,0	0,2	0,7	0,1	0,3	0,7	0,1	0,3	0,8
Methane Behaviour Quantification																			
Peak CH_4 location		L/F*	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F
Face Sweep Index	→ 0	N/A	N/A	0,22	N/A	N/A	0,24	N/A	N/A	0,29	N/A	N/A	0,29	N/A	N/A	0,30	N/A	N/A	0,35
% CH_4 recirculation (%)	→ 0	N/A	N/A	42	N/A	N/A	25	N/A	N/A	25	N/A	N/A	25	N/A	N/A	28	N/A	N/A	32

* Left front, i.e. at the drum on the return air side

Table 9c

Test results for the retrofitted hood ventilation system

		Test No.																	
Parameter	**Req.**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
Operating Parameters																			
CH_4 release rate (m^3/s)	APTR[**]	95	198	568	90	197	571	99	198	568	95	201	570	100	198	567	97	196	564
Scrub. vol. flow rate (m^3/s)	10	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7	6,7
FC* vol. flow rate (m^3/s)	6	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1	5,1
FC outlet from face (m)	APTR	15	15	15	20	20	20	25	25	25	15	15	15	20	20	20	25	25	25
Spray syst. pressure (bar)	APTR	15	15	15	15	15	15	15	15	15	20	20	20	20	20	20	20	20	20

* FC – Force column

** APTR – As per test requirement

Table 9d

Test results for the retrofitted hood ventilation system

		Test No.																	
Parameter	**Req.**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
Statutory Requirements																			
LTR velocity (m/s)	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Cab velocity (m/s)	> 0,4	0,6	0,4	-1,2	0,6	0,4	-1,2	0,6	0,4	-1,2	0,6	0,7	-1,2	0,6	0,7	-1,2	0,6	0,7	-1,2
Peak CH_4 level (%)	< 1,4	0,1	0,3	0,7	0,1	0,2	0,7	0,1	0,3	1,0	0,1	0,2	0,8	0,1	0,2	0,7	0,1	0,3	1,0
Methane Behaviour Quantification																			
Peak CH_4 location		L/F*	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F	L/F
Face Sweep Index	→ 0	N/A	N/A	0,39	N/A	N/A	0,50	N/A	N/A	0,34	N/A	N/A	0,55	N/A	N/A	0,65	N/A	N/A	0,45
% CH_4 recirculation (%)	→ 0	N/A	N/A	15	N/A	N/A	17	N/A	N/A	12	N/A	N/A	16	N/A	N/A	18	N/A	N/A	14

