SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

SIMRAC

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Final Project Report

Title: METHANE LAYERING IN BORD AND PILLAR WORKINGS

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Executive Summary

This report reviews the state of knowledge on the occurrence, investigation, detection, monitoring, prevention and dispersion of methane layers in coal mines. Mining practice throughout the world in respect of methane layering is generally reliant on the results of fundamental work completed in the 1960's in the UK. These studies involved simple tunnels, consistent with longwall situations, and their applicability to bord-and-pillar arrangements is often assumed but has not been tested. Experimental work using scale models validated by selected underground tests is needed to close the knowledge gap.

Flammable gases could accumulate and remain undetected in extensive areas of bord-and-pillar workings outbye of the face where ventilation may be problematic. Due to the relatively high incidence of ignitions at the working face, it is important to prevent any layering in the face area providing a fuse which could transmit a flame to an explosive accumulation of gas elsewhere. A high standard of ventilation along the full length of the last-through-road will prevent such an eventuality. Ventilation monitoring in the last-through-road is therefore important.

The results of this research project, including findings from the literature survey, practical experience, underground observations in South African collieries and industry consultation (via discussions and a seminar at Kriel), have provided a basis for preparing draft practical guidance on the control of methane layering risks in collieries. The most effective preventative measure against the formation of methane layers is adequate and continuous ventilation. A guidance philosophy is, therefore, proposed which places the emphasis for minimising layering hazards at working faces on ventilation standards and on gas monitoring in non-working sections where operational constraints do not allow air quantities to be maintained.

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Abbreviations

Continuous miner	CM
Computational fluid dynamics	CFD
International Energy Agency	IEA
International labour organisation	ILO
National Energy Research Development and Demonstration Council	NERDDC
National Coal Board	NCB

Symbols

Froude number	F_N
Layering number	L_N
Reynolds number	R_e
Mean ventilation velocity	u
Velocity of methane layer	U
Characteristic dimension	D
Roadway width	w
Gas emission rate	v
Acceleration due to gravity	g
Density of air	ρ_a
Density difference between gases	$\Delta\rho$
Dynamic viscosity	μ
Cross-sectional area	A
General body methane concentration	c

1 Introduction

This report was prepared by Wardell Armstrong with the assistance of the University of the Witwatersrand in accordance with a contract issued by the Director General : Mineral and Energy Affairs dated 18 December 1996.

The primary aim of this report is a review of the state of knowledge on the occurrence, investigation, detection, monitoring, prevention and dispersion of methane layers in coal mines. The applicability of this information is assessed in relation to bord and pillar mining operations in South Africa. Specific outputs required from the project were:

- a worldwide literature review of the occurrence and treatment of methane layering in coal mines with particular reference to bord-and-pillar mines;

- a critical review of existing knowledge and data on methane layering in bord-and-pillar workings in South Africa;

- a bibliography of relevant technical papers and reports;

- a practical guidance note for use at collieries;

- firm recommendations as to further underground, test gallery or experimental scale model research needed to address any identified knowledge gaps.

At the commencement of the project, Professor Phillips met the Chairman of both COLEEAG (Mr J C Viljoen) and SIMCOL (Mr H C van Zyl) to confirm the project objectives and clarify the detailed scope of work to be included in the final report. The following technical issues were highlighted as of particular, practical importance to South African coal mines:

- methane accumulations in roof cavities;
- the occurrence, detection and treatment of methane layers in high roadways.

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1.1 Research methodology

An important element of the project is industry consultation. This was achieved by means of a workshop held at Kriel to which ventilation specialists and other coal industry representatives were invited. The preliminary findings of the research were presented and the practical requirements of the industry discussed.

A literature search was undertaken to locate relevant literature. The following sources were explored:

- Coal abstracts : a two part CD-ROM of abstracts produced by IEA Coal Research covering a wide range of mining-related publications from 1987 onwards.

- Worldwide Mining : a full text database on CD-ROM of Mining Journal, Mining Magazine and Mining Annual Review from 1981 onwards.

- Wardell Armstrong library : reports and papers obtained for previous major studies on gas control in underground coal mining and methane prediction for collieries.

- University of the Witwatersrand : publications from both the Applied Science library and the Department of Mining Engineering.

- South African mining houses : technical information relating to ventilation matters.

Ventilation and roadway cross-section data typical of South African collieries were obtained by examination of plans supplied by mining companies. Ventilation simulations were also performed using a computer network program. Four South African collieries were visited to gain practical experience of the ventilation and gas monitoring problems encountered in both high and medium height bord-and-pillar workings. Observations were made of the procedures, methods and equipment routinely used by mine personnel for the detection of methane at roof level. Discussions on the design and limitations of available monitoring equipment were held with a manufacturer and also with users at collieries.

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2 Methane flow and layering in coal mine roadways

2.1 Methane layers

The naturally occurring gas, sometimes known as firedamp, emitted from coal seams consists predominantly of methane with lesser concentrations of ethane and higher hydrocarbons, carbon dioxide and nitrogen often present. In this report the terms methane and firedamp are used interchangeably. Mixtures containing between 5 per cent and 15 per cent methane in air are explosive. The most explosive (stoichiometric) mixture of methane and air (about 10 per cent methane) expands some seven times when it burns at constant pressure without losing heat (Burgess, 1934). Methane is colourless, odourless and tasteless and therefore an instrument is needed to confirm its presence.

Methane has a tendency to stratify and form horizontal layers near the roof of mineworkings other than where there are high ventilation velocities. This occurs because the density of methane is only 0.55 that of air. Methane layers can also flow against the ventilation stream in some circumstances. Due to natural mixing processes, the contact between air and methane is gradational (Figure 1). Raine (1960) defines a methane layer as an accumulation *"containing percentages within or above the explosion range of firedamp (ie, 5% or over)"*, thus relating it to the hazard. He also considered a layer as extending for a length greater than the width of the roadway in which it was found. Bakke and Leach (1962) define thickness of a layer as the perpendicular distance between the roof and the edge of the layer. They considered the edge of the layer as the point where the concentration is one hundredth of the concentration at the roof.

2.2 Characteristics of methane flow

The characteristics of methane flows in both coal mines and scale models used to study its behaviour have been reviewed in detail by Jones (1994). The ventilation in mine roadways is usually turbulent, and the eddies disperse any gas entering the air stream. An emission of gas is dispersed across the flow (transverse dispersion) and also in the direction of flow (longitudinal dispersion) as a result of turbulent eddies and the variation in velocity across the roadway.

Emission
point

30   20   IO   5   I

methane concentration (%)

SLOPE
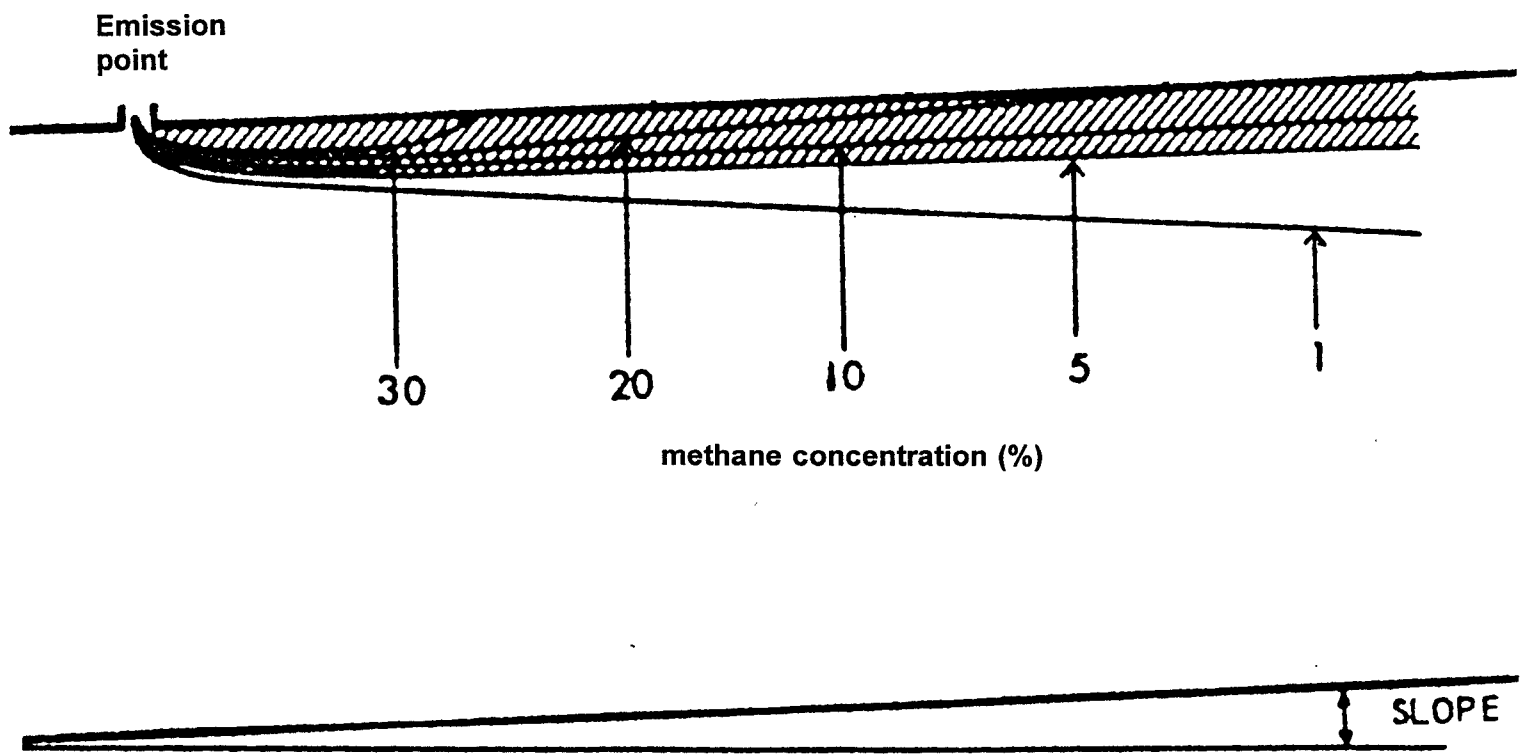
Figure 1   Diagram showing methane layering in the roof of
a gently inclined roadway. (Modified from Leach
and Barbero, 1963b)

Turbulent flow fluctuates randomly and has eddies that produce rotational movement and dissipate energy. These eddies transport airborne contaminants; thus, turbulence is a major mechanism for the dispersion of gas. Turbulent flow occurs when the inertial forces acting on the fluid are much greater than the viscous forces. The ratio of these forces is represented by the Reynolds number:

$$R_e = \frac{uD\rho_a}{\mu} \qquad - (1)$$

where u is fluid velocity (m/s), D is a characteristic dimension of the system (eg. roadway width in m), ρ_a is air density (kg/m^3) and μ is dynamic viscosity (Pa.s).

Turbulent flow only occurs at high Reynolds numbers, when the flow velocity exceeds a critical velocity above which interaction between molecules leads to turbulence. A minimum Reynolds Number of 2300 is needed to produce turbulence in the flow through a smooth pipe. In general, a Reynolds number of less than 2000 indicates laminar flow and a value above 4000 is indicative of turbulent flow. Between these values, the nature of the flow is determined by roughness of the conduit and upstream disturbances of the fluid.

The buoyancy effect of methane is an additional complication. Bakke and Leach (1960) showed that the dispersion of methane layers depends on the ratio of the energy required to overcome the density gradient to the energy available to produce turbulent dispersion of the layer. The value of the ratio is known as the Richardson number.

2.3 Dispersion of layers

If methane enters a mine roadway at roof level, it can form a buoyant layer of gas. Molecular diffusion always transports gas from the layer into the air below, but at such a slow rate that normally the dispersion of the layer is caused almost entirely by the turbulence of the ventilation air flow. The effects of turbulence on the dispersion of gas in a layer are characterised by the Richardson number (R_i) which is the ratio of the work (or energy) per unit volume (W_1) required to overcome the buoyancy of the gas layer to the energy per unit volume (W_2) available due to the turbulence.

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The Richardson number has been applied to the mean flows in a mine roadway by Bakke and Leach (1960) who also identified a layering number L_N of similar form except that it was more readily obtainable because it required measurement of only the mean ventilation velocity (u) and the roadway width (w) together with an estimation of the gas emission rate (v). The layering number was defined as:

$$L_N = u \,/\, \sqrt[3]{g \Delta \rho v \,/\, \rho_a w}$$

(2)

In the above equation, the density difference, $\Delta \rho$, is the difference between the density of the fluid in the stream and that of the fluid which is entering to form the layer. In a mine roadway, $\Delta \rho$ is the difference between the density of air and methane, ρ_a is the density of air and g is acceleration due to gravity. Bakke and Leach used a small scale model with a flow of water and saline solution to demonstrate the dependence on L_N of the layering of fluids of different density. Whilst the layering number is useful for direct practical application it does not provide a complete and unique characterisation of the flow conditions which determine the dispersion of layers, and therefore it ought to be interpreted via its connection with the Richardson number.

The direct dependence of the dispersion of layers on the Richardson number was also demonstrated by Hall and colleagues (Hall et al, 1975; Hall, 1979) who, by dimensional analysis, identified two main groups of controlling parameters. The first of these may be viewed as a dimensionless concentration.

$$C_o = \frac{v}{uw^2}$$

(3)

The second, which is the product of the relative density difference $(\Delta \rho / \rho_a)$ and the inverse of the square of the Froude number $(F_N = u/(gw)^{\frac{1}{2}})$, is an approximate form of the Richardson number:

$$R_i = g \frac{\Delta \rho \, w}{\rho_a \, u^2}$$

(4)

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2.4 Aerodynamic characteristics of bord-and-pillar workings

The ventilation of bord-and-pillar workings has historically received less attention than other aspects of mine airflow (Martinson, 1987). Airflow in bord and pillar workings differs from that in longwall workings due to the repeated abrupt expansions and contractions where longitudinal roadways intersect transverse cross-cuts. Ventilation resistance effects have been studied using a 1:100 scale model and are also the subject to a current SIMRAC research project. Singh and Singh (1992) examined pressure distributions in bord-and-pillar workings using a ventilation network programme. They showed that, for a fixed length panel, the relative influence of the cross-headings on the equivalent resistance of the workings increases with the number of headings. The actual aerodynamic resistance of the workings are, therefore, less than if computed merely as parallel, unconnected roadways. The results also show a systematic variation in flows and hence velocities, in the cross-cuts between roadways. It is possible, therefore, that airflow could be static in some of the cross-cuts in extensive bord and pillar workings.

2.4.1 Reynolds Number

Inserting typical values of $\rho_a = 1.0 kg/m^3$ (for the Highveldt) and a dynamic viscosity for air at 20°C of 18.2 μPa.s in the expression for Reynolds number yields:

$$R_e = 5.5uD \times 10^4 \tag{5}$$

With the exception of sealed-off areas, all ventilation flows in underground coal mines are usually considered to be fully turbulent. Original experimental work on methane layering and its interpretation by Bakke, Leach and others also assumes fully turbulent flow. Information obtained from various South African bord-and-pillar mines appears to confirm that, even in extreme cases of 10 or more intakes, flows are likely to be turbulent. Table 1 below shows minimum air velocities for various roadway widths necessary for laminar and turbulent flow conditions to obtain.

Table 1

Roadway sizes and air velocities for different flow conditions

Roadway width (m)	2	4	6	8	Flow conditions
Air velocity (m/s)	0.018 0.036	0.009 0.018	0.006 0.012	0.005 0.009	Laminar (R_e = 2000) Turbulent (R_e = 4000)

Air density = 1.0 kg/m^3, dynamic viscosity of air (20°C) = 18.2μPa.s.

2.4.2 Froude number

The Froude Number characterises the potential of the ventilation airflow to disperse methane. It is similar in some respects to layering number but takes no account of the methane emission rate. The Froude number is a quantity relating to the gas mixing process in the presence of buoyancy forces:

$$F_N = \frac{u^2}{g \, (\Delta\rho/\rho_a) \sqrt{A}} \tag{6}$$

Where u is airspeed, g is the acceleration due to gravity, $\Delta\rho/\rho_a$ is the difference in density between air and methane divided by the density of air and A is cross-sectional area. Substituting appropriate values:

$$F_N = \frac{u^2}{4.4 \sqrt{A}} \tag{7}$$

where u has units of m/s and A is in m^2.

In South African bord-and-pillar workings, Froude Numbers in roadways typically vary from 0.0004 to 0.4. A low value is indicative of conditions favourable to methane layering.

2.4.3 Layering number

The layering number is useful for highlighting conditions in which methane layering could occur, indicating the need for monitoring and determining a suitable air velocity to disperse layers. The concept is well established and has been demonstrated as a useful guide in longwall mines. Whether the critical values applied to continuous longwall tunnels are

equally applicable to bord-and-pillar workings with their multiplicity of regular intersections has yet to be confirmed.

In the absence of contrary indications it would seem reasonable to apply available critical values to bord-and-pillar workings in South Africa. Thus, circumstances in which layering may be a problem can be identified, the potential magnitude of the problem quantified and the need for further research assessed. The layering number is obtained from:

(8)

$$L_N = \frac{0.6u}{\sqrt[3]{v/w}}$$

where u is air velocity (m/s), v is methane emission rate (m^3/s) and w is roadway width (m).

Most publications refer to the original experimental work at the Safety in Mines Research Establishment (SMRE) in the UK which suggests a layering number of 5 is generally necessary to minimise the likelihood of layering in horizontal roadways. In contrast, observations in European longwall workings seem to indicate a value of 2 would suffice as a working criterion. The apparent discrepancy between the values obtained by controlled equipment and those observed in working mines may largely be due to the generally more turbulent conditions in the latter as a result of obstructions, equipment, personnel movement and the roughness of the roof. A balanced view (NCB, 1966) is that a layering number of 2 or less indicates a need for monitoring to confirm the absence or otherwise of layering and, where practicable, a value of 5 should be used as a ventilation design parameter.

3 Methane layering hazards in coal mines

Methane layering in the roof of mineworkings has been a principal contributory factor in major underground coal mine explosions in various countries.

A methane explosion occurred in the Yasinovskaya-Glubokaya coal mine in the former Soviet Union in 1988 when unprotected switchgear was reported to have ignited methane in roof voids. The voids were up to 3m high, containing methane concentrations of around 5% (BPG, 1988).

Examination of explosions in UK mines between 1951 and 1980 (Turton 1981) indicates the important contributory role of methane layering under various descriptive headings:

- degassing a district;

- inadequate ventilation;

- roadhead accumulation;

- roadhead cavity;

- layering (low velocity);

- drivage (ventilation stopped).

At least 17 out of 25 of these incidents appear to have been attributable to the occurrence of methane layering in inadequately ventilated roadways. In 1965 an explosion at Cambrian colliery in the UK, was caused by ventilation short-circuits at a longwall panel reducing the airflow from $11m^3/s$ to $0.5m^3/s$ thus allowing firedamp in the return airway to migrate 150m uphill where it accumulated. Electricians testing an open gate-end box inadvertently ignited the gas mixture. Details of methane accumulations in headings at three other collieries where explosions occurred are provided in Table 2. Improved protection of electrical equipment, monitoring and safer working practices have since been introduced to reduce the explosion risk. Such precautions recognise the inevitability of

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methane layering hazards occurring under certain conditions, but allow the gas to be safely dispersed without creating a significant explosion risk.

Table 2								
Examples of explosions in headings in British coal mines following a fan stoppage (after Turton, 1981)								
Colliery	Date	Length of heading (m)	Method of auxiliary ventilation	Length of time fan stood	Estimated Quantities			
					Methane emission rate (m³/s)	Total gas accumulated (m³)	Drivage volume (m³)	Average methane concentration %
Tower	1962	100	Forcing	1 ½ hours	0.0098	53	825	6.4
Houghton Main	1975	400	Exhausting	9 days	0.0028	2,200	3,200	69
Golborne	1979	587	Forcing	12 hours	0.050	2,200	4,400	50

Remote methane monitoring can assist in reducing the risk but such precautions are of little value unless care is taken to select suitable sites for detectors and properly maintain the equipment. Following the death of 14 miners in a coal mine in Northern Spain, in August 1995, the mine owners reported that the explosion was caused by firedamp but alarms equipped to detect dangerously high levels of gas had sounded no warning (World Coal, 1995).

Mr Jan Raath, a previous Government Mining Engineer, expressed reservations on the gas monitoring capability of South African coal mines where many methanometers are installed but there is some uncertainty as to whether they are read properly or whether the right conclusions are drawn from the readings (Mining Journal, 1993).

Busygin and Petchenko (1992) analysed the causes of methane ignitions in the coal mines of the Donbass in the former Soviet Union. They suggested a reason for the lack of success in forestalling gas problems when remote methane monitoring systems were available was due to a lack of gas sensors in return airways. This is a clear indication that in some mining countries, the basic principles of monitoring for safety are either not understood or not applied in practice.

Some authorities appear to have blind faith in modern technology to satisfactorily minimise risks. This attitude is epitomised by a Turkish State Minister who stated at a press

conference, following the loss of 272 miners in an underground explosion at the Incirharmani coal mine in northern Turkey (March 1992), that no fault had been found with safety measures in the pit where "modern technology was being used" (Mining Journal, 1995).