* Left front, i.e. at the drum on the return air side

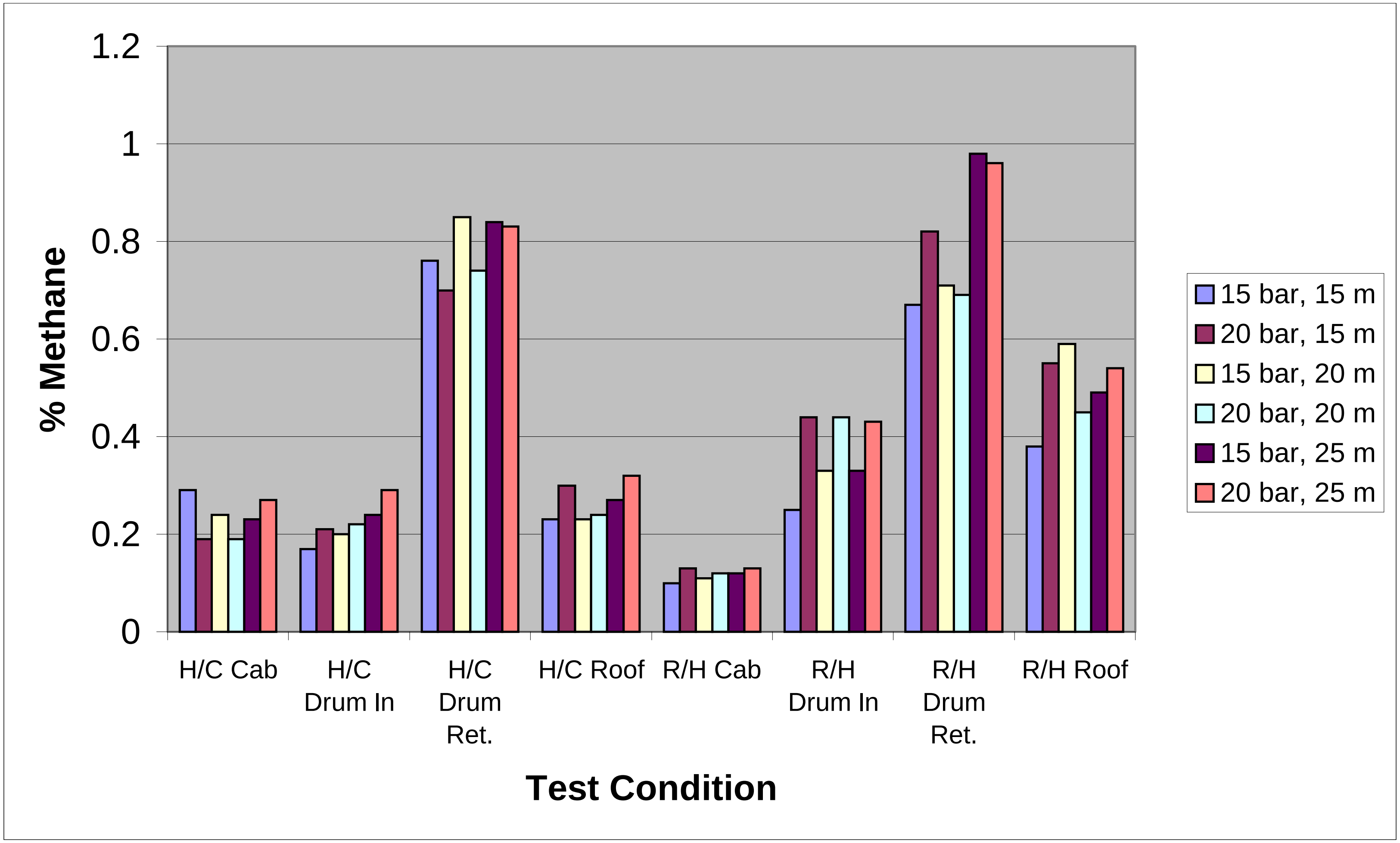

Figure 9: In-heading methane distribution for the high release rate test

10 Statistical Analysis

To determine whether variations in methane release rates, water supply pressure, exhaust column outlet position, and their various combinations had a significant influence on the peak methane levels recorded in the heading, or whether these changes were due to statistical chance, a factorial analysis of variance (ANOVA) was conducted on the data.

To statistically quantify the ability of the ventilation systems, in their varying configurations, to control methane, the peak methane values recorded in the test section were used as basis the analysis. This was done as the main factor used underground to determine the risk of methane is the maximum levels recorded. The factors used for the ANOVA analysis were the;

- Ventilation system used,
- The distance of the force column outlet from the face,
- The methane release rate,
- And the methane monitoring points.

The ANOVA table and the analysis are discussed in detail in Appendix A. The discussions of the main factors and their interactions are also discussed in Appendix A.

From the factorial analyses the following conclusions can be deduced:

- The type of ventilation system used i.e. the half-curtain or retrofitted hood system, has a significant effect on the peak methane levels recorded, with a MS value of 0,194.
- The effect water pressure has on peak methane concentrations is insignificant. The results show that when the system is operating in the range of 15 bar and 20 bar, the methane levels are well below the legal limits. It has to be over stressed that this holds true for the peak methane levels recorded, but when considering the face sweep index, were a ratio is used, a different result is obtained (Refer to section 11.6)

- There is strong evidence that the distance of force column outlet from the face has a significant effect on the peak methane levels recorded at various methane release rates for both ventilation systems.
- The methane release rate (low, medium and high) has a significant effect on the peak methane levels recorded in the test section. It has to stressed that both ventilation systems performed well in keeping the peak methane levels below the required legal limit.
- In addition to the effect the changing of one of the above mentioned variables has on peak methane levels, various two-factor combination effects were also investigated. The results of the investigated two-factor interactions are shown in table 10.1

Table 10

Two-factor interaction analysis

Two-factor interaction	Statistical Significance
Ventilation system type x F/C distance	Significant
Ventilation system type x methane release rate	Significant
F/C distance x methane release rate	Significant
Ventilation system type x water pressure	Insignificant
Water pressure x F/C distance	Insignificant
Water pressure x methane releases rate	Insignificant

- Upon investigating possible three-factor and higher order interactions it was found that the interactions are statistically insignificant related to the peak methane levels recorded in the test section.

11 Discussion

11.1 Last Through Road (LTR) Velocity

The LTR velocity was not a parameter that was investigated in this test series. The LTR velocity was set to 1 m/s and measured, and corrected if necessary before each test session started. For all the tests, the LTR velocity was 1,0 ± 0,1 m/s.

11.2 Airflow Past the Operator's Cab

During the course of the test series, the outlet position of the force column and the water pressure of the spray system were varied. These changes can have a definite effect on the air velocities measured past the operator's cab. For each test setting, the airflow past the operator's cab was measured at approximately the height of the CM operator's head.

For the half-curtain system, the air velocities past the operator, for all the test settings, was well above the required 0,4 m/s. As could be expected, the lowest airflow past the operator was measured when the force column outlet was 25 m from the face, i.e. 0,7 m/s at 15 bar water pressure and 0,8 m/s at 20 bar.

For the retrofitted hood system, the case was different. When the force column outlet was 20 m from or closer to the face, the air velocity past the cab met the requirements, although it was generally less than half the value recorded for the same conditions with the half-curtain system in place. It was, however, found that when the outlet was 25 m from the face, a negative flow condition over the cab, i.e. away from the face, was present. It appears that air from the column reaches the back of the model but does not have enough energy to push up and over the cab position. This caused a negative flow condition at the cab. This was the case with a water supply pressure of both 15 and 20 bar. It is also interesting to note that the negative flow had the same magnitude for the test conditions of both 15 and 20 bar. With the water spray system switched off, the negative flow over cab stayed the same, i.e. 1,2 m/s.

11.3 Peak Methane Levels Recorded

The peak allowable level of 1,4 % methane by volume was never reached or exceeded during the test series. This was true for both ventilation set-ups. Refer to Figure 9.

The peak methane levels recorded during the half-curtain tests were in the region of 0,85 % by volume. These levels were recorded on the return air side of the cutter head during the high methane release rate tests (± 580 L/min), with the force column outlet at 20 m from the face and at a water pressure of 15 bar. The methane level with the force column outlet at 25 m from the face is 0,83 % by volume - very close to the peak of 0,85 % by volume. For the medium release rate tests, the peak methane levels recorded were in the region of 0,30 % by volume, and for the low methane release rate tests, in the region of 0, 05 % by volume. It is interesting to note that the peak methane levels are generally higher when the water supply pressure is 15 bar.

For the retrofitted hood system, the peak methane levels were generally higher (approx. 15 %) than for the half-curtain system, with peak levels reaching 0,98 % by volume. Again, the peaks were recorded on the return air side of the cutter head. During the medium release rate tests, the peak methane levels recorded were in the region of 0,30 % by volume, and for the low release rate tests, in the region of 0,15 % by volume. No distinct pattern between water supply pressure and peak methane values can be observed for this system. However, it has to be noted that there is a definite increase in the peak values when the force column outlet is moved beyond 20 m, i.e. 25 m, from the face.

From the perspective of peak methane levels, both ventilation systems comply with the regulatory requirements. However, it should be kept in mind that this is a steady state simulation and that methane levels may differ under dynamic conditions.