Methane layering hazards are generally a manifestation of inadequate ventilation. Whilst methane layering hazards occur in longwall workings, particularly in association with development headings, the problem is potentially more acute in bord-and-pillar operations due to:

(a)   the difficulty of either adequately ventilating or satisfactorily sealing extensively worked areas;

(b)   a significant proportion of coal production comes from blind headings which are not always effectively ventilated.

There is a suggestion that technical solutions to some of the perceived problems in South African collieries may be available from the USA and Australia where mechanised bord-and-pillar mining methods are also used. Australia, USA and South Africa are the largest suppliers of coal on the world's export markets and there are similarities between the coal industries of these countries (Hardman, 1996). Substantial coal production comes from both underground bord-and-pillar and longwall mining methods in these countries in addition to surface-mining techniques (Table 3). In a number of respects, South Africa is significantly different from the advanced coal producing countries of USA and Australia:

●   unacceptably high explosion risks in underground coal mines

●   a high proportion of underground coal production reliant on bord-and-pillar mining methods

●   most of production from low gas content seams

●   extensive working of thick seams in a single lift.

Table 3						
Saleable underground coal production by mining methods (based on Hardman, 1996)						
Mining method	Australia (1995)		United States[1] (1995)		South Africa (1995)	
	Mt	%	Mt	%	Mt	%
Longwall	39	68	161	50	14	12
Bord & pillar and pillar (stoop) recovery	18	32	161	50	99	88

1. National Mining Association, 1997.

The methane contents of coal seams worked in the USA vary from very low to $22m^3/t$. Methane drainage techniques are practised on gassy longwall coalfaces to allow planned coal production targets to be achieved. In addition to gas released as a function of rate of coal extraction, some Australian underground mines also have to contend with gas and coal outburst risks. The in-situ gas contents of Australian coals are as high as $20m^3/t$ in deeper operations and the composition of seam gas varies from virtually pure methane to almost wholly carbon dioxide in some locations. In contrast, methane contents of seams in South African coal mines are considered to be generally low, although few measurements are available.

The control of methane layering is particularly difficult in high roadways due to the inaccessibility of the roof for gas testing and the low air velocities that can occur in large cross-section openings. Should, as is likely, mechanised bord-and-pillar mining continue to be the preferred method of underground coal extraction in South Africa, methane layering problems could increase as almost half of the coal reserves are in seams of 4m to 6m thickness (Baxter, 1995). The need for research on methane layering is therefore explained.

It is generally recognised that explosion risks are unacceptably high in South African coal mines. Nevertheless, serious explosions have also occurred in recent years in other coal mining countries which have access to state-of-the-art technology. Technology alone, therefore, is insufficient to ensure the safety of underground coal mining operations from gas emissions. Important additional factors (Creedy et al, 1997) include:

- an understanding of the basic principles of gas control by the colliery management and supervisory staff;

- provision of suitable technical training;

- a motivated workforce;

- a disciplined approach to design and implementation of control measures;

- setting and maintenance of sound, basic operational standards;

- good supervision; and

- technical support from specialists as required.

The adoption of safe practices can be encouraged by appropriate legislation. Adherence to mining legislation is not automatic and examples of problems can be found in countries where both the legislation and safety technology are well-developed. Following an explosion that killed 10 miners in September 1989 in a US coal mine, three officials were sentenced to imprisonment for failing to adhere to safety procedures and misinforming inspectors (Coal, 1996). The explosion also prompted a review of US state and federal mine safety laws.

An enquiry into an explosion at Westray mine, Canada in which 26 miners died revealed numerous violations of safety regulations. The adequacy of both enforcement standards and penalties for infringement were also questioned. The mining method in use was bord-and-pillar with partial pillar extraction (Mining Journal, 1995). There is a divergence of views as to the probable origin of the methane. One expert believed the gas originated close to the working face where layers had built-up undetected, whereas others suggest the gas migrated from an adjacent abandoned area that was neither properly sealed-off or adequately ventilated.

A need to reduce the risk of further disasters by retraining mine management and others was identified in Australia following an explosion at Moura No.4 underground mine in 1986

when 12 men perished. This objective was achieved by the preparation of extensive pre-course reading and reference works, and by conducting a training seminar of one week duration for the target group. The seminar was well attended. Participants were surveyed and rated the content, conduct and organisation of the seminar highly. The seminar and the pre-course reference material addressed a wide range of topics relevant to mine explosions, including mine fires, spontaneous combustion, explosions of methane and coal dust, the explosibility of mine atmospheres, emergency procedures and the investigation of mine disasters. The seminar included lectures, practical exercises, demonstrations and discussion sessions. After the seminar all mine managers confirmed that they intended to use the reference material in training at mines and indicated a high level of support for a range of further training courses on similar topics for similar and different groups from the coal mining industry. The report (NERDDP, 1989) suggested that if standards of training adequate to significantly reduce the risk of further disasters were to be achieved throughout the industry the success of this project ought to be built upon in the near future. A genuine commitment to similar training sessions was required from industry and from government.

A further explosion occurred at Moura in August 1994 resulting in 11 fatalities, raising questions concerning the safety of Australia's mining industry (Mining Journal, 1995) relative to other Australian industries. In the world coal mining context, however, ILO (1994) figures show Australia to have the lowest overall number of fatalities per million tonnes of coal mined in the period 1988 to 1993.

These examples have attracted widespread interest due to their rarity. In some countries such problems are more common. Serious deficiencies in regulation and enforcement of gas control and other safety procedures are yet to be overcome in, for instance, China and the former Soviet Union. According to Coal Age (1997), at least 91 coal miners recently died in a gas explosion at the Dongcun mine in China's Shanxi province.

All coal mining countries set some upper limits of permissible methane or flammable gas concentrations that should not be exceeded in mine airways. All limits include a factor of safety in that they are substantially less than the 5 per cent lower explosive limit of methane in air under normal conditions of temperature and pressure. However, the actual values used vary from country to country, although some countries with current and

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former cultural associations adhere to essentially similar legislation. There is no correlation between the magnitude of permissible methane concentration limits and the occurrence of gas explosion incidents. Perversely, the opposite seems to be the case. For example, 1 per cent flammable gas is the maximum allowed in the return roadway of a Chinese coal mine whereas up to 1.4 per cent would be permitted in South Africa and, provided no electricity was present, 2 per cent in the United Kingdom and Australia. Where ventilation air velocities are low and methane layers can form in the roof, a general body air concentration is totally inadequate as a measure of methane hazard.

Of greater importance than the setting of precise action levels for gas, are the locations at which the concentrations are measured, the procedures used, and the actions taken as a consequence of the measurements. Mining legislation in the advanced mining countries is generally aimed at requiring the concentrating of monitoring and control efforts in proportion to the degree of expected risk, conditioned on the basis of previous incidents considered as serious by the regulatory authority.

A wide range of activities at a colliery interact in some way with measures inherent in mining legislation, regulations, codes of practice and local instructions which are designed to minimise gas-related risks. The large number of managed activities in a typical coal mine which have a bearing on the control of gas-related risks are listed in Table 4. Thus, the importance of ensuring all colliery staff have an appreciation of methane hazards is illustrated.

Table 4

**Managed activities in a typical coal mine
which have a bearing on control of gas-related risks.**

1.	Control of flammable dust
2.	Provision of explosion suppression barriers
3.	Use of flameproof electrical equipment and cables
4.	Control of explosives and their use below ground
5.	Control and use of alternative blasting techniques
6.	Provision of adequate fire and rescue facilities
7.	Provision of suitable methane drainage facilities (if appropriate)
8.	Control of the discharge of drained methane gas
9.	Control of access to the mine and parts of the mine
10.	Control of lamps or lights
11.	Restriction of contraband in the underground environment
12.	Inspection of underground workings
13.	Provision of suitable materials
14.	Supervision of mining operations
15.	Reporting of problems during the shift
16.	Communication between staff at shift changeover
17.	Use of mechanical and electrical plant
18.	Provision for restricting the use of unsuitable plant
19.	Maintenance and repair of plant
20.	Supervision of mechanical and electrical operations
21.	Use of permitted lights
22.	Restriction of smoking materials below ground
23.	Support of excavated areas
24.	Keeping of mine plans
25.	Training
26.	Provision of adequate information and warning signs and notices
27.	Control of the mine ventilation
28.	Monitoring and measurement of mine gas concentrations
29.	Use of auxiliary ventilation
30.	Degassing of headings
31.	Frictional ignition precautions
32.	Provision of methane detectors
33.	Use of ventilation sheets or brattices
34.	Qualifications of employees

While South Africa should not accept the current level of explosion risk in its underground coal mines, it should recognise that ready-made solutions are unlikely to be found elsewhere. Nevertheless, an understanding of the achievements and failures in controlling gas risks in other coal mining countries should be helpful in guiding progress in South Africa.

4 Worldwide methane layering research and guidance

4.1 Early European research

The problem of methane accumulating at the highest part of badly ventilated coal workings has been recognised by miners for centuries. The "penitent" or "fireman" of coal mines in Britain in the 17th Century is depicted as applying his candle to the roof of a roadway to ignite the gas prior to the commencement of a working shift. The first controlled experiments to examine the phenomenon of methane layering in tunnels were carried out by Coward (1937) in the UK against a background of recurrent firedamp explosions in coal mines. Coward introduced his work with the statement:

> *"On several occasions in the last few years, during investigations into the causes of explosions of firedamp in coal mines, attempts have been made to ascertain the source of the firedamp and to explain how firedamp is lighter than air and therefore tends to rise to the highest parts of the accessible roof; also that firedamp and air tend to mix by the process of diffusion, and as a result of turbulence caused by the movement of solid bodies or by the rapid movement of the gas itself; but there is no quantitative information available on these subjects".*

His aim was to further the understanding of the circumstances in which explosive mixtures of firedamp and air could accumulate in mine roadways and hence contribute to the development of preventative measures. Although unable to explain the experimental results in terms of the mathematical physics, Coward laid the foundations for subsequent quantitative studies through relatively primitive experiments in three different galleries:

(i)   a concrete chamber 30m in length, 1.8m in height and 1.5m wide with a gradient of 1 in 10 and eight rectangular roof cavities each about 1.2m x 1.2m x 0.3m in size;

(ii)   an underground test roadway some 213m in length with an arched section 2.4m high, a width of 1.2m and a gradient of 1 in 30;

(iii)   a laboratory scale model roadway 7.3m in length with an approximately 0.5m square section and adjustable inclination.

The experiments involved introducing methane at known flow rates into the roof and floor of the various galleries and studying the rate of movement of the gas along the roof using top-feed flame safety lamps as detectors. The effects of air movement, air flow direction and angle of inclination were also examined in broad detail. The findings included:

- methane released in the floor at a rate of about 4.5 l/s could accumulate in the roof; gas released from small floor breaks would probably disperse in the general body of the air;

- turbulence caused by a person walking in the test gallery delayed the migration of the gas to the end of the gallery up to four times the static result;

- as the angle of inclination of a gallery is increased there is at first a rapid increase in the rate of movement of firedamp but at higher angles the rate becomes virtually constant;

- the greater the rate of supply of methane, the smaller the slope at which a maximum, constant flow is obtained.

Mathematical representation of the results was not attempted. Further research was delayed due to the war.

The occurrence of firedamp in the roof in layers or cavities was identified as a common feature in a number of colliery explosions in the late 1950's. A sub-committee on mining explosions, chaired by Sir Andrew Bryan, on behalf of the Safety and Health Committee of the Coal Industry National Consultative Council, recommended in 1959 that:

"The SMRE [Safety in Mines Research Establishment] should give priority to the research which they are conducting into means of tackling the gas layer problem".

Bakke (1959) reported on progress with the research at the Safety in Mines Research Establishment (SMRE) in an interim paper. The various flow processes which take place in mine roadways are considered. Due to wall roughness, relatively small roadway dimensions in UK coal mines and Reynold's numbers substantially greater than the value of 3000 above which flow is turbulent in smooth pipes, the ventilation flow in mines is accepted as invariably fully turbulent. Previous work by Richardson (1920) is cited as probably more important than Reynold's number in describing the mixing behaviour of two fluids of dissimilar densities. Richardson argued that the natural buoyancy of a lighter fluid on top of a heavier fluid would tend to reduce or totally damp out turbulent mixing of the two layers. This is because when turbulent eddies carry the lighter fluid downwards, work must be done against gravity to replace it with the heavier fluid from below. Richardson's number is used to express the energy balance, a value greater than unity reflecting the condition when no turbulent mixing of the two layers should occur. Bakke rearranged Richardson's number in a form applicable to the mining situation :

$$g\Delta\rho v/\rho_a \; DU(U-u)^2 \tag{9}$$

where g is acceleration due to gravity, $\Delta\rho$ is the density difference between pure methane and air, v is the methane emission rate, ρ_a is air density, U is the velocity of the methane layer and u the ventilation velocity. Assuming the methane velocity is one third of the air velocity of 100 ft/min (0.5 m/s) in a horizontal roadway of width 9 ft (2.7 m), Richardson's number will exceed unity, predicting the persistence of layering for a methane emission rate of 25 cu.ft/min (11.8 l/s) or more. This analysis is an over simplification of the layering situation but it indicates the importance of Richardson's concepts. In the absence of turbulent mixing, any mixing which does occur will involve molecular diffusion, a very slow process.

Bakke then described laboratory experiments to study the mixing behaviour of fluids with different densities, and at different inclinations, to test the theoretical ideas introduced above. The following tentative conclusions were drawn :

(i)   *"Richardson's number, which is an expression of buoyancy forces compared with inertial forces, is a relevant factor when considering the mixing of methane with ventilation flow".*

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(ii)   *"In horizontal roadways, for a given methane emission and volumetric ventilation flow, increasing roadway dimensions will favour the stratification of methane in roof layers".*

(iii)   *"In inclined roadways, the rate of mixing is better when the slope is large, because it is the component of gravity perpendicular to the roof only which contributes to the decrease in mixing owing to buoyancy".*

An SMRE research report by Bakke and Leach (1960) describes theoretical and experimental studies of layering phenomena.   They developed their theories from experimental work using ventilation velocities and configurations typical of British coal-mining, that is, long straight tunnels of arch section up to 2km in length with widths from 3 to 4m. Generally, methane was injected at roof level. Many of the experiments involved the use of liquids of different densities to simulate methane layering effects. Bakke and Leach deduced that the behaviour of roof layers depended on:

(i)   the slope of the roof;

(ii)   the coefficient of skin friction for the layer;

(iii)   the resistance coefficient for the ventilation flow; and

(iv)   a dimensionless factor termed the "layering number".

By choosing suitable conditions it was possible to assume (i), (ii) and (iii) were constant leaving the layering number as the primary independent variable.

The layering number takes account of the combined effect of the fluid properties of methane and air as expressed in L_N equation (8) and reproduced below for convenience of reference:

(10)

$$L_N = \frac{0.6u}{\sqrt[3]{v/w}}$$

Where u = air velocity in m/s,
v = methane flow in m^3/s,
w = layer width in m (usually taken as roadway width for a rectangular section roadway).

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For practical purposes, Bakke and Leach recommended that the ability of a buoyant firedamp roof layer to move against a descending airflow in an inclined roadway, could be compensated for by increasing the layering number by 10%.

The authors sought to apply their findings by suggesting practical ways of controlling methane emissions in the roof of roadways. They emphasise that while ventilation quantity can be used to control methane emissions, some layering is an inevitable consequence of mixing by turbulent diffusion and hence cannot be totally avoided. In addition, they stress that because methane layering is a complex phenomenon involving such factors as rate of emission, ventilation velocity, roadway slope and ventilation direction, it is not practicable to define a single airflow velocity which will ensure a satisfactory rate of dispersion in all conditions. The layering number is helpful for assessing the effectiveness of particular methods for preventing or dispersing methane layers in particular situations. The value depends strongly on air velocity; doubling the velocity doubles the layering number. However, to achieve the same result by treating the methane flow requires a decrease in emission by a factor of eight. As a general rule they tentatively suggest that when methane emission rates are low an appropriate control response would be to increase air velocity but if they are high then a means of reducing emission rate should be sought. In horizontal tunnels it is suggested that the layering number should not be less than 5.

Contemporaneous work by Leach and Barbero (1963a) demonstrated how baffles can be used to elevate air velocities and hence disperse methane layers in certain situations. Baffles should be placed as close to the emission source as possible, but if the required air velocity is substantially higher than the existing airway velocity the resulting pressure drop may be unacceptably high. Trials were also made of a compressed-air powered device for sucking layered methane from the roof and discharging it at floor level (Figure 2). Although not practical for use in coal mines, this device could be considered a fore-runner of the modern air mover.

6in. to 12in.
FROM ROOF

GOOD SEAL
AGAINST ROOF

FLOW OF
METHANE LAYER

EDGES TO TOUCH
SIDES OF ROADWAY

COMPRESSED
AIR

DISCHARGE OF
NON-INFLAMMABLE
MIXTURE
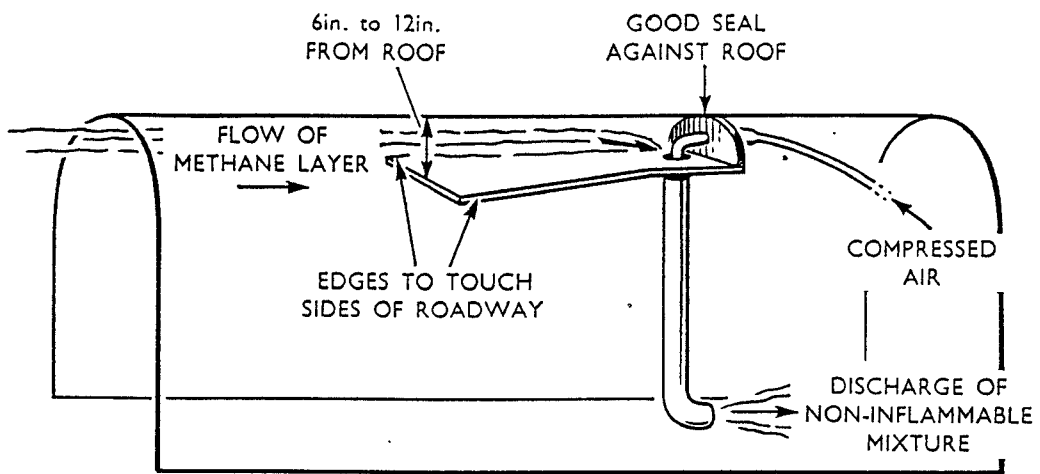
Figure 2   **Removal of a methane layer from the roof using an ejector device.** (After Bakke and Leach, 1962)

By this time, researchers were generally of the opinion that remedy of methane layering was not necessarily difficult, the problem being to detect the need for treatment.

An excellent practical paper on methane layering was published by Raine (1960), a former District Inspector of Mines and Quarries in the United Kingdom. Raine examined the occurrence of firedamp layering on the basis of observations made in underground coal mines in the Yorkshire coalfield, Britain. Although specifically aimed at longwall workings, many of the principles established are also applicable to bord-and-pillar mining. He recognised that a methane layer of only 25mm to 50mm thickness, although containing a negligible volume of gas, could constitute a major hazard by providing a fuse to connect an ignition source to a larger body of gas. The size of roadways may differ but the average air velocities of 0.14 m/s to 4.6 m/s typical of UK longwall mines at that time are comparable with those experienced in South African bord-and-pillar mines. Relevant and still apposite, factors identified by Raine include:

- dangers from methane layering are high in mechanised mines due to the ready availability of ignition sources;

- early detection of layers is essential, and, the physical difficulty of examining high roofs in roadways should not be under-estimated.

He observed that air velocity profiles in roadways vary depending on the size, shape, method of lining of a roadway, obstructions and air quantity. Under normal conditions, according to Raine, layering would not be expected if the air velocity at the roof was of the order of 0.5 m/s. This criterion has been subsequently misused in the UK when an average air velocity of 0.5 m/s has been suggested as sufficient to prevent layering.

Raine also assessed the effectiveness of various control techniques for methane layers. Hurdle sheets appeared to be satisfactory for dispersing static accumulations of methane but not always effective for dealing with layers especially in high roadways (greater than 3 m) with low mean velocities (0.5 m/s). In these instances, difficulty was experienced in getting the air to rise above the sheet. Where inclined sheets were used, being preferred over vertical sheets due to their lower aerodynamic resistance to airflow, air velocity was reduced at roof level due to the air flowing beneath rather than above the sheet. Compressed-air venturi tubes proved effective at dispersing layers although users were reminded of the need to provide efficient earthing to preclude electrostatic sparking.

Methane drainage from short boreholes was proposed as a possible means of reducing the gas flow feeding a layer in certain situations.