11.4 Operating Parameters

Water Supply Pressure

The water supply pressure was measured at the left front spray block. Before each test, the pressure was checked and adjusted if required. For all the tests, the water supply pressure was within ± 1 bar of the required pressure.

Force Column Volumetric Flow Rate

The force column exhaust volumetric flow rate was measured each day before a test session started. Initially the exhaust flow rate was measured for all column lengths, i.e. 15 m, 20 m, and 25 m from the face. It was found that for all three cases, the exhaust flow rate was practically measured to be constant at 4,3 m^3/s. Although an exhaust flow rate of 6,0 m^3/s was specified, it was decided to keep the test set-up as is, as this would more closely simulate underground practices.

Scrubber Volumetric Flow Rate

The design volumetric flow rate of the scrubber used was 10 m^3/s.

For the half-curtain tests, the volumetric flow rate of the scrubber was measured and found to be 8,6 m^3/s. Again, using the same philosophy as for the force column, this volumetric flow rate for the scrubber was used for all the tests.

With the increased flow resistance caused by fitting the retrofitted hood to the same scrubber, a drop in the volumetric flow rate was observed. The flow rate through the scrubber was measured to be 5,1 m^3/s. This flow rate was used throughout the test series.

11.5 Methane Release Rate

The methane release rate was measured electronically and kept to within ± 5 % of the required flow rate.

Due to the range of the electronic flow meter, the methane flow rate for the high release rate tests was reduced from the required 600 L/min to 565 L/min. This was done to ensure accurate flow rate readings, as the top-end limit of the flow meter is 610 L/min.

11.6 Methane Behaviour Quantification

Location of the In-heading Peak Methane Level

For all the tests, the peak methane levels were recorded on the return air side of the cutter head. This indicates that the general flow pattern in the heading complies with the design philosophy of moving air past the cab towards the face, across the face and out via the scrubber.

Face Sweep Index

From the Face Sweep Index (i.e. the methane conditions at the face - see Section 8.4), it appears that the half-curtain system induces a more effective airflow across the face than the retrofitted hood system.

Force column outlet position effect:

As the force column outlet is moved away from the face, the two ventilation systems behave differently.

- For the retrofitted hood system, the face sweep conditions deteriorate when the column is moved from 15 m to 20 m away from the face. This is most likely because the force column causes more general turbulence in the heading when placed at 20 m from the face, reducing the combined effect of the of the directional sprays at the cutter head and force column air stream. When the column is moved further back to 25 m, the effect of the force column is much less (refer to the cab velocities measured). In this position, the directional sprays at the cutter head have the more dominant effect, and hence improved face sweep conditions are observed.

- For the half-curtain system on the other hand, the combination of the half curtain and force column complements the action of the directional sprays in moving air across the face towards the scrubber intake, which is located further back than the intakes of the retrofitted hood system. The result is overall better 'face - sweeping' conditions. With the force column outlet 20 m or closer to the face, no marked difference in the face sweep conditions is observed. However, with the outlet at 25 m, a reduction in the face sweep action can be observed. In fact, the conditions approach those of the retrofitted hood system. It is therefore clear that when the force column is 25 m away from the face, its effect on in-heading methane control is limited.

Water supply pressure effect:

With regard to the effect of the supply water pressure on the face sweep action the following observations were made. For both systems, an improvement in the face sweeping is observed when the supply pressure is reduced from 20 bar to 15 bar. For the half curtain, an average improvement of 28 % is observed and for the retrofitted hood, an average of 38 %. This effect is also evident in the peak methane levels recorded in that the peaks recorded are higher when the water supply pressure is 15 bar. This due to the fact that more methane is swept across the face at the lower supply pressure, resulting in higher peaks being recorded on the return air side of the cutter head.

Taking these factors into account, and looking at the general in-heading methane levels, which are higher for the retrofitted hood system, it is appears that the half-curtain system is better in controlling and diluting methane at the face.

It has to be borne in mind that the surface ventilation tunnel simulation test results and conclusions correspond to the static test conditions unlike the dynamic conditions existing underground.

% Methane Recirculation

When viewing the results for the percentage methane recirculation, it appears that the half-curtain system causes nearly double the amount of recirculation than the retrofitted hood system. On closer investigation though, the reason for this is clear.

For the retrofitted hood system, the general methane levels at the face are 33 % higher than for the half-curtain system (refer to the roof, cutter head intake and return levels - Figure 9). Since the methane release rate is the same, it is clear that the retrofitted hood system must be removing less methane from the face area. This could be caused by a combination of factors, namely reduced scrubber volume, less effective sweeping of the face and reduced airflow towards the scrubber intakes. Whatever the reason, it means that less methane enters the scrubber and hence leaves the scrubber. The methane in the air leaving the scrubber is then recirculated. Using the elevated levels at the return air side of the cutter head and the 'reduced' methane levels recorded at the operator's cab to calculate the percentage methane recirculation, a false indication of the percentage methane recirculation is obtained. Although the volumetric flow rate of the scrubber is reduced by the retrofitted hood, thus 'improving' the calculated percentage recirculation, it is difficult to verify whether the retrofitted hood in fact produces less recirculation than the half-curtain system. To verify this, the methane levels at the scrubber outlet need to be determined and used to calculate the recirculation.

Regarding the two ventilation systems individually, it is difficult to evaluate the percentage methane recirculation because the methane concentration at the scrubber outlet is unknown. It is suggested that a specific test be developed to measure system re-circulation.

General Observations

In general, for the half-curtain system, the methane levels measured at the operator's cab, the cutter head air intake side and the roof are all in the same region. For the retrofitted hood, on the other hand, the cab levels are generally lower than those measured by the roof and cutter head air intake side sensors. It is also observed that the peak levels for the retrofitted hood are similar to or higher than those for the half-curtain system. From these observations it appears that the half-curtain system removes more methane from the heading than the retrofitted hood system. It has to be kept in mind that the volumetric flow rate for the retrofitted hood is 35 % lower than that of the half-curtain system. To offset this, however, the same amount of ventilating energy is used for both systems, with significantly different results.

12 Conclusions

- Both the ventilation systems are able to keep the peak methane levels below the maximum allowable levels for the methane emission levels of 80 L/min, 200 L/min and 600 L/min.
- It is clear that for the same scrubber unit and force column set-up, the half-curtain ventilation system has better in-heading methane dilution and control ability than the retrofitted hood system at a methane emission level of 600 L/min.
- During the tests with a methane emission level of 600 L/min, it was found that when the force column outlet is moved further than 20 m from the face, its effect is significantly reduced. At 25 m, a negative flow over the cab is induced when the on-board ventilation is switched off (scrubber and spray fan system).
- The half-curtain system promotes the 'sweeping action' across the face better than the retrofitted hood system during the methane release rate of 600 L/min. This may be related to the location of the scrubber inlets.
- Better 'face sweeping' is obtained with a water supply pressure of 15 bar than with 20 bar at methane release rates of 80 L/min, 200 L/min and 600 L/min.
- The half-curtain ventilation system is able to maintain the required ventilation across the operator's cab for all test conditions. For the retrofitted hood system, this requirement is not met when the force column is 25 m from the face.
- To determine the percentage methane recirculation, it will be necessary to measure the methane levels at the scrubber outlet.

13 Future Work

From the results it appears that the distance of the force column from the face can have a significant effect on the ability to control methane at the face. The interaction between the on-board and off-board ventilation system components needs to be closely evaluated to more clearly define the application of the system in order to obtain optimum results from the system.

From the calculation of the ‘recirculation’, it can be seen that there is a definite difference between the ‘design’ value for recirculation and the ‘measured’ recirculation. A specific test should be designed to measure this quantity.

In addition, with regard to the prescribed face volumetric flow rate, this quantity should be more accurately defined, or different quantities should be defined, to arrive at the minimum auxiliary ventilation system requirements.