Practical experiments were conducted on methane layering in an actual mine roadway by James and Purdy (1962) which supported the theoretical work of Bakke and Leach (1960) and confirmed the usefulness of the layering number for practical ventilation planning applications. The test site consisted of an inclined roadway to which methane could be piped from cross-measure drainage boreholes located in the return airway of a neighbouring longwall face to generate roof layers as required. Both uphill and downhill sections of roadway with gradients of 1 in 10 were included in the test length. The effect of varying ventilation velocity and methane emission was examined separately. It was shown that under certain conditions an increase in the air velocity had little effect on the layer length whereas any decrease in the methane emission rate always effected some reduction in layer length.

In 1962, Bakke and Leach provided an overview of their work on methane layering in a paper presented to the Midland Institute of Mining Engineers. Little new material is included but some aspects are clarified. For instance, the ventilation air velocity used in calculating values of layering number in the SMRE investigations was confirmed as the average measured in the top half of the roadway. However, layering numbers can be calculated using air velocity measured at any position provided a consistent approach is adopted and no attempt is made to relate the results to other sites where a different method has been used. General comparisons of Layering numbers between different sites, or obtained by different persons, should therefore be made with caution. A reminder is also given of the simple properties of layers:

- Within a short distance from the roof emission source, the velocity attains a constant value unaffected by further dilution, and,

- the rate of mixing (measured as the rate of increase of layer thickness) of a given layer is constant.

Generally, for horizontal layers, if the layering number is 5 or more, the layer length will not decrease much if the velocity is increased further. However, if less than 5, a relatively small decrease in velocity may result in a considerable increase in layer length. As a layer can form in minutes or fractions of a minute the importance of keeping layers under control is clearly illustrated. It must be stressed that these observations were established from work on continuous tunnels and have yet to be tested for bord-and-pillar configurations where there are regular roadway intersections.

Leach and Barbero (1963) studied the characteristics of methane layers where the air was at rest, in two full size roadway sections inclined at 1 in 27 and 1 in 10 respectively. The former was of arched cross-section 2.4 m x 2.4 m with 75 m of its 210 m length used for the test and the latter was of rectangular cross-section 1.8 m high by 1.5 m wide and about 30 m in length.

They demonstrated that methane released at the roof of a sloping, unventilated roadway will flow uphill along the roof. The flow is induced by the buoyancy arising from the density difference between methane and air. It is opposed by the frictional drag at the roof and the turbulent transfer of momentum into the body of the air.

The results obtained were found to be in reasonable agreement with previous theoretical work by Ellison and Turner (1959) who deduced that the velocity of a layer, U, is given by:

$$U = \left\{ g \frac{\Delta \rho v \sin a}{\rho_a w c_w} \right\}^{1/3} \qquad (11)$$

where g is acceleration due to gravity, $\Delta \rho / \rho_a$ is the relative density difference between methane and air, a is the inclination of the roof and c_w is a skin-friction coefficient assumed to have a value of 0.017 in the rectangular roadway (Leach and Barbero, 1963c). Data obtained from previous experimental work on free streaming layers by Coward (1938) and Georgeson (1942) was also analysed and found to be reasonably consistent with theory.

The experiments of Leach and Barbero (1963) confirmed that an assumption, inherent in the above equation, of negligible mixing of the methane layer and the air below was reasonable. Figure 3 shows the results of experiments made in the rectangular tunnel.

Mean layer velocity : ft/min

140

Theoretical curve
(Ellison & Turner (1959)) ▬▬
Velocity of layer front ...... ●
Velocity from methane
concentration measurement .. O
Georgeson (1942) .. .. ▲

120

100

80

60

40

20

0

0   0·05   0·2   0·5   1·0   .2   4   6   8   10

V/D : (cu.ft/min)/ft

V is the methane flow rate in cu. ft/min
D is the tunnel width in ft
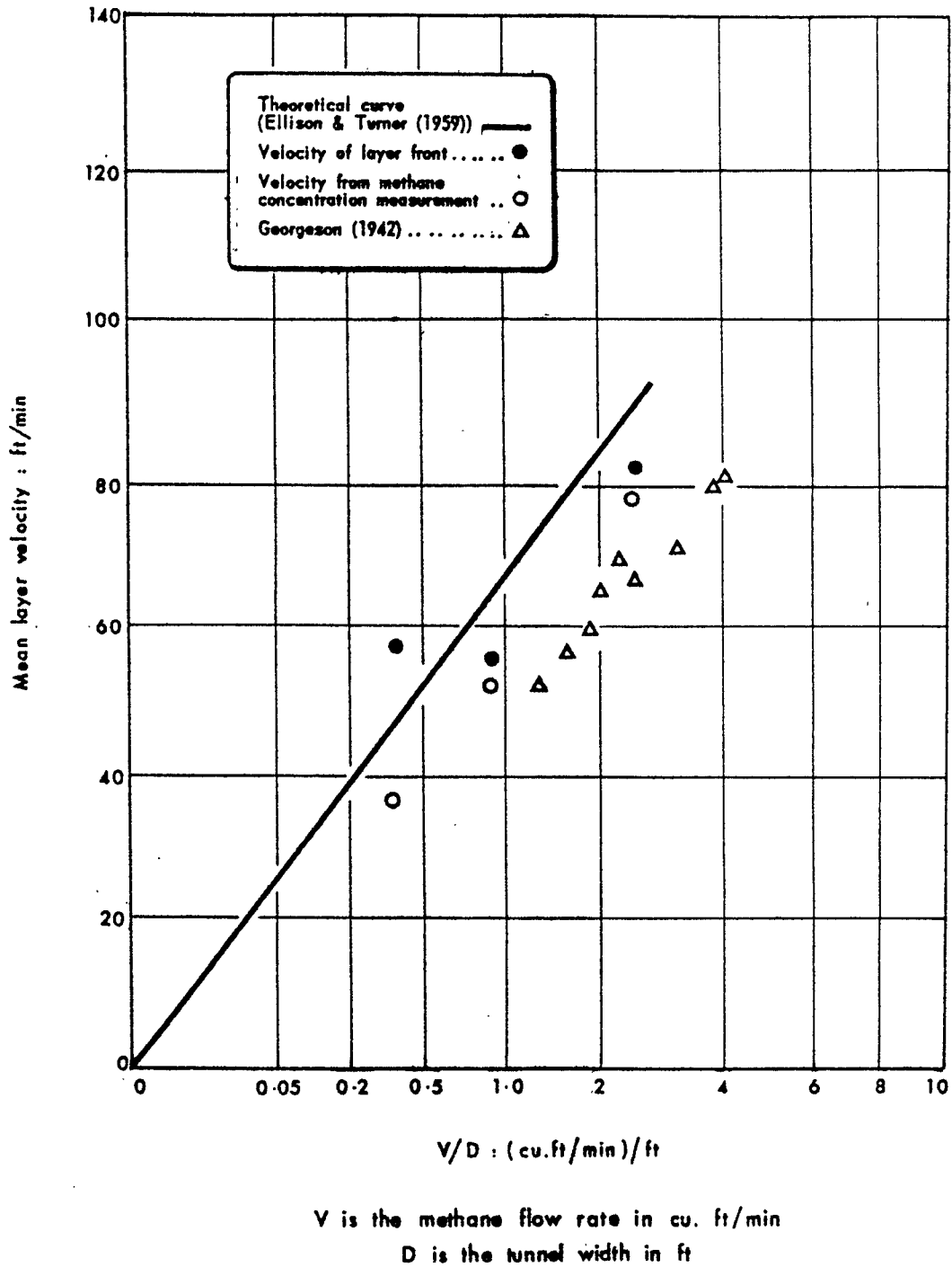
Figure 3   Velocity of free streaming methane layers in a
1.8m x 1.5m rectangular section tunnel of slope
1 in 10. (After Leach and Barbero, 1963b)

METHANE LAYER FLOWING OUT OF TUNNEL

CLOSED
END

AIR FLOWING INTO TUNNEL

OPEN
END
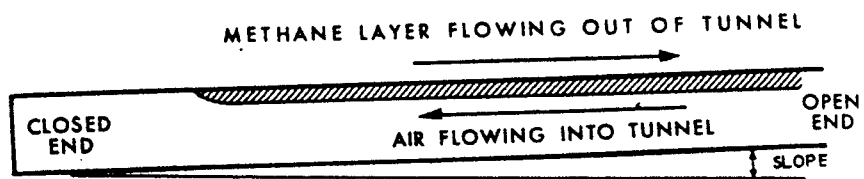
SLOPE

FLOW OF METHANE AND AIR IN A TUNNEL
OF SMALL SLOPE, CLOSED AT ONE END

Figure 4   **Methane layer flowing from an inclined blind heading without mechanical ventilation.** (After Leach and Barbero, 1963b)

Incorporated also are the results of 107 experiments by Georgeson (1942); each of the nine points on the graph is the mean of up to 37 independent experiments. As an example, the velocity of a methane layer ascending a 1.5 m wide roadway of slope 1 in 10 would be about 0.2 m/s for a methane emission rate of 0.47 l/s, The type of situation which may arise in an unventilated, descending heading is illustrated in Figure 4.

Bakke and Leach (1964) recognised that the use of mixing baffles or local ventilation has limited application to auxiliary ventilated headings. They, therefore, undertook a series of experiments using a simulated 60 m long, force ventilated heading to examine the effect of introducing an additional fan and short length of ducting to increase the airspeeds in the vicinity of the face. They proved, analytically and by experiment, that the general body concentration is given by the rate at which methane is emitted divided by the fresh air quantity and is independent of any recirculation. After conducting various experiments with the main auxiliary ventilation duct at distances of 4.5 m and 12.3 m from the face (Table 5), they concluded that :

- extensive layers will not form from methane sources at the face of the heading for gas emission rates up to 4.7 l/s and mean air velocities down to 0.06 m/s with the main auxiliary ventilation duct 4.5 m from the face,

- with similar conditions but where the methane source is some distance from the face, extensive layers can form.

It was also discovered that when at the 4.5 m position, the main duct performed better when placed in the roof compared with the floor but the opposite occurred when the main duct was 12.3 m from the face. No reduction in layer length was obtained at this position when the recirculation fan was started. It is interesting to note that irrespective of the air quantities and ventilation configurations used, significant methane layers occurred.

The NCB (1964) reported the development of a pocket methane probe capable of obtaining samples from heights of 1.8 m or more. The probe consists of an inflatable tube of about 50 mm diameter with a small diameter sampling tube attached.

Table 5

Results of layering experiments in a simulated heading
(after Bakke and Leach 1964)

State of recirculation fan	Distance of main duct from face (m)	Duct in roof or floor (R/F)	Methane release rate (l/s)	Ventilation air speed (m/s)	Length of layer (m)
Off	4.5	R	4.7	0.06	1.68
Off	4.5	F	4.7	0.06	3.20
Off	4.5	R	4.7	0.14	0.15
Off	4.5	F	4.7	0.14	1.37
On	4.5	F	4.7	0.42	2.29
Off	12.5	R	4.7	0.15	4.42
On	12.5	R	4.7	0.50	4.42
Off	12.5	F	4.7	0.15	3.20

Titman *et al* (1965) developed a theory to describe the accumulation of methane in unventilated roof cavities. Small-scale experiments and observations made in a large roof cavity in an underground coal mine largely confirmed the theoretical approach. The theory considers a low flow of methane into a roof cavity with a mixture of methane and air leaving the base at the same rate such that the process can be treated as one of molecular diffusion enhanced by a bulk flow of gas. Steady state expressions (when concentration no longer changes with time) were developed relating the concentration of methane at a particular level to height of cavity and methane flow rate for three different simple geometric shapes (parallel-sided, wedge and pyramid shaped).

The average concentration of methane in a cavity of a particular shape, in the steady state, was shown to depend only on a parameter defined by :

$$\frac{\text{Volume flow of methane} \times \text{height of cavity}}{\text{diffusion coefficient} \times \text{area of cavity base}}$$

Winter (1966) reported on methane layering observations in the Ruhr coalfields of Germany. In horizontal and slightly inclined workings methane layers were only found when layering numbers were less than 2 or 3. The reasons for this apparent contradiction of the findings of Bakke and Leach were cited as:

- the rarity of single emission sources

- not all gas entering at roof level

- some of the methane entering roadways was already mixed with air.

In the Barbara experimental mine, Poland (Sobala and Kozlowski, 1966) stone dust barriers suspended in the roadway were found to act as baffles encouraging effective mixing of firedamp and air, thus preventing layering.

Bruyet (1967) examined the problem of methane accumulation in headings in French collieries during stoppages of auxiliary ventilation systems. He described a deflection device which could be installed in ducting to reduce the velocity of air arriving at the heading face during degassing operations and at the same time enhance airflow into the roof area to dissipate roof layers before they emerged into the main ventilation.

Bakke and Leach (1967) described experiments with methane and also nitrous-oxide layers in a wind tunnel which showed that probes may not accurately sample very thin layers due to the flow disturbance caused by the presence of the probe. For instance, a roof layer which had a concentration of 15 per cent at the roof, and exhibited a concentration of 2 per cent 13 mm lower, was measured to have a concentration of 2 per cent using a cylindrical probe touching the roof. However, when the methane concentration was uniform over a distance of 8 mm the sampling error was negligible.

Leach and Slack (1964) reviewed the earlier SMRE work on methane layering and presented a nomogram to assist colliery engineers in the calculation of layering numbers. Statutory gas monitoring results from three coal mines in the former Northumberland and Cumberland Division in the United Kingdom had been examined by a senior National Coal Board (NCB) scientist. Out of the 74 locations investigated, layering was evident on occasions in at least seven out of nine locations where the Layering number was less than 1.7. No layering had been observed in the remaining 65 sites where the Layering number was greater than 1.7. A more detailed survey in the North Western and North Eastern Divisions of the NCB, but still based on statutory sampling locations, revealed 83 return roadways for which the Layering number was 1.5 or greater in which no layers were found but 4 out of 12 return roadways with a Layering number less than 1.5 exhibited layering.

In conclusion, the authors recommended that, as a precautionary measure, monitoring of the roof should be undertaken at statutory general body sampling locations where there were indications of a Layering number less than 2. They also noted that six out of eighteen major explosions that occurred between 1951 and 1961 involved methane roof layers.

Fischer (1973) reported on full-scale testing relating to methane roof layers at the Tremonia Experimental Mine in Dortmund, Germany. An equation was derived for estimating the length of a layer in the direction of ventilation in a smooth, concrete lined roadway with a cross-sectional area of $6m^2$:

$$L = 10^4 \times V^{0.74} \times e^{-2u} \tag{12}$$

where L is the length (m) of the 5 per cent concentration limit in the direction of ventilation, V the gas emission rate (m^3/s) and u the mean ventilation speed (m/s). Their observations, when varying gas emission rate and ventilation air speed, were in general accordance with the findings of Bakke and Leach. The principal contribution of this work was in describing the behaviour of methane layers when ignited. Layers formed in the smooth roadway were very long but ignited without great violence (flame speeds 2 to 3 m/s). When dummy supports were introduced into the smooth roadway, layers became shorter and thicker and the flames more turbulent (maximum flame speed 25 m/s). Static pressures up to 4 to 5 kPa and dynamic pressures as high as 200 to 300 Pa occurred. Tests were also made in roof cavities with volumes from 2 to 15 m^3 and heights up to 3 m above the supports. Cavities, open at the base, were filled with homogeneous, flammable gas mixtures. When ignited from below the gas in smaller cavities burnt quietly from the bottom to the top and the gas in larger cavities burnt with greater violence. Explosions occurred in cavities not completely open at their base and also when the gas was ignited at the top or in the centre of the cavities. When pure methane was fed into cavities open at the base, gas layers were formed with a concentration increasing upwards. On ignition, a long-lasting flame with strong turbulence was produced with the burning gases expanding into the roadway.

4.1.1 Gas concentration and Froude number

An attempt was made by Bakke, Leach and Slack (1967) to obtain a correlation between gas emission processes, ventilation and the probability of an ignition P ie. an ignition risk index.

As in all their work of that period, the assumption was made that Reynolds number was unimportant, in [longwall] mines. General body methane concentration (c) and the Froude number (F_N) in the return roadway of a longwall face were considered to be the critical factors.

National Coal Board data for April 1965 were statistically analysed and from the correlations the following ignition probabilities were estimated:

$$P_{face} = 0.003 \, (c^2/F_N)^{0.9} \qquad\qquad (13)$$

$$P_{gateroad} = 0.0013 \, (c^2/F_N)^{0.9} \qquad\qquad (14)$$

The analysis of ignitions in longwall gate roads was mainly based on occurrences related to shotfiring. The parameters obtained were typical values and not temporally related to ignition occurrences. The authors considered the variable c^2/F a better index of risk for ignition than the layering number alone as the latter only describes how well the gas is mixing with the ventilation, whereas the former also incorporates an indication of the quantity of gas involved. Later work in longwalls (CEC, 1985) was unable to confirm a correlation between gas emissions at the coalface shearer with either c^2/F or c in the return.

The above analysis is too simplistic to take account of the range of ignition contributory factors which must be considered in South African bord-and-pillar mines. Nevertheless, the concept of the easily determined parameter combining gas concentration and the gas mixing process may have application for ranking potential gas accumulation risk as a stage of concern higher than layering potential. Currently, insufficient information is available to evaluate this suggestion.

4.2 Recent European research

Recent research has focused on causes and prevention of frictional ignitions, the related topic of machine ventilation, gas flow in coal seams, gas emission prediction and gas drainage techniques. Processes which can lead to methane layering in coal mine workings have been studied particularly in connection with:

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- control of gas at the return end of longwall retreat coalfaces in the UK and France. This work has involved underground measurements, scale modelling and CFD modelling;

- methane and ventilation in continuous miner headings.

However, layering has not been studied as a process in the above work other than in respect of accounting for the buoyancy property of methane in physical and computer modelling.

4.3 Research and guidance in Australia

Australian coal seams have geological similarities with those in South Africa. Seams up to 12m thick are worked but not subjected to full extraction (Sleeman, 1986). In 1995 about 18 million tonnes of coal were extracted from bord-and-pillar mines in Australia, representing 32 per cent of underground coal production. No recent research on methane layering has been reported and the industry relies on the UK results of the 1960's. Layering problems are treated using venturi airmovers driven by a portable compressor or brattice scoops. Good ventilation standards are usually maintained in continuous miner headings. A common method is to form a "narrow side return" with brattice (Figure 5) to ensure continuous and effective removal of any pollutants arising in the heading. Where auxiliary fan and duct systems are used they are invariably exhausting to remove gas and dust from the heading.

Guidance on the detection and dispersal of methane roof layers is offered by Strang and Mackenzie-Wood (1985) reproducing, almost verbatim, advice in a National Coal Board document from the UK (NCB, 1979).

Coal mines regulations in New South Wales (Coal Mines Regulation Act, 1912) require flammable gases to be remotely monitored from the surface if the concentration in a return exceeds 0.5 per cent.

Colliery disasters at Box Flat in 1972, Kianga 1975 and Moura No.4 in 1986 indicated a need for more centralised and directed coal mining safety research in Queensland (Roberts, 1991). The safety in Mines Testing and Research Station (SIMTARS) was therefore established. While SIMTARS probably has the facilities to undertake methane layering research, it does not appear to have been identified as necessary.

4.4 Research and guidance in the USA

In 1995 some 161 million tonnes of coal was won from bord-and-pillar operations in the USA. Methane layering is not perceived as a major problem as seams are generally little higher than 2m and required face ventilation standards are high. No recent research on methane layering appears to have been undertaken, reliance again being placed on the early UK work.

United States mine safety legislation (MSHA, 1996) does not explicitly mention methane layering hazards but requires standards of ventilation and inspection which mitigate against hazardous occurrences in general. Ventilation must be applied to within 3m of a face unless an alternative approach has been specified and approved as capable of meeting dust and gas control requirements. When an auxiliary ventilation fan is stopped, ventilation shall be maintained on gas-affected faces using a line brattice or other means. In any mine opened after March 30, 1970, intakes and returns are to be separated from belt haulage entries. Pre-shift inspection is required of entries and rooms (developed after 15 November, 1992) extended more than two cross-cuts off an intake airway without permanent ventilation controls where intake air passes by or through them to reach a section where work is scheduled.

At least every 7 days, a certified person is required to examine unsealed worked-out areas where no pillars have been recovered. Methane and oxygen concentrations are to be determined together with airflow direction and quantity.