14 References

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APPENDIX A - Statistical Analysis

To statistically quantify the ability to control methane through the dust control systems, the peak value of the methane levels recorded is used for analysis. Efforts were made to explain in simple terms on the application of statistics as an analysis tool on the laboratory data. The discussions of the main factors and their interactions are discussed hereafter. The Analysis of Variance (ANOVA) table gives, for each term in the model, the degrees of freedom, the sums of squares (SS), the adjusted means squares (MS), the F-statistic from the adjusted means squares, and its p-value. P (probability) - values are often used in statistics, where one either rejects or fail to rejects a hypothesis. The smaller the p-value, the smaller is the probability that one would be making a mistake by rejecting the importance of the factor effects on measured peak methane concentration levels. In this study a cut-off p-value of 0,05 was used (95 % confidence level). In the above ANOVA table, some p-values were printed as 0,000, meaning that significant evidence of factor effects.

Analysis of Variance (ANOVA): The peak value of the methane data was used to perform an analysis of variance (ANOVA). The peak methane level concentration is obtained for the same experimental conditions with the entire system on, were selected from the entire test data, i.e., methane levels recorded at the CM left, CM right, CM operator and face roof. The discussion of the ANOVA models used below and their underlying assumptions can be found in the standard statistics books. Factor analyses were carried out by constructing tables of each two-factor combination of the independent variables of the tests.

The typical two-factor ANOVA table is shown in Table 15.1. Essentially the peak methane concentration data is in the form of M_{ijklm} (%). The subscripts have the following definitions:

i = dust control system, i = 0 is half-curtain system, i = 1 is retrofitted hood system
j = distance, j = 1 is 15 m, j = 2 is 20 m and j = 3 is 25 m from face

k = pressure, k = 1 and 2 respectively indicate pressures of 1 500 kPa (15 bar) and 2 000 kPa (20 bar).
l = methane release rate, l = 1, 2, and 3 are discharge rates of low, medium and high volume (L/min) respectively.
m = sample location, n = 1 is left, n = 2 is center, n = 3 is right and n = 4 is roof.

The influence of the experimental parameters on the peak methane concentration levels was examined by drawing scatter diagrams with the peak methane concentration as the dependent variable and the pressure, distance, dust control system, methane release rates as an independent variable.

Table A.1

Typical Two-factor ANOVA table

Source of Variation	SS	Df	MS
Factor A	$SSA = nb\sum(\overline{Y}_{i..} - \overline{Y}_{...})^2$	a-1	$MSA = \frac{SSA}{a-1}$
Factor B	$SSB = na\sum(\overline{Y}_{.j.} - \overline{Y}_{...})^2$	b-1	$\mathrm{MSB} = \frac{\mathrm{SSB}}{\mathrm{b}-1}$
Interactions AB	$SSAB = n\sum\sum(\overline{Y}_{ij.} - \overline{Y}_{i..} - \overline{Y}_{.j.} + \overline{Y}_{...})^2$	(a-1)(b-1)	$\mathrm{MSAB} = \frac{\mathrm{SSAB}}{(\mathrm{a}-1)(\mathrm{b}-1)}$
Error	$SSE = \sum\sum\sum(\overline{Y}_{ijk} - \overline{Y}_{ij.})^2$	ab(n-1)	$MSE = \frac{SSE}{ab(n-1)}$
Total	$SSTO = \sum\sum\sum(\overline{Y}_{ijk} - \overline{Y}_{...})^2$	Nab-1	

Factorial Analysis: The peak methane level concentration data for the combination of experimental conditions are tabulated in Table 15.2. The aggregated analyses of variance of these data are summarized in Table 15.3.

Table A.2

Peak methane concentrations from the 2×2×3×3 factorial experiments (dust control system×pressure × distance×methane release rate)

	Half-Curtain System						Retrofitted Hood System					
	Pressure –15 bar			Pressure – 20 bar			Pressure –15 bar			Pressure – 20 bar		
Distance (m)	Methane release rate, L/min			Methane release rate, L/min			Methane release rate, L/min			Methane release rate, L/min		
	80	200	600	80	200	600	80	200	600	80	200	600
	0,07	0,30	1,03	0,06	0,27	0,59	0,08	0,30	0,84	0,12	0,23	0,83
15	0,05	0,27	0,64	0,04	0,22	0,74	0,10	0,33	0,81	0,11	0,25	0,87
	0,05	0,25	0,62	0,04	0,24	0,78	0,11	0,32	0,67	0,11	0,28	1,18
	0,07	0,30	0,96	0,08	0,26	0,73	0,09	0,27	0,94	0,12	0,25	0,88
20	0,07	0,31	0,82	0,05	0,23	0,76	0,11	0,25	0,97	0,17	0,34	0,63
	0,07	0,30	0,76	0,05	0,26	0,75	0,11	0,28	0,66	0,16	0,35	0,88
	0,08	0,30	0,94	0,07	0,31	0,79	0,11	0,32	1,01	0,13	0,26	0,85
25	0,08	0,25	0,73	0,08	0,23	0,83	0,21	0,42	1,24	0,16	0,31	1,15
	0,08	0,24	0,85	0,05	0,25	0,87	0,17	0,46	1,09	0,16	0,32	1,33

The main factors of the statistical analysis are: dust control system type, water pressure, auxiliary column distance and methane release rates. From the factorial analyses, following conclusions can be deduced:

- Effect of dust control system type (half-curtain and retrofitted hood system) on the peak is significant with a mean square (MS) value of 0,194.
- The effect of water pressure in half-curtain and retrofitted hood systems on the results of peak methane dust concentrations is insignificant. The results show, when the system is operating in the range of 15 bar and 20 bar, the methane levels are well below the legal limits. However, the study stresses the aspect of maintaining the water pressures in the 15 to 20 bar range and reiterates the recommendations of “Underground Mechanical Environmental Control” work.

Table A.3

Aggregated ANOVA of Data in Table 15.2

Source of Variation	Df	SS	MS	F Value	Pr> F
A (System Type)	1	0,1942	0,1942	25,23	0,000
B (Pressure)	1	0,0045	0,0045	0,59	0,445
C (Column Distance)	2	0,1368	0,0684	8,89	0,000
D (Methane Release Rate)	2	11,4272	5,7136	742,15	0,000
A×B	1	0,0096	0,0096	1,25	0,266
A×C	2	0,0603	0,0302	3,92	0,024
A×D	2	0,0543	0,0272	3,53	0,034
B×C	2	0,0052	0,0026	0,34	0,713
B×D	2	0,0064	0,0032	0,42	0,661
C×D	4	0,1037	0,0259	3,37	0,013
A×B×C	2	0,0167	0,0084	1,09	0,341
A×B×D	2	0,0139	0,0069	0,91	0,408
B×C×D	4	0,0313	0,0078	1,02	0,404
Higher order interactions (A×B×C×D)	80	0,6153	0,0077		
Total	107	12,6799			

- There is a strong evidence of position of auxiliary ventilation column from the face on peak methane concentration levels recorded during the coal cutting operation in various methane release rates during both type dust control systems (the MS value for the column distance is 0,0684).
- The rate of methane release (low, medium and high) while cutting has a pronounced effect on the system's methane dilution efficiency (highest MS value of 5,713). However, both systems, based on average methane recorded at various locations during the tests indicated that the systems performed well in controlling the methane levels below the legal limits under fully operational conditions.
- The following two-factor interactions viz., system type × column distance, system type × methane release rates, column distance × methane release rates in the analysis are statistically significant. Thus, the laboratory tests have clearly indicated

that the above two-factor interactions play an important role in terms of methane dilution effectiveness of ventilation and dust control system.

- However, two-factor interaction effects, viz., system type × water pressure, water pressure × column distance, water pressure × methane release rates do not have significant effects with pressures varying from 15 bar to 20 bar.
- From the ANOVA table, we observe that the three-factor interaction and higher order interactions are statistically insignificant in diluting the methane levels below the legal limit for the test conditions.
- Finally, the main factors, such as pressure, methane release rate across face and position of auxiliary ventilation system affecting both half-curtain system and retrofitted hood systems equally, are well demonstrated.