4.4.1 Methane layers and mine fires

Methane and hydrogen are identified as gases likely to form layers during an underground fire (Mitchell, 1990). In some circumstances, layered gases can propagate flames against ventilating airflows, possibly towards the firefighters. Flame spread may, however, be limited where oxygen deficient smoke is present. Mitchell provides a formula and nomogram for estimating minimum air velocities to prevent layering, based on the original work by James and Purdy (1962) and Leach (1964). The applicability of the results to bord-and-pillar systems is not questioned.
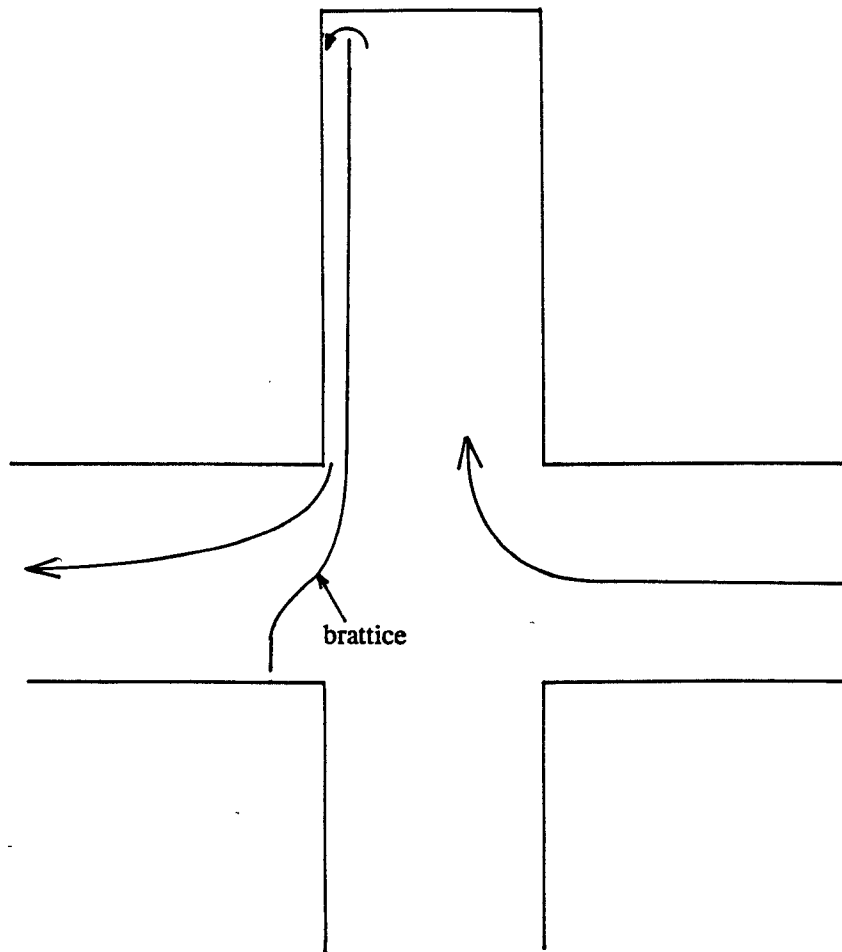
Figure 5   **Narrow-side brattice ventilation of headings commonly used in Australia**

INDUCED
AIR

COMPRESSED
AIR

ENTRAINED
AIR
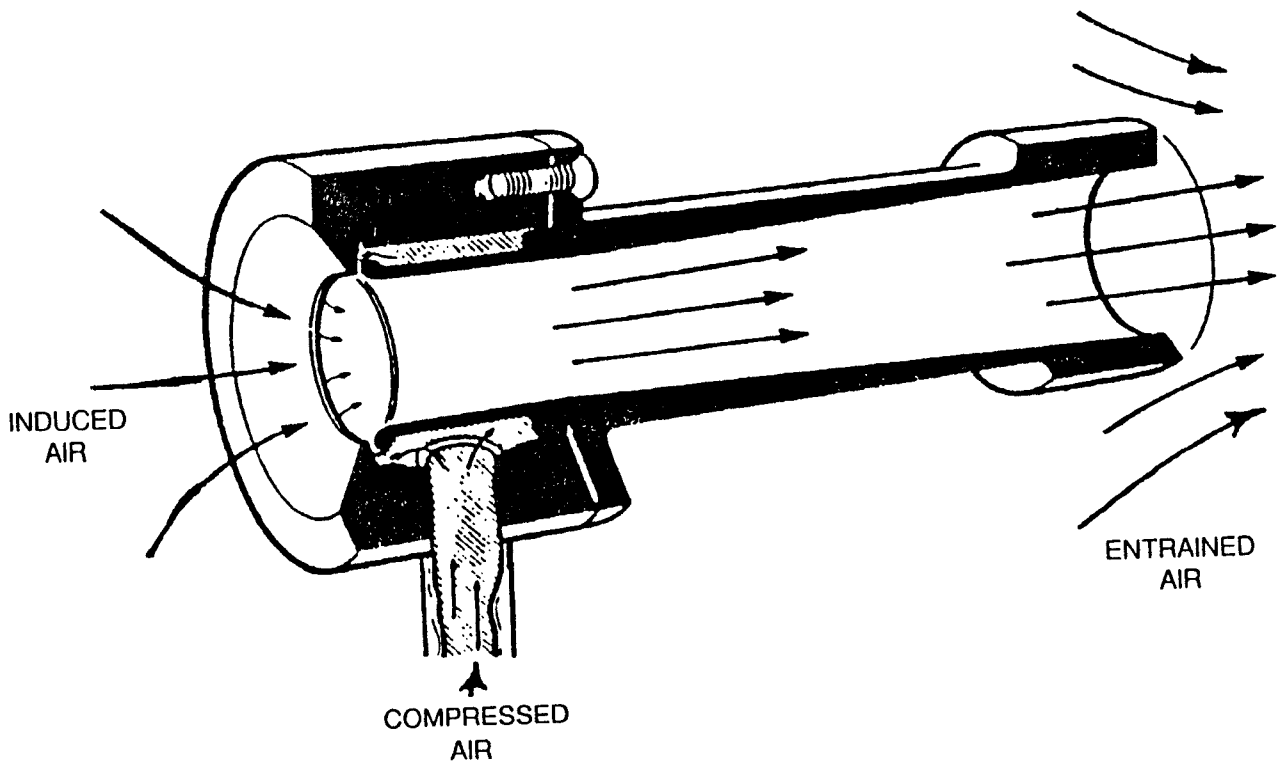
Figure 6   **Modern compressed air-powered venturi device**

4.5 Guidance on the control of methane layering in UK coal mines

In longwall working, the need for special measures to combat methane layering has been recognised for many years. Abolition of stable holes, which were used for moving shearers into the next cut at the end of longwall coalfaces, in the late 1960's and early 1970's reduced some of the methane problems. Whittaker (undated) reviewed the environmental considerations of [longwall] face end developments about 30 years ago. He suggested that air velocities of 1m/s or more were needed to disperse methane layers in return roadways associated with advancing longwall coalfaces. However, if the available airflow met other needs, the required velocities may be obtained by local ventilation devices such as a compressed-air powered venturi air-mover (Figure 6). These devices, placed in the "fresh" air of the main ventilation current with the jet angled at the affected area have proved effective at dispersing and preventing methane layering in UK mines where the problem cannot be removed by design of the mining layout.

Raine (1960) reports observations suggest layering would not occur *"in conditions of normal firedamp emission"* if the air velocity at the roof was in the order of 0.5 m/s. Although derived from an over-simplification of the problem, this value is still used in UK mines for assessing auxiliary ventilation requirements in near horizontal development headings (single roadway). Often the minimum velocity criterion is used as an average minimum velocity and therefore the derived air quantity will not necessarily produce the desired effect in the roof due to the velocity profile in a roadway section. In many long, single headings it is impracticable to achieve minimum air velocities of 0.5 m/s throughout their length due to duct leakages and obstructions to airflow. Gas accumulations in a heading are removed in a controlled manner following a specified degassing procedure. A typical arrangement is shown in Figure 7.

The detection and treatment of firedamp in layers at the roof of a mine roadway is described in National Coal Board Information Bulletins. Air samples should be taken at roof level at 20 yard (18m) intervals along the whole length of the heading and at breaks, faults, fissures and, if cross-measures, at coal seam intersections. NCB Information Bulletin 60/220 (1961) recommends roof monitoring to be carried out using a probe and aspirator to draw gas into the methanometer (or specially adapted flame lamp). Tee junctions on the main auxiliary duct can be used to disperse layers in headings provided the face air quantity is not compromised.

Jet ventilation techniques are also applicable in blind headings for preventing roof layering. Recirculation is likely to occur but need not be hazardous providing the amount of "fresh" air entering the heading is enough to dilute the total emitted methane quantity to a safe concentration (Bakke, Leach and Slack, 1964).

Experience in UK development headings (single roadway) is that even with high ventilation quantities layering will occur at roof level in the cutting zone if there is a methane feeder, however small, near to the heading face and no other local ventilation arrangements are made (Wing, 1992).

Risks of methane accumulating in dangerous quantities in headings have been reduced by wider use of auto-start facilities on fans reducing the number of protracted ventilation stoppages and the need for degassing operations in headings. A reduction in frictional ignitions and a substantial reduction in fan stoppages of over 30 minutes were obtained in 1991/92 in the Southern District of the UK Mines Inspectorate. Instrumental in the process was the introduction of an informal qualitative risk assessment carried out into ventilation systems.

In December 1994, the mining assets of British Coal were privatised. Great importance was attached to the need to maintain and continue improving safety standards in the UK coal mining industry. Prior to privatisation, the Health and Safety Commission (HSC) identified areas where the statutory regime needed strengthening (Langdon, 1997). These included:

- the ventilation of blind ends; and

- frictional ignitions.

The revised requirements are addressed in the Owners Operating Rules Regulations, 1993. The owner of a mine must prepare written rules, send copies to the Health and Safety Executive, and ensure they are brought to the attention of all persons at the mine, whether or not they are employed by the owner.
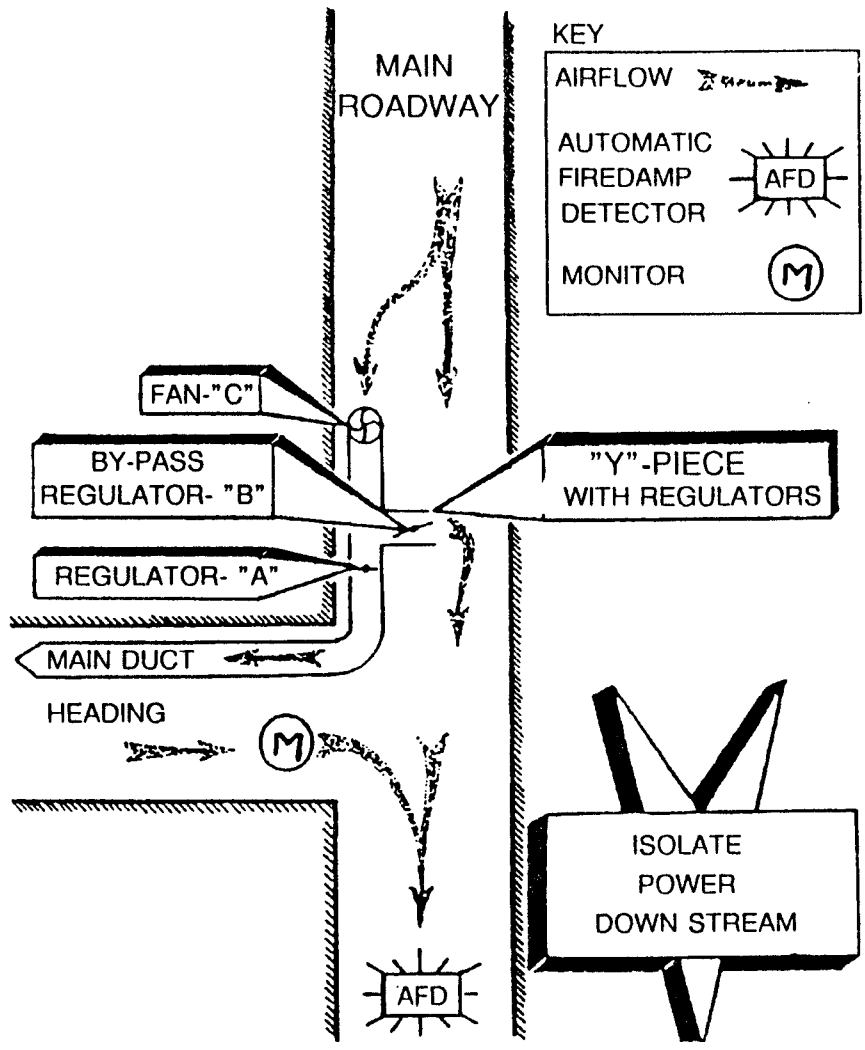
Figure 7   **Arrangements for the degassing of long development headings, with forcing ventilation, in a British longwall mine**
(After British Coal, 1991)

All operations at the mine must, so far as is practicable, be undertaken in accordance with the rules which must be observed by all persons who work at the mine. No specific guidance regarding the content of the operating rules is included in the legislative document, only the topics to be considered are listed.

Examples of relevant technical guidance, in general accordance with those currently applied to UK coal mines, can be found in documents produced by the former British Coal, namely:

- Best Practice for Ventilation of Headings - Notes for Guidance (NG/4).

- Ventilation Systems, Equipment and Plannings - Codes and Rules (CR/5).

Training packages designed to promote safer headings, prepared by British Coal Skill Scope (British Coal, 1991) involved videos, computer simulations and workbooks.

Industry guidance on the use of the layering number as an indicator of ventilation requirements was published by the National Coal Board (NCB) in a Production Department Information Bulletin (NCB, 1966). Revised, but less detailed technical guidance together with a metric formula for layering number was incorporated in a handbook for colliery ventilation officers (NCB, 1979) which is still in use as a reference document.

The following statement appears in recent British Coal (1991) training notes:

"The ventilation system must deliver a sufficient quantity of air to ensure that the velocity in the heading is high enough to prevent accumulations of methane. (A roof layer is one example of an accumulation of methane)".

Notes for guidance on the ventilation of headings suggest:

"Air velocities in the heading should always be sufficient to prevent methane accumulations at all positions within the heading".

Neither the means of achieving the above nor the impracticality of such a solution in many situations is discussed, nor is mention made of how to estimate an appropriate minimum air velocity.

Two systems for dispersing methane accumulations over heading machines are, however, mentioned. These are machine mounted fans and Coanda air curtains. The Coanda system (Figure 8) is preferred as it not only provides sufficient air velocity to disperse methane from the potentially stagnant area above the machine, but also keeps dust away from the driver. A small fan mounted within the machine passes air into a pipe containing a narrow slot. A "curtain" of air is directed to the roof which acts as a barrier against dust migration and a current of air to disperse methane layers in the roof.

4.6 Outcome of worldwide review

Most of the fundamental research on methane layering was completed in the 1960's in the UK in respect of hazards on longwall faces. Present guidance on the prevention and treatment of layering in Australia, the USA and the UK relies on this original work which has not been formally validated for application to bord-and-pillar operations.

System off   **System on**
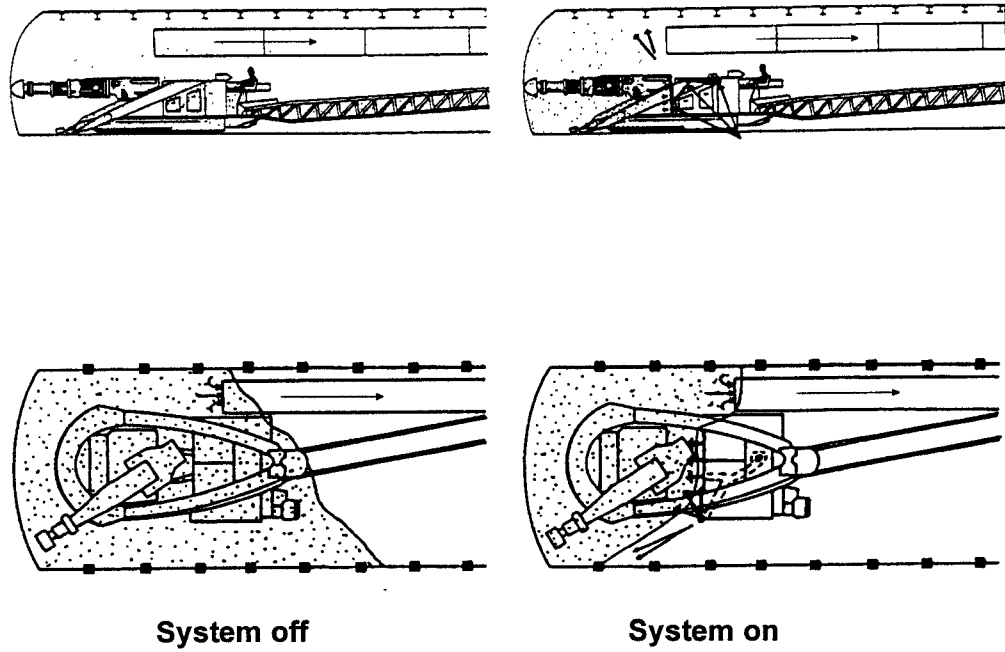
Figure 8   The effect of a Coanda Air Curtain System
on a heading machine. (After British Coal, 1991)

5 Relevant methane research and guidance in South Africa

5.1 Historical guidance in South Africa

In response to concerns following explosions in the mid 1980's, a working group of experienced officials (Holding 1987) proposed guidelines on colliery ventilation standards. The guidance was intended to provide a basis for developing Mine Managers' Codes of Practice specific to ventilation at each colliery involving consultation between the mine manager and the Mines Inspectorate.

In a constructive criticism of ventilation in bord-and-pillar workings attention was drawn to:

> "The practice of applying positive ventilation only to headings in the face region which are occupied for the purpose of carrying out mining operations".

Air velocity is arguably the most important factor in determining whether methane layering will occur. The recommended minima proposed in the guidelines for bord-and-pillar workings were:

(i)   a minimum velocity of 0.5m/s in the last-through-road

(ii)   a general minimum velocity of 0.15m/s in travelling roads and workings areas not otherwise specified.

The reason expressed for recommendation (ii) above was a perceived need to disperse any heat generated by spontaneous combustion. Methane layering was not mentioned.

Rib pillar mining and stooping was identified as the most difficult to ventilate satisfactorily due to the "enhanced methane emission associated with high percentage extraction systems and the fairly complex ventilation circuitry associated with bord-and-pillar mining". The need for effective, monitored, gas bleeder systems is mentioned. The report also emphasises the importance of gas monitoring and the benefits of remote, continuous monitoring systems.

The final statement in the document is apposite:

"Codes of Practice do not in themselves prevent accidents. The prevention of accidents depends on the effective implementation of the provisions agreed upon".

Various papers published in South Africa include mention of the detection and control of gaseous hazards although the role of methane layering is not always explicit. The following review provides an indication of the level of knowledge and understanding, and its development over time in respect of methane layering in bord-and-pillar workings.

Holding (1981) produced a reminder of the acute hazards of methane. An increase in methane concentration could arise due to:

- workings approaching a faulted area;

- workings approaching a previously unworked area;

- gas release in abandoned workings as a result of interaction with current workings;

- dewatering;

- barometric pressure fluctuations;

- changes to the ventilation circuit.

He emphasised the importance of considering air speed not just air quantity to disperse and dilute gas but expressed reservations on the use of layering numbers. Brattice hurdles were suggested as the easiest means of raising air velocity. The weakness of this approach, however, was that hurdles could be removed by passing traffic and the effect of too many would be a reduction in air flow. Alternative methods of increasing air velocity included local fans, air movers or possibly recirculation systems. He suggested that if methane was a problem in headings they should be force ventilated rather than exhaust ventilated.

King (1982) noted that single block walls were commonly used to separate intakes and returns and also to "seal off" disused areas. No guidance existed on the design and

placement of strategic explosion proof stoppings needed to combat the risk of explosions in abandoned workings. The possibility is mentioned of using barrier pillars to minimise the number of explosion-proof stoppings required to properly seal off an area. The implication of this paper is that older workings may not only provide a methane reservoir but also a potential for methane to escape and form layers leading to them.

Phelps (1983) discussed problems related to the detection and monitoring of gases in the face area of mechanised collieries but makes no mention of methane layers or the methods involved in detecting them. Marais (1989) highlighted the importance of early detection and measurement of the amount of methane present to allow appropriate corrective action to be taken. He also emphasised the need to recognise that when diluted methane was detected it must have passed through the explosive range somewhere between the point of emission and the monitoring location.

The technical literature reveals situations where methane layering hazards are likely to be present in South African collieries. For instance, at Ermelo mine, boreholes were drilled into the roof of the worked lower C-seam through a sandstone parting into the upper C-seam (Liebowitz and Cook, 1992) to prevent the build-up of excess gas pressure. Generally, two boreholes were drilled at each intersection. The gas flows tend to be variable in magnitude and longevity. Such methane emissions at roof level provide an ideal opportunity for the development of extensive methane layers which would remain undetected unless probed close to roof level.

A report on the Ermelo explosion of 9 April 1987 (Phillips, 1992) points to methane layering as a probable major contributory factor. The principal features of the Ermelo incident insofar as they can be determined are:

(i)   A methane accumulation in the roadways of a previously worked section in which the ventilation had been reduced, as is normal practice, to ensure adequate supplies to the current coal production section. Subsequently, a ventilation short-circuit resulted in a further, and unplanned, reduction in air quantity.

(ii)   Methane sources in the form of methane drainage boreholes drilled in the roof at each intersection. It is postulated that the methane flow would have increased as a result of the reduction in absolute pressure due to the ventilation changes.

(iii)   No evidence, from the monitoring and detection methods in use, of the presence of gas in the disused area of working up to the day of the explosion.

(iv)   An unknown cause of ignition.

It is possible that the ventilation short-circuit reduced the air velocity below the critical value at which a methane layer rapidly increases in length. A large expanse of layered methane could, therefore, have accumulated over a period of a few hours providing both the fuse from the ignition source, whatever its nature, and the explosive medium.

Apparently, where accumulations of water and methane pressures are identified as a possible cause of roof falls it is a fairly common practice in some mines to intersperse roofbolted boreholes with open, free-draining boreholes.

Hazards associated with methane layering are not limited only to underground coal mine workings in South Africa. Explosions of naturally occurring methane in the gold mines of the Evander and Welkom areas are a reminder that principles developed for coal mines may have wider application.

Guidance on flammable gas (methane and hydrogen) has been prepared for managers of metal mines by the Association of Mine Managers (STS, 1989) based on a   document originally compiled in 1973. Specific reference is made to roof layering and its hazards:

●   sufficient air flow should be allowed through airlocks to prevent roof layers forming where flammable gas is known to be present and ventilation blowers should be directed at the source of any gas emission;

●   an air velocity of 0.25 m/s will not prevent layering where flammable gas is issuing from the hanging wall;

- once mixed with air, flammable gas will not separate out again;

- in some instances, velocities of 1 m/s or more have not prevented layering, for example, in inclined workings;

- layers are not always cleared from the high point of workings on restoration of ventilation following a prolonged stoppage;

- when dispersing flammable gas, anti-static hoses should be used with any compressed air devices and anti-static or canvas ducting used with local fans;

- gas can be cleared from cracks and fissures in the hanging wall using a ventilation "hedgehog". This consists of a blanked-off vent pipe with air hoses or steel pipes inserted at intervals and fed directly into the gas bearing breaks.

The responsibilities and duties of various personnel for testing, reporting and clearing flammable gas occurrences are also described.

The dangers of gas accumulating in blind ends following a ventilation failure are well recognised. Kruger (1974) described a device developed at the Welkom Gold Mining Company to reduce this hazard. A degree of ventilation was maintained to development ends following a fan or power failure, by directing compressed air into an emergency fan causing it to rotate and deliver some 1m³/s to the auxiliary ventilation duct. Although not necessarily efficient, the "Emergency Compressed Air Blower" was found to be effective.

The occurrence and treatment of gas emissions into working areas of underground mines in general is discussed in the Mine Ventilation Society of South Africa publication *Environmental Engineering in South African Mines* (Greig, 1989). The concept of layering number is introduced but unfortunately there is an error in the formula as published. The density term is defined as 1 - density of gas relative to air divided by density of gas relative to air. It should read density difference between air and gas divided by air density. The erroneous formula leads to a value of 0.5 instead of 0.6 in the numerator of equation (8). Layering numbers of less than 5 are suggested as indicative of a layering potential and greater than 8 of a low risk. It is emphasised *"that the calculation of a "layering number"*

does not eliminate the need for testing for the presence of layers on site. Whenever inflammable gas emanations from strata are suspected, tests for the presence of a roof layer must always be carried out".

Greig considers it advantageous to ventilate development ends using forcing systems to disperse gas. The re-use of air from developments (series ventilation) for a second face should be avoided. In contrast with current UK guidance, automatic restart of fans in gassy headings is not recommended. A method for dispersing a methane layer using a high velocity air jet is also illustrated (Figure 9). The air quantity passing through the fan is higher than the airflow in the roadway which leads to recirculation. Recirculation in such instances is, however, beneficial in encouraging the dispersion of methane. In discussing the example, the author advises a methane monitor should be installed to trip the fan if the methane concentration immediately downstream of the emission point increases to say, one per cent. Clearly, an electrically powered fan is being considered. A hydraulically or air-powered fan would not be similarly constrained.

A system using hydraulically driven fans for dispersing methane in coal workings up to 4.5m high has been described by De Kock and Smit (1988). The "Hydravert" ventilation system can, for instance, be installed near the face in a high ignition risk area. This system does not appear to be used widely at present in South African bord-and-pillar coal mines. Currently, great reliance appears to be placed on electrically powered jet fans placed at the mouth of headings.

5.2 Recent research in South Africa

Landman (1992) analysed the exposure of coal miners in South Africa to explosion risks. A sharp increase in the percentage contribution of explosion fatalities to the overall fatality rate in coal mines was evident in the 1980's. In the same decade there were an average 5.5 explosions per year, compared to the 2.6 explosions per year for the preceding thirty years. Landman summarised his analysis of the 1980's thus:

CH$_4$ at 0,005 m^3/s

CH$_4$ ROOF LAYER

Explosive concentration
against hangingwall

V = 0,2 m/s
Q = 2 m^3/s

Condition 1 - No fan

CH$_4$ at 0,005 m^3/s

V = 0,2 m^3/s
Q = 2 m^3/s

3 m^3/s at 0,25% CH$_4$
recirculating

5 m^3/s

V = 0,2 m/s
Q = 2 m^3/s

CH$_4$ = 0,25 %

Condition 2 - Fan handling 5 m^3/s
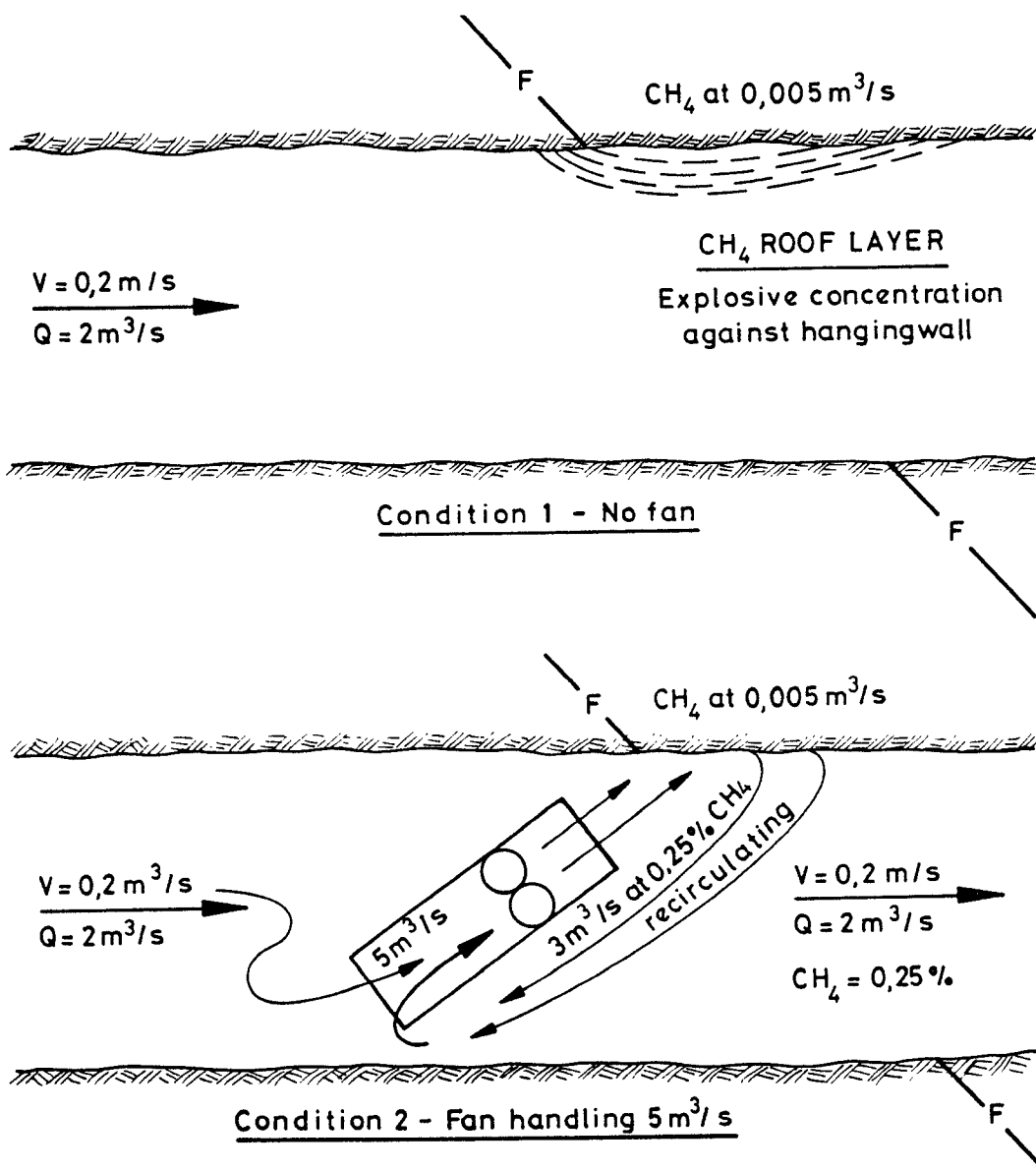
Figure 9   Dispersion of a methane layer with a high velocity air jet
(After Greig, 1989)

- an increase in the risk of fatality despite a reduction in the frequency of explosions;

- productivity improvements responsible for a 57% rise in risk (each underground worker produces a large volume of coal per shift or year and hence increases his exposure to the explosion hazard);

- more severe explosions responsible for a 43% rise in risk.

Of the 169 fatalities due to explosions during the 1980's, face explosions were responsible for 49%, non-face explosions for 40% and explosions in abandoned areas (including bord-and-pillar goaf) for 11%. Landman noted that of the 47 face ignitions between 1980 and 1991, only the Bosjesspruit explosion on 30 March 1984 and the Durban Navigation explosion on 5 September 1991, both in longwalls, were in other than bord-and-pillar types of mining system. The significant number of explosions in non-face areas, and associated with pillar type mining systems, highlights the difficulties of controlling methane in bord-and-pillar environments using ventilation methods.

Landman observed that three quarters of all explosions start in or close to the working face, the dominant source of ignition being frictional. Due to the concerns in respect of frictional ignition risks, SIMRAC subsequently commissioned a research project (COL 226) to identify measures for improving the situation (Phillips, 1996).

Landman considered that the explosion accident statistics indicated needs in three different areas:

(i)   prevention of explosion propagation ("post-ignition" research);

(ii)   effective maintenance of the mining environment and conditions ("pre-ignition" research);

(iii)   training of miners and engineers to communicate the latest knowledge in order to foster an awareness of the hazard and an expertise to control it.

The present study on methane layering impinges on all three of the above areas.

Recent research aimed at reducing methane hazards in collieries has been undertaken on behalf of SIMRAC (van Zyl et al, 1995). The project (COL 030) included investigation and modelling of methane flow in coal seams together with the measurement and computer simulation of ventilation and gas distributions around continuous miners in bord-and-pillar sections. The following stages of development of a section were studied:

- full heading development;

- fully developed split to the right;

- partial heading;

- partial split to the right; and

- full split to the left.

Simulated ventilation conditions generally involved a jet fan (4 to 5m^3/s), an on-board scrubber (10m^3/s) and a last-through-road air velocity of 1.5m/s. The effect on the local ventilation of replacing directional water sprays at the cutting head with non-directional sprays was examined. The impacts on methane dispersion of changing jet fan positions and use of ducted ventilation were also studied. Gas monitoring systems were demonstrated which could provide a useful indication of the effectiveness of the available ventilation in dispersing methane released in the heading. These systems would not, however, necessarily provide a measure of the gas hazard in a dormant section where local ventilation was temporarily halted as some air movement is needed to ensure representative gas mixtures pass across the gas detectors. In addition, detectors would not normally be positioned to detect roof layering.

Most studies, have concentrated on the methane hazards generated during coal production activities which is reasonable considering the juxtaposition of methane release and frictional ignition risk at the cutting head of a continuous miner.

An analysis was made of methane occurrences at the Secunda collieries as part of project COL 030 (van der Merwe, 1993). Gas emissions at these mines are generally considered to be very low. Correlations between geological disturbances, recorded methane emissions and ignition events were sought. Reported methane occurrences were few with only 16 per year from 4 large mines, although the precise criteria used to identify an "occurrence" are not clear. The data treatment used was essentially statistical correlation, insufficient detail being available to facilitate causal analysis or consideration of specific processes such as methane layering.

A review for SIMRAC under project COL 303 of the current status of research on seam gas content measurement and gas emission in collieries identified a general lack of basic methane-related data for South African mines (Creedy, 1996). Suggestions were made on how this knowledge gap could be filled and also how greater use could be made of existing remote monitoring systems for analysing methane emissions at collieries. Such data, even if available, may not be sufficiently specific to enable the prevalence of methane layering to be assessed. This current project, therefore, includes, in Chapter 6, a survey of ventilation data and underground observations from which an appraisal is made of the potential for, and possible extent of, methane layering problems in South African collieries.

Recent methane research has mainly focused on problems associated with high production, active mining operations, whereas methane layering is a hazard which tends to develop when or where mining activities are not taking place. For this reason its occurrence has received relatively little attention. In advanced mining countries where there is considerable experience of working gassy coal mines, precautions against methane layering hazards are incorporated within routine mining practises and the processes which lead to layering are generally well-understood. A substantial proportion of this knowledge has been gained in longwall mines but the basic principles are the same irrespective of the method of coal extraction adopted.

Although the fundamental principles of methane layering are independent of the mining method there is some doubt as to how existing empirical guidance derived from experiments and experience of long tunnels with few side branches can be applied to bord-and-pillar networks in practice.

5.3 The present situation

Existing literature and guidance in South Africa recognises methane layering as a potential problem in coal mines. However, the only available detailed technical guidance is directed at gold mines. Whilst recent research projects have examined ventilation issues relevant to the control of methane layering risks, no fundamental research has previously been undertaken on methane layering in bord-and-pillar workings in South African collieries.

6 Methane layering in South African collieries

6.1 Practical investigations

A technical seminar was held at Kriel to which delegates representing the major coal mining houses and the mines inspectorate were invited. The aim of the seminar was to steer the direction of research to ensure consistency with the practical needs of the industry, to provide an opportunity to exchange and debate technical views and to disseminate the results of previous, related research on gas emission prediction. Details of the seminar are provided in Appendix 1. A technical questionnaire was also circulated to gather information on practical experiences of methane emissions and layering in South African collieries.

Ventilation and roadway data obtained from the examination of ventilation and rescue plans have been used to determine the range of air velocities that may be expected in intakes where the number of parallel roadways typically vary from 1 to 11.

Computerised ventilation simulations, based on an idealised bord-and-pillar network, have been used to determine the possible ranges of mean velocity values that might occur and also the sensitivity of velocities to defects in the ventilation arrangement.

Four underground mines were visited to observe ventilation methods and gas monitoring techniques applied to continuous miner headings, conventional sections, worked-out sections and outbye intake areas. Methods of sealing-off and abandoning worked out areas were also examined. An understanding was thus obtained of the practical difficulties and logistical problems associated with monitoring and controlling ventilation to minimise gas risks in bord-and-pillar workings. In addition, talks were held with a supplier of monitoring equipment and ventilation officials at collieries.

6.2 Industry Consultation

In accordance with the research contract, an industry consultation seminar was held at the Kriel Club and presentations made by representatives of the University of the Witwatersrand and Wardell Armstrong. The seminar was considered to be a success in that it attracted 45 attendees from all the major underground coal mining companies, the mines inspectorate and other organisations. Details of the seminar and the attendance list are included in Appendix 1.

The principal benefits and findings of the seminar can be summarised thus:

- raised awareness of methane layering hazards among colliery staff

- some weaknesses exposed in the understanding of methane hazards and emission processes in collieries among ventilation practitioners

- accounts of methane layering occurrences confirmed as a real problem of potentially serious nature but relatively infrequent

- a reminder was given of the relevance of methane layering studies to gold mines as well as collieries

- the potential for methane layering to occur but remain undetected was demonstrated as significant

- precautions against methane layering should be viewed as one element within a suite of ignition and explosion prevention measures. A desire to trade one line of defence against another should be resisted

- reinforced the need for potential and pragmatic guidance on estimation of methane emissions and methane control practice.

6.3 Response to technical questionnaires

During the Kriel seminar, the Chairman of SIMCOL suggested that a questionnaire could be sent to attendees to gather further information on various experiences of gas emissions that were being reported at the meeting.

Five responses were received and these are reproduced in Appendix 2. Details of the emissions are summarised in Table 6. The significant emissions reported were mainly associated with seam intersections by intrusive igneous structures. A large methane layer was reported where gas had escaped from a sealed area to affect workings in which ventilation had virtually ceased due to an accidental short-circuit. It was observed that smoke released from a Draeger tube formed a flat layer beneath the methane layer.

	Table 6		
Gas emissions and methane layering reported in South African bord-and-pillar mines			
Colliery	Date	Geology	Circumstances of the occurrence
Springfield	November 1974	Many dykes	Greater than 5% methane layers in intakes and returns with 20m³/min air available. Gas concentrations increased rapidly when a coal cutter intercepted a borehole.
Goedshoop	August 1996	Burnt coal beneath sill	Greater than 80% methane in dyke development for some 65 minutes after forcing fan stopped.
Secunda Collieries	-	-	No occurrences reported.
DNC No 5 Shaft	1995	Dyke intersection	Over 600 l/s in one heading. Emissions persisted for some 3 weeks.
DNC No 7 Shaft	June 1994	-	400m long, 1m thick layer of greater than 5 percent methane (limit of detection instrument) in 3.2m high roadway. Ventilation ceased due to short-circuit caused by accidental damage to stopping. Gas from sealed areas.
Matla No 3 Mine	-	-	Current minor emissions detected in unventilated headings in particular section. Methane sometimes detected very close to slips, persisting for 2 to 3 days.

6.4 The potential for methane layering in South African collieries

The critical layering numbers established from European research mentioned in the previous chapter can be used to examine conditions in which methane layering could occur in bord-and-pillar workings. Worst case ventilation conditions are likely to be encountered where there are a large number of intakes. A typical situation could involve, say, 10 intake roadways of 6m wide and 4m high section and a total air quantity of 48m³/s. The average air speed in each roadway in this example is, therefore, 0.2m/s. The possible methane layering scenarios are illustrated in Table 7 below. Situations are considered all of which involve two return airways (24m³/s of air in each) and either:

(a)   a methane source in the intake, or

(b)   an emission source in one of the two return roadways.

	Table 7 Conditions in which methane layering could arise (refer to text for further details)			
Location of gas source	**Critical layering number**	**Minimum methane emission (l/s)**	**General body methane concentration if layer dispersed (%)**	
			In the intake roadway	**In the main return**
Intake roadway	2 5	1.30 0.08	0.027 0.002	0.003 0.0002
Return roadway	2 5	162 10	- -	0.68 0.04

Table 7 shows that very low methane emissions at roof level may be sufficient to initiate methane layering in the intakes of bord-and-pillar workings. In addition, monitoring of general body methane concentrations, whether by fixed or portable equipment will not detect the levels of gas emission which could generate extensive layering in the intakes. Methane layers are less likely to occur and, if they did, less likely to escape notice in return airways compared with intake airways, due to the higher gas flows required to initiate them.

In practice, more severe conditions may be encountered where the principal intake roadway is separated from the other roadways, normally under intake pressure, by brattice screens. Ventilation of such isolated areas may then be reliant on leakage airflows, possibly as low as 2 or 3 m^3/s distributed over 6 or 7 roadways and possibly more in some instances.

Ventilation and rescue plans from collieries provide an indication of typical ventilation and leakage quantities, mining heights, roadway cross-sectional areas and average last-through-road velocities. For the purposes of this study collieries were examined which provided data representative of:

●   seam heights in the range 2 to 5m;

●   conventional and mechanical bord-and-pillar mines; and

●   Natal and the Highveldt.

The results of this desk study are summarised in Table 8. However, some care is necessary in interpreting the figures due to differences in the basis of source data. Some plans show airflow at the face and in the return at the outbye end of the section, others provide intake and return flows at the outbye end.

A detailed comparison was made between air quantities measured at the face with those outbye in the return at two mines involving 17 sections in total. Leakage airflows ranged from 15 to 65 per cent of the total quantity in the section with a mean of about 40 per cent.

Section intakes in many mines generally involve between 4 and 12 roadways and a dual or single return. Sometimes, fairly extensive outbye areas are ventilated by intake air (Figure 10). Non-producing sections in mines are frequently ventilated by a single main intake and a single main return formed using brattice stoppings, leaving an extensive area of bord and pillar working ventilated only by uncontrolled leakage air (Figure 11). In a worst case example, an estimated 0.013 m/s was the average air velocity over 18 roadways. Assuming a critical layering number of 2, a methane emission as low as 0.0002 l/s could form a layer in such conditions and this quantity of gas would be undetectable in the general body of the air.

The environmental advantages of concentrating intake air in a dedicated roadway include greater quantities available at the face, an ostensibly reduced air demand for the district to meet air velocity minima in the last-through-road and improved dispersion of diesel fumes from vehicles. A disadvantage, however, is low air velocities in the partially isolated workings and an increased potential for methane layering. Whether the risk can be satisfactorily reduced by monitoring is discussed elsewhere in this report.

Information on the occurrence of methane in the general body or in sealed-off areas was not always provided on ventilation plans. In many instances the gas may have been undetectable and therefore merited no comment. Nevertheless, the insertion of zero values on plans would confirm that this was the case. Data on gas compositions in sealed-off areas were only available for 2 out of 5 mines studied.

67
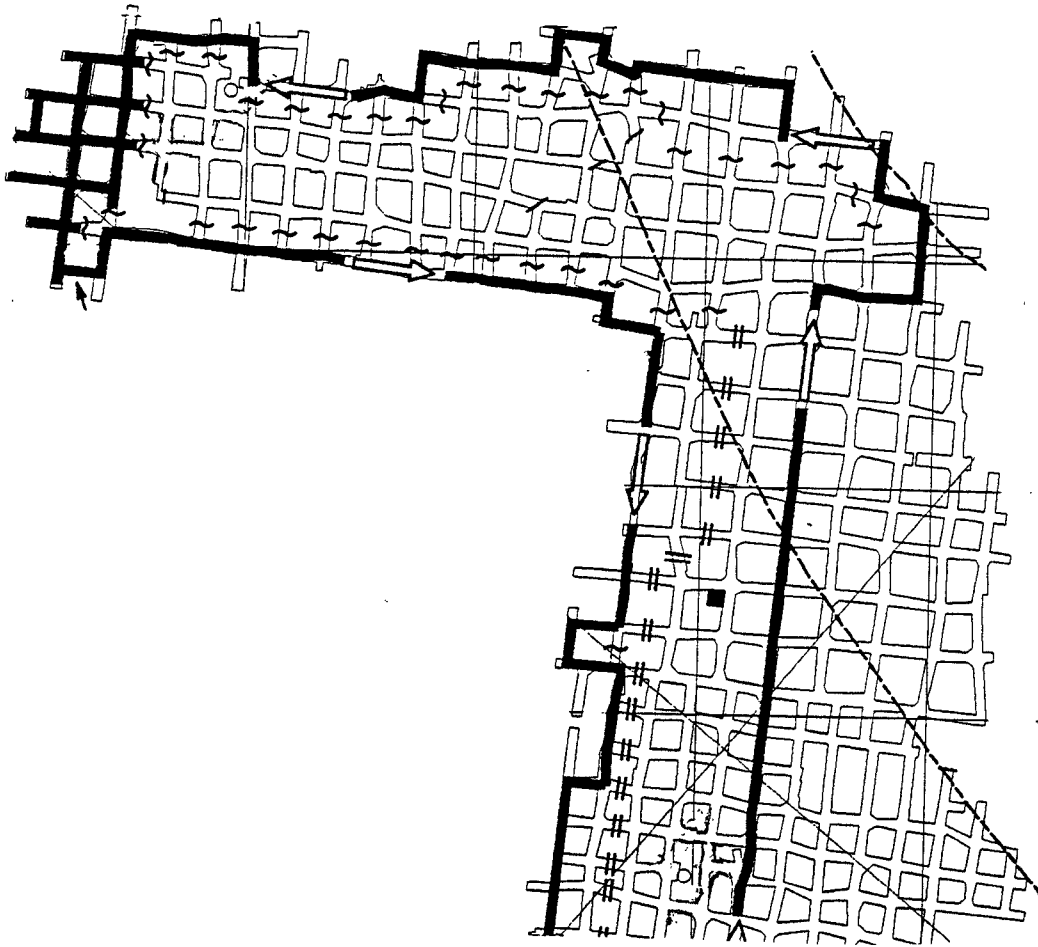
Figure 10   **Plan of a bord-and-pillar section showing multiple outbye intake roadways**
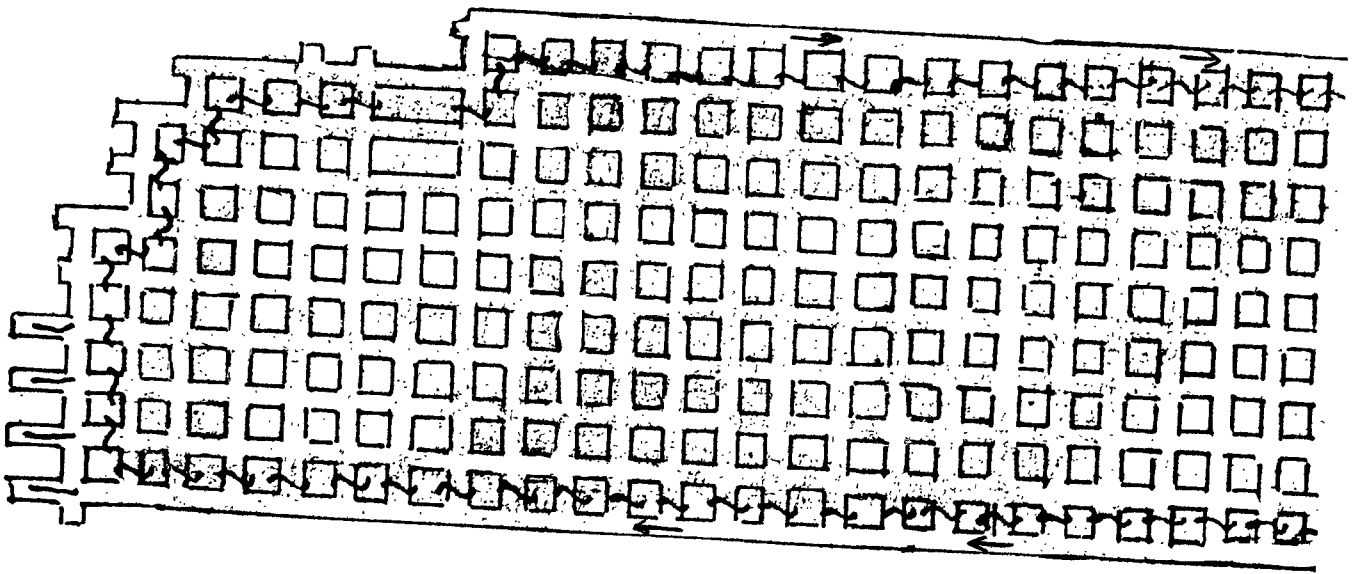
Figure 11   Plan of a bord-and-pillar section showing dedicated ventilation roadways and extensive low velocity, leakage ventilated areas within the panel

Table 8

Summary of data extracted from ventilation plans, 1996/97

Mine	Seam	Section *	Total airflow (m³/s)	Max. number of intakes **	Max. number of returns	Average bord width (m)	Average mining height (m)	Average face velocity (m/s)	Methane in sealed areas (%)
A	2	(i)	32	6	1	7.4	4.4	1.0	0 - 14.1
		(ii)	35	7	1	7.3	4.8	1.0	
		(iii)	35	6(1)	1	7.1	3.1	1.3	
		(iv)	34	7	1	7.3	4.4	1.0	
	4	(i)	43	6(1)	1	7.2	4.3	1.2	0 - 1.8
		(ii)	42	19(1)	1	7.0	4.4	1.0	
B	2	(i)	43	5	1	7.0	4.2	1.2	Sealed areas annotated according to proximity to explosive range. All shown safe.
		(ii)	46	6	1	6.6	3.9	0.4	
		(iii)	50	6	1	6.9	3.9	1.8	
		(iv)	44	5	1	7.2	3.9	1.1	
		(v)	38	8	1	6.8	2.4	1.2	
	4	(i)	36	6	1	6.6	3.2	1.3	
		(ii)	44	6	1	6.9	3.0	1.6	
		(iii)	45	7	2	6.7	2.9	1.4	
C	2	(i) and (ii)	111.8	10	3	6.8	4.5	1.1	No data
		(iii)	62.1	6	1	7.0	4.7	1.0	
		(iv) and (v)	114.2	12	2	6.8	3.6	1.3	
		(vi)	37.8	6	1	7.1	2.9	1.2	
		(vii)	44.4	7	3	6.9	4.1	1.1	
		(viii) and (ix)	149.7	11	4	6.8	4.2	1.0	

Table 8 cont'd.

Mine	Seam	Section *	Total airflow (m³/s)	Max. number of intakes **	Max. number of returns	Average bord width(m)	Average mining height (m)	Average face velocity (m/s)	Methane in sealed areas (%)
C	4	(i)	70.1	6	1	6.3	4.1	1.0	No data
		(ii)	64.7	5	6	6.9	4.0	1.5	
		(iii) and (iv)	127.2	12	2	6.8	3.9	1.3	
		(v) and (vi)	124.7	11	2	6.8	4.1	1.4	
		(vii) and (viii)	127.3	12	4	6.6	4.1	1.2	
		(ix)	53.7	7	1	6.9	4.1	1.1	
		(x)	97.6	5	2	6.8	4.2	1.7	
		(xi)	80.8	8	1	6.9	4.5	1.1	
D	2a	(i)	55.5	5	1	7.2	4.8	1.8	No data
		(ii)	35.6	14	3	7.3	4.3	1.1	
		(iii)	68.9	4	1	7.1	4.2	2.5	
		(iv)	40.3	7	1	7.2	4.3	1.1	
		(v)	59.1	4	4	7.3	4.2	2.0	
D	2b	(i)	72.5	7	1	6.6	3.6	-	No data
D	2c	(i)	32	5	1	7.0	4.3	1.0	0.05 to 32.9
		(ii)	42	4(1)	1	7.0	4.2	1.2	
		(iii)	35	13	3	7.2	4.6	1.0	
		(iv)	38	4(1)	2	7.2	4.4	1.1	
		(v)	35	7	1	7.2	4.1	1.1	
		(vi)	48	4(1)	1	6.9	3.9	1.2	
		(vii)	56	5(2)	1	7.0	4.5	1.2	
		(viii)	45	5(2)	1	6.9	3.7	1.1	
		(ix)	35	5(2)	1	6.5	4.6	1.0	
		(x)	28	4	1	6.6	4.2	1.0	

Table 8 cont'd.

Mine	Seam	Section *	Total airflow (m³/s)	Max. number of intakes **	Max. number of returns	Average bord width (m)	Average mining height (m)	Average face velocity (m/s)	Methane in sealed areas (%)
E	a	(i)	70.2	5	3	6.4	3.0	2.1	No data
	b	(i)	66.8	8	7	6.6	2.2	1.9	
		(ii)	27.5	6	6	6.8	1.3	2.0	
		(iii)	35.6	4	1	7.1	1.9	2.5	
	C	(i)	61.0	4	2	5.5	1.9	1.3	
	D	(i)	67.0	9	2	6.4	2.4	2.4	

*   Two numbers indicate double or back to back pair of sections.

**   Value shown is total number of roadways excluding the designated return. A value in parentheses indicates the number of roadways forming a brattice defined intake.

6.5 Bord-and-pillar ventilation modelling

A geometrically uniform section of bord-and-pillar working was modelled using a commercial network simulation computer program (VNET PC) in order to assess the effect of various ventilation conditions and defects on mean airway velocities. Thus, situations could be identified, subject to the availability of a gas emission source, in which methane layering could develop. A mean air velocity of less than 0.1m/s was arbitrarily selected as a low velocity at which layering could develop as a result of relatively low methane emissions in the roof. The model consisted of 12 intakes and one return roadway with 7 cross-cuts including the last-through road. The return and the working face was assumed to be separated from the intakes with brattice sheeting exhibiting an equivalent resistance of $20Ns^2 m^{-8}$. The basic layout is illustrated in Figure 12. The percentage of roadways with a mean air velocity of less than 0.1m/s, on a pillar by pillar basis, was calculated for each situation (Table 9). Included are the roadways with brattice stoppings.

Table 9						
Ventilation simulations of bord-and-pillar workings						
Model	Pressure drop (Pa)	Total airflow (m³/s)	Minimum velocity in last-through-road	Ventilation defect	Roadways with velocity below 0.1m/s	
					No.	(%)
1	10	50	1.6	Brattice leakages at assumed resistance.	31	27
2	10	113	0.8	Penultimate outbye return brattice removed (A in Fig 12).	18	16
3	2.5	54	0.4	As above but assuming some short-circuiting of ventilation.	39	34
4	10	72	0.6	Inbye return brattice removed (B in Fig 12).	19	17
5	10	57	0.5	Brattice removed left of centre of last-through-road (C in Fig 12).	25	22

The simulations are idealised but nevertheless demonstrate the sensitivity of the distribution of air velocities in bord-and-pillar workings to changes in leakage paths. Any failure of brattice stoppings will lower the velocity along part or all of the last-through-road. Outbye brattice defects will have a serious effect on the last-through-road velocity but the increased leakage flow across the intake roadways decreased the number of locations in which there is a potential for methane layering to occur.

6.6 Methane detection in South African collieries

6.6.1 Instruments

A range of instruments are used in South African collieries for flammable gas detection. A committee of suppliers, users, legislators and others assisted the South African Bureau of Standards to devise a specification for flammable gas detectors. Initially based on British Standard BS 6020, revisions are now being proposed to ensure conformity with International Standards.

The general types of instrument available and the difficulties of ensuring equipment is correctly calibrated, maintained and used in South African mines have been discussed candidly by Tyszowiecki and Moore (1996). Apparently, personnel have witnessed users check gas detectors at test stations in the lamp room, without the test gas being turned on, and then proceeding underground without apparently recognising a problem. When certain users were asked what the function of a CO monitor was, responses included testing temperatures, testing locos, testing methane and even dust measurement. This confusion was considered to reflect a shortcoming of translation from English or Afrikaans to Fanakolo. It also indicates inadequacies in training. According to van Sittert (1994) training is of primary importance with regards to gas monitoring. The Training Officer at the mine must be conversant in all aspects of the monitoring equipment and trained by the original manufacturer. Thus, the manager is able to discharge his obligations under Regulation 2.10.2, "*The manager shall not permit any incompetent or inexperienced workman to be employed on dangerous work or work upon the proper performance of which the safety of persons depends*".
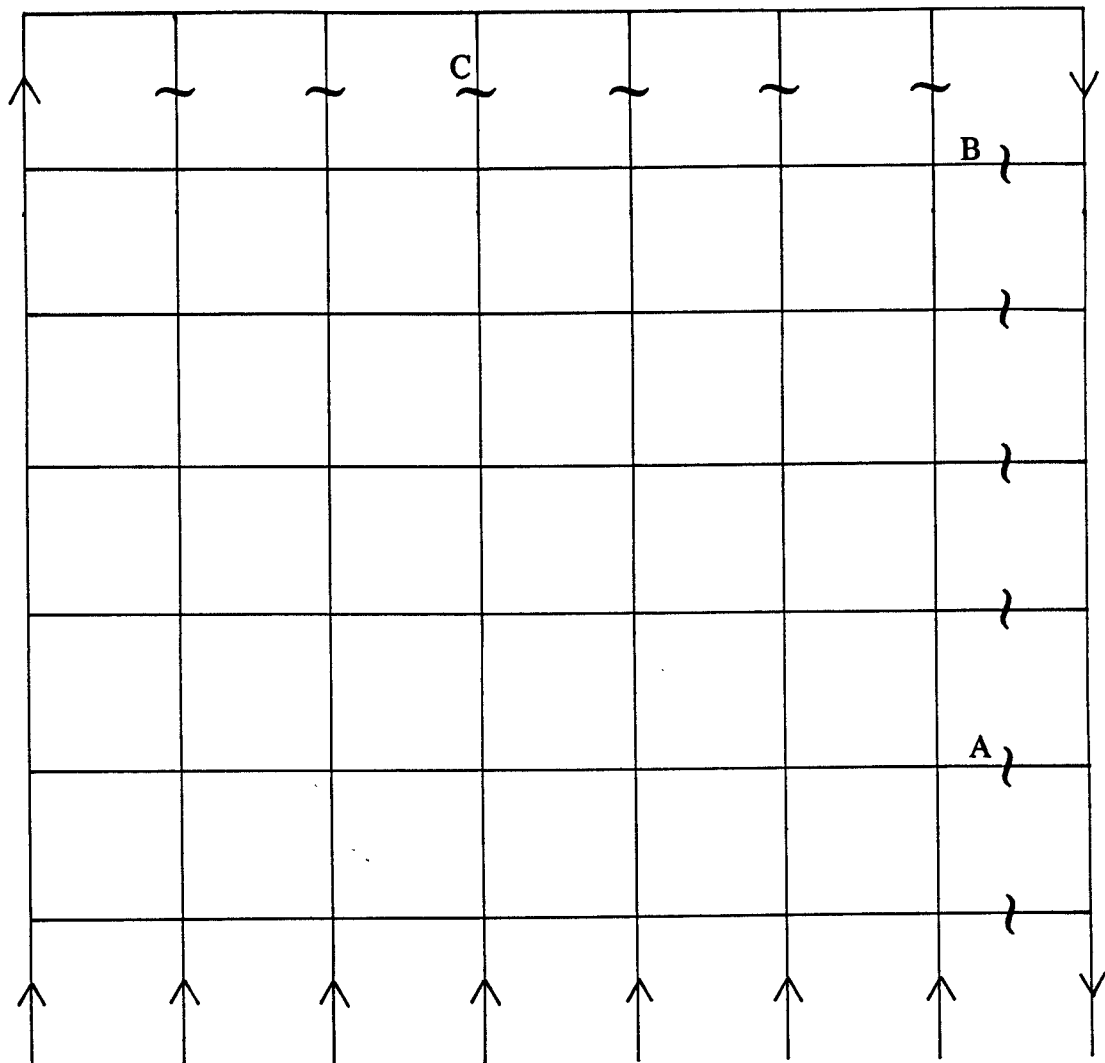
Figure 12   Idealised ventilation network used to study
air velocity distributions

Most of the flammable gas detection instruments in use at collieries measure methane concentrations in the range 0 to 5% using a catalytic oxidation device. This type of instrument is used in mines throughout the world. However, it can give misleading results if switched on in a methane-rich atmosphere (Figure 13). For example, an instrument activated in a 60% methane-air mixture, will read about 4%. This occurs because the device responds to temperature change caused by the oxidation of the combustible gas, but in high gas concentrations the reaction is limited by the availability of oxygen.

An instrument activated at or below 5% methane will register full scale deflection or indicate an out of range value and also enter alarm mode if the concentration exceeds 1.4%.

The instruments usually used by ventilation departments at South African mines are either continuous reading or sample over a short period of time and they display the reading.

The advantages and disadvantages of the currently available types of flammable gas monitoring instruments used in South African collieries are compared in Table 10.

The major shortcoming of readout visibility when an instrument is held against a high roof could be overcome by separating the display and the detector, allowing the detector to be raised to the roof. However, the joining wire would be vulnerable to damage. An intrinsically safe communication link between transducer and display (eg. infra red) would be required for a practical instrument.

The alternative method of manually drawing a sample to the instrument through a long probe and aspirator is impractical due to the length of probe required, the possibility of sample dilution by leakages and the time involved in flushing and filling the sample probe. However, it should be possible to devise a simple, reliable mechanised sampling system that would permit this approach to be used.
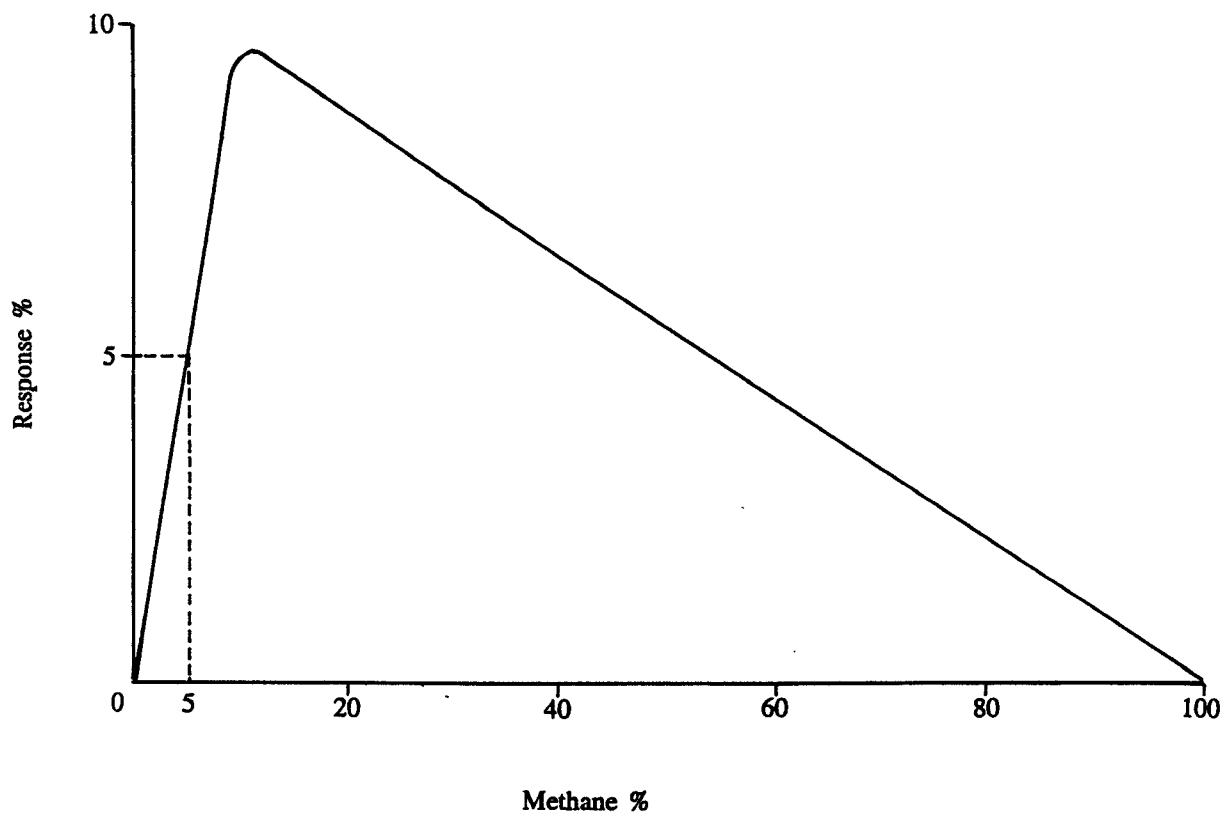
Figure 13   Response of methanometers using pellistors when activated
in different methane concentrations in air

Table 10	
The suitability of current flammable gas detectors for the detection of layers	
Advantages	**Disadvantages**
• Relatively lightweight, compact, continuously reading instruments can be raised to the roof if required. • Some instruments will indicate maximum or peak gas concentrations. • Automatic logging of readings available on some instruments. • Visual and audible alarms available. • Reliable provided operated, maintained and calibrated correctly.	• Pellistor based instruments will not measure flammable gas concentrations greater than about 5 per cent. • A thin methane layer may not be detected due to the disturbance caused by the presence of an instrument or probe at the roof. • When held against a high roof, instruments are difficult to read. • No reliable probe is available for drawing a sample rapidly from the roof to a hand-held instrument.

6.6.2 The use of safety lamps for detecting methane layers

Holding (1977) expressed concern on reviewing responses to Colliery Ventilation Certificate Examinations on the topic of testing for methane roof layers using a safety lamp. Most candidates described a method of holding the lamp up to the roof and closing the side vents on the false assumption that gas would enter through the bonnet at the top. The only safe and reliable way of using a flame safety lamp to detect methane layers is by attaching a sampling probe and aspirator bulb. Nowadays, electronic methanometers are the only instruments in most countries, including South Africa, available in mines for the detection of methane layers.

6.6.3 Detection of methane layers

In South African collieries the monitoring method recommended by the Inspectorate involves raising the gas detection instrument to the roof using a suitable roof or scaling pole. There are various practical difficulties with this approach in high seam sections eg. of 4m or more:

- a rod of sufficient length to reach the roof is not always readily available at the face or other sampling sites;

- access for roof sampling may involve a combination of unsteady stepladders and a short rod;

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- most instruments are difficult to read when held against a high roof although a preset audio or visual alarm will sound if the methane concentration is 1.4% or higher;

- the operator may require an assistant to stand back from the rod to obtain a reading. Other than at the face, gas monitoring is usually a solo task and there must be considerable doubt as to how effective any gas monitoring is outbye of face areas in high roadway bord and pillar workings;

- the rarity of significant gas concentrations in many mines, the multiplicity of areas which require testing to ensure there are no methane layers and the difficulty of sampling and reading the instrument must in combination be a deterrent to effective monitoring.

There are practical problems with monitoring the roof at the face of headings. It is not desirable to work under an unsupported roof and hence safe access is precluded in many headings to the area most likely to exude gas. Gas testing prior to working or examination of non-working headings can therefore be problematic. Where headings are continuously ventilated to a reasonable standard, general body gas concentration measurements will provide an indication of significant methane ingress, disperse layers and obviate the need for testing at roof level. Practices at some South African mines require continuous mechanical ventilation of headings which intersect dykes where there is an identified gas emission risk.

6.7 Control of methane layering in bord-and-pillar workings

6.7.1 Headings

Various methods have been devised for ventilating headings in South African bord-and-pillar workings. The techniques aim to provide sufficient fresh air at a high enough velocity to both dilute and rapidly disperse methane. The design and selection of a heading ventilation system for a particular section at a mine depends on many factors, not just the perceived gas hazard, such as:

- bord width;

- mining height;

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- length of heading;

- coal extraction method;

- advance rate.

The methods of heading ventilation include:

(i)   Use of jet fans positioned at the mouth of a heading, either free-standing or roof-mounted.

(ii)   Hydraulically driven fans installed in the heading near the face in a normally high risk area (De Kock and Smit, 1988).

(iii)   A forcing or exhausting fan and duct system.

(iv)   Fan and duct system with a brattice on the opposite side of the heading.

(v)   Scoop brattice to the full height of the roadway.

(vi)   Natural ventilation caused by the air velocity in the last-through-road passing the end of the heading.

In mechanised sections, the rate of gas mixing and dispersion is enhanced by dust scrubbers and water spray systems mounted on the cutting machine.

Ventilation practices vary from mine to mine depending on gas hazards and custom. Where fan and duct systems are used to ventilate headings, they may run continuously, irrespective of coal production, if a gas emission hazard is present. However, where mechanical ventilation systems are employed it is probably more common to operate them only during active mining. In these situations, methane layers could accumulate in non-active headings. Natural ventilation effects are largely ineffective beyond about 10m from the mouth of a heading and are highly dependent on air velocity in the last-through-road (Meyer, 1992). Natural ventilation cannot be relied on to prevent methane layering in the roof of headings.

Scoop brattices offer the advantage that ventilation is maintained during non-production periods and with this method it should be possible to prevent layering in high seam sections provided gas emission rates are low. To be effective, the brattice must be extended sufficiently close to the face. This in turn requires roof support to be installed to provide safe access and also a means for suspending the brattice.

The continuity of the section ventilation is dependent on the total quantity of air being supplied and the integrity of brattice screens outbye of the face region. While the air velocity at the return end of the face may be continuously monitored deficiencies along the face area arising, perhaps due to a displaced brattice, will not necessarily be detected, especially if no production is taking place towards the intake side. During a production shift, the miner is responsible for measuring and recording the last-through-road velocity at each heading. It is vital that he is aware of the importance of this reading and also equipped with suitable measuring equipment and trained in its use. A practical method for reducing the likelihood of a short-circuit of air affecting the face air velocity involves the use of a small forcing fan at the intake end.

Analysis of statistics for South African collieries for the period 1982 to 1993 show similar numbers of fatalities from explosions in the face area, abandoned areas and outbye areas of 78, 59 and 81 respectively (Phillips, 1995). However, it must be remembered that many of the non-face explosions occur close to working sections and so the face area remains of extreme importance. New ground is being continually exposed at the face, it is the most common location of gas release and there is also the ever present risk of frictional ignition from the cutting tools. Existing technologies have the capability of controlling gas-related risks at the face. Ventilation arrangements appropriate to most of the circumstances encountered in South African collieries are available. Satisfactory schemes will be compatible with the mining and roof support methods but will only be effective if properly implemented, maintained and monitored.

Detection and prevention of methane layering in headings is important for two reasons:

(i)   reduction of gas explosion risk;

(ii)   reduction of likelihood of propagating a flame, or explosion into a larger accumulation of gas elsewhere.

The last-through-road has an important role in separating the relatively high ignition risk face zone from extensive outbye areas in which gas could accumulate in certain circumstances. Provided a fresh air quantity with a sufficiently high velocity is swept across the mouth of each heading, there can be no continuity of methane layers originating in the headings. Last-through-road velocities typically required and attained in South African collieries should satisfactorily disperse any layers emerging from inadequately ventilated headings.

6.7.2 Outbye areas

Examination of ventilation plans from a range of South African collieries indicates air velocities are probably too low to prevent methane layering in some extensively worked areas outbye of the face. Other situations in which layers could develop include:

●   a section prior to abandonment in which the air quantity has been reduced in order to serve a new face elsewhere;

●   at stoppings to sealed-off areas;

●   goafs associated with pillar recovery.

6.8 Summary of the current situation

Methane layering is rarely reported in South African collieries. However, some layering could be occurring but may not necessarily be detected. Available instrumentation is not ideally suited for measuring methane concentrations in the roof of high roadways. Even if more user-friendly equipment was available it would not be practicable to examine all sites where layering could occur and a risk minimisation strategy should recognise this.

7 Developing specific guidance on methane layering for South African bord-and-pillar mines

Draft guidance is presented in Appendix 3 incorporating principles which if adopted will enable methane layering hazards to be minimised. The practical difficulties of monitoring gas concentrations in high roadways are recognised as are the limited availability of staff resources in South African collieries. Strong emphasis is placed on the need to ensure continuity of fresh air ventilation in all headings and a high standard of fresh air ventilation at the face of producing CM sections. Thus, the likelihood of gas accumulations and explosions at working faces can be minimised. Irrespective of these precautions, a quantity of air in the last-through-road of sufficient velocity to prevent layering (current Code of Practice minimum velocities, in most instances, are likely to be sufficient for this purpose) will ensure that any ignition, flame or explosion at the face will not propagate to outbye areas where explosive mixtures of gas could accumulate in certain circumstances. There is an implicit assumption that stone dusting is kept up to the last-through-road to remove the potential for propagation of a dust explosion beyond the face area. This is current practice.

It is neither practicable nor reasonable to continue ventilating worked-out sections to the same standard as working sections due to the finite supply of air available. Emphasis in these changed circumstances should, therefore, be directed at the introduction of effective monitoring schedules involving gas detection in the roof and air velocity monitoring in the general body of bord-and-pillar workings in which ventilation quantities have been reduced pending sealing-off.

Clarification is, however, needed of responsibilities in respect of inspection, monitoring, reporting and action to ensure the advice of the ventilation officer or environmental superintendent is sought at all stages. Thus, the necessary expertise can be developed and exploited to the full through the ventilation department.

The draft guidance does not include any unnecessarily onerous proposal for collieries. In fact, raising section ventilation practices and standards to a level commensurate with that needed to satisfactorily address frictional ignition risks at the face will contribute significantly to a reduction in any risks associated with methane layering.

The philosophy proposed can be summarised as directed at minimising risks associated with methane layering in working sections and identifying and controlling the hazard in non-working sections.

The suggestions relating to face operations are considered reasonably consistent with, and underline the importance of, the gas control measures incorporated in official South African guidance. Revised *Guidelines for a Code of Practice for the Ventilating of Mechanical Miner Sections in Coal Mines* (Department of Minerals Energy Affairs, 1994) include the following ventilation objectives in respect of flammable gas:

- a flammable gas concentration of less than 1.4%

- a minimum air velocity in the last-through-road of at least 1.0m/s

- effective secondary ventilation in headings

- all non-coal headings in an advancing section positively ventilated

- regular determination and recording of critical ventilation data

- inspections of gassy sections at intervals not exceeding one hour

- automatic electrical isolation of mechanical cutting if any components of the secondary ventilation system cease to operate

- properly planned and managed ventilation changes

- special precautions when approaching burnt coal and geological anomalies

- continuous gas monitoring in the heading being mined

- measurement of the flammable gas emission rate to assist in the design of an effective ventilation system.

Whilst elements are identified which are necessary to reduce explosion risks, secondary ventilation methods which cannot guarantee delivery of fresh air to the face continue to be accepted.

Any framework for combatting methane layering hazards in South African bord-and-pillar workings, should recognise the principal factors responsible for occurrence of layering (Table 11), together with an understanding of the role of methane layering control in the chain of events which can lead to a serious ignition (Table 12).

Table 11
Factors contributing to the occurrence of methane layering hazards in bord-and-pillar workings

Principal factor	Specific factors
Natural occurrences of methane	Coal seam in roof Coal seam in floor Fractured or permeable "reservoir" rock Worked seam In solution in strata water Fault zones Accumulations associated with igneous intrusions, devolatilized or burnt coal
Opportunities for gas accumulation and layering in mine workings	Roof cavities Leaking stoppings Unventilated areas of bord and pillar workings Unventilated headings Near-horizontal workings
Ventilation, quantity and management	Air velocity too low in through roadways Inadequate auxiliary ventilation in headings Uncontrolled degassing of workings

Table 12		
An assessment of ignition risk from methane layering in bord-and-pillar mines		
Potential failure	**Possible causes of failure**	**Preventative measures**
Failure to prevent an ignition	Inadequate or unreliable auxiliary ventilation in headings. Deficiencies in machine ventilation systems. Worn picks, blocked sprays, low water pressure.	Use of suitably designed and protected equipment. High standards of maintenance. Effective monitoring.
Failure to exclude ignition sources	Electrical power and frictional ignition sources associated with continuous miners. Smoking and other illegal activities.	Strict training and supervision of staff. Contraband searches on entry to the mine.
Failure to disperse methane layering	Insufficient ventilation capacity. Inadequate local ventilation arrangements.	Methane control procedures. Availability of air movers and other suitable equipment.
Failure to detect methane layers	Incorrect monitoring locations. Lack of suitable monitoring equipment. Inadequately trained staff.	Site specific monitoring programme. Suitable monitoring probes, especially for high roadway sections. Training.
Failure to prevent methane layering	Ventilation quantities too low. Unreliable ventilation.	Ventilation planning. Locally enhanced roof ventilation.
Failure to prevent emission of methane.	Methane emissions are a natural consequence of underground coal working.	Methane drainage.

8   Conclusions and recommendations

The specific outputs required of the project have been completed. These are:

- a worldwide literature review (Chapter 4);

- an appraisal of the significance of existing knowledge to bord-and-pillar coal workings in South Africa (Chapters 5, 6 and 7);

- preparation of draft practical guidance on methane layering for use by collieries (Appendix 3);

- a bibliography (References).

The first three Chapters of the report introduce the fundamentals of layering and examine the implications of the methane layering hazard with an international perspective.

8.1 Conclusions

The principal conclusions of the research are as follows:

- Most of the fundamental research on methane layering assumes linear, non-branching roadways therefore some caution is required in applying results to bord-and-pillar mining methods.

- The layering number concept developed by Bakke and Leach (1960) is a useful practical indicator of the potential for methane layering but its predictions should be tested by observation and measurement to confirm applicability to bord-and-pillar workings.

- In assessing methane explosion risk in collieries, consideration is needed of both operational and non-operational underground sites where methane can accumulate.

- Analysis of circumstances leading to explosions in South African coal mines and elsewhere demonstrates the importance of detecting, monitoring, dispersing and preventing methane layering.

- Local ventilation equipment which is capable of safely dispersing methane layers and ventilating roof cavities should be readily available at any mine where a layering problem is identified and staff trained in its effective application.

- Irrespective of the effectiveness of amelioration measures, wherever practicable, the priority should be to design ventilation and gas control systems to prevent methane layers occurring in the first instance.

- Methane layers can occur in low-gas mines.

- Methane layers can form rapidly in the absence of adequate ventilation. More attention should be given to non-productive periods in the mine during which gas can accumulate and constitute a hazard when work, and local ventilation, re-commences.

- It is not always possible to prevent conditions arising favourable to the occurrence of methane layering in bord-and-pillar mines.

- Portable methane monitoring equipment at the mine should be capable of sampling gas at roof level, especially in high roadways where air velocities may be low.

- Fixed methane monitors will not yield representative data for non-production areas without some continuity of ventilation to cause air movement.

- Opinions of colliery officials and ventilation staff on the practicality of monitoring outbye areas of a section for methane layering are mixed. Observations made in this study would suggest that, if such monitoring takes place it may not be reliable. In addition, there are usually too few ventilation staff to effectively monitor all areas of a mine where layering could occur.

- Field investigations have provided an insight into the practical difficulties of monitoring for methane layers in bord and pillar workings. The accepted sampling method involves raising the methanometer to the roof, but suitable rods are not always available and instruments are difficult to read in high roadways.

- Gas monitoring resources should be directed at areas identified to be of highest risk. The concept of layering number, which provides a means of assessing and comparing gas hazards from place to place in a mine, could be helpful in determining locations potentially vulnerable to layering and also defining minimum air quantities.

- High concentrations of methane could exist at roof level but once dispersed in the ventilation the gas may not necessarily be detectable with normal gas detection instruments.

- The safety of underground mining operations from methane layering, or any other hazard, does not depend entirely on technology. As important are understanding, training, motivation, standards of work and supervision.

8.2 Recommendations

8.2.1 Draft guidance

The results of this research project including findings from the literature survey, practical experience, underground observations and industry consultation have been used as a basis for the preparation of draft practical guidance notes (included as Appendix 3). It is recommended that this draft guidance is considered by the industry.

8.2.2 Further research needs

The aspect of layering that warrants further research relates to the sometimes expansive partially ventilated workings outbye of the face. There is a need to know the minimum ventilation requirements, when and how best to monitor such areas and how to pre-empt problems. Concepts established for single continuous roadways should be tested for applicability to roadways with regular intersections.

Fundamental research could be undertaken using a perspex scale model of a bord and pillar section. Much work has already been published on preserving aerodynamic similarity in scale models compared with the full-scale equivalent and use could be made of these results (eg. Aitken et al, 1988; Jones 1994a, 1994b). Jones found that a Reynolds number of 6000 or greater was necessary to ensure turbulent flow in a longwall coalface model. Variables to be examined with a scale model include:

- methane emission location;

- number of emission sources;

- rate of gas emission;

- airflow distribution;

- air velocity.

Thus, the conditions for layering to occur can be established for room and pillar mines and the layering numbers obtained compared with the results of longwall based research. Further insight into the variability and magnitude of air velocities in different bord and pillar ventilation configurations may be gained from a computer network model incorporating the findings of current SIMRAC research project COL465 *Development of an airflow simulation network program for bord-and-pillar workings*.

Flow visualisation techniques should be used with a model to facilitate demonstration of findings to the industry for training purposes and also to raise awareness of the phenomena.

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Appendix 1

**Details of the Industry consultation seminar
held at the Kriel Club, 20 May 1997**

Ref: HRP/sp/073

Tel: (011) 716-5136
Fax: (011) 339-8295
Date: 9 May 1997

Name

Fax No.

Dear

SIMRAC PROJECT   COL 409

Methane Layering in Bord and Pillar Workings

One of the research projects approved by SIMRAC in the 1997 programme deals with the lack of information regarding the formation of methane layers in bord and pillar working. The project has been awarded to the Wardell Armstrong Partnership in the United Kingdom, with some input from the Department of Mining Engineering at Wits.

So far the research indicates that methane layering has been an important factor in major explosions in underground coal mines in various countries. Available rules and guidance aimed at prevented methane layering emphasise the need to provide adequate ventilation but the means and criteria to be employed are often not explicitly stated. A prevailing view appears to be that methane layering is, in particular, likely to occur in high roadways due to the lower air velocities in airways with large cross-sectional areas.

The research project recognises the importance of industry consultation in steering its progress to ensure that the industry gets a research report that meets its needs, addresses the correct concerns and presents conclusions that can be applied. In order to achieve this, a seminar has been arranged to be held at the Kriel Club, Kriel on Tuesday 20 May at 9 a.m. to which you are cordially invited to attend, or to send appropriate delegates. A programme is attached.

We would be most appreciative if you could fax to Mrs Parker at the above fax number a list giving the names of likely attendees as soon as possible to allow catering arrangements to be made. If you require directions to the Kriel Club please indicate this on your reply.   I would hope that we have your support in this matter, so that this research project can be successfully completed for the benefit of the coal mining industry.

Yours sincerely

H R PHILLIPS
Professor and Head of Department

D.P. CREEDY
Wardell Armstrong

THE KRIEL CLUB

TUESDAY, 20th MAY 1997

SAFETY IN MINES RESEARCH ADVISORY COMMITTEE
PROJECT COL409
METHANE LAYERING IN BORD-AND-PILLAR WORKINGS

SEMINAR PROGRAMME

8.30 - 9.00 a.m.	Coffee and registration
9 a.m.	Welcome and introduction to the aims of the seminar Professor H.R. Phillips
9.15 a.m.	Explosions in South African collieries and the role of methane layering Professor H.R.Phillips
9.45 a.m.	Methane prediction in collieries, the findings of SIMRAC Project COL303 Dr D.P. Creedy
10.30 a.m.	Break for coffee
11.00 a.m.	Methane layering in bord-and-pillar workings Dr D.P. Creedy Discussion chaired by Mr D.R. Hardman
12.30 p.m.	Lunch
1.30 p.m.	Explo Stop - a means of extinguishing fires and explosions in headings Centrocen Pty. Ltd.
2.30 p.m.	Meeting close and farewell

Wardell Armstrong- University of the Witwatersrand, Department of Mining Engineering
METHANE LAYERING SEMINAR - KRIEL

TUESDAY 20 MAY 1997   **ATTENDANCE LIST**

SURNAME	INITIAL	TITLE/POSITION	COMPANY	TELEPHONE No.	FAX No.
BARNARD	M C	Enviro Supt	Amcoal - Goedehoop	(0135) 687-5300	(0135)687-5426
BEMBE	KP	Enviro Control off	Amcoal - Geodehoop	(0135) 687-5300	(0135)687-5426
BRYDEN	D		Kloppersbos		
COETZER	W J J	Training Supt	Ingwe Eng Train Ctre	(0135)689-3120	(0135)689-3110
CRONJE	B	M/O Prodn	Ingwe - Koornfontein	(013)2953111	(013)2953111 x 3225
CRONJE	T	Enviro Supt	Khutala		
De KOCK	A		Miningtek		
Du PLESSIS	K	Insp of Mines	Min & Energy Aff - Mpum	(0135)656-1448	(0135)903288
Du PLESSIS	M	Snr Insp of Mines	Min & Energy Aff - Mpum	(0135)656-1448	(0135)903288
Du PLOOY	M H	Prodn Mngr	Amcoal - Goedehoop	(0135) 687-5300	(0135)687-5426
FOURIE	M	Vent Supt	Ingwe - Koornfontein	(013) 295-3111	(013)2953111 x3225
GIBSON	M I	Prodn Mngr	Ingwe - Koornfontein	(013) 296-3111	(013)295-3111 x3225
GILLILAND	C		Centrocen		
GUME	F	Vent & Health mngr	Ingwe - Khutala	(0135) 993660	(0135) 648-1411
GUTHRIE	J		AAC - HO		
HOLROYD	D	Coll'y Enviro Off	Amcoal - Bank	(013) 291-5300	(013) 291-5312
JACOBS	W		Ingwe - Douglas		
KOEN	D		Centrocen		
MAGARA	B	Sect Mngr	Amcoal - Bank	(013) 291-5300	(013) 291-5312
McLAREN	K B	Sect Mngr	Amcoal - Bank	(013) 291-5300	(013) 291-5312
MOORCROFT	H	Snr Div Enviro Eng	AAC - HO	(011) 638-3453	(011) 638-2610
MOSIA	A	Insp of Mines	Min & Energy Aff - Mpum	(0135)656-1448	(0135)903288
NIEMAN	J	Vent Supt	Ingwe - Delmas	(0157) 2171	(0157)2687
NUMA	M B	E.C.S.	Kriel	(017) 617-1402	(017) 648-1390
PELICANO	D	Chief Enviro Off	Sasol Coal	(017) 614-7035	(017)614-5251
ROMAN	N		New Denmark	(017) 799-0057	(017) 712-5523
SHAND	P	Chief Envir	Iscor - Hlobane	(0386) 71201	(01386) 71493
SIMELANE	A		Sasol Coal	(017) 614-7036	(017) 614-7043
STEENKAMP	B	Prodn Mngr	Ingwe - Delmas	(0157) 2171	(0157)2687
STOLTZ	J G	Env off	Amcoal - Arnot	(0132)97-8111	(0132)97-8029
TATTON	A	Vent Supt	Ingwe - Matla # 1	(017)616-2236	(017)616-2610
THOMPSON	D A	M/O	Rietspruit	(0135) 846-6241	
THOMSON	C A S	Enviro Off	Amcoal - Arnot	(0132)97-8111	(0132)97-8029
TOLLEMACHE	W	Sect Mngr	Amcoal - Bank	(013) 291-5300	(0130 291-5312
VAN AARDT	A	Vent Supt	Ingwe	(013) 295-3111	(013)295-3111 x3225
VAN DIJK	R		Centrocen	(011) 466-2430	(011) 466 - 2414
VAN SCHALKWYK	G B D	Chief Envir Off	Sasol Coal	(017) 614-6024	(017)614-5251
VAN TONDER	G	Mngr: Health & Safe	Iscor - Durnacol	903422) 22355	(03422) 22238
VAN VUUREN	P H	U/g Mngr	Sasol - Twisdraai	(017) 614-7005	(017) 614-7043
VAN ZYL	H C	Snr Div Mining Eng	Amcoal - HO	(011)638-9111	(011)638-2901
VAN ZYL	A J	Vent Supt	Rietspruit	(0135) 846-6241	
VERMEULEN	P	Vent Supt	Khutala	(0135) 648-1411	(0135) 648-1423
VILJOEN	P L J		Sasol Coal	(017) 614-5048	(017)614-5251
YOUNG	K	Vent Supt	Ingwe - Matla	(017) 616-2428	(017) 616-2417
YSSEL	P J	Supt Enviro Control	Sasol Coal	(017) 614-6795	(017)614-5251

Appendix 2

Questionnaire and responses on experiences
of methane emissions and layering in
South African collieries

QUESTIONNAIRE
METHANE IN BORD AND PILLAR WORKINGS.

(a) Past Experiences of Methane Emissions

Details of any unusually high gas flows

Approximate date:

Mine:

Type of Section: (*e.g. CM/Roadheader/Conventional*)

Method of Working: (*e.g. bord and pillar, pillar extraction, longwall*)

Geological features: (*e.g. dyke/fault/sill below/sill above/burnt coal*

Gas content of coal (if known)

      Max. methane concentration:

      Time for concentration to build up:

Ventilation quantity:

Unusual specific emission (m^3 gas emitted per tonne mined):

Air flow in return:

Average gas concentration in return (usual):

Max. gas concentration in return (exceptional):

(b) Past Experiences of Methane Layering

Approximate date:

Mine:

Section/area of mine: (*e.g. heading/outbye*)

Air velocity:

Roadway height: Roadway width:

Max. methane concentration detected :

Length of Layer (if known):

Source of gas:

Remedial action:

General description of the circumstances:

(c) Current Monitoring for Methane Layering

Is routine monitoring undertaken for layering   *Y/N?*

If so, in what parts of the mine?

(e.g. headings/ventilated by low quantities/unsealed outbye areas/all outbye areas)

Please fax completed forms to Professor Huw Phillips at Dept. of Mining Engineering,

University of the Witwatersrand - Fax No. 011 339 8295 by 6 June 1997

QUESTIONNAIRE COMPLETED BY MR ....

QUESTIONNAIRE
METHANE IN BORD AND PILLAR WORKINGS.

(a) Past Experiences of Methane Emissions

Details of any unusually high gas flows

Approximate date: 9 August 1996

Mine: Goedehoop Colliery

Type of Section: Dyke Development

Method of Working: Bord and pillar

Geological features: Burnt coal beneath sill

Gas content of coal (if known): $2,7m^3/Ton$

Max methane concentration: 94%

Time for concentration to build up: 1 hour 5 minutes 0,7% 1 - 83% with force fan switched off

Ventilation quality:

Unusual specific emission (m^3 gas emitted per tonne mined): 0,01 $2m^3/s$ (Steve Development)

Air flow in return: $75,0m^3/s$

Average gas concentration in return (usual): 0,1%

Max. gas concentration in return (exceptional): 0,3%

(b) Past Experiences of Methane Layering

Approximate date:

Mine:

Section/area of mine:

Air velocity:

Roadway height: Roadway width:

Max. methane concentration detected :

Length of Layer (if known):

Source of gas:

Remedial action:

General description of the circumstances:

(c) Current Monitoring for Methane Layering

Is routine monitoring undertaken for layering: Yes

If so, in what parts of the mine? : Headings, unsealed outbye areas and sealed areas

Additional comment: Force fan was stopped at time of incident. *Dal* volume, fan restarted $47m^3/s$

QUESTIONNAIRE COMPLETED BY MR TIENIE BARNARD - GOEDEHOOP COLLIERY - A DIVISION OF AMCOAL COLLIERY AND INDUSTRIAL OPERATIONS LIMITED

QUESTIONNAIRE
METHANE IN BORD AND PILLAR WORKINGS.

(a) Past Experiences of Methane Emissions

Details of any unusually high gas flows

Approximate date: For approximately 2 months during 1995

Mine: No 5 Shaft, DNC

Type of Section: Conventional

Method of Working: Bord and pillar

Geological features: Dyke intersection

Gas content of coal (if known): Liberation from one heading calculated to be ($16m^3$/sx4%) = 640l/s @ 100% CH_4

Max. methane concentration: After dilution (2 force fans) with $16m^3$/s air was measured to be 4%

Time for concentration to build up: Without ventilation exceeded SMAC concentration (1,4%) almost immediately

Ventilation quality: Good - $16m^3$/s

Unusual specific emission (m^3 gas emitted per tonne mined): Above condition persisted in one heading for approximately 3 weeks without any mining being done

Air flow in return: Two return airways each handling approximately $20m^3$/s

Average gas concentration in return (usual): In this section it varied between 0,6% up to 2,5%

Max. gas concentration in return (exceptional): As above

(b) Past Experiences of Methane Layering

Approximate date: June 1994

Mine: No 7 Shaft, DNC

Section/area of mine: 700 Area sealed off

Air velocity: Not measurable

Roadway height: 3,2m   Roadway width: 5,5m

Max. methane concentration detected : 5% plus (due to type of detection instrument used)

Length of Layer (if known): Approximately 400m long and about 1m thick

Source of gas: Sealed off area

Remedial action: Repaired broken stopping

General description of the circumstances: LHD accidentally knocked over stopping thus short circuiting air causing almost zero airflow for dilution purposes

(c) Current Monitoring for Methane Layering

Is routine monitoring undertaken for layering: Yes

If so, in what parts of the mine?: Production headings; Return airways and bleeder roads

Additional comment: The thickness of the layer could accurately be seen by releasing Dräger smoke tube gas below the layer, this smoke cloud rose to form a flat smoke layer beneath the methane layer.

QUESTIONNAIRE COMPLETED BY MR G VAN TONDER - CHIEF ENVIRONMENTAL CONTROL - ISCOR MINING - DNC MINE

QUESTIONNAIRE
METHANE IN BORD AND PILLAR WORKINGS.

(a) Past Experiences of Methane Emissions

Details of any unusually high gas flows

Approximate date: NONE - SEE ATTACHED

Mine:

Type of Section:

Method of Working:

Geological features:

Gas content of coal (if known):

Max methane concentration:

Time for concentration to build up:

Ventilation quality:

Unusual specific emission (m^3 gas emitted per tonne mined):

Air flow in return:

Average gas concentration in return (usual):

Max. gas concentration in return (exceptional):

(b) Past Experiences of Methane Layering

Approximate date:

Mine:

Section/area of mine:

Air velocity:

Roadway height: Roadway width:

Max. methane concentration detected :

Length of Layer (if known):

Source of gas:

Remedial action:

General description of the circumstances:

(c) Current Monitoring for Methane Layering

Is routine monitoring undertaken for layering: No

If so, in what parts of the mine?

QUESTIONNAIRE COMPLETED BY MR ALLAN TATTON - MATLA COLLIERY NO. 3 MINE

METHANE IN BORD & PILLAR WORKINGS

MATLA COLLIERY NO. 3 MINE

A)   Past Experiences of Methane Emissions :

Matla No. 3 Mine does not have a history of unusually high methane emissions. However, a particular section is currently mining under a surface stream and on occasion, if headings are left unventilated, contaminations of ± 1,4% have been known to build up over a period of approximately 1 hour.

Only on rare occasions are any concentrations of methane detected in return air-ways.

From the above information you can see it is quite difficult to accurately answer your individual questions.

B)   Past Experiences of Methane Layering :

Experience of Methane Layering is much the same as outlined in questions (a), although emissions of methane can sometimes be found in very close proximity, ± 5mm, to slips running through a section. These generally cause a problem for 2 to 3 days.

QUESTIONNAIRE
METHANE IN BORD AND PILLAR WORKINGS.

(a) Past Experiences of Methane Emissions

Details of any unusually high gas flows

Approximate date: NONE

Mine:

Type of Section:

Method of Working:

Geological features:

Gas content of coal (if known):

Max methane concentration:

Time for concentration to build up:

Ventilation quality:

Unusual specific emission (m^3 gas emitted per tonne mined):

Air flow in return:

Average gas concentration in return (usual):

Max. gas concentration in return (exceptional):

(b) Past Experiences of Methane Layering

Approximate date: NONE

Mine:

Section/area of mine:

Air velocity:

Roadway height: Roadway width:

Max. methane concentration detected :

Length of Layer (if known):

Source of gas:

Remedial action:

General description of the circumstances:

(c) Current Monitoring for Methane Layering

Is routine monitoring undertaken for layering:

If so, in what parts of the mine?

QUESTIONNAIRE COMPLETED BY MR D PELICANO - CHIEF ENVIRONMENTAL OFFICER -
SECUNDA COLLERIES - SASAL COAL

QUESTIONNAIRE
METHANE IN BORD AND PILLAR WORKINGS.

(a) Past Experiences of Methane Emissions

Details of any unusually high gas flows

Approximate date: November 1974

Mine: Springfield Colliery

Type of Section: Conventional

Method of Working: Bord and pillar

Geological features: Plenty of dykes in area

Gas content of coal (if known): Not known

Max methane concentration: + 5%

Time for concentration to build up: Rapidly within a few minutes of intercepting a borehole by a coal cutter

Ventilation quality:

Unusual specific emission (m^3 gas emitted per tonne mined):

Air flow in return: $\pm$ 20m^3/mm

Average gas concentration in return (usual): + 5% roof layer intake and return

Max. gas concentration in return (exceptional):

(b) Past Experiences of Methane Layering

Approximate date:

Mine:

Section/area of mine:

Air velocity:

Roadway height: Roadway width:

Max. methane concentration detected :

Length of Layer (if known):

Source of gas:

Remedial action:

General description of the circumstances:

(c) Current Monitoring for Methane Layering

Is routine monitoring undertaken for layering:

If so, in what parts of the mine?

QUESTIONNAIRE COMPLETED BY MR H C VAN ZYL - SPRINGFIELD COLLIERY

Appendix 3

Draft practical guidance for South African collieries

APPENDIX 3

DRAFT PRACTICAL GUIDANCE FOR SOUTH AFRICAN COLLIERIES

The Control of Risks Arising from Methane Layering in Bord-and-Pillar Workings

1   The results of SIMRAC research project COL409 (Methane layering in bord-and-pillar workings) including findings from the literature survey, practical experience, underground observations and industry consultation provide a basis for suggesting practical guidance to South African collieries. The following notes are intended to be considered as a draft discussion document.

2   Any methane emitted in the roof of a mine roadway will form a layer. However, provided the velocity of ventilation air is sufficiently high, the gas will be rapidly dispersed and not present a hazard. Layering occurs because of the natural buoyancy of methane which has a density roughly half that of air.

3   The main factors which influence layering are:

●   airflow turbulence - which depends on air velocity, roadway roughness, bends and obstructions. Note that obstructions can cause low velocity regions

●   direction of airflow - air moving counter to the layer flow will more effectively disperse gas than air flowing in the same direction as the layer

●   shape of roadway - uphill layer flow will increase with increase in roadway inclination up to a certain angle above which no further increase occurs

●   rate of gas emission - the higher the gas emission rate, the smaller the slope at which a maximum layer flow rate will occur

●   location of emission - roof emissions invariably lead to some layering. Floor and face emissions can form roof layers if methane flows are sufficiently high in relation to the ventilation airflow.

4   Layering is a complex phenomenon and a single airflow cannot be defined which will ensure satisfactory dispersion of methane in all conditions.

5   A layering number can be estimated to assist both in the identification of locations with methane layering potential and the design of ventilation arrangements to control the hazards. The layering number L_N is obtained from:

$$L_N = \frac{0.6u}{\sqrt[3]{v/w}}$$

where u is air velocity in m/s, v is methane emission in m³/s and w is roadway width in m.

Methane emission rate is difficult to determine when general body flammable gas concentrations are below the detection limit of portable monitoring instruments. In such instances, a working estimate may be obtained by assuming a concentration of say 0.05 per cent in the ventilation air.

Until confirmatory data is obtained specific to bord-and-pillar workings, it is suggested that layering numbers for horizontal roadways are interpreted thus:

$L_N \leq 2$:   then investigation and monitoring for methane layers should be considered

$L_N \geq 5$:   ventilation sufficient to minimise any layering hazard.

6   In large cross-section airways, the fact that flammable gas cannot be detected in the general body using portable instruments is no proof of the absence of sufficient methane to form layers.

7   The most effective preventative measure against the formation of methane layers is adequate and continuous ventilation. A guidance philosophy is therefore proposed which places the emphasis for minimising layering hazards in working sections on maintaining ventilation standards and on gas monitoring in non-working sections where operational constraints do no allow air quantities to be maintained.

8   Once methane is dispersed in air it will not separate out and is no longer a hazard provided the concentration does not approach the lower flammable limit.

9   The most likely sources of both gas and ignitions are found in the headings of operational sections. Continuous ventilation of all blind ends and high standards of fresh air ventilation in CM sections will minimise the explosion risk in the face area. The likelihood of frictional sparking caused by roof falls in worked-out areas igniting methane layers is low as the turbulence caused will tend to disperse the gas and any sparks will usually occur at floor level.

10   The ventilation of extensive outbye areas of intake roadways leading to a working section can be problematic. Where both single intake and single return roadways are formed using brattice, air velocities will be low in the isolated roadways and there may be a potential for methane layers to develop.

11   The distribution of air velocities in parallel intakes and associated cross-cuts are unlikely to be uniform. Damaged or disarrayed brattices, depending on their location can lead to significant changes in airflow distribution allowing methane layers to develop in near stagnant areas.

12   In working sections where a possibility of gas emission in outbye areas has been established, all intake roadways should, in general, be ventilated rather than a specific single intake formed using brattice stoppings in cross-cuts. Estimation of layering numbers supported by underground monitoring investigation should be used to confirm the adequacy of ventilation quantities.

13   A high standard of ventilation across the full length of the working face would ensure that any explosion that did occur in a heading could not be propagated by a methane layer to accumulations of gas in an outbye area should they be present. It is also essential that stone dusting is maintained across the full length of the last-through-road to ensure an ignition or explosion will not propagate a coal dust explosion beyond the face area.

14   It is recommended that existing last-through-road air velocity requirements are strengthened with the air velocity remotely monitored at the return end of the face (already a common practice in some mines). The miner should be equipped with a suitable, portable velocity monitoring instrument and encouraged to conscientiously record readings between every heading at hourly intervals and to both rectify and report any deficiency immediately to the ventilation officer and a nominated underground official.

15   Worked-out districts should be monitored for methane layering if the ventilation quantity has been reduced below the operational minimum and arrangements made to seal off all roadways with an appropriate standard of stopping as soon as possible. The ventilation officer should devise a monitoring and reporting scheme appropriate to the identified level of risk, to the satisfaction of the Manager.

16   Where methane layering is detected, provision should be made to disperse the gas by locally increasing the air velocity. This may involve adjusting or increasing the section ventilation or introducing an auxiliary ventilation device. Brattice hurdles should only be used with caution and the effects carefully monitored. The detection of methane layering should also trigger more regular and intensive monitoring of the section in accordance with a revised scheme approved by the Manager.

17   There is a broad range of approaches which may be applied to the prevention or amelioration of methane layering problems in bord-and-pillar mines and these are summarised in Table A1.

18   There should be no interruptions to local ventilation where it is employed to disperse gas and prevent layering. If the emission source is active, a layer can form rapidly when the ventilation effect is removed.

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19   The accumulation of methane layers in blind headings with low gas makes can usually be prevented by maintaining the continuity of ventilation. In many instances even low circulating airflow quantities will suffice.

20   Areas temporarily sealed-off or isolated pending re-entering for stooping should be re-ventilated with caution using a planned, systematic degassing procedure and confirmed as safe by monitoring. Particular attention should be given to the direction and flow of dispersed gas and measures taken to prevent adverse impact on ventilation and the safety of operations elsewhere in the mine.

21   Non-working sections in which ventilation quantities have been reduced should be examined for flammable gas layers and accumulations before increasing airflows if production is to be restored. A safe procedure should be devised to remove any flammable gas. If necessary. down-stream operations should be suspended until the gas has been removed.

22   The practice of leaving open holes whilst roof-bolting in roadways, prone to roof falls attributed to water and gas pressures above, can encourage the formation of methane layers. The problem is likely to be particularly acute at junctions in high roadway sections where air velocities are invariably low. The impracticality is recognised of increasing the main ventilation quantity to achieve a sufficiently high air velocity to ensure the gas is dispersed. Due to the number and general inaccessibility of emission locations, local ventilation or hurdle sheets may also be unsatisfactory. An approach to consider is to connect a number of boreholes with lightweight pipework (of the type used in United States mines) and discharge the gas through a diffuser into a main return airway. The drainage effect can be assisted with a suitable airmover device.

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Table A1

**Suggested methods for preventing and controlling methane layering
in South African bord-and-pillar workings**

	Gas emission source	Treatment options
1.	Dewatering/degassing borehole in roadway roof.	Continuous local ventilation and monitoring. Local methane drainage using venturi device. Increase main ventilation quantity.
2.	Fractures in roadway roof.	Continuous local ventilation and monitoring. Increase main ventilation quantity.
3.	Migration from completed or non producing sections.	Improve ventilation of non-working sections and implement precautions to ensure safe dilution of displaced gases. Seal off and monitor stoppings. Ensure high ventilation standard in last-through-roads of downstream, series ventilated working sections thus ensuring a migration barrier between potential gas source and high ignition risk coal production areas.
4.	Leakage through stopping.	Pressure-balance stopping to halt gas leakage. Enhance main ventilation airflow to disperse gas and provide migration barrier as above. Improve stopping design and construction. Local ventilation and monitoring.
5.	Geological feature (eg., fault, dyke).	As for 2 above.
6.	Working heading and immediate roof	Jet fan, fan and duct, and brattice systems. Enhance existing machine-mounted ventilation systems involving some or all of following: dust scrubber, air-movers, coanda curtain

